
Duct Injection for SO₂ Control

DESIGN HANDBOOK

Volume 1

Process Design and Engineering Guidelines

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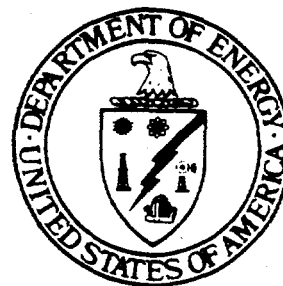
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United States Department of Energy
Pittsburgh Energy Technology Center



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Raytheon
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Babcock & Wilcox

a McDermott company

We have no objection from a patent
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1.0 INTRODUCTION

Improving the environmental acceptability of burning coal by reducing emissions with acid rain potential has become one of the priority energy goals for the United States of America. The U.S. Department of Energy - Pittsburgh Energy Technology Center (PETC) has been at the forefront of this effort beginning with its 1986 Acid Rain Initiative Study. This strategic investigation determined that the principal sources of SO₂ emissions nationwide include not only high-sulfur "dirty coals" but medium-sulfur coals as well.

As a result of this finding, PETC developed a comprehensive program of coal-related, acid-rain research and development with a major activity area centering on flue gas cleanup and control of SO₂ emissions. Particular emphasis was placed on the retrofit measures for older coal-fired power plants which predate the 1971 New Source Performance Standards.

Candidate emission control technologies fall into three categories, depending upon their point of application along the fuel path (i.e., pre, during, or post combustion). The post-combustion, in-duct injection of a calcium-based chemical reagent seemed promising. Preliminary studies showed that reagent injection between the existing air heater and electrostatic precipitator (ESP) could remove between 50-60% of the SO₂ and produce an environmentally safe, dry, solid waste that is easily disposed. Although SO₂ removal efficiencies were less, the estimated capital costs for duct injection technology were low making the economics of duct injection systems seem favorable when compared to conventional wet slurry scrubbers under certain circumstances.

With the promulgation of the Clean Air Act Amendments of 1990 came more incentive for the development of low capital cost flue gas desulfurization (FGD) processes. A number of technical problems had to be resolved, however, before duct injection technology could be brought to a state of commercial readiness. The Duct Injection Technology Development Program was launched as a comprehensive, four-year research effort undertaken by PETC to develop this new technology. Completed in 1992, this Duct Injection Design Handbook and the three-dimensional predictive mathematical model (discussed in Section 4.0 of this handbook) constitute two primary end products from this development program.

The aim of this design handbook and the accompanying math model is to provide utility personnel with sufficient information to evaluate duct injection technology against competing SO₂ emissions reduction strategies for an existing plant. The handbook will enable the development of a conceptual design and the determination of economic feasibility. Should this technology be well-suited for a specific need, the handbook and model provide design information to allow the utility or others to complete the required detailed engineering.

1.1 Design Handbook Organization and Use

1.1.1 Design Handbook Organization

This handbook consists of twelve sections and five appendices. The sections have been organized to present a logical sequence of steps which you, the user, will need to take in order to 1) gain a basic understanding of duct injection technology, 2) decide whether a duct injection process is feasible for a specific plant, and 3) implement the retrofit of this technology:

- Section 1.0 gives a general background and basic understanding of duct injection technology including dry sorbent injection (DSI) and duct spray drying (DSD).
- Sections 2.0 and 3.0 provide enough criteria and information to allow utility personnel to make decisions regarding the technical and economic feasibility of retrofitting duct injection technology to a specific plant.
- Sections 5.0 - 10.0 provide detailed design and specification information for actually retrofitting the equipment and modifying the existing plant.

A section (Section 4.0) is also included which describes the use of the mathematical model to complement the decision making and design processes outlined in this handbook. Due to the computer hardware required to run the model, it is likely that the typical handbook user will not be able to use the model. Therefore, the design handbook has been written as a "stand alone" document which can be used by itself or interfaced with the model if the user has the capability to exercise it.

Section 11.0 of the handbook presents general operation and maintenance guidelines. Only equipment which is unique to the duct injection process, e.g., slurry or water atomizers, slurry pumping, etc., is covered. Standard-type plant equipment such as water pumps and blowers are not addressed in this section. Modifications to the operation and maintenance of existing plant equipment, such as to the ash handling system and ESP, required after the retrofit is completed is also discussed in this section.

After the design of the duct injection retrofit is fairly well established, a detailed capital and operating cost estimate may be prepared. The economic guidelines and methodology presented in Section 12.0 will facilitate the preparation of this estimate.

Five appendices are attached to this handbook:

- Appendix A - Case Studies contains complete sample case studies for both DSI and DSD to serve as examples for determining the feasibility and actual design of these processes as presented in this handbook.
- Appendix B - Process Chemistry provides a discussion of duct sorbent injection chemistry. The various physical and chemical factors affecting the process kinetics are discussed.
- Appendix C - Sorbent Selection contains data and information to help the user select the sorbent which is best suited to a specific plant.
- Appendix D - Duct Injection Waste Characterization and By-Product Utilization summarizes the chemical, physical, and mineralogical characterization of typical wastes from duct injection processes. Utilization and/or disposal options for this waste are discussed in detail.
- Appendix E - Bid Specifications contains the equipment bid specifications which may be used to purchase the necessary equipment.

1.1.2 How to Use this Design Handbook

It is recommended that the user of this handbook begin by reading the overview of duct injection technology provided in Section 1.2. A technical description of the processes and the advantages and disadvantages of the technology are presented in this subsection. Also, the terminology used throughout this handbook is introduced in Section 1.2.

After reading Section 1.2, it is recommended that the user proceed to Section 2.0. This is a critical section of the design handbook. The objective of this section is to enable the user to determine, by completing a set of exercises, if duct injection technology is a feasible option for a specific plant. If the user's plant is determined to be a suitable candidate for this technology, on a preliminary basis, the user will be instructed to proceed to Section 3.0.

Section 3.0 will aid the user in developing the process design criteria necessary for conceptual design. These criteria may also be used as input to the duct injection predictive model. Establishing the primary process design parameters, such as calcium to sulfur ratio, recycle requirements, duct residence time, necessary droplet size, mass of waste produced, impact on ESP emissions, etc., will allow rough estimates of capital and operating costs to be determined. Based on these estimates, the user should be able to make a decision regarding the feasibility of duct injection at the plant. The user will also have the necessary information to select which of the two duct injection options (DSI or DSD) and which sorbent are best suited for the specific application.

If the user has access to the computer hardware required to run the predictive model, it is strongly recommended that this be done after working through Sections 2.0 and 3.0. Section 4.0 briefly describes the model and the input data required to run it. A detailed users guide is not included in this handbook; rather, it is a separate document which can be obtained with the computer model. This section ends with a description of the model output and suggestions on how to apply the information provided by the model to the design of the duct injection installation.

If the decision making process and conceptual design/economic feasibility determination of Sections 2.0 and 3.0 indicate that duct injection is well-suited for the user's specific plant, then the detailed design of the duct injection system can be initiated using Sections 5.0 - 10.0. These sections give information and criteria to guide the user through the generation of material and energy balances, P&ID development, individual equipment sizing and design, equipment layout and arrangement, development of control and instrumentation requirements, selection of material and lining requirements, and preparation of equipment bid specifications.

Section 11.0 of the handbook provides general guidelines which will enable the user to develop an O&M manual specific to the anticipated installation before operation begins. Guidelines are given for all of the major operating parameters and operating procedures. Safety aspects, start-up/shutdown suggestions, and turndown considerations are covered for both DSI and DSD. General guidelines for inspection and maintenance are given for equipment unique to the duct injection process and also for existing plant equipment which will be affected after the duct injection retrofit (such as the ESP, ash handling system, etc.). Process troubleshooting suggestions are provided for common system problems.

Once the detailed design is nearly complete, Section 12.0 can be used to obtain guidance for generating a detailed capital cost associated with retrofitting either a DSI or DSD system. Most of the user's cost estimate will be based on quotes from equipment suppliers but other

costs need to be estimated. Guidelines for developing operating and maintenance costs are also provided. This section allows estimation of levelized costs to determine the economic impact of adding a duct injection system on the cost of generating a kilowatt of power and in removing a ton of SO₂.

The case studies for DSI and DSD, included in Appendix A, are sample products generated by completing the entire detailed design process prescribed in this handbook.

1.2 Overview of Duct Injection Technology

Several types of sorbent (reagent) can be injected into the ductwork downstream of the boiler air heater(s) for the purpose of removing SO_2 ; however, this design handbook only discusses the use of calcium-based sorbents. Sorbent injection is accomplished by either of two processes: the injection of dry, hydrated lime with accompanying humidification water in dry sorbent injection (DSI), or the injection of slaked lime slurry in duct spray drying (DSD). In both processes, the lime is injected into the existing ductwork between the air heater(s) and the particulate collection device (assumed to be an electrostatic precipitator). Coal fly ash, products from the reaction of SO_2 with the lime, and unused sorbent are thus collected in the electrostatic precipitator (ESP).

Duct injection technology was developed as a low capital cost alternative to conventional FGD scrubber systems. In addition to low initial investment, other significant advantages of a duct injection system are its simplicity and that it may be applied at plants with limited available space and/or difficult construction access, because the existing duct(s) is used as the reaction vessel. Modifications to the duct(s) are required to install the injection equipment (humidification and/or sorbent injection nozzles), but no large reactor vessels are required. A duct injection process results in few changes to the existing flue gas system, and minimal plant real estate is required. The retrofit of a duct injection system is relatively simple, and it can be accomplished quickly.

