WET STACKS DESIGN GUIDE

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REPORT SUMMARY

The expense of flue gas reheat has led to increased application of less expensive wet stacks downstream of wet FGD (flue gas desulfurization) systems. Good data is necessary to properly design the wet stack system or serious problems can occur. This design guide summarizes all the latest information and provides guidance on developing detailed design specifications.

Background

A wet stack is a chimney stack, or flue that exhausts saturated, completely scrubbed flue gas downstream from a wet FGD system. All recently designed and constructed wet FGD systems have installed wet stacks. The cost savings over reheating are very significant. However, there are a number of technical issues that utilities must address to achieve a successful installation. This guide provides answers to these questions whether the installation is new or retrofit.

Objectives

- To provide background information and updates of previously published information.
- To summarize current state-of-the-art design.
- To list and discuss important parameters and options.
- To give specific recommendations for wet stack design.

Approach

Investigators collected the information from a literature survey, in-house expertise of contractors, phone contacts with vendors, a utility advisory committee, and a limited number of site visits. They collated and summarized the information to produce the report, which the advisory committee also reviewed.

Results

Information in the guide covers the entire design spectrum for all three wet stack scenarios—a new plant with a wet stack (green field site), a retrofit FGD system with a

wet stack, and conversion of an unscrubbed or reheated stack to wet stack operation. Some of the important issues addressed include regulatory considerations, stack liquid discharge, plume downwash, corrosion/chemical attack, stack height, stack liner geometry, gas velocity in the liner, and liquid collection devices and drainage. In addition, the report also provides a guide to developing a wet stack specification.

EPRI Perspective
Because most new FGD systems include wet stacks, it is imperative that accurate, reliable information is available. This guide contains the most up-to-date information and should be useful for personnel responsible for wet stack designs, specifications, or operation. In addition, the survey of known wet stacks and the listings of suppliers, manufacturers, and contractors for wet stacks also should be good starting points for information on specific situations. Care must be taken to use these recommendations with good engineering judgment and consideration to site specifics.

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ABSTRACT

Because of the high cost of reheat, wet stacks are being considered for new or retrofit applications of wet flue gas desulfurization (FGD) systems in the United States. All retrofit systems designed for compliance with Phase I of the Acid Rain Control program under the Clean Air Act have used wet stacks. For Phase II, utilities with existing wet FGD systems could benefit from overscrubbing. For those units that currently use bypass reheat, this could be accomplished by closing the bypass to treat the entire boiler flue gas stream. This would require conversion to wet stack operation.

Due to the level of interest in these wet stack scenarios for future FGD applications, the Electric Power Research Institute (EPRI), in a tailored collaboration with New York State Electric & Gas (NYSEG), retained Burns & McDonnell and DynaFlow Systems to prepare a design guide for wet stacks. The purpose of this guide is to provide the utility industry with information and recommendations concerning the design and specification of wet stacks.

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BACKGROUND AND OBJECTIVES

1.1 Introduction

A "wet stack" is a chimney, stack, or flue that exhausts saturated, completely scrubbed flue gas. A wet stack is located downstream from a wet flue gas desulfurization (FGD) system. These systems spray slurry into the gas stream, which reduces the sulfur dioxide (SO_2) content, saturates the flue gas, and reduces the temperature of the flue gas to 115 to 130 degrees F. Wet stack operation discussed here does not use any flue gas reheat system or partial bypass.

The 1990 Clean Air Act Amendments (CAAA) require utilities to reduce emissions of sulfur dioxide. Several utilities have added wet FGD systems to comply with Phase I of the CAAA. Other utilities have decided to eliminate partial bypass and scrub 100 percent of their flue gas, to reduce sulfur dioxide emissions as part of their Phase II Compliance Plan. New or retrofit FGD systems typically use wet stack operation because of reduced operating and maintenance costs.

Elimination of stack gas reheat or partial gas bypass eliminates several problems. However, the design of stacks for wet operation must address several new issues that were not present in unscrubbed or reheated gas stack designs. Some of the important issues to consider in the design of a wet stack include the following:

- Regulatory considerations.
- Stack liquid discharge.
- Plume downwash.
- Corrosion/chemical attack.
- Stack height.
- Stack liner geometry.
- Gas velocity in the liner.
- Liquid collection devices and drainage.

The economics favor wet stack operation as compared to stack gas reheat operation. However, there are trade-offs. It is important to make the correct decision, since the results can have a significant impact on the capital and operating costs of an FGD system.

The purpose of this guide is to provide the utility industry with information and recommendations concerning the design and specification of wet stacks. However, these recommendations should not be used without applying good engineering judgment and consideration to site specifics. Operating conditions, design conditions, and economics all play important roles. Goals of the *Wet Stacks Design Guide* are to:

- Provide background information.
- Update previously published information.
- Present current state-of-the-art design.
- Identify the parameters and options that should be considered.
- Give specific recommendations regarding wet stack design.

It is assumed that those who will use this guide have a general familiarity with stack designs and FGD systems. This guide is intended for personnel responsible for designs, specifications, or operation of wet stacks.

The *Wet Stacks Design Guide* focuses on three different scenarios:

- A new plant with a wet stack (green field site).
- A retrofit FGD system with a wet stack.
- Conversion of an unscrubbed or reheated stack to wet stack operation.

Section 1 of this guide provides fundamentals on processes important to wet stacks and discusses objectives. Section 2 addresses new or retrofit wet stack design. Section 3 discusses conversions to wet stack operation. A guide to develop specifications for wet stacks is presented in Section 4. Section 5 includes references and the Appendix includes a glossary, list of known wet stacks, results of the wet stacks industry survey, stack liquid discharge measuring techniques, and process flow chart outlines for new or retrofit wet stack designs and conversions to wet stack operation.

1.2 Scenarios for Wet Stack Utilization

Designing the stack for wet operation without reheat is a viable option for a wet FGD system for both power plant designers and operators concerned with reducing maintenance and increasing system efficiency. There are three primary scenarios for wet stack utilization:

- New unit with wet stack.
- Retrofit scrubber with wet stack.
- Conversion to wet stack operation.

The first scenario occurs when adding a new unit that incorporates a wet scrubber and a wet stack. In this case, the designer is given the most freedom regarding liner material selection and stack geometry. State-of-the-art wet stack design should be used that is based on the latest analytical, experimental and field data available. The goal is to produce a design that minimizes corrosion problems and operating costs.

The second scenario is adding a new wet scrubber to an existing power plant. In this case, the most important design consideration is whether or not the existing stack, liner and ductwork are capable of accommodating the new wet environment from a material standpoint and from an operational standpoint. If not, then the existing chimney liner must be modified. Due to the outage time required to modify an existing stack, it is usually more economical to build a new stack for scrubbed gas and use the existing stack for gas bypass around the scrubber as needed.

The third scenario is operating an existing wet scrubber with reheat or some percentage of bypass. In order to decrease SO_2 emissions and reduce operating and maintenance costs, the unit would be converted to 100 percent wet operation which would completely eliminate reheat or gas bypass. Deciding whether to convert an existing stack to wet operation involves the ability of the existing material to withstand the cool, wet conditions and whether the gas velocity will result in moisture reentrainment from the stack walls. Required modifications could include the need to line the stack, build liquid collection devices (such as drains and gutters) into the stack, or improving the mist elimination system to limit droplet carryover.

1.3 Problems with Reheat Systems

In the past, flue gas reheat systems (in-line, indirect hot air or direct combustion and bypass) have been specified to decrease moisture plumes and/or reduce ground level SO_2 concentrations. Unfortunately, these systems have proven to be overly expensive and minimally effective. The minimal benefits associated with reheat have been well documented documented.(2). Reheat systems are quite expensive due to high installation and operating costs. In-line and indirect hot air systems also have high maintenance costs and are likely to negatively affect plant reliability. Wet stack operation offers advantages of improved thermal efficiency, reduced maintenance costs, and higher plant reliability. The issues related to problems with reheat are summarized below.

1.3.1 Effectiveness

Reheat is utilized for both physical and environmental issues. Physical issues are the prevention of condensation or the corrosion of the duct and liner wall surfaces. Environmental issues are after the gas leaves the stack such as liquid fallout, plume rise and plume visibility. The effectiveness of reheat in serving these purposes is discussed in the following sections.

1.3.1.1 Physical.

Water that is not removed by the scrubber can condense on the duct walls and absorb SO_2 to form dilute sulfuric acid in the ductwork and stack. Concerned about the stack liner's exposure to an acidic environment, many utilities have used stack gas reheat to increase flue gas temperatures. Reheat increases the temperature of the flue gas above the water saturation level and helps evaporate some of the liquid. Reheat is intended to reduce or prevent condensation of vapor from the gas and promote evaporation of liquid (suspended droplets and the liquid film on the walls), by decreasing the relative humidity of the saturated, scrubbed gas. To completely prevent condensation in the duct and stack, it is necessary to keep the inside wall surface temperature above the dewpoint temperature of the stack gas mixture. The bulk of the stack gas must be maintained at a high enough temperature to prevent water condensation on the duct and liner surfaces. A reheat system that is not operating properly would allow water on these surfaces to absorb acid. Condensed acid deposition on these surfaces could cause corrosion.

Having sufficient heat capacity to evaporate droplets suspended in the gas flow does not assure complete evaporation. This is due to the limited rate of heat transfer to the droplets. These droplets can range in size from small (1 to 30 µm), which are carried over directly from the mist eliminators, to large (200 to 1000 µm), which are produced by reentrainment from the duct walls and also from carryover from the mist eliminators, if plugged or not operating properly. Some reentrainment is virtually inevitable in a duct/stack system. Reheat will evaporate the fine mist (d<50 µm) but is completely ineffective in evaporating the larger droplets (d>200 µm) that have been reentrained by the gas flow from the deposited liquid film. These droplets are too large to be appreciably reduced in size by the reheat during the residence time in the duct and stack.

1.3.1.2 Environmental.

In addition to preventing condensation in the ductwork and stack, reheat is also used to:

- Decrease stack liquid discharge.
- Increase plume rise.
- Eliminate a visible plume.

The large droplets are more likely to cause stack liquid discharge detectable at ground level near the stack. Reheat cannot be justified solely on the basis of eliminating stack liquid discharge. The large droplets are not evaporated because they do no have the sufficient residence time required to evaporate completely. They are only reduced in size. Reheat will lower the relative humidity of the flue gas. However, lower moisture content of the gas may result in higher acid concentrations in the droplet deposition.

Reheating provides about 10 to 20 feet (3-6m) of additional plume rise which is a small increase relative to the stack height. Therefore, this results in only a small decrease in ground level concentrations compared to wet stack operation. In addition, there is an increase in overall emissions from the plant on a pounds per million BTU basis as more energy is required for the same plant output. As indicated in Section 2, the estimated annual energy costs for flue gas reheat on a 325 MW unit is $456,000.

Saturated flue gas will form a visible plume. A visible plume has no physical impact on the environment, but it could be considered aesthetically undesirable. Prevention of a visible plume with reheat cannot be achieved within the normal reheat temperature ranges. Vapor plume formation is highly dependent on meteorological conditions. The prevention of a visible plume by reheat under all meteorological conditions is beyond practical limits. For the typical reheat case, the visible length of the plume is decreased by approximately one-third the length of a wet plume.

1.3.2 Economics/Thermal Efficiency

In an economic evaluation, capital, operating and maintenance costs must be considered. The most significant disadvantage of a reheat system as part of the FGD process is cost. Reheaters are expensive. Capital costs associated with reheaters include the costs of the reheat equipment and installation. Operating costs include energy and capacity charges. The energy costs to reheat the flue gas are usually the most significant costs. Operational costs are high due to the significant percent of boiler heat input required. Installed reheat systems are an expensive consumer of energy. Maintenance costs are difficult to determine, but should consider the labor and material expenses required to replace reheat coils. All of these costs should be evaluated when determining the economics of reheat.

The heat required to vaporize entrained liquid depends on the amount of liquid present, the thermal conductivity of the material, and the amount of heat loss to the environment. Residence time is usually not sufficient for reheat to evaporate the large droplets in the flue gas stream. Also, the energy required to reheat the flue gas reduces the thermal efficiency of the steam generating unit or boiler. For example, on a 600 MW unit, the unit derating resulting from reheater steam use was 1.4 percent. Additional power is also required for in-line reheat systems because of the pressure loss across the reheater tube bundles. These costs need to be included in the economic evaluation for reheat design.

1.3.3 Maintenance

In general, reheat systems require a significant amount of upkeep. During a typical outage, plants with reheat systems put a large amount of labor and expenses toward repairing their reheat system. This is especially true with in-line reheat systems not constructed from corrosion resistant materials. Corrosion forces the removal of reheater tubes, and sometimes entire reheat systems require replacement. Pluggage is a major maintenance item because the finned tubes installed in the heat exchanger are easily fouled by deposits of solids. If a reheat system is used, corrosionand pluggage are reduced by using nickel alloy materials for the reheat system, using a pH control system, and installing efficient mist eliminators.

1.3.3.1 Corrosion.

Corrosion of the various reheat systems used in FGD systems reduces unit efficiency and requires expensive maintenance. In-line steam reheaters experience various levels of corrosion ranging from moderate to extreme, depending on the materials of construction. Chloride stress corrosion cracking and acid corrosion have been serious problems for in-line reheat systems. At many facilities, stress corrosion and acid attack have forced the removal of reheater tubes; at several facilities, entire reheat systems have required replacement. Without chlorides present, corrosion problems decrease considerably when expensive higher grade alloys are used in manufacturing the reheater. Reheater corrosion problems usually require the unit to be off-line to make the necessary repairs, which is another disadvantage of operating a reheat system.

Corrosion resistance and other advantages and disadvantages of different materials of construction are provided in Table 2-5 in Section 2. To select corrosion resistant materials of construction for absorber outlet ducts and stack liners, it is important to understand the operating environment. There are basically four types of flue gas which may be present downstream of an FGD system:

- Unscrubbed or bypass flue gas.
- Scrubbed, nonreheated flue gas.
- Reheated, scrubbed flue gas.
- Partial bypass reheat or mixed flue gas.

Unscrubbed or bypass flue gas is typically 250 to 350 degrees F (121-177 °C), which is usually above the sulfuric acid dewpoint temperature. Depending on the sulfur content of the coal and the moisture content of the flue gas, the sulfuric acid dewpoint of the unscrubbed bypass gas is 260 to 300 degrees F (127-149°C). Unscrubbed flue gas produces an acid aerosol that is entrained in the gas stream. Corrosion in an unscrubbed duct/stack system is only a problem if the acid in the flue gas condenses, which will produce concentrated sulfuric acid.

Scrubbed gas is typically 115 to 130 degrees F (46-54°C)and is completely saturated and may contain condensed water. Scrubbed gas duct or liner surfaces are always wet and below the acid dewpoint and therefore require corrosion resistant material. Corrosion problems with wet operation are less than with reheat operation. However, wet operation may require a larger area of ductwork to be fabricated from corrosion resistant materials than reheat.

Reheated, scrubbed flue gas is typically 150 to 190 degrees F (66-88 °C). Stack gas reheaters normally provide 30 to 60 degrees F (17-34 °C) of reheat. The intent of reheat is to eliminate condensation. If liquid droplets are formed, they will be evaporated through reheat. For aneffective reheat system, the flue gas must be reheated sufficiently so that the resulting duct or liner wall temperature is above the dewpoint temperature of the flue gas. In many installations, reheat systems have proven to be not totally effective. Corrosion of the ductwork in the mixing zone is typically a problem. With reheat, the moisture in the flue gas is evaporated, which lowers the pH of the mixing zone and creates a more corrosive environment. (1,2). Louisville Gas and Electric Mill Creek Units 1, 2, 3 and 4 has experienced downstream corrosion of carbon steel ductwork due to ineffective reheat. Mill Creek Units 1 and 3 are being lined with Alloy C276. At TMPA Gibbons Creek, carbon steel absorber outlet ducts and duct to stack had to be lined with vinyl ester coating due to corrosion.

Partial bypass reheat is the worst from a corrosion standpoint because of particulate buildup and condensation of sulfuric acid. Wet scrubbers do a good job of removing remaining particulate from the gas stream. The FGD industry has learned through experience that of all the corrosive environments that can be found within a wet scrubber system, one of the most severe conditions is mixing scrubbed and unscrubbed flue gas. The scrubbed gas, which has passed through the absorbers, has already been dropped well below its acid dewpoint. Although this scrubbed gas does not contain any significant concentration of sulfuric acid vapor, its temperature is low enough to cool the bypass gas stream significantly when the two flue gas streams are mixed. The sulfuric acid dewpoint of the mixed gas will be about 250 degrees F (121 °C). (10). This is based on 15% moisture and 1.0 ppm H_2SO_4 in the flue gas.

The temperature of the metal surfaces in the ductwork downstream of the confluence of the bypass duct and the absorber outlet duct is typically at or below 200 degrees F (93 °C). Bypassed or mixed gas coming into contact with these surfaces will result in sulfuric acid condensation. The concentration of the acid that condenses will be approximately 60 to 70 percent H_2SO_4 and is capable of producing severe corrosion of ductwork, dampers and stack liners. The continuous bypass flow provides an essentially unlimited supply of acid vapor for further condensation, which can result in a continuous cycle of condensation and corrosion. The moist flue gas will also cause particulate scale to build up on duct or liner surfaces, which adds to the corrosion problems.

1.3.3.2 Pluggage.

A problem with in-line reheat is that tube bundles tend to plug. Plugging occurs when dissolved solids carry over from the absorber through the mist eliminator. Deposition of dissolved solids on the hot heat exchanger surface creates scaling on the tube bundles. Plugging can be a more severe problem than corrosion because it increases pressure drop across the reheater, thus decreasing heat transfer and increasing fan discharge pressure requirements.

In-line reheaters can also use pressurized hot water as the heating medium instead of steam. This type of in-line reheater, which operates at lower temperatures, tends to have less corrosion but experiences more pluggage. Pluggage problems for pressurized hot water systems have been a major maintenance item because the finned tubes installed in the heat exchanger are easily fouled by solids deposition. (13).

1.3.4 Reliability

The reliability of reheat systems is critical to the economics of operating a power plant and maintaining a clean environment. The FGD industry mistaken thought that simple heat exchangers inside or outside the ductwork environment could be used at relatively high operability rates. In fact, while corrosion prevention is the most commonly cited reason for using reheat, the reheat systems are subject to the very problems that they are intended to prevent.

To avoid the problems with pluggage and corrosion, some plants use indirect hot air reheat. Indirect hot air reheat heats air in an external heat exchanger and then mixes it with the exit flue gas. Indirect hot air reheat systems are more reliable than in-line reheat. Because these systems are normally external to the flue gas stream, they are not as prone to plugging or corrosion.

A very common reheat method is partial bypass reheat. Partial bypass reheat may not require the maintenance that other reheat systems require. However, this reheat method produces a very corrosive environment (sulfuric acid condensation and buildup of solids) in the absorber outlet duct and stack and also increases SO_2 emissions. Eliminating partial bypass reheat would decrease SO_2 emissions and allow utilities to bank or sell the excess SO_2 allowances.

1.4 Important Considerations for Wet Stack Design and Operation

Several potentially important issues must be considered for the design of a wet stack. A summary of these issues are presented in this Section. More detail will be presented in later sections.

1.4.1 Regulatory Considerations

To meet Environmental Protection Agency (EPA) regulations and appropriately address permitting issues, the following topics need to be considered:

1.4.1.1 Ground Level Concentrations/Dispersion Modeling.

Projects involving the construction of a new wet stack or the modification of an existing stack to wet operation must consider the effects of the pollutant emissions on ambient air quality. Ground level concentrations (GLC) must be attained so meet the requirements of the National Ambient Air Quality Standards (NAAQS). Demonstration of NAAQS compliance by dispersion modeling is needed for the criteria pollutants - sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter less than 10 microns in size (PM-10). Prevention of significant deterioration (PSD) increments also exist for SO_2, NO_2, and PM-10. The purpose of the PSD program is to prevent large increases in GLC in attainment areas. The cumulative increase in GLC is accounted for since the baseline data must not exceed the PSD increment. The state/local air quality control program must track changes in increment consumption through modeling. Changes to stack parameters associated with conversion to wet stack operation might require reassessment of increment consumption. Dispersion modeling uses computational techniques to estimate atmospheric concentrations of contaminants from different types of sources.

1.4.1.2 Permitting Issues.

With regard to PSD permit program applicability, an existing stack that has been modified through physical change or change in method of operation will *not* require a permit unless there is an accompanying increase in emissions. However, an air quality impact analysis may be required by the EPA, state, or local air quality agency. In conjunction with this analysis, the issues of stack height and dispersion techniques must be addressed. For new stacks, good engineering practice (GEP) stack height regulations apply. The GEP height is a function of the height of the building or other nearby structure. The stack height regulation is covered by the EPA in Title 40 Code of Federal Regulations (CFR) Part 51. Most states have adopted stack height regulations consistent with these federal requirements.

These regulations require that the degree of emissions limitation required for control of an air pollutant shall not be affected by the portion of the stack height above GEP, or by any other dispersion technique. Dispersion techniques include the manipulation of stack parameters. Installation of a choke on a stack would constitute a dispersion technique. The regulations do not prohibit the installation of a choke. Rather, they prohibit inclusion of its effect on plume rise in the air quality analysis or in the setting of emission limits.

1.4.2 Sources of Liquid in Wet Stacks

The liquid inside the stacks comes from the moisture content of the gas flow entering chimneys of units with a wet FGD system. The moisture is vapor in the gas and droplets of various diameters carried by the gas stream. The vapor content is usually the maximum that can occur when the flue gas is saturated with water vapor. If there is an induced draft (I.D.) fan between the absorber and the stack, the fan temperature rise will result in a lower than saturation vapor content. What happens to the vapor and liquid content before the gas reaches the top of the liner defines how much liquid and in what form it is discharged from the stack. The major gas liquid flow processes that may lead to the stack liquid discharge are described in the next four subsections, including the major features of the stack liquid discharge. A description of the liquid flow balance in wet stacks is provided on pages 4-3 to 4-5 of Reference (1). Liquid flow rates typical for wet ducts and stacks are given in Section 2, "Condensation Calculations."

1.4.2.1 Mist Eliminator Carryover.

The gas stream leaving the mist eliminator is saturated with water vapor and entrained fine liquid droplets are carried by the gas flow under ideal design and operating conditions. It is important that the mist eliminators operate properly to minimize the size and rate of droplet carryover. The mist eliminators are meant to reduce carryover of liquid and slurry to the downstream ductwork. Mist eliminator problems can result in increased liquid carryover. Some larger droplets may also be present in the gas stream that have been reentrained from the mist eliminator blades, the mist eliminator support structure, and areas of solids buildup on the mist eliminator. During the wash cycles, washing the mist eliminator can also increase the amount of liquid carried with the gas flow downstream of the mist eliminator.

A field evaluation of the mist eliminator performance can be made by performing visual inspections. If carryover problems are noticeable, stack liquid discharge is probable if effectiveliquid collectors are not installed in the duct and the stack. The mist eliminator selection, operation performance and possible problems are described in Reference (3).

1.4.2.2 Deposition of Entrained Liquid Droplets.

As droplets flow with the flue gas, they will impinge on internal surfaces due to droplet trajectory paths controlled by the earth's gravity, centrifugal forces on the droplets when the gas flow turns, and gas drag forces. Large droplets (100-2000 μm) deposit more readily from the gas flow path, intermediate droplets (10-200 μm) deposit partially, and small droplets (0.1-10 μm) deposit hardly at all. The higher the gas velocity and sharper the turn of the flue gas path, the more likely that significant numbers of droplets will impinge on walls, turning vanes, baffles, and on internal duct components (bracing, gusset plates and expansion joints).

Small to medium droplets can also deposit on surfaces due to gas flow patterns in separation regions and by turbulent deposition. The turbulent deposition of fine droplets due to adiabatic condensation (due to pressure reduction with elevation change) along the height of the stack is small. The gas velocity, duct geometry, stack geometry, and droplet size govern the amount and location of liquid deposition. The major deposition area in the stack is on the liner opposite of the breeching duct.

Liquid deposition can be promoted and liquid collected by properly designed collection devices, vanes, and baffles installed in the duct system. Maximum deposition and collection of the liquid on the duct walls and stack liners must be achieved in order to control stack liquid discharge. One of the main objectives of physical flow modeling is to design and develop liquid collectors such as ceiling gutters, side wall channels, and floor guides to collect deposited liquid before reentrainment can take place. This process is discussed in Section 2 under "Laboratory Flow Modeling."

Another deposition area is on the choke surface in stacks that have chokes. Some of the fine droplets entrained in the gas flow will be deposited on the choke surface and the liquid collected on the choke will lead to stack liquid discharge if the local gas velocities in the choke are high enough to drag the liquid up to the top of the choke.

1.4.2.3 Condensation.

One of the sources of liquid in the wet duct/stack system is condensation of water vapor from the saturated gas flow. Two types of condensation take place in wet stacks.

Adiabatic Condensation (or bulk condensation) occurs in the bulk of the gas as the pressure of the saturated gas flow decreases due to pressure loss and elevation change along the height of the stack. The decrease of absolute pressure of the saturated gas causes water vapor to condense on other fine droplets or small solid particles in the bulk of the gas. Droplets formed by this heterogeneous condensation will tend to be very small. Only a very small fraction of this adiabatic condensation reaches the liner surface by turbulent deposition process. The rest is discharged, which creates the familiar white plume and evaporates as the plume mixes with the outside air.

Thermal Condensation (or wall condensation) due to heat transfer is important in wet stacks. Since the saturated flue gas temperature is usually between 120 to 130 degrees F (49-54 °C), heat transfer through the liner, the annulus and the concrete shell to the cooler surrounding ambient air causes water vapor to condense on the inside of the stack liner. The rate of condensation due to heat transfer are functions of the liner and shell construction and the liner insulation, the gas flow conditions, and the atmospheric conditions (i.e., ambient temperature, wind velocity, and barometric pressure.).

Annulus pressurization of the brick liner stacks increases the rate of condensation on the liner surfaces. Leakage of pressurizing air through the liner in older brick stacks can significantly increase the condensation. Insulation of alloy and FRP liners reduces the thermal condensation rate significantly. Condensation rates are calculated for three selected typical stack designs in Section 2 under "Condensation Calculations."

1.4.2.4 Reentrainment.

The liquid on the liner surface produced by deposition and condensation flows in the form of film or rivulets as governed by gravitational, surface tension, and gas shear forces. The gas shear force can shear the liquid off the surface, causing reentrainment. This is the most frequent source of stack liquid discharge and fallout of liquid droplets in the vicinity of the stack.

Reentrainment most frequently occurs because of one or more of the following:

- High gas velocity shear near rough surfaces with liquid deposits.
- Instability of the liquid film (waves and ripples) on vertical stack liner surfaces. This occurs because as gravity is pulling the liquid film or droplet down, the gas drag forces are pulling the liquid film or droplet upward.
- Surface discontinuities and protrusions that disrupt gas and liquid flow locally.
- Vanes and baffles that cause gas flow separation and recirculating liquid flow and reentrainment.
- Gas flow patterns that drag liquid along the surface to reentrainment sites.
- Strong vortex patterns that can pick water up in the core of the vortex from horizontal or vertical surfaces.

Reentrainment takes place at locations such as:

- Duct walls, roofs, floors, and stack liner surfaces.
- Dampers, damper blade guides, and trusses.
- Thermal expansion joints.
- Trailing edges of turning vanes.
- Duct junction corners.
- Breeching duct area changes.
- Stack floor.
- Stack liner surface, particularly in the entrance region and the intersection with the breeching duct.
- Internal solid buildup or scaling on surfaces.

- Stack liner contraction sections.
- Stack choke surfaces.

Liquid reentrainment at these locations will be in the form of large droplets (200-1500 µm) and will be discharged at the top of the stack if not prevented by a combination of favorable gas flow path design and an optimized liquid collector system. Droplets over 100 µm do not evaporate outside of the stack and they will likely reach the ground level.

1.4.2.5 Washing of Wet Fans.

Occasionally, induced draft fans will be located between the absorbers and the stack of a utility power plant when retrofitted with an FGD system. These fans usually require periodic or continuous washing to prevent solids buildup on the fan impellers, which can cause fan rotor imbalance. All of the liquid sprayed into the fan inlet leaves the fan impeller as droplets. Most of the liquid will be propelled by the high centrifugal force field to the fan scroll, where it deposits but immediately reentrains due to the high gas stream velocity. Most of the washing liquid will escape the fan discharge as droplets entrained in the gas stream, causing additional liquid load in the ducts and in the stack. Fans should preferably be located upstream from the absorber to avoid these problems.

1.4.2.6 Stack Liquid Discharge.

The stack liquid discharge (SLD) is also known as rainout or acid mist fallout. It is important to note that all wet stacks have some amount of stack liquid discharge. However, stack liquid discharge is only a problem if the droplets are large enough that they are detectable at ground level near the stack.

The amount of liquid discharged at the top of the stack is a result of gas and liquid flow processes that take place in the ductwork and stack system between the discharge of the absorbers and the top of the stack liner. The source of the liquid discharge can be categorized by the liquid flow process and by the droplet sizes as follows:

- Liquid droplets carried from the absorber to the top of the stack liner by the gas stream without depositing along the gas flow path. Only small droplets (<50 µm) travel through theducts without deposition. This means that most conventional scrubber designs, with horizontal ducts connecting the absorber to the stack, will result in deposition of most large droplets on the duct surfaces.
- Droplets reentrained from liquid deposition and condensation on duct surfaces that can be discharged. These are large drops and they are usually the major contributors to the stack liquid discharge.

- Droplets formed by bulk condensation. These represent a large liquid flow rate but very fine droplets, which results in a negligible effect on the stack liquid discharges detectable at ground level.
- Liquid deposited and condensed on the liner flows upward in those areas of the stack where the gas velocity is higher than the flow reversal velocity for the liner material. The droplet sizes reentrained at the top of the liner where velocities are highest can be quite large (300-2000 μm), depending on the liner top geometry. The upper section of a stack choke is usually in this mode of upward liquid flow.

The quantity and location of the fallout at a given plant is a function of the droplet size distribution of the discharged liquid and atmospheric conditions such as ambient temperature, wind, relative humidity, and turbulence level. The very small droplets of the bulk condensation make the gas plume white and visible. The plume is cooled as it mixes with the surrounding air. This cooling results in condensation on the small droplets in the plume. The increase in diameter is only 1 to 10 μm, and therefore, the droplets of the bulk condensation do not fall to the ground and cannot be detected. The mixing with the drier air away from the stack causes droplet evaporation. The balance between the cooling and mixing processes defines the length of the visible plume. Therefore, it is a function of the ambient air temperature and the air relative humidity.

One of the major objectives in developing an effective wet stack design is to limit stack liquid discharge to a minimum acceptable level. The purpose is to limit the droplet size that will exit the stack. If the droplets are small enough they will evaporate before hitting the ground. However, if the droplets are large they will land on plant structures, equipment, cars, etc. Based on the wet stack survey, fallout of liquid droplets, if noticeable, occurs usually within a half-mile radius of the stack.

1.4.3 Corrosion/Chemical Attack

With wet stack operation, corrosion is less severe than with reheat but it still must be considered. However, the corrosion can be prevented. The floors of the ductwork should be sloped to provide proper drainage of the corrosive liquid after shutdown of the unit. The exposed materials of the ductwork and the stack liner must be resistant to chemical attack. Several types of material are available for both the scrubber outlet duct and the stack liner. The materials are selected considering their corrosion resistance to the chemical properties of the flue gas downstream fromthe absorber. Corrosion prevention can be achieved with current liquid collection technology and material availability. Refer to Section 2 of this design guide dealing with materials of construction for more information.

1.4.4 Plume Downwash

Designing for a low velocity plume can decrease the amount of stack liquid discharge. However, it increases the potential for plume downwash at elevated wind velocities. During downwash episodes, saturated flue gas comes in contact with the liner extension, stack hood and stack shell. This can lead to deterioration of the stack construction materials due to exposure to acid in the flue gas. It also increases the potential for ice formation on the top of the stack. The potential deterioration problem is a long-term situation caused by continual exposure to SO_2 and has been evident in recent years by the deteriorating conditions of tombstones, stone buildings, and the top of stack shells. The icing problem can occur at below freezing conditions all winter long, every winter, and creates a potential danger to people and property. Across-wind at the top of the stack will deflect the plume from its vertical path. As the ratio of vertical plume momentum to horizontal wind momentum $((\rho V^2)_{FLUEGAS} / (\rho V^2)_{WIND})$ falls below a value of about 2.0 for a single flue stack, the plume may become partially entrained in the vortex patterns that are formed on the downwind side of the stack. This phenomenon is known as plume downwash. To reduce the frequency of downwash, the momentum ratio must be increased, either by reducing the liner diameter or by installing a choke at the top of the liner.

For a multiple flue stack, the equivalent momentum ratios for initiation of plume downwash are higher and vary with the wind direction. The reduced static pressure in the wind vortices generated off the stack shell and liner extensions can draw the flue gas into a downwash pattern along the stack shell. In the process, the saturated flue gases that are drawn into the vortices come into contact with the roof and sides of the stack liner and shell.

The interaction of a plume with the across-wind is a function of the following parameters:

1. Stack and liner geometry such as:
- Liner extension diameter.
- Shell diameter.
- Liner extension.
- Roof shape.
- Number of liners.
2. Wind direction, velocity, and air density at the top of the stack.
3. The annual frequency of wind occurrence as a function of wind velocity.
4. Liner exit gas velocity and gas density.

5. Plume buoyancy due to flue gas temperature.

The most important fluid dynamic parameter is the momentum ratio between the stack exit flow and the across-wind. This ratio defines the relative influence of each flow upon the other and is determined by the densities and velocities of the flue gas and the wind. This momentum ratio is defined as $(\rho V^2)_{FLUEGAS}/(\rho V^2)_{WIND}$). Plume downwash is most likely to occur during reduced unit load operation where stack discharge velocities are reduced and during high wind conditions. Plume downwash is least likely to occur under the opposite conditions of high unit load operation and low wind velocity. For a multiple flue stack, the liner extension height above the shell is also very important for minimizing plume downwash. The selection of the stack top geometry and stack discharge velocity for good plume escape must also consider the stack discharge velocity for plume dispersion and stack liner velocity. This is to prevent reentrainment of liquid from the stack liner, expansion joints, and stack choke.

1.4.5 Icing Potential

Whether ice forms on the top of the stack depends on the temperature of the surface, the temperature of the mixture of saturated flue gas and cold ambient wind, and whether water vapor will condense out of the mixture. Ice formation is most likely at plants where below freezing temperatures are common and last for extended periods of time.

The locations for potential ice formation are discussed below:

The liner extension for single or multiple liners	-	The liner extension is the first element exposed to plume downwash. If the liner extension is liners uninsulated, the surface should always be above freezing temperature. No ice could form but some condensation might occur that would then run down to the stack roof.An insulated extension might have some ice formation.
The hood for a single flue stack	-	The hood is the second element exposed to plume downwash. A hood for a single flue stack is usually connected to the stack, liner, and liner extension, which helps to keep it warm. When ice forms on an outward sloping hood, it usually forms off the upwind edge and/or in the downwind half at two locations about 45 degrees off the axis of the wind direction. These icicles form similar to those on the roof valley of a house.
The roof of a multiple liner stack	-	The stack roof usually does not directly touch the liners to permit expansion and movement of the liners. The roof will receive heat from inside the stack. Liquid must be drained from the roof area. Drains should preferably be located on the inside of the column to

keep from freezing.

Railings	-	The metal railings at the top of the shell will quickly cool to the mixture temperature of the flue gas and ambient air and will be the first surfaces to form ice. This is the most likely place for ice to form.
Platform near top of stack	-	A metal platform on the outside of the stack near the top can also be exposed to low concentrations of flue gas. Since it is metal and exposed to the ambient and flue gas mixture temperature, it may also experience occasional ice buildup. This is the second most likely place for ice to form.
Shell	-	The shell will receive some heat from inside the stack. If ice forms on the shell, it is expected to be in the downwind side of the stack. This condition occurs when visible downwash can be seen on the downwind side of the stack shell.

Icing usually does not cause serious ice buildups that can fall to the ground. However, when the icing conditions are occurring, the platform near the top of the stack, the railings, and possibly the roof may be slippery.

The potential for icing can be reduced by the following steps:

1. Select a stack liner discharge velocity that minimizes plume downwash over the expected operating range of the unit at the existing local wind conditions and that is consistent with other design objectives.
2. In cold ambient temperature with high wind conditions, run the unit near full load. This may be a natural situation, since more power is consumed in below freezing weather.
3. Use heated annulus air or electrical heating elements to heat the stack hood or roof or other areas where ice forms on the top of the stack.
4. Insulation is not required on sloped rainhoods constructed of a corrosion resistant material.

1.4.6 Dispersion (Ground Level Concentrations Within Acceptable Limits)

In addition to emission standards, power facilities must meet standards for ground level concentrations set by state and federal regulations. Meeting emission standards does not assure the meeting of ground level concentration standards. Ground level concentrations (GLC) aredependent on emissions, stack height, flue gas characteristics, nearby terrain and building features, and meteorological conditions. Flue gas from a wet stack system is cooler and therefore less buoyant than reheated flue gas, so stack gas reheat systems should have lower ground level concentrations than wet systems.

Based on previous experience, actual modeling rarely shows reheat to be the difference between compliance and noncompliance.

If predicted ground level concentration modeling from new or modified sources proves to be a problem, a number of methods to decrease concentrations through reduced emissions can be examined as part of a feasibility study. For new sources, increased stack height could be considered. SO_2 removal efficiency may also be enhanced by using dibasic acid (DBA) or by mechanical modifications to the design of the absorbers. This could offset the increase in ground level concentrations caused by eliminating reheat (lower plume rise). Meeting ground level concentration standards through reduction in emissions is likely to be a more effective solution than stack gas reheat.

1.4.7 Installed Costs

The installed cost of an FGD system without reheat may be lower than the installed cost of a FGD system with reheat. (4).

A wet stack system does not require additional fuel costs or equipment costs associated with reheat. These costs however are partially offset by the more expensive liner construction material required for the corrosive environment of a wet stack and by the larger liner diameter required to promote liquid collection.

The height and diameter of a wet stack can be minimized by controlling the quantity and size of liquid droplets entering the stack. Components (liquid collectors and drains) to reduce the quantity and size of liquid droplets entering the stack should be used if they are more cost-effective than a larger stack. In addition, stacks can be reduced in size by selecting alternative liner materials that allow a higher stack velocity.

1.4.8 Maintenance Costs

A wet FGD system operating without reheat may typically have lower maintenance costs than a FGD system with reheat.

Partial bypass reheat requires additional ductwork that needs to be maintained. The area where the bypass ductwork meets the outlet ductwork is a highly corrosive environment and is usually a high maintenance area.

Wet stack operation requires less equipment to be maintained. In-line reheaters require routine maintenance of piping, valves, reheater tubes, condensate drain traps, etc. In-line reheaters also require periodic replacement due to corrosion.

1.4.9 CEM Systems

The Continuous Emission Monitoring (CEM) Systems requirements for wet stack applications are generally the same for unscrubbed and reheat applications with the exception of monitoring opacity. Opacity monitors will not function properly in a wet stack because water droplets will result in high opacity readings. The EPA has exempted wet stack units from monitoring opacity that are otherwise, affected by the acid rain program. However, no such exemption has been granted for new source performance standard units. In addition there may be local requirements for monitoring opacity.

1.5 Contents of the Design Guide

The main contents of the design guide is presented to provide the industry with information concerning the design and specification of wet stacks.

1.5.1 Information About Key Issues

A main objective of the *Wet Stacks Design Guide* is to provide the latest information about key issues. For example, the design guide contains discussion on gas velocity, liner materials of construction, liquid collection devices and drainage, continuous emissions monitoring systems, flow modeling, etc. This guide is not a step by step guide, but is intended to provide background information and identify the parameters to consider in wet stack design, in order to help utilities and engineers select the right path. A key to successful design of a wet stack is understanding the choices available. This design guide focuses on what options should be considered, what the constraints are, and what effect variations in the parameters have on the design of a wet stack. For example, the design guide discusses the impact a choke has on a brick lined chimney and the options available regarding alloy liner construction.

1.5.2 Knowledge of the State-of-the-Art

Another main objective of this *Wet Stacks Design Guide* is to summarize the latest technology available regarding wet stacks. This design guide is a follow-up to EPRI's Report CS-2520 *Entrainment In Wet Stacks* (1), that was published in 1982. The *Wet Stacks Design Guide* contains a presentation of the latest information available, updating what has been done in the last 12 years. A total of twenty five existing units were retrofitted with wet scrubbers under Phase I of the 1990 Clean Air Act Amendments. Each of these units has a wet stack. This design guide will summarize the latest wet stack technology used for the Phase I scrubber projects, as well as new units that are under construction and units that have eliminated reheat and converted to wet stack operation.

1.5.3 Preliminary Assessment of Feasibility

New or retrofit FGD units are typically designed for wet stack operation. A feasibility study is normally conducted to determine layout, materials of construction, economics, construction time, etc. The *Wet Stacks Design Guide* addresses what needs to be considered during the feasibility study phase of a new or retrofit wet stack project. The design guide also identifies what needs to be considered when studying a conversion to wet stack operation. For example: Will the existing stack exit velocity be acceptable for wet stack operation? Is the existing stack liner material acceptable from a corrosion standpoint or does it need to be relined? How much outage time will be required to make the conversion? Does the existing stack need to be repermitted?

1.5.4 Overview of Project Implementation

The *Wet Stacks Design Guide* is intended to provide the wet stack designer with information and recommendation concerning the design and specification of wet stacks. A systematic process is provided in Sections 2 and 3 to assist the designer in identifying the important issues that need to be addressed in the design process.

The design guidelines are provided in two phases: the feasibility study and the design process. These phases provide the designer with the process that leads to a bid specification and identifies what to specify for work scope, what information to provide in the specifications, and what to expect in terms of state-of-the-art operation.

During project implementation it is important that the model study vendor review the preliminary wet duct/stack layout in order to minimize pressure loss and optimize liquid collection and drainage. A flow model study needs to be performed during the design process in order to determine liquid collection devices and minimize stack liquid discharge.

2

NEW/RETROFIT WET STACK DESIGN

2.1 Process That Leads to a Specification

The designer must follow a logical process to develop a bid specification for a new or retrofit wet stack . This involves evaluating specific design issues that are important to wet stack design. The engineering process that leads to a bid specification and the completion of a wet stack design is discussed in this section. The *Wet Stacks Design Guide* provides a step-by-step process that leads to a bid specification.

The design of a new or retrofit wet stack may be broken down into two distinct phases of work:

Phase I - Feasibility Study
Phase II - Design Process

A process flow chart outline is included in Appendix E.1 and provides more detail regarding the description of each major design issue.

2.1.1 Phase I - Feasibility Study

The Phase I feasibility study includes the following steps:

1. Address regulatory issues.
2. Define existing plant considerations.
3. Define operating parameters.
4. Determine stack height.
5. Establish liner material options.
6. Perform operating conditions vs. liner design compatibility analysis.
7. Select design velocity limit to prevent liquid reentrainment for each candidate liner material.
8. Perform a preliminary economic analysis of liner material options for wet stack operation.

9. Select liner material(s) for wet stack operation.
10. Determine reheat system design requirements (if necessary).
11. Perform economic analysis of wet stack vs. reheat operation (if necessary).
12. Select wet stack or reheat operation (if necessary).

The wet stack decision process needs to include a feasibility study comparing wet stack versus reheat unless it has already been decided to utilize wet stack operation, then the activities involving comparison with reheat can be deleted. The study should include permit considerations, dispersion modeling, preliminary design choices (such as velocity limits for liner materials), and preliminary economics.

The study should consider the tradeoff between SO_2 removal efficiency and velocity/ liner material and ground level concentrations. Obtaining an air permit is an important issue and will determine whether or not a utility can operate with a wet stack. The feasibility study should address all considerations necessary to make sure that the wet stack design will work.

2.1.1.1 Identification of Issues (Phase I)

A number of important issues must be addressed during the Phase I feasibility study for the design of a new or retrofit wet stack. This includes the following:

- Gas velocity in the liner.
- Liner materials of construction.
- Miscellaneous materials of construction.
- Stack height.
- Foundation requirements as affected by liner choice.
- Geometry.
- Liquid collection devices and drainage.
- Operating conditions.
- Continuous emissions monitoring (CEM) system considerations.
- Evaluation for wet operation.
- Outage time.
- Cost.

A detailed discussion of each issue that is important to new or retrofit wet stacks is included in this section of the design guide.

2.1.1.2 Evaluation of Issues (Phase I)

During the wet stack Phase I feasibility study phase, several critical issues must be evaluated. For example: What material will be used for construction of the stack liner? The liner diameter is established based on liner material. Each of the specific design issues identified in this section needs to be evaluated from a technical and an economics standpoint for the wet stack designer to decide how to proceed.

2.1.1.3 Economics (Phase I)

Economic evaluation of a new or retrofit wet stack should include the following factors:

- Capital costs.
- Operating costs.
- Maintenance costs.
- Outage costs.

Capital costs for a chimney include the cost of the concrete shell, liner, foundation, and miscellaneous items such as access platforms, doors, elevator, rainhood, pressurization system, drain system, protective coatings, electrical, etc. Capital costs for a reheat system include the reheaters, supports, piping, valves, condensate traps, heat exchangers and pumps (for hot water reheaters), controls, insulation, etc.

Operating costs for a wet stack are small compared to a reheat system. If the liner is constructed out of acid resistant brick then pressurization fans are required, which have an operating cost. Reheat systems typically have high operating costs due to the energy usage. A sample calculation of in-line reheat energy costs is shown in Table 2-1.

Table 2-1
Example of Flue Gas Reheat Estimated Annual Energy Costs

Assumptions

Flue Gas Flow Rate	1,300,000 acfm (610 m3/s)@ 175 degrees F (79°C)
Flue Gas Specific Volume	16.0 cu.ft./lb (0.2 m3/kg)
Flue Gas Specific Heat	0.26 Btu/lb/degree F (1080J/kg/°C)
Reheat Temperature Rise	40 degrees F (22°C)
Outlet Temperature	175 degrees F (79°C)
Boiler Efficiency	84%

Table 2-1
Example of Flue Gas Reheat Estimated Annual Energy Costs

Assumptions

Coal Cost	1.15/mmBtu
Unit Capacity Factor	0.75

Calculated ValuesFlue Gas Flow Rate

(1,300,000) (60)/16 = 4,875,000 lbs/hr (614 kg/s)Heat Added to Flue Gas
(4,875,000) (0.26) (40) = 50.7 MMBtu/hr (14.9 MMJ/s)Heat Input
50.7/0.84 = 60.4 MMBtu/hr (17.7 MMJ/s)Annual Cost of Fuel for Reheat
(604) (1.15) (0.75) (24) (365) = $456,352

Chimney maintenance costs will vary depending on choice of liner material. Coated carbon steel liners have required periodic recoating, whereas Alloy C276 clad liners have required little or no maintenance. Maintenance on brick liners can include repair of cracks, replacement of liner bands, replacement of expansion joints, etc. All chimneys require periodic inspection.

Outage time does not apply to a new wet stack, since the unit has not yet been placed into operation. For a retrofit wet stack, outage time depends on how long it will take to tie the new absorber inlet duct to the existing ductwork. Outage costs can be minimized by scheduling the ductwork tie-in to take place during a normal maintenance outage. Outage costs per day will vary depending on time of year (energy demand), loss of revenue, and cost of replacement power.

To compare the cost of wet stack versus reheat operation, the economic analysis should be based on present value. The number of years considered should be the design life of the FGD system. Initial capital costs, periodic or annual maintenance costs, and annual energy costs need to be converted to present value to compare the options on an equal basis.

2.1.2 Phase II - Design Process

Table 2-2 describes Phase II, which is the process for the design of a wet stack. This table provides a brief description of each step of the design process, designation of each step of the design process, designation of responsibility, and a reference in the guide where background information is provided.

The design process phase essentially takes the feasibility study and turns it into a bid specification. During this phase it is necessary to establish the design criteria, define the stack and inlet duct geometry, perform the flow model study to determine liquid collection devices, and prepare the bid specifications and drawings.

Several items considered during the feasibility study phase should be revisited or finalized during the design process phase. This includes such items as the subsurface investigation and foundation requirements, stack and inlet duct geometry, liquid collection devices, etc.

Detailed design of the chimney foundation, concrete column, liner, and access platforms is normally provided by the chimney contractor. The electrical design (with the exception of the obstruction lighting) is usually performed by the engineer. This is because the electrical raceway system must be designed ahead of time in order to be embedded in the chimney foundation. The chimney-related scope of work is typically included in a separate contract. However, if schedule and site constraints warrant it, the chimney may be included in the FGD system contract.

Table 2-2
Phase II Wet Stack Design Process

Step	Description	Responsibility	Reference
1. Preliminary Design	Perform component-by-component design	Engineer	Section 2 - "Specific Design Issues"
2. Preliminary Design Review	Adjust design for suitability and compatibility for liquid collection	Engineer and modeling company	Section 2 - "Evaluation for Wet Operation"
3. Fluid Dynamic Design	Perform flow model study	Modeling company	Section 2 - "Evaluation for Wet Operation"
4. Preparation of Bid Specification	Prepare bid specifications for chimney contract	Engineer	Section 4 - "Guide to Develop Specifications for Wet Stacks"
5. Final Design	Perform detailed design of chimney for construction	Chimney contractor	----

Note: The utility is an active participant in all major decisions in all steps of the design process.

2.1.3 Recommendations

The following sections of the design guide provide specific recommendations concerning each design issue. Some of the recommendations are provided below to help the designer develop a specification for a new or retrofit wet stack:

- Perform a feasibility study for wet stack operation. The feasibility study should address all specific design issues necessary for satisfactory wet stack operation. (Phase I)
- Address regulatory considerations first. Permitting is an important issue and will determine whether a utility can operate with a wet stack. Stack height requirements are provided later in this design guide. (Phase I)
- Perform a technical evaluation of liner material options. Size the liner diameter based on recommended velocity limits to prevent liquid reentrainment. Perform a preliminary economic analysis of liner material options. (Phase I)
- Base the wet stack economic analysis on the present value of costs over the life of the FGD system. Evaluate capital costs, maintenance costs, and operating costs in the economic analysis. (Phase I)
- Perform a flow model study to determine liquid collection devices and minimize pressure loss through the duct system. The flow model study should be performed by a qualified flow model firm. (Phase II)
- During preparation of the bid documents, finalize the stack and inlet duct geometry, foundation type, and liquid collection devices. (Phase II)

The process flow chart of new or retrofit stack designs is indicated in Figure E-1 of Appendix E. The flow chart indicates the step-by-step process that leads to a specification for a wet stack.

2.2 Specific Design Issues

This part of the *Wet Stacks Design Guide* deals with specific design issues such as gas velocity, liner materials of construction, stack height, etc. For each design issue, the information is presented in the following categories:

- Background information on why the design issue is important, the effects of variations in design parameters, etc.
- State-of-the-Art information on what has been done recently on wet stacks constructed for Phase I of the Acid Rain Control program under the Clean Air Act.
- Guidelines or recommendations to help the wet stack designer evaluate the alternatives and making the right decisions.

Due to space considerations, the design guide does not include all of the information available on a specific subject. For example, the section on materials of construction could include several more materials and be expanded to fill an entire volume. Such a document has already been written by EPRI and is titled *Guidelines for FGD Materials Selection and Corrosion Protection (5)*. For this design guide, the subjects are covered in enough detail to provide a general overview of all of the major issues to consider in designing of a wet stack. Additional details can be found in the resources that are referenced where appropriate in the guide.

2.2.1 Gas Velocity in the Liner

The gas velocity within the liner is a significant factor in minimizing liquid reentrainment into the gas stream. Liquid droplets either carried over from the mist eliminator or condensed on cold walls are deposited on the ductwork and stack liner surfaces. As the droplets accumulate, they are pulled downward by gravity while the gas drags the liquid in the same direction as the flow of the gas. When the force from the gas reaches or exceeds gravity and surface tension, the liquid is sheared from the ductwork or liner walls. Liquid then reenters or is reentrained into the gas stream and is carried out of the stack. When this occurs the gas velocity is referred to as the critical reentrainment velocity.

Wet stack designers should select the liner diameter based on liquid collection considerations. Selecting the liner diameter so that the gas velocity is less than the critical reentrainment velocity (with a desirable margin) increases the opportunity for liquid to be collected within the stack rather than being emitted with the gas stream.

The critical reentrainment velocity varies depending upon the liner's surface roughness and material. Surfaces with a high level of discontinuities and roughness, such as a brick liner, will be more likely to reentrain liquid compared to smoother surfaces, such as an alloy liner. Therefore, the liner diameter will depend upon the liner material selected. Brick liners, for instance, will require a larger diameter than an alloy liner with the same gas volume flow rate.

The recommended liner velocity range for sizing the liner diameter of various liner materials is provided in Table 2-3. The results of the industry survey regarding the type liner material and exit velocity used are summarized on Table 2-4. The average liner velocity and the stack exit velocities are the same for constant diameter liners without choke and they can be compared directly. Appendix C gives more details of the industry survey.

In stacks that have chokes, some of the fine droplets entrained in the gas flow will be deposited on the choke surface, and the liquid collected on the choke will lead to stack liquid discharge if the local gas velocities in the choke are high enough to exceed the flow reversal velocity. The gas velocity on the choke increases from the liner velocity up to 80 to 120 fps exit velocity, which is the usual design range for chokes. The choke exit velocity normally exceeds the flow reversal velocity. Flow reversal velocity is the flue gas velocity at which the flow of the liquid on the stack walls is reversed from down to up flow.

The magnitude of the liquid discharge is a function of the choke geometry, the gas velocity variation through the choke, the droplet size distribution, and the spatial variation of the different size droplets. Flow reversal velocity is in the range of 50 to 90 fps for common liner materials (1). Therefore, liquid film will be flowing upwards over a large percentage of the choke surface for most choke geometries. The liquid should be collected at the top of the choke and drained out to reduce the stack liquid discharge.

Table 2-3
Recommended Stack Velocity Range for Stack Liner Diameter Sizing

	Liner Velocity[1]	
Material	**(ft/sec)**	**(ft/min)**
Acid Brick: (Radial tolerance of construction is 1/8 inch)	45-55	2700-3300
Borosilicate Glass Block	50-60	3000-3600
Fiberglass Reinforced Plastic	50-60	3000-3600
Alloy	60-70	3600-4200
Coatings	60-70	3600-4200

[1]Area average velocity ($V_{avg} = Q/A$) inside the liner. 1ft/s=0.3048m/s, 1 ft/min=0.0005 m/s

Table 2-4
Existing Wet Stack Liner Material and Exit Velocity Ranges[1]

Liner Material	Reported Number of Liners	Exit Velocity Range (ft/s)
Acid Resistant Brick	36	23-111
Nickel Alloy	12	50-75
Coated Carbon Steel	6	43-75
Titanium Clad Carbon Steel	4	60-94

Table 2-4
Existing Wet Stack Liner Material and Exit Velocity Ranges[1]

Liner Material	Reported Number of Liners	Exit Velocity Range (ft/s)
Fiberglass Reinforced Plastic	5	61-111
Fibrecrete 214/222 Lined Carbon Steel	2	59-98
Glass Block Lined Carbon Steel	1	43
Total	66	

[1]Based on results of industry survey. See Appendix C. 1ft/s=0.3048m/s, 1 ft/min=0.0005 m/s

Final selection of the gas velocity within the liner should also be coordinated with draft considerations in determining fan size.

2.2.2 Stack Liner Materials of Construction

Several types of liners and coating systems are available and have been used successfully in wet flue gas desulfurization environments. Advantages and disadvantages of each system must be considered prior to the selection of the liner material or coating. The following sections describe the more common materials that currently are considered for wet stack applications. These materials have been previously utilized with some degree of success. Other materials and suppliers may be available and acceptable, and should be evaluated on a case by case basis. Operating conditions, design conditions, and economics all play important roles in this decision. Advantages and disadvantages for several different liner and coating system options and estimated installation costs are presented in Table 2-5.

2.2.2.1 Acid Resistant Brick.

Acid resistant brick is a solid kiln-fired brick made of clay, shales or mixtures of clay and shale, and conforms to the requirements of ASTM C980, "Standard Specification for Industrial Chimney Lining Brick." ASTM C980 defines three types of brick that are categorized by compressive strength, water absorption and acid solubility. Of the three types, Type III has the most stringent requirements, allowing the least amount of water absorption and acid solubility while Type I allows the highest levels. Because of the stringent requirements, Type III brick is the most difficult and expensive to manufacture. Due to availability limitations for Type III brick, most brick liners for FGD applications are constructed using Type II bricks.

The physical properties and chemical requirements for Type I, Type II, and Type III brick as defined by ASTM C980, "Standard Specification for Industrial Chimney Lining Brick," are presented in Table 2-6.

As previously stated, chimney brick can be manufactured from clay, shale, or a mixture of clay and shale. Bricks manufactured from clay are called fireclay bricks and are typically buff color. Bricks that are manufactured from shale are called red shale bricks and are red in color. Red shale usually has a higher iron oxide content than fireclays. The iron oxide acts as a flux which permits a lower firing temperature for shale than for fireclay. Fireclay and red shale brick provide comparable physical and chemical characteristics when fired at their respective temperatures. If fireclay and red shale brick are fired at the same temperature, red shale brick will typically be denser and have lower absorption characteristics than the fireclay brick. When properly manufactured, both will meet the requirements of ASTM C980.

Table 2-5
Liner Material of Construction

Liner Material or Coating	Advantages	Disadvantages	Estimated Installed Cost Per Square Foot
Acid Resistant Brick	_ Good corrosion resistance _ Cost effective _Liquid adheres to the porous surface	Surface discontinuities reentrain liquid Not recommended in high seismic areas Maintenance of liner accessories Annulus pressurization	$45 - 55
Protective Coating on Carbon Steel	Fair corrosion resistance Ability to retrofit to existing steel liner systems	Surface preparation prior to placement Frequency of repair and maintenance Limited acceptable selections	$55 - 60
Borosilicate Foamed Glass Block on Carbon Steel	Good corrosion resistance Good insulator (ductwork & liner should not be insulated) Ability to retrofit to existing steel liner systems Good surface for liquid flow	Cannot tolerate abrasion or physical and mechanical abuse Limited source of supply Care in installing	$75 - 80

Fiberglass Reinforced Plastic	Good corrosion resistance Easy to add liquid collectors	Maximum 300°F (149°C)(approx.) gas temperature exposure Quality control during fabrication Limited source of supply Compressive strength limitations usually requires two support levels and expansion joint	$85 - 90
Alloy C276	Excellent corrosion resistance	Welding quality control High material costs Welding seams Iron contamination Acid cleaning Condensation	$85 - 95 Wallpaper on Carbon Steel $110 - 120 Roll Clad $120 - 130 Solid
Titanium Grade 2 on Carbon Steel	Excellent corrosion resistance	Welding process Welding quality control High material costs	$80 - 90 Wallpaper

[1]Information provided by research from utilities, contractors, engineers and material suppliers based on cost and performance of past applications.

Brick liners use potassium silicate mortar that conforms to the requirements of ASTM C466, "Standard Specification for Chemically Setting Silicate and Silica Chemical - Resistant Mortars." These inorganic mortars are resistant to most of the strong acids present in the scrubbed flue gas from coal-fired power plants, except for significant concentrations of acid fluorides or hydrofluoric acid. Potassium silicate mortars are more resistant to sulfation than the sodium silicate mortars or other types of silicate based cements.

Table 2-6
Physical Properties And Chemical Requirements Of Acid Resistant Brick[1]

	Minimum Compressive Strength, Gross Area, psi		**Maximum Water Absorption by 2-h Boiling, %**		
Designation	**Average of 10**	**Individual**	**Average of 10**	**Individual**	**Maximum Average Weight Loss by H_2SO_4 Boil test, %**
Type I	8,500	8,000	6.0	7.0	20
Type II	10,000	9,000	4.0	5.0	12
Type III	12,000	10,000	1.0	1.5	8

[1]Per ASTM C980, "Standard Specification for Industrial Chimney Lining Brick." 1 psi = 6.895 kPa

Brick liners have been widely used by the power plant industry. These liners generally require the lowest initial capital cost expenditure compared to other types of liners. However, maintenance for a brick liner can generally be higher than for an alloy or FRP liner. Typical maintenance for a brick liner would include repair of brick cracks, repair or replacement of bands, maintaining the pressurization fans, and repair of expansion joint seals at the rainhood and breeching.

Brick liners should be designed and constructed in accordance with the recommendations of ASTM C1298, "Standard Guide for the Design and Construction of Brick Liners for Industrial Chimneys."

2.2.2.1.1 Annulus Pressurization

Because of the porous characteristics of brick and mortar, brick liners operating under wet FGD conditions should use an annulus pressurization system. Annulus pressurization is not needed for other liner materials. An annulus pressurization system consists of fans that provide ambient air under positive pressure into the annular space of the stack, so that permeation of the flue gas and liquids through the liner and liner cracks is minimized. The pressure created by these fans should exceed the maximum anticipated positive pressure inside the liner by a minimum of one inch water gauge. Flue gas and liquids that permeate the liner create a highly corrosive environment and can cause damage to the liner bands and concrete column.

Airtight seals are required at all openings in the stack and liner to minimize air leakage from the pressurization system. Airlocking chambers should be provided at door locations to provide safe passage into and out of the chimney. Pressurizing fans are typically in the range of 30,000 cfm to70,000 cfm (14-33m^3/s) flow rate and 3 to 4 inches water gage pressure rise for a 500 MW to 650 MW unit.

An adjustable damper can be provided at the top of the chimney for use when reduced pressurization pressure and flow rate are acceptable. Excessive annulus pressurization could lead to air leakage through cracks in the brick into the inside of the liner and cause increased liquid condensation in the flue gas.

2.2.2.1.2 Target Walls and Linings

Some brick liners operating under wet FGD applications have experienced differential liner growth resulting in a permanent deflection of the liner. Although the cause of this permanent deflection has not been determined, wet saturated conditions and non-uniform temperature appear to be contributing factors. EPRI has previously funded laboratory and field studies directed at preventing this problem. The results of this study are presented in Reference (11). Precautions such as installing a target wall in the bottom of the liner should be considered. Mixing of gases with a non-uniform temperature profile should also take place prior to entering the stack.

A target wall or target lining provides protection to the brick liner from the wet flue gas. Target walls or target linings can be constructed partially or fully around the inside circumference of the brick liner and should extend from the bottom of the liner to one or two liner diameters above the breeching entry.

A target wall is an acid resistant brick wall constructed independent of the brick liner. An air space should be provided between the target wall and the brick liner.

A target lining is constructed directly against the inside surface of the brick liner. The lining can be constructed using borosilicate glass block with an adhesive membrane which provides a good moisture and chemical resistant barrier. Alabama Electric's Lowman Station Units 2 and 3 recently installed a Pennguard Block lining on the bottom 48 feet of the inside surface of the brick liners when the units were converted from partial bypass to wet operation. Operating results are not yet available.

Another method that has been considered to reduce the direct impingement of wet gases exiting the breeching on to the interior surface of the liner is to provide a bottom entry into the brick liner. This can be accomplished by providing an alloy breeching thimble section that extends below the bottom of the brick liner.

Target walls may be needed for good liquid collection and reduced reentrainment from brick liners in the stack entrance region when the breeching duct velocity is high (greater than 55 feet per second).

2.2.2.1.3 Seismic Design

Brick liners should be designed to be structurally adequate to resist earthquake loads. The seismic analysis should be performed using the dynamic response spectrum analysis method. A site specific response spectrum or the design response spectra given in theACI-307 with 5 percent damping should be used. Site specific response spectrum should be based on a minimum of 80 percent probability of not being exceeded in 50 years. The ACI-307 response spectrum is the same spectrum that has been adopted for use in the design of steel chimney liners by the Task Committee of the American Society of Civil Engineers. (8) (9)

The effective peak ground acceleration, which is used to evaluate the magnitude of the seismic activity, should be determined in accordance with the seismic ground acceleration maps found in Reference (6).

Because brick liners are not resistant to tension loads, tall independent brick liners may not be suitable for high seismic areas. Since a brick liner's geometry is sensitive to seismic effects, diameters and wall thicknesses can be varied to optimize the liner's bending and overturning resistance. Some brick liners designed for effective peak ground accelerations in excess of 0.05 may not be able to meet design criteria for allowable stresses and stability against overturning.

The ASTM C1298 brick liner design guidelines permit using an earthquake reduction factor of 0.75 provided the risk of potentially extensive damage to the liner is understood. The risk of damage or failure of a brick liner due to an earthquake is sometimes accepted based on the premise of the concrete column's ability to confine the damage.

2.2.2.1.4 Liner Bands

Circumferential liner bands should be provided around the liner to minimize vertical cracking and to add stability to the liner if cracking occurs. The minimum band size recommended is 3/8 x 3 inch plate spaced at five foot centers. Materials of construction will depend upon the operating conditions and effectiveness of the annulus pressurization system. For applications where the pressurization system is working effectively and the exterior of the liner remains dry, bands constructed of carbon steel with a protective coating system are adequate. For applications where liquid permeates the brick and is in contact with the bands, a nickel alloy material should be used for this corrosive environment. Use of carbon steel bands in a wet environment may require future maintenance and possibly future replacement. Several utilities replaced their carbon steel liner bands due to corrosion.

Allegheny Power System's Mitchell Station Unit 3 operating without annulus pressurization has a brick liner with bands that are exposed to an excessive amount of liquid that has leached through the liner. Due to the excessive amount of corrosive liquid, the bands on the liner are fabricated from Alloy 625 and appear to be in good condition.

2.2.2.2 Borosilicate Foamed Glass Block.

Borosilicate foamed glass block is an inorganic manufactured product that is chemically resistant to most acids, solvents and weak bases. Its closed cell composition is impervious to liquids and gases and provides a low thermal conductivity. This product is manufactured in block form and is installed directly against the surface that it is to protect. An adhesive membrane is used behind and between the blocks and serves as a moisture and chemical-resistant barrier. This block can operate at temperatures up to 960 degrees F (516°C), however, the adhesive membrane is limited to 200 degrees F (93°C).

The glass block is an excellent insulator and the ductwork and liner should not be insulated if glass block is used. Without insulation there is a thermal gradient through the block that allows heat to dissipate.

Borosilicate glass block is manufactured by Elf Atochem under the trade name Pennguard Block. Borosilicate glass block is well suited for lining carbon steel liners and ductwork. Since this block is easily damaged, areas that are susceptible to physical or mechanical abuse should be protected with acid resistant gunite or an abrasion resistant coating. Internal bracing is difficult to line with block. Membrane coatings or alloy materials are recommended for internal braces.

Michigan South Central Power Agency's Endicott Station Unit 1 has a free standing steel stack that has been lined with Pennguard Block. This liner system was installed in 1989 in conjunction with conversion to wet stack operation and is reported to be in good condition. (22)

Borosilicate glass block has been considered for attachment directly to the inside surface of a concrete shell to provide protection against wet flue gas. Although glass block can provide an effective corrosion resistant barrier, there are risks involved when utilizing this system. Damage to the concrete column is possible if leakage through the block develops. Location of the leakage and the extent of damage to the concrete column would be difficult to detect and evaluate with this system. The site specific situation and risks involved should be evaluated when considering this system on a utility wet stack.

2.2.2.3 Protective Coatings on Carbon Steel Liner.

A wide variety of coatings are available, and several of which are applicable to wet FGD operations. One such coating is the flakeglass reinforced, vinyl ester system. This system is a glass-filled, thermosetting, resin-based, corrosion-resistant lining system. The vinyl ester resins are more durable and corrosion resistant than the polyester resins that had been used in older liner coating applications. This coating system should be applied in three layers. The first layer is a primer coat that is used to prevent abrasive-blasted steel from developing rust bloom. The lining is then trowel-applied in two 30-40 mil layers. Trowelling and subsequent rolling allows the glassflake filler in each layer to be properly oriented to the substrate and achieve maximum resistance to water vapor permeation. In order to ensure adequate coverage, the two layers of resin can be applied using different color pigments. Historical experience indicates that this coating system may develop permeability, and liquid may eventually seep through and reach the carbon steel substrate. Coating systems other than the flakeline resin systems have been utilized but only with a limited degree of success.

The performance of any coating is dependent on surface preparation and application. Strict quality control measures are required. The coatings need to be applied under good weather conditions or under a controlled environment. The coating should not be applied at temperatures less than 50 degrees F(10 °C) or greater than 120 degrees F (49 °C). In order to get optimum performance out of a coating, application and curing conditions are critical. The steel substrate surface requires significant surface preparation prior to application of the coating. All sharp edges and imperfections must be ground smooth. Degreasing the surface and then sand blasting to a white metal blast (SSPC SP-5) is required. Blasting should take place only over an area that canbe primed within the same day. Surface preparation and installation should carefully follow the manufacturer's written instructions.

Coatings have been used successfully in some wet stack applications and have failed in others. There is some risk involved in using a coating system and the potential for failure should be realized. Maintenance to repair chips and blisters should be anticipated. Total lining replacement is typically required after a life of about 8 to 10 years. However, coatings can represent substantial savings and have been included as an alternative for cost comparison.

2.2.2.4 Fiberglass Reinforced Plastic.

Fiberglass reinforced plastic (FRP) is a composite material made of glass reinforcement and a thermosetting resin. FRP is a lightweight laminated product that provides good service in cool, wet, dilute acid environments. Due to size and shipping restraints, these liners are usually filament wound in sections on-site.

The FRP liner inner surface is a corrosion resistant barrier that consists of a glass mat and resin. Vinyl ester resins are recommended instead of the polyester resins, which have been used on many past projects. Vinyl ester resins provide higher temperature and corrosion resistance and have a lower coefficient of thermal expansion. The structural wall of the FRP liner is composed of continuous glass strands that are helically wound around a mandrel.

FRP is suitable for the low temperatures that are characteristic of wet scrubbed conditions and is not recommended for bypass conditions or temperature excursions. Exposure to bypass conditions will result in loss of strength and shorten the life of an FRP liner. An inlet water spray quench system is recommended to reduce the effects of bypass temperature excursions. FRP liners downstream of FGD systems that do not have bypass capability do not need a quench system. FRP liners should be designed, fabricated and erected in accordance with the recommendations of ASTM D5364, "Guide for Design, Fabrication, and Erection of Fiberglass Reinforced Plastic Chimney Liners With Coal-Fired Units."

An FRP liner was installed at Louisville Gas and Electric's Trimble County Station Unit 1 and is in good condition after four years of wet operation. A quench system was not installed because Trimble County does not have bypass capability.

2.2.2.5 Stainless Steel.

Stainless steel covers a wide variety of corrosion resistant materials. Operating parameters and environmental factors greatly affect alloy performance, especially pH, temperature, and chlorides and oxygen levels. The corrosion resistance of stainless steel is improved by increasing molybdenum (Mo), nitrogen (N), chromium (Cr), and nickel (Ni) contents. Molybdenum and to a lesser extent nitrogen improve resistance to pitting. Chromium aids in the development of protective passive surface films and increases corrosion resistance in oxidizing environments. Nickel assists in the renewal of damaged passive films and stabilizes the austenitic microstructure with its improved fabricability and weldability.

On average, chloride levels in the new FGD systems will likely be much higher than earlier FGD systems because of the requirement for zero-discharge water systems. Designs specifyingchlorides above 15,000 ppm have been fairly common, and some designs have anticipated sustained operation above 30,000 ppm chloride. Closed loop operation causes chloride levels to increase, thereby increasing the possibility of pitting and/or crevice corrosion of stainless steel. Stainless steels that have been used successfully in scrubbers may not perform well in FGD outlet ducts or stack liners. These locations are wetted by essentially unbuffered mist and/or condensate. Absorption of residual SO_2 can cause the pH to drop to below 2. Due to the potential for high chlorides and low pH in the absorber outlet duct and stack, stainless steels are not recommended. For these areas, a nickel alloy material such as Alloy C276 or Alloy C22 is recommended.

2.2.2.6 Nickel Alloys.

High nickel alloys are an effective corrosion resistant material in wet FGD applications. Nickel alloys containing high percentages of chromium and molybdenum provide good resistance to pitting and crevice corrosion in a high chloride, low pH environment.

Although several different nickel alloys may be adequate for FGD applications, Alloy C276 (ASTM B575, UNS N10276) and Alloy C22 (ASTM B575, UNS N06022) have been shown to provide the best overall corrosion resistance characteristics. Alloy C276 contains 16 percent molybdenum and 15.5 chromium. Alloy C22 contains approximately 13 percent molybdenum and 22 percent chromium. These alloys have performed well in numerous wet FGD environments and offer approximately the same level of corrosion resistance. The two products have successfully withstood a wide range of acid concentrations and extremely high chloride levels, in conditions ranging from 130 degrees F saturated flue gas to full system bypass.

2.2.2.6.1 Solid Alloy

Alloy C276 and Alloy C22 is produced in bar stock, plate, and sheet. Liners constructed using this material could be fabricated from solid alloy plate, from carbon steel plate with an alloy sheet lining, from roll clad plate, or from Resista-clad plate. Although liners fabricated from all of these applications are highly corrosion resistant, liners fabricated from solid Alloy C276 plate offer the most corrosion resistance. Since welding between the alloy material and carbon steel is a potential source of dilution and contamination, the use of solid alloy plate eliminates this concern. However, the use of solid alloy plate also requires the highest initial capital cost.

Stiffeners on the exterior of the liner can be fabricated from carbon steel, since this material is not in contact with the flue gas. Any internal stiffening such as bracing in the ductwork should be fabricated from alloy material.

Pennsylvania Power Company's Bruce Mansfield Station Unit 3 stack has two liners fabricated from solid Alloy 625 material. Alloy 625 is a nickel alloy containing a higher chromium content and lower molybdenum content as compared to Alloy C276. These liners are reported to be in excellent condition.

2.2.2.6.2 Wallpaper Lining

Alloy sheet lining involves the welding of thin alloy sheets, usually 1/16-inch thick, to a carbon steel liner. This approach has been commonly referred to in the industry as a "wallpaper lining." The sheet lining is installed with lapped joints. The jointsexposed to flue gas must be fully seal welded to ensure protection of the carbon steel liner surface. The sheets are attached to the liner with plug welds and intermittent fillet welds. The plug welds should be covered with cap plates to eliminate any concerns with dilution. From a design standpoint, only the carbon steel portion of the liner should be considered structurally effective in supporting the liner.

This lining process can be installed on a new or existing carbon steel liner. If the lining is to be installed on an existing liner, the liner support steel should be evaluated to accommodate the additional load of the sheet lining. An Alloy C276 sheet lining was utilized at Cane Run Unit 6 stack. After several years of operation, the material is performing well. However, buckles in the lining sheets have developed throughout the liner due to thermal stress.

2.2.2.6.3 *Roll Clad*

Alloy clad plate consists of alloy sheet, usually 1/16-inch thick, that is roll bonded to a thicker carbon steel backing plate. The two metals are mill rolled under heat and pressure until they are integrally bonded over the entire interface. Clad plates are readily joined by welding. However, on the clad side, it is important to minimize dilution to maintain adequate corrosion resistance of the weld metal. Lukens Steel Company, Creusot-Loire, and Japan Steel Works fabricate roll clad plate utilizing the process described above.

Alloy C276 clad liner plate has recently been installed for Allegheny Power Service Cooperative's Harrison Station Units 1, 2, and 3 and for Pennsylvania Electric Company's Conemaugh Station Units 1 and 2. Alloy C276 clad plate liners were also installed at Louisville Gas & Electric's Cane Run Units 4 and 5. The liners on both of the Cane Run units are in excellent condition after 8 and 9 years of operation, respectively.

2.2.2.6.4 Resista Clad

Another type of lining system that utilizes alloy as a lining material is a process called Resista-clad. SPF Corporation of America uses this process where alloy sheet can be bonded to the carbon steel backing by the use of resistance welding. 1/16-inch thick alloy sheets are bonded to carbon steel backing. The carbon steel plates are welded together and then a batten strip of alloy is laid over the joints and seal welded to the alloy lining.

2.2.2.7 Titanium.

Titanium is a highly corrosion resistant, very strong, and extremely light metal. The major producer of this material in North America is the Titanium Metals Corporation of America (TIMET).

Titanium can be supplied as bar stock, strip, sheet, or plate conforming to the requirements of ASTM B265, "Standard Specification for Titanium and Titanium Alloy strip, Sheet, and Plate." Numerous titanium alloy grades have been developed, but for wet FGD corrosive applications there are basically two grades considered for use:

- Grade 2 - Pure titanium with 0.02 percent iron added for increased strength.
- Grade 7 - Pure titanium with 0.15 percent palladium added for additional corrosion resistance.

Costs for grade 7 titanium material are much higher than Grade 2. The material cost can only be obtained on the date the material is purchased since palladium is extremely expensive and the market price fluctuates.

Grade 7 titanium has been used in the absorber inlet wet dry interface areas at Louisville Gas and Electric Company's Trimble County Unit 1. LG&E reports some general corrosion of the Grade 7 Titanium after several years of operation.

The Clover Project Units 1 and 2 has Grade 2 titanium liners. The Contractor has provided a five year guarantee on the material. These units are not yet in operation. Grade 2 titanium was used to line the existing chimney carbon steel liners at Big Rivers's Green Station Units 1 and 2 and are reported to be in good condition. Grade 2 titanium has also been installed in the outlet common header duct at Potomac Electric's Dickerson Units 1, 2, and 3.

The linings installed in the chimney liners at Green Station Units 1 and 2 and have performed well. The Green Station Unit 1 lining was installed in late 1987 and an inspection in 1990 found no sign of corrosion after nearly three years of operation. The unit has been running scrubbed gas exclusively. Soon after installing the titanium, severe corrosion developed in the inlet to the chimney. It was determined that the corrosion was due to the leaching of free fluorides contained in a gunite material applied to the floor of the ductwork upstream of the inlet to the chimney. The fluoride source was removed and the titanium was repaired and no further corrosion has developed in over two years.

The common header duct lining at Dickerson Station has experienced general corrosion, pitting, hydriding, and cracking in some areas. (23, 24) It should be noted that the titanium at Dickerson Station is installed in the mixing zone downstream of particulate scrubbers and precipitators. This is a very severe environment. The mixed gas has a temperature of 180 degrees F and produces considerable acidic condensate in the common header duct. The primary cause of the corrosion is fluoride attack.

Titanium cannot be arc welded to carbon steel. In order to use this material as a lining, the SPF Corporation of America uses a process called "Resista-Clad" in which titanium lining is bonded to carbon steel backing using resistance welding that does not damage the titanium. The titanium sheet is bonded to carbon steel backing or edge strips which can be welded to carbon steel ductwork or a chimney liner. A batten strip of titanium is laid over the joints and seal welded to the titanium.

Another method of installation requires fabrication of the carbon steel edge strips in a manner that allows an overlap of the titanium sheets. For new liner construction, the titanium can be resistance welded to thicker carbon steel similar to Alloy C276 or Alloy C22 clad plate. The carbon steel portion of the plate is welded at the joints and titanium batten strips are laid over the joints and seal welded to the titanium sheets.

2.2.2.8 Insulation.

For stacks operating under reheat or bypass conditions, insulation is provided to resist the formation of acid droplets condensing on the surface of the liner, which can be extremely corrosive to a carbon steel or lower grade alloy material. A wet stack with a flue gas temperature of 130 degrees F (54 °C) typically will not require insulation on the exterior surface of a steel or alloy liner since the liner is already operating in a wet condition.

The insulation of alloy and FRP liners should be considered and evaluated for reduced wall condensation rate. Insulation of these liners reduces the rate of wall condensation down to a range of 15 to 30 percent of the condensation rate without insulation. The combined cost of the insulation and the liquid collection should be estimated to decide if the liner should be insulated. The effect of insulation on condensation rate at different ambient temperatures is presented later in Section 2 under "Condensation Calculations."

Uninsulated liners should have a protective coating on any carbon steel plate or stiffeners on the exterior of the liner. The solid Alloy 625 liners at Pennsylvania Power Company's Bruce Mansfield Station Unit 3 are not insulated. However, the coated carbon steel liners at Bruce Mansfield Units 1 and 2 are insulated. Insulation is installed on coated steel liners to reduce the temperature gradient across the coating, which may help in extending the life of the coating. The wet stack survey data indicated that the liners for all three Bruce Mansfield units were in good to excellent condition.

2.2.3 Miscellaneous Materials of Construction

Because of the corrosive environment associated with FGD operations, materials on the stack other than the liner also need to be evaluated.

2.2.3.1 Protective Coatings.

Protective coatings should be applied to areas of the stack that are subject to the corrosive effects of flue gas downwash or the leaking of flue gas and liquid through a brick liner.

2.2.3.1.1 Exterior of Shell

Gas exit velocities on wet FGD stacks should be designed for a lower velocity than for reheat or bypass stacks. Consequently, plume rise on the gas exiting a wet stack is not as high. With the gas velocity low and heavily saturated with liquid, it is common for the flue gas to come in contact with the upper portion of the stack. This condition is called downwash. As the gas comes in contact with the concrete shell, liquid condenses on the concrete. Over time this condensate can deteriorate unprotected concrete on the upper portion of the stack.

To protect the upper portion of the concrete stack against downwash, a protective coating system should be applied to the top 50 to 100 feet (15-30 m) of the chimney. Applying two coats of an acrylic emulsion coating system is an acceptable protection system for the concrete surface. A high-build (4 to 6 mils dry film thickness) epoxy coating has also been used for this application. The painting system selected should be checked for compatibility with the concrete curing compound and for compatibility with any FAA painting requirements.

2.2.3.1.2 Exterior of Adjacent Stacks

A stack that is located adjacent to and downwind of another stack may be subject to the corrosive effects of flue gas impinging on its concrete surface. If the upwind stack is significantly shorter than the downstream stack, the potential for concrete corrosion is increased. Two coats of an acrylic emulsion coating system are recommended for this application.

Louisville Gas and Electric's Cane Run Unit 5 stack is 240 feet 6 inches (73 m) tall. The adjacent Unit 6 stack is 500 feet 10 1/2 inches (153 m) tall. Because of the differences in stack heights, flue gas from the Unit 5 stack impinges on the Unit 6 stack. The outside of the Unit 6 concrete shell has consequently been damaged. Maintenance has been performed to patch cracks and to coat the outside of the Unit 6 chimney shell.

2.2.3.1.3 Interior of Shell for Use with Brick Liners

For a stack with a brick liner, flue gas may enter the annular space of the stack if the liner is leaking or if the pressurization system is not performing adequately. This condition can be severe enough to result in corrosion of the interior surface of the concrete shell. Additional protection should be provided by applying two coats of an acrylic emulsion coating system to the interior concrete surfaces.

A bitumastic coating has been applied to the inside surface of the concrete column at Allegheny Power Service Cooperative's Mitchell Station Unit 3 stack. This stack has a brick liner without an annulus pressurization system. The chimney was placed into operation in 1982. Excessive leaching has taken place through the brick liner. The coating on the inside surface of the column has provided protection for the concrete in this environment.

2.2.3.1.4 Liner Bands

Liner bands can be a potential maintenance concern if the band material or coating system is not properly selected to resist the corrosive environment. Uncoated carbon steel bands have failed on several stacks. A coating system using a first coat of high-build epoxy with a second coat of polyurethane can be used for this application. However, in severe environments with excessive leakage through the liner, this coating system may not be adequate and alloy bands may be required.

Allegheny Power Service's Mitchell Station Unit 3 has a brick liner with excessive liquid leaching through the brick. Due to the excessive amount of corrosive liquid, Alloy 625 material was used to fabricate the bands. The bands are reported to be in good condition.

2.2.3.2 Trim Materials.

Trim materials associated with the stack should also be selected to provide adequate corrosion protection.

2.2.3.2.1 Rainhoods and Roofs

The rainhood at the top of the stack is exposed to flue gas, so the rainhood material must withstand this corrosive environment. Liquid reentrained in the flue gas is deposited on the rainhood surface. In addition, the continuous cycle of evaporation and deposition increases the acid content of liquids deposited on the rainhood surface. Accordingly, the rainhood material must resist higher acid concentrations than the liner. FRP is an excellent choice for use with a brick or FRP liner. This material is lightweight and corrosion resistant. An FRP rainhood was used for the brick liners at Deseret Generation and Transmission Cooperative's Bonanza Station Unit 1 and at Cincinnati Gas and Electric Company's Zimmer Station Unit 1 and for the FRP liner at Louisville Gas and Electric's Trimble County Unit 1. Based on our industry survey, none of these stations have reported problems with their rainhoods.

Nickel alloy liners should use a solid nickel alloy material for rainhoods. Use of clad plate is not recommended because the bottom carbon steel surface of the rainhood may be exposed to downwash and corrode. Louisville Gas and Electric Company's Cane Run Station Units 4, 5, and 6 use solid Alloy C276 for their rainhoods without any reported problems.

Stainless steels have been used on occasions for rainhoods, but most stainless steels cannot resist the high acid concentrations that may occur at these locations. Pennsylvania Power Company's Bruce Mansfield Unit 1 and 2 stack has a Type 316 stainless steel roof that appears to be holding up well. The liners project 20 feet (6 m) above the roof.

Use of coated carbon steel rainhoods is not recommended for rainhood applications because of maintenance concerns for the coating system.

Stacks with multiple liners use a roof instead of a rainhood system at the top of the stack. Roofs should be provided with a minimum slope of one-quarter inch per foot to permit adequate drainage. Roof materials consistent with those referenced for rainhoods should be used. In addition, concrete roofs can be utilized. Type V sulfate resistant cement is recommended for the concrete. A coating system can be applied to the top of the concrete to provide additional protection. The stack for Units 1 and 2 at Henderson Municipal Utilities Station Two has a concrete roof made with Type V cement.

2.2.3.2.2 Lightning Protection System

Since most of the items associated with the lightning protection system are located at the top of the stack, materials of construction for these items must provide adequate corrosion resistance. The air terminals should be fabricated from a solid rod made of Alloy C276. Conductors, attachments, and fasteners located within the top 25 feet (8 m) of the stack should be lead covered.

2.2.3.2.3 Platforms and Ladders

To provide adequate protection against downwash and liquid fallout, exterior platforms and ladders located within the top 100 feet (30 m) of the stack should be fabricated from a corrosion resistant material. This includes all platform steel, grating, handrails, ladders, ladder fall prevention devices, and attachments. Typically, Type 317LMN stainless steel provides sufficient corrosion protection at these locations. Items fabricated from Type 317LMN are not readily available and material substitutions may need to be evaluated.

2.2.3.2.4 Electrical Conduit

All rigid steel conduits and accessories within the top 100 feet (30 m) on the exterior of the stack should be installed with a bonded PVC jacket. Conduit located within the top 100 feet (30 m) on the exterior of the stack should be supported with Type 316stainless steel unistruts, clamps, and fasteners. Due to corrosion resistance and weathertight requirements, all electrical boxes located within this area should be NEMA 4X.

2.2.3.2.5 *Elevators*

Exterior elevators that extend to the top of a stack should use a mast (rack and guide rails) that is fabricated from Type 316L stainless steel for the upper 50 feet (15 m). Type 316L stainless steel is the most corrosion resistant form of stainless steel that is commonly available from the major elevator manufacturers. Although Type 317LMN stainless steel would provide superior corrosion resistance, fabricated components using more corrosion resistant materials may not be available from the elevator manufacturers. Landing enclosures located within the top 50 feet (15 m) of the stack should be coated with a protective coating system such as a high-build epoxy.

2.2.4 Height

Stack height is determined by the Environmental Protection Agency's publication, EPA-450/4-80-023R, "Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Document For the Stack Height Regulations)." Determination of the stack height should be confirmed by an air quality dispersion model that is performed in compliance with the state and national ambient air quality standards. The information should be presented to the State Environmental Protection Agency for approval.

Good engineering practice (GEP) stack height can be computed using the following equation:

GEP = Hb + 1.5 L

Where Hb = height of nearby structure

and L = lesser of height or projected width of nearby structure

EPA's guidelines provide a more definitive description and definition of the variables associated with determining GEP stack height and should be reviewed in detail prior to GEP determination.

2.2.5 Foundation Requirements as Affected by Liner Choice

The liner material selection will affect the size and cost of the stack foundation. Liners that are heavier will provide more dead load and a larger seismic load than a lighter weight liner. Liners constructed of brick produce the largest foundation loads and liners constructed of FRP produce the smallest foundation loads. Since increased dead load is beneficial in resisting the overturning effects of wind or earthquake, the overall effect of the loading conditions must be evaluated. In general, the foundation for a brick liner should be larger in width and depth and require more piling than a foundation for an FRP or alloy lined stack.

2.2.6 Geometry

A variety of factors should be considered in determining the overall geometry configuration of a new wet stack. The stack liner geometry should provide the most economical configuration to accommodate the physical and design constraints required. The stack liner diameter should be based on the recommended gas velocities to accommodate the liquid flow on the liners. Platforms, access system, and means of inspection must be considered in the stack diameter selection. Stack diameters can be plumb, single tapered or multiple tapered. Stack liner geometry should also be evaluated to minimize the design implications associated with wind and earthquake loads. The major items for the preliminary stack design are discussed in the following sections from the stack floor to the top of the stack. For examples of stack geometry for a brick, FRP, and metal lined stack, refer to Figures 2-1, 2-2, and 2-3, respectively.

2.2.6.1 Stack Floor Geometry.

Floors must be designed to promote drainage of liquid which will collect in the bottom of a wet stack. Steel and alloy liners can utilize conical hoppers or sloped floors. FRP liners traditionally utilize a 90 degree mitered elbow, and liquid is collected in a drain at the elbow. Brick liners use a built up sloped brick floor with a drainage system. Floors or conical hoppers should be located a sufficient distance below the breeching sill to prevent the liquid that has been collected on the stack bottom from being reentrained. Reference (1) recommends that the hopper for brick liners be located a minimum of one half liner diameter below the sill of the breeching, to prevent flue gas from sweeping liquid from the hopper up the liner wall. This distance can be reduced to about 4 feet for cost reduction, but the draining liquid may have to be protected from the gas flow. Flow modeling can define whether protective grating or baffles are needed and what the geometry should be.

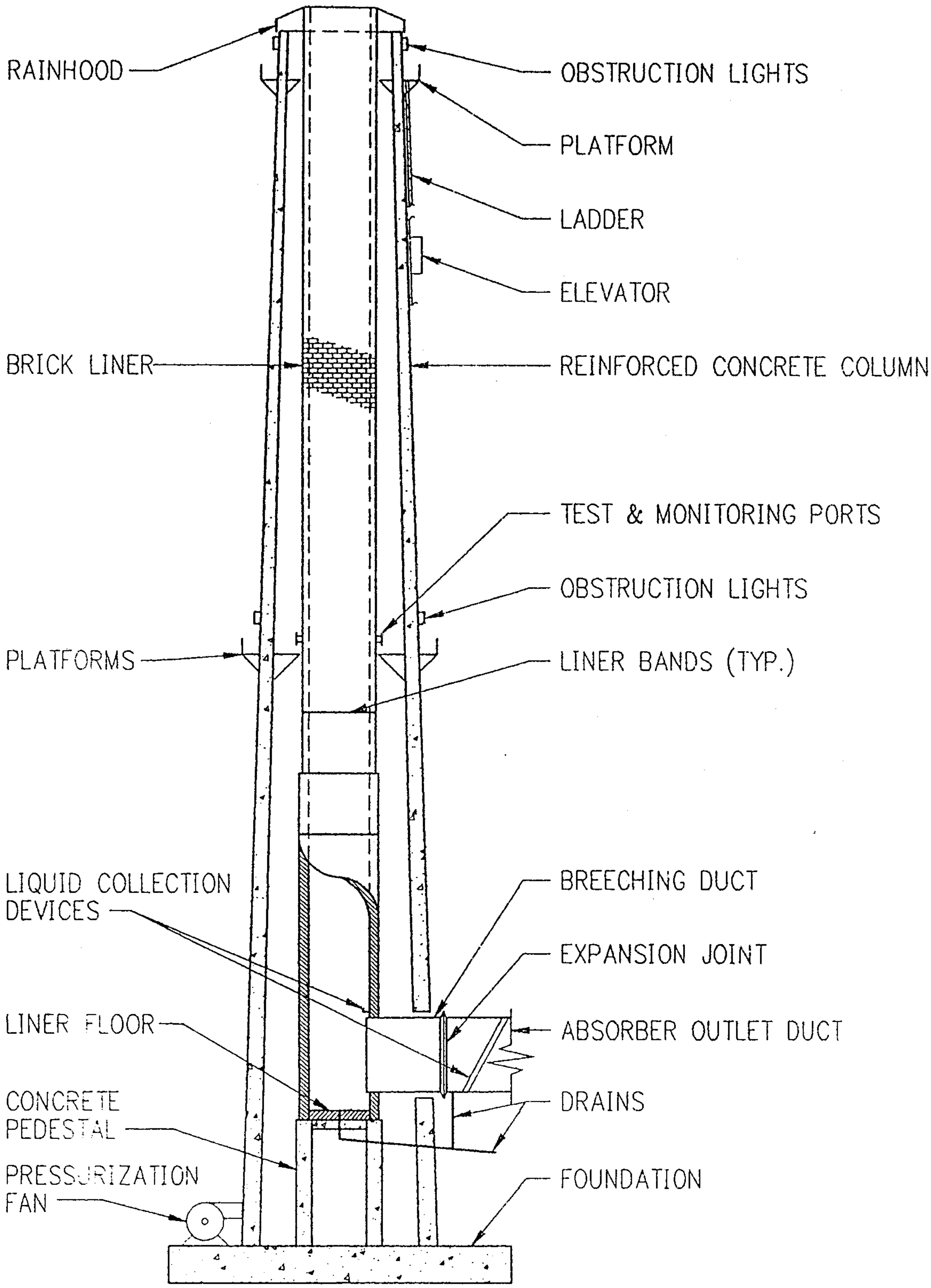

Figure 2-1 Chimney with Brick Liner

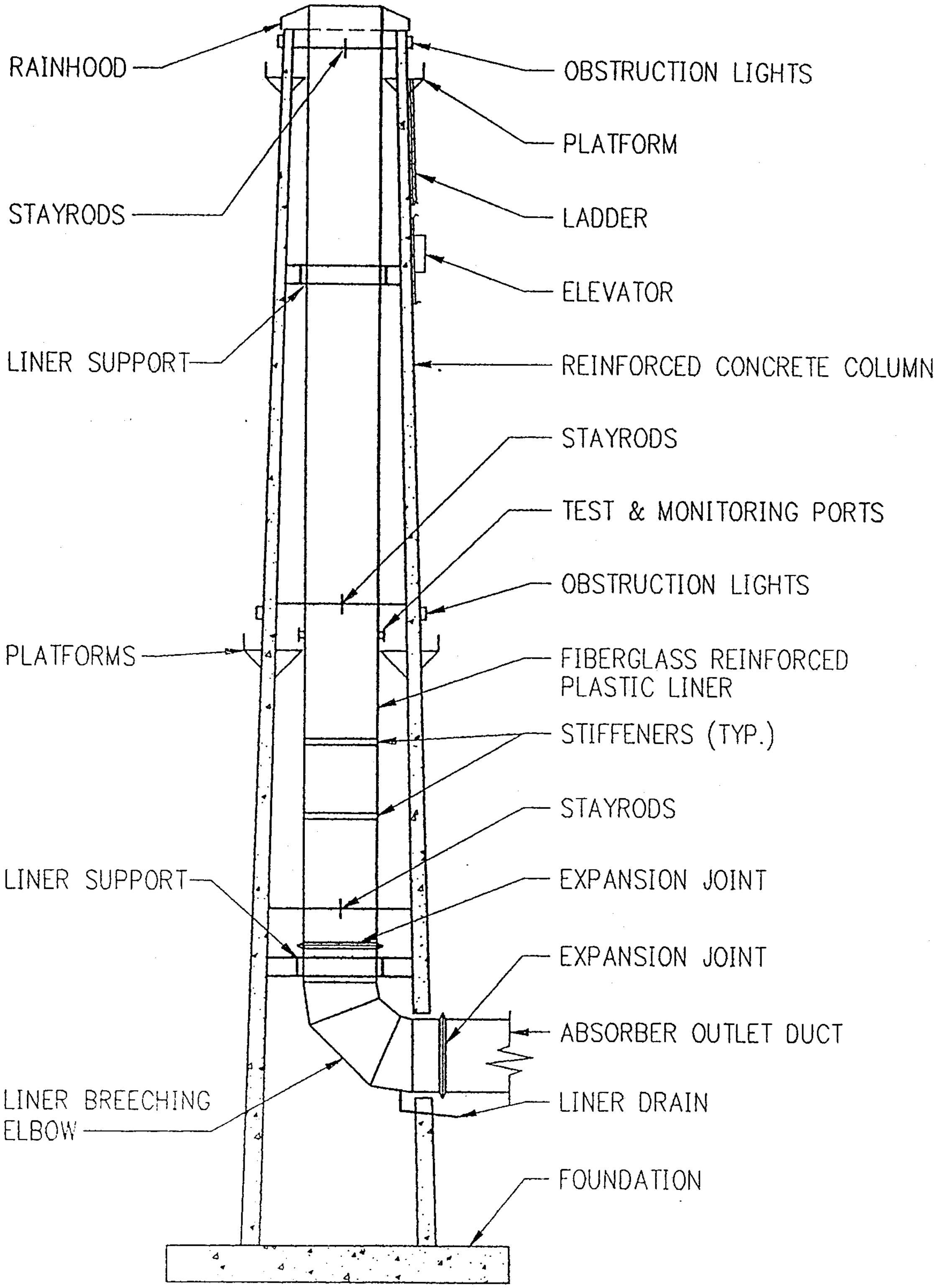

Figure 2-2 Chimney with Fiberglass Reinforced Plastic Liner

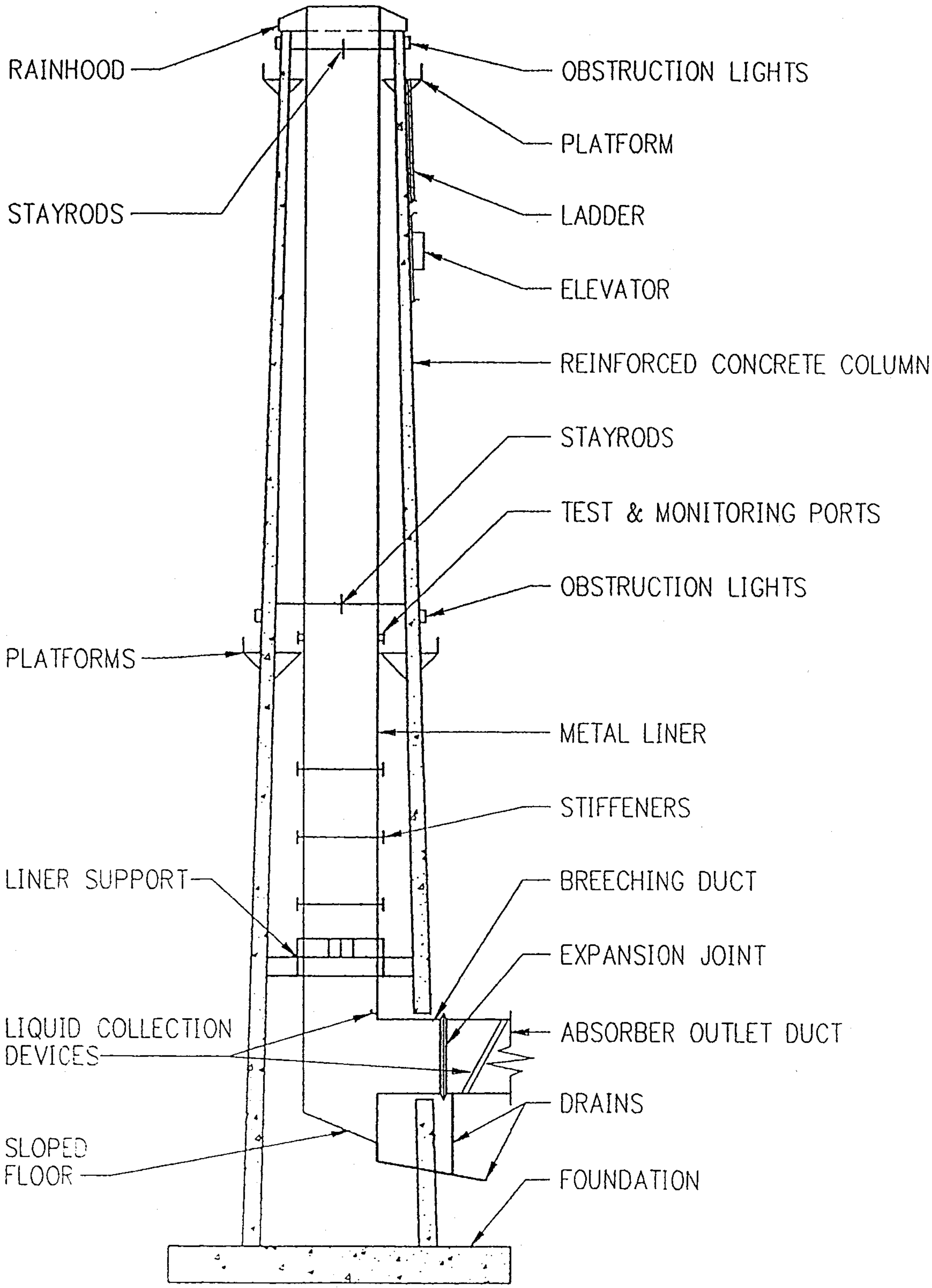

Figure 2-3 Chimney with Metal Liner Typical for Allloy, Glass Block or Protective Coating Liner System

For alloy or FRP liners, the conical hopper, sloped floor or elbow material should be the same material as the liner. Sloped floors in brick liners are supported from an elevated concrete support structure or the concrete foundation. Brick liner floors consist of multiple layers of materials that provide corrosion and thermal protection to its support structure. These floors should be constructed of the following layers of materials: lead pan over asphaltic impregnated felt, acid resistant mortar fill sloped to the drain, and a minimum of two layers of acid resistant brick and mortar. The lead pan should be returned up the side of the brick liner to provide protection to the wall.