Additional advantages to using a duct injection system include:

- minimal operation and maintenance personnel requirements
- generation of a dry solid waste product
- no requirement for a gas reheat system

Few O & M personnel are required for a duct injection system due to its simplicity and limited new equipment requirements. The dry solid waste produced is an advantage because it can typically be handled by the existing fly ash handling system. No dewatering equipment such as thickeners or vacuum filters are needed. A flue gas reheat system is not required in the system design because the temperature of the gas after sorbent injection/humidification is sufficiently above the saturation temperature as to minimize corrosion potential in the ESP, duct work, ID fans, and chimney.

Disadvantages of duct injection technology are:

- SO_2 removal is limited to 50-70%
- low reagent utilization
- use of relatively expensive reagents
- an increase in particulate loading to the ESP
- the potential for solids deposition in the ductwork and ESP
- little full-scale operating experience in the U.S.

Because of the limited contact time and moisture available for the calcium-sulfur reactions, SO_2 removal in duct injection applications is restricted to about 50-70%. This range of SO_2 removal includes that which occurs in the ESP; typically, the SO_2 removal in the ESP is 20-30% of the total. Reagent utilization is typically fairly low in duct injection processes (30-40%) for the same reasons noted above - limited contact time and availability of moisture. Lime (either hydrated or pebble quicklime) is considerably more expensive than the limestone

typically used in wet FGD processes. The increase in particulate loading to the ESP may increase the overall particulate emissions from the system. Depending upon the particulate emissions regulation, additional specific collection area (SCA) and/or other modifications may have to be added to maintain an acceptable level of emissions.

Sufficient residence time in the ductwork must be available for evaporation of water in the injected droplets. If the droplets (water in DSI or slurry in DSD) do not evaporate almost completely before they impact the internal duct surfaces and/or before they enter the ESP, solids build-up will occur on the duct surfaces and/or internal surfaces of the ESP. If droplets impinge upon any obstructions, turning vanes, or bends in the ductwork before the evaporation is complete, moist solids will build up on these obstructions or duct surfaces. Substantial solids build-up would cause flue gas pressure transients and disruptions in the flue gas path, which will likely exacerbate the build-up problem. Should evaporation be incomplete upon entering the ESP, wet solids will agglomerate on the plates of the ESP preventing it from functioning properly.

Duct injection technology has been successfully demonstrated at the pilot-plant scale. However, full-scale applications of this technology are limited. DSI has been demonstrated at 104 MW (Coolside testing at Ohio Edison's Edgewater Station). DSD will be demonstrated at Pennsylvania Electric's Seward Station on one-half of a 147 MW unit beginning in late 1992.

Although lower in capital cost than conventional scrubber systems, the inherently moderate SO_2 removal and low sorbent utilization tend to drive the levelized cost of duct injection (in terms of dollars per ton of SO_2 removed) relatively high. Factors which favor a low capital cost, high levelized cost technology (such as DSI or DSD) are:

- low sulfur coal
- requirement for a moderate SO_2 removal
- small to medium-sized plants
- low plant capacity factors
- short remaining plant life

These are the general plant criteria which should be considered when evaluating the application of duct injection technology to a specific plant.

1.2.1 Dry Sorbent Injection (DSI)

DSI is a duct injection process in which dry hydrated lime sorbent and (optionally) recycled solids collected in the ESP are injected into the flue gas flow just downstream of the air heater(s). Water is injected downstream of, or in the same plane as, the sorbent injection to cool and humidify the gas to the specified approach to saturation temperature. The humidification water also wets the sorbent enhancing the calcium-sulfur reactions. The fly ash, reaction products, and unused sorbent are collected in the ESP from which a portion of the solids may be recycled for reinjection with the fresh sorbent. The remaining solids are transported to an ash silo and ultimately to a landfill for disposal unless a utilization option is available.

The chemistry of DSI is relatively straightforward. Pebble lime sorbent, which is mostly made up of calcium oxide [CaO], is atmospherically hydrated (either off-site or on-site) to hydrated lime, which is mostly dry calcium hydroxide [Ca(OH)_2]. This hydrated lime is then injected into

the duct(s). The majority of the SO_2 captured converts to calcium sulfite hemi-hydrate $[\text{CaSO}_3 \cdot \frac{1}{2}\text{H}_2\text{O}]$; the balance forms calcium sulfate di-hydrate $[\text{CaSO}_4 \cdot 2\text{H}_2\text{O}]$ (gypsum). Reference Appendix B - Process Chemistry for a more detailed description of the process chemistry.

1.2.1.1 Process Description

The process components are grouped into areas according to function, e.g., sorbent storage and preparation, flue gas system, etc. Figures 1-1 and 1-2 show simplified DSI process flow diagrams for off-site and on-site hydration, respectively. Area 100 - Sorbent Storage and Preparation System is different for the two alternative forms of reagent receiving and preparation; therefore, this area is described separately for both types of reagent. The remainder of the DSI process is the same for either reagent.

Area 100 - Sorbent Storage and Preparation System

Off-site hydration - The hydrated lime is transported to the plant site by either enclosed truck or rail car. From the truck or rail unloading area, the hydrate is pneumatically conveyed to a hydrate silo(s) for storage. The sorbent is fed from the silo(s) through a screw feeder to the injection piping and pneumatically transported and blown into the flue gas duct(s). Fluidizing air is used to facilitate flow of the hydrated lime out of the silo(s) into the feeder.

On-site hydration - Pebble lime is transported to the plant site by either enclosed truck or rail car. From the truck or rail unloading area, the pebble lime is pneumatically conveyed to a pebble lime silo(s) for storage. The lime is fed from the silo(s) through a weigh belt feeder to an atmospheric hydrator unit where the pebble lime is hydrated to dry hydrated lime (calcium hydroxide) using raw (fresh) water. The product from the hydrator is pneumatically transferred to a hydrate bin for short-term storage. The sorbent is fed from the bin, through a screw feeder, and then pneumatically injected into the duct(s) as described above for off-site hydration. Fluidizing air is used to facilitate flow of the hydrated lime out of the bin into the feeder.

Area 200 - Humidification/Sorbent Injection System

Fresh hydrate is injected into the flue gas flow path using sorbent injectors. There are different designs available for these injectors, but they generally consist of simple piping from which the sorbent is injected (along with its conveying air) cocurrent with the flue gas. Recycled solids from the existing ash silo or from a new recycle bin may also be injected pneumatically using similar injectors. Dual-fluid nozzles, using compressed air for atomization, are used to inject humidification water into the duct downstream of, or in the same plane as, the fresh sorbent/recycle solids injection point. The majority of the SO_2 removal occurs in this section of the duct.