2.2.6.2 Breeching Duct Geometry.

Breeching duct dimensions are typically rectangular, with the long dimension in the vertical direction to minimize the structural effects on the column and liner. It is beneficial to increase the height to width ratio of the breeching by transitioning the width narrower and the height taller as the breeching approaches the liner and by keeping the floor level. This minimizes the amount of liner cross-sectional area that is interrupted at the breeching openings. The height (H) to width (W) ratio (H/W) of the breeching duct opening should be in the 2.5 to 3.5 range for good liquid flow on the liner wall opposite the breeching duct.

For brick liners, the breeching opening width may dictate the diameter of the liner. The ASTM C1298 brick liner design guidelines recommend that the opening width not exceed one half the internal diameter of the liner at the opening elevation.

For tall breeching openings, the vertical edge of opening should be designed to have adequate stability as a column element. Multiple and single openings under axial compression should be reinforced or proportioned to fully restore the structural capacity of the entire cross-section. Brick liners utilize brick pilasters and alloy liners utilize vertical jamb stiffeners to provide vertical edge stability.

2.2.6.3 Liner Geometry.

Steel, alloy and FRP liners are typically, but not necessarily limited to, plumb or constant diameters. Several different support methods are available for these types of liners. For steel and alloy liners, a common arrangement is to support the liner at or near the base or breeching entry. The liner is supported in compression, and bumpers or stay rods are used to provide lateral support.

Tall steel and alloy liners supported in compression would need to evaluate the cost of increased wall plate thicknesses versus providing a second support level near the top of the chimney to support most of the liner in tension. An expansion joint would be required above the lower support to accommodate thermal movements.

FRP liners are generally supported with the majority of the liner in tension. Supports are provided at two locations, one near the top and the second near the breeching level, with an expansion joint located above the breeching level.

Expansion joints in wet stack liners are a problem because they tend to collect liquid, resulting in complete liquid reentrainment at the expansion joint cavities. Therefore, expansion joints should be avoided or provided with liquid collectors.

Because of structural considerations to accommodate breeching openings and design loads, brick liners can be plumb or tapered. Depending upon the breeching opening elevation as well as other factors, brick liners can be supported from the stack foundation, from a concrete pedestal or from a corbelled support in the concrete column. Chimneys with breeching openings that are less than 50 feet above the foundation would probably use a brick liner that is supported directly off the foundation. Breeching openings that are more than 50 feet (15 m) above the foundation should consider utilizing a concrete pedestal to support the lining. For tall brick liners with thick walls at the base, it is generally more economical to use a concrete pedestal for high breeching entries.

Brick liners in high seismic locations sometimes use a corbel supported liner to reduce the seismic loads. The liner is constructed in short segments that are supported from concrete ledges in the chimney called corbels. This method of construction is not recommended for wet stack applications. Liquid and flue gas leaking through the brick liner can attack the concrete support system. Additionally, it is difficult to pressurize the annular space areas at each of the corbel sections.

Tennessee Valley Authority's Paradise Station Units 1 and 2 have a stack with a corbel supported brick liner. In order to add a pressurization system to the stack after the reheaters were taken out of service, an extensive system of ductwork had to be erected on the exterior of the chimney. This pressurization system was incorporated to protect the corbels and the concrete column from flue gas liquid that could leak through the brick liner. Further information on this pressurized corbel supported chimney liner can be found in Reference (7). These two units also have duct and stack liquid collectors installed.

2.2.6.4 Choke Geometry.

Stacks that operate with a low discharge velocity sometimes have problems with downwash or insufficient plume rise. To reduce these problems, a choke can be incorporated at the top of the liner. Chokes are designed to increase the gas exit velocity by decreasing the discharge diameter. It must be noted that the use of a choke, which constitutes a "dispersion technique" under EPA stack height regulations, cannot result in a relaxation of the emission limitation for the facility. Chokes will increase draft losses and the fan pressure rise should be selected accordingly. Chokes will also cause a positive pressure inside the liner and increase the leaching problems with a brick liner. Chokes can be fabricated from corrosion resistant alloys and FRP. If a choke is installed on a wet stack liner, a choke liquid collector will be needed at the top of the choke, because the choke discharge velocity usually exceeds the liquid reversal velocity for the choke surface material. The choke surface material for recent choke designs is nickel alloy or FRP, even for brick liners.

An Alloy C276 choke was installed on the top of the brick liner at the Bailly Station Units 7 and 8 stack. An Alloy C276 liquid collection ring was installed around the exterior of the choke to collect the liquid from the choke surface and drain it to the ground level. The stacks at Allegheny Power Services' Mitchell Station Unit 3 and at D.B. Wilson Station Unit 1 have brick liners with brick chokes. The stack at Michigan South Central's Endicott Station Unit 1 has a borosilicate glass block liner with a choke fabricated from Alloy C22. Based on discussions with plant personnel and the industry survey data, stack liquid discharge has not been a problem at these plants.

2.2.6.5 Multiple Versus Single Liners.

Stacks can be designed to enclose a single or multiple number of liners. Each liner can also be designed to accommodate a single or multiple number of operating units. Economics, plant layout, ductwork layout, and the need to perform maintenance during unit outages should be considered when evaluating these options. The capital cost for a stack with multiple liners is typically less than the combined costs of several stacks with individual liners. However, this savings is partially offset by the increased costs associated with a larger foundation, longer ductwork, and possibly larger pressure rise induced draft fans.

Building a single large diameter liner to serve multiple units is not recommended, because if maintenance needs to be done on one unit, both units need to be out of service. Multiple units operating within a common liner also cause additional design considerations such as gas temperature differentials, variable flow rates, and continuous emissions monitoring system certification. The continuous emissions monitoring systems for a liner serving multiple units would need to locate its equipment in the upstream ductwork rather than in the stack, in order to monitor readings from individual units. Another concern would be with one unit off line, low load operations would result in a low exit velocity causing potential downwash problems. For good liquid collection, a one breeching duct per liner design configuration is recommended. The combination of flows from multiple units into a single flue may qualify as a "dispersion technique" under EPA stack height regulations. The emission limit for the units may not be influenced by the effect of any dispersion technique.

2.2.6.6 Downwash Guidelines.

The parameters that affect plume downwash and the consequences of allowing plume downwash are discussed in Section 1 of this Report.

Momentum Ratio (MR) is the ratio of vertical plume momentum to horizontal wind momentum:

$$MR = (\rho V^2)_{\text{flue gas}} / (\rho V^2)_{\text{wind}})$$

MR is the most important fluid dynamic force ratio that affects plume downwash. The individual parameters within this ratio have the following importance for wet stack plume downwash:

1. Flue gas density ($\rho_{\text{flue gas}}$) is almost constant for saturated flue gas at about 0.066 lb/ft^3 (1.06 kg/m^3) at sea level ambient pressure. Reheat will decrease this value by 5 to 10 percent.

2. Wind density (ρ_{wind}) varies with ambient temperature at sea level ambient pressure from 0.090 lb/ft^3 (1.44 kg/m^3) at -20 degrees F (-29C) to 0.071 lb/ft^3 (1.14 kg/m^3) at 100 degrees F (38C), about a 25 percent spread.

3. Reduced ambient pressure at high elevation plants reduces density by 10 percent to 20 percent but it changes both density values by the same amount.

4. The flue gas discharge velocity ($V_{\text{flue gas}}$) is at the highest stack elevation and is set by the liner or choke discharge diameter and the low load to high load flue gas volume flow rate. This value can be anywhere in the range from 20 fps to 120 fps (6-37 m/s) for a wet stack plume discharge.

5. The wind velocity magnitude, direction and frequency of occurrence varies significantly across the country but this information is usually available at weather stations and airports located near existing or new power plant sites. The information needed is what is usually referred to as the "windrose" data in graphical or tabular form which includes:

- Wind velocity and frequency as a function of direction (22.5 degree sectors).
- The cumulative data is usually supplied on a yearly basis, but the data is also available on a monthly basis (or more frequently) if time of year is important.

  When reviewing the wind data, a judgement must be made when selecting a worst wind magnitude and cumulative frequency of occurrence to eliminate unusually high windstorms of short duration that seldom occur.

Items 1, 2, 3, and 5 can usually be set for a specific plant site. Item 4, the flue gas discharge velocity, must then be selected to satisfy the requirements for:

- Plume downwash.
- Plume dispersion.
- Liquid collection and drainage.

For plume downwash considerations, design decisions must be made concerning the extent of allowable downwash and the cumulative amount of time that downwash occurs over the period of a typical year. Factors to be considered are:

- Unit load schedule versus time.
- Windrose data.
- Geometry of the top of the stack.
- Extent of downwash allowed:
  - None (may not be achievable).
  - On liner extension.
  - On roof or hood.*
  - On stack shell.
- Cumulative time of downwash (per year):
  - Zero (may not be achievable).
  - Less than 2 days (0.5 percent).
  - 2 to 4 days (0.5 to 1 percent).*
  - 4 to 8 days (1 to 2 percent).

*The extent of downwash and cumulative time of downwash marked are suggested values at which to start the evaluation of downwash and its effect on stack discharge velocity.

If the resulting stack discharge velocity is unreasonably high, the downwash criteria may have to be relaxed to allow more downwash and time duration.

A wind tunnel model study of the stack top for a specific plant and geometry is required for an accurate evaluation of the extent of plume downwash and cumulative time of downwash. Presented below are some approximate guidelines that can be used for preliminary evaluate the degree of plume downwash expected, and select starting geometries of the stack top for wind tunnel selection.

The momentum ratio ranges presented below represent a variation from intermittent downwash, which is nearly continuous for the low momentum ratio, to intermittent for the larger momentum ratio. Below the lower momentum ratio for each range, the downwash is continuous. Above the upper momentum ratio for each range, the downwash is almost unnoticeable. The following two momentum ratio ranges are discussed below:

- MR1 - Momentum Ratio range for intermittent downwash to roof or hood.
- MR2 - Momentum Ratio range for intermittent downwash to the shell.

For all stack top geometries discussed below, the stack shell diameter should be as small as practical to contain the number of liners.

Single Flue Stacks

1. For an angled hood and no liner extension.

- MR1 {{congruent}} 3 to 5
- MR2 {{congruent}} 2 to 3

2. For a flat or angled roof and a short liner extension (extension {{congruent}} 0.5 extension diameter).

- MR1 and MR2 are expected to be lower (10 to 20 percent).

Two Flue Stacks

1. For a flat roof plus a liner extension of about one liner extension diameter.

   Best wind direction:

- MR1 ≅ 1.5 to 2.0
- MR2 ≅ 1.1 to 1.5

   Worst wind direction:

- MR1 ≅ 3.5 to 5
- MR2 ≅ 3 to 4.5

2. For a minimum liner extension of 0.75 extension diameter, the MR values above will remain the same for the best wind direction, but the MR values above for the worst wind direction will rise by 10 to 20 percent.

3. For a taller liner extension of 1.5 extension diameters, the MR values above for the best wind direction will remain the same, but the MR values above for the worst wind direction will drop by 10 to 20 percent.

4. A chamfered stack top (2 sides) will increase the best wind direction MR values slightly (10 to 20 percent) but will reduce the worst wind direction MR values by 30 to 50 percent.

Three and Four Flue Stacks

1. The best wind direction MR values are expected to be similar to single flue stacks.
2. The worst wind direction MR values are expected to be similar to the two flue stacks.

In most locations, there is a prevailing wind direction where the highest wind velocities occur for longer periods of time. For single flue stacks this has no effect on the extent or duration of plume downwash. However, for multiple flue stacks, it will be advantageous to orient the multiple flue arrangement so that the prevailing wind is aligned with the best wind direction which gives the lowest MR values.

This will result in the lowest cumulative time for plume downwash for a specific combination of flue gas discharge velocity and stack top geometry.

The plume downwash guidelines can be used to obtain preliminary estimates of the stack top design to limit the extent and duration of plume downwash:

1. Select a plume downwash criteria at a specific unit load.
2. Select a basic stack top design except for flue gas discharge velocity.
3. Obtain the windrose data and select reasonable design wind velocities.
4. Select the appropriate MR guideline value compatible with steps 1 and 2.
5. Calculate the corresponding flue gas discharge velocity, flue gas discharge area and the preliminary stack top geometry.
6. Compare the results in step 5 to values compatible with good plume dispersion, stack liquid collection and drainage, and construction cost.
7. Repeat steps 1 through 6 until satisfactory results are obtained for all important criteria by making appropriate compromises.

The final stack top geometry should be optimized by wind tunnel plume downwash studies, particularly for multiple flue stacks where downwash minimization is important.

2.2.6.7 Annular Space.

Sufficient space should be provided between the inside of the concrete column and the outside of the liners to allow for inspection and maintenance for the full height of the stack. A minimum annular space of 2'-6"(0.76 m) is recommended. If platforms, ladders and an elevator are located on the interior of the stack, sufficient annular space needs to be provided for these items. The size of the annular space should account for differential movements that may occur between the concrete column and the liner due to wind, seismic, or thermal expansion. Damage to platforms or the liner may occur if sufficient space is not provided. Access and adequate clearance for clean-out doors and continuous emissions monitoring equipment also needs to be considered. Ports should be accessible and provide sufficient clearance between the column and liner to insert EPA test probes. To minimize annular space requirements, doors can be provided in the column. Monorails can be used to assist in installation of the probes.

In order to ensure personnel safety, the annular space should be well ventilated, especially when an interior access system is used.

2.2.7 Liquid Collection Devices and Drainage

Saturated gas flow and condensation on the surfaces are normal operating conditions for wet stacks. Some mist eliminator liquid carryover and the liquid condensed from the large amount of vapor present in the gas result in a higher liquid load in the duct and stack flow passages than with reheat. Liquid collection devices are recommended to collect the liquid in the outlet ductwork and in the stack before it exits the chimney. Liquid collectors and drains are an important design consideration in a duct/stack system for wet operation. The behavior of the gas/liquid flow is described in Section 1, "Sources of Liquid in Wet Stacks" and the guidelines for selecting the duct stack geometry suitable for wet operation is discussed in Section 2, "Geometry." The general information about the liquid collection system is described here while design and development tools are described in Section 2, "Evaluation for Wet Operation."

Reference (1) provides a description of typical liquid collection devices. The *Wet Stacks Design Guide* provides the latest technology regarding liquid collector locations. The tools used for these new developments are discussed in Section 2, "Evaluation for Wet Operation." The successful design and operation of a wet stack liquid collection system starts with the mist eliminators and includes all elements of the absorber duct, breeching duct, stack entrance, stack liner and stack discharge. Each element along the gas flow path is important.

The liquid collectors collect all the deposited liquid and condensed liquid from the duct and stack surfaces. The type, size, geometry, and location of liquid collectors are selected to utilize gas shear and gravitational forces to collect the liquid and drain it out of the system before reentrainment can take place.

The actual design and optimization of the liquid collectors is site-specific work, and depends on the duct-stack geometry, gas velocity levels, and three-dimensional gas and liquid flow patterns. The best liquid collection system has to be optimized for each specific unit. A flow model studyshould be performed by an experienced modeling company to determine the optimum location and configuration of the liquid collection devices. Descriptions of the major liquid collection areas are given in the following subsections.

2.2.7.1 Mist Eliminator System.

The mist eliminator system is the first and most important element of the liquid collectors in a wet duct stack system. The selection of the best mist eliminators to match the absorber and duct design result in reduced liquid load in the duct stack system and a less elaborate liquid collection system. In flue gas desulfurization (FGD) service, the function of the mist eliminators (MEs) is to remove entrained scrubbing slurry from the flue gas before it travels out of the absorber into the downstream ductwork and stack. The mist eliminators are located downstream of the absorber spray zones, where the flue gas contacts the scrubbing slurry that removes sulfur dioxide. Slurry content of the liquid carryover can cause solids buildup in the outlet ductwork and stack, high particulate emissions, and corrosion. The amount of liquid that the flue gas carries into the mist eliminator will depend on droplet size, the gas velocity, the liquid-to-gas ratio, the washing method, etc.

The amount of liquid droplet carryover into the wet duct stack system from the mist eliminators can be minimized by:

1. Selecting the most suitable mist eliminator elements for the operating conditions of the installation.
2. Using two stage mist elimination.
3. Using gas velocities with a safe margin under the critical reentrainment velocity for the mist eliminator blades selected.
4. Achieving a sufficiently uniform velocity profile into the second stage mist eliminator to keep all regions below the critical reentrainment velocity.
5. Selecting effective washing techniques and procedures to prevent solids buildup on the mist eliminators without entraining wash spray in the gas flow.
6. Establishing inspection and maintenance procedures for the mist eliminators.
7. Maintaining good pH control to reduce solid precipitation in the mist eliminators.

Reference (3) describes all essential aspects of the mist eliminator design, application, operation, and maintenance necessary for an effective mist elimination system. The measured laboratory performance of several commercially available mist eliminators is also furnished in this reference.

2.2.7.2 Ductwork.

Since liquid deposition and condensation take place in the ductwork as well as in the stack, it is important to do as much liquid collection in the ductwork as possible. Layout of the ductwork geometry, sizing of the ductwork, liquid collection devices and sufficientdrainage should be considered in the design of the ductwork connecting the absorber and the stack. Liquid collection is easier in horizontal gas flow ducts than in the vertical flow stack liner. An effective liquid collection system installed in the ductwork will result in reduced liquid load for the stack liquid collectors.

Absorber towers often have a 90 degree turn at the top of the absorber where entrained fine droplets deposit on the ceiling or on the vanes if equipped with turning vanes. Turning vanes promote deposition and reduce pressure losses at the same time. Therefore, the cost of the turning vane addition can be justified in most cases. Liquid collectors should be provided on the vanes to collect the liquid and prevent reentrainment.

In straight rectangular duct sections simple sidewall collectors and slanted or V-shaped ceiling collectors can be used. Figure 2-4 shows generic examples of ductwork liquid collectors. The actual details are a function of the ductwork geometry, gas velocity, and liquid loading in the gas flow. These collectors are usually L-shaped cross sections and their sizes range from 2" x 2" to 6" x 6" (0.05m x 0.05m to 0.15m x 0.15m) depending on the duct geometry and gas velocities.

Liquid collectors located on the outside wall are used downstream of 90 degree duct bends Turning vanes and baffles can be added to the bends to promote deposition; when equipped with liquid collectors, they provide additional liquid collection in the duct system.

Round ducts have to be equipped with liquid collectors also. Usually fewer collector elements are needed but they are more difficult to install because they have to follow the curved surface contour in round ducts.

Internal bracing in rectangular ducts should be avoided. Bracing provides additional impingement surfaces and reentrainment sites. If internal bracing has to be used in breeching ducts, diamond shaped bracing is recommended for its better draining qualities.

Liquid collectors in the breeching duct represent an effective last collection stage before entering the liner. Good liquid collection in the ducts means reduced liquid load on the stack.

Liquid collects and drains in the duct expansion joint cavities on the side walls but the liquid reentrains at the expansion joint cavity in the ceiling. Commercially supplied duct expansion joints collect some liquid in the cavities but suitable additions to the expansion joints are needed for good liquid collection. Properly designed plates and partial covers can improve the liquid collection in the expansion joints. They should be used when the complete liquid collection system needs this additional increment of improvement.

Guillotine dampers are better for wet ducts than louver dampers because they present smaller surface areas for liquid deposition and the lower reentrainment rate represents a smaller liquid collection problem in the duct. The liquid droplets deposit on damper surfaces in the gas stream and usually reentrain from these surfaces as larger droplets.

The absorber can be placed directly under the liner in the bottom of the chimney, however that will require a larger chimney shell. The only ductwork is a transition from the absorber discharge to the liner inlet. Liquid collection is required in the transition duct to prevent liquid reentrainment.

2.2.7.3 Stack Liner and Choke.

The stack liner opposite the breeching duct generally receives more liquid deposition than any other area downstream of the absorber. Therefore, the liquid collection in the stack entrance zone is critical. As liquid enters the liner, it is deposited on the liner wall opposite the breeching. Gas flow patterns then tend to drag the liquid around the inside circumference of the liner back to the breeching. A liquid collector added around the breeching prevents this liquid from being reentrained into the gas stream. Figure 2-5 shows generic examples of stack and choke liquid collectors. The size, shape, and location of these liquid collectors are functions of the liner material, stack geometry, gas velocity, and liquid loading. Typical liquid collectors are a gutter above the breeching duct and two flow guides on the liner along the sides of the breeching entrance. Liquid collected in the liner entrance should drain to the liner floor or hopper where it can be removed by a drain. A full circumference liquid collector ring may be needed in some installations in conjunction with the liner entrance liquid collectors.

If the maximum projection or offset between bricks on the interior surface of the liner exceed 1/8 inch (0.003m), then partial reentrainment may occur on the wall opposite the breeching duct. Different methods can be used to reduce the surface discontinuities in this area on the brick liners, such as careful construction of the bricks over this area. The removal of the protruding mortar from the joints makes the surface smoother for liquid flow. A coating used over the brick provides a smoother surface. A smoother target wall can be installed over the selected brick area where reentrainment may take place.

Brick surface tolerance on the inside face of the liner at NIPSCO's Bailly Station was limited to 1/8-inch (0.003m). During construction of the acid brick liner at NYSEG's Kintigh Station, the contractor was directed to avoid locating lateral offsets in the brick liner on the wall opposite to the breeching duct within 100 feet (30 m) of the breech opening and to remove all loose mortar, particularly in this critical reentrainment area.

The horizontal weld beads on alloy liners can cause a local liquid reentrainment in the stack above a velocity of approximately 40 fps (12 m/s). The height of the weld bead should be the minimum possible and not exceed the standard for good weld quality of 1/8-inch (0.003m). To achieve liner design velocities for smooth metal, horizontal weld beads must be ground flat and smooth. If the shape of the weld bead is gradually rising and falling, liquid reentrainment is reduced. Similarly, the rings of FRP liners should be glued together with material mostly on the outside of the liner. Only minimum inward protrusion with smooth transitions is recommended. Pennguard block liner seams should be made as smooth as possible by removing the excess adhesive protruding inside the surface during construction.

The liquid condensing along the stack liner flows down on the surface when liner gas velocities are below the liquid reversal velocity. This liquid reentrains at the expansion joints by the gas flow in the expansion joint cavity. Most of the reentrained droplets discharge from the stack. For this reason, the liner suspension should be designed so that liner expansion joint is not needed. If an expansion joint is installed, it should be equipped with liquid collectors especially designed for expansion joints. Only laboratory flow modeling can be used to design and develop liner expansion joint collectors that are effective at all operating loads of that unit.

A choke designed for the top of the liner increases the stack discharge velocity that usually exceeds the liquid film flow reversal velocity for the choke material. The recommended choke material is solid alloy for alloy and brick stack liners. FRP choke should be used with FRP liners. Liquid reaching the top of the choke is discharged and falls to the ground within the near vicinity of the stack. Chokes for a wet stack have to be equipped with an effective liquid collector to prevent this liquid discharge. Horizontal weld beads should always be ground flat and smooth on the inside of the choke surface.

Allegheny Power Services' Mitchell Station Unit 3 had a model study performed and installed all of the recommended liquid collection devices. The liquid collection devices are working well and have had no problems with stack liquid discharge after 12 years of operation. Louisville Gas and Electric's Trimble County Unit 1 has three liquid collectors in the 26-foot diameter absorber outlet duct that consists of 4-inch gutters around the inside of the duct. Three drains in the absorber outlet duct which drain back to the absorber building sump. At Trimble County, the stack exit velocity is high and results in some localized stack liquid discharge. However, since the plant is located out in the country, there have been no consequences due to stack droplet discharge. Louisville Gas and Electric's Cane Run Units 4, 5, and 6 had model studies performed to evaluate liquid collection. All of the liquid collection devices recommended by the model study were installed on Unit 5. On Unit 6 most of the recommendations were followed. A baffle wall was installed in the chimney inlet and a sloping floor and trench were installed in the bottom of the liner to drain off liquid. Cane Run does not have any reported problems with discharge.

2.2.7.4 Chimney Roof (To Prevent Icing).

Stacks with a roof instead of a rainhood are relatively flat to serve as a walking surface. Because of the tendency for liquid fallout accumulation in this area, discharged liquid and rain water sometimes freeze on the roof during cold weather. Ice formation at drain locations may prevent liquid from entering the drains. In order to prevent this occurrence, roof slopes should be sufficient to prevent liquid from pooling and multiple drains are recommended. The roof drain should be separate from the liner or choke liquid collector drains because of pressure differences and different disposal methods.

2.2.7.5 Drains.

The collected liquid has to be drained out of the duct-stack system. In general, drains can be installed in the horizontal absorber outlet ducts, duct expansion joints, stack floor, liner expansion joint collectors, and choke collectors. The preliminary wet stack design should plan an adequate drainage system by considering the drainage needs discussed in thissection. The final number of drains needed and their optimum location are specified as one of the results of the laboratory flow modeling.

The absorber duct drains are most effective if a trench or scupper is installed across the duct in the floor with a drain. The drains, if installed in duct expansion joints, are selected based on local conditions. Sloping the floor of the absorber ducts eliminates water puddles after shutdown when all the liquid from the walls drains to the floor. The sloping floor does not alter the liquid flow on the duct floor during operation because the gas shear dominates the liquid motion on the floor.

Duct floor drains may be required where liquid pools can build up and water reentrainment from the pool may take place.

The stack floor drains often require a wire cage or equivalent over the inlet to prevent plugging by flaking solid scale.

The stack liner expansion joint collector drains and the choke liquid collector drains have to be individually pressure-balanced with siphons or drain pots. These drains connect points of different static pressure levels inside the liner.

Since the liquid is acidic, the material selection for the drain line and the means of final disposal must be evaluated. FRP pipe is commonly used for wet FGD drain line applications. FRP pipe provides good chemical resistance to these acids and is more economical and more readily available than stainless steel or nickel alloy pipes. Drain lines are sized to prevent pluggage and ease of cleanout. The six to eight inch minimum diameter drain pipes used have much larger liquid flow capacity than needed. Seal pots or siphons should be provided as needed, to prevent air inflow under negative pressure which would prohibit liquid discharge through the drain line. Different drain lines can be connected only if the static pressure at the flue gas end is the same; in other cases pressure seal pots are required. Chimney drain lines should use pipe crosses, tees, or wyes with bolted blind flanges for clean out. The drain lines should slope without horizontal sections to reduce pluggage. Access to cleanout connections should be provided.

Outdoor FRP drain lines should have a steep enough slope to prevent freezing. For long, relatively flat horizontal runs of drain line, the pipe should be heat traced and insulated.

2.2.7.6 Disposition of Collected Liquids.

The liquid discharging from drain pipes has to be recycled into the FGD system or properly disposed of. The following liquid disposal methods should be considered:

2.2.7.6.1 Waste Sump or Return to Process

Liquid collected from within the ductwork or stack can be routed to the waste sump or returned to the FGD system process. Liquid routed to the waste sump does not reenter the process and is disposed of. Liquid returned to the process can be routed to the absorber reaction tank. Liquid returned to the process may be of sufficient volume and pH level that it could change the operational characteristics of the FGD process. Thevolume and pH of the liquid returned to the process should be considered to compensate for any operational changes that may be needed.

2.2.7.6.2 Single Versus Multiple FGD Modules

A single stack liner that serves multiple FGD modules may produce large volumes of liquid for disposal. Drainage pipe diameters need to be sized accordingly. If the liquid collected from multiple FGD modules is returned to the FGD process, the volume of liquid may be too large to be returned to a single FGD module without significant changes to its operational characteristics.

2.2.8 Operating Conditions

The design of the stack liner and its components is based primarily on the range of flue gas conditions at the stack inlet. The stack operating conditions affect the selection of the liner's materials of construction, the liner diameter and the design of the annulus pressurization system and the liquid collection devices.

The stack inlet flue gas and ambient air conditions that can affect stack liner design include:

- Temperature.
- Pressure.
- Moisture content.
- Flue gas composition.
- Flue gas flow rate.
- Flue gas liquid content.

These stack inlet conditions are a function of the fuel burned in the boiler, the operation of the boiler, the boiler load, air leakage into the system, heat loss from the system, and the wet FGD System. The following sections provide discussions of how these conditions are factored into a wet stack design.

2.2.8.1 Flue Gas Calculations.

Flue gas calculations are needed to predict the range of operating conditions for a wet stack design. Normal design procedure uses combustion calculations to estimate the range of gas conditions at the FGD inlet and an energy balance to estimate the range of flue gas conditions at the stack breeching entrance. The first step is to calculate the gas conditions at the FGD inlet using the following inputs:

- The desired range of boiler loads and corresponding heat inputs.
- The fuel heating value and composition.
- The excess air at the boiler outlet.
- The air leakage (upstream of the ID fans) into flue gas flow in the air preheater, gas ducts and other equipment operating below atmospheric pressure.
- The flue gas outleakage from a pressurized boiler to the FGD inlet or downstream from the ID fans.
- The flue gas temperature and pressure at the inlet to the wet FGD absorbers.
- The plant barometric pressure.
- The absolute humidity ratio of the ambient air.

Using the previous inputs, the combustion calculations result in the following outputs:

- Gas composition and molecular weight.
- Density.
- Mass flow rate.

- Specific heat.
- Saturation temperature.

These outputs are then used with the following inputs for the FGD absorber energy balance:

- Air inleakage and flue gas outleakage, if any, from the absorber inlet to the stack inlet.
- Flue gas pressure at the stack inlet.
- SO_2 removal efficiency.

The outputs of the absorber energy balance define the remaining gas conditions at the stack inlet:

- Gas composition and molecular weight, including the addition of water vapor and the removal of SO_2 (and the addition of CO_2 if limestone reagent is used and the reaction tank is integral to the absorber module).
- Gas density.
- Mass flow rate.
- Specific heat.

2.2.8.2 Temperature.

The flue gas and ambient air temperature ranges need to be determined. These temperatures affect the design of a wet stack. When a wet FGD system is used with a coal-fired boiler, the saturated flue gas temperature at the absorber outlet usually ranges from 120 degrees F to 130 degrees F (49-54° C). For a specific plant the saturation temperature can be estimated for a range of boiler loads and fuels using the calculation procedure described in the previous subsection, "Flue Gas Calculations."

For a typical bituminous coal, either of the following variations in FGD inlet conditions would result in approximately 5 degrees F (3° C) increase in FGD outlet gas temperature:

- 50 to 60 degrees F (28-33° C) increase in inlet gas temperature.
- 2.0 to 2.5 percent by volume increase in inlet gas moisture content.

Other factors affecting the temperature of the gas entering the stack could include the following:

- Barometric pressure.
- Heat loss in the ductwork from the FGD absorber to the stack.

- Temperature rise through an induced draft fan if located downstream of the FGD absorber.
- Subcooling of the gas below the adiabatic saturation temperature if the scrubbing liquor is not recirculated. For example, a once-through system using sea water as the scrubbing liquor would cool the gas by an amount equal to the heat gain by the sea water.
- Any other method of subcooling, such as a condensing heat exchanger downstream of the absorber.
- Reheat, if used.

For a conversion from heated to wet stack operation, the range of absorber outlet temperatures should be obtained from existing FGD operating data. For design of a new plant or for retrofit of an FGD system at an existing plant, the range of FGD outlet temperatures should be estimated using flue gas calculations described in Section 2. For plant elevations at or near sea level, the saturation temperature may also be estimated using a standard pressure, high temperature psychrometric chart for air.

The ambient air temperature design range can vary from -20 degrees F to 110 degrees F (-29 to 43°C) depending on season and plant location. The atmospheric temperature has a significant affect on the stack effect and the flue gas pressure in the stack, relative to the ambient pressure outside the stack and in the stack annulus. The temperature range noted above produces anambient air density change of +/- 13 percent about standard ambient temperature of 68°F (20°C). The coldest ambient air temperature within the design range will increase the rate of condensation inside the stack liner, requiring that the liquid be collected and drained out of the stack.

2.2.8.3 Pressure.

The total and static pressure of the flue gas inside the stack is a function of the following:

- Ambient temperature and barometric pressure.
- Total pressure losses in the stack entrance.
- Total pressure frictional losses through the liner.
- Total pressure losses across expansion joints, corbel joints, and other stack liner breeching openings, expansions or contractions.
- Pressure variation with height (stack effect).
- Static pressure changes across area expansions or conical contractions and chokes.

The total (P_T) is the sum of the static (P_S) pressure and the gas velocity head (VH) at the same duct or stack liner cross section.

$$P_T = P_S + VH$$

Total pressure loss from the stack breeching duct to the stack discharge plume is the value needed for determining the ID fan requirements for the stack. The maximum differential static pressure between the flue gas and the stack annulus at the same elevation is the pressure needed to select the fans for the annulus pressurization with brick stack liners.

The combination of these total pressure losses, static pressure changes, and ambient pressure and temperature changes can result in the following:

1. Fan total pressure rise requirements of +2 to +4 inches w.c. (0.5 to 1.0 kPa) and flue gas pressures higher than ambient pressures for:

- Highest ambient temperature within the design range.
- Highest barometric pressure within the design range.
- High choke discharge velocity (110 fps (34 m/s)).
- Moderate stack liner velocity (50-60 fps(15-18 m/s).

2. Fan total pressure requirements of 0 to -2 inches of water (0 to -0.5 kPa) and flue gas pressures lower than ambient pressures for:

- Coldest ambient temperature within the design range.
- Lowest barometric pressure within the design range.
- No discharge choke.
- Low stack liner velocity (40-50 fps (12-15 m/s)).

Calculations for a specific stack, geographic location, and boiler load range can be carried out. The most recent issue of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Handbook, Fundamentals, Chapter 32, Duct Design, provides a detailed discussion of the calculations needed.

2.2.8.4 Stack Effect.

The stack effect is the hydrostatic pressure difference between the inlet and the top of the stack. This is due to the lower density of the heated gas in the stack compared to the density of ambient air. Therefore, the stack effect is calculated by multiplying the density difference of the gas in the stack and the ambient air with the height of the stack. Net stack draft is the operating pressure at the inlet of the stack liner and is calculated by subtracting the fluid friction and exit losses from the stack effect.

For wet stack design the worst case conditions are the maximum stack gas flow rate resulting in the highest friction loss in combination with the hottest and most humid ambient conditions. These conditions can normally be expected to produce a positive gas pressure at the stack inlet. The stack effect at worst case conditions is generally only 0.2 to 0.3 inches w.c. (0.05-0.07 kPa) for wet stack operation, a small amount compared to the friction and exit losses at full load.

2.2.8.5 Stack Flow and Density.

The flue gas volumetric flow rate in the stack liner is calculated from the flue gas mass flow rate divided by the flue gas density. The range of flue gas mass flow rates are estimated using the calculations described above.

To determine the maximum design mass flow rate, conservative values for the inputs to the flue gas calculations should include the following:

- Maximum coal burn rate.
- Lowest coal heating value.
- Maximum allowable excess air leaving the boiler.
- Maximum expected air leakage rates.
- Minimum expected flue gas leakage rates.

However, the worst case design volumetric flow rate cannot exceed the head/flow capacity of the induced draft fans for retrofits.

The worst case design mass flow rate and the nominal design mass flow rate with usual safety factors should be compared and the stack design should be evaluated at both conditions, as well as partload conditions.

The flue gas density is directly proportional to the barometric pressure and the flue gas molecular weight, and indirectly proportional to the flue gas Rankine temperature (460 + degrees F). The approximate value of saturated flue gas density at the stack inlet for sea level conditions is about 0.067 lb/ft^3 (1.07 kg/m^3). For the three parameters mentioned above, the flue gas density will change as follows:

- Temperature - A 6 degree F (3°C)change in flue gas temperature causes about 1 percent change in density.
- Barometric Pressure - For plants at high elevation, the flue gas density decreases significantly (-15 percent at 4400 feet (1341 m)). Atmospheric pressure changes due to weather can cause a +/- 10 percent variation around the average local ambient pressure.
- Flue Gas Composition - The flue gas molecular weight due to combustion and saturation changes only a small amount from air, usually to a smaller value. The affect on density is usually less than 5 percent.

All of these individual effects could combine in a reduced density direction.

The range of flue gas volumetric flow rate in the stack liner will be used to:

- Calculate flue gas velocity at each different cross sectional area in the stack system.
- Revise the sizes for the flue gas flow passages for satisfactory liquid deposition, collection, and drainage if needed to achieve acceptable velocity levels.
- Select laboratory model test conditions to develop liquid collectors and drains for the stack system.
- Estimate pressure losses that are proportional to flue gas velocity head.

2.2.8.6 Moisture and Liquid Content at Stack Inlet.

All of the water vapor content of the stack inlet flue gas flow comes from the absorber outlet where the flue gas is saturated. The liquid content of the stack inlet flue gas flow comes from the following sources:

- Mist eliminator droplet carryover, which consists of very small drops (<10 µm) that never contact a mist eliminator blade and larger droplets that reentrain from the mist eliminator blades, structure or solid buildups.
- Condensation on the duct surfaces upstream of the stack inlet, which adds liquid on the duct surfaces.
- Deposition of droplets on duct surfaces, vanes, baffles and structure, which removes droplets from the gas flow stream.
- Reentrainment of droplets from duct surfaces, vanes, baffles, and structure, which adds large droplets to the gas flow stream.
- Installation of liquid collectors on duct walls and ceilings, vanes, baffles, and structure, which collects liquid from these surfaces and guides the liquid to the duct floor of stack bottom drains for removal from the duct stack system.

The geometry of the ducts between the absorbers and the stack inlet, the amount of vanes, baffles, and liquid collectors in the ducts, and the effectiveness of the mist eliminators and duct liquid collectors will determine the amount of liquid, drop sizes, and distribution of liquid in the stack breeching duct at the stack inlet.

For a detailed discussion on the effectiveness of mist eliminator systems, refer to Reference (3). To maintain effectiveness, it is very important to keep mist eliminators clean by washing to prevent sludge buildup. Some recommendations for washing mist eliminators include:

- Use fixed grid spray systems.
- Use high quality wash water.

- Have a frequent wash cycle. (Thirty second duration every 30 to 60 minutes.)
- Wash the upstream sides of each mist eliminator module at a minimum.
- Provide wash coverage of 180 to 200 percent to ensure adequate overlap of adjacent spray patterns.
- Use a nozzle to mist eliminator spacing of 2 to 3 feet (0.6-0.9 m).

To achieve and maintain duct liquid collector effectiveness between the absorber and the stack inlet:

- Use a physical laboratory flow model to develop and optimize the vanes, baffles, and liquid collectors.
- Carefully inspect the installed geometry before FGD system start-up to insure correct installation.
- Inspect the duct system after about 4 months operation to evaluate liquid flow patterns on the surfaces and at liquid collectors, and to determine the amount of detrimental solids buildup.
- After the first inspection, incorporate any obviously needed changes and establish a cleaning/washdown schedule for future operation.

2.2.9 CEM System Considerations

CEM system considerations include provisions for field testing, installation and/or modification of platforms and access systems, and compliance to EPA testing requirements.

2.2.9.1 Provisions for Field Testing.

EPA regulations specify that a quality control program includes calibrations and calibration checks for the CEM equipment installed. Provisions for field testing need to be made not only to meet regulatory requirements, but to provide preventive maintenance and to ensure proper functioning of the monitoring equipment. It may be required to cut holes in existing chimney liners and concrete shells in order to get the probes through. Access into the annulus space must also be considered. For conversion to wet stack operation, flow monitors need to be recalibrated for the revised flow conditions.

2.2.9.2 Platforms and Access Systems.

Extensions to existing platforms may be required to provide access to new port locations. Existing ports may be reused wherever possible. If ultrasonic flow monitoring is used, an additional platform landing will be required approximately one liner diameter above the main testing platform. Modification to existing handrails may be required at certain locations to provide clearance for the monitoring equipment enclosure boxes.

To provide continuous access to the monitoring location and personnel safety, an elevator for accessing equipment on tall stacks is advisable. Platform enclosures may be needed to provide personnel and equipment with weather protection during the winter months. For personnel working in enclosed conditions, adequate ventilation should be ensured.

2.2.9.3 Testing Requirements.

Minimum testing requirements are satisfied if the EPA siting criteria for port locations are adhered to, and if no cyclonic or stratified flow conditions exist. The following requirements are the same for wet, reheated, or bypass operations.

2.2.9.3.1 No Cyclonic Flow

EPA 40 CFR Part 60, Appendix A, Method 1 states that the flow condition is unacceptable if the average yaw angle is greater than 20 degrees. If potential flow measurement problems are significant, it is recommended that a 3-D traverse be done to more accurately determine the flow characteristics of each unit. These characteristics must be discussed with the regional EPA to determine acceptability. If unacceptable, an evaluation of flow straightening must be done. This could include the addition of straightening vanes near themonitor location and/or modification of the deflection plates at the base of the stack. Any modifications would likely require a three-dimensional flow model study.

2.2.9.3.2 Distance Downstream of Breech Entry

According to EPA test methods for gas sampling (EPA 40 CFR Part 60 Appendix A), flow monitors should be located a minimum of eight stack or duct diameters downstream and two diameters upstream from any flow disturbance. If necessary, two stack or duct diameters downstream and one-half diameter upstream from a flow disturbance may be employed. The purpose is to make sure flue gas sample data obtained are accurate enough so that the total emissions can be accurately calculated.

2.2.10 Evaluation for Wet Operation

The preliminary duct and stack design is completed using the component by component guidance of Section 2, "Specific Design Issues." Next, the complete wet duct and stack geometry is evaluated for wet operation as an integrated system, where the individual components operate together as a unit.

The first objective of this evaluation is to review the preliminary duct and stack design as a complete system for wet operation. How well will all the flow passages work together as a system from the absorber outlet to the top of the stack, and how suitable are they to be outfitted with liquid collectors to achieve minimum stack liquid discharge? If improvements are possible through modification to the duct and stack geometry, are the gains in reduced stack liquid discharge worth the cost of the geometry changes?

The second objective is to design an effective liquid collection system that is optimized for the integrated geometry and for the range of operating conditions and absorber combinations.

The combined wet duct and stack systems use a variety of design methods. The best methods that have been developed are described in the following subsections. The design methods and tools used to achieve these objectives are:

- Preliminary Design Review Based on Experience.
- Laboratory Flow Modeling, 3-D.
- Computer Flow Modeling, 3-D.
- Computer Program Calculations, 2-D.

These are summarized in the first four subsections below.

The subsection on "Comparison of Experimental and Computer Modeling" is an overview of the basic gas/liquid flow processes that need to be evaluated in a wet system using the design tools,and summarizes the usefulness of the experimental and computer tools to carry out the evaluation needed.

The last two subsections are a discussion of the system tests and inspections conducted after the unit is in operation to help identify how well the final duct stack geometry and the installed liquid collection system are working. If there are wet operation problems, then the tests and inspections can identify the causes and practical solutions.

2.2.10.1 Preliminary Design Review Based on Experience.

The first two steps in Phase II is to perform a component by component design and then adjust the design for liquid collection requirements. The results of these first two steps should be evaluated by a preliminary design review.

The preliminary duct and stack liner design geometry for new construction must be reviewed to assess how well all individual components will work together as an integrated system. The second goal of design modifications implemented at this phase of wet stack design is to make the integrated geometry more suitable for liquid collection. This review should be based on actual field experience with liquid collectors designed for different power plants. This modified wet duct and stack design is the starting geometry for the design of the liquid collection devices. It also optimizes gas flow passages by experimental flow modeling. It is important to get the engineer and modeling company together to review the preliminary design.

2.2.10.2 Condensation Calculations.

A larger portion of the liquid flow on the liner surfaces is due to condensation then to deposition of the droplet carryover from the mist eliminators. The condensation on the liner cannot be measured in a laboratory scale model of the stack. Therefore, analytical calculations are required to define the amount of condensed liquid flow rate in the stack.

The basic description of the adiabatic bulk condensation and the thermal wall condensation processes is given in Section 1, "Sources of Liquid in Wet Stacks." It discusses the methods to predict condensation rates in the duct and the stack and calculated condensation data for typical sample stacks are presented here.

Liquid condensation occurs continuously on all wet duct and stack liner surfaces because the flow gas is saturated and the liner's inside surface temperatures are lower than the gas dew point temperature. But the rate of condensation per unit surface area can vary significantly depending on geometry, materials, temperatures, and wind speed.

The duct and stack condensation rate cannot be measured in experimental flow models. 3-D computer modeling can be adapted for condensation calculations, but it is too complex and expensive for this essentially two-dimensional process.

A 2-D condensation analysis is satisfactory to calculate the condensation rate that accounts for stack geometry, mass flow, heat loss, gas psychrometric conditions and the ambient atmosphericpressure variation along the height of the stack. Assuming axial symmetry for the stack, all the variables can be described or calculated as a function of vertical height with computer programs developed for this purpose as design tools.

A 2-D computer program was used to calculate condensation rates for 22 cases as quantitative examples for this design guide. The authors selected a 550-MW unit operating with brick, alloy and FRP liners in the same shell as typical choices for a new duct stack design. Figures 2-1 to 2-3 show the geometry of typical stacks.

Table 2-7 gives the geometric parameters and gas flow conditions for our three sample stacks. The ambient temperature 0 degrees F, 50 degrees F, and 100 degrees F (-18, 10, and 38°C) and wind velocities of 20 mph (9 m/s) and 40 mph (18 m/s) represent typical conservative conditions for most parts of the U.S. The selected operating variables and the calculated results are given in Table 2-8. The major conclusions drawn from the results of these calculations are as follows:

- The bulk condensation in the liner is a function of stack height.
- For brick liners, the pressurizing air leakage through the liner increases the bulk condensation by additional cooling.
- The wall condensation is directly proportional to the temperature difference between the gas and ambient air.
- The liner material does not affect the wall condensation rate significantly because the thermal resistance of the liner is a small fraction of the total thermal resistance between the flue gas and the ambient air. Figure 2-6 shows the effect of ambient temperature for eight selected cases.
- The wall condensation may be reduced by a factor of about 6 by insulating the outside of the alloy or FRP liners with a 2-inch (0.05 m) fiberglass layer. Increasing the insulation thickness from 2 inches (0.05 m) to 4 inches (0.1 m) will result in a small reduction in condensation rate. Therefore, more than 2-inch (0.05 m) insulation is seldom required. Insulation does not eliminate the liner condensation but can reduce it significantly.
- A wind speed increase from 20 mph to 40 mph (9-18 m/s) increases the condensation rate by only a few percent because the convective heat transfer levels off above 20 mph.
- Having more than two liners in a shell increases the total wall condensation rate by about 5 percent. This is mainly due to a higher condensation rate on the liner extension above the shell.

The condensation in the ductwork is primarily thermal wall condensation; adiabatic condensation (due to pressure reduction with elevation change) is negligible. Therefore, the rate of condensation here is not as important as in the stack, because most of the condensed liquid andthe deposited droplets can be collected and drained out before they enter the stack. The duct condensation rate is calculated either by a 2-D computer program or by hand calculation for the various ductwork surfaces.

The results of the condensation calculation are used to design the liquid collectors and to plan for the liquid disposal system.

The estimated ranges of the liquid flow rates in the wet duct and stack of the typical 550-MW unit are listed here. These numerical values help the stack designer to estimate the amount of liquid flow to be controlled and accounted for in a wet duct stack system:

- Mist eliminator carryover
  - The vapor mass flow rate in the saturated gas stream is rather large. The total vapor content at saturation temperatures 115°F to 130 °F (46-54 °C)is equivalent to a liquid flow rate of — 1,100 to 1,800 gpm (250-410 m3/h)
  - The fine liquid mist of diameters <10 μm with high efficiency mist eliminators — .3 to 1.5 gpm (0.1-0.3 m^3/h)
- Duct wall condensation — 1-5 gpm (0.2-1.1 m^3/h)
- Stack wall condensation — 1-6 gpm (0.2-1.4 m^3/h)
- Bulk condensation in the stack — 6-8.4 gpm (1.4-1.9 m^3/h)
- Deposition of liquid droplets — 1-12 gpm (0.2-2.7 m^3/h)
- Droplets reentrained from the walls, diameters 20-2,000 μ m — 0-10 gpm (0-2.3 m^3/h)
- Liquid in drains — 2-12 gpm (0.4-2.7 m^3/h)
- Stack liquid discharge (a function of the duct/stack design and the effectiveness of the liquid collectors installed) — 0-15 gpm (0-3.4 m^3/h)

Table 2-7
Condensation in Stacks - Selected Typical Program Inputs

Operating Parameters:		
Volume Flow Rate of Flue Gas	=	1,800,000 acfm
Inlet Temperature of Flue Gas	=	130.00 °F
Atm. Press. at Grade Level	=	29.92 inHG
Vertical Distance from Breeching Duct Floor to Liner Floor	=	4.00 ft

Table 2-7
Condensation in Stacks - Selected Typical Program Inputs

		Liner Material		
Breeching Duct:		**Brick**	**FRP**	**Alloy**
Stack Entrance Loss Coefficient	=	1.9	0.48	1.9
Breeching Duct Area (ft^2)	=	720.0	545.0	720.0
Breeching Duct Dimensions	=	15'Wx48'H	26'4 3/8"ID	15'Wx48'H
Geometry - Major Internal Dimensions:				
Grade Level to Top of Liner	=	500.0	'500.0'	500.0'
Number of Computational Sections	=	4	3	3
Shell Material	=	Concrete	Concrete	Concrete
Breeching Duct Floor Elevation	=	4.00'	4.00'	4.00'
Liner ID	=	29'1 5/8"	26'4 3/8"	25'2 7/8"
Liner Thickness	=	1'4"	1"	5/16"
Shell OD	=	45'9 5/8"	45'9 5/8"	45'9 5/8"
Shell Thickness	=	1'	1'	1'
Air Gap	=	6'	9'3"	9'3"
Top of Stack Elevation	=	500.0'	500.0'	500.0'
Liner ID	=	29'1 5/8"	26'4 3/8"	25'2 7/8"
Liner Thickness	=	8"	5/8"	1/4"
Shell OD	=	37'	37'	37'
Shell Thickness	=	9"	9"	9"
Air Gap	=	2'6"	4'6 1/4"	5'1 1/4"

1ft = 0.3048m, 1 in. = 0.0254 m, F = 1.8xC+32, 1 acfm = 472cm^3/s, 1in. Hg = 3.39kPa, 1 ft^2 = 0.093 m^2

Table 2-8
Condensation in Stacks-Calculated Results for Selected Typical Stacks

Run Number	Liner Material	Liners per Shell	Insulation Thickness (inches)	Ambient Temp. (F)	Wind Velocity (mph)	Velocity (ft/s)	Pressurizing Air Flow (acfm)	Leakage Air Flow (acfm)	Condensation Bulk (gpm)	Condensation Wall (gpm)	Wall Condensation per unit area gpm / 1000 ft2
73	Brick	1	0	0	20	45	70000	10000	8.42	4.31	0.0942
74	Brick	1	0	50	40	45	70000	10000	8.19	2.74	0.0599
75	Brick	1	0	50	20	45	70000	10000	8.19	2.73	0.0597
76	Brick	1	0	100	20	45	70000	10000	8.01	1.05	0.0229
77	FRP	1	0	0	20	55	0	0	6.04	4.28	0.1033
78	FRP	1	0	50	40	55	0	0	6.04	2.83	0.0683
79	FRP	1	0	50	20	55	0	0	6.04	2.76	0.0666
80	FRP	1	0	100	20	55	0	0	6.05	1.07	0.0258
81	FRP	1	2	0	20	55	0	0	6.03	0.94	0.0227
82	FRP	1	2	50	40	55	0	0	6.04	0.6	0.0145
83	FRP	1	2	50	20	55	0	0	6.04	0.6	0.0145
84	FRP	1	2	100	20	55	0	0	6.05	0.23	0.0056
85	Alloy	1	0	0	20	60	0	0	6.31	5.89	0.1486
86	Alloy	1	0	50	40	60	0	0	6.3	3.88	0.0979
87	Alloy	1	0	50	20	60	0	0	6.3	3.74	0.0943
88	Alloy	1	0	100	20	60	0	0	6.31	1.45	0.0366
89	Alloy	1	2	0	20	60	0	0	6.28	0.97	0.0245
90	Alloy	1	2	50	40	60	0	0	6.29	0.62	0.0156
91	Alloy	1	2	50	20	60	0	0	6.29	0.61	0.0154
92	Alloy	1	2	100	20	60	0	0	6.3	0.23	0.0058
93	Alloy	2	0	0	20	60	0	0	6.35	6.22	0.1569
95	Brick	1	0	0	20	45	0	0	6.01	3.13	0.0684

Conversions: 1 inch=0.0254 m, °F=1.8×C+32, 1 mph=0.447m/s, 1 ft/s=0.305 m/s, 1 acfm=472 cm^3/s, 1 gpm=0.23m^3/h, 1 gpm/ft^2=2.4 $m^3/h/m^2$

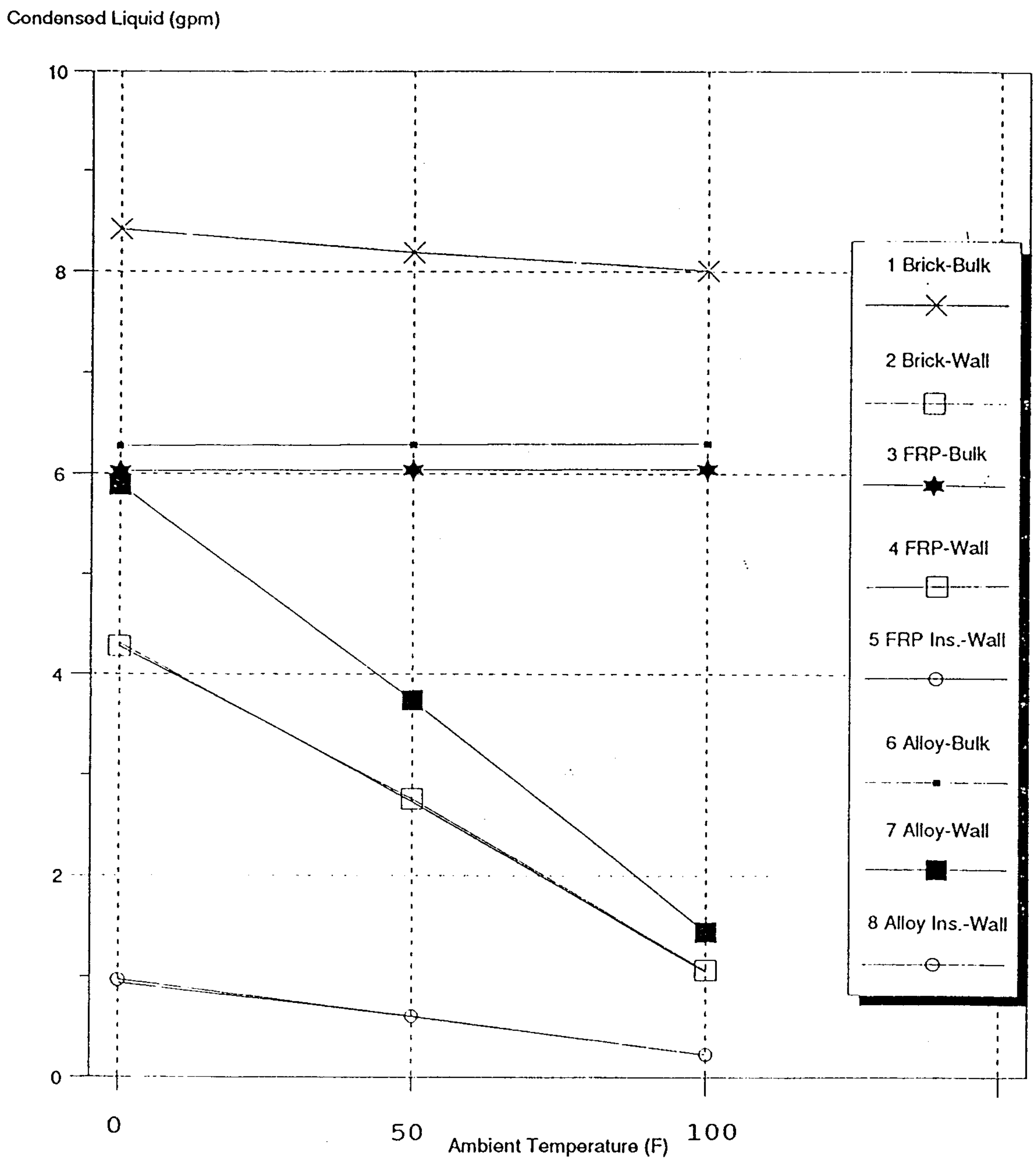

Figure 2-4 The Effect of Ambient Temperature on Condensation in Selected Typical Stacks

2.2.10.3 Laboratory Flow Modeling.

An experimental gas flow model study is a valuable engineering tool used to evaluate wet operation of the absorber outlet duct and stack system from each FGD module mist eliminator to the top of the stack.

The primary objectives of flow modeling includes:

1. Preventing the discharge from the top of the stack of droplets that are large enough to reach the ground before evaporation.

2. Investigating the potential for plume downwash and for icing on the stack liner or shell at low ambient temperatures.

3. Providing velocity profile and swirl patterns at the CEM elevation that satisfy EPA requirements.

Laboratory flow modeling provides the following for wet stack design:

1. Design and development liquid collectors experimentally where needed in the absorber outlet ducts and stack liner entrance region to prevent large droplets from reaching the stack liner. The collectors collect liquid from duct and stack surfaces, prevent reentrainment, and guide the liquid to locations where it can be drained out of the system. This development work is conducted on a scale model of the wet duct and stack system from the outlet of each absorber to approximately two stack liner diameters above the top of the breeching duct. Even though the absorber outlet duct region is not a part of the chimney design, the duct liquid collector designs should be developed here and provided to the owner so that an integrated complete system of liquid collectors can be developed for the unit.

2. Evaluation the liner material and liner surface discontinuities as produced by the construction technique. A laboratory test determines liquid reentrainment and drainage behavior over the range of operating conditions represented by the range of boiler operation and confirms or selects the stack liner design velocity. This step can be eliminated if sufficient reliable information already exists for the selected liner material.

3. Evaluation of reentrainment at liner expansion joints in a laboratory test rig and development of a liquid collector design to collect and drain the liquid from the liner expansion joints.

4. Development of the optimum choke geometry, liquid collectors and drains to prevent reentrainment and discharge of large droplets from the top of the choke.

5. Wind tunnel tests that evaluate downwash of the wet plume, which could lead to stack surface deterioration, unacceptable SO_2 ground level concentrations, or icing problems at the top of the stack. The final geometry of chimney cover shape and the extension of the liner will be specified as a result of this work.

6. Modeling of the absorber outlet ductwork, stack liner breeching duct, and stack liner up to two liner diameters above the CEM elevation. This measures the gas velocity profile and swirl angles for comparison to EPA requirements at the CEM station.

2.2.10.4 Computer Modeling.

The use of computer programs for computational fluid mechanics in general have been increasing during the last 15 years. How and where computer programs can provide help and information for the wet stack designers is described here briefly. The applicable programs can be separated into two categories: 3-D and 2-D computer programs.

These categories of computer modeling are compared to the laboratory experimental flow modeling in the following subsections from the wet stack design point of view only.

2.2.10.4.1 3-D Computer Programs

These are commercially available programs designed for general three-dimensional fluid mechanics calculations. These are not ready to be used for wet stack design. They need significant work to set them up for the geometry and flow processes of wet stacks. They have the potential to handle all aspects of the gas-liquid flow in wet stacks, but at the present stage of development they cannot describe some of the most important wet stack flow processes, such as reentrainment and liquid flow on surfaces with gas flow. Therefore, the complete wet stack analysis with all the necessary details from the absorber to the top of the stack will not be possible by 3-D computer code in the near future.

The 3-D computer models are useful to calculate steady gas flow patterns in the duct and stack. They are good for major flow patterns, but they become complex and slow running programs as small details are included that require larger computers (i.e. flow in expansion joint cavity, flow around trusses, flow near liquid collectors). The 3-D computer models are very good at describing the trajectories of liquid droplets of all sizes and their impact on deposition points in the duct system when combined with the gas flow calculations. These codes can be used to calculate deposition on the choke cone surface with assumed points of droplet origin. Some of the codes come with trajectory subroutines that yield very detailed quantitative results.

The condensation on the liner of a wet stack could be described by a 3-D computer code, but a suitable condensation subroutine is not available.

Several available 3-D computer codes are written for dispersion modeling only. The degree of complexity and accuracy of these codes vary a great deal as they account for the terrain and atmospheric conditions over large distances from the stack. Computerized modeling verified by field dispersion measurements is the best tool at this time to predict the plume dispersion process. Plume downwash at the top of the stack could be predicted by an elaborate 3-D computer model but it has not been done yet.

2.2.10.4.2 2-D Computer Programs

These programs are specifically written for selected flow processes. Therefore, their use is important and the results are good, but they are limited to one detail of the complete wet stack design work.

Special purpose 2-D computer programs can be very useful for providing quantitative results in cases where experimental models are not applicable and 3-D codes are too time-consuming for the objectives. Their use often yields satisfactory results for 2-D processes such as droplet trajectories and deposition, condensation, and fan washing.

2.2.10.5 Comparison of Experimental and Computer Modeling.

Experimental laboratory modeling and computer modeling can help with wet stack design. The objective of this section is to provide information for the wet stack design process about the capabilities of these modeling techniques. The different flow processes important to wet stack design are listed in Table 2-9 and the applicability of the modeling methods is identified.

Experimental flow modeling's main advantage is that it can be used for all gas-liquid processes of primary importance in wet duct stack systems except the condensation calculation. It can provide information about the large scale flow patterns as well as local details everywhere in the flow passages. It is the only modeling technique that provides information necessary for the design and development of the liquid collection system, liquid film flow, reentrainment, liquid flow around liquid collectors and drain flow. It gives a good overall view of all events and the observer can see connections of flow patterns in the entire system.

Experimental modeling's limitation is that it relies heavily on observations; therefore, it is qualitative in many respects of gas-liquid flow evaluation. The value of the experimental results depends on the experience of the observer. The number of droplet sizes that can be observed for trajectory and place of deposition is limited because observations can differentiate only if they are made with the injection of a mono particle size spray.

Computer modeling's advantages are: Its results provide a rather large volume of detailed and quantitative information. It is very applicable for trajectory calculation, and condensation can be calculated only by computer modeling. It can generate results easily for different operating conditions after the first run.

Computer modeling's limitations are: 1) It cannot describe the flow of liquid on the surfaces as sheared by the gas flow. 2) It cannot model the reentrainment at surface discontinuities. 3) It cannot model the gas flow separation and liquid collection around liquid collectors.

Based on the present state of wet stack design, the designer can rely primarily on experimental modeling complemented by computer modeling for condensation calculation and dispersion modeling.

Table 2-9
Basic Tools and Their Applicability for Designing Wet Stacks and Liquid Collectors

Basic Process Studied for Wet Stack Design	3D Experimental Modeling	3D Computer Modeling	2D Computer Calculations
Three Dimensional Gas Only Flow Patterns	Yes	Yes	No
Droplet Trajectories	Yes	Yes	Yes
Droplet Impingement or Deposition	Yes	Yes	Yes
Droplet and Film Flow on Surfaces	Yes	No	No
Droplet Reentrainment	Yes	No	No
Gas and Liquid Flow Around Liquid Collectors	Yes	No	No
Condensation	No	Yes	Yes
LiquidFlow Into Drains	Yes	No	No
Wet Fan Washing	No	No	Yes
Scaling and Solid Build Up	No	No	No
Gas Velocity at CEM Level	Yes	Yes	No
Plume Downwash	Yes	Yes	No
Plume Dispersion	Yes	Yes	No

2.2.10.6 Full Scale Field Tests and Inspections.

After the wet stack is placed into operation, the effectiveness of mist eliminators and downstream liquid collection devices should be tested to verify that design objectives have been met. Reference (1) evaluates various methods for carryover measurements and recommendations for obtaining accurate results.

Effective operation of the liquid collection devices and drainage systems should also be verified during an off-line inspection of the liner system. Gas and liquid flow on the liner and around the liquid collectors can be determined by observing the pattern of residue on the internal surfaces. If heavy solids buildup or deposits are found and are causing stack liquid discharge, necessary improvements can be defined based on this inspection.

2.2.10.7 Flow Measurements at CEM Level.

Flow measurements can be taken to confirm operational characteristics of the FGD system and liquid collection devices. Several of these measurements are required by EPA and are performed as part of the continuous emissions monitoring certification and testing. Information that can be provided from the CEMS measurements includes:

- Stack gas flow rates at different operating loads.
- Gas velocity levels and yaw angles of the cyclonic flow.

Additional in-place testing at the CEM level can measure the effectiveness of the liquid collection system. These tests can be performed as needed to establish the liquid flow in the stack. The following liquid flow measurements are not mandatory tests performed as part of the CEM system; however, they would be beneficial in furnishing several or all of the following information:

- Measurements of entrained droplet size distribution using VDA method.
- Qualitative amount of liquid near the wall by impingement methods.
- Liquid flow direction on wall (up, down or slanted) by observations at the ports covered by plexiglass cover.
- Qualitative droplet sizes, using a suitable impingement probe exposed to the flow for a few seconds.

Where there is a large amount of entrained liquid, the droplets may interfere with the CEMS velocity and angle measurements. This situation shows that liquid collection and drainage must be improved even though the stack liquid discharge is acceptable.

2.2.11 Outage Time

Outage time is the amount of time necessary for an existing unit to be out of service due to repairs, maintenance, modifications, etc. The outage may be due to an emergency (unscheduled) or it may be routine (scheduled). Outage time applies only to an existing, operating unit. Therefore, the designer does not need to consider outage time for a wet stack on a new unit. For a retrofit FGD project, outage time is the time it takes to tie the new FGD system ductwork into the existing ductwork.

Outage time for ductwork tie-ins should be scheduled during a normal maintenance outage. For example, during a scheduled two-week outage at Henderson Station 2, portions of the existing Units 1 and 2 ductwork were removed, portions of the new FGD system ductwork were installed, temporary power was supplied to the seal air fans on the new absorber inlet guillotine dampers, and the existing bypass damper linkages were welded in the open portion. This enabled work to proceed on the FGD system after the duct tie-ins had been completed and the units were returned to operation. When the FGD systems are completed, they can be placed into operation by opening the inlet dampers. Therefore, no additional outage time is required.

Outage time for retrofit wet stacks should be minimized for economic reasons. Depending on unit size, energy demand, loss of revenue, cost of replacement power, etc., outage time can be very expensive. Some examples of outage costs are $70,000 per day for a 440-MW unit burninglocally mined lignite coal to $125,000 per day for a 700-MW unit burning Powder River Basin coal. To minimize the outage time required for a retrofit wet stack project, the ductwork connections or tie-ins should be made during a scheduled maintenance outage.

2.2.12 Cost

Costs for a new or retrofit wet stack are, for the most part, site specific. Budgetary costs for a new chimney may be obtained from one or more experienced chimney contractors. Chimney liner costs may be obtained from the liner material vendors, fabricators, or chimney contractors. They will need to know basic information, such as stack height, number of liners, liner diameter, liner material, breeching duct size and height above grade, etc., in order to develop a budgetary price.

It is important to include material and labor in the installed cost of a liner system. For example, an alloy supplier will provide an estimate for the cost of the material. However, the material also has to be shop fabricated and field erected. It is necessary to obtain budgetary pricing from alloy fabricators and chimney contractors in order to determine the total estimated installed cost of the liner. Cost estimates can also be based on published data or on similar projects.

The chimney foundation is a fairly small percentage (10 to 13 percent) of the overall cost of a brick-lined chimney. Depending on the subsurface investigation, the foundation can either be supported on soil, piles, or drilled shafts. The foundation requirements are site specific and the type of foundation element is selected by the engineer. Due to the height of wet stacks and the weight involved with brick liners, many chimney foundations are supported on either piling or drilled shafts. A soil supported foundation is typically larger than a pile- or drilled shaft-supported foundation. The size of the foundation can be determined by preliminary structural analysis and the cost determined by using the latest *Means Building Construction Cost Data*, by contacting chimney contractors for a price, or by comparison with previous projects.

The estimated installed cost of an elevator can be obtained by contacting an elevator vendor such as Alimak or Champion Elevator. Similarly, budgetary prices for pressurization fans and dampers can be obtained from equipment suppliers.

Cost for various liner materials are included in Table 2-5. A summary of typical material items to be included in a cost estimate are provided in the following Table 2-10.

Table 2-10
Cost Items for Chimney with Brick Liner

Item
1.Piling and Foundation
2.Chimney Shell
3.Miscellaneous Steel
4.Inlet Duct
5.Brick Liner(s)
6.Pressurization Fans
7.Electrical
8.Elevator
9.Engineering
10.Model Study

3

CONVERSION TO WET STACK OPERATION

3.1 Process That Leads to a Specification

A wet stack conversion project involves changing the operating conditions for an existing stack from reheated or bypass gas to fully wet scrubbed gas. Eliminating reheat or using an existing stack for scrubbed gas on an FGD retrofit project would require a wet stack conversion.

In order to develop a bid specification for a conversion to wet stack operation, the designer must follow a logical process. This involves evaluating specific design issues that are important to wet stack design. The engineering process that leads to a bid specification for a wet stack conversion project is discussed in this section.

Included in this section of the *Wet Stacks Design Guide* is a step-by-step process that leads from the feasibility study to a bid specification. A process flow chart outline is included in Appendix E.2 and provides more information regarding the description of each major design issue.

Design of a wet stack conversion project may be broken down into two distinct phases of work:

Phase I - Feasibility Study.
Phase II - Design Process.

3.1.1 Phase I - Feasibility Study

The Phase I feasibility study includes the following steps:

1. Address regulatory issues.
2. Define existing plant considerations.
3. Define operating parameters.
4. Review existing design parameters.
5. Evaluate stack height.
6. Evaluate existing stack, liner, and absorber outlet duct.

7. Determine liner insulation requirements.
8. Determine liner alternatives.
9. Establish liner material options.
10. Perform operating conditions vs. liner design compatibility analysis.
11. Select design velocity limit to prevent liquid reentrainment for each candidate liner material.
12. Determine impact of liner modifications on existing construction.
13. Perform preliminary economic analysis of liner material options.
14. Select liner material(s) for wet stack operation.
15. Evaluate fan alternatives.
16. Collect baseline performance data.
17. Determine reheat system design requirements.
18. Perform economic analysis of wet stack vs. reheat operation.
19. Select wet stack or reheat operation.

The wet stack decision process needs to include a feasibility study comparing wet stack operation versus reheat operation. The study should include permit considerations, dispersion modeling, preliminary design choices (such as liner material alternatives), and preliminary economics.

The study should consider the tradeoff between SO_2 removal efficiency and velocity/liner material and ground level concentrations. Obtaining an air permit is an important issue and will determine whether or not a utility can operate with a wet stack. The feasibility study should address all considerations necessary to make sure that the wet stack design will work.

One of the biggest factors involved in a conversion to wet stack is the existing liner. The existing liner must be evaluated to determine whether or not it is acceptable for wet operation, whether it needs to be relined or replaced, or, depending on the outage time available, whether it would be more economical to build a new stack. Steps 9 through 14 above apply only to the options of relining or replacing the existing stack liner.

3.1.1.1 Identification of Issues (Phase I)

A number of important issues must be addressed during the Phase I feasibility study for the design of a wet stack conversion project, including:

- Gas velocity in the liner.
- Chimney inlet considerations.
- Materials of construction.
- Condition of existing chimney and ductwork.
- Code requirements for stack modifications.
- Adequacy of existing chimney foundation.
- Adequacy of existing steel stacks.
- Operating conditions.
- Wet fans.
- Location of opacity monitors.
- Liquid collection devices and drainage.
- Model study testing to minimize pressure loss and optimize liquid collection.
- Evaluation of performance through stack droplet testing.
- Outage time.
- Cost.

3.1.1.2 Evaluation of Issues (Phase I)

During the wet stack Phase I feasibility study phase, several critical issues such as what the existing liner is made of, must be evaluated. This will determine whether or not the existing liner can handle saturated flue gas. If the existing stack is relined, the existing liner support, stack, and stack foundation may need to be analyzed for additional loads. If the existing liner material is acceptable, what will the exit velocity be for wet stack operation? If the exit velocity is too high, then additional liquid collection devices or a larger diameter chimney liner may be required. Can the existing scrubber performance be enhanced by organic acid additions to reduce SO_2 emissions? This could affect permitting of a wet stack.

Each key issue identified in the process flow chart outlines what needs to be evaluated from a technical and an economics standpoint, so the wet stack designer can decide how to proceed.

3.1.1.3 Economics (Phase I)

Economic evaluation of a wet stack conversion should include the following factors:

- Capital costs.

- Operating costs.
- Maintenance costs.
- Outage costs.

Capital costs for a wet stack conversion project include the cost of the chimney shell and liner modifications, as well as such miscellaneous items as access platforms, doors, elevator, pressurization system, drain system, protective coatings, electrical, etc. Capital costs for a reheat system include the cost of new reheaters, supports, piping, valves, condensate traps, heat exchangers and pumps (for hot water reheaters), controls, insulation, etc.

Operating costs for a wet stack are fairly minor compared to a reheat system. If the liner is constructed out of acid resistant brick, then pressurization fans are required, which have an operating cost. Reheat systems typically have high operating costs due to energy use. A sample calculation of in-line reheat energy costs is shown in Section 2, Table 2-1.

Chimney maintenance costs will vary depending on choice of liner material. Coated carbon steel liners have required periodic recoating, whereas Alloy C276 clad liners have required little or no maintenance. Maintenance on brick liners can include repair of cracks, replacement of liner bands, replacement of expansion joints, etc. All chimneys will require periodic inspection.

Outage time is critical for a wet stack conversion project. The outage costs associated with modifying, relining or replacing the existing chimney liner must be included in the economicevaluation. Outage costs can be minimized by scheduling the wet stack conversion project to take place during a normal maintenance outage. Outage costs per day will vary depending on time of year (energy demand), loss of revenue, and cost of replacement power. Depending on the outage time required to line an existing stack, it may be more economical to construct a new wet stack and either abandon the existing stack or use the existing stack for emergency bypass.

To compare the cost of wet stack versus reheat operation, the economic analysis is usually based on present value. The number of years considered should be the remaining design life of the unit or FGD system. Initial capital costs, periodic or annual maintenance costs, and annual energy costs need to be converted to present value in order to compare the options on an equal basis.

3.1.2 Phase II - Design Process

Table 2-2, which is included in Section 2, describes the design process for a wet stack conversion project. This table provides a brief description of each step of the Phase II design process, designation of responsibility, and a reference in the guide where background information is provided.

The design process phase essentially takes the feasibility study and turns it into a bid specification. During this phase it is necessary to establish the design criteria, define chimney liner and inlet duct geometry, perform the flow model study to determine needed liquid collection devices, and prepare bid specifications and drawings. Several of the items considered during the feasibility study phase should be revisited or finalized during the bid specification phase. This includes such items as design parameters, liner, geometry, liquid collection devices, etc.

Detailed design of chimney modifications required for wet stack conversion is normally provided by the engineer. However, depending on the in-house expertise of the engineering firm responsible for specifications and modifications necessary to the existing stack, it may be more cost effective for a qualified chimney contractor to analyze the existing chimney shell and perform the detailed design of the new chimney liner or modifications to the existing liner. Chimney contractors have developed computer programs specifically for analysis and design of chimney shells and liners. The chimney-related scope of work is typically included in a separate furnish and construct type of contract.

3.1.3 Recommendations

The following recommendations may assist the designer in developing a specification for a wet stack conversion project:

- Perform a feasibility study comparing wet stack versus reheat. The feasibility study should address all specific design issues necessary for satisfactory wet stack operation. (Phase I)
- Address regulatory considerations first. Permitting is an important issue and will determine whether or not a utility can operate with a wet stack. Converting to wet stack operation may affect ground level concentrations. Perform a dispersion model based on Good Engineering Practice requirements for stack height. If increased ground level concentrations prove to be a problem, then organic acid additives or mechanical modifications to the absorber could be considered to improve SO_2 removal efficiency. (Phase I)
- Evaluate existing liner materials of construction for wet stack operation. If the existing material is acceptable, then evaluate exit velocity to prevent liquid reentrainment. If a new liner is required, perform a preliminary economic analysis of liner material options. (Phase I)
- Stacks considered for conversion to wet operation may have been designed before incorporation of present day design standards. Modifications required for the concrete shell and liner should be evaluated in accordance with present day

structural design standards. This may result in additional modifications to the structure, other than that required solely for conversion to wet operation. (Phase I)

- Modifications to a stack liner may change the loads being applied to the foundation. If foundation loads have changed, an analysis should be performed to confirm the adequacy of the existing foundation and piling. This also applies to situations where an existing liner may need to be demolished and a new liner installed. (Phase I)
- Base the wet stack versus reheat economic analysis on the present value of costs over the remaining life of the plant or FGD system. Consider capital costs, maintenance costs, operating costs, and outage costs in the economic analysis. (Phase I)
- Perform a flow model study to design liquid collection devices and measure pressure loss through the duct system. Design flow control devices, if needed, to control stack liquid discharge and pressure losses. The flow model study should be performed by a qualified flow model firm. (Phase II)
- During preparation of bid documents, establish new design parameters, finalize chimney liner and inlet duct geometry, and finalize liquid collection devices. (Phase II)

The process flow chart for a conversion to wet stack operation is indicated in Figure E-2 of Appendix E. The flow chart indicates the step-by-step process that leads to a specification for a wet stack conversion project.

3.2 Specific Design Issues

This section deals with specific design issues for stacks that are being converted to wet operation. Background and state-of-the art information as well as guidelines and recommendations are provided for each issue discussed. The information presented in Section 2 on materials of construction is also applicable to Section 3.

3.2.1 Gas Velocity in the Liner

Stacks that operate under reheat, partial bypass or full bypass generally have been designed for a higher gas velocity in the liner than new wet stacks. Operating the stack wet, by eliminating the reheat, the gas velocity decreases, the density increases, which result in system pressure loss decreases by 5 to 10 percent compared to the system pressure loss with a reheat temperature rise of 30 to 60 degrees F (17-33°C).

Operating an existing liner that is converted to wet stack operations usually has a gas velocity in excess of the recommended velocity presented in Table 2-3 for wet liners; this makes liquid collection within the liner more difficult. Existing liners that are converted to wet operations and have velocities that exceed these recommendations may require that the majority of the liquid be collected in the absorber top and absorber outlet ductwork. The effectiveness of removing liquid via collection devices located only in the absorber top and absorber outlet ductwork should be evaluated. Entrained droplets may impinge on the liner, form liquid streams; a larger fraction of the liquid may become reentrained as larger droplets at higher gas velocity. If the wet gas velocity is higher than the flow reversal velocity for the liner, all deposited and condensed liquid will flow upward to the top of the liner and be reentrained there.

If gas velocities in the ductwork are high, liquid collection in the ductwork may also be difficult and, therefore, the gas velocities in the absorber outlet ductwork should be evaluated. Ductwork for reheated or bypass gas should be sized for 60 feet per second (18 m/s). Ductwork for wet stacks should be sized for 50 feet per second (15 m/s). Critical reentrainment velocities in the ductwork are difficult to determine and are not available. Reference (1) provides liquid collection guidelines that can be used in this evaluation.

If the liner velocity is lower than the range of recommended maximum values, the liquid reentrainment rate is lower and the need for liquid collectors is reduced.

A flow model study should be performed to evaluate liquid reentrainment and liquid collection in the ductwork and liner, based on the anticipated gas velocities. If adequate liquid collection cannot be accomplished at the anticipated velocities, a new liner and/or ductwork sized for a lower gas velocity should be considered.

3.2.2 Chimney Inlet Considerations

Stacks operating with partial bypass reheat may have separate ductwork entering the liner for scrubbed and bypass gases. Bypass is when the flue gas is routed around the scrubber and is not treated by the FGD system. Partial bypass reheat is when hot bypass gas is used to raise the temperature of the wet flue gas exiting the scrubber. This mixing of gas is normally performed in the ductwork. Conversion to wet stack operation precludes any bypass ductwork. With all the flue gas entering the liner through the scrubbed gas ductwork, the head capacity of the induced draft fans should be evaluated for the increased pressure loss through the system.

Separate bypass ductwork entrances in the liner should be sealed where the ductwork penetrates the liner. Sealing the opening flush with the interior surface provides improved gas flow patterns within the liner. It also eliminates the possibility for corrosion developing in the dead leg of the bypass duct and the liquid reentrainment at the cavity opened to the damper.

Eliminating reheat may involve changes to the size or elevation of the absorber outlet ductwork. In such case the openings in the stack and liner may need to be modified or added. If modification to existing openings or incorporation of a new opening is required, the stack and liner should be analyzed to ensure that they are structurally adequate to accommodate these changes. For example, at Louisville Gas & Electric's Cane Run Unit 5, a concrete sheath was added to reinforce the existing chimney column and a new opening was cut for the new absorber outlet duct.

3.2.3 Materials of Construction

Materials of construction associated with the existing liner and ductwork should be evaluated for suitability to wet flue gas conditions.

3.2.3.1 Suitability of Existing Liner Material.

An existing stack designed for reheated or bypass gas conditions typically uses a liner made of carbon steel, brick, or FRP with a quench system. Original material selection criteria may not have included the corrosive environment anticipated for conversion to a wet stack application.

3.2.3.1.1 Existing Steel Liners

Many existing reheat and bypass liners have been constructed using bare carbon steel plate. This liner material has been used successfully in some bypass or reheat applications, but is not considered acceptable for wet applications. Carbon steel will corrode rapidly under wet acidic conditions.

Steel liners with an existing gunite lining are also not considered acceptable for wet operation. Gunite is porous and tends to develop cracks through which liquid can penetrate and attack the substrate material. Conversion to wet operation requires removal of the gunite and relining with a corrosion resistant material.

If liquid collection can be effectively collected without modifying the existing liner geometry, applying corrosion protection to the carbon steel liner should be considered. Since the available options involve extensive field construction, an extended unit outage is required to perform this work. The expense of performing these modifications and the lost revenue associated with the unit outage needs to be evaluated against the construction costs for a new stack that requires a minimal amount of unit outage.

The following modification options can provide corrosion protection to the carbon steel liner (Refer to Section 2 of this report for the corrosion resistant characteristics of each material):

- Alloy wallpaper lining.
- Borosilicate glass block lining.
- Protective coating.

Surface preparation is required before applying a lining or coating. The liner's interior surface must be blast-cleaned. The degree of cleanliness and the surface profile for the blast-cleaning depends upon the lining or coating being installed. A coating system on an existing liner typically requires weld preparation, surface preparation, testing for pH of the surface, and neutralizing acids, if necessary. Coating also requires careful control of humidity and temperature, which limits installation. (18, 19, 20) If alloy wallpapering is used, field measurements should be taken to verify existing dimensions before cutting and fitting the lining sheets. (21) Existing welds must be ground flush for alloy linings and smoothly transitioned for coatings.

Louisville Gas & Electric's Cane Run Unit 6 FGD system was originally designed for reheat. The stack liner was constructed of uncoated carbon steel. The oil-fired reheat system was subsequently eliminated and the unit was converted to wet operation. To accommodate the wet flue gas, the existing carbon steel liner was repaired and then lined with Alloy C276. Pennsylvania Power's Bruce Mansfield Units 1 and 2 were also originally designed for reheat. The original gas reheaters were replaced and then abandoned because of various operating problems. The carbon steel liners are protected with fluoroelastomer and polyester coating systems.

Existing carbon steel liners can be lined with borosilicate glass block to provide corrosion protection. Installation of the block is similar to installing a new liner except that additional surface preparation may be required for cleaning the interior surface of the liner. Michigan South Central's Endicott Station Unit 1 is a freestanding steel stack that was originally lined with two inches of gunite. (22) During the wet stack conversion project, the gunite lining was removed and replaced with a Pennguard Block lining system. The existing carbon steel choke was replaced with a choke fabricated from Alloy C22. An Alloy C22 lined carbon steel hopper was added in the bottom of the stack. The Pennguard Block lining is reported to be in good condition.

3.2.3.1.2 *Existing Brick Liners*

Existing brick liners operating under reheat or partial bypass conditions that are constructed with ASTM C980 brick and ASTM C466 potassium silicatemortar can be considered for conversion to wet operations. Since liquid can be easily reentrained from the rough edges of the mortar joints or brick projections, evaluation of the gas velocity within the liner to prevent liquid reentrainment is important. Inspection of the interior surface of the brick liner should be inspected for roughness.

Modifications that should be considered for an existing brick liner before conversion include:

- Installing pressurization seals at all openings.
- Installing pressurization fans.

- Adding target wall or target lining.
- Installing larger diameter drain line.
- Installing corrosion resistant coating or material for bands.
- Repairing of existing liner cracks.
- Adding liquid collection devices.

The unit outage time associated with performing these modifications is not as extensive as the outage time required for steel liner modifications.

Alabama Electric Cooperative's Lowman Station Units 2 and 3 have eliminated partial bypass and converted their stack to wet operation. The stack has two existing brick liners, one for each unit. The modifications performed on the brick liners, which have only recently been completed are as follows. Operating results are not yet available.

- Installing Pennguard Block lining on the bottom 48 feet (15 m) of the inside liner surface to act as a target wall to minimize the potential for further leaning.
- Modificating of existing drain lines.
- Installing fabric expansion joint seals at the roof.
- Repairing minor cracks in the brick liners.

New York State Electric and Gas's Kintigh Station Unit 1 was designed as a reheated system but was converted to wet operation during the construction of the stack. The brick liner's mortar joints were smoothed in the area opposite the breeching inlet, and liquid collection gutters were added. A flow model study evaluated liquid flow patterns and liquid collection devices. According to the survey data, no liquid discharge was reported.

3.2.3.1.3 Existing Fiberglass Reinforced Plastic Liners

Fiberglass reinforced plastic (FRP) liners operating under reheat or partial bypass typically are installed with a quench spray system. The quench system protects the liner from high flue gas temperatures and is designed to activate at temperatures of about 325 degrees F (163°C). Since wet operations would result in lower gas temperatures, the quench system could be removed from these units. FRP is very suitable for wet stack operation since temperature and acidity levels are lowered.

FRP liners are usually designed to be supported at two elevations and require an expansion joint located directly above the lower support. Expansion joints tend to collect large volumes of liquid. If not previously installed, liquid collection and drainage devices should be provided at the expansion joints in order to minimize liquid build up.

3.2.3.2 Suitability of Existing Ductwork Material.

The suitability of the existing ductwork material is related to the configuration of the reheat or bypass system being eliminated. Three types of reheat and bypass configurations are generally used:

- In-line reheat system.
- Bypass reheat in the absorber outlet duct.
- Bypass reheat in the stack.

The ductwork material downstream of an in-line reheat system needs to be evaluated. The original reheat system may keep the gas temperatures high enough to avoid corrosion concerns. If the existing material downstream of the reheaters is carbon steel or some other type of noncorrosion resistant material, protection or replacement of this material is required if the reheat system is eliminated. Modification options to protect the existing ductwork plate are the same as for a steel liner:

- Alloy wallpaper lining.
- Borosilicate glass block lining.
- Protective coating.

At Michigan South Central's Endicott Station Unit 1, the ductwork downstream of the in-line reheaters was fabricated from Type 316L stainless steel. When the reheat system was eliminated, the portion of the ductwork between the damper and the stack was lined with Pennguard Block on the duct walls and roof and Alloy C22 on the duct floor. (22) The ductwork is reported to be in good condition after 6 years of operation.

Partial bypass gas entering the absorber outlet ductwork creates an extremely corrosive environment in this mixing zone. High chloride and acid concentrations develop at these locations. An Alloy C276, Alloy C22, or borosilicate glass block lining on the ductwork isrequired at and downstream of the mixing zone, consistent with the material requirements associated with alternating wet/dry conditions.

If a bypass reheat system routed directly to the stack liner is eliminated, an increased volume of flue gas will be treated by the absorber and exited into the absorber outlet duct. Any changes to the flue gas related to the elimination of bypass operation should be evaluated. Typically, only minimal changes to the corrosive characteristics of the gases are expected. In general, if the original material selected for the absorber outlet is performing adequately, the material should continue to perform adequately after removal of the partial bypass reheat.

3.2.4 Condition of Existing Chimney and Ductwork

The condition of the existing chimney and ductwork should be evaluated before conversion to wet operation. Using the existing stack and ductwork versus constructing a new stack should be predicated on the condition of the existing system and its adaptability to design modifications. An interior and exterior inspection of the stack liner and ductwork is recommended.

3.2.4.1 Existing Steel Liners and Ductwork.

Several issues should be considered in the modifications associated with steel liners and ductwork:

- Condition of the existing liner and ductwork.
- Design adequacy of the existing liner and ductwork.
- Design adequacy of the existing liner support system.

For steel liners and ductwork, ultrasonic plate thickness readings should be taken to determine if corrosion has reduced the original plate thicknesses. The liner and ductwork should be analyzed to confirm the design adequacy of the existing plate thickness with the additional dead load from the corrosion resistant lining system. Stayrods and bumpers that provide lateral support for the liner should be inspected. If existing expansion joints within the liner do not have liquid collection devices, they should be added to prevent accumulation of liquid at these locations.

The design adequacy of a steel liner's support system should also be confirmed. Adding a corrosion resistant lining system to a steel liner will increase the amount of dead load carried by the support system. Reinforcing or replacing the support system may be required.

3.2.4.2 Existing Brick Liners.

Brick liners operating under reheat or unscrubbed conditions may not have an existing annulus pressurization system. For a stack to accommodate a pressurization system, fabric expansion joint seals should be provided at all openings to prevent leakage. In order to allow safe personnel access into and out of the pressurized annulus, air-locks or air chambers should also be provided.

An existing annulus pressurization system sized for reheat or bypass conditions may not furnish adequate pressure and volume when the stack is converted to wet operation. The pressurization requirements should be recalculated based on the worst draft condition, which is the lower scrubbed gas temperature. Existing fans should be modified or replaced as required.

Liner bands on a brick liner with reheat may not be designed for the corrosive environment associated with a wet system. Consequently, conversion to wet operations may require that the existing liner bands be coated or replaced with a more corrosion resistant material.

An inspection of the exterior and interior surfaces of the brick liner should be performed. Cracks in the brick liner should be repaired to prevent leakage of the flue gas. Excessive mortar projecting from mortar joints could be removed to minimize reentrainment of liquid. Mortar and brick should be inspected for soundness. Any soft appearance of the mortar or brick indicates that the material has not been performing adequately under past operating conditions. Soft mortar joints should be repaired by tuck-pointing. This involves removing the soft mortar and replacing it with new potassium silicate mortar.

A target wall or target lining can be added to the interior of an existing brick liner. Target walls or linings will protect an existing liner from future deterioration and may minimize irreversible liner growth that results in leaning liners.

Drainlines within the liner should be inspected and evaluated to ensure that the existing drains can handle the increased volume of liquid slurry to be removed. If the existing drains are not adequate, they should be replaced with larger drainlines as required.

3.2.4.3 Existing Fiberglass Reinforced Plastic Liners.

FRP liners that are being converted from reheat to wet operation should be inspected to ensure that there are no inherent problems with the liner prior to conversion. The corrosion barrier, which is not considered part of the structural wall, should be inspected for signs of cracking, abrasion, or chemical attack. Blisters, delaminations, entrapped air and cracking of the corrosion barrier should be repaired. Fly ash on the inside surface of the liner should be removed. Operation of the spray quench system can cause buildup of ash on the liner. FRP liners with spray quench systems in frequent operation may have a heavier buildup of fly ash than nonquenched units.

3.2.5 Code Requirements for Stack Modifications

Stacks being considered for conversion to wet operation may have been designed before incorporating present day design standards. Modifications performed to the concrete shell and liner should be evaluated in accordance with present day structural design standards. This may result in additional modifications to the structure other than that required solely for conversion to wet operation. Good engineering judgment is required to evaluate many of these structural design issues. An experienced chimney design and construction company should be consulted.

3.2.5.1 Concrete Shell.

New and existing stacks should be designed or analyzed in accordance with the American Concrete Institute's ACI 307 titled *Standard Practice for the Design and Construction of Reinforced Concrete Chimneys* (8). This standard covers design and construction related issues for the stack's concrete shell. The standard does not include the design of liners, but does include the effects of the liner on the concrete shell.

The ACI 307 standard has had several revisions over the years. These revisions have included major changes in methods of analysis and computation of wind and seismic loads. Many existing concrete chimney shells being considered for conversion might not meet present day design standards. Ultimate strength design procedures in accordance with the latest ACI 307 standard are recommended, although older stacks may also need to be evaluated based on working stress design principles from the 1979 edition of ACI 307. Since most older stacks were designed using working stress design principles, stress values could be analyzed for comparison to their original allowables.

Examples of concrete shell modifications for wet stack conversion that require an analysis of the existing concrete shell are:

- Adding a new breeching opening or enlarging an existing breeching opening.
- Resupporting a liner off the existing shell.
- Increasing or reducing the dead load of a liner supported from the concrete shell.
- Additional wind load due to choke installation.

Major changes, such as adding a new breeching opening, may not be structurally possible or may require adding a reinforced concrete sheath around the exterior of the shell before cutting the opening. For example, at Louisville Gas & Electric's Cane Run Unit 5, a new breeching opening was cut into the existing concrete shell. For the shell to structurally accommodate the new opening, a concrete sheath was added locally around the shell at the opening location before the opening was cut. Most wet stack conversions would not require this extensive of a modification and would try to reuse existing openings. Based on an economic evaluation, cutting a new opening was the selected option.

3.2.5.2 Steel Liners.

New or existing steel liners should be analyzed in accordance with the guidelines of ASCE's *Design and Construction of Steel Chimney Liners* (9). Many steel liners have been designed and installed before incorporation of this design guideline in 1975.

Changes in design procedures, a reduction in plate thickness due to corrosion, or the addition of a lining or coating dead load may result in the liner being structurally inadequate to accommodate liner modifications. The ASCE design guidelines permit incorporating vertical stiffening on the exterior of the liner to increase buckling resistance if the existing plate thickness is inadequate. The expense of stiffening and the expense and outage time required to line or coat an existing liner should be evaluated against construction of a new liner.