FIGURE 1-1
 DRY SORBENT INJECTION - OFF-SITE HYDRATION
 SIMPLIFIED PROCESS FLOW DIAGRAM

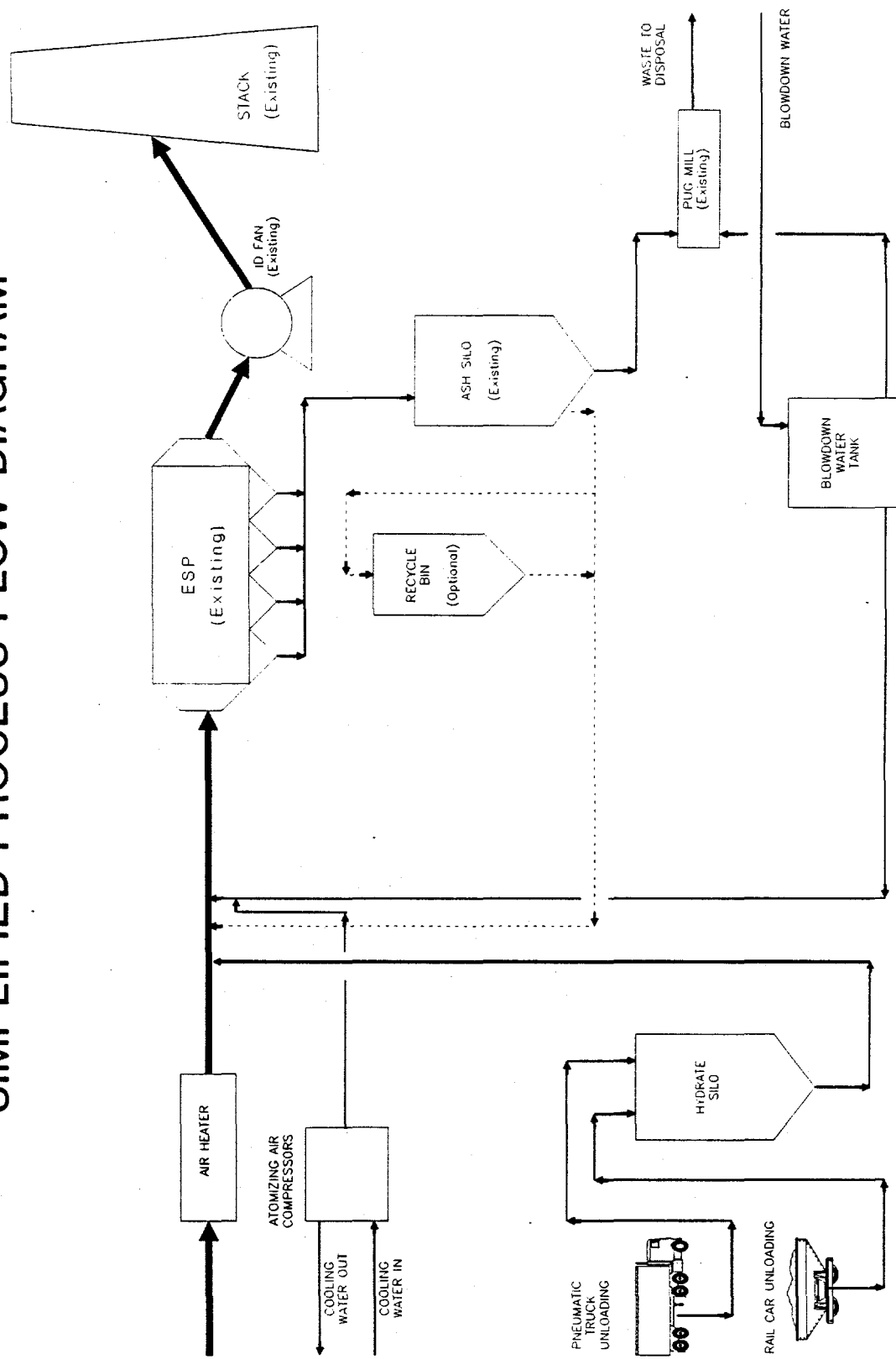
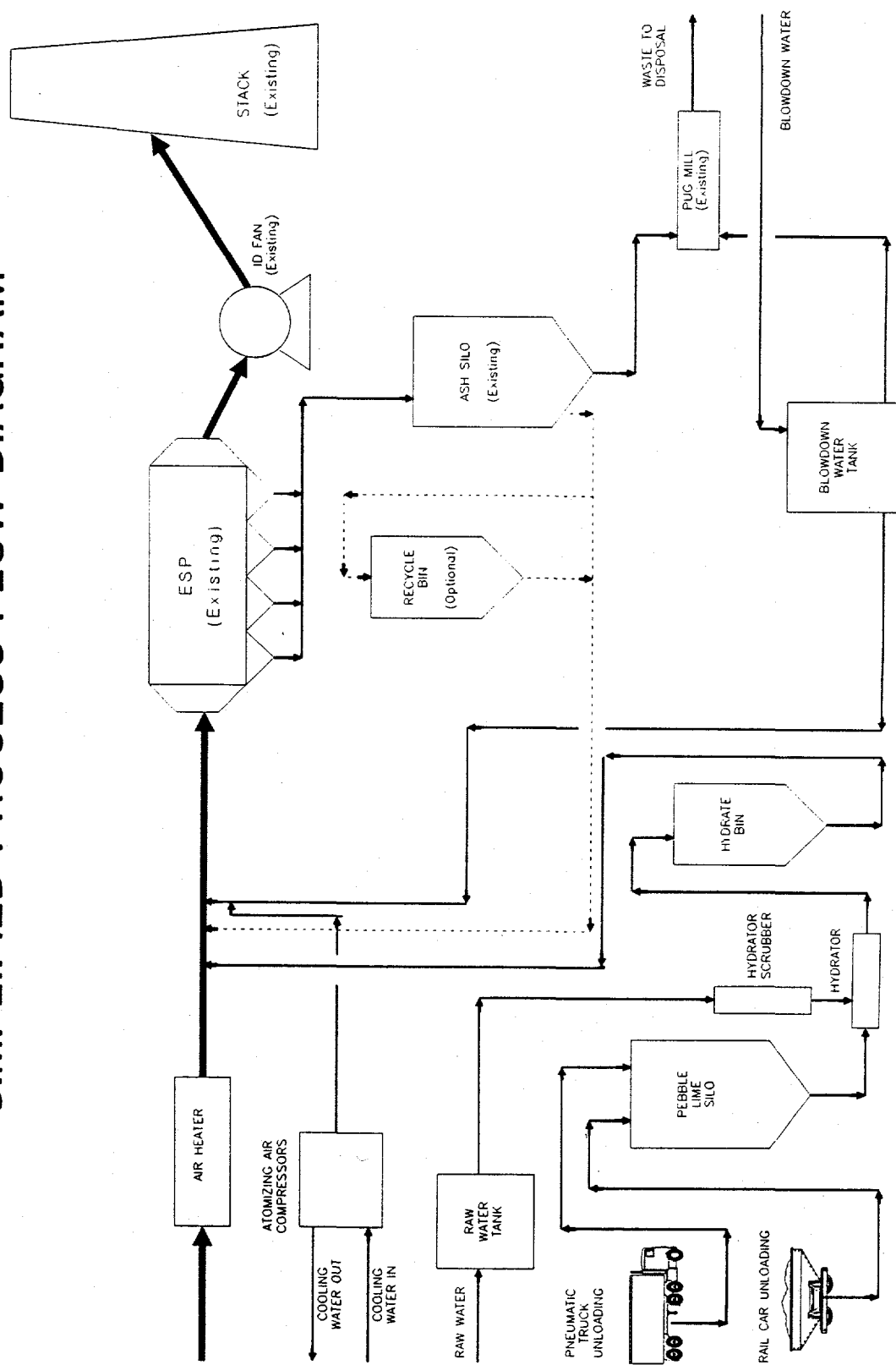


FIGURE 1-2
 DRY SORBENT INJECTION - ON-SITE HYDRATION
 SIMPLIFIED PROCESS FLOW DIAGRAM



Area 300 - Flue Gas System

Modifications to the existing ductwork are required to accommodate the array of dual-fluid nozzles and sorbent injectors. Flue gas flow correction devices may need to be installed upstream of the injection point to ensure relatively uniform velocity and temperature profiles at the injection point. Internal duct bracing and/or stiffeners should be removed to minimize sites for solids deposition. Devices may need to be installed to mitigate the negative impacts of any solid build-up; sootblowers, sonic horns, and rappers are examples of such devices.

Additionally, modifications to the duct externals may be required to facilitate the retrofit and operation of a DSI system:

- shoring up existing support steel and adding load cells/strain sensors for solids deposition
- adding access doors/viewports, test ports, and access platforms
- adding insulation

Modifications may also be required to the existing ESP. If ESP performance upgrades are required to control particulate emissions, several options, including increasing SCA, are available. ESP operating and maintenance considerations may require rapping cycle modifications and/or power-off rapping. Miscellaneous ESP modifications include maintenance and/or replacement of access doors, adding fluidizing air stones in the hoppers, and adding insulation at various locations to prevent cooling and resulting condensation and corrosion of the ESP surfaces.

Area 400 - Recycle System

To improve sorbent utilization, a portion of the solids collected in the ESP may be reinjected into the ductwork. These recycle solids are pneumatically transferred from the ash silo either directly back to the duct injection point(s) or to a recycle bin first and then to the duct(s). In either case, the solids are metered using a rotary feeder and then pneumatically transferred through the injection piping to the injectors in the duct. The recycle solids injectors are separate from the fresh hydrate injectors. Fluidizing air is used to facilitate flow of the recycle solids out of the silo or bin into the feeder.

Area 500 - Waste Handling System

The solids collected in the ESP are typically conveyed to an ash silo for temporary storage before being transported for utilization or final disposal. Due to the significant increase in solids loading caused by the addition of a DSI system, the capacity of the existing ash handling system may need to be increased and/or a new ash handling system might be needed. Incremental ash silo capacity may also be required if the existing storage capacity is not adequate. The waste solids are typically fed to an existing pug mill or rotary unloader where they are conditioned with blowdown water to control dusting and are then trucked to a waste disposal site. As with the conveying and storage equipment, additional equipment may be required to condition the increased waste solids.

Area 600 - General Support Equipment

General support equipment consists of the atomizing air compressors and receiver which supply the compressed air for the humidification water atomizing nozzles, humidification water

pumps, humidification water filters to filter any impurities/solids out of the blowdown water before it is injected into the duct, waste conditioning water pumps to pump the blowdown water to the pug mill, and a blowdown water tank. Two other items needed for the on-site hydration of pebble lime are a raw water tank and hydration water pumps to pump raw water to the hydrator.

Area 700 - Miscellaneous

This equipment area consists of the electrical supply switchgear and motor control centers, buildings and enclosures, HVAC, lighting, controls, and instrumentation.

1.2.1.2 Technical Aspects of Dry Sorbent Injection

Many factors influence the performance of a DSI system including the sorbent type, quantity of sorbent injected (calcium to sulfur stoichiometric ratio), quantity of recycle solids injected, relative humidity of the flue gas (approach to saturation temperature), and gas and solids residence time in the duct. Different sorbents may have different particle sizes which affect the amount of available surface area of the solid upon which the SO_2 in the gas will have to react. The quantity of sorbent injected affects the chances of an SO_2 molecule interacting with a lime particle; as more sorbent is injected, more SO_2 will be removed up to a point. After that point, injection of additional sorbent will yield incrementally diminishing returns in terms of SO_2 removal. The quantity of injected sorbent is usually reported as the number of moles of calcium hydroxide divided by the number of moles of SO_2 entering the duct injection point; this is referred to as the calcium to sulfur stoichiometric ratio or Ca/S ratio for short. Figure 1-3 shows a typical relationship of SO_2 removal versus Ca/S ratio for DSI.