If the existing steel liner plate thicknesses are inadequate and adding vertical stiffeners is not viable, then buckling stresses may be reduced by providing an additional liner support. If the liner is supported only at the bottom, providing a new second support near the top of the stack can reduce buckling stress by supporting most of the liner in tension. This would reduce the compressive stresses in the bottom of the liner. This modification requires that a new expansion joint be added above the lower existing support.

3.2.5.3 Brick Liners.

Existing brick liners are generally considered to be acceptable materials of construction for conversion to wet operation, and accordingly, major structural modifications are not typically required.

Older brick liners may not have been designed in accordance with current seismic standards. A seismic analysis should evaluate existing stress levels and factors of safety against overturning. This analysis should be performed in accordance with ASTM C1298 "Standard Guide for the Design and Construction of Brick Liners for Industrial Chimneys." Modifications to reduce seismic loads in a brick liner are not practical. If stress levels exceed the recommended allowables, the decision to utilize the structure needs to be made based on the knowledge of potential risk of damage from a seismic event.

Adding a new breeching opening to an existing brick liner is generally not recommended. Pilasters along the sides of an opening must be constructed monolithically with the liner to adequately transfer loads. Transferring pre-existing loads into new pilasters is difficult and poses potential to damage the existing liner.

3.2.5.4 FRP Liners.

Existing FRP liners are also generally considered acceptable materials of construction for conversion to wet operation. A modification, such as adding a new breeching opening into an existing FRP liner, should be evaluated based on the liner's geometry. FRP liners often use a 90 degree radiused elbow directly below a support, which provides limited options for new breeching locations. Repositioning the bottom support steel may need to be considered. Modifications to FRP liners should be performed in accordance with the recommendations of ASTM D5364, "Guide for Design, Fabrication, and Erection of Fiberglass Reinforced Plastic Chimney Liners With Coal-Fired Units." Another reference for information in this area is EPRI TR101654, "Guidelines for the Use of Fiberglass Reinforced Plastic in Utility FGD Systems."

3.2.6 Adequacy of Existing Chimney Foundation

Stack liner modifications may change the loads being applied to the foundation. If foundation loads have changed, an analysis should be performed to confirm the adequacy of the existing foundation and piling. This also applies to situations where an existing liner may be demolished and a new liner reinstalled. Demolition of an existing steel or FRP liner and its replacement with a brick liner may not be possible. A brick liner is much heavier and would apply a larger dead load and earthquake overturning moment to the foundation.

3.2.7 Adequacy of Existing Steel Stacks

Existing steel stacks should be evaluated for material and design compatibility before conversion to wet operation. Gunite linings are often used on reheat or unscrubbed steel stacks. In addition to providing corrosion protection for reheat or unscrubbed conditions, the gunite also provides dead load and stiffness to the structure. Gunite lining systems are generally not suitable to wet operation and need to be removed before conversion. Steel stacks are flexible structures with low damping and accordingly are susceptible to dynamic wind loads. Removal of the gunite and its replacement with another corrosion resistant material will change the natural frequency and dynamic characteristics of the stack. A structural analysis should be performed to determine these design implications. These lining changes may result in a stack that has a large wind deflection and increased stresses. Damping devices or helical strakes may need to be added to the stack to reduce excessive wind vibration and stress levels; however, stiffening may also be required.

Michigan South Central's Endicott Station Unit 1 has an existing steel stack. The stack was originally lined with two inches of gunite. The gunite had experienced cracking, spalling and acid attack. Before the stack's conversion to wet operation, the gunite was removed and replaced with a Pennguard Block lining. The modified stack was evaluated for overturning and for dynamic wind loads. The original foundation was determined to be adequate to resist overturning. However, the dynamic wind evaluation required that a tuned mass dampener be added to the existing stack to prevent excessive stresses at critical wind velocities. The stack is reported to be in good condition. (22)

3.2.8 Operating Conditions

For a wet stack conversion project, the evaluation of the existing stack liner and its components must consider the range of flue gas conditions at the stack inlet. The gas conditions depend on the coal burned, the operating conditions of the upstream equipment including the boiler, air heaters, particulate control equipment, fans and the wet FGD system. The stack operating conditions affect the suitability of existing materials of construction and liner diameter, and the design of the annulus pressurization system and the liquid collection devices.

The stack inlet flue gas and ambient air conditions that can affect the evaluation of the existing stack liner include:

- Temperature.
- Pressure.
- Moisture content.
- Flue gas composition.
- Flue gas flow rate.
- Flue gas liquid content.

For an existing FGD system, flue gas conditions can be obtained from existing FGD operating and test data. For a new FGD system on an existing boiler and stack, the stack inlet flue gas conditions can be calculated. Refer to Section 2, "Operating Conditions" for a description of the flue gas calculations and additional discussion of flue gas and ambient conditions.

3.2.8.1 Temperature.

When a coal-fired boiler is equipped with a wet FGD system without flue gas reheat, the saturated flue gas temperature at the stack inlet usually ranges from 115 to 130 degrees F (46-54°C). For a specific plant, the saturation temperature can be estimated for a range of boiler loads and fuels using flue gas calculations described in Section 2, "Operating Conditions."

The range of absorber outlet temperatures should also be obtained from existing FGD operating data for comparison to calculated values.

3.2.8.2 Pressure.

The total and static pressure of flue gas inside the stack is a function of the following:

- Ambient temperature and barometric pressure.

- Total pressure losses in the stack entrance.
- Total pressure frictional losses through the liner.
- Total pressure losses across expansion joints, corbel joints, and other stack liner breeching openings, expansions or contractions.
- Pressure variation with height (stack effect).
- Static pressure changes across area expansions or conical contractions and chokes.

Total pressure loss from the stack breeching duct to the stack discharge plume is the value needed for determining the I.D. fan requirements for the stack. The maximum differential static pressure between the flue gas and the stack annulus at the same elevation is the pressure needed to design the fans for the annulus pressurization system with brick stack liners. For a wet stack conversion project, flue gas pressure data should be collected and, after correction to saturated non-reheat conditions, compared to model study and calculated values.

3.2.8.3 Stack Effect.

The stack effect is the hydrostatic pressure difference between the inlet and the top of the stack. This is due to the lower density of the heated gas in the stack compared to the density of ambient air. Therefore, the stack effect is calculated by multiplying the density difference of the gas in the stack and the ambient air with the height of the stack. Since the flue gas without reheat will be more dense than with reheat, the stack effect will be reduced with a wet stack conversion.

Net stack draft is the operating pressure in the breeching duct at the inlet of the stack liner and is calculated by subtracting the fluid friction, plus the inlet and exit losses from the stack effect. For a wet stack conversion the fluid friction and exit losses will be less since the flue gas volume and velocity will be reduced, assuming that the liner diameter stays the same.

3.2.8.4 Stack Flow and Density.

The flue gas volumetric flow rate in the stack liner is calculated from the flue gas mass flow rate divided by the flue gas density. The calculation of flue gas mass flow rate and flue gas density discussed in Section 2, "Gas Flow and Density," can also be used to calculate stack inlet flow conditions for wet stack conversion projects over a range of boiler loads.

Wet stack conversion is a new FGD system installed on an existing plant with the existing stack considered for conversion to wet operation. Field unit flow condition measurements can also be used. However, the measurements must be adjusted for the FGD module temperature reduction, water vapor evaporation, and pressure loss.

When reheat or bypass is being eliminated, field measurements at the outlet of the absorber modules can be used to obtain a direct measurement of the flue gas flow conditions at the stack entrance for saturated gas flow conditions at selected loads. Stack entrance or CEM flue gas flow measurements can also be used if they are adjusted for gas density, reheat, air flow and/or bypass gas changes.

All of the calculated and field measured flue gas flow rates and gas conditions obtained should be compared and used to select the range of stack inlet gas flow conditions for evaluation of the existing stack for wet operation. If a change of coal or boiler operation is also planned, it must be factored into the flow rate estimates.

3.2.8.5 Moisture and Liquid Content at Stack Inlet.

The water vapor content of the stack inlet flue gas flow is the same as the absorber outlet, where the flue gas is saturated. The liquid content of the stack inlet flue gas flow comes from the following sources:

- Mist eliminator droplet carryover, which consists of very small drops (<10 μm) that never contact a mist eliminator blade and larger droplets that reentrain from the mist eliminator blades, structure or solid buildup.
- Condensation on the duct surfaces upstream of the stack inlet, which adds liquid on the duct surfaces.
- Deposition of droplets on duct surfaces, vanes, baffles and structure, which removes droplets from the gas flow stream.
- Reentrainment of droplets from duct surfaces, vanes, baffles, and structure, which adds large droplets to the gas flow stream.
- Installation of liquid collectors on duct walls and ceilings, vanes, baffles, and structures, which collects liquid from these surfaces and guides the liquid to the duct floor of the stack bottom drains for removal from the duct stack system.

Refer to Section 2, "Operating Conditions," for additional discussion of droplet formation and carryover. For a detailed discussion on the effectiveness of mist eliminator systems, refer to reference (3).

3.2.9 Wet Fans

If the FGD system has reheat and the I.D. fans are installed downstream of the absorbers, the fans will become wet fans after a wet stack conversion. Only a few existing FGD systems were designed for wet fans, primarily because of the high cost associated with the requirements for corrosion resistant materials and the inherent problem of rotor imbalance due to scale buildup. For most installations wet fans should be considered only if they can be constructed of nickel alloy and a spare fan is installed to permit a regular maintenance program of cleaning and rebalancing.

Occasionally, induced draft fans will be located between the absorbers and the stack of a utility power plant when retrofitted with an FGD system. These fans usually require periodic or continuous washing to prevent solids buildup on the fan impellers, which can cause fan rotor imbalance. All of the wash liquid sprayed into the fan inlet leaves the fan impeller as droplets. Most of the liquid will be propelled by the high centrifugal force field to the fan scroll, where it deposits but immediately reentrains due to the high gas stream velocity. Most of the washing liquid will escape fan discharge as droplets entrained in the gas stream, causing additional liquid load in the ducts and in the stack. The fan wash method can be optimized for effective washing with the minimum wash flow rate. Two dimensional computer calculations are used to optimizethe fan washing. The duct and stack liquid collection system must be designed to account for the extra liquid carryover from the wet fan wash system.

3.2.10 Location of Opacity Monitors

Opacity monitors will not function properly in a wet stack because water droplets will result in high opacity readings. The EPA recognizes this and has exempted wet stack units from monitoring opacity that are otherwise affected by the acid rain program. However, no such exemption has been granted for New Source Performance Standard units. In addition, there may be local requirements for monitoring opacity. If a unit converts to wet stack operation and is still required to monitor opacity, the opacity monitors will have to be located upstream of the scrubber. Sometimes, there is not a good measurement location between the particulate removal device and the scrubber. Opacity monitors located upstream will not be able to monitor the beneficial affects of the particulate removal from the scrubber. Furthermore, some units use the scrubber as the sole particulate removal device. These cases should be evaluated with the applicable agency.

3.2.11 Liquid Collection Devices and Drainage

The conversion of an FGD System from reheat to wet operation usually requires the design and installation of an effective liquid collection system. In Section 2, "Liquid Collection Devices and Drainage," the liquid collection devices for new and retrofit FGD were identified and discussed. Next is a discussion about necessary special considerations of the collection system for conversion.

The amount of vapor and liquid carryover from the mist eliminator is the same as with reheat. The condensation rate increases in ducts and the stack without reheat. The gas velocities are 5 to 10 percent lower than with reheat before conversion but they are usually higher than the gas velocities that would be selected for the design of a new wet stack for the same gas flow rate.

Due to the amount of liquid condensation and deposition on the duct and stack surfaces and the relatively high gas velocities, design of liquid collectors and drains is an important part of the retrofit process.

Mist eliminator operation and performance have to be reviewed before the conversion to make sure they can operate without reheat. Mist eliminator washing procedures will need to be optimized to limit the amount of liquid droplet carryover. In some instances, it may be necessary to modify or replace the mist eliminators or mist eliminator wash system. Mist eliminators have to be inspected and exchanged if damaged or if solid scaling is excessive. The pH control has to be good to ensure that solid precipitation in the mist eliminators and the downstream duct work is minimized.

Liquid collection devices should be installed on the turning vanes if the vanes are located in the ductwork between the absorber and the stack.

In straight rectangular duct sections, simple sidewall collectors and slanted or V-shaped ceiling collectors can be used. These collectors are usually L-shaped cross sections and their sizes range from 2" x 2" to 6" x 6" (0.05 m x 0.05 m to 0.15 m x 0.15 m, depending on duct geometry and gas velocities.

Round ducts have to be equipped with liquid collectors also. These usually require fewer collector elements, but they are more difficult to install because they have to follow the curved surface contour in round ducts.

Internal bracing is often installed in rectangular ducts originally designed for reheat operation. Bracing provides additional impingement surfaces and reentrainment sites for liquid droplets. Liquid collectors should be designed for the braces, which reduce the reentrainment of large droplets.

Liquid collectors in the breeching duct represent an effective last collection stage before entering the liner. Good liquid collection in the ducts means reduced liquid load on the stack.

Liquid collects and drains in the duct expansion joint cavities on the side walls, but the liquid reentrains at the expansion joint cavity in the ceiling. Expansion joints are reasonably good, but not highly effective liquid collectors. Properly designed plates and partial covers can improve the liquid collection in the expansion joints. They should be used when the complete liquid collection system needs this additional improvement.

Louver dampers are usually used in FGD systems with reheat. It is seldom justified to replace the louver dampers with guillotine dampers for wet conversion. Guillotine dampers present smaller surface areas for liquid deposition and the lower reentrainment rate represents a smaller liquid collection problem in the duct. The liquid droplets deposit on the blades of louver dampers in the gas stream and reentrain from these surfaces as larger droplets. The duct and stack liquid collectors have to be designed to collect the liquid reentrainment from the louver damper.

The stack liner opposite the breeching duct receives the most liquid deposition downstream of the absorber. The liquid collection in the stack entrance is important. Typical liquid collectors are a gutter above the breeching duct and two flow guides on the liner along the sides of the breeching entrance. As liquid enters the liner, it is deposited on the liner wall opposite the breeching. Gas flow patterns then tend to drag the liquid around the inside circumference of the liner back to the breeching. A liquid collector added around the breeching prevents this liquid from being reentrained into the gas stream. Liquid collected in the liner entrance should drain to the liner floor or hopper, where it can be removed by a drain. A full circumference liquid collector ring may be needed in some installations in conjunction with the liner entrance liquid collectors. The high gas velocity in conversions makes the stack liquid collector design more elaborate.

Brick liners with a 1/8-inch (0.003 m)or greater radial tolerance may experience partial reentrainment from the wall opposite the breeching duct. Different methods can be used to reduce the surface discontinuities in this area on the brick liners. The removal of the protrudingmortar from the joints makes the surface smoother for liquid flow. A coating used over the brick provides a smoother surface. A smoother target wall can be installed over the existing brick surface area where reentrainment may take place.

Liquid condensing along the stack liner flows down on the surface when liner gas velocities are below the liquid reversal velocity. This liquid reentrains at the expansion joints and most of the reentrained droplets discharge from the stack. Existing expansion joints should be equipped with liquid collectors specially designed to match the expansion joint geometry. Only laboratory flow modeling can be used to design and develop liner expansion joint collectors that effective at all operating loads of that unit.

A choke, if present at the top of the liner increases the stack discharge velocity which usually exceeds the liquid film flow reversal velocity for the choke material. Liquid reaching the top of the choke is discharged and falls to the ground within the near vicinity of the stack. Chokes for wet conversion must be equipped with an effective liquid collector to prevent this liquid discharge.

Collected liquid must be drained out of the duct stack system. In general, drains can be installed in the horizontal absorber ducts, duct expansion joints, stack floor, liner expansion joint, liner collectors, and choke collectors. The number of drains needed and their optimum location are specified as one of the results of laboratory flow modeling.

Absorber duct drains are most effective if a trench or scupper is installed across the duct in the floor with a drain. The existing duct construction, trusses, and frames limit the possible drain locations in the ducts of a conversion unit. Drains can be installed in duct expansion joints, depending on the local gas flow conditions.

Stack floor drains often require a wire cage or equivalent over the inlet to prevent plugging by flaking solid scales.

The stack liner expansion joint collector drains and the choke liquid collector drains have to be individually pressure balanced with siphons or drain pots. These drains connect points of different static pressure levels inside of the liner.

Drain lines located outdoors should have a steep enough slope to prevent freezing. For long, relatively flat, horizontal runs of drain line, the pipe should be heat traced and insulated.

Liquid discharging from the drain pipes must be recycled into the FGD system or properly disposed of. The disposal methods for unit conversion are the same as for new or retrofit units. Methods of liquid disposal are discussed in Section 2, "Liquid Collection Devices and Drainage."

3.2.12 Laboratory Flow/Modeling for Conversion

The geometry of the ductwork and the stack is inherited from the reheat system and cannot be altered in most of conversion cases. For this reason, gas flow passages are less suitable for gas liquid flow and for installation of liquid collectors than optimized flow passages of new or retrofit units.

Experimental flow modeling is the best tool to evaluate existing duct stack geometry and to design liquid collection devices needed for a successful conversion. Because of the geometric limitations, the modeling work is more critical and more difficult. Objectives and results of laboratory flow modeling for new designs are described in Section 2, "Laboratory Flow Modeling."

Laboratory flow modeling provides the following results for conversion to wet operation from reheat:

1. Evaluation of existing duct and stack gas flow passages for gas liquid flow or wet operation. Existing surface discontinuities, duct bends, stack liner surface and geometry are evaluated with air and water flow simulating the field conditions.

2. Design of duct and stack modifications to make the geometry more suitable for wet operation. These modifications are limited to internal changes only. Internal changes are inserts, target walls, turning vanes, baffles that make the flow more favorable for liquid collection and promote the deposition of liquid droplets entrained in the gas flow.

3. Flow modeling to decide if reheat duct openings can stay open to the isolation damper or whether they must be blanked off at the duct interfaces.

4. Evaluation of wet operation with existing internal trusses. Decide if they are acceptable or need to be equipped with liquid collection devices or replaced with a more suitable truss design.

5. Design and development of liquid collectors. Experimentally used where needed in the absorber outlet ducts and stack liner entrance region to prevent large droplets from reaching the stack liner, to collect liquid from duct and stack surfaces, to prevent reentrainment, and to guide liquid to locations where it can be drained out of the system.

6. Definition of the best location for drains, selection of drain locations possible within the geometric limitations, and experimental evaluation of the final drain system.

7. Evaluation of reentrainment at liner expansion joints in a laboratory test rig and development a liquid collector design to collect and drain liquid from liner expansion joints.

8. Development of the optimum choke liquid collectors and drains to prevent reentrainment and discharge of large droplets from the top of the choke, if there is a choke in the existing liner.

9. Measurement of pressure losses in the model, scaling them to field operating conditions and comparing to the available pressure rise of the existing I.D. fan. Reducing pressure losses if needed.

10. Wind tunnel tests to evaluate downwash of the wet plume that could lead to stack surface deterioration, unacceptable SO_2 ground level concentrations, or icing problems at the top of the stack. The final geometry of the chimney cover shape and the extension of the liner will be specified as a result of this work.

11. Use of a model of the absorber outlet ductwork, stack liner breeching duct, and stack liner up to two liner diameters above the CEM elevation, measurement of the gas velocity profile and swirl angles to compare to EPA requirements at the CEM station.

3.2.13 Evaluation of Performance Through Stack Droplet Testing

Depending upon the location of the plant, surrounding parties, and utility management, the potential for acid droplet fallout can become a major concern. The amount of stack fallout may be quantified through stack droplet testing.

The Los Angeles Department of Water and Power performed stack droplet tests at the Intermountain Generating Station (IGS) to determine the effect of eliminating reheat at that plant. The Video Droplet Analyzer (VDA) developed by Southern Research Institute for mist eliminator performance testing was used to collect data on the size quantity and distribution of droplets during operation with and without reheat.

The VDA consists of a probe-mounted video camera and a strobe illuminator. Droplet size and quantity for each range of droplet diameter are measured. Droplet data and gas velocity (independently determined) for each measurement point are then used to calculate the carryover rate.

The VDA was selected for carryover measurements at IGS because it permitted the collection of data inside the stack where it would not be influenced by atmospheric conditions. The initial baseline testing indicated the amount of fallout would increase 500 fold without reheat. Therefore, it was concluded a liquid collection system would be required to control fallout. A model study was performed to develop an effective liquid collection system with the goal being to reduce fallout of problematic droplets (over 100 micron diameter) during operation without reheat to the levels measured for the unmodified system while operating with reheat. Follow-up stack droplet testing would be used to evaluate the performance of the liquid collection system.

Stack droplet testing performed on the IGS Unit 1 a with liquid collector system has indicated satisfactory performance of the liquid collection system. The amount of liquid fallout for droplets over 100 micron diameter were reduced 99.4% by the liquid collection system during operation without reheat and is just 2-1/2 times the original amount with the reheat system in service. These percentage reductions and the measured amount of liquid discharge in gpm are summarized in thetable below. This is the only quantitative data currently available in the industry. The achievable effectiveness of the liquid collection system is site specific.

Table 3-1
Measured Liquid Fallout[1]

Volume of liquid fallout (Droplets > 100 micron diameter)

	Unit 1 Without Liquid Collectors		**Unit 1 With Liquid CollectorsUnit 1**
Load	With Reheat gpm	W/O Reheat gpm	W/O Reheat gpm
100%	0.0040	1.76	0.010
Capture	*99.8%*	*0.0% Base*	*99.4%*

[1]Intermountain Generating Station. 1 gpm = 0.23 m^3/h

3.2.14 Outage Time

Converting an existing stack to wet operation will typically require more outage time than constructing a new stack. As referenced in Section 2, "Outage Time," a new stack can be constructed while the unit remains in operation with tie-in performed during a scheduled maintenance outage. Stacks converted to wet operation may require an extended outage to modify or replace the liner.

Each liner system should be independently evaluated to determine the extent of modifications and outage time required. The outage time represents a considerable expense to a utility and therefore should be evaluated with the costs of the other options.

The extent of modifications and amount of outage time required to perform the modifications depends on the compatibility of the existing liner material and the acceptability of the flue gas velocity from a liquid collection standpoint. Liners constructed from a corrosion resistant material, such as brick or FRP, will require considerably less outage time for conversion as compared to coating, sheet lining, or replacing an existing steel liner. In general, work required on the exterior of a liner may be performed during unit operation, while work performed on the interior of the liner would require an outage.

Converting a brick or FRP liner may only require a minimal outage time of days or weeks to make modifications, such as adding liquid collection devices and upgrading drainage systems. Converting of an existing steel liner that requires coating, relining, or replacing may take severalmonths of outage time. For example, relining an existing 600-foot-tall steel liner with alloy sheet lining would require an outage time of approximately 3 to 4 months. Demolishing an existing steel liner and replacing it with a new alloy clad liner, would require an outage time of approximately 8 months. Since large volumes of alloy material are not generally stockpiled for immediate delivery, an outage schedule should consider the lead time associated with obtaining the alloy plates or sheets, as well as the time required for the cladding process.

Some examples of the outage time required for wet stack conversion projects are as follows:

- Louisville Gas & Electric Company:
  - At Cane Run Unit 4, 9 months was required to demolish the existing chimney and construct a new chimney and alloy liner in 1987-1988.
  - At Cane Run Unit 5, a 6 month outage was used to modify the existing chimney and construct a new alloy liner in 1986-1987.

  - At Cane Run Unit 6, 4 months was required to wallpaper the existing chimney liner in 1985-1986.
- Michigan South Central Power Agency:
  - At Endicott Station, 3 months was required to demolish existing gunite lining, modify the existing stack, and install new Pennguard Block lining in 1989.

3.2.15 Cost

The costs associated with converting a stack to wet operation is site specific and depends upon the extent of modifications and materials of construction involved. In general, the cost to modify to an existing brick or FRP liner would be substantially less than coating, sheet lining or replacing an existing steel liner. Modification costs for alloy sheet lining or alloy cladded plate are expensive due to the cost of materials involved. Alloy material costs also tend to fluctuate due to market changes in the cost of nickel, molybdenum, and cobalt. For this reason, it is sometimes difficult to obtain firm pricing for projects with substantial lead times before construction. To avoid delivery problems and price fluctuations, utilities sometimes purchase alloy material in advance of a project. As referenced in Section 2, "Cost," budgetary costs can be obtained from chimney contractors and from material suppliers.

Because of substantial costs incurred by the utility for outage time, performing the work on an overtime or double-shift basis may be an advantage. Labor costs would increase but would probably not exceed the expense associated with lost revenue from the difference in outage time.

4

GUIDE TO DEVELOP SPECIFICATIONS FOR WET STACKS

Once the decision has been made to utilize wet stack operation, it is necessary to prepare a bid specification for the wet stack. For a new or retrofit wet stack, the chimney can either be a separate contract or part of the FGD system contract. This section of the guide addresses key issues that should be included in a wet stack bid specification. These guidelines should not be used without applying good engineering judgement and consideration to site specifics.

4.1 Step-by-Step Process

Preparing a bid specification for a wet stack is a step-by-step process. Design criteria for the wet stack is determined based on plant considerations, applicable codes and performance requirements, and is included in the bid specification. General arrangement drawings that define duct and chimney geometry are also typically included. A flow model study should be performed in order to design the necessary liquid collection devices. At this point, the bid specifications can be prepared. Exhibit drawings showing the wet stack arrangement and typical design details are included with the specifications to define the scope of work and obtain competitive bids.

4.1.1 Establish Design Criteria

Minimum standards for design materials and construction are established in the bid specifications. The chimney contractor is normally responsible for the design of the wet stack to meet the specified operating conditions and any applicable codes, such as the latest edition of the American Concrete Institute (ACI 307) - Standard Practice for the Design and Construction of Cast-In-Place Reinforced Concrete Chimneys.

New stacks are typically designed in accordance with the latest wind and seismic sections in the applicable steel stacks or concrete chimney codes. Dynamic wind loads should be evaluated in relationship to the chimney's critical wind velocity and natural frequency. Wind effects from adjacent structures and nearby chimneys should be considered. Closely spaced chimneys can cause an amplification of the vortex shedding wind loads for both the new and existing chimneys. Spacing between adjacent chimneys can be increased in order to decrease the amplification factor for the vortex shedding wind loads.

In addition, a subsurface investigation is usually performed to determine the most appropriate foundation type. For example, the subsurface investigation may require that a deep, pile-supported foundation be implemented, versus a shallow, soil-supported foundation.

4.1.2 Define Absorber Outlet Duct and/or Bypass Duct Geometry

General arrangement drawings that indicate chimney inlet duct size, elevation and configuration are typically included with the bid specifications. The duct arrangement is influenced by the number of absorbers, the size of absorber, and the operating conditions of the unit (bypass or no bypass). Normally, the absorber outlet duct and bypass duct arrangement is defined before to specifying the chimney inlet configuration.

4.1.3 Define Chimney/Liner Geometry

Chimney shell and liner geometry should be defined as early as possible in the initial study phase of a wet stack project. Some flexibility is required to accommodate different scrubber arrangements and sizes available. Refer to Sections 2 and 3 of this design guide for more information on chimney geometry requirements.

4.1.4 Perform Model Study

Laboratory flow modeling conducted before the final design phase is recommended to design liquid collection devices for the absorber outlet duct and stack. The objectives of a flow model study are as follows:

- Experimental evaluation of the absorber outlet duct and stack liner in order to assure proper geometry.
- Design of liquid collection devices.
- Determination of drainage locations.

Laboratory flow modeling is a valuable tool in the design of a successful wet stack system and should be conducted by an experienced model testing firm.

4.1.5 Determine Liquid Collection Devices

Liquid collection devices are critical to the successful operation of a wet stack system. After the flow model study is performed, liquid collection devices can be located and incorporated into the bid drawings. If the model study is to be performed after the chimney contract is awarded, then bid quantities need to be provided with the specifications to cover any liquid collection devices.

4.1.6 Prepare Bid Specifications

The bid specifications can be generated once the feasibility study, preliminary layouts and material selections have been completed. The bid specifications should be as detailed and complete as possible to ensure competitive bids and a successful wet stack system. Major items included in the bid specifications are discussed below in the subsection, "What to Specify."

4.1.7 Prepare Bid Drawings

Drawings are prepared and included with the bid specifications in order to clearly define the scope of work. As a minimum, the bid documents include a site plan, chimney general arrangement, typical details, and electrical drawings.

4.1.7.1 Site Plan.

A site plan included with the bid specifications conveys the arrangement of the power plant in relation to the area for the proposed construction. This will allow the contractor to plan his construction operations. It also indicates restricted or congested areas on the plant site that the contractor must contend with.

4.1.7.2 Chimney General Arrangement.

A general arrangement of the chimney included in the bid documents gives the bidders general guidelines about the scope of work. Major features of the wet stack are typically included on the chimney general arrangement drawing. The chimney general arrangement is meant to serve only as a guideline and is not intended to provide final design information. The chimney inlet duct elevation may need to be adjusted depending upon the absorber height.

4.1.7.3 Typical Details.

Typical details the owner or specifier wishes to incorporate into the final design are included in the bid specifications. Typical details may include platforms and handrails, rainhoods, expansion joints, duct supports, test ports, insulation and lagging, lining systems, and liquid collection devices such as gutters.

4.1.7.4 Electrical.

Electrical drawings include items, such as an electrical grounding grid, obstruction lighting, test platform power and lighting, personnel elevator power wiring, conduit, annulus pressurization wiring (if applicable), and electrical equipment layout.

4.2 What to Specify

This section discusses items included in a bid specification for a wet stack.

4.2.1 General Requirements

In the general requirements section of the specifications, scope of work must be clearly defined. Construction schedules, submittal schedules, temporary construction power and chimney design and construction requirements should also be specified. The general requirements must be specific to a new chimney or to an existing chimney that is to be modified.

4.2.1.1 Scope of Work.

The scope of work for the wet stack contract must be clearly defined in the bid specifications. A complete description of the entire project may also be included in the specifications. A new or retrofit wet stack, which involves constructing a new stack, is usually designed, furnished, and constructed by a chimney contractor who must comply with a performance specification that is usually prepared by an architectural/engineering firm. A conversion to wet stack, which involves converting an existing stack to wet operation, is usually designed by an architectural/engineering firm that produces a construction contract specification.

All work to be performed under a certain contract is clearly defined to avoid any change orders or schedule delays later. The specification should also clearly state that the contractor is responsible for furnishing and erecting all materials (if applicable), and for providing supervision, labor, tools and transportation required for construction of the work specified. Work by others is included in multiple contract projects, to assist the contractor with on-site coordination and scheduling issues. A general work sequence may be helpful in avoiding unnecessary construction delays. A list of contract drawings and reference drawings is also helpful to the contractor performing the work.

4.2.1.2 Site Requirements.

Consideration is given to site requirements, such as construction parking, access roads, laydown areas and any plant restrictions that might impact construction efforts.

4.2.1.2.1 Construction Parking

Construction parking areas may be identified to provide sufficient parking for all construction personnel. Construction parking areas may need to be maintained throughout construction and restored to the original condition after construction (if so desired).

4.2.1.2.2 Access Roads

The bid specifications may include a section to provide and maintain vehicular access to the site and within the site during construction. New access roads may need to be constructed to perform the work. Restrictions should be imposed on existing access roads which cannot support construction activities.

4.2.1.2.3 Laydown Areas

Construction laydown areas may need to be considered in the bid specifications. The following items should be addressed:

- Adequate area for construction material storage.
- Provisions for substantial, weathertight enclosures (if necessary for storage of materials).
- Control of temperature and humidity according to manufacturers' recommendations.
- Platforms, blocks or skids to protect materials from soiling or staining.

4.2.1.2.4 Safety Barrier

A provision addressing the need for a safety barrier around the base of the chimney which would protect personnel working below from falling objects is typically included with the specification. Chimney contractors usually require a 50 foot wide safety zone around the base of the chimney during construction of the concrete shell and exterior platforms, ladders, etc. A debris net on the outside of the chimney shell is typically required to catch falling objects during construction.

4.2.1.2.5 Coinciding Construction Activities

This section alerts the contractor of any concurrent construction activities in the chimney area. This allows the chimney contractor to make necessary provisions regarding coordination of construction activities between different contractors and/or the owner. For example, other construction activities within the safety barrier zone cannot take place while the concrete chimney shell is being constructed.

4.2.1.2.6 Plant Restrictions

Restrictions on construction imposed by the owner or plant operations are noted in this section. Restricted access or laydown areas may be addressed. Plant outage schedules may also be included in this section.

4.2.1.3 Project Meetings and Schedules.

This section of the bid specifications includes requirements for the following:

1. Project Meetings:

- Preconstruction conference.
- Finalizing schedules.
- Progress meetings.
- Coordination conferences.

2. Schedules and Reports:

- Initial coordination submittals.
- Work progress schedule.
- Work progress reports.
- Schedule of values.

4.2.1.4 Submittals.

Submittal requirements specify what items must be reviewed by the engineer before fabrication or construction. Submittals include both compliance submittals and miscellaneous submittals. Compliance submittals include shop fabrication drawings, product data, and samples which are submitted by the contractor, subcontractor, manufacturer or the supplier. Miscellaneous submittals include technical reports, administrative submittals, certificates and guarantees.

4.2.1.5 Temporary Utilities and Facilities.

Temporary utilities and facilities are specified to address water distribution, drainage, dewatering equipment, enclosure of work, heat, ventilation, electrical power distribution, lighting, hoisting facilities, stairs, ladders and access roads. In general, the specifications usually require the contractor to furnish, install and maintain temporary utilities required for construction, safety and security.

4.2.1.6 Chimney Design and Construction Requirements.

This section of the bid specifications include minimum standards for design, materials, and construction. The contractor is normally responsible for detailed design of the wet stack, whether it be new or retrofit construction. Specific design parameters for the piling, foundation, chimney shell, liner and/or lining material should be included in this section so the contractor can perform the final design. The wet stack geometry can be included in this section of the specifications unless indicated on the drawings. The operating conditions for the unit, such as maximum gas flow rate, maximum temperature and gas exit velocity at maximum gas flow, should be specified in this section. Specific site conditions such as the location of nearby structures and chimneys are considered for vortex shedding wind loads on the new of existing chimneys.

4.2.2 Site Work

A bid specification for a new or retrofit wet stack that involves constructing a new stack includes excavation, backfill, and foundation piling, if necessary. Modification of an existing stack (if converted to wet operation) may require the designer to analyze the existing stack and foundation, including piling, for new wind and seismic loads, depending on applicable code requirements. The existing stack and foundation also needs to be analyzed for additional dead load, if the existing liner is revised.

4.2.2.1 Excavation and Backfilling.

A new stack will require excavation and backfill for the chimney foundation. Dewatering requirements for the excavation during construction should be addressed. Proper fill material and backfilling procedures are typically also be addressed.

4.2.2.2 Piling or Drilled Shafts.

This section address as furnishing all labor, equipment, and materials necessary to install foundation piling or drilled shafts for the chimney structure, if applicable.

4.2.3 Concrete

The concrete section of the bid specifications for a new wet stack include such items as formwork, reinforcement, concrete materials and quality control. The contractor submits the concrete mix design, which should preferably be based on field experience. However, where sufficient or suitable strength test data is not available, concrete shall be proportioned on the basis of a laboratory trial mix design.

4.2.3.1 Materials.

Materials of construction relating to the concrete work are usually specified. Concrete materials typically comply with applicable building codes, ACI standards, and ASTM requirements that are referenced in the concrete section of the specifications. The following items should be specified:

- Type of Portland cement (and fly ash if applicable).
- Fine aggregate.
- Coarse aggregate.
- Mixing water.
- Admixtures (water reducing type, air-entraining type, retarding type, high range water reducing type, etc.).
- Mix proportions (based on field experience or laboratory trial batches).
- Compressive strength.
- Slump.
- Air Content.

4.2.3.2 Foundation.

Foundation requirements for a new wet stack is included in the concrete section of the bid specifications. In most cases involving a new stack, the chimney contractor is responsible for designing the chimney foundation, including the number and layout of piling, if required. Pile type and capacity is generally determined by the architect/engineer.

4.2.3.3 Chimney Column, Construction Tolerances.

The chimney column or concrete chimney shell may require special cement or concrete additives in the mix design to facilitate rapid construction and withstand the potentially corrosive environment at the top of the column. Construction tolerances for vertical alignment of centerpoint, diameter and wall thickness for a new chimney column conform to ACI 307.

4.2.3.4 Brick Liner Support Pedestal.

The liner support pedestal usually are specified to meet the same concrete requirements as the chimney column.

4.2.3.5 Roof Slab.

Specifications for a concrete roof slab should consider either a corrosion-resistant sealant applied on the concrete surface or a sulfate-resistant cement, such as ASTM C150 Type V cement.

4.2.4 Liner

Liner materials of construction, strength requirements, construction requirements, and ambient considerations are specified in this section.

4.2.4.1 Materials.

Liner materials of construction for a new chimney liner are specified in the bid documents. Material selected should conform to the respective ASTM standards unless specifically noted otherwise. Refer to Sections 2 and 3 of this guide for liner material discussions.

4.2.4.2 Strength Requirements.

Strength requirements for various liner materials is dictated by the structural design of the liner. For example, the yield strength of a steel liner and the compressive strength of a brick liner is specified.

4.2.4.3 Construction Requirements.

Construction requirements for the selected liner materials are typically included in the bid specifications. These requirements are based primarily on good construction practice, recognized and accepted throughout the industry. Unique construction requirements are also included in the bid specifications.

4.2.4.4 Construction Tolerances.

Construction tolerances depend on the liner materials of construction selected. Construction tolerances are either specified or referenced to a specific code or standard.

4.2.4.5 Ambient Conditions.

Ambient conditions may adversely affect the quality of liner construction depending on liner material selected. Certain materials such as coatings, adhesive membranes, or mortars, may need to be stored and installed in a controlled environment to provide satisfactory performance.

4.2.5 Ductwork and Expansion Joints

The chimney inlet duct and expansion joint section includes provisions for the contractor to design, fabricate, furnish, deliver and erect these items. The ductwork and expansion joint section specify the materials of construction, design criteria and fabrication and erection requirements.

4.2.6 Miscellaneous Metals

Structural and miscellaneous metals are included in the metals section of the bid specifications. Miscellaneous metals include such items as platforms and ladders, liner or roof support framing, and test ports.

4.2.6.1 Platforms and Ladders.

The materials of construction for wet stack platforms and ladders are specified. Carbon steel is typically specified for the entire ladder except for the upper 50 to 100 feet, which should be fabricated from a more corrosion resistant material. The ladder should also include a Saf-T-Climb device for personnel safety. Wet stack platforms may be fabricated from carbon steel with the exception of the upper portion of the stack, in which case the material should be similar to the upper portion of the ladder. The extent and type of corrosion-resistant materials specified will depend on the environment the materials are exposed to.

4.2.6.2 Liner or Roof Support Framing.

Material selection should be considered when specifying the liner or roof support framing. The environment to which the materials are exposed to will dictate material selection.

4.2.6.3 Test Ports.

Test port materials are typically specified and conform to applicable ASTM standards depending on the materials selected. The materials selected will depend on such factors as location on stack, corrosive environment, intended purpose of test port, and material costs.

4.2.7 Insulation and Lagging

It is unnecessary to maintain the temperature of the saturated, absorber outlet flue gas above a certain minimum temperature. However, insulation may reduce the amount of condensation in a metal or FRP liner. If insulation is required, the insulation and lagging materials and design are specified in the bid documents.

4.2.8 Access Doors

Access doors are usually specified for the chimney liner at floor level or in the chimney inlet ductwork for cleanout and maintenance. Access doors may be required in the chimney shell for annular platform and test port access. Access doors may also be specified for a brick liner support pedestal, if applicable.

Additional liner access doors provide adjacent to liquid collectors to visually inspect the condition of the collectors and determine if the drain pipes need to be cleaned. These access doors should be at the following locations:

- Liner entrance area above breeching duct.
- Near expansion joint drains.
- At the choke.

The size and location of the access doors may need to be evaluated and determined by the flow modeling company.

4.2.9 Protective Coatings

Protective coating systems for each particular component of the wet stack are included in the bid specifications, if needed. Interior and exterior coating systems may also be considered for the stack shell and liner. An exterior protective coating may also be considered for the chimney inlet duct, if fabricated using wallpapered construction or a clad plate material.

4.2.9.1 Shell Exterior/Interior.

Protective coatings may be considered for the upper portion of the concrete shell of a wet stack. As discussed in Section 2 of this guide, several coating systems have been used on existing wet stacks for corrosion resistance. Additional consideration is given to coating the exterior of adjacent existing stacks, which may be subject to the corrosive effects of saturated flue gas from the wet stack.

4.2.9.2 Liner Exterior/Interior.

If a carbon steel liner, an alloy clad liner or a wallpapered carbon steel liner is selected, then an exterior coating system may be specified. If a coated carbon steel liner is to be used, then the interior coating must also be specified. Refer to Section 2 of this guide for additional information on recommended lining systems.

4.2.9.3 Structural and Miscellaneous Steel.

The coating system selected for structural and miscellaneous steel is evaluated based on the environment the steel is exposed to, access requirements for maintenance, cost of the coating system, and performance history.

4.2.10 Special Construction (Tuned Mass Damping System).

Special construction may be necessary when converting an existing stack to wet operation. For example, structural modifications may be necessary when converting a steel stack to wet operation. If the existing gunite coating lining is removed and an alloy or glass block lining is installed, this will change the overall mass of the stack and affect the natural frequency of the structure. A dynamic analysis is typically performed for vortex shedding wind loads. If resonance at critical wind speeds is a problem, then structural modifications, such as helical stakes, stiffenersor the addition of a tuned mass dampener, may be necessary to ensure the structural integrity of the existing steel stack.

4.2.11 Personnel Elevator

The bid specifications for a new wet stack may require furnishing and installing an electric rack-and-pinion drive personnel elevator. Design requirements, such as conformance to applicable sections of ANSI, access to established platform elevations, minimum lifting capacity and minimum design wind loads (for exterior elevators) are typically included. The exposed metal work of the elevator and supporting structure should be galvanized or protected with a coating system, if fabricated from carbon steel. For the upper 50 to 100 feet of the chimney, the mast and rack is usually specified to be

Type 316 stainless steel material. The electrical power supply and wiring also needs be specified.

4.2.12 Mechanical

The following mechanical sections are typically included in the wet stack bid specifications.

4.2.12.1 Drain Piping.

The specifications provide for all pipe, fittings, hangers, supports and accessories required to complete the chimney corrosive drain piping systems associated with the liquid collection system. Specific piping material should be specified for each application. FRP or alloy piping is normally specified for drain pipe material. Minimum piping installation standards are usually also addressed.

4.2.12.2 Pressurization System Fans/Dampers.

This section of the bid specifications applies to a concrete chimney with an acid resistant brick liner. An annulus pressurization system is required to keep flue gases contained within the liner. The pressurization system section should include furnishing and installing the required number of fans, including drive motors, controls and accessories.

4.2.12.3 Louvers.

The bid specification include a section requiring the contractor to furnish and install louvers to provide ventilation between the chimney liner and shell.

4.2.13 Electrical

The electrical section of the bid specifications include provisions to furnish and install all electric equipment, wiring (including plant interface wiring), grounding and lighting necessary for a wet stack system.

4.2.13.1 Grounding.

Grounding for all new electrical equipment are included in the bid specification. The grounding requirements for a new wet stack are similar to the requirements for a dry stack. Any new electrical equipment used in a wet stack conversion project needs to be properly grounded.

4.2.13.2 Obstruction Lighting.

The bid specifications include furnishing and installing obstruction lighting, including temporary obstruction lighting during construction. Obstruction lighting must comply with governing standards of the U.S. Department of Transportation, Federal Aviation Administration Advisory Circulars (FAA) and the National Electrical Manufacturers Association (NEMA).

4.2.13.3 Lightning Protection System (Master Label).

The bid specification include provisions to furnish and install a complete chimney lightning protection system, including a below-grade, chimney ground system. The contractor may need to provide a Master Label C plate issued by Underwriters' Laboratories, Inc., and attach the plate to the base of the chimney.

4.2.13.4 Plant Interface Wiring, Power Panel and Disconnect Switch.

The electrical section of the bid specifications address plant interface wiring, the power panel and the disconnect switch. The contents of this section is usually similar to standard power plant chimney electrical requirements.

4.2.13.5 Pressurization System Fan Wiring and Controls.

The pressurization system fan wiring and controls section of the specifications usually follow the same general requirements of a dry chimney.

4.3 What to Ask For

This section describes the Contractor's responsibilities for information that is typically submitted and the inspection and testing that is usually be performed for the design and construction of a wet stack or wet stack modifications.

4.3.1 Warranties/Guarantees

The Contractor is typically required to furnish a performance and payment bond. A performance bond is a guarantee that all work will be carried out in accordance with the Contract Documents. A payment bond guarantees that the Contractor will pay all lawful claims for payment to subcontractors, material suppliers and labor supplied in performing the work under the Contract.

Normally, a one-year warranty is specified for material and labor (one year from initial operation). If an unproven technology is being proposed by the Contractor, then an extended warranty would be needed.

4.3.2 Design Calculations

The Contractor may be requested to submit calculations that confirm the adequacy of the design. The calculations confirm that the design was performed in accordance with the codes, standards, and specification requirements specified. Design calculations are sealed by a professional engineer registered in the state where the stack is being constructed.

4.3.2.1 Chimney Foundation.

Design calculations for the chimney foundation may also be required for submittal. The following is a list of items included with this submittal:

- Foundation layout and size.
- Foundation loads.
- Soil bearing pressure load or pile loading.
- Factor of safety against overturning.
- Radial and tangential design moments.
- Radial and tangential reinforcing steel requirements.
- Shearing stress calculations.

4.3.2.2 Concrete Shell.

The concrete shell calculations are specify all design loads and operating conditions used. Calculations are provided for representative elevations throughout the height of the chimney. The following information is typically provided with these calculations:

- Wind analysis and resulting loads.
- Dynamic seismic analysis and resulting loads.
- Column geometry, including diameters and wall thicknesses.
- Column deflections.
- Thermal stresses.

- Reinforcing steel requirements.

4.3.2.3 Liner.

Calculations are also typically submitted for the liner design. The design loads, operating conditions, and material properties are specified. Load combinations applicable to theliner material are addressed per the governing code requirements. Information that submitted with the liner design is as follows:

- Loads and stresses for wind, seismic, thermal, and dead load conditions.
- Liner geometry, including diameters and wall thicknesses.
- Liner deflections.
- Factor of safety against overturning (brick liners).
- Factor of safety against buckling (steel or alloy liners).

4.3.2.4 Pressurization Fan Size.

The Contractor is usually required to size the pressurization fans if a brick liner is to be constructed or converted to wet operation. The information that the Contractor is required to furnish is as follows:

- Fan manufacturer and model number.
- Fan static, pressure including accessory losses at the design point.
- Fan volume flow rate at the design point.
- Fan motor manufacturer and type.
- Fan motor horsepower rating.
- Fan performance curves, including capacity versus static pressure, efficiency, and shaft horsepower.
- Design basis for determining fan size and leakage values.
- Drawings of the fan housing and base frame.

4.3.3 Materials Testing

To confirm compliance with specification requirements, the Contractor is required to submit material testing results and certifications for materials of construction.

4.3.3.1 Acid Resistant Brick.

Certified laboratory test reports may be submitted for each lot of brick manufactured. Brick should not be shipped until it is confirmed that the certified laboratory test reports comply with ASTM C980 and the specified requirements. Random sample testing of the brick delivered to the jobsite may also be performed in the field, as needed.

4.3.3.2 Brick Mortar Certification.

The brick mortar manufacturer typically submit certification that the mortar conforms to ASTM C466. Mortar data submittals usually includes the following information:

- Mix proportions and mix methods.
- Application temperature information.
- Curing and curing protection required.

4.3.3.3 Fiberglass Reinforced Plastic.

Material components of the FRP liner such as resin and glass is typically be certified for compliance with the appropriate ASTM standards and specification requirements. All materials, prior to and during fabrication, and the completed sections of the liner may be subject to laboratory tests. Resin batch numbers and shelf life are recorded for future reference. For each batch of material, resin gel time tests are performed in accordance with ASTM D2471 and resin viscosity tests are performed in accordance with ASTM D2393.

4.3.3.4 Alloy Material Certifications.

Material certification reports are usually furnished for all alloy materials and for the alloy welding materials. Certification reports should verify that the chemical composition of the material is in conformance with the ASTM or specification requirements.

4.3.3.5 Concrete Material Certifications/Mix Design.

Mill certificates may be submitted for the cement being utilized to confirm its conformance with ASTM C150 and to ensure that the correct type is being furnished. Certifications are also required for the coarse and fine aggregate (ASTM C33) and for any admixtures (ASTM C494) that will be utilized.

Concrete mix design proportions and compressive strength test results submittals are used to substantiate the proposed mix design.

4.3.4 Construction Procedures

The Contractor is responsible for his construction means, methods, techniques, sequences or procedures. The Engineer or Owner usually do not dictate and approve the Contractor's construction practice. Submittal of construction procedures are only required to confirm that the work can be performed within schedule and meet the intent of the Contract Documents.

4.3.4.1 Foundation Construction.

Chimney foundations are large mass concrete placements that require substantial planning and coordination. Before placement, the Contractor, Engineer and Owner review and coordinate the following issues:

- Concrete placement scheme (terracing or full lifts).
- Method of concrete placement (pump trucks, buckets, or chutes).
- Concrete delivery schedule.
- On-site concrete testing requirements.
- Method of concrete curing.
- Adequacy of formwork.
- Adequate personnel and equipment available.

4.3.4.2 Hot or Cold Weather Concrete Procedures.

Precautions need to be taken to ensure that hot or cold weather conditions do not adversely affect the quality of the concrete. ACI 305R provides the guidelines and recommendations for hot weather concreting. Although several options are available, the most commonly used hot weather concreting construction techniques are:

- Using ice or cold water in the concrete mix.
- Applying cold water spray to aggregates.
- Placement of concrete during the coolest time of the day or evening.

ACI 306R provides the guidelines and recommendations for cold weather concreting. Due to the difficulty and expense of providing cold weather protection, construction of the chimney shell during the winter is not recommended. In some instances, cold weather situations cannot be avoided and precautions need to be taken to ensure that the concrete is not damaged. Insulating blankets are commonly used to protect the concrete while it cures and is often used during occasional cold periods of weather. An adequate supply of blankets or other means of protection should be readily available on-site in cold weather.

The Contractor may be requested to submit their hot and cold weather concrete procedures for approval and be prepared to implement these procedures on short notice, if needed.

4.3.4.3 Liner Construction.

Liner construction procedures are important for scheduling and coordination. Liner materials of construction can use a considerable amount of laydown area. Access to and installation of these materials needs to be coordinated with other constructionactivities in the area. Scheduling and laydown areas associated with liner materials may be submitted and incorporated within the overall project schedule.

4.3.4.4 Welding Procedures.

Submittal and implementation of welding procedures is essential in maintaining quality control of welding for a wet stack application. Since the quality of the weld affects the corrosion resistance of an alloy liner, a high level of quality control needs to be enforced during welding. Coated carbon steel liners also require high quality welds to ensure proper performance of the coating system. For weld fabrication requirements for lining applications, refer to ASTM D4618, to NACE Standard RP0178-89, "Standard Recommended Practice Fabrication Details, Surface Finish Requirements, and Proper Design Considerations for Tanks and Vessels to be Lined for Immersion Service," and to NACE Standard RP0292-92, "Standard Recommended Practice Installation of Thin Metallic Wallpaper Lining in Air Pollution Control and Other Process Equipment."

Horizontal weld seams in a wet stack are typically limited to 1/8-inch (0.003 m) reinforcement or projection on the inside of the liner. Horizontal welds on the inside of a choke are usually ground flush to prevent liquid reentrainment. Vertical weld seam reinforcement in a wet stack, including the choke, are also typically limited to 1/8-inch (0.003 m). Limiting the size of the horizontal weld seams is more critical than the vertical weld seams with regard for minimizing liquid reentrainment.

For all welding processes, that Contractor prepares and submits for approval the welding procedure specification (WPS) and the procedure qualification test results (PQR). For carbon steel welding, the welding procedure specification includes the nonmandatory information included in Appendix E of AWS D1.1 in addition to the mandatory information listed in Appendix IV, Table IV-1 of AWS D1.1. For alloy welding, the welding procedures typically address all essential and nonessential variables of Section IX of the ASME Boiler and Pressure Vessel Code. Only approved welding procedures are typically used.

4.3.4.5 Coating Procedures.

Proper preparation and application of a protective coating is important to ensure its corrosion resistance and longevity. The following submittals may be required to ensure that the coating is properly installed:

- Surface preparation procedures.
- Application procedures, including thickness tolerances.
- Curing procedures.
- Test procedures and test results.
- Coating formulation with number and thickness of coats required.
- Weld repair procedures.
- Manufacturer's standard data and recommendations for surface preparation, application, curing and testing.
- Quality control reports and certifications.
- Temperature, humidity, and ventilation conditions to be maintained during application and curing.

4.3.5 On-Site Testing and Inspection

Ongoing on-site testing and inspection is required throughout the project's construction phase. Testing confirms that the materials of construction meet contract requirements. Inspections verify that the Contractor is performing the work in accordance with specification requirements.

4.3.5.1 Piling.

Piling is often used to support the chimney foundation. Several types of piling systems, such as steel H-piles or auger cast concrete piles, are commonly used. Tests and inspection application to piling are as follows.

4.3.5.1.1 *Load Test*

The Contractor typically is required to install test piling to confirm design conditions and to verify that the installed piling will provide an adequate factor of safety versus the design loads calculated. The piling is tested for compression, uplift, and lateral loads, as applicable.

4.3.5.1.2 Grout Cube Tests

A qualified testing laboratory may be retained by the Owner to perform grout testing for pressure grouted, auger cast piling systems. Testing is performed in accordance with CRD-C 620 and ASTM C109. The results of the cube tests are used to substantiate evidence of adequate strength and uniform consistency of the grout.

4.3.5.1.3 Visual Inspection

Piling may be inspected to ensure correct installation and location. Augercast pile reinforcing steel should be inspected before placement. Steel H-piles should be inspected to confirm that the flanges are oriented properly with respect to the strong and weak axis direction. Recommended piling installation tolerances are as follows:

- Piles should not exceed a variation from the vertical of more than 1/4 inch (0.006 m) per foot of pile length.
- The center of the pile head shall not vary from plan location at the

cutoff by more than 3 inches.

4.3.5.2 Foundation.

Inspection of the chimney foundation is required before and during concrete placement.

4.3.5.2.1 Embedded Items

Placement and positioning of all embedded items should be verified. Examples of items that are typically embedded in a chimney foundation are:

- Anchor bolts.
- Electrical conduits.
- Grounding.
- Drains.

4.3.5.2.2 Reinforcing Bar Placement

Reinforcing steel embedded in or projecting out of the foundation may be inspected to confirm correct number, size and spacing. Splice lengths and dowel projection lengths may also be verified. If mechanical splice connectors are used, the connectors are capped off to provide protection from the wet concrete. Mud or debris is removed from the rebar before placement of the concrete.

4.3.5.2.3 Concrete Placement

Inspection during concrete placement is performed to ensure that the concrete is being properly placed. Inspection also confirms that the concrete is vibrated after its placement. Concrete should be placed in lift heights that permit the concrete to be vibrated into the lower section. The Contractor should select a placement sequence so a minimal amount of concrete surface area is exposed at a given time. This reduces the opportunity for the concrete to develop its initial set and maintains a working surface that is easy to vibrate.

4.3.5.2.4 Concrete Testing

Concrete testing is usually performed on-site by a qualified laboratory testing company. Before placement, the concrete is tested for temperature, slump, and air content. Concrete cylinders are taken to perform compression strength tests.

4.3.5.3 Concrete Column.

Inspection of the concrete column is performed during construction to confirm that the chimney is being constructed in accordance with the design drawings.

4.3.5.3.1 Dimensional Tolerances

Dimensional tolerances for the concrete column are established by ACI 307. Vertical alignment of the column's centerpoint are taken by plumbing down to a reference point on the chimney foundation. The column's diameter is taped and measurements taken for out-of-roundness tolerances.

4.3.5.3.2 Location of Openings

The orientation, elevation, and size of openings in the column should be confirmed. The breeching opening should be accurately located in order to avoid misalignment problems with the absorber outlet duct tie-in. Since the breeching is typically installed before the outlet ductwork, a survey crew should position the breeching from an established benchmark that can also be used by the absorber contractor.

4.3.5.3.3 Reinforcing Bar Placement

Vertical reinforcing bars should be counted and bar sizes checked for each concrete lift height to confirm that the bar quantities match the design requirements. Horizontal bars are checked for size and location. Splice lengths and concrete cover are also be checked.

4.3.5.3.4 Wall Thickness

Wall thicknesses are typically measured to verify conformance with the design requirements.

4.3.5.3.5 Concrete Testing

Concrete testing is typically performed for each lift section (jump form) or for each 8-hour shift (slip form) by a qualified laboratory testing company. Testing is normally performed in the bottom of the chimney at the point of discharge from the concrete truck. Temperature, slump, and air content of the concrete are measured and recorded. Concrete cylinders are taken to verify compressive strength.

4.3.5.4 Acid Resistant Brick and Mortar.

Materials of construction and construction tolerances is typically monitored for liners constructed of acid-resistant brick and mortar.

4.3.5.4.1 Mortar Cube Strength Tests

During construction of the brick liner, mortar cubes is taken daily for compressive strength tests. This testing is usually performed on-site by a qualified testing laboratory. It is recommended that two sets of mortar cube samples should be tested: one set that is cured in the bottom of the stack to represent actual insitu conditions during construction, and another set cured under laboratory conditions in accordance with ASTM guidelines. Since the mortar curing process is heat sensitive, compression strength test results from mortar cured in the bottom of the stack may indicate if adequate heat is provided during construction in cold weather.

4.3.5.4.2 Visual Inspection of the Liner

Inspection during construction of the brick liner may be used to confirm that the following recommended construction practices are maintained:

- Projections on the inside face of the liner should not exceed 1/8 inch (0.003 m).

- The liner's vertical axis should not be off the theoretical axis by

more than 0.1 percent of its height nor 1 inch (0.03 m), whichever is greater. Also, the center of the liner should not vary by more than 1 inch (0.03 m) in 10 feet (3 m).

- Neither the diameter nor the radius of the liner should differ by more than 2 percent from that specified.
- During the liner's construction and curing period, a minimum temperature of 50 degrees F should be maintained in the shell's interior.

4.3.5.5 Metal Liners.

On-site inspection of metal liners is primarily related to welding quality control. Welding inspection for alloy materials is critical to ensure the corrosion resistance of the weld in a wet environment.

4.3.5.5.1 Welder Qualifications

For carbon steel welding, all welders are typically be qualified by passing tests prescribed in the AWS D1.1 Standard Qualification Procedure. Welders should have been tested within the past 12 months and their qualifications may be considered in effect unless the welder is not engaged in a given process of welding for more than six months.

For alloy welding, all welders are typically be qualified in accordance with Section IX of the ASME Boiler and Pressure Vessel Code. In addition, as a minimum the tests should meet the radiographic acceptance criteria of QW-191 of Section IX.

4.3.5.5.2 Welding Inspection

Verification inspection and testing of welds for carbon steel liners may be performed in accordance with AWS D1.1 and ASCE's "Design and Construction of Steel Chimney Liners." Inspection of material and workmanship may verify conformance with the AISC Manual of Steel Construction Specifications and Codes and the AISC Quality Criteria and Inspection Standards.

For alloy welding, all welds should be visually inspected by an AWS Certified Welding Inspector (CWI) qualified per AWS Standard QC1. All alloy welds that will be exposed to flue gas is tested using liquid penetrant examination according to Article 6 of ASME Section V. All liquid penetrant testing is performed by an ASNT Level II inspector. Certification verifying the qualifications of the welding inspector should be submitted before of welding operations start.

4.3.5.5.3 Weld Quality Workmanship Standards

The Contractor usually prepares and submits workmanship samples for approval prior to the start of work. The workmanship samples are visually inspected and liquid penetrant tested prior to submittal. The approved workmanship samples are visibly displayed at the shop and jobsite for the benefit of the welders and inspectors, as examples of acceptable weld surfaces.

4.3.5.6 FRP Liners.

Inspection and testing of a FRP liner is typically performed during the liner's fabrication and installation.

4.3.5.6.1 Physical Testing

Physical testing may be performed and submitted for representative wall samples. The following tests may be performed as appropriate:

- Resin - glass ratio for interior and exterior layers per ASTM D2584.
- Barcol hardness for surface cure per ASTM D2583.
- Tensile modulus per ASTM D638.
- Flexural modulus per ASTM D790.
- Compressive modulus per ASTM D695.
- Coefficient of thermal expansion per ASTM E228.
- Coefficient of thermal conductivity per ASTM C117 or C518.
- Specific gravity per ASTM D792.
- Chemical resistance per ASTM C581 or D4398.
- Heat-deflection temperature per ASTM D648.
- Flame retardancy per ASTM E84.

4.3.5.6.2 Visual Inspection

Wall samples may be provided by the Contractor for use as representative samples of visual standards for the liner. The liner appearance is typically free from defects including delaminations, cracks, bubbles, pinholes, and other defects affecting strength or serviceability.

For curing considerations, the air temperature in the work area is maintained at a minimum of 50 degrees F (10°C). All resins and FRP components are stored in accordance with the manufacturer's recommendations. The resin temperature at its point of use should typically be between 60 degrees F (15°C) and 75 degrees F (24°C).

4.3.5.7 Glass Block.

All glass block lining installation may be subject to inspection. Quality control procedures and requirements for installing a Pennguard Block lining system may be performed in accordance with Pennwalt Specifications CES-320 and CES-325. Specific items that typically are inspected or tested are presented below:

4.3.5.7.1 Blast Profile

For installation on steel liners, any existing fly ash buildup or coating should be removed and any abrupt contours or edges on welds should be rounded off smoothly by grinding. The interior steel substrate surface should be blast cleaned to white metal in accordance with SSPC-SP5.

For installation on brick liners, the condition of the inside surface of the liner should be inspected. Fly ash buildup may require that the surface be cleaned by hydroblast or sandblast. Mortar joints should be inspected. Protruding mortar should be chipped off.

4.3.5.7.2 Visual for Oxidation

After sandblasting the steel substrate, an inspection should be performed to confirm that rust bloom on the steel has not developed. A primer should be applied on the sandblasted steel substrate to protect the steel from formation of flash rust during the period of time between completion of sandblasting and application of the block lining system.

4.3.5.7.3 Surface Contamination Tests

The inside surface of the liner should be tested to confirm the removal of any existing acids. Any existing acid on the steel should be neutralized with an ammonia water rinse followed by a light, brush blast cleaning in accordance with SSPC-

SP7. The pH of the blast cleaned surface should be 6 to 7. The Contractor should take pH readings in all four quadrants at 20 foot (6 m) intervals throughout the height of the stack. The steel substrate surface should also be inspected for chloride contamination. If the chloride concentration is greater than 10 micrograms per square centimeter, the surface is contaminated and should be recleaned.

4.3.5.7.4 Workmanship Standards

The installation procedure and workmanship standards of the lining system should be verified by installing the system on a 4 foot by 4 foot (1.2 m x 1.2 m) transparent plexiglass sheet. The test panel should be visually inspected, mallet tested, and tested for adhesion. Testing procedures and acceptance criteria should be in accordance with the manufacturer's requirements.

4.3.5.7.5 Temperature and Humidity

Inspection should be performed to ensure that the lining system is being installed under the proper temperature and humidity conditions. During the installation of the lining, the Contractor should measure and record air temperature, temperature of the surface being lined, moisture dewpoint, and relative humidity. Inspection guidelines for these issues are:

- Relative humidity in the working area where the lining system is being installed should not be greater than 90 percent.
- The substrate temperature in which the block lining is installed must be at least 5 degrees F (3°C) above the moisture dewpoint temperature.
- Temperature of the substrate, ambient air temperature in the work area, and curing temperature should be between 50 degrees F (10°C) and 90 degrees F (32°C).

4.3.5.7.6 Visual

Visual inspection of the lining system should include the following items:

- All joints must be full and 1/8-inch (0.003 m) minimum thickness.
- No air voids should exist between the adhesive coated block and the adhesive coated substrate.
- The adhesive membrane is trowel applied.

4.3.5.8 Protective Coatings.

All protective coating installation work is typically inspected. The services of a quality control coating inspector certified by NACE are usually required. Items that are typically inspected or tested are presented in this Section.

4.3.5.8.1 Blast Profile

The interior surface of the liner should be inspected to ensure that surface preparation is being adequately performed. The surface of the metal to be lined should be blasted to obtain a white metal surface as defined in SSPC-SP5. The sand or grit used for blasting should be clean and dry and produce a minimum surface profile of 2.0 mils when measured with a Keane-Tator comparator, Model No. 372.

4.3.5.8.2 Visual for Oxidation

After blasting, inspection should confirm that surface rust has not developed. All surfaces to be coated as well as coated surfaces requiring additional thickness should be primed. All sand, dust or grit should be removed by brushing, air blasting, or vacuuming before priming. The blasted surface must be primed within the same work shift (8 to12 hours) and before any visible surface rusting develops. In the event of surface rusting, the area must be reblasted.

4.3.5.8.3 Surface Contamination Tests

Surface contamination tests measuring pH, chloride concentrations, and ferrous sulfate concentrations should be performed before applying primer. Tests should be performed using a "kTA Surface Contamination Kit" from kTA-Tator or approved equal. If the pH is less than 5.0, the chloride concentration is greater than 10 micrograms per square centimeter, or the ferrous sulfate concentration is greater than 20 micrograms per square centimeter, the surface is contaminated and should be recleaned. High pressure water or sodium bicarbonate solution should be used to remove the contamination.

4.3.5.8.4 Thickness

Random wet film thickness readings should be taken during the coating. A minimum of four readings should be taken per 100 square feet (9 m^2). After the coatings are fully cured, dry film thickness measurements should be taken, based on a 6-foot (1.8m) square grid pattern. Each measurement should consist of the average of three random readings taken near the center.

4.3.5.8.5 Temperature and Humidity

Inspection should be performed to ensure that the coating system is being installed under the proper temperature and humidity conditions. During the installation of the coating, the Contractor should measure and record air temperature, substrate temperature, moisture dewpoint, and relative humidity. Inspection guidelines for these issues are:

- Relative humidity in the work area should not be greater than 90 percent.
- Surface temperature must be at least 5 degrees F (3°C) above the dew point of the air in the work area.

- Temperature in the work area should be between 50 degrees F (10°C) and less than 120 degrees F (49°C), or it should be within the manufacturer's recommendations.

4.3.5.8.6 Spark Test

The cured coating should be tested for discontinuities in accordance with NACE RP0188-90, "Standard Recommended Practice for Discontinuity (Holiday) Testing of Protective Coatings." Pinholes should be repaired.

4.3.5.9 Elevator Load Test.

The Contractor usually conducts a load test of the personnel elevator witnessed by the Owner and Engineer. The Contractor should furnish the Engineer and Owner with a copy of the load test procedure. The Contractor usually certifies in writing that the elevator meets all the applicable local, state, and federal codes for safety and performance.

4.3.5.10 Pressurization Fans.

Pressurization fans for brick liners will require on-site testing and start-up upon delivery to the jobsite. The Contractor is typically required to perform the following procedures during the installation of the fans:

- Level the fan to the foundation using shim stocks; grout and anchor.
- Align the rotating assembly.
- Check for proper rotation of motor.
- Verify balance of fan.
- Perform functional test of pressurization system.

4.3.5.11 Electrical.

Completion of the electrical and grounding system is typically one of the last items to be completed on a new chimney installation. Before demobilization of the electrical subcontractor, all electrical and grounding components associated with the chimney should be checked.

4.3.5.11.1 Obstruction Lights

All obstruction lights should be inspected to verify that they are operational. If strobe lights are used, the photocell should be checked to verify the correct daytime and evening intensity levels. The alarm contacts should also be checked to verify that the lights are not malfunctioning.

4.3.5.11.2 Grounding

The grounding system for the chimney should be checked for continuity. The ground resistance should be measured and recorded at the ground cable risers. All physical connections between the ground cable and air terminals should be checked.

4.3.5.11.3 Electrical System Checkout

The electrical system for the chimney should be inspected. Examples of items that should be inspected are as follows:

- Confirm correct voltage level at the power panel.
- Reset transformer taps, if required.
- Test each ground fault interrupter receptacle to ensure proper operation.
- Check that all ambient lights are operational.
- Verify proper position of disconnect switches and power panel breakers.

4.3.5.11.4 Lead and PVC Coated Components

Grounding and conduit components at the top of the chimney require additional corrosion protection. A visual inspection should be performed to verify that all grounding cables and fittings in this area are lead covered. All conduits located at the top of the chimney should also be inspected to verify that PVC coated material was used.

5

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A

GLOSSARY

A.1 Nomenclature

$A (ft^2)$	Area
C_l	Pressure loss coefficient
C_d	Drag coefficient
d (μm)	Droplet diameter
d_p (ft)	Characteristic diameter of particles $(6 \times \text{volume part}/\pi)^{½}$
D (ft)	Diameter of the stack
E_o	Eotvos Number
f	Friction factor
F_a (lbf)	Acceleration force
F_D (lbf)	Gas drag force
F_f (lbf)	Frictional force
F_g (lbf)	Gravitational force
F_s (lbf)	Surface tension force
$g (ft/s^2)$	Gravitational constant
h_t (in. W.C.)	Total pressure loss
h_v (in. W.C.)	Gas velocity head
h_f (Btu/lbm)	Enthalpy of fluid
h_v (Btu/lbm)	Enthalpy of vapor
K_{oa} $(Btu/hr/ft^2/^{o}F)$	Overall heat transfer coefficient
L (ft)	Length
m (lbm/hr)	Mass flow rate
n_L (pcf)	Concentration of particulate size d_p at the stack exit
n_o (pcf)	Concentration of particulate of size d_p at the stack entrance

P_L	Fractional penetration of the stack flow (DU/ν)
q (Btu/hr)	Heat transfer
Q_L (gal/min)	Liquid flow rate
Q_G (ft^3/min)	Gas volumetric flow rate
R_d (ft)	Radius of curvature of droplet path
R_e	Reynolds number
T (°F)	Temperature
U_* (ft/s)	Shear velocity (shear stress at wall)
U (ft/s)	Mean velocity in the stack
v (ft/s)	Deposition velocity
V_d (ft/s)	Droplet velocity
V_g (ft/s)	Gas velocity
V_t (ft/s)	Terminal velocity of droplet relative to gas
V_+	Non-dimensional deposition velocity (v/u_*)
α	(means "is proportional to")
Δ	(means "delta" or "difference")
μ (lbf s/ft^2)	Dynamic viscosity of the gas
ν (ft^2/s)	Kinematic viscosity of the gas
ρ (lbm/ft^3)	Density of the gas
ρ_p (lbm/ft^3)	Density of a particle with diameter d_p
σ	Surface tension
τ (s)	Relaxation time of spherical particles ($\rho_p d_p^2/18\mu$)
τ_+	Non-dimensional relaxation time ($\tau u_*^3/\nu$)
μm	Micrometer (0.001 mm)

A.2 Definitions

absolute humidity - the weight (or mass) of water vapor in a gas water-vapor mixture per unit volume of space occupied.

absorber - general term for those gas/liquid contacting devices designed primarily for the removal of SO_x pollutants. i.e. scrubber.

absorption - the process by which gas molecules are transferred to a liquid phase during scrubbing.

air cubic feet per minute (acfm) - a gas flow rate expressed with respect to operating conditions (temperature and pressure).

ambient - pertaining to the conditions (pressure, air quality, temperature, etc.) of the surrounding environment of a plant or scrubbing system.

annual outage - a scheduled period of time (generally four to six weeks) set aside by the utility once per year to shut down the boiler and/or FGD system for inspection and maintenance.

annulus - the space between a chimney liner and a chimney shell.

base load - a generating station which is normally operated to take all or part of the normal load of a system and which, consequently, operates at a constant output.

breeching - the section of ductwork in an FGD system between the absorber outlet duct and the stack.

British thermal unit (Btu) - the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit, averaged from 32 degrees to 212 degrees F.

bypass gas - flue gas which bypasses a scrubber for the purpose of raising wet flue gas temperatures above the saturation temperature.

bypass reheat - a system that increases the temperature of the saturated flue gas leaving an FGD system above dew point by ducting a slip stream of particle-cleaned flue gas from the ESP exit duct past the FGD system to the absorber outlet duct or directly to the stack.

capacity factor - the ratio of the average load on a boiler for the period of time considered to the capacity rating of the boiler (actual kWh produced/theoretical kWh produced x 100).

carryover - entrained solids, slurry droplets, and/or liquid droplets that leaves with the flue gas stream exiting a particular stage of a scrubber or absorber.

chimney - a vertical structure at a power plant which encloses one or more flues that exhaust combustion gases. A chimney is typically constructed out of reinforced concrete.

chloride - a compound of chlorine with another element or radical.

choke - the constricted upper section of a steel stack or chimney liner.

cladding - a thin sheet of corrosion resistant alloy (usually nickel alloy or titanium) that is either resistance welded or roll bonded to carbon steel plate.

closed water loop - the water loop of an FGD system is closed when the fresh makeup water added exactly equals the evaporative water loss leaving via the stack and the water chemically or physically bonded to the sludge product.

column - a reinforced concrete chimney shell. Usually encloses one or more chimney liners. The purpose of the column is to protect the liner from weather and to act as a wind shield.

Computational Fluid Dynamics (CFD) - the use of finite element analysis methods to simulate heat transfer, temperature profiles and fluid and particle movement in boilers and air pollution control equipment.

corrosion - the deterioration of a metallic material by electrochemical attack.

damper - a plate or set of plates or louvers in a duct used to stop or regulate gas flow.

dewpoint - the temperature at which vapor contained in saturated flue gas begins to condense.

direct combustion reheat - a flue gas reheat system that boosts the temperature of the saturated gas from the absorber above dewpoint; this is accomplished by injection of the hot combustion products generated by oil or gas reheater burners into the gas stream.

efficiency - Ratio of the amount of a pollutant removed to the total amount introduced to the normal operation.

entrainment - the suspension of solids, liquid droplets, or mist in a gas stream.

erosion - the action or process of wearing away of a material by physical means (friction).

electrostatic precipitator (ESP) - an air pollution device used to remove particles from an exhaust stream by initially charging them with electrodes and then collecting them on oppositely charged plates.

expansion joint - a small section of ductwork or piping that is designed to passively expand or contract as required by the flexing of more rigid duct runs, piping, or pieces of equipment as such components are exposed to varying external and internal temperatures.

flue gas desulfurization (FGD) system - an SO_2 removal system that uses a wet or dry process downstream of a boiler to reduce sulfur dioxide emissions.

fly ash - fine solid particles of noncombustible ash carried out of the boiler by the exiting flue gas.

forced outage - the FGD system is taken out or forced out of service to make necessary repairs or modifications regardless of boiler availability such that the system is unavailable for service.

heat exchanger - device used to transfer sensible and/or latent heat from one stream of material to another to raise or lower the temperature of one of the materials.

induced draft (ID) - a fan used to move an enclosed stream of gases by creating a negative relative pressure in the stream to effectively draw the gas through the system.

indirect hot air - a flue gas reheat system in which reheat is achieved by heating ambient air with an external heat exchanger using steam at temperatures of 350 to 450 degrees.

in-line reheater - a heat exchanger installed in the wet flue gas duct downstream of the mist eliminator, usually consisting of hot water or steam coils used to boost the wet flue gas temperature above dewpoint.

liner - the flue located inside of a chimney or stack that exhausts combustion gases.

lining - a metal, organic, or inorganic type material applied to a shell of an FGD system component which is intended to protect the shell from abrasion, heat, and/or corrosion.

liquid collection devices - devices such as gutters, troughs and drains used in absorber outlet ductwork or stack liners within an FGD system to collect liquid carried over from a wet scrubber.

load factor - the ratio of the average load in kilowatts supplied during a designated period to the peak or maximum load in kilowatts occurring in that period.

mist - dispersion of liquid particles in a gas stream, carryover from a gas-liquid contact operation.

mist eliminator - a piece or section of pollution hardware used to remove a dispersion of liquid particles from a gas stream.

megawatt (MW) - unit used to describe gross or net power generation of a particular facility. One watt equals one joule per second. One megawatt equals 10^6 watts.

micrometer - unit of measure equivalent to 0.0000394 inch or 0.001 mm.

new (as opposed to retrofit for FGD systems) - FGD unit and boiler were designed at the same time, or space for addition of an FGD unit was reserved when the boiler was constructed.

NO_x - a symbol meaning oxides of nitrogen (e.g., NO and NO_2).

NSPS (New Source Performance Standards) - environmental regulations that apply to a new installation, referring primarily to the Federal NSPS that applies to installations beginning construction on or after August 17, 1971.

opacity - the degree to which emissions reduce the transmission of light and obscure the view of an object in the background.

open water loop - the water loop of an FGD system is open when the fresh makeup water added exceeds the evaporative water loss leaving via the stack and the water chemically or physically bonded to the sludge product.

outage - that period of time when the boiler and/or FGD system is shut down for inspection and maintenance. Outages may be either forced or scheduled.

particulate matter - finely divided solid particles entrained in the gas stream (fly ash, coal fines, dried reaction byproducts, etc.).

peak load - a boiler that is normally operated to provide power during maximum load periods.

pH - the hydrogen ion concentration of a water or slurry to denote acidity or alkalinity.

plume (stack plume) - the visible emission from a flue (stack).

plume downwash - the phenomenon which occurs when the flue gas exits a stack and the vapor plume drops below the top of the stack before evaporating or dispersing into the atmosphere. Usually occurs on stacks which operate at a relatively low exit velocity.

ppm (parts per million) - units of concentration that in wastewater applications is equal to milligrams per liter and in air pollution applications is equal to moles of pollutant to million moles diluent.

pressure drop - the difference in force per unit area between two points in a fluid stream, due to resistive losses in the stream.

rain hood - the component at the top of a stack which covers the annular space.

reheat - the process of increasing the flue gas temperature down stream of a wet scrubber. Reheat can be supplied by in-line, indirect hot air, direct combustion or by partial bypass of unscrubbed flue gas.

reheater - device used to raise the temperature of the scrubbed gas stream to prevent condensation and corrosion of downstream equipment, avoid visible plume, and/or enhance plume rise and dispersion.

relative humidity (also relative saturation) - the ratio of the weight (or mass) of water vapor present in a unit volume of gas to the maximum possible weight (or mass) of water vapor in unit volume of the same gas at the same temperature and pressure. The term "saturation" refers to any gas-vapor combination, while "humidity" refers specifically to an air-water system.

removal efficiency:

> **particulate matter** - the actual percentage of particulate matter removed by the emission control system (mechanical collectors, ESP, or fabric filter and FGD) from the untreated flue gas.
>
> **SO_2** - the actual percentage of SO_2 removed from the flue gas by the FGD system.
>
> **total unit design** - the designed percentage of mass of SO_2 or particulate matter entering the stack to the mass of the material in the flue gas exiting the boiler regardless of the removal efficiency of an individual component or the percentage of the exiting flue gas actually being scrubbed.

retrofit - the FGD unit will be/was added to an existing boiler not specifically designed to accommodate an FGD system.

saturated - the situation when a gas or liquid is filled to capacity with a certain substance. No additional amount of the same substance can be added under the given conditions.

saturation temperature - the temperature to which flue gas drops when it is saturated by scrubbing in a wet FGD system.

scale - deposits of slurry solids (calcium sulfite or calcium sulfate) that adhere to the surfaces of FGD equipment, particularly absorber/scrubber internals and mist eliminator surfaces.

scheduled outage - a planned period of time set aside periodically for inspection and maintenance of the boiler and/or FGD system.

scrubber - a device that promotes the removal of pollutant particles and/or gases from exhaust streams of combustion or industrial processes by the injection of an aqueous solution or slurry into the gas stream. i.e. absorber.

sludge - the material containing high concentrations of precipitated reaction byproducts and solid matter collected and/or formed by the FGD process (composed primarily of calcium-based reaction byproducts, excess scrubbing reagent, fly ash, and scrubber liquor).

slurry - a watery mixture of insoluble matter (usually lime or limestone).

SO_x - a symbol meaning oxides of sulfur (e.g., SO_2 and SO_3).

stack - a vertical structure at a power plant which encloses one or more flues that exhaust combustion gases.

stack flue - the inner duct or liner in a stack through which the flue gas is conveyed.

stack exit velocity - the exiting velocity of the flue gas out the top of the stack.

stack liner velocity - area average gas velocity inside the liner.

stack liquid discharge - liquid that is discharged from a stack and falls to the ground prior to evaporating.

standard conditions - a set of physical constants for the comparison of different gas volume flow rates (68 degrees F, 29.92 inches Hg, barometric pressure.

standard cubic feet per minute (scfm) - units of gas flow rate at standard conditions.

steel stack - a vertical structure at a power plant that exhausts combustion gases. The primary supporting shell is made of steel.

superficial gas velocity - the area average flue gas velocity through a mist eliminator or other component of an FGD system.

temperature, dry bulb - the temperature of a gas or mixture of gases indicated by a thermometer after correction for radiation.

temperature, wet bulb - a measure of the moisture content of air (gas) indicated by a wet bulb psychrometer.

total controlled capacity (TCC) - the gross rating (MW) of a unit brought into compliance with FGD, regardless of the percent of flue gas treated at the facility.

turning vanes (i.e. vanes) - devices used in ductwork or chimney liners to control gas flow direction. Usually fabricated from flat or curved plates.

unit rating:

> **gross** - maximum continuous generating capacity in MW
>
> **net** - gross unit rating less the energy required to operate ancillary station quipment, inclusive of emission control systems.

wallpaper - thin sheets of corrosion resistant alloy material welded to new or existing carbon steel plate.

water loop - all aqueous mass flows from inlet (e.g., seal water, quench water, scrubber liquor) to outlet of an FGD system (e.g., evaporation via stack, pond evaporation, waste disposal).

wet stack - a chimney, stack, or flue that exhausts saturated, completely scrubbed flue gas. Wet stacks are located downstream from a wet FGD system. Wet stack operation does not utilize any flue gas reheat system or partial bypass. Wet stacks are equipped with corrosion resistant liners for handling the wet, acidic flue gas exiting the FGD system.

zero discharge - a pollution regulation requiring that no effluent waste stream be discharged back into the environment, with the exception of evaporation via ponds and stacks (e.g., pond runoff or direct piping of spent slurry or waste into nearby waterways or tributaries would be prohibited).

A.3 Abbreviations

absolute	abs	inside diameter	id
actual cubic feet per minute	acfm	interior	int
alloy	aly	kilowatt	kW
ambient	am	lining	lng
average	avg	low-alloy steel	las
bottom	bot	maintenance	maint
brick	brk	manager	mgr
British thermal unit	Btu	material	matl
bypass	byp	maximum	max
carbon steel	cs	megawatt	mW
center line	cl	mile	mi
clean out	co	minimum	min
clear	cl	minute	min
column	col	module	mdl
concrete	conc	negative	neg or (-)
condensate	cnds	nickel steel	ns
continue, continuous	cont	nitrogen oxide	NO_x
contractor	contr	no data available	nda
corrosion	crsn	not applicable	na
corrosion-resistant	cre	not available	na
cubic foot	cu ft	outside diameter	od
damper	dmpr	particulate matter	
degrees Celsius	°C	< 10 microns in size	pm10
degrees Fahrenheit	°F	parts per million	ppm
demolition	dml	percent	pct or (%)
dew point	dp	plate	pl

diameter	dia	plus or minus	porm or (±)
draft	dft	positive	pos
efficiency	eff	pound	lb
elevation	el	pound force per square foot	psf
engineer	engr	pound force per square inch	psi
equation	eq	pound per cubic foot	pcf
example	ex	pressure	press
expansion jt	exp jt	reheater	rhr
exterior	ext	reinforced concrete	rc
firebrick	fbck	required	reqd
floor drain	fd	research and development	R&D
foot	ft	scale model	scmod
foot per second	fps	square foot	sq ft
forced-draft	fd	stainless steel	sst
foundation	fdn	standard	std
galvanize	galv	static pressure	st pr
gallon per minute	gpm	steel	stl
galvanize	galv	sulfur dioxide	SO_2
glass block	glb	sulfur trioxide	SO_3
gutter	gut	sulfuric acid	H_2SO_4
horizontal	horiz	temperature	temp
hour	hr	temperature differential	td
inch	in	velocity	vel
inches of water column	in H_2O	viscosity	visc
induced-draft	id	water	H_2O
inlet	inl		

A.4 Units and Conversion Factors

To Obtain	Multiply	By
Atmospheres	Feet of water @ 4°C	2.950 x 10-¨
Atmospheres	Inches of mercury @ 0°C	3.342 x 10-¨
Atmospheres	Pounds per square inch	6.804 x 10-¨
Inches of mercury @ 0°C	Pounds per square inch	2.036
Kilowatts	Btu per minute	1.758 x 10-¨

Temperature Conversions:

$^{\circ}F = 1.8 \times t^{\circ}C + 32$

$^{\circ}C = (t^{\circ}F - 32)/1.8$

Liquid Load Conversion:

$$\text{Liquid Load (grains / acf)} = \frac{Q_L(\text{gal / min} \times 57{,}700)}{Q_G(\text{acfm})}$$

B

LIST OF KNOWN WET STACKS

The list of known wet stacks has been generated from several sources. The first source is from a published industry list of Phase I Scrubber construction projects. The second source is from the 1991 Energy Information Administration (EIA) Form 767 Scrubber Data. The third and final source is based on professional experience in the Flue Gas Desulfurization (FGD) industry. The format of this list is based upon the premise that each individual liner represents a separate wet stack. The list includes units presently on line and units which were under construction at the time this guide was written.

Table B-1
List of Known Wet Stacks

NUMBER	UTILITY	PLANT(S)/ UNIT(S)
1	ALLEGHENY POWER SERVICE	HARRISON 1
2	ALLEGHENY POWER SERVICE	HARRISON 2
3	ALLEGHENY POWER SERVICE	HARRISON 3
4	ALLEGHENY POWER SERVICE	MITCHELL 3
5	AMERICAN ELECTRIC POWER	GAVIN 1
6	AMERICAN ELECTRIC POWER	GAVIN 2
7	ARIZONA PUBLIC SERVICE	FOUR CORNERS 1
8	ARIZONA PUBLIC SERVICE	FOUR CORNERS 2
9	ATLANTIC CITY ELECTRIC	BL ENGLAND 2 *
10	BIG RIVERS ELECTRIC	D B WILSON 1
11	BIG RIVERS ELECTRIC	RD GREEN 1
12	BIG RIVERS ELECTRIC	RD GREEN 2
13	CENTRAL ILLINOIS LIGHT CO	DUCK CREEK 1
14	CENTRAL ILLINOIS PUB SERV	NEWTON 1
15	CINCINNATI GAS & ELECTRIC	ZIMMER 1
16	DESERET GEN & TRANS COOP	BONANZA STATION 1-1
17	DUQUESNE LIGHT CO	ELRAMA 1
18	DUQUESNE LIGHT CO	ELRAMA 2
19	DUQUESNE LIGHT CO	ELRAMA 3
20	DUQUESNE LIGHT CO	ELRAMA 4
21	HENDERSON MUNICIPAL	HENDERSON 1
22	HENDERSON MUNICIPAL	HENDERSON 2
23	INDIANAPOLIS POWER & LIGHT	PETERSBURG 1
24	INDIANAPOLIS POWER & LIGHT	PETERSBURG 2
25	INTERMTN POWER PROJECT	INTERMTN PWR STA 1
26	INTERMTN POWER PROJECT	INTERMTN PWR STA 2
27	KENTUCKY UTILITIES	GHENT 1
28	LOUISVILLE GAS & ELECT	CANE RUN 4
29	LOUISVILLE GAS & ELECT	CANE RUN 5
30	LOUISVILLE GAS & ELECT	CANE RUN 6
31	LOUISVILLE GAS & ELECT	TRIMBLE COUNTY 1
32	MICHIGAN SOUTH CENTRAL	ENDICOTT 1
33	MINNESOTA POWER AND LIGHT	SYL LASKIN 1
34	MINNESOTA POWER AND LIGHT	SYL LASKIN 2
35	MINNESOTA POWER AND LIGHT	CLAY BOSWELL 3
36	NEW YORK STATE ELEC & GAS	KINTIGH 1
37	NEW YORK STATE ELEC & GAS	MILLIKEN 1
38	NEW YORK STATE ELEC & GAS	MILLIKEN 2
39	NORTHERN INDIANA PUB SERV	BAILEY 7,8
40	OLD DOMINION/VIRGINIA PWR	MT. STORM 3 *
41	OLD DOMINION/VIRGINIA PWR	CLOVER 1
42	OLD DOMINION/VIRGINIA PWR	CLOVER 2
43	ORLANDO UTILITIES COMM	STANTON ENERGY 1
44	ORLANDO UTILITIES COMM	STANTON ENERGY 2
45	OWENSBORO MUN UTIL	ELMER SMITH 1,2
46	PACIFICORP	HUNTER (EMERY) 2

NUMBER	UTILITY	PLANT(S)/ UNIT(S)
47	PACIFICORP	JIM BRIDGER BW74
48	PACIFICORP	NAUGHTON 3
49	PACIFICORP	DAVE JOHNSTON 4
50	PENNSYLVANIA ELECTRIC	CONEMAUGH 1
51	PENNSYLVANIA ELECTRIC	CONEMAUGH 2
52	PENNSYLVANIA POWER	BRUCE MANSFIELD 1A
53	PENNSYLVANIA POWER	BRUCE MANSFIELD 1B
54	PENNSYLVANIA POWER	BRUCE MANSFIELD 2A
55	PENNSYLVANIA POWER	BRUCE MANSFIELD 2B
56	PENNSYLVANIA POWER	BRUCE MANSFIELD 3A
57	PENNSYLVANIA POWER	BRUCE MANSFIELD 3B
58	PLAINS ELECTRIC GEN.	ESCALANTE 1
59	PSI ENERGY G & E	GIBSON 4 *
60	PSI ENERGY G & E	GIBSON 5 *
61	SEMINOLE ELECTRIC COOP	SEMINOLE 1
62	SEMINOLE ELECTRIC COOP	SEMINOLE 2
63	SIKESTON BOARD OF MUN UTIL	SIKESTON 1
64	SOUTHERN ILLINOIS PWR CO	MARION 4
65	SOUTHERN INDIANA G & E	A B BROWN 1
66	SOUTHERN INDIANA G & E	A B BROWN 2
67	SOUTHERN INDIANA G & E	CULLEY 2,3
68	CITY OF SPRINGFIELD	SOUTHWEST 1
69	TENNESSEE VALLEY AUTH	CUMBERLAND 1
70	TENNESSEE VALLEY AUTH	CUMBERLAND 2
71	TENNESSEE VALLEY AUTH	PARADISE 1
72	TENNESSEE VALLEY AUTH	PARADISE 2

Notes:
1. One wet stack liner per line of data.
2. * – indicates wet stack data was not available.

C

RESULTS OF SURVEY

C.1 Wet Stack Survey Data

The data collection phase of the study involved identifying utilities operating or constructing wet stacks in the United States. These utilities were then contacted and asked to complete a short questionnaire covering various aspects of the wet stack system geometry and operating conditions. The survey data represents information collected from approximately 31 utilities which operate 68 wet stack liners. Data from several units under construction have also been included. The data includes all of the important design and operating parameters of the wet stacks.

The first step in the data collection phase of the wet stack study consisted of preparing a short questionnaire. The questionnaire focused on topics such as the wet stack system geometry and operating conditions of the unit. Questions about problems encountered during unit operation, such as plume down wash and stack liquid discharge, were also included in the survey. (Refer to Section 1 of the Wet Stacks Design Guide for a description of plume down wash and stack liquid discharge.)

The criteria used to identify a wet stack include: 1) a full load stack temperature of 135 degrees F (57°C) or less (which assumes that no bypass gas or reheat is used to raise flue gas absorber exit temperatures) and 2) a unit which operates with a wet scrubber.

The list of wet stacks identified by this criteria and the respective plant personnel contacts were generated from the 1991 Energy Information Administration Form 767 Scrubber Data. This data was sorted in ascending order of full load stack temperatures. All utilities with units reporting a full load stack temperature of 135 degrees F (57°C) or less were contacted. Additional questionnaires were also sent to utilities appearing on a published industry list of Phase I scrubber construction projects.

Once the list of identified wet stack units was compiled, each contact was sent a blank questionnaire with a letter explaining the purpose of the survey. The utilities gathered data during the next several weeks. Once a utility had filled out the questionnaire as completely as possible, the completed questionnaire was either sent back via fax or the information was relayed via the telephone. In general, most of the data requested was furnished by the utilities. However, some utilities had difficulty obtaining various pieces of information and in those cases the data was omitted. Additional information was filled in such as stack inlet and exit velocities using the information provided by the utilities.

The data provided on the completed questionnaires was then converted to a spread sheet format for record keeping purposes and ease of manipulation. Responses for certain categories could then be easily compared for several different utilities simultaneously.

Nearly half of the utilities that participated in the study reported some instance of down wash or stack liquid discharge. The severity of the problems encountered varied from very infrequent light misting to heavy rain. The location of stack liquid discharge fallout reported ranged from the area immediately surrounding the stack up to one-half mile from the stack. Only one utility reported stack liquid discharge fallout beyond the plant site.

Several direct relationships are apparent from the wet stacks data. Stack liquid discharge appears to be directly related to a lack of liquid collection devices such as gutters in the liners and absorber outlet ductwork. In addition, stack droplet discharge seems to be more prevalent on units with an exit velocity greater than 75 ft/s (23 m/s). However, this relationship does not hold true in every case.

Based on reported data, a direct relationship between an FGD system which utilizes a particular type of mist eliminator and occurrences of stack liquid discharge is not apparent. However, the City of Springfield, Missouri eliminated stack liquid discharge problems at their Southwest Unit 1 station by inclining the existing mist eliminators 20 degrees.

Downwash problems were reported much less frequently than stack liquid discharge problems in the survey. The only serious case of plume downwash was reported by Seminole Electric Cooperative's Seminole Station Units 1 and 2. The exit velocity reported for these units is relatively low at 33 ft/s (10 m/s). Downwash was reported by several units to be more prevalent on cold days. In addition, the reported cases of downwash in this survey occurred only on units with brick liners without chokes.

Acid resistant brick liners are the most prevalent wet stack liners in service in the United States. This is due mostly to economic considerations. Of the 36 acid resistant brick liners operating as wet stacks, 34 (or 94 percent) operate with annulus pressurization fans. Significant acid leaching through the brick liner has occurred on units operating without annulus pressurization fans. For example, Mitchell Unit 3, which is operated by Allegheny Power Service Corporation has experienced significant acid leaching through the brick liner without annulus pressurization.

Wet stack liners constructed with acid resistant brick are typically operated between -3.0 to +3.0 inches of water column (-0.75 to 0.75 kPa) static pressure in the liner at the breeching level.