Recycle of sorbent produces an improvement in sorbent utilization. By providing multiple exposures of sorbent to the flue gas, recycling increases the opportunity for a given sorbent particle to react with SO_2 . For a given level of SO_2 removal, increased utilization of the reagent will result in less unreacted sorbent in the waste product. Thus, recycle also will reduce the total quantity of waste which must be utilized or disposed.

Significant calcium-sulfur reactions will occur at duct injection conditions only if moisture is present. The relative humidity of the flue gas, then, has a substantial impact on SO_2 removal. Because relative humidity is very difficult to measure in a particulate-laden gas stream, the flue gas moisture content is typically reported in terms of how closely the actual (dry bulb) flue gas temperature approaches the saturation (wet bulb) temperature of the gas. This "approach temperature" provides an indirect measure of flue gas moisture content; the lower the approach temperature, the closer the gas is to being saturated. Reagent utilization and SO_2 removal are both strongly dependent on the relative humidity of the flue gas. As the approach to saturation temperature decreases, the potential for greater SO_2 removal and reagent utilization increases for a given Ca/S ratio. The operating approach temperature should be as low as practical, but there is a practical limit to how far the approach temperature can be lowered. As the gas becomes more moist, the potential for wall wetting, corrosion, and deposition of solids becomes greater. Figure 1-4 shows a typical relationship of SO_2 removal versus approach to saturation temperature for DSI.

SO₂ Removal vs. Ca/S Ratio

DSI - No Recycle

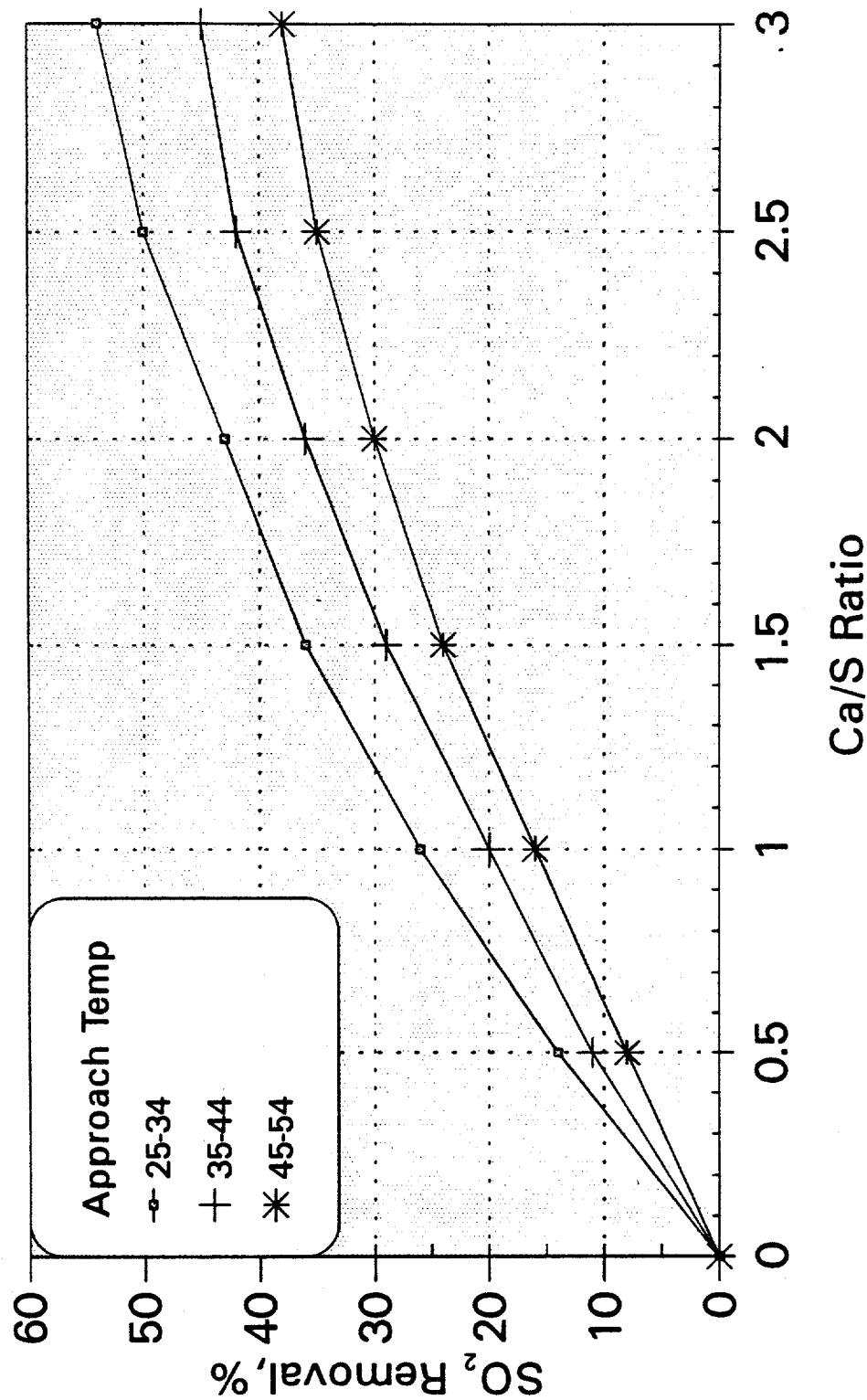


Figure 1-3

Source: Beverly DITF, Meredosa, EPRI, Coolside (no recycle, no additive)

SO₂ Removal vs. Approach Temperature

DSI - No Recycle

Ca/S Ratio approx. = 2.0

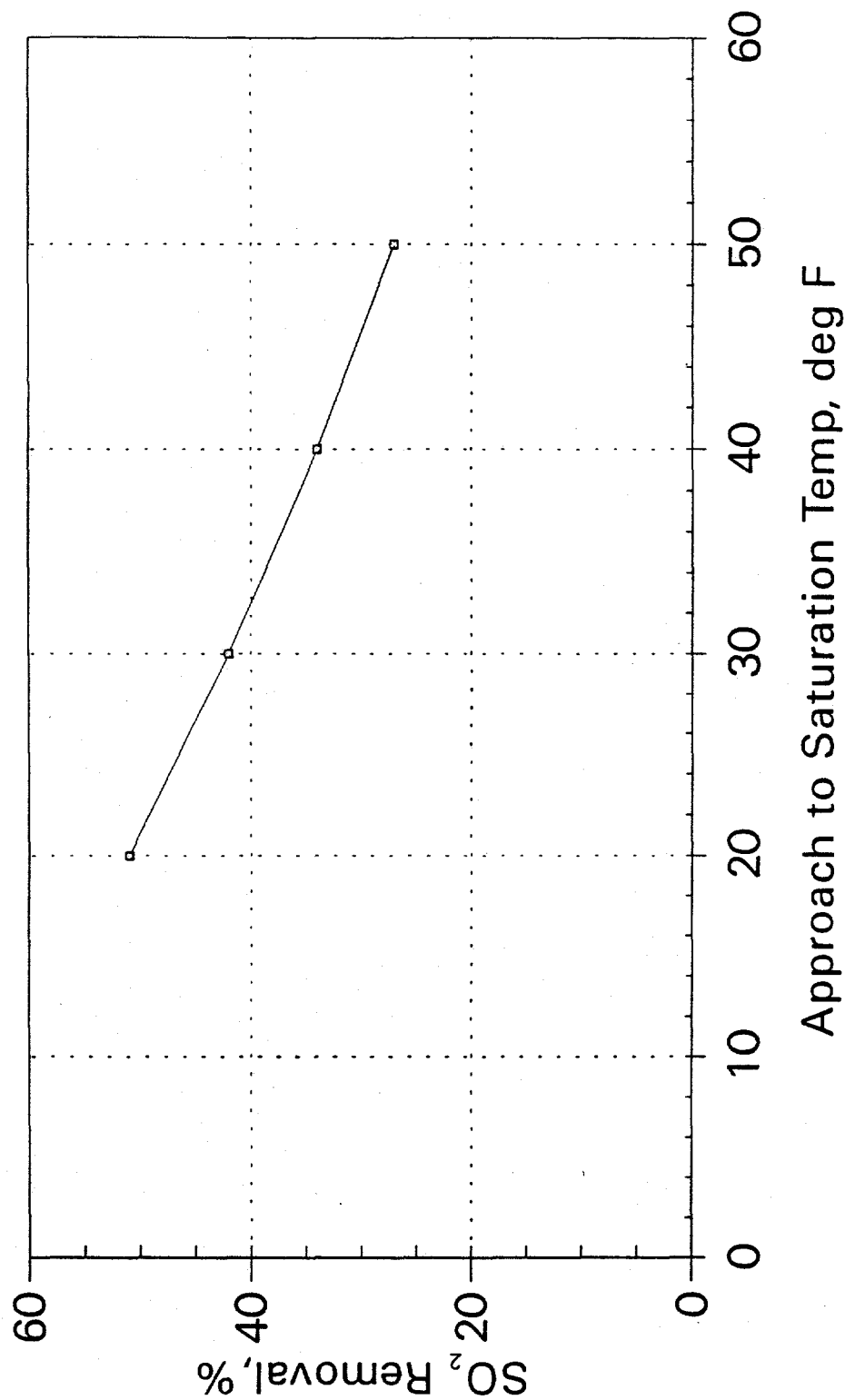


Figure 1-4

Source: Beverly DITF, Meredosia, EPRI, Coolside

The relative humidity of flue gas (or approach to saturation temperature) not only affects SO_2 removal but ESP performance as well. Humidifying the flue gas reduces the gas volume. The decrease in flue gas volume flow rate results in a higher net ESP SCA and a lower velocity. The increase in gas density allows the ESP to operate at higher power levels without back corona (sparking). These effects may allow better performance to offset the increase in particulate loading.