Table C-1
Wet Stack Survey Data

TABLE C-1

WET STACK SURVEY DATA

UTILITY	STATION	UNIT	SIZE (MW)	LOCATION	LINER HEIGHT (FEET)	LINER INLET DIAMETER (FEET)	INLET VELOCITY (FPS)	LINER OUTLET DIAMETER (FEET)	EXIT VELOCITY (FPS)	CHOKE INLET DIAMETER (FEET)	CHOKE OUTLET DIAMETER (FEET)	CHOKE HEIGHT (FEET)	RAIN HOOD MAT'L	DISTANCE FROM TOP OF LINER (FEET)	LINER MATERIAL
ALLEGHENY POWER SERVICE COOP	HARRISON	1,2,3	3 x 684	SHINNSTON, WV	820'–0"	26'–0"	57	26'–0"	57	N/A	N/A	N/A	C276	22'–0"	C276 CLAD CARBON STEEL PLATE
ALLEGHENY POWER SERVICE COOP	MITCHELL	3	300	NEW EAGLE, PA	375'–0"	22'–0"	42	20'–0"	50	22'–0"	20'–0"	20'–0"	FRP	3'–3" APPROX	ACID RESISTANT BRICK
AMERICAN ELECTRIC POWER	GAVIN	1,2	2 x 1300	CHESHIRE, OH	772'–0"	42'–0"	NDA	42'–0"	NDA	N/A	N/A	N/A	FIBERGLASS	NDA	ALLOY & BRICK
ARIZONA PUBLIC SERVICE	FOUR CORNERS	1,2	2 x 190	FRUITLAND, NM	250'–0"	11'–6" X 18'–0"	39	14'–0"	52	N/A	N/A	N/A	N/A	N/A	ACID BRICK
BIG RIVERS ELECTRIC CORPORATION	GREEN	1	264	SEBREE, KY	269'–9"	15'–0"	94	15'–0"	94	N/A	N/A	N/A	304 SST	4'–9"	TITANIUM CLAD CARBON STEEL
BIG RIVERS ELECTRIC CORPORATION	GREEN	2	264	SEBREE, KY	269'–9"	15'–0"	94	15'–0"	94	N/A	N/A	N/A	304 SST	4'–9"	TITANIUM CLAD CARBON STEEL
BIG RIVERS ELECTRIC CORPORATION	WILSON	1	509	CENTERTOWN, KY	599'–6	34'–0"	28	22'–0"	67	34'–0"	22'–0"	75'–0"	FRP	30'–0"	ACID BRICK
CENTRAL ILLINOIS LIGHT CO.	DUCK CREEK	1	441	CANTON, IL	437'–0"	36'–0"	16	19'–0"	59	N/A	N/A	N/A	N/A	N/A	FIBRECRETE LINED ASTM A242 PL
CENTRAL ILLINOIS PUBLIC SERVICE	NEWTON	1	617	NEWTON, IL	218'–0"	18'–7"	98	18'–7"	98	N/A	N/A	N/A	N/A	N/A	FIBRECRETE 214/222
CINCINNATI GAS & ELECTRIC CO.	ZIMMER	1	1426	MOSCOW, OH	514'–3"	43'–9"	29	42'–0"	31	N/A	N/A	N/A	FIBERGLASS REINFORCED PLASTIC	0	BRICK
DESERET GENERATION AND TRANSMISSION COOP	BONANZA	1	400	VERNAL, UT	600'–0"	30'–0"	37	26'–0"	50	N/A	N/A	N/A	FRP	0	ACID RESISTANT BRICK
DUQUESNE LIGHT CO	ELRAMA	1–4	100,100, 125,185	ELRAMA, PA	392'–0"	BREECH 40' x 12'	75	26'–0"	68	N/A	N/A	N/A	316L SST	EVEN WITH TOP	ACID RESISTANT BRICK
HENDERSON MUNICIPAL UTILITIES	HENDERSON STATION TWO	1,2	2 x 172	SEBREE, KY	350'–0"	16'–0"	62	16'–0"	62	N/A	N/A	N/A	REINF. CONC. (W/ TYPE V CEMENT)	16'–8"	ACID RESISTANT BRICK
INDIANAPOLIS POWER & LIGHT	PETERSBURG	1,2	240,420	PETERSBURG, IN	621'–0" INCLUDES CHOKE	#1–21'–6" #2–29'–6"	#1 – 45 #2 – 45	#1–21'–6" #2–29'–6"	#1 – 90 #2 – 89	#1–21'–6" #2–29'–6"	1–15'–3" 2–20'–10"	#1–16'–8" #2–23'–0"	EPOXY COATED CONCRETE SLAB	25'–0"	ACID RESISTANT BRICK & MORTAR
INTERMOUNTAIN POWER PROJECT	INTERMOUNTAIN POWER GENERATING STATION	1,2	840,840	DELTA, UT	715'–0"	28'–0"	70	28'–0"	70	N/A	N/A	N/A	REINFORCED CONCRETE	30'–0"	FRP
KENTUCKY UTILITIES	GHENT	1	557	CARROLLTON, KY	580'–0"	42'–0"	22	37'–0"	28	N/A	N/A	N/A	317L SST	0'–6"	ACID RESISTANT BRICK
LOUISVILLE GAS & ELECTRIC	CANE RUN	4	163	LOUISVILLE, KY	165'–6"	15'–6"	53	15'–6"	53	N/A	N/A	N/A	C276	5'–0"	C276 ALLOY (1/16" THICK) (4' OF LIN. IS 1/4")
LOUISVILLE GAS & ELECTRIC	CANE RUN	5	209	LOUISVILLE, KY	152'–4"	15'–6"	61	15'–6"	61	N/A	N/A	N/A	C276	5'–0"	C276 ALLOY (1/16" THICK) (4' OF LIN. IS 1/4")
LOUISVILLE GAS & ELECTRIC	CANE RUN	6	272	LOUISVILLE, KY	484'–0"	21'–0"	41	19'–0"	50	N/A	N/A	N/A	C276	5'–0"	C276 ALLOY (1/16" THICK) (20' OF LN. IS 1/4")
LOUISVILLE GAS & ELECTRIC	TRIMBLE COUNTY	1	566	BEDFORD, KY	760'–0"	18'–0"	111	18'–0"	111	N/A	N/A	N/A	FRP	7'–0"	FRP
MICHIGAN SOUTH CENTRAL POWER AGENCY	ENDICOTT	1	55	LITCHFIELD, MI	235'–3"	16'–7 1/2"	14	16'–7 1/2"	43	16'–7 1/2"	9'–8"	13'–9"	N/A	N/A	PENNGUARD BOROSILICATE GLASS BLOCK
MINNESOTA POWER AND LIGHT CO	SYL LASKIN	1,2	2 x 58	AURORA, MN	300'–0"	13'–6"	58	10'–6"	96	N/A	N/A	N/A	N/A	N/A	ACID RESISTANT BRICK, CORLOCK B MORTAR
MINNESOTA POWER AND LIGHT CO	BOSWELL	3	365	COHASSET, MN	700'–0"	36'–0"	33	29'–0"	50	N/A	N/A	N/A	1/4" FRP	10'–0"	FIRE BRICK

Conversions: 1 inch = 0.0254 m, 1 ft = 0.3048 m

TABLE C-1

WET STACK SURVEY DATA

UTILITY	STATION	UNIT	SIZE (MW)	LOCATION	LINER HEIGHT (FEET)	LINER INLET DIAMETER (FEET)	INLET VELOCITY (FPS)	LINER OUTLET DIAMETER (FEET)	EXIT VELOCITY (FPS)	CHOKE INLET DIAMETER (FEET)	CHOKE OUTLET DIAMETER (FEET)	CHOKE HEIGHT (FEET)	RAIN HOOD MAT'L	DISTANCE FROM TOP OF LINER (FEET)	LINER MATERIAL
NEW YORK STATE ELEC. & GAS CORP.	KINTIGH	1	691	BARKER, NY	612'-6"	34'-11 3/8" I.D.	28.5	26'-8" I.D.	49	N/A	N/A	N/A	REINFORCED FIBERGLASS (FRP)	0	ACID-RESISTANT BRICK
NEW YORK STATE ELEC. & GAS CORP.	MILLIKEN	1,2	155,167	LANSING, NY	229'-0"	13'-6"	49	12'-0"	61	N/A	N/A	N/A	N/A	N/A	FRP
NORTHERN INDIANA PUBLIC SERVICE	BAILLY	7,8	7 - 174 8 - 346	CHESTERTON, IN	474'-6"	33'-0"	34	20'-2 1/2"	90	33'-0"	20'-2 1/2"	26'-0"	CONCRETE ROOF	10'-0"	SEE COMMENTS
OLD DOMINION ELECT COOPERATIVE/ VIRGINIA POWER	CLOVER	1,2	400 EACH	CLOVER, VA	337'-0"	22'-3"	60	22'-3"	60	N/A	N/A	N/A	SOLID TITANIUM ASTM B265 GRADE 2	0 SLOPES TO SHELL	TITANIUM CLAD CARBON STEEL
ORLANDO UTILITIES COMMISSION	STANTON ENERGY	1,2	465	ORLANDO, FL	442'-0"	23'-5" I.D.	45	19'-0" I.D.	68	N/A	N/A	N/A	FRP	0	ACID RESISTANT CLAY ASTM C279 H
OWENSBORO MUNICIPAL UTILITIES	ELMER SMITH	1,2	1-151 2-265	OWENSBORO, KY	420'-0"	24'-0"	69	24'-0"	69	N/A	N/A	N/A	N/A	N/A	ACID BRICK
PACIFICORP	DAVE JOHNSTON	4	360	GLENROCK, WY	249'-0"	23'-0"	50	23'-0"	50	N/A	N/A	N/A	N/A	N/A	STEEL - POLYESTER COATING
PACIFICORP	HUNTER	2	446	CASTLE DALE, UT	600'-0"	NDA	NDA	24'-0"	65	N/A	N/A	N/A	FRP	DATA UNAVAIL-ABLE	BRICK
PACIFICORP	JIM BRIDGER	4	561	POINT OF ROCKS, WY	500'-0"	35'-1"	47	31'-0"	61	N/A	N/A	N/A	FRP	DATA UNAVAIL-ABLE	BRICK
PACIFICORP	NAUGHTON	3	326	KEMMERER, WY	470'-0"	31'-4"	32	27'-6"	42	N/A	N/A	N/A	RUBBER LIKE VITON (BETWEEN LINER&COLUMN)	N/A	ACID RESISTANT BRICK
PENNSYLVANIA ELECTRIC	CONEMAUGH	1,2	850,850	NEW FLORENCE, PA	404'-10"	33'-0"	53	28'-0"	73	33'-0"	28'-0"	31'-0"	CONCRETE ROOF SUPT'D BY STUCT STEEL	19'-6"	C276 ALLOY (1/16" THK) (TOP 20' IS SOLID)
PENNSYLVANIA POWER CO.	BRUCE MANSFIELD	1,2	2 x 914	SHIPPINGPORT, PA	950'-0"	19'-2"	75	19'-2"	75	N/A	N/A	N/A	N/A	N/A	COATED CARBON STEEL
PENNSYLVANIA POWER CO.	BRUCE MANSFIELD	3	914	SHIPPINGPORT, PA	600'-0"	19'-2"	75	19'-2"	75	N/A	N/A	N/A	N/A	N/A	INCONEL 625 PL 1/4"
PLAINS ELECTRIC GENERATION AND TRANSMISSION COOP	ESCALANTE	1	233	PREWITT, NM	450'-0"	22'-0"	58	20'-0"	70	N/A	N/A	N/A	FRP	0	BRICK
SEMINOLE ELECTRIC COOP	SEMINOLE	1,2 (IDENTICAL OPP UNITS)	2 x 652	PALATKA, FL	675'-0"	42'-0 7/8"	24	36'-0"	33	N/A	N/A	N/A	316L SST	5'-0"	ACID RESISTANT BRICK AND MORTAR
SIKESTON MUNICIPAL UTILITIES	SIKESTON	1	261	SIKESTON, MO	435' SHELL 340' DRY 373' WET	15'-4" DRY 17'-0" WET	53 DRY 43 WET	15'-4" DRY 17'-0" WET	53 DRY 43 WET	N/A	N/A	N/A	INCONEL 625	20'-0"	WET LINER 80 MIL POLYESTER FLAKEGLASS
SOUTHERN ILLINOIS POWER CO-OPERATIVE	MARION	4	173	MARION, IL	400'-0"	6'-0" x 27'-6"	30	16'-6"	23	N/A	N/A	N/A	WAS FIBERGLASS REPLACED WITH RUBBER EXP JNT	0	BRICK
SOUTHERN INDIANA GAS AND ELECTRIC	A B BROWN	1	265	WEST FRANKLIN, IN	496'-6"	15'-9 1/4"	72	14'-0"	91	N/A	N/A	N/A	FRP	4'-0"	RED SHALE, ACID BRICK (30'-171')
SOUTHERN INDIANA GAS AND ELECTRIC	A B BROWN	2	265	WEST FRANKLIN, IN	494'-6"	18'-0"	55	14'-0"	91	N/A	N/A	N/A	FRP	4'-6"	RED SHALE, ACID BRICK (90')
SOUTHERN INDIANA GAS AND ELECTRIC	CULLEY	2,3			385'-6"	25'-11"	44	23'-0"	73	23'-0"	20'-0"	2'-6"	FRP	0	TYPE II FIRECLAY BRICK ASTM C980
CITY OF SPRINGFIELD	SOUTHWEST	1	194	SPRINGFIELD, MO	390'-0"	18'-0"	49	12'-0"	111	N/A	N/A	N/A	FRP	0	2% POROUS BK, SAUEREISEN 65 MORTAR
TENNESSEE VALLEY AUTHORITY	CUMBERLAND	1,2	2 x 1300	CUMBERLAND CITY, TN	635'-0"	38'-6"	59	38'-6"	59	N/A	N/A	N/A	C276 (SOLID)	0	C276 (ROLL BOND)
TENNESSEE VALLEY AUTHORITY	PARADISE	1,2	2 x 704	DRAKESBORO, KY	600'-0"	33'-0"	41	26'-0"	66	N/A	N/A	N/A	316L CAP	N/A	ACID RESISTANT BRICK

Conversions: 1 inch = 0.0254 m, 1 ft = 0.3048 m

TABLE C-1

WET STACK SURVEY DATA

UTILITY	STATION	UNIT	DATE OF LATEST INSPECT	CONDITION OF LINER	LIQUID COLLECTION DEVICES IN LINER	INSULATION TYPE	INSULATION THICKNESS (INCHES)	NUMBER OF BREECHING DUCTS	ORIENTAION OF BREECHING DUCTS	HEIGHT OF BREECHING DUCT (FEET)	WIDTH OF BREECHING DUCT (FEET)	BREECHING DUCT VANES	LIQUID COLLECTION DEVICES IN BREECHING	CONDITION OF DUCT
ALLEGHENY POWER SERVICE COOP	HARRISON	1,2,3	NEW	NEW	NONE	N/A	N/A	1 PER UNIT TOTAL OF 3	90 DEG APART (SEE SURVEY)	26'-0" DIA SOLID C276	26'-0" DIA SOLID C276	NONE	NONE	NEW SOLID C276
ALLEGHENY POWER SERVICE COOP	MITCHELL	3	10-93	GOOD	SLPD PL @ STK INLET; ANNULUR RING ON LINR WALL ABV DUCT	N/A	N/A	1	90 DEG ENTRY	40'-0"	12'-0"	NONE	FLOOR RAMP	GOOD
AMERICAN ELECTRIC POWER	GAVIN	1,2	N/A	N/A	YES	N/A	N/A	6	36 DEGREES	36'-0"	7'-0"	NDA	YES	N/A
ARIZONA PUBLIC SERVICE	FOUR CORNERS	1,2	1989	GOOD	DRAINS	N/A	N/A	2	180 DEG OPPOSED	11'-6"	18'-0"	YES	DRAINS	GOOD
BIG RIVERS ELECTRIC CORPORATION	GREEN	1	SPRING '94	GOOD	NONE, CONICAL DRAIN AT BOTTOM	JOHNSMAN-VILLE 1001 SPINGLAS BLK	2	1	HORIZONTAL FLOW	23'-0"	14'-0"	NONE	LOW POINT	GOOD
BIG RIVERS ELECTRIC CORPORATION	GREEN	2	SPRING '94	GOOD	NONE, CONICAL DRAIN AT BOTTOM	JOHNSMAN-VILLE 1001 SPINGLAS BLK	2	1	HORIZONTAL FLOW	23'-0"	14'-0"	NONE	LOW POINT	GOOD
BIG RIVERS ELECTRIC CORPORATION	WILSON	1	SPRING '94	GOOD	NONE, CONICAL DRAIN AT BOTTOM	NONE	N/A	1	HORIZONTAL FLOW	44'-0"	15'-6"	NONE	LOW POINT	GOOD
CENTRAL ILLINOIS LIGHT CO.	DUCK CREEK	1	4-1-94	SCATTERED HOLES THROUGHOUT	HOPPER AT BOTTOM	MINERAL WOOL	2	1	HORIZONTAL	20'-0"	20'-0"	NONE	NONE	PROTECTED BY 1/16 HASTALLOY
CENTRAL ILLINOIS PUBLIC SERVICE	NEWTON	1	10/94	NEARING END OF SERVICE LIFE	NONE	NONE	N/A	2	OPPOSING	29'-0"	10'-0"	NDA	NONE	GOOD
CINCINNATI GAS & ELECTRIC CO.	ZIMMER	1	SPRING '94	GOOD	DRAIN SYSTEM	N/A	N/A	6	EQUALLY SPACED OVER 180 DEGREES	36'-0"	7'-0"	NONE	NICKEL ALLOY OPEN DUCT DRAIN	GOOD
DESERET GENERATION AND TRANSMISSION COOP	BONANZA	1	3-93	GOOD MINOR CRACKS	SLOPING FLOOR TO DRAIN	N/A	N/A	1	ENTERS @ 84'-0 TO BOTTOM OF DUCT	38'-0"	12'-0"	NONE	DRAIN IN BOTTOM OF DUCT	GOOD
DUQUESNE LIGHT CO	ELRAMA	1-4	6-94	OUTSIDE "WICKING" NEEDS CLEAN	STACK DRAIN IN BASE	N/A	N/A	1	HORIZONTAL	40'-0"	12'-0"	NONE	NONE	GOOD
HENDERSON MUNICIPAL UTILITIES	HENDERSON STATION TWO	1,2	NOT IN OPERA-TION	NOT IN OPERATION	GUTTERS ABOVE BREECHING; LEAD GUTTERS & DRAINS	N/A	N/A	2 (1 / LINER)	N/A	12'-0" TO 22'-2" VARIES	12'-0" TO 6'-6" VARIES	NONE	SIDE GUTTERS ON ABSORBER OUTLET	NOT IN OPERATION
INDIANAPOLIS POWER & LIGHT	PETERSBURG	1,2	N/A	UNDER CONSTRUC-TION	WALL & ROOF COLLECTORS IN OUTLET DUCTS	N/A	N/A	1	NEAR HORIZ BOT & SLOPING ROOF & WALLS	#1 - 35'-1" #2 - 41'-6"	#1 - 9'-6" #2 - 13'-6"	NONE	WALL/CEILING ANGLE COLLECTORS	NEW CONSTRUCTION
INTERMOUNTAIN POWER PROJECT	INTERMOUNTAIN POWER GENERATING STATION	1,2	N/A	N/A	FRP AT EXPANSION JOINTS AND TOP COLLECTOR	N/A	N/A	1 (1 / LINER)	60 DEGREES	ROUND 28'-0" DIAMETER	ROUND 28'-0" DIAMETER	NONE	RING COLLECTOR	N/A
KENTUCKY UTILITIES	GHENT	1	N/A	N/A	INTERNAL GUTTERS AND DRAINS	N/A	N/A	2	125 DEGREES APART	40'-0" / 40'-0"	17'-10" / 11'-4"	NONE	GUTTERS	N/A
LOUISVILLE GAS & ELECTRIC	CANE RUN	4	4-89	NO SEVERE INDICATIONS FOUND	DRAIN	N/A	2	2	VERTICAL	18'-5 1/2"	9'-0"	NDA	DRAINS	NDA
LOUISVILLE GAS & ELECTRIC	CANE RUN	5	4-91	NO SEVERE INDICATIONS FOUND	DRAIN	NDA	2	2	VERTICAL	21'-0"	9'-0"	NDA	DRAINS	NDA
LOUISVILLE GAS & ELECTRIC	CANE RUN	6	4-92	NO SEVERE INDICATIONS	DRAIN	NDA	2	1	VERTICAL	26'-0"	8'-0"	NDA	DRAINS	NDA
LOUISVILLE GAS & ELECTRIC	TRIMBLE COUNTY	1	10-93	EXCELLENT FOR 3 YEARS OF OPERATION	GUTTERS AT BOTTOM OF LINER	N/A	N/A	1	SIDE INLET 160 FT ABOVE GRADE	ROUND 18'-0" DIAMETER	ROUND 18'-0" DIAMETER	YES	TRENCHES	STILL IN GOOD SHAPE
MICHIGAN SOUTH CENTRAL POWER AGENCY	ENDICOTT	1	10-22-93	GOOD	C22 TROUGH OVER INLET DUCT. C22 SLPD FLR DRN	N/A	N/A	2	FROM SIDE, HORIZONTAL	10'-0" 10'-0" (BYPASS)	7'-6" 5'-3" (BYPASS)	N/A	C22 BYPASS DUCT DRAIN TROUGH	GOOD
MINNESOTA POWER AND LIGHT CO	SYL LASKIN	1,2	9-93	GOOD	NONE	N/A	N/A	2	180 DEG, OPPOSING	6'-0"	12'-0"	YES, AT 90 DEG TURN INTO STACK	BACK END OF SCRUBBER M.E.	GOOD REPLACED IN 1993
MINNESOTA POWER AND LIGHT CO	BOSWELL	3	EXTERNAL SUMMER 1993	INTACT - SFTY STRAPS INSTALLED	SCUPPER DRAIN SYSTEM	N/A	N/A	2	180 DEGREES	31'-6"	15'-0"	N/A	DRAINS IN DUCT	GOOD

Conversions: 1 inch = 0.0254 m, 1 ft = 0.3048 m

TABLE C–1

WET STACK SURVEY DATA

UTILITY	STATION	UNIT	NUMBER OF ANNULUS PRESSURIZATION FANS	ANNULUS PRESSURE (IN H2O)	MIST ELIMINATOR TYPE	MIST ELIMINATOR MANUFACTURER	M.E. LOCATION IN DUCT OR ABSORBER	OFF–LINE CLEANING SCHEDULE AND PLUGGAGE HISTORY	CORRECTIVE MEASURES TAKEN: NEW OR MODIFIED	ABSORBER	PRECIPITATOR OR BAGHOUSE	NUMBER OF ABSORBERS	NUMBER OF PRECIPITATORS OR BAGHOUSES
ALLEGHENY POWER SERVICE COOP	HARRISON	1,2,3	0	N/A	FLEXICHEVRON STYLE VII–3–1.5	KOCH ENGINEERING	TOP OF ABSORBER VESSEL	NEW	N/A	GEESI VERT FLOW, WET MAGNESIUM ENHANCED	PRECIPITATOR	1 PER UNIT	2 PER UNIT
ALLEGHENY POWER SERVICE COOP	MITCHELL	3	0	ANNULUS VENTILATION ONLY	CHEVRON	MUNTERS MODEL T276	ABSORBER OUTLET	UNKNOWN	N/A	YES	PRECIPITATOR	3	2 (SERIES)
AMERICAN ELECTRIC POWER	GAVIN	1,2	2	NDA	NDA	NDA	ABSORBER	N/A	N/A	YES	YES	6	NDA
ARIZONA PUBLIC SERVICE	FOUR CORNERS	1,2	2	0.25	CHEVRON STACKED 4 SINGLE PASS	FIBERGLASS CO PER APS SPEC	SEE COMMENTS	NEVER; CHEMICALLY CONTROLLED	ADDED NA2S204	CHEMICO VARIABLE VENTURI	N/A	2 EACH U1 2 EACH U2	NONE
BIG RIVERS ELECTRIC CORPORATION	GREEN	1	0	UNKNOWN	VERTICAL FLOW CHEVRON	MUNTERS	TOP OF ABSORBS VERTICAL FLOW	ONCE A YEAR DURING ANNUAL OUTAGE	N/A	VERTICAL SPRAY TOWER	PRECIPITATOR	2 60 %	2 50 %
BIG RIVERS ELECTRIC CORPORATION	GREEN	2	0	UNKNOWN	VERTICAL FLOW CHEVRON	MUNTERS	TOP OF ABSORBS VERTICAL FLOW	ONCE A YEAR DURING ANNUAL OUTAGE	N/A	VERTICAL SPRAY TOWER	PRECIPITATOR	2 60 %	2 50 %
BIG RIVERS ELECTRIC CORPORATION	WILSON	1	1 (ONE SPARE)	UNKNOWN	HORIZONTAL FLOW CHEVRON	MUNTERS NARYL	BACK OF ABSORBER HOR FLOW	EACH ABSORBER ONCE A MONTH	MODIFIED WASH NOZZLES, WATER QUALITY	HORIZONTAL FLOW WEIR TYPE SPRAY	PRECIPITATOR	4 33 %	2 50 %
CENTRAL ILLINOIS LIGHT CO.	DUCK CREEK	1	0	N/A	N/A	N/A	N/A	N/A	N/A	RILEY STOKER SCRUBBER	PRECIPITATOR	4 MODULES	1
CENTRAL ILLINOIS PUBLIC SERVICE	NEWTON	1	NDA	NDA	NDA	NDA	NDA	NDA	NDA	DUAL ALKALI SYST. 1 PRECOOLER. 1 MODULE/ABSRBER	ELECTROSTATIC PRECIPITATOR	4	1 PRECIPITATOR WITH 2 SECTIONS
CINCINNATI GAS & ELECTRIC CO.	ZIMMER	1	2	2	FULL CONE	SPRAYING SYSTEMS	IN EACH OF THE 4 QUADRANTS IN THE ABSORBER	CLEANED EVERY 16 DAYS NO PLUGGAGE	THEY WILL MODIFY THIS YEAR	N/A	PRECIPITATOR	0	2
DESERET GENERATION AND TRANSMISSION COOP	BONANZA	1	2	1.5 – 2.0	1 LEVEL BULK ENTRAIN. SEPAR 2 LEVELS CHEV	NOT AVAILABLE	IN ABSORBER	CLEAN EVERY 4–6 MONTHS	N/A	N/A	ECOLAIRE BAGHOUSE	3 50% MODULES	2 BAGHOUSES
DUQUESNE LIGHT CO	ELRAMA	1–4	2	RANGE – 2 TO 4	CHEVRON	G.E.	INT ON SCRBBR AND EXT IN THEIR OWN VESSEL	ONCE PER YEAR	N/A	CHEMICO – VENTURI TYPE	MECHANICAL COLLECTOR AND ELECT PRECIP	(5) (4 FOR FULL LOAD)	(4) (1 PER BOILER)
HENDERSON MUNICIPAL UTILITIES	HENDERSON STATION TWO	1,2	2	3.75	VERTICAL CHEVRON	WHEELABRATOR AIR POLLUTION CONTROL	ABSORBER OUTLET	N/A	N/A	COUNTERCURRENT VERTICAL SPRAY TOWER	PRECIPITATOR	1 PER UNIT	1 PER UNIT
INDIANAPOLIS POWER & LIGHT	PETERSBURG	1,2	2 – 100% CAPACITY	NDA	2 STAGE CHEVRN VIII–2–1.5/ VIII–3–1.5	KOCH	ABSORBER	N/A	N/A	OPEN WET LIMESTONE SPRAY TOWER	PRECIPITATOR	1 PER UNIT	2 SETS IN SERIES 2 BOXES/SET
INTERMOUNTAIN POWER PROJECT	INTERMOUNTAIN POWER GENERATING STATION	1,2	N/A	N/A	4 PASS OPEN CHEVRON	GEESI	ABOVE RECYCLE SPRAYERS IN ABSORBER	NO PLUGGING	ME WASH SYSTM IS EXCELLENT, SEE COMMENTS	GEESI FGD WET LIMESTONE	GEESI BAGHOUSE	6 PER BOILER	1 PER BOILER
KENTUCKY UTILITIES	GHENT	1	2 @ 100%	10	FLEXI CHEVRON	KOCH	ABSORBER TOP VERTICAL FLOW	N/A	N/A	FORCED OXIDATION LIMESTONE TRAY TOWER	PRECIPITATOR	3 @ 50%	2 @ 50%
LOUISVILLE GAS & ELECTRIC	CANE RUN	4	0	N/A	NDA	KOCH	ABSORBER	NDA	BIGGER CONE NOZZLES	WET SPRAY TOWER	ELECTROSTATIC COLLECTION PLATES	2	1 PRECIPITATOR (2 SIDES)
LOUISVILLE GAS & ELECTRIC	CANE RUN	5	0	N/A	NDA	KOCH	ABSORBER	NDA	NDA	WET SPRAY TOWER	PRECIPITATOR COLLECTION PLATES	2	1 PRECIPITATOR (2 SIDES)
LOUISVILLE GAS & ELECTRIC	CANE RUN	6	0	N/A	NDA	KOCH	ABSORBER	NDA	NDA	2	PRECIPITATOR COLLECTION PLATES	2	1 PRECIPITATOR (2 SIDES)
LOUISVILLE GAS & ELECTRIC	TRIMBLE COUNTY	1	0	ATMOSPHERIC	CHEVRON 317 LM	ABB/CE	UPPER ABSORBER AREA	WASH ONCE PER DAY – NO PROBLEMS	N/A	VERTICAL WET LIMESTONE COUNTER CURRENT	PRECIPITATOR ABB/CE	4 TOTAL 3 IN USE	4 SECTIONS 5 FIELDS DEEP
MICHIGAN SOUTH CENTRAL POWER AGENCY	ENDICOTT	1	0	N/A	CHEVRON 2 LEVEL, 4 PASS POLYURETHANE	POLLY MANUFACTURING	TOP OF ABSORBERS	SEMI–ANNUAL CLEANING *	SEE COMMENTS	B&W VERT FLOW WET LIMESTONE	PRECIPITATOR	1	1
MINNESOTA POWER AND LIGHT CO	SYL LASKIN	1,2	0	NATURAL DRAFT	CHEVRON	KREBS ENGINEERING	OUTLET PRIOR TO BREECHING INTO STACK	INSPECT EVERY 3 MONTHS	N/A	KREBS ELBAIR	NONE	2	NONE
MINNESOTA POWER AND LIGHT CO	BOSWELL	3	3 FANS – FRESH AIR ONLY	ATMOSPHERIC	PUNCH PLATE AND ZIG ZAG TYPE	KREBS ELBAIR	LOCATED IN SCRUBBER	TWICE PER YEAR, INFREQUENT PLUGGAGE	N/A	VENTURI	BAGHOUSE ON UNITS 1 & 2	1	2

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TABLE C–1

WET STACK SURVEY DATA

UTILITY	STATION	UNIT	NUMBER OF ANNULUS PRESSURIZATION FANS	ANNULUS PRESSURE (IN H2O)	MIST ELIMINATOR TYPE	MIST ELIMINATOR MANUFACTURER	M.E. LOCATION IN DUCT OR ABSORBER	OFF–LINE CLEANING SCHEDULE AND PLUGGAGE HISTORY	CORRECTIVE MEASURES TAKEN: NEW OR MODIFIED	ABSORBER	PRECIPITATOR OR BAGHOUSE	NUMBER OF ABSORBERS	NUMBER OF PRECIPITATORS OR BAGHOUSES
NEW YORK STATE ELEC. & GAS CORP.	KINTIGH	1	2	5	CHEVRON 2 STAGE–2 PASS VERTICAL FLOW	PEABODY / ABB (PPSI)	TOP OF ABSORBER	3 MONTH CYCLE	NONE	COUNTER – CURRENT UP FLOW RUBBER LINED C.S.	ELECTROSTATIC PRECIPITATOR	6 @ 25% EACH	2 @ 50% EACH
NEW YORK STATE ELEC. & GAS CORP.	MILLIKEN	1,2	0	N/A	CHEVRON	MUNTERS DV210 DV2130 – UNIT 1 T–271 – UNIT 2	IN ABSORBER (LOCATION PROPRIETORY)	NEW	N/A	YES	PRECIPITATOR	2 TOTAL (1 PER UNIT	2 TOTAL (1 PER UNIT
NORTHERN INDIANA PUBLIC SERVICE	BAILLY	7,8	2 40 HP	NDA	HORIZONTAL	NDA	ABSORBER OUTLET	WASHED DAILY ON–LINE; NO FORCED OUTAGE	N/A	PURE AIR	PRECIPITATOR	1	UNIT 7 – 1 UNIT 8 – 2
OLD DOMINION ELECT COOPERATIVE/ VIRGINIA POWER	CLOVER	1,2	N/A	N/A	FRP CHEVRON 2 STAGE 2 PASS	ABB/CE	TOP OF ABSORBER	N/A	N/A	WET LIMESTONE COUNTER CURRENT VERT SPRAY TWR	BAGHOUSE	3 TOWERS PER UNIT	1 PER UNIT
ORLANDO UTILITIES COMMISSION	STANTON ENERGY	1,2	2	4.5	3 STG, 2 PASS 2 CHEV; 1 PASS 1 @ 45 DEG	ABB / MMFG	TOP OF VERT SPRAY TOWER	6–9 MOS, MOD–SEV PLUGGAGE REPL 6–7 YRS	ADD SUPPORTS TO REDUCE BUCKLING	CE (ABB) WET LIMESTONE	PRECIPITATOR WHEELABRATOR	3 2 IN SERVICE	1
OWENSBORO MUNICIPAL UTILITIES	ELMER SMITH	1,2	2	1.8	HORIZONTAL 3 PASS	WHEELABRATOR AIR POLLUTION CONTROL	ABSORBER	NDA	NDA	2 MODULES OPEN SPRAY TOWERS	COLD SIDE PRECIPITOR FOR EACH UNIT	2	2
PACIFICORP	DAVE JOHNSTON	4	0	N/A	STAINLESS STEEL	MUNTERS	BOTTOM (DOWNWARD FLOW)	NO PROBLEMS LATELY	OLD M.E. WAS PLASTIC. HAD PROBLEMS	VENTURI PARTICULATE SCRUBBER	NONE	3 VESSELS	NONE
PACIFICORP	HUNTER	2	2	10.0 APPROX	CHEVRON	CHEMICO	UPPER ABSORBER	VERY LITTLE LINED	N/A	N/A	PRECIPITATOR COOLSIDE	4	2
PACIFICORP	JIM BRIDGER	4	2	5.0 – 10.0 APPROX	CHEVRON	UNIVERSAL OIL PRODUCTS	TOP	NO PROBLEMS	N/A	TRAY TYPE UOP	PRECIPITATOR COOLSIDE FLAKT	3	1 ESP W/ 6 GAS BYPASS
PACIFICORP	NAUGHTON	3	2	3.5 – 4	CHEVRON UPPER IS 3 PASS LOWER IS 4 PASS	UPPER ARE UOP LOWER ARE MUNTER	NEAR OUTLET OF ABSORBERS	NORMALLY ONCE A YEAR	LOWER SET UPGRADED TO STAINLESS	U.O.P. NON REGENERATIVE WET SODIUM	BUELL PRECIP.	2	1
PENNSYLVANIA ELECTRIC	CONEMAUGH	1,2	N/A	N/A	2 STAGE MULTI–PASS CHEVRON STYLE	ABB ENVIRONMENTAL SYSTEMS	ABSORBERS	NEW 12/94, NONE THUS FAR	N/A	COUNTER CURRENT OPEN SPRAY TOWERS	WEIGHTED WIRE ELECTROSTATIC PRECIPITATOR	2 PER UNIT WITH SHARED SPARE	2 PER UNIT
PENNSYLVANIA POWER CO.	BRUCE MANSFIELD	1,2	0	0	VERTICAL FLOW	MUNTERS T–272	ABSORBER	EVERY 3 MNTHS.	REPLACED IN '86 OR '87.	VENTURI	NONE	1 SCRUBBER, ABSORBER 6 TRAINS	0
PENNSYLVANIA POWER CO.	BRUCE MANSFIELD	3	0	0	HORIZONTAL FLOW	MUNTERS T–135	ABSORBER	EVERY 3 MNTHS.	REPLACED IN '84	HORIZONTAL WEIR	PRECIPITATOR	5	4
PLAINS ELECTRIC GENERATION AND TRANSMISSION COOP	ESCALANTE	1	2	1.6	CHEVRON	COMBUSTION ENGINEERING	ABSORBER	CLEANED APPROX 4–5 MONTHS	N/A	VERTICAL, CNTR–CURRENT, SPRAY CONTACTOR	BAGHOUSE	3	2
SEMINOLE ELECTRIC COOP	SEMINOLE	1,2 (IDENTICAL OPP UNITS)	2	1.3 – 1.5	1ST STG 2 BND 2ND STG 4 BND CHEVRON	PEABODY ABB	TOP 20% OF BEND	CLEANED EVERY 5–8 WEEKS	MODIFY SUMMER '95	PEABODY PROCESS, INC	PRECIPITATOR	5 PER UNIT	2 PER UNIT
SIKESTON MUNICIPAL UTILITIES	SIKESTON	1	0	N/A	2 PASS 2 STAGES CHEVRON	B&W	ABSORBER	MINIMUM	NOT NEEDED EXCELLENT SYSTEM	WET LIMESTONE	PRECIP. ELECT.	3 AT 60%	1
SOUTHERN ILLINOIS POWER CO–OPERATIVE	MARION	4	2	N/A	CHEVRON TYPE WITH PREWASH TRAY	1 STAGE (3 PASS/STAGE) 1.5" APART	4' ABOVE LAST TRAY	6 MONTH OUTAGE	REPLACE OLD WITH NEW SAME DESIGN	TRAY TOWER	PRECIPITATOR	2 (20'x 20'x 35')	1
SOUTHERN INDIANA GAS AND ELECTRIC	A B BROWN	1	1	5.0 – 6.0	4 PASS	ABB FLAKT	HORIZONTAL ACROSS TOP OF ABSORBER	2 X /YR NO PLUGGAGE	N/A	FMC DUAL ALKALI	PRECIPITATOR BUELL	2	2
SOUTHERN INDIANA GAS AND ELECTRIC	A B BROWN	2	2	6.0	NDA	WATSON	HORIZONTAL ACROSS TOP OF ABSORBER	2 X /YR NO PLUGGAGE	N/A	FMC DUAL ALKALI	PRECIPITATOR BUELL	2	2
SOUTHERN INDIANA GAS AND ELECTRIC	CULLEY	2,3	2	6.3	2 STAGE HORIZONTAL & VERTICAL	MUNTERS	ABSORBER	NDA	NDA	WET LIMESTONE SCRUBBER	PRECIPITATOR	1	2
CITY OF SPRINGFIELD	SOUTHWEST	1	1 TO 2	5.5	CHEVRON 3 PASS BOT 4 PASS TOP	WHEELABRATOR	HORIZONTAL JUST BELOW OUTLET	3 TIMES/YR (BEFORE MODIFICATION)	MODIFIED BY INCLINING 20 DEG	UOP, NOW WAPC TRAY	PRECIPITATOR	2	1
TENNESSEE VALLEY AUTHORITY	CUMBERLAND	1,2	0	0	2 STAGES CHEVRONS 2 PASS & 4 PASS	ABB	HORIZONTAL, VERTICAL GAS FLOW	N/A	N/A	LIMESTONE SPRAY TOWER	PRECIPITATOR	3 – 50% MODULES PER UNIT	6 PRECIPITATORS
TENNESSEE VALLEY AUTHORITY	PARADISE	1,2	2 PLUS 1 SPARE	2	2 PASS CHEVRONS	CEILCOTE / TVA	HORIZONTAL DUCT	EVERY 12 WEEKS AS REQUIRED	NDA	WET LIMESTONE VENTURI SPRAY TOWER	PRECIPITATOR	5 + 1 SPARE	4

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TABLE C–1

WET STACK SURVEY DATA

UTILITY	STATION	UNIT	FLOW RATE: 100 % FLOW CONDITION (ACFM)	ABSORBER OUTLET TEMPERATURE (DEG F)	FULL LOAD STACK TEMPERATURE (DEG F)	FULL LOAD STACK PRESSURE (IN H20)	SO2 CONTENT OF FLUE GAS (PPM)	O2 CONTENT OF FLUE GAS (%)	MOISTURE CONTENT (%)	SULFUR CONTENT OF COAL (%)	DOWNWASH ELEVATION CHANGE (FEET)	DOWNWASH FREQUENCY OF OCCURRENCE (%)	DOWNWASH EFFECT AMBIENT CONDITIONS HAVE ON
ALLEGHENY POWER SERVICE COOP	HARRISON	1,2,3	1,817,189	119	119	14.25 PSIA	865 #/HR	442,159 #/HR	523,053 #/HR	3.5 BURNED	NEW UNITS	NEW UNITS	NEW UNITS
ALLEGHENY POWER SERVICE COOP	MITCHELL	3	950,000 @ STACK INLET	125 – 130	125 – 130	SLIGHTLY NEGATIVE	354 #/HR	215,000 #/HR	340,000 #/HR	2.6	N/A	N/A	N/A
AMERICAN ELECTRIC POWER	GAVIN	1,2	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA
ARIZONA PUBLIC SERVICE	FOUR CORNERS	1,2	480,000 (TWO TRAINS)	120	120	1.3 – 1.4	700	5.0	SUPERSATUR DOWNSTREAM VENTURI SCRUB	0.7 – 1.1	N/A	N/A	N/A
BIG RIVERS ELECTRIC CORPORATION	GREEN	1	1,000,000 @ 300 DEG F	126	125	0.5	6.4 LBS PER MILLION BTU	7.0	SATURATED	3.8	N/A	N/A	N/A
BIG RIVERS ELECTRIC CORPORATION	GREEN	2	1,000,000 @ 300 DEG F	126	125	0.5	6.4 LBS PER MILLION BTU	7.0	SATURATED	3.8	N/A	N/A	N/A
BIG RIVERS ELECTRIC CORPORATION	WILSON	1	1,528,120 TO 3 MODULES	125	124	2.45	5.6 LBS PER MILLION BTU	5.5 @ ABSORBER INLET	SATURATED	3.1	N/A	N/A	N/A
CENTRAL ILLINOIS LIGHT CO.	DUCK CREEK	1	1,005,000	135	135	–0.1	350	10.0	16.4	3.25	N/A	N/A	N/A
CENTRAL ILLINOIS PUBLIC SERVICE	NEWTON	1	1,600,000	125	125	NDA	70	2.5	SUPER– SATURATED GAS STREAMS	2.5 – 3.0	NDA	NDA	NDA
CINCINNATI GAS & ELECTRIC CO.	ZIMMER	1	2,590,000	130	130	–8.05	5.37	6.34	3.69	3	N/A	N/A	N/A
DESERET GENERATION AND TRANSMISSION COOP	BONANZA	1	1,175,000 – 2,000,000	120 – 122	120 – 122	+0.1 (24.9 IN Hg ABSOLUTE)	18–20	CO2 CONTENT 11.4 – 11.8	14.5	0.45	N/A	N/A	N/A
DUQUESNE LIGHT CO	ELRAMA	1–4	541,000 PER ABSORBER)	130	120	+1	80	8	100+	APPROX 1.8	N/A	N/A	LONG OR SHORT PLUME
HENDERSON MUNICIPAL UTILITIES	HENDERSON STATION TWO	1,2	745,000 DESIGN	135 ANTICIPATED	UNKNOWN	UNKNOWN	DATA NOT AVAILABLE	DATA NOT AVAILABLE	4.77 DESIGN	4.25 DESIGN	N/A	N/A	N/A
INDIANAPOLIS POWER & LIGHT	PETERSBURG	1,2	#1 – 990,000 #2 – 1,830,000	125	125	2.0	WILL VARY 4 TO 24 PPMVD H2SO4/SO3	9.3 (VOLUME, DRY BASIS)	12.8 (VOLUME, WET BASIS)	NDA	N/A	N/A	N/A
INTERMOUNTAIN POWER PROJECT	INTERMOUNTAIN POWER GENERATING STATION	1,2	2,590,000	118	117	1.5	60	5.5	SATURATED	0.6	N/A	N/A	N/A
KENTUCKY UTILITIES	GHENT	1	1,800,000	128	128	2	250 PPMV	2.5	4.7% BY WEIGHT	5.67 LB SO2 PER MILLN BTU UPPER	N/A	N/A	N/A
LOUISVILLE GAS & ELECTRIC	CANE RUN	4	595,410	132	NDA	NDA	< 1.2 LBS PER MILLION BTU	9	12.3	3	NDA	NDA	NDA
LOUISVILLE GAS & ELECTRIC	CANE RUN	5	695,211	126	NDA	NDA	< 1.2 LBS PER MILLION BTU	10.5	12.8	3	NDA	NDA	NDA
LOUISVILLE GAS & ELECTRIC	CANE RUN	6	854,109	136	NDA	NDA	< 1.2 LBS PER MILLION BTU	10.6	13.0	3	NDA	NDA	NDA
LOUISVILLE GAS & ELECTRIC	TRIMBLE COUNTY	1	1,687,479	NOT MEASURED	125	+ OR – 0.5	275	6.2	13.5 TO 14 SUPER SATURATED	2.95	N/A	N/A	N/A
MICHIGAN SOUTH CENTRAL POWER AGENCY	ENDICOTT	1	187,219	130	130	DATA UNAVAILABLE	240 (ABSORBER OUTLET)	8.5	7–15	3.5 – 5.0	N/A	N/A	N/A
MINNESOTA POWER AND LIGHT CO	SYL LASKIN	1,2	500,000	97 ON 10–93, 120–125 IN SUMMER	125–130	0.19	302	6.9	SATURATED	0.8 – 1.0	N/A	N/A	MORE PLUME AT –50 F VS +80 F
MINNESOTA POWER AND LIGHT CO	BOSWELL	3	1,995,829	128	130 – 140	–1.18	380 – 500	8	11 – 12	0.65	NDA	NDA	NDA

Conversions: 1 inch = 0.0254 m, 1 ft = 0.3048 m

TABLE C–1

WET STACK SURVEY DATA

UTILITY	STATION	UNIT	FLOW RATE: 100 % FLOW CONDITION (ACFM)	ABSORBER OUTLET TEMPERATURE (DEG F)	FULL LOAD STACK TEMPERATURE (DEG F)	FULL LOAD STACK PRESSURE (IN H20)	SO2 CONTENT OF FLUE GAS (PPM)	O2 CONTENT OF FLUE GAS (%)	MOISTURE CONTENT (%)	SULFUR CONTENT OF COAL (%)	DOWNWASH ELEVATION CHANGE (FEET)	DOWNWASH FREQUENCY OF OCCURRENCE (%)	DOWNWASH EFFECT AMBIENT CONDITIONS HAVE ON
NEW YORK STATE ELEC. & GAS CORP.	KINTIGH	1	1,640,000	122	130	NEUTRAL	200	8	SATURATED	2.0 TO 3.0	N/A	N/A	N/A
NEW YORK STATE ELEC. & GAS CORP.	MILLIKEN	1,2	417,100	124	124	0.60 AT FLUE INLET	97	UNKNOWN	APPROX. 13% BY VOLUME	3.2	NDA	NDA	NDA
NORTHERN INDIANA PUBLIC SERVICE	BAILLY	7,8	1,730,000	NDA	NDA	NDA	NDA	NDA	NDA	3.O – 3.2	PLUME DIPS OCCASIONALLY BUT NO DNWSH	N/A	N/A
OLD DOMINION ELECT COOPERATIVE/ VIRGINIA POWER	CLOVER	1,2	1,388,600	121	120–130	NDA				0.5 – 2.0	N/A	N/A	N/A
ORLANDO UTILITIES COMMISSION	STANTON ENERGY	1,2	1,162,000	125 – 130	125 – 130	–2.4 (29.66 Hg ABS)	0.2 LB PER MILLION BTU	6.3	12	<1%	N/A	N/A	N/A
OWENSBORO MUNICIPAL UTILITIES	ELMER SMITH	1,2	1,864,000	NDA	NDA	NDA	50–150 PPM @ ABSORBER OUTLET	7.0–8.0	SATURATED AT ABSORBER OUTLET	4.2–5.8 LB PER MILLN BTU	N/A	N/A	N/A
PACIFICORP	DAVE JOHNSTON	4	1,240,000	125 – 130	125 – 130	–1 TO +3	1.15 LBS PER MILLION BTU	3	SATURATED	0.5	N/A	N/A	N/A
PACIFICORP	HUNTER	2	1,769,000	262 @ 11.4 PSIA	118	+3.0 @ SCRUBBER OUTLET	632 DRY	5.0 – 6.0	SATURATED 9% BY VOL DRY SIDE	0.50	N/A	N/A	N/A
PACIFICORP	JIM BRIDGER	4	2,750,000 @ 250 DEG F	120 (SOME BYPASS)	126	–3.0 TO +3.0	0.2 LB/MILL BTU @ 91% EFFICIENCY	5.0 – 6.0	SATURATED 11% BY VOL DRY SIDE	0.65	N/A	N/A	N/A
PACIFICORP	NAUGHTON	3	1,500,000	120	120	DATA UNAVAILABLE	0.350 TO 0.480 LB PER MILLION BTU	5	BY WEIGHT NORMALLY 9% AS DESIGNED	.75 DESIGN APPROX .9 ACTUAL	N/A	N/A	N/A
PENNSYLVANIA ELECTRIC	CONEMAUGH	1,2	2,700,000	122	120	1.0 AT BREECHING	1800 #/HR MAXIMUM	700,000 #/HR MAXIMUM	350 #/HR MAXIMUM	2.25 LB PER MILLN BTU	VARIES FROM 0' TO 200' VERTICALLY	DEPENDS ON WIND SPEED; VARIES CONTINUALLY	WIND SPEED ON PLUME DISCH & RISE
PENNSYLVANIA POWER CO.	BRUCE MANSFIELD	1,2	1,305,000 PER FLUE. 2 FLUES PER UNIT	130	130	2	<100	5	15 TO 20	3.5 TO 4	N/A	N/A	N/A
PENNSYLVANIA POWER CO.	BRUCE MANSFIELD	3	1,305,000 PER FLUE	130	130	3	<100	5	15	3.5 TO 4	N/A	N/A	N/A
PLAINS ELECTRIC GENERATION AND TRANSMISSION COOP	ESCALANTE	1	1,320,000	124.5 – 350	125	0.5	41 (ABSORBER OUTLET)	6.5 STACK 3.1 BOILER	UNKNOWN	0.6 – 0.8	N/A	N/A	N/A
SEMINOLE ELECTRIC COOP	SEMINOLE	1,2 (IDENTICAL OPP UNITS)	2,000,000	120 – 125	120 – 125	DATA UNAVAILABLE	280 (IN STACK)]	4.8 (BY VOLUME)	13.2 (BY VOLUME)	2.0 – 3.0	15 – 20	75% OF TIME	LESS DOWN–WASH ON WARM DAY
SIKESTON MUNICIPAL UTILITIES	SIKESTON	1	591,825	130 WET 280 DRY	130 WET 280 DRY	–1	1800 DRY 240 WET	7	6 DRY 15 WET	3	N/A	N/A	N/A
SOUTHERN ILLINOIS POWER CO–OPERATIVE	MARION	4	296,000	130	130	2.4" (DUCT TO TOP STACK)	1.2 LBS PER MILLION BTU	8	SAT VAPOR 13%	2–4	N/A	NOT A PROBLEM	N/A
SOUTHERN INDIANA GAS AND ELECTRIC	A B BROWN	1	840,000	125	130	2.1	1511 #/HR	3.8	9.3	3.5 – 4.0	N/A	N/A	N/A
SOUTHERN INDIANA GAS AND ELECTRIC	A B BROWN	2	840,000	136	UNKOWN	1.7	1015 #/HR	6.52	10.85	3.5 – 4.0	N/A	N/A	N/A
SOUTHERN INDIANA GAS AND ELECTRIC	CULLEY	2,3	1,383,478	128	128	1.0	115	7.2	14.2	#1 3.01 #2 3.02 #3 3.75	N/A	N/A	N/A
CITY OF SPRINGFIELD	SOUTHWEST	1	750,000	110	110	2.0 TO 3.0	200	6.0 TO 7.0	SATURATED	2.0 – 2.5	N/A	N/A	N/A
TENNESSEE VALLEY AUTHORITY	CUMBERLAND	1,2	4,100,000	125	125	ATMOSPHERIC TO 1"	90	6.5	13.5	2.8	N/A	N/A	N/A
TENNESSEE VALLEY AUTHORITY	PARADISE	1,2	2,100,000	125	135	ATMOSPHERIC	300 – 275	6 – 8	12	2.8	N/A	N/A	N/A