Gas and solids residence time in the duct must be adequate for the humidification water droplets to evaporate. The water droplets must vaporize before they impact a duct wall, a turning vane, or the inlet of the ESP. If the humidification droplet evaporation is not complete in this time frame (usually 1-2 seconds) then there will be adverse effects on the duct walls and ESP performance.

1.2.2 Duct Spray Drying (DSD)

DSD is a duct injection process in which pebble lime is slaked in a ball mill or other type of slaker and mixed with recycled solids collected in the ESP to form a slurry. This slurry is pumped to the duct(s) where it is injected into the flue gas flow just downstream of the air heater(s). Dual-fluid nozzles, using compressed air to atomize the slurry droplets, are used for slurry injection. The water in the slurry evaporates, which cools and humidifies the gas to the specified approach to saturation temperature. The fly ash, reaction products, and unused sorbent are collected in the ESP from which a portion of the solids are recycled for reinjection with the fresh sorbent. The remaining solids are transported to an ash silo and ultimately utilized or sent to a landfill for disposal.

Rotary atomizers were also considered and tested for injecting slurry in DSD. Very limited data are available for these types of atomizers. Furthermore, the configuration of the existing ductwork at the vast majority of power plants is not conducive to rotary atomizers. Round, vertical ducts, with the gas flowing downward, would be the most likely candidates for rotary atomization, and this configuration is rare among candidate power plants. For these reasons, dual-fluid nozzles will be the only atomizers discussed in this design handbook.

The chemistry of DSD is relatively straightforward. Pebble lime sorbent, which is mostly made up of calcium oxide $[\text{CaO}]$, is slaked to calcium hydroxide $[\text{Ca}(\text{OH})_2]$ slurry, and then injected into the duct(s). The majority of the SO_2 captured converts to calcium sulfite hemihydrate $[\text{CaSO}_3 \cdot \frac{1}{2}\text{H}_2\text{O}]$; the balance forms calcium sulfate dihydrate $[\text{CaSO}_4 \cdot 2\text{H}_2\text{O}]$ (gypsum). Reference Appendix B - Process Chemistry for a more detailed description of the process chemistry.

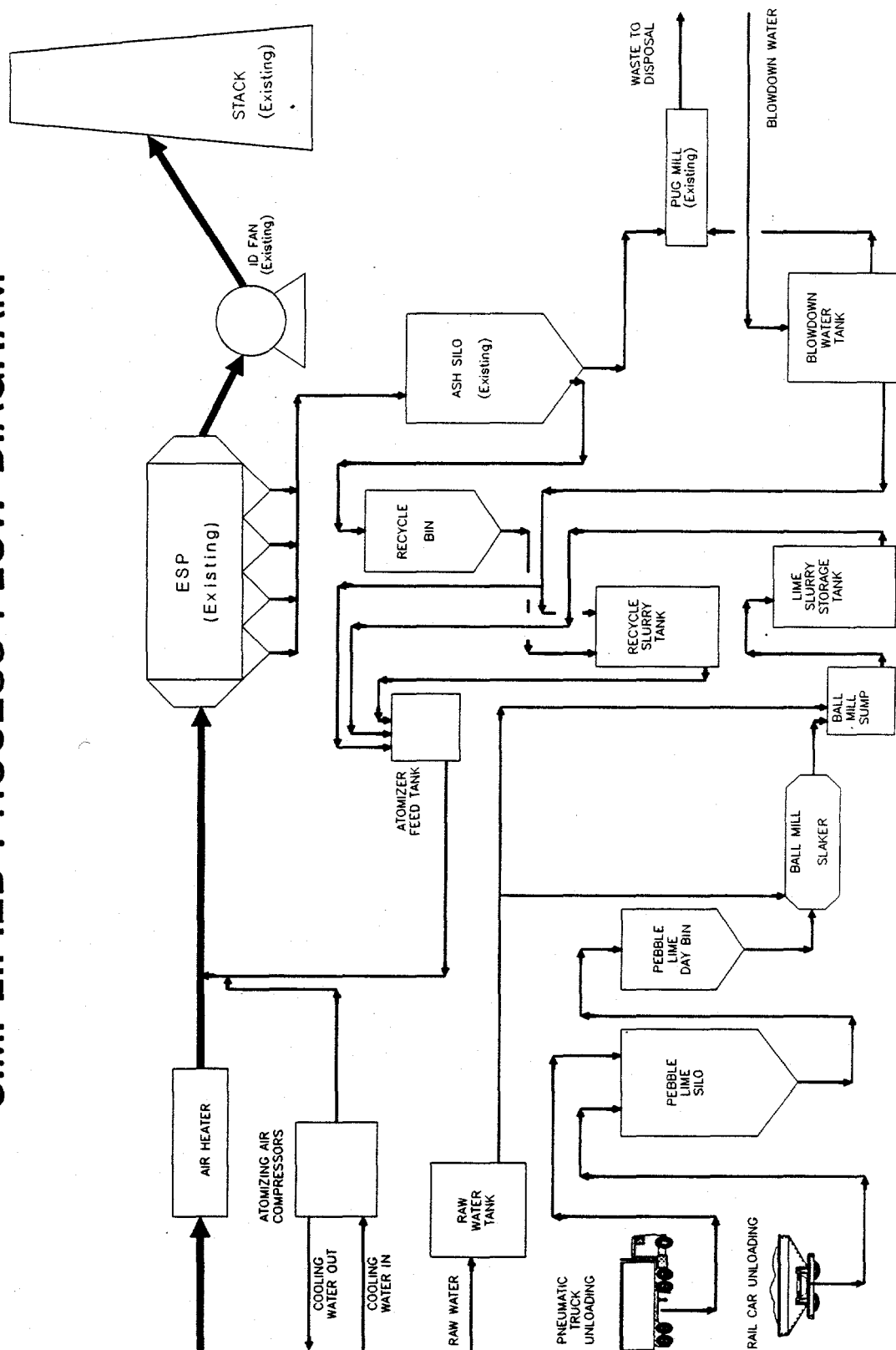
1.2.2.1 Process Description

The process components are grouped into areas according to function, e.g., sorbent storage and preparation, flue gas system, etc. Figure 1-5 shows a simplified DSD process flow diagram.

Area 100 - Sorbent Storage and Preparation System

Pebble lime is transported to the plant site by either enclosed truck or rail car. From the truck or rail unloading area, the pebble lime is pneumatically conveyed to a pebble lime silo(s) for storage. If the silo(s) has to be located relatively far away from the injection ductwork due to rail car unloading or other site-specific constraints, the pebble lime from the storage silo(s)

FIGURE 1-5
DUCT SPRAY DRYING
SIMPLIFIED PROCESS FLOW DIAGRAM



is pneumatically conveyed to a small pebble lime day bin located near the injection point. If the silo(s) can be located close to the duct injection point, a separate day bin is not required.

From the day bin (or silo) the lime is fed through a weigh belt feeder to a ball mill or other type of slaker where the pebble lime is slurried to calcium hydroxide using raw (fresh) water. If necessary, a slaking water heater is utilized to heat the raw water before it contacts the lime in the slaker; this is done to maintain a high slaking temperature (170-190°F) which results in the most reactive slurry. The slurry product from the slaker is pumped through a lime grit screen to a lime slurry storage tank for short-term storage. The lime slurry sorbent is then transferred from the storage tank to the atomizer feed tank from which it is pumped to the flue gas duct(s).

Area 200 - Humidification/Sorbent Injection System

Fresh lime slurry is injected cocurrently into the flue gas flow path using dual-fluid nozzles. Compressed air is injected into the nozzles to atomize the slurry droplets. It is in this section of the duct that the majority of the SO₂ removal occurs.

Area 300 - Flue Gas System

Modifications to the existing ductwork are required to accommodate the array of dual-fluid nozzles. Flue gas flow correction devices may need to be installed upstream of the injection point to ensure relatively uniform velocity and temperature profiles at the injection point. Internal duct bracing and/or stiffeners should be removed to minimize sites for solids deposition. Devices may need to be installed to mitigate the negative impacts of any solid build-up; sootblowers, sonic horns, and rappers are examples of such devices.

Additionally, modifications to the duct externals may be required to facilitate the retrofit and operation of a DSD system:

- shoring up existing support steel and adding load cells/strain sensors for solids deposition
- adding access doors/viewports, test ports, and access platforms
- adding insulation

Modifications may also be required to the existing ESP. If ESP performance upgrades are required to control particulate emissions, several options, including increasing SCA, are available. ESP operating and maintenance considerations may require rapping cycle modifications and/or power-off rapping. Miscellaneous ESP modifications include maintenance and/or replacement of access doors, adding fluidizing air stones in the hoppers, and adding insulation at various locations to prevent cooling and resulting condensation and corrosion of the ESP surfaces.

Area 400 - Recycle System

To improve sorbent utilization, and to maintain an adequately high percent solids in the feed slurry, a portion of the solids collected in the ESP are reinjected into the ductwork. These recycle solids are pneumatically transferred from the ash silo to a recycle bin. From the recycle bin, these solids are metered using a rotary feeder into a recycle slurry tank where they are slurried with blowdown water. Fluidizing air is used to facilitate flow of the recycle solids out of the bin into the feeder. The recycle slurry is then pumped from the recycle slurry

tank through a recycle grit screen to the atomizer feed tank where it mixes with the fresh lime slurry. If necessary, the fresh sorbent/recycle solids slurry is diluted with blowdown water in the feed tank to attain the desired feed slurry solids content. The feed slurry is then pumped to the nozzles in the duct.

Area 500 - Waste Handling System

The solids collected in the ESP are typically conveyed to an ash silo for temporary storage before being utilized or transported to final disposal. Due to the significant increase in solids loading caused by the addition of a DSD system, the capacity of the existing ash handling system may need to be increased and/or a new ash handling system might be needed. Incremental ash silo capacity may also be required if the existing storage capacity is not adequate. The waste solids are typically fed to an existing pug mill or rotary unloader where they are conditioned with blowdown water to control dusting and are then trucked to a waste disposal site. As with the conveying and storage equipment, additional equipment may be required to condition the increased waste solids.

Area 600 - General Support Equipment

General support equipment consists of the atomizing air compressors and receiver which supply the compressed air for the slurry atomizing nozzles, slaking water pumps which pump raw water to the slaker, dilution water pumps for supplying blowdown water to dilute the feed slurry in the atomizer feed tank, recycle ash water pumps which pump blowdown water to the recycle slurry tank, waste conditioning water pumps to pump blowdown water to the pug mill, and the raw water and blowdown water tanks.

Area 700 - Miscellaneous

This equipment area consists of the electrical supply switchgear and motor control centers, buildings and enclosures, HVAC, lighting, controls, and instrumentation.

1.2.2.2 Technical Aspects of Duct Spray Drying

Many factors influence the performance of a DSD system including quantity of sorbent injected (calcium to sulfur stoichiometric ratio), quantity of recycle solids injected, relative humidity of the flue gas (approach to saturation temperature), solids content of the feed slurry, and gas and solids residence time in the duct. The quantity of sorbent injected affects the chances of an SO_2 molecule interacting with a lime particle; as more sorbent is injected, more SO_2 will be removed up to a point. After that point, injection of additional sorbent will yield incrementally diminishing returns in terms of SO_2 removal. The quantity of injected sorbent is usually reported as the number of moles of calcium hydroxide divided by the number of moles of SO_2 entering the duct injection point; this is referred to as the calcium to sulfur stoichiometric ratio or Ca/S ratio for short. Figure 1-6 shows a typical relationship of SO_2 removal versus Ca/S ratio for DSD.

Recycle of sorbent produces an improvement in sorbent utilization. By providing multiple exposures of sorbent to the flue gas, recycling increases the opportunity for a given sorbent particle to react with SO_2 . For a given level of SO_2 removal, increased utilization of the reagent will result in less unreacted sorbent in the waste product. Thus, recycle also will reduce the total quantity of waste which must be utilized or disposed.

SO₂ Removal vs. Ca/S Ratio DSD w/Recycle

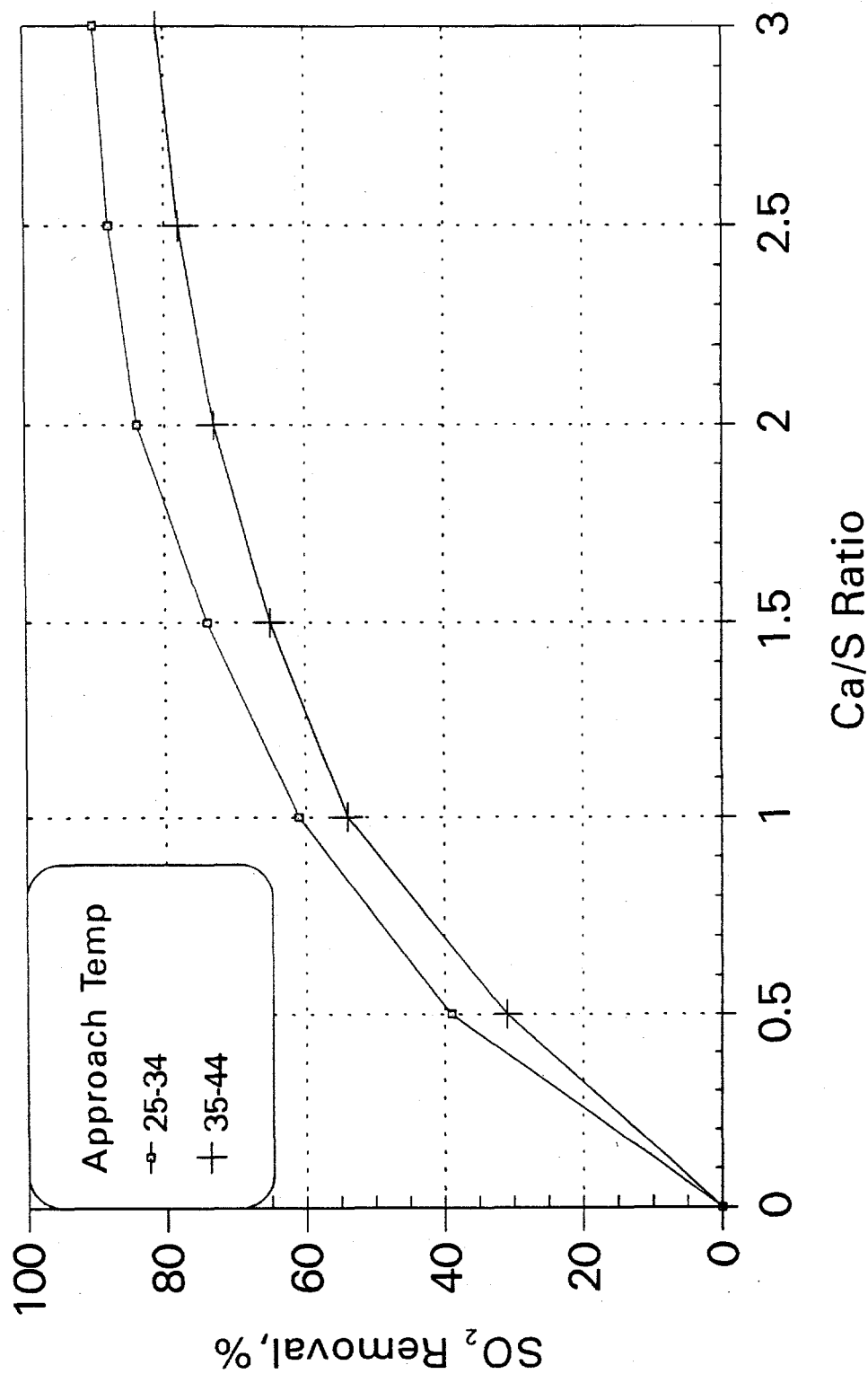


Figure 1-6

Source: Beverly DITF

Significant calcium-sulfur reactions will occur at duct injection conditions only if moisture is present. The relative humidity of the flue gas, then, has a substantial impact on SO_2 removal. Because relative humidity is very difficult to measure in a particulate-laden gas stream, the flue gas moisture content is typically reported in terms of how closely the actual (dry bulb) flue gas temperature approaches the saturation (wet bulb) temperature of the gas. This "approach temperature" provides an indirect measure of flue gas moisture content; the lower the approach temperature, the closer the gas is to being saturated. Reagent utilization and SO_2 removal are both strongly dependent on the relative humidity of the flue gas. As the approach to saturation temperature decreases, the potential for greater SO_2 removal and reagent utilization increases for a given Ca/S ratio. The operating approach temperature should be as low as practical, but there is a practical limit to how far the approach temperature can be lowered. As the gas becomes more moist, the potential for wall wetting, corrosion, and deposition of solids becomes greater. Figure 1-7 shows a typical relationship of SO_2 removal versus approach to saturation temperature for DSD.

The relative humidity of flue gas (or approach to saturation temperature) not only affects the SO_2 removal but ESP performance as well. Humidifying the flue gas reduces the gas volume. The decrease in flue gas volume flow rate results in a higher net ESP SCA and a lower velocity. The increase in gas density allows the ESP to operate at higher power levels without back corona (sparking). These effects may allow better performance to offset the increase in particulate loading.

The solids content of the feed slurry pumped to the duct injection point affects how easily the resulting slurry droplets will dry. A relatively dilute feed slurry (less than 20% solids) will likely result in significant wall deposits even at moderate approach temperatures. More concentrated feed slurries (30-40% solids) result in better drying of the slurry droplets and lower achievable approach temperatures without wall deposition.

Gas and solids residence time in the duct must be adequate for the slurry droplets to evaporate. The water in the slurry droplets must vaporize before they impact a duct wall, a turning vane, or the inlet of the ESP. If the drying of the slurry droplet is not complete in this time frame (usually 1-2 seconds), then there will be adverse effects on the duct walls and ESP performance.