Conversions: 1 acfm = 472 cm^3/s, °F = 1.8x°C+32, 1 inch water = 0.249 kPa, 1 ft = 0.3048 m,

TABLE C-1

WET STACK SURVEY DATA

UTILITY	STATION	UNIT	DOWNWASH EFFECT OPERATING CONDITIONS HAVE ON	DOWNWASH CONSEQUENCES OF	STACK DROPLET DISCHARGE QUANTITY	STACK DROPLET FREQUENCY	STACK DROPLET EFFECT OF AMBIENT CONDITIONS	STACK DROPLET EFFECT OF OPERATING CONDITIONS	LOCATION OF FALLOUT	SIZE OF DROPLET FALLOUT	CONSEQUENCES OF DROPLET DISCHARGE	COMMENTS
ALLEGHENY POWER SERVICE COOP	HARRISON	1,2,3	NEW UNITS	NEW UNITS	NEW UNITS	NEW UNITS	NEW UNITS	NEW UNITS	NEW UNITS	NEW UNITS	NEW UNITS	3 IDENTICAL UNITS WITH COMMON STACK SHELL AND SEPARATE LINERS;
ALLEGHENY POWER SERVICE COOP	MITCHELL	3	N/A	N/A	UNMEASUR-ABLE	VERY INFREQUENT	N/A	N/A	N/A	N/A	N/A	UNITS 2 & 3 SHARE COMMON STACK WITH COMMON LINER
AMERICAN ELECTRIC POWER	GAVIN	1,2	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NEW SCRUBBERS NOT IN OPERATION
ARIZONA PUBLIC SERVICE	FOUR CORNERS	1,2	N/A	N/A	NDA	NDA	INCREASE AS AMBIENT TEMP DROPS	NONE	DOWNWIND APPROX 250'	NDA	CORROSION STRUCT STEEL, SHT MTL ROOFS	M.E.'S: ABSORBER AFTER 180 DEG FLUE GAS TURNAROUND AFTER I.D. FANS IN DUCT
BIG RIVERS ELECTRIC CORPORATION	GREEN	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
BIG RIVERS ELECTRIC CORPORATION	GREEN	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
BIG RIVERS ELECTRIC CORPORATION	WILSON	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
CENTRAL ILLINOIS LIGHT CO.	DUCK CREEK	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
CENTRAL ILLINOIS PUBLIC SERVICE	NEWTON	1	NDA	NDA	LARGE	CONTINUOUS	FALL CLOSER TO STACK W/ LOW TEMPS	MORE GAS FLOW, MORE DISCHARGE.	FROM STACK DOWNWIND APPROX 1/2 MI	VARIOUS	SALT DEPOSITION AND STAINING	
CINCINNATI GAS & ELECTRIC CO.	ZIMMER	1	N/A	N/A	LIGHT MISTING	TWICE PER YEAR	NDA	NDA	WITHIN 300 YD RADIUS	MIST	THEY PROVIDE A RINSE STATION FOR CARS	
DESERET GENERATION AND TRANSMISSION COOP	BONANZA	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	APPROX GRADE EL. 5028'-0"
DUQUESNE LIGHT CO	ELRAMA	1-4	N/A	N/A	UNMEASURED	INTERMITTENT	N/A	LITTLE	60 FT AROUND STACK	1/8" MAX	FEW - PARKING LOT TOO FAR	
HENDERSON MUNICIPAL UTILITIES	HENDERSON STATION TWO	1,2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	IDENTICAL UNITS WITH COMMON STACK
INDIANAPOLIS POWER & LIGHT	PETERSBURG	1,2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	IN SERVICE MAY '96
INTERMOUNTAIN POWER PROJECT	INTERMOUNTAIN POWER GENERATING STATION	1,2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	REPLACED EXISTING ME's WITH MUNTERS MODEL 8801-1.35; 2-PASS SINUSOIDAL
KENTUCKY UTILITIES	GHENT	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	SCHEDULED FOR STARTUP 11-94
LOUISVILLE GAS & ELECTRIC	CANE RUN	4	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	
LOUISVILLE GAS & ELECTRIC	CANE RUN	5	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	
LOUISVILLE GAS & ELECTRIC	CANE RUN	6	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	
LOUISVILLE GAS & ELECTRIC	TRIMBLE COUNTY	1	N/A	N/A	SOME RAIN MOSTLY FROM COOLING TWR	NDA	TEMPERATURE AND HUMIDITY	NDA	LOCALIZED	MISTING	NONE (OUT IN COUNTRY)	STACK HAS 2 LINERS. ONLY 1 IS USED UNIT 2 IS NOT IN OPERATION
MICHIGAN SOUTH CENTRAL POWER AGENCY	ENDICOTT	1	N/A	N/A	VERY SPARSE	VERY RARELY	NDA	NDA	GENERALLY OFF SITE	FINE MIST	NDA	FREQUENTLY PLUGGED UNTIL PROCESS CONVERTED TO IN-SITU FORCED OXIDATION
MINNESOTA POWER AND LIGHT CO	SYL LASKIN	1,2	GAS FLOW AND LOAD	N/A	NO PROBLEMS	N/A	N/A	N/A	N/A	N/A	N/A	
MINNESOTA POWER AND LIGHT CO	BOSWELL	3	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	

Conversions: 1 acfm = 472 cm^3/s, °F = 1.8x°C+32, 1 inch water = 0.249 kPa, 1 ft = 0.3048 m,

TABLE C-1

WET STACK SURVEY DATA

UTILITY	STATION	UNIT	DOWNWASH EFFECT OPERATING CONDITIONS HAVE ON	DOWNWASH CONSEQUENCES OF	STACK DROPLET DISCHARGE QUANTITY	STACK DROPLET FREQUENCY	STACK DROPLET EFFECT OF AMBIENT CONDITIONS	STACK DROPLET EFFECT OF OPERATING CONDITIONS	LOCATION OF FALLOUT	SIZE OF DROPLET FALLOUT	CONSEQUENCES OF DROPLET DISCHARGE	COMMENTS
NEW YORK STATE ELEC. & GAS CORP.	KINTIGH	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
NEW YORK STATE ELEC. & GAS CORP.	MILLIKEN	1,2	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	UNIT 2 WILL BE IN SERVICE ON OR ABOUT 1/1/95 WITH UNIT 1 TO FOLLOW IN 6/95
NORTHERN INDIANA PUBLIC SERVICE	BAILLY	7,8	N/A	N/A	NONE	N/A	N/A	N/A	N/A	N/A	N/A	ACID RESISTANT BRICK LINER WITH SAUEREISEN NO. 65 MORTAR; CHOKE ALLOY C276
OLD DOMINION ELECT COOPERATIVE/ VIRGINIA POWER	CLOVER	1,2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	UNIT ONE DUE ON LINE 4-1-95 UNIT TWO DUE ON LINE 4-1-96
ORLANDO UTILITIES COMMISSION	STANTON ENERGY	1,2	N/A	N/A	0.003 LB/ 10X6 BTU (PARTICULATE)	N/A	N/A	N/A	N/A	N/A	N/A	UNIT 2 IDENTICAL TO UNIT 1; UNIT 2 ON-LINE 6-96; GRADE EL 82'-0 SEE QUEST. FOR ADD'L INFO.
OWENSBORO MUNICIPAL UTILITIES	ELMER SMITH	1,2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	UNITS 1 AND 2 SHARE COMMON STACK AND A COMMON LINER
PACIFICORP	DAVE JOHNSTON	4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	PLANT ELEVATION IS 4900 TO 5500 FEET
PACIFICORP	HUNTER	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	PERFORMED MODEL STUDY
PACIFICORP	JIM BRIDGER	4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	PERFORMED MODEL STUDY PLANT ELEVATION IS 6600 FEET
PACIFICORP	NAUGHTON	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
PENNSYLVANIA ELECTRIC	CONEMAUGH	1,2	NONE APPARENT	NO APPARENT PROBLEM	LIGHT, CLEAR DROPLETS; FALLOUT VARI	VARIES FROM SPORATIC TO NONE	COLD TEMP/ HIGH HUMIDITY INCR. FALLOUT	NO APPARENT EFFECT	WITHIN 1000' RADIUS OF STACK	UP TO 1/2" DIA OR MORE	NO APPARENT PROBLEMS; EVALUATING	
PENNSYLVANIA POWER CO.	BRUCE MANSFIELD	1,2	N/A	N.A	SPRINKLE TO VERY HEAVY RAIN	RAINS EVERYDAY SOMEWHERE AROUND PLANT	WIND DIR., HUMIDITY	HIGHER VELOCITY, HIGHER RAIN	MOST WITHIN 1/2 MILE	VARIES	WASH CARS, CLEAN HOUSES	
PENNSYLVANIA POWER CO.	BRUCE MANSFIELD	3	N/A	N/A	SPRINKLE TO VERY HEAVY RAIN	RAINS EVERYDAY SOMEWHERE AROUND PLANT	WIND DIR., HUMIDITY	HIGHER VELOCITY, HIGHER RAIN	MOST WITHIN 1/2 MILE	VARIES	WASH CARS, CLEAN HOUSES	
PLAINS ELECTRIC GENERATION AND TRANSMISSION COOP	ESCALANTE	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
SEMINOLE ELECTRIC COOP	SEMINOLE	1,2 (IDENTICAL OPP UNITS)	N/A	CORROSION	DIFFICULT TO QUANTIFY	N/A	N/A	N/A	N/A	N/A	CORROSION; DAMAGE TO CARS	BREECHING SPOOL PIECE LINED WITH C22 OR C276
SIKESTON MUNICIPAL UTILITIES	SIKESTON	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
SOUTHERN ILLINOIS POWER CO-OPERATIVE	MARION	4	N/A	N/A	LIGHT MISTING	YEAR ROUND	N/A	VERY LITTLE	500' RADIUS	1/8" TO 1/4"	RUINS CAR PAINT	THEY PROVIDED A PORTION OF THE LAST INSPECTION REPORT. MAJOR PROBLEMS WITH EXPANSION JOINT.
SOUTHERN INDIANA GAS AND ELECTRIC	A B BROWN	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
SOUTHERN INDIANA GAS AND ELECTRIC	A B BROWN	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
SOUTHERN INDIANA GAS AND ELECTRIC	CULLEY	2,3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
CITY OF SPRINGFIELD	SOUTHWEST	1	N/A	N/A	NON-MEASURABLE	NONE SINCE M.E. MODIFICATIONS	NONE HOT, MORE COLD	NDA	NDA	NDA	NDA	
TENNESSEE VALLEY AUTHORITY	CUMBERLAND	1,2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	UNIT 1 STARTUP 10/13/94 UNIT 2 SCHEDULED TO STARTUP IN DECEMBER
TENNESSEE VALLEY AUTHORITY	PARADISE	1,2	N/A	N/A	LOW DURING NORMAL OPERATION	NDA	NDA	COLD UNIT STARTUP AND FAN WASHING	WITHIN 100 YARDS OF STACK	NDA	NDA	

Conversions: 1 acfm = 472 cm^3/s, °F = 1.8x°C+32, 1 inch water = 0.249 kPa, 1 ft = 0.3048 m,

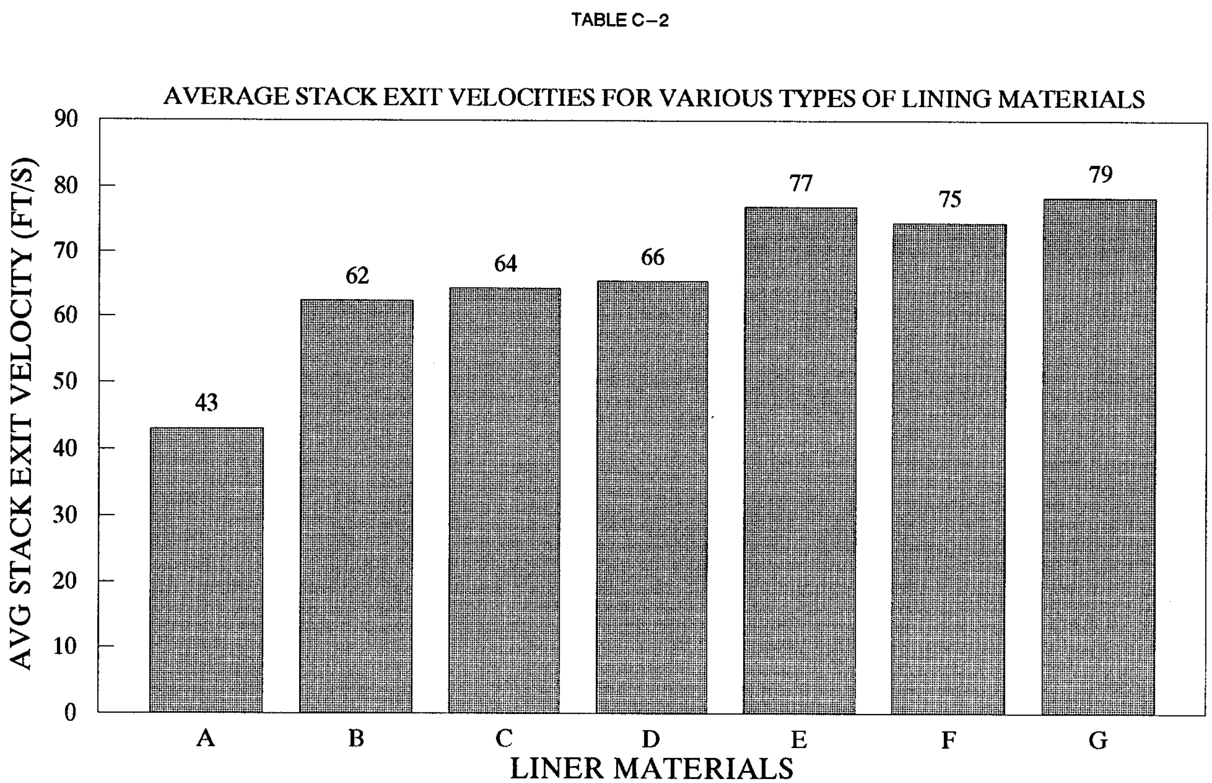
C.2 Average Stack Velocities for Various Types of Lining Materials

The stack exit velocity averages for various types of wet stack liners are shown in Table C-2. The exit velocities averages range from 43 ft/s (13 m/s) for Pennguard borosilicate glass block and polyester flake glass lined, carbon steel liners to 79 ft/s (24 m/s) for fibrecrete 214/222 lined, carbon steel liners. The stack exit velocities and the recommended stack liner velocities in Table 2-3 can be compared for constant diameter liners without a choke.

The wet stack industry survey indicates a total of 72 individual wet stack liners currently exist in the United States. Of these, data was collected on 68 of the liners. Of the 68 liners, 36 of them are constructed from acid resistant brick. The survey indicates that 12 liners are constructed out of Alloy 625 or Alloy C-276. The other four alloy liners use titanium. Only 11 of the 68 liners in the database use FRP or coated carbon steel liners.

The majority of the Phase I scrubber projects are currently under construction and do not yet have operating data available. Therefore, insufficient data exists which would allow any conclusions to be drawn concerning recommended stack exit velocities.

Table C-2



MATERIAL LEGEND
A – GLASS BLOCK LINED CARBON STEEL
B – NICKEL ALLOY WITH CARBON STEEL
C – ACID RESISTANT BRICK
D – COATED CARBON STEEL
E – TITANIUM CLAD CARBON STEEL
F – FIBERGLASS REINFORCED PLASTIC
G – FIBRECRETE 214/222 LINED CARBON STEEL

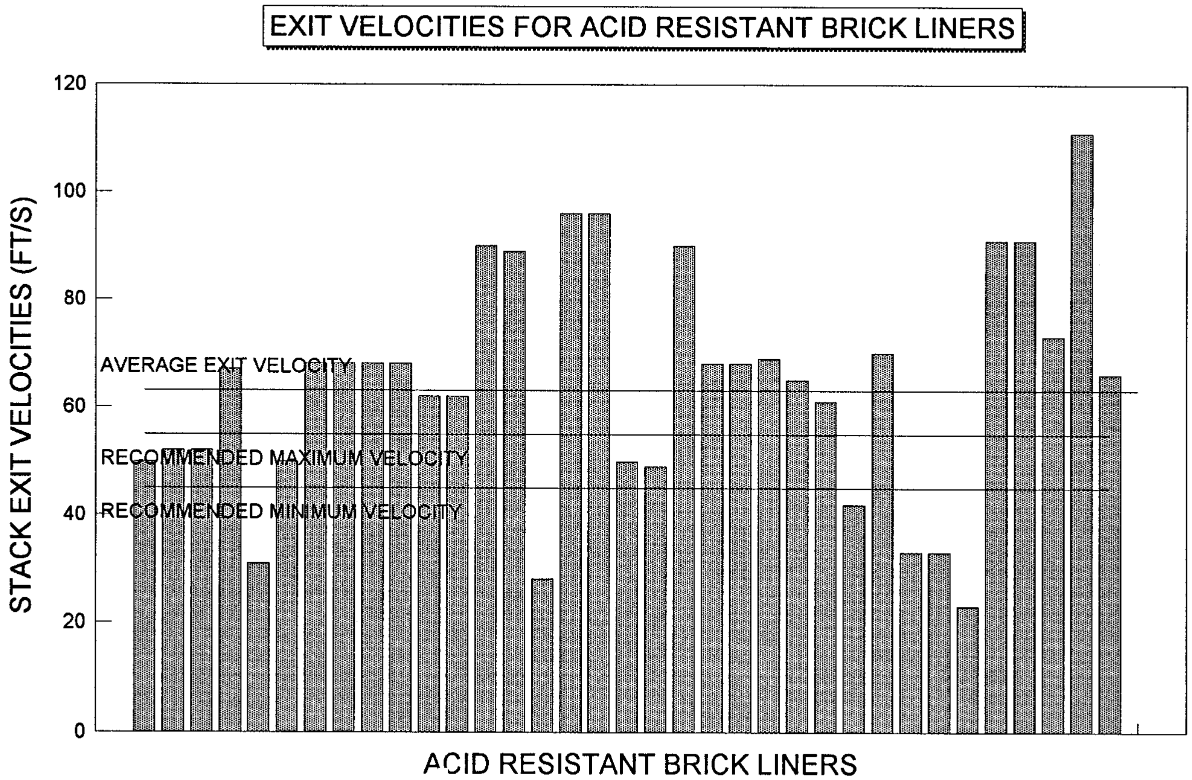
Conversions: 1 ft/s = 0.3048 m/s

C.3 Exit Velocities for Existing Acid Resistant Brick Liners

The stack exit velocity data for existing acid resistant brick liners as reported by the different utilities is shown graphically in Table C-3. Table C-3 also shows the range of maximum liner velocities recommended for new wet brick liners in Section 2 of this design guide. The majority of the existing stack exit velocities do not fall within the recommended liner velocity range. This could be due to the following factors:

- The brick liners may not have been originally designed for wet operation.
- For tapered liners and liners with a choke, the stack exit velocity may be significantly higher than the average liner velocity.

Table C-3



Conversions: 1 ft/s = 0.3048 m/s

INFORMATION BASED ON INDUSTRY SURVEY

D

STACK LIQUID DISCHARGE MEASURING TECHNIQUES

Measurement methods for determining stack liquid discharge include a video droplet analyzer (VDA), laser optical particle counter, hot-wire anemometer, treated paper, dye tracers, chemical element balance and the phase Doppler particle analyzer (PDPA). These methods were originally developed for carryover measurement in mist eliminators, where gas flow velocities are about 25 percent in order of magnitude compared to flow velocities in wet stacks which range from 40 to 80 ft/s (12-24 m/s).

The video droplet analyzer employs a video camera and a synchronized high-speed strobe illuminator hooked up to a probe. Droplets are "frozen" as they pass through the sensing zone at a rate of 30 frames per second. Droplet size and quantity for each range of droplet diameter are measured. Gas velocities are measured by an independent procedure, for eg. a conventional s-

type pitot. Droplet data and gas velocity for each measurement point are then used to calculate the amount of stack liquid discharge. The VDA offers the advantages of in-situ sampling and a relatively wide spectrum of droplet sizes (30 to 5300 microns) monitored. One disadvantage of the VDA method is the required independent measurement of gas velocity, which has to be accurately gauged at each measurement point. Other disadvantages include the bulkiness of the accessory equipment and the technical expertise required to operate the equipment and to interpret the collected data.

A probe-mounted model of the laser optical particle counter is the PCSV-P manufactured by Insitec. The PCSV-P uses a low intensity He-Ne laser beam that splits into two separate beams prior to transmission across the probe viewing zone. Droplet diameters are measured directly through the analysis of light rays refracted by single droplets passing through the laser beams. The PCSV-P offers the advantage of both liquid discharge and gas velocity measurements in one probe. A major drawback of this method is that measurements for droplets bigger than 100 microns in diameter are not accurate. Also disadvantageous is the bulky associated equipment and the technical expertise needed to install and operate the apparatus, as well as, to evaluate the data.

The Army Insecticide Measurement System (AIMS) made by KLD Associates, is a hot-wire anemometer that employs a heated platinum sensor wire in a bridge circuit to generate a voltage pulse when a droplet cools the wire after impingement. Gas velocity is also determined, although in relatively humid gas streams, the readings are inaccurate. Portability of equipment and ease of installation and operation of the AIMS unit are advantages of this method. However, the largest droplet size that can be measured is only about 800 microns and the sensor wire is fragile and prone to breakage.

The treated paper method uses a piece of paper exposed to the gas stream to produce stains when droplets impact the paper. One way of preparing the treated paper is by soaking filter paper in a 1% solution of potassium ferrocyanide. An apparatus to hold and expose the treated paper has to be custom made since such equipment is not at present commercially available. The advantages of this method are the relatively simple equipment set-up and the immediate qualitative indication of droplet size and quantity. Disadvantages of the treated paper method include the time consuming process of treating the paper and the tedious placement and removal of the paper in the gas stream. Other disadvantages are the required independent measurement of gas velocity and the cumbersome apparatus.

In the dye tracer method, a foreign substance not typically found in the source liquors is added to the system. When the stack liquid discharge is sampled, the tracer concentrations are then used to determine the contributions of each source. It is imperative to use tracers that are stable under the operating conditions, not affected by the collection process and easily analyzed in the samples. Tracers like the fluorescent dyes fluorescein and rhodamine could be used. The dye tracer method offers the advantage of a relatively easy sampling method. Disadvantages include the care prerequisite in applying the dyes and analyzing liquid discharge samples. Another disadvantage of this method is the potential degradation of the dyes and/or the complication of analysis by other chemicals that may be present in the system.

The chemical element balance method assesses the differences in the chemical composition of the streams contributing to stack liquid discharge. This method assumes that the slurry from the absorber has a composition and solids content equivalent to that of the stack liquid discharge. This method measures a solids carryover. The liquid discharge is then calculated on the basis of the contributing stream compositions. The advantages of the chemical balance method are the easy sampling procedure and the use of the inherent differences in the contributing streams without adding chemicals to the system. The major disadvantages of this method are the extensive chemical analysis of the samples and the likelihood of difficulty in differentiating between sources that have similar compositions.

The phase Doppler particle analyzer made by Koch Engineering Company Inc., uses two intersecting laser beams to provide a sensing zone. As droplets pass through the probe volume, they scatter light which is analyzed to determine droplet size, count and velocity. An advantage of the PDPA is the broad range of droplet sizes (0.5 to 1500 microns) which can be measured. The analysis of the data collected using the PDPA provides droplet size, velocity distributions, various mean diameters, and the volume flux (cc/cm^2-s or gpm/ft^2). Koch claims that comparative tests with other measurement methods have been evaluated and show good correlation. In any case, the PDPA presents itself as a possible alternative method in addition to the other fore-mentioned methods for measuring stack liquid discharge.

E

PROCESS FLOW CHART OUTLINES

Included in this section are the process flow chart outlines for a new or retrofit wet stack and for a wet stack conversion. These outlines provide a detailed listing of flow chart activities that are presented in Figures E-1 and E-2. Additional descriptions of these activities are found in Sections 2 and 3.

E.1 Process Flow Chart Outline For New/Retrofit Wet Stack

Note: A diagram of this process flow chart is provided in Figure E-1.

1.0 Feasibility Study (Phase I)
- 1.1. Address Regulatory Issues
- 1.1.1 Dispersion Modeling
- 1.1.2 Permit Requirements
- 1.1.3 Tradeoffs Between SO_2 Removal Efficiency, Liner Material/Exit Velocity, and Ground Level Concentrations
- 1.1.4 Scrubber Performance Enhancement to Increase Removal Efficiency and Decrease Ground Level Concentrations
- 1.1.5 Wet Lands
- 1.1.6 Flood Plains

1.2 Define Existing Plant Considerations
- 1.2.1 Number of Units
- 1.2.2 Number of Liners
- 1.2.3 Bypass Options
- 1.2.4 Reliability Requirements
- 1.2.5 Operating Philosophy
- 1.2.6 Outage Time Available
- 1.2.7 Plant Layout/Location
- 1.2.8 Proximity to Existing Chimneys or Structures (Vortex Shedding between 2 Structures)
- 1.2.9 Future Use/Operating Conditions/Design Life Span
- 1.2.10 Soil Conditions
- 1.2.11 Preliminary Economic Analysis Guidelines
  - 1.2.11.1 What to Consider
  - 1.2.11.2 Ways to Estimate Non-Standard Items Such as Model Study, Liquid Collection System, Etc.

- 1.3 Define Operating Parameters
    - 1.3.1 Gas Flows
    - 1.3.2 Gas Temperatures
        - 1.3.2.1 Scrubbed Gas Operating Range
        - 1.3.2.2 Bypass Gas Operating Range
        - 1.3.2.3 Upset Conditions (Air Heater Failure)
    - 1.3.3 Pressure
    - 1.3.4 FGD System Type
    - 1.3.5 Coal Analyses or Coal Composition
    - 1.3.6 Flue Gas Composition
    - 1.3.7 Efficiency of Mist Eliminators
    - 1.3.8 Scrubbed Only or Combined Scrubbed/Bypass

- 1.4 Determine Stack Height
    - 1.4.1 Good Engineering Practice (GEP) Requirements
    - 1.4.2 Draft Considerations
    - 1.4.3 Adjacent Building Sizes
    - 1.4.4 Local Conditions, Terrain

- 1.5 Establish Liner Material Options
    - 1.5.1 Acid Resistant Brick
    - 1.5.2 Coated Carbon Steel
    - 1.5.3 Borosilicate Glass Block on Carbon Steel
    - 1.5.4 Fiberglass Reinforced Plastic
    - 1.5.5 Nickel Alloy
    - 1.5.6 Titanium
    - 1.5.7 Combination/Multiple Materials

- 1.6 Perform Operating Conditions vs. Liner Design Compatibility Analysis
    - 1.6.1 FGD System Type vs. Liner Material Options
    - 1.6.2 Operating Conditions vs. Liner Material Options
    - 1.6.3 Design Constraints (seismic, temperature, etc.) vs. Liner Material Options

- 1.7 Select Design Velocity Limit to Prevent Liquid Reentrainment for Each Candidate Liner Material
    - 1.7.1 Breech Entry
    - 1.7.2 Liner
    - 1.7.3 Liner or Choke Exit

- 1.8 Perform Preliminary Economic Analysis of Liner Material Options for Wet Stack Operation
    - 1.8.1 Capital Costs
        - 1.8.1.1 Chimney Column

1.8.1.2 Liner
1.8.1.3 Breeching
1.8.1.4 Foundation
1.8.2 Operating Costs
1.8.3 Maintenance Costs
1.8.4 Present Value Analysis

1.9 Select Liner Material(s) for Wet Stack Operation

1.10 Determine Reheat System Design Requirements (if necessary)
1.10.1 Materials of Construction
.10.2 Energy Requirements
1.10.3 Energy Source
1.10.4 Equipment Requirements

1.11 Perform Economic Analysis of Wet Stack vs. Reheat Operation (if necessary)
1.11.1 Capital Costs
1.11.2 Operating Costs
1.11.3 Maintenance Costs
1.11.4 Present Value Analysis

1.12 Select Wet Stack or Reheat Operation (if necessary)

2.0 Design Process (Phase II)

2.1 Perform Component-by-Component Design
2.1.1 Establish Design Criteria
2.1.1.1 Subsurface Investigation
2.1.1.2 Foundation Type
2.1.1.2.1 Soil Bearing
2.1.1.2.2 Piling
2.1.1.2.3 Drilled Shafts
2.1.1.3 Chimney Foundation Design Requirements
2.1.1.4 Reinforced Concrete Chimney or Steel Stack Design Requirements
2.1.1.5 Liner Design Requirements
2.1.1.6 Ductwork Design Requirements
2.1.1.7 Miscellaneous Design Requirements

2.1.2 Define Absorber Outlet Duct and/or Bypass Duct Geometry
2.1.2.1 Evaluate Mixing Zones

2.1.2.2 Damper Locations
2.1.2.3 Expansion Joint Locations

2.1.3 Define Chimney Geometry
2.1.3.1 Liner Height
2.1.3.2 Liner Diameter(s)
2.1.3.3 Liner Base Elevation (At Grade or Above Grade)
2.1.3.4 Annulus Space
2.1.3.5 Plumb or Tapered Liner
2.1.3.6 Plumb or Tapered Column
2.1.3.7 Choke
2.1.3.8 Liner Projection above Column
2.1.3.9 Liner Floor Configuration
2.1.3.10 Breech Opening Orientation, Size, Elevation
2.1.3.11 Access Requirements
2.1.3.11.1 Interior vs. Exterior Platforms, Ladders, and Elevator
2.1.3.11.2 Continuous Emissions Monitor (CEM) Access
2.1.3.11.3 Testing Access
2.1.3.11.4 Inspection Access
2.1.3.11.5 Maintenance Access

2.2 Adjust Design for Suitability and Compatibility for Liquid Collection

2.3 Perform Flow Model Study
2.3.1 Physical Flow Model
2.3.2 Condensation Calculations
2.3.3 Determine Liquid Collection Devices
2.3.3.1 Gutters and Flow Guides
2.3.3.2 Vanes and Baffles
2.3.3.3 Drains and Troughs
2.3.3.4 Liner Floor Drainage
2.3.3.5 Drain Pipes and Gas Seals

2.4 Prepare Bid Specifications, for Chimney Contract
2.4.1 General Requirements (Including Safety Issues for Confined Space)
2.4.2 Site Work
2.4.3 Concrete
2.4.4 Masonry
2.4.5 Metals: Structural and Miscellaneous
2.4.6 Thermal and Moisture Protection
2.4.7 Doors
2.4.8 Finishes
2.4.9 Conveying Systems

2.4.10 Mechanical
2.4.11 Electrical

2.5 Perform Detailed Design of Chimney for Construction

E.2 Process Flow Chart Outline For Conversion to Wet Stack Operation

Note: A diagram of this flow chart is provided in Figure E-2.

1.0 Feasibility Study (Phase I)

1.1 Address Regulatory Issues
1.1.1 Dispersion Modeling
1.1.2 Permit Requirements
1.1.3 Tradeoffs Between SO_2 Removal Efficiency, Liner Material/Exit Velocity, and Ground Level Concentrations
1.1.4 Scrubber Performance Enhancement to Improve Removal Efficiency and Decrease Ground Level Concentrations

1.2 Define Existing Plant Considerations
1.2.1 Number of Units
1.2.2 Number of Liners
1.2.3 Bypass Options
1.2.4 Reliability Requirements
1.2.5 Operating Philosophy
1.2.6 Outage Time Available
1.2.7 Plant Layout/Location
1.2.8 Location of FGD Systems
1.2.9 Location of Fans
1.2.10 Capacity of Fans
1.2.11 Future Use/Operating Conditions/Design Life Span
1.2.12 CEM Systems
1.2.13 Soil Conditions
1.2.14 Preliminary Economic Analysis Guidelines
1.2.14.1 What to Consider
1.2.14.2 Ways to Estimate Non-Standard Items Such as Model Study, Liquid Collection System, Etc.

1.3 Define Operating Parameters
1.3.1 Gas Flows
1.3.2 Gas Temperatures
1.3.2.1 Scrubbed Gas Operating Range
1.3.2.2 Bypass Gas Operating Range

1.3.2.3 Upset Conditions (Air Heater Failure)
1.3.3 Pressure
1.3.4 FGD System Type
1.3.5 Coal Analyses or Coal Composition
1.3.6 Flue Gas Composition
1.3.7 Efficiency of Mist Eliminators
1.3.7.1 Determine Existing System Liquid Carryover
1.3.7.2 Measure Droplet Size and Quantity
1.3.8 Scrubbed Only or Combined Scrubbed/Bypass

1.4 Review Existing Design Parameters
1.4.1 Foundation
1.4.2 Reinforced Concrete Chimney or Steel Stack
1.4.3 Liner
1.4.4 Ductwork

1.5 Evaluate Existing Stack Height
1.5.1 Good Engineering Practice Requirements (GEP)
1.5.2 Draft Considerations
1.5.3 Adjacent Building Sizes
1.5.4 Local Conditions, Terrain

1.6 Evaluate Existing Stack, Liner, and Outlet Duct
1.6.1 Material(s)
1.6.2 Condition (Inspection Reports)
1.6.3 Structural Integrity for Current Code Requirements
1.6.4 Flue Gas Velocity
1.6.5 Ability to Incorporate Liquid Collection Devices
1.6.6 Acceptability of Existing Stack Height per Step 1.5 above.
1.6.7 Ability to Convert Annulus to Pressurized System
1.6.8 Effect of Conversion on Existing CEM Instruments and Locations

1.7 Determine Insulation Requirements
1.7.1 Liner
1.7.2 Ductwork

1.8 Determine Liner Alternatives
1.8.1 Existing Liner Acceptable
1.8.2 Modify or Reline Existing Liner
1.8.3 Replace Existing Liner
1.8.4 Construct New Chimney

1.9 Establish Liner Material Options
1.9.1 Acid Resistant Brick

1.9.2 Coated Carbon Steel
1.9.3 Borosilicate Glass Block on Carbon Steel
1.9.4 Fiberglass Reinforced Plastic
1.9.5 Nickel Alloy
1.9.6 Titanium
1.9.7 Combination/Multiple Materials

1.10 Perform Operating Conditions vs. Liner Design Compatibility Analysis
1.10.1 FGD System Type vs. Liner Material Options
1.10.2 Operating Conditions vs. Liner Material Options
1.10.3 Design Constraints vs. Liner Material Options

1.11 Select Design Velocity Limit for Each Candidate Liner Material
1.11.1 Breech Entry
1.11.2 Liner
1.11.3 Liner or Choke Exit

1.12 Determine Impact of Liner Modifications on Existing Construction
1.12.1 Evaluate Existing Chimney
1.12.1.1 Revised Liner Loads
1.12.1.2 Conformity with New Code Requirements
1.12.1.3 New Breech Opening Requirements, Reinforcing.
1.12.2 Evaluate Existing Chimney Foundation
1.12.2.1 New Liner Arrangement
1.12.2.2 Revised Liner Loads
1.12.3 Evaluate Construction Access Requirements

1.13 Perform Preliminary Economic Analysis of Liner Material Options
1.13.1 Capital Costs
1.13.1.1 Chimney Column
1.13.1.2 Liner
1.13.1.3 Foundation
1.13.2 Operating Costs
1.13.3 Maintenance Costs
1.13.4 Outage Costs
1.13.5 Present Value Analysis

1.14 Select Liner Material(s) for Wet Stack Operation

1.15 Evaluate Fan Alternatives
1.15.1 Keep Existing
1.15.2 Modify Existing
1.15.3 Eliminate Existing Wet Fans
1.15.3.1 Modify Existing Fans

1.15.3.2 Add New Fans Upstream of FGD System
1.15.3.3. Consider Fan Wash Systems
1.15.4 Annulus Pressurization System
1.15.5 Consider Draft Changes Resulting from Conversion to Wet Stack Operation

1.16 Collect Baseline Performance Data
1.16.1 Stack Droplet Test
1.16.1.1 With Reheat
1.16.1.2 Without Reheat
1.16.2 Determine Required Performance of Modified System

1.17 Determine Reheat System Design Requirements
1.17.1 Materials of Construction
1.17.2 Energy Requirements
1.17.3 Energy Source
1.17.4 Equipment Requirements

1.18 Perform Economic Analysis of Wet Stack vs. Reheat Operation
1.18.1 Capital Costs
1.18.2 Operating Costs
1.18.3 Maintenance Costs
1.18.4 Outage Costs
1.18.5 Present Value Analysis

1.19 Select Wet Stack or Reheat Operation

2.0 Design Process (Phase II)

2.1 Perform Component-by-Component Design
2.1.1 Establish New Design Parameters
2.1.1.1 Wind
2.1.1.2 Seismic
2.1.1.3 Codes
2.1.2 Define Chimney Geometry
2.1.2.1 Liner Height
2.1.2.2 Liner Diameter(s)
2.1.2.3 Liner Base Elevation (At Grade or Above Grade)
2.1.2.4 Annulus Space
2.1.2.5 Plumb or Tapered Liner
2.1.2.6 Choke
2.1.2.7 Liner Projection above Column
2.1.2.8 Liner Floor Configuration

2.1.2.9 Breech Opening Orientation, Size, Elevation
2.1.2.10 Access Requirements
2.1.2.10.1 Interior vs. Exterior Platforms, Ladders, and Elevator
2.1.2.10.2 Continuous Emissions Monitor (CEM) Access
2.1.2.10.3 Testing Access
2.1.2.10.4 Inspection Access
2.1.2.10.5 Maintenance Access

2.2 Adjust Design for Suitability and Compatibility for Liquid Collection

2.3 Perform Flow Model Study
2.3.1 Physical Flow Model
2.3.2 Condensation Calculations
2.3.3 Determine Liquid Collection Devices
2.3.3.1 Gutters and Flow Guides
2.3.3.2 Vanes and Baffles
2.3.3.3 Drains and Troughs
2.3.3.3 Liner Floor Drainage
2.3.3.5 Drain Pipes and Gas Seals

2.4 Prepare Bid Specifications for Chimney Contract
2.4.1 General Requirements (Including Safety Issues for Confined Space
2.4.2 Site Work
2.4.3 Concrete
2.4.4 Masonry
2.4.5 Metals: Structural and Miscellaneous
2.4.6 Thermal and Moisture Protection
2.4.7 Doors
2.4.8 Finishes
2.4.9 Special Construction
2.4.10 Conveying Systems
2.4.11 Mechanical
2.4.12 Electrical

2.5 Perform Detailed Design of Chimney for Construction

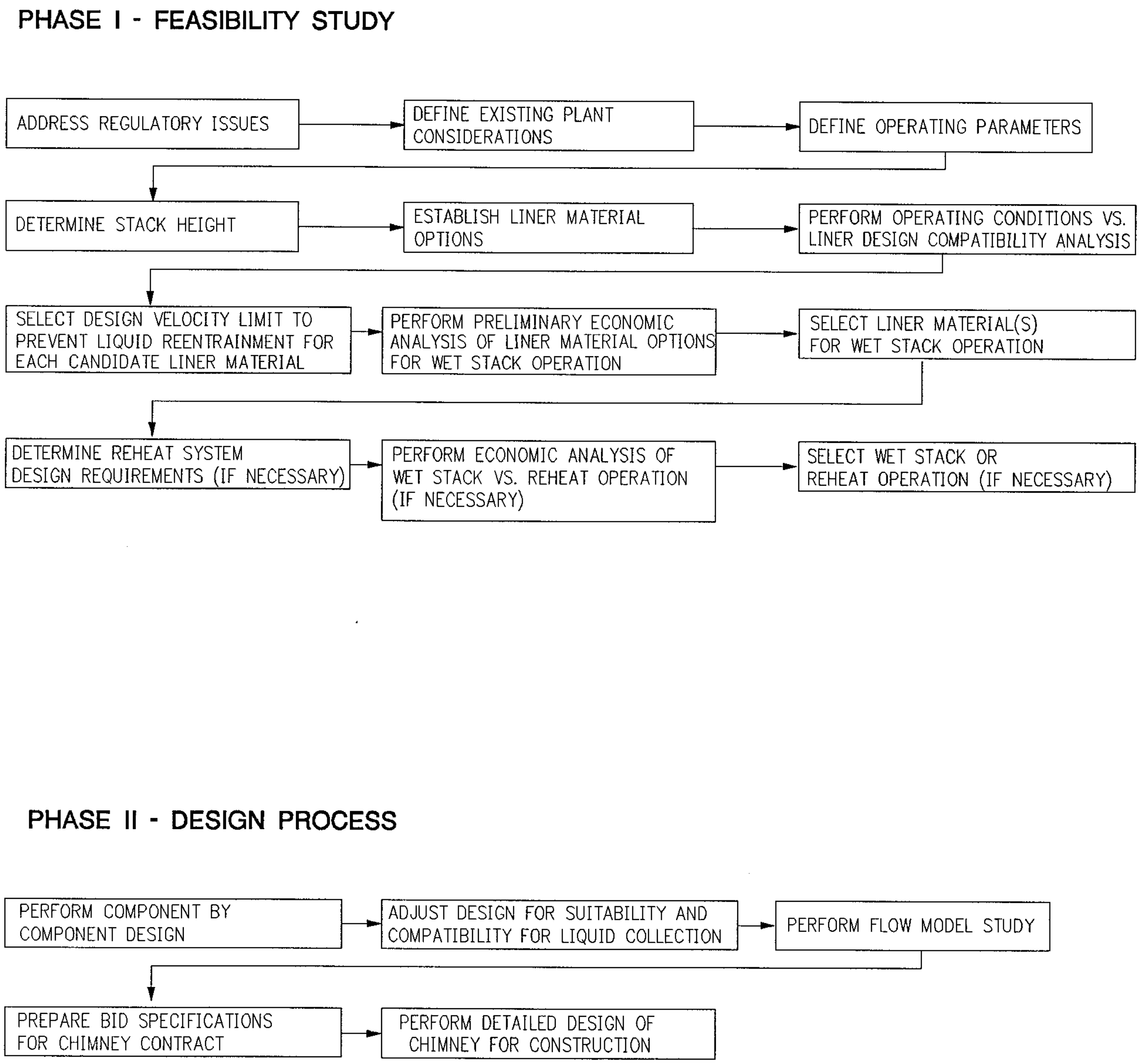


Figure E-1 Process Flow Chart for New/Retrofit Wet Stack Design

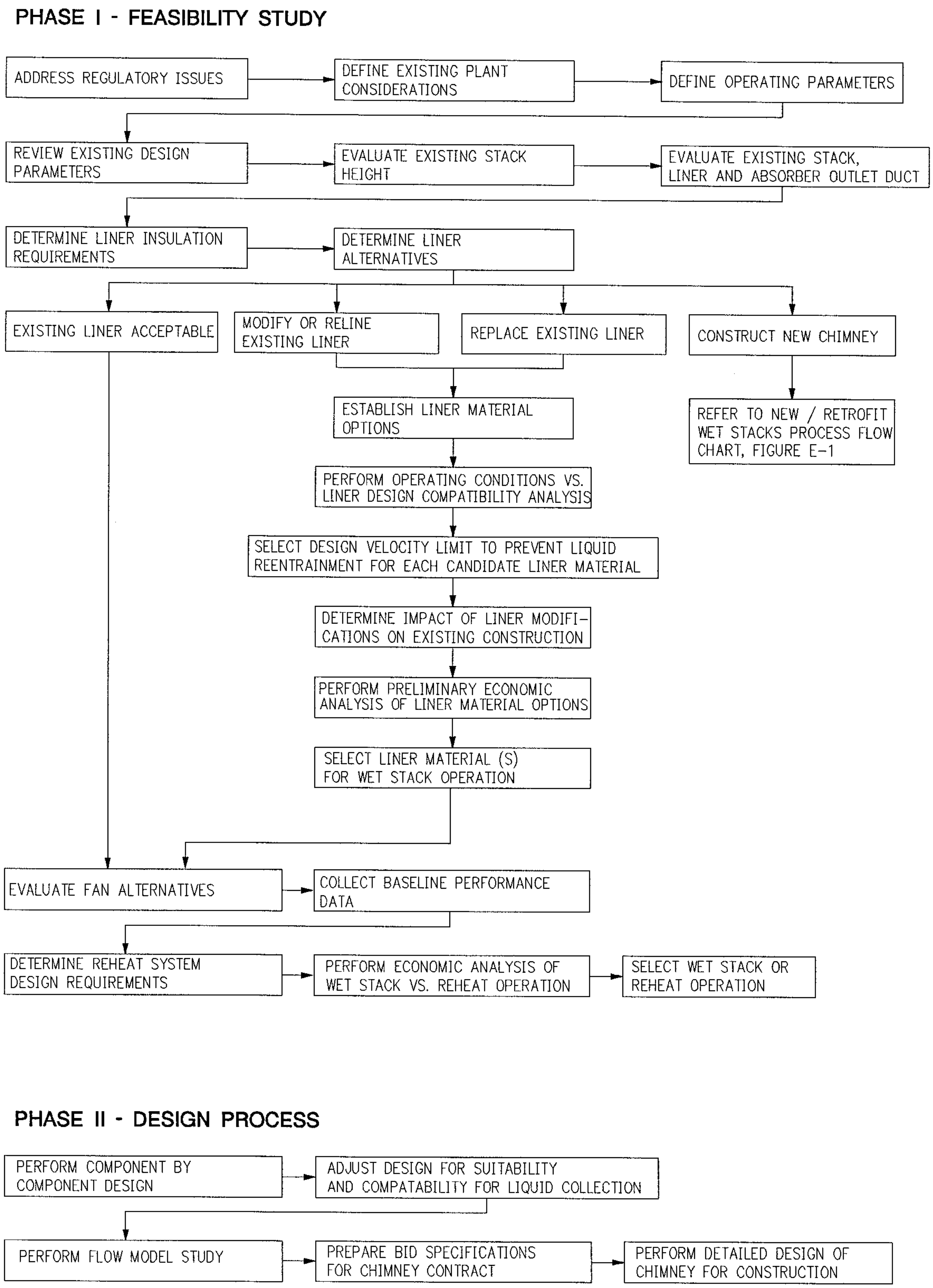


Figure E-2 Process Flow Chart for Conversion of Existing Stack for Wet Operation

F

SUPPLIERS, MANUFACTURERS, AND CONTRACTORS FOR WET STACKS

The following is a representative list of major suppliers, manufacturers, and contractors for wet stacks. These companies do not represent a complete and comprehensive list of all companies that may be available. For the most part, these lists provide a guide to the companies that have been involved with the majority of utility stack projects. Other companies may be available for each category listed. These other companies as well as those listed should be evaluated by the designer.

F.1 The following is a list of several companies that manufacture chimney brick.

- Beldon Brick Company - fireclay or red shale
- Continental Clay Company - fireclay or red shale
- Glen Gery Brick - fireclay
- Sioux City Brick and Tile Company - red shale
- Watkins Brick Company - red shale

F.2 There are two potassium silicate mortars conforming to ASTM C466 that are commonly used for wet FGD applications:

- Corlok B as manufactured by Elf Atochem.
- Sauereisen No. 65 as manufactured by Sauereisen Cements Company.

F.3 Two of the largest manufacturers of flakeglass reinforced vinyl ester systems are as follows:

- Dudick, Inc. - Protecto-Flake 900.
- Masterbuilders, Inc. - Flakeline 180.

F.4 Three manufacturers of FRP liners are:

- An-Cor Industrial Plastic.
- Composite Construction & Engineering, Inc.

- Ershigs, Inc.

F.5 Suppliers of Alloy C276 and/or Alloy C22 are:

- Allegheny-Ludlum, Alloy AL 276.
- Creusot-Loire, Alloys H C22 and H C276.
- G.O. Carlson, Alloy GOC-276.
- Haynes International, Hastelloy Alloys C-22 and C276.
- Inco Alloys International, Inconel Alloy 622 and Inco Alloy C-276.
- Jessop, JS Alloy 276.
- VDM Technologies, Nicrofer 5621hMoW (Alloy C22) and Nicrofer 5716hMoW (Alloy C276).

F.6 The following companies are the major manufacturers of lightning protection systems:

- Thompson Lightning Protection, Inc.
- Robbins Lightning Protection.
- AC Lightning Security, Inc.

F.7 The major manufacturers of chimney elevators are:

- Alimak.
- Champion Elevators, Inc.

F.8 Three major chimney design and construction companies specializing in new chimney construction, as well as modifications to existing chimneys are:

- Custodis-Cottrell.
- Pullman Power Products Corporation.
- Zurn Balcke-Durr.