SO₂ Removal vs. Approach Temperature

DSD

Fresh Ca/S Ratio approx. = 1.0

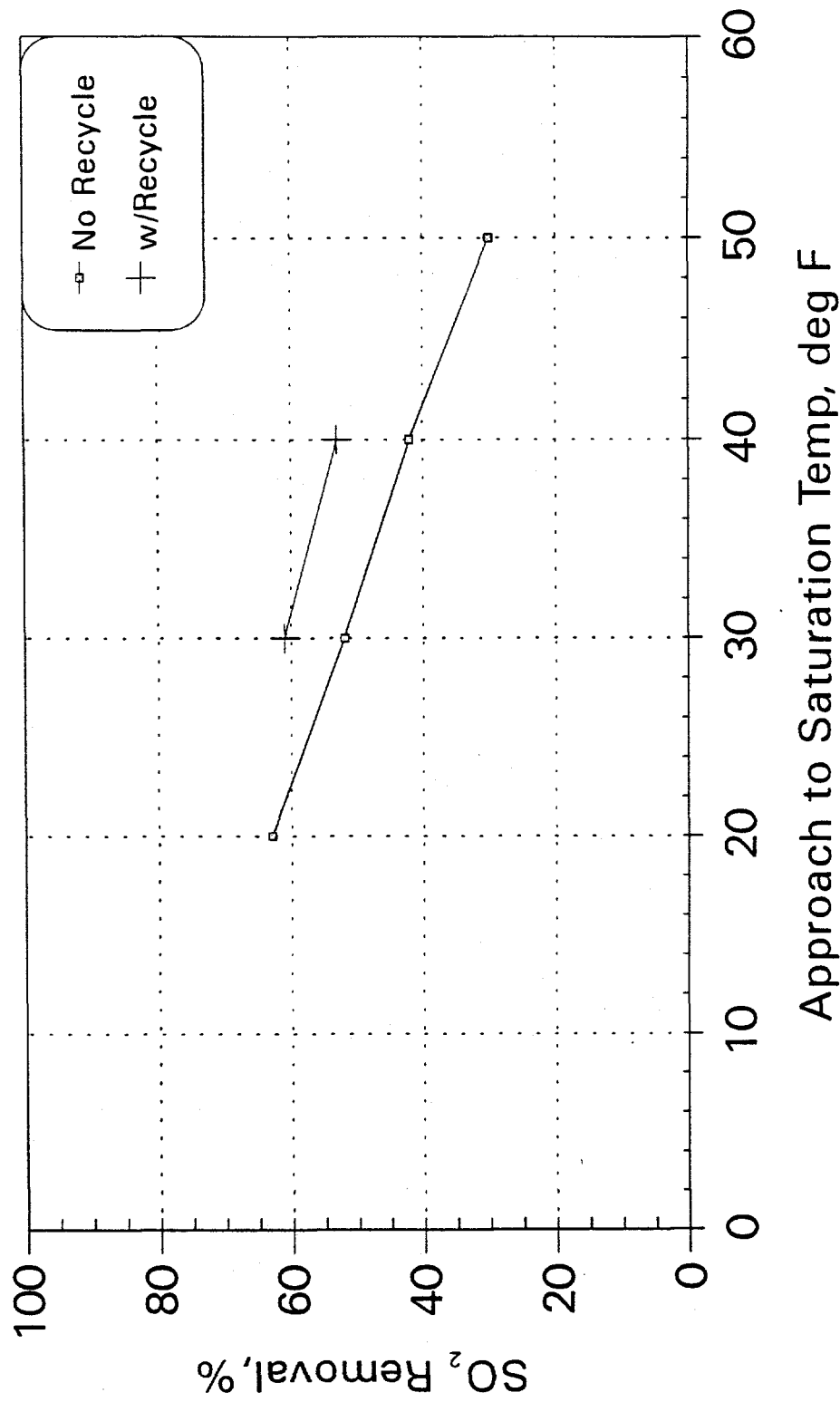


Figure 1-7

Source: Beverly DITF

1.3 References

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2. Muzio, L. J., Offen, G. R., and McElroy, M. W., "Assessment of Dry Sorbent Emission Control Technologies - Part II. Applications", JAPCA, August 1987, Volume 37, No. 8, pages 968-980.
3. "Economic Evaluation of Flue Gas Desulfurization Systems", EPRI Report No. GS-7193, Volume 1, February 1991.
4. "Fundamental Investigation of Duct/ESP Phenomena: 1.7 MW Pilot Parametric Testing Results", Radian Corporation, U.S. DOE-PETC Contract No. DE-AC22-88PC88850, Topical Report No. 2, July 1991.
5. Beverly DITF Monthly Status Reports, Gilbert Commonwealth/Southern Research Institute, U.S. DOE-PETC.
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2.0 DECISION MAKING CRITERIA FOR SITE-SPECIFIC APPLICATIONS

The acid rain provisions (Title IV) of the 1990 amendments to the Federal Clean Air Act offer operators of coal-fired boilers many options in reducing sulfur oxide emissions. This section provides information to guide potential users to determine if duct injection technologies are a viable choice to meet their SO₂ reduction needs. If, at the completion of the exercises in this section, the user determines that duct injection is viable, then the system design process can proceed as described in Section 3.0.

The criteria fall into three general categories:

- **SO₂ Removal (Section 2.1)**

Can duct injection meet the SO₂ removal requirements of the user's application?

- **Technical (Section 2.2)**

Are there technical limitations which would make this retrofit infeasible?

- **Economic (Section 2.3)**

Can duct injection be cost effective for the user's application?

Some of the data required to complete the exercises in Sections 2.1-2.3 may not be readily available to the user. Section 2.4 provides guidance in obtaining the necessary information to conduct these evaluations. The data collected on Worksheet 2-1 are to be evaluated by the above criteria.

2.1 SO₂ Removal

Can Duct Injection Meet the SO₂ Removal Requirements of the User's Application?

The standard duct injection technologies (DSI and DSD) are capable of up to 50% SO₂ removal within the proven operating conditions and without the use of additives. Duct injection is capable of up to 70% SO₂ removal under certain operating conditions including the use of additives. Achieving 50 to 70% SO₂ removal will likely involve additional operating costs and higher risk.

At the time of this publication, if the user required level of SO₂ removal is greater than 70%, duct injection is not considered feasible.

2.2 Technical

Are there Site-Specific Technical Limitations Which Would Make this Retrofit Infeasible?

The potential technical roadblocks for retrofitting duct injection systems are organized into five major categories.

1. Is the plant ductwork of sufficient size and geometry to provide the necessary drying time for slurry or humidification or slurry droplets?

2. Can the existing particulate control device maintain particulate emissions and opacity compliance after the retrofit of duct injection?
3. Can the user's ash handling system be upgraded to accommodate the increased waste solids generated by duct injection?
4. How will the existing waste disposal program be affected by duct injection?
5. Can the existing chimney be used after the duct injection retrofit?

The following guidelines are general and not intended to be representative of all applications. The user must base decisions on not only the information gathered for these exercises, but on first-hand knowledge of the site and equipment performance characteristics. This section is included to make the user aware of some of the most common retrofit problems that could be encountered. The user must weigh each issue carefully with all of the known aspects of the particular application. The technical issues discussed below can, but do not necessarily, represent absolute Go/No Go decisions.

2.2.1 Is the Plant Ductwork of Sufficient Size and Geometry to Provide the Necessary Drying Time for Humidification or Slurry Droplets?

Unlike many SO₂ absorption processes, duct injection does not use absorber vessels or other new chambers for SO₂-reagent reactions. The existing plant ductwork and particulate collector act as the reaction vessel in duct injection processes.

The slurry or the dry hydrate and humidification water, or slurry, are injected into the ductwork downstream of the air heater and upstream of the particulate control device. The water or slurry droplets must evaporate before colliding with duct walls, obstructions, elbows or bends. Failure to reach adequate levels of evaporation results in wall wetting, wet solids deposition and ductwork plugging.

Typically, the atomizer nozzles are installed at the beginning of the longest straight run of duct between the air heater and particulate collector. There are many variables affecting the evaporation rate of droplets including flue gas temperature, flue gas velocity, droplet size, amount of liquid injected and final flue gas temperature. Even with sophisticated three-dimensional computer models, accurately predicting evaporation rates and droplet trajectories is difficult.

There are two areas of concern: the first and most straightforward is droplet/solids deposition on surfaces directly downstream of the atomizer plane. These surfaces include turns or bends in the ductwork, internal bracing, turning vanes, perforated plates, etc. For typical utility boiler flue gas conditions (300°F, 60 ft/sec) and using dual-fluid atomizers suitable for duct injection:

A minimum of two seconds residence time in the longest straight run of duct, before duct injection is installed, is recommended to operate without deposition over a normal range of operating conditions for duct injection.

It is recommended that all internal obstructions be removed. Internal bracing should be replaced by external stiffeners. Note that this one second residence time value is very general, but it is a good rule of thumb. For a more detailed analysis, refer to Section 3.0.

Applications requiring lower quantities of water or slurry (due to low initial temperature or higher approach temperature), or those achieving a finer drop size due to improvements in atomizer technology, may require less than 2 seconds.

The second concern of wall wetting and wet solids deposition is wall impingement from the atomizer spray pattern and jet entrainment/flue gas expansion. Atomizer spacing and wall clearance guidelines have been established. This imposes some practical limitations on the size and geometry of the duct in which the atomizers are installed. Wall impingement is less likely in square ducts than in tall, narrow ducts since the required number of atomizers can more easily be arranged within the acceptable spacing guidelines.

A minimum of two (2) feet clearance is required between the perimeter atomizer and the duct roof and sidewalk. Three (3) feet or more is required between the bottom most atomizer and the duct floor.

It is important to note that most of the problems associated with wet solids deposition and plugging can be solved by installing additional equipment, such as new specially-designed ductwork and/or duct hoppers to collect and remove deposits; however, these modifications are not usually cost effective.

2.2.2 Can the Existing Particulate Control Device Maintain Particulate Emissions and Opacity Compliance after the Retrofit of Duct Injection?

This section will focus primarily on electrostatic precipitators (ESPs). Fabric filters in most cases will maintain emissions compliance with duct injection. Some modifications may be required, such as cleaning cycle, insulation, and ash removal procedures, but in general, fabric filters are considered the ideal particulate control device for duct injection processes.

ESPs, however, are by far the great common particulate control device on candidate plants for duct injection retrofit. They represent one of the most important and difficult to evaluate issues affecting the retrofit feasibility of duct injection. Regardless of the site specifics, there will be a variety of modifications required to enable any ESP to operate reliably downstream of duct injection. These include changes to T-R set control settings, rapper sequence/pattern modifications, adding insulation and changes to hopper ash removal procedures. This discussion is not intended to address these issues, but to help the user determine if the size and design of a candidate ESP can accommodate duct injection or if enlargement or replacement of the existing unit is required.

First, the user should assess the current operating status of the candidate ESP. The user should compare the measured emissions and opacity to the regulatory limits.

If performance is marginal and opacity exceedences are frequent, the ESP should be upgraded or replaced before considering duct injection.

A poorly or marginally performing ESP will not be capable of achieving emissions compliance after the retrofit of duct injection.

Depending on the desired SO₂ removal and coal sulfur content, duct injection will increase the mass loading to an ESP by 5-15 gr/acf; this corresponds to an increase in loading to the ESP by a factor of 3-12. An ESP basically operates on an efficiency basis which means that, at any set operating condition, an increase in inlet mass loading will result in an increase in outlet

emissions. Therefore, in order to maintain particulate outlet loading and opacity levels while the inlet loading increases, ESP efficiency must increase.

One factor that may result in a net increase in ESP efficiency is the positive effect of low temperature, high humidity flue gas resulting from the water or slurry injection. Humidification in most cases will result in ideal ESP electrical conditions because the high humidity lowers the surface resistivity of the particulate. However, it is possible to reduce the resistivity too far, which may result in higher reentrainment emissions from the ESP. This is discussed in Section 6.3.4. Reentrainment emissions account for a large percentage of the total emissions from most ESPs and can be caused by rapping, velocity scouring, hopper sweepage and electrical repulsion. Flue gas velocity has a strong effect on reentrainment regardless of what causes the reentrainment. ESPs operating with high flue gas velocities (greater than 6 ft/sec) may not operate efficiently under duct injection conditions since reentrainment will likely be worse. These ESPs may require enlargement or other upgrades. ESP upgrade strategies are discussed in Section 6.3.4.2.

There is insufficient operating experience to predict with much accuracy what effect duct injection will have on the performance of a given ESP. The successful full-scale utility installations of spray dryers and DSI systems have ESPs larger than 500 SCA. There is limited pilot-plant data on smaller ESPs, which have indicated mixed results. These include pilot studies of lime spray dryers and DSI and DSD systems. In some programs, low-resistivity reentrainment resulted in excessive opacity and mass emissions. From these results, a conservative assessment suggests that a minimum of 400 SCA may be necessary to operate a duct injection process across the expected range of operating conditions and maintain outlet emissions at, or below, the candidate plants allowable particulate emission limit. This is extremely application specific and may vary considerably. For the purposes of this exercise, however, the user should assume that **if the candidate ESP has less than 400 SCA, some sort of upgrade may be required.** If there is no space provided (i.e., empty field) to add collection area, the user should determine if there is adequate space to enlarge the existing ESP. Enlarging an existing ESP, adding an additional ESP in series or in parallel, or replacing the existing ESP with a new ESP or fabric filter are all expensive options. This must be evaluated carefully.

2.2.2 Can the User's Ash Handling System Be Upgraded to Accommodate the Increased Waste Solids Generated by Duct Injection?

As described above, duct injection can increase the solids collected in the ESP by a factor of 3 to 12.

In addition to capacity concerns, the physical and chemical properties of the duct injection waste solids may require other upgrades to the ash handling system. These properties include increased moisture, increased cohesivity, low temperature and increased alkalinity. The most significant potential problems are a general decrease in flowability and increased moisture/condensation which can lead to plugging. Each type of ash removal system (pneumatic, mechanical, or wet sluice) will be affected differently.

Even though many ash handling systems are oversized, it is unlikely that many will have sufficient excess capacity to handle the duct injection burden. **Upgrades to the ash handling and storage system will be necessary.** In many cases, complete replacement of the ash handling system will be the most cost-effective choice. The example economic analysis in Section 2.3 includes a new ash handling system.

2.2.4 How Will the Existing Waste Disposal Program be Affected by Duct Injection?

In addition to the impacts on the ash handling equipment and its operation, the increase volume and altered characteristics of the duct injection solid waste will require a review of the user's solid waste disposal program. Duct injection waste is not considered hazardous by any of the current federal standards. The user should review the information in Appendix D "Waste Characterization and By-Product Utilization" with the terms and conditions of the current waste disposal permit. This could have a major impact on whether or not the retrofit of a duct handling system is practical.

The increased waste volume will likely affect long-term disposal plans because the existing site will reach capacity at a faster rate. If the current disposal site capacity is reached before the plant is scheduled for closure, additional disposal site(s) and associated permits will be required.

The physical properties may require changes in landfill practices due to differences in strength and flowability (see Appendix D).

If fly ash is currently a usable or saleable by-product, the duct injection waste may affect its suitability. Duct injection waste is probably not suitable as an admixture for cement per the ASTM-C618 requirements, but other favorable utilization options are described in Appendix D and should be evaluated in order to reduce disposal costs.

All of these issues must be reviewed by the user before proceeding with a duct injection retrofit.

2.2.5 Can the Existing Chimney be Used after the Duct Injection Retrofit?

There are concerns that the low temperature, high humidity flue gas conditions from duct injection processes may lead to corrosion and erosion in chimney flues designed for hot, dry flue gas. Many of the plants which may consider duct injection are expected to be older units equipped with carbon steel or non-acid resistant brick stack liners. **Stacks with carbon steel or non-acid resistant brick liners may require upgrades.** It is recommended that the user contact the stack OEM or chimney specialist to evaluate the suitability of the existing stack for a duct injection retrofit.

Application on units sharing a common stack flue present a special problem. If duct injection flue gas mixes with hot untreated flue gas from another unit, even small concentrations of SO_3 will likely result in the formation of H_2SO_4 droplets, which can cause severe corrosion and a possible visible acid plume.

Stacks which are evaluated to be unsuitable for duct injection may require the installation of an acid resistant liner (e.g., brick, FRP, flaked glass) or a flue gas reheat system downstream of the ESP. It may, however, be more economical in many cases to erect a new chimney (with acid resistant materials) on units retrofit with duct injection systems due to the outage requirements for relining a chimney or the high operating cost of a flue gas reheat system.

2.3 Economic

Can Duct Injection be Cost Effective for the User's Application?

The viability of duct injection as an SO₂ control technology depends upon its cost effectiveness. This section will present a generic economic analysis of the DSI and DSD processes based on a hypothetical application. This information is intended to help the user determine if duct injection costs fall within an acceptable range, and provide a point of comparison to other options under consideration. A very detailed cost analysis of each process is contained in Appendix A for the example case studies. Guidelines for the user to estimate costs based on a specific design are provided in Section 12. This section will present the total capital cost requirements and levelized control costs for a hypothetical application. In addition, the cost impacts of major plant upgrades, such as new ESPs and chimneys, are addressed. For comparison purposes, duct injection costs are compared with wet flue gas desulfurization for the same cases. The effect of plant size, coal sulfur and SO₂ removal on these costs are presented in a series of sensitivity analyses to allow the user to compare these cost data with the candidate application.

2.3.1 Capital and Levelized Costs

The hypothetical reference plant used in the detailed cost analyses presented in Appendix A is a 250 MW net generating capacity plant located in Ohio. The plant fires a 2.6% sulfur bituminous coal and has a 55% annual capacity factor. The plant is assumed to have a remaining plant life of 15 years and the existing plant arrangement will cause the retrofit of a duct injection system to be of medium difficulty. Both the DSD and DSI processes are designed for 50% removal of the SO₂ entering with the flue gas. For comparison purposes only, a Furnace Sorbent Injection Process (FSI) was evaluated under mostly the same criteria except for approach to saturation temperature, which was set at 80°F, and a Limestone Forced Oxidation Wet Scrubber Process (LSFO) was also evaluated under mostly the same criteria except for SO₂ removal, which was set at 95%. The process design basis for all configurations is listed in Table 2-1.

The factors involved in deciding to install a duct injection system revolve around the system capital and levelized costs. The capital cost is the total capital required to purchase, construct, and start-up a duct injection system. The main component of the capital cost is the equipment capital and installation costs. The equipment installation costs include all required earthwork, concrete, and associated tasks involved in construction, and all labor charges, taxes, construction equipment and fees. Process and project contingencies, as well as general facilities and engineering fees are also included in the capital cost.

Figure 2-1 presents the total capital requirement of the DSD, DSI, FSI, and LSFO processes in 1992 dollars. The capital cost requirement is only slightly more for DSI than for DSD. However, the capital requirement for the FSI process is approximately 25% less than that of the duct injection processes, and the LSFO process is approximately three times that of the duct injection processes. The increased capital cost for LSFO is due to the larger and more complex equipment requirements for the scrubber system compared to the duct injection systems.

Although duct injection technologies offer very low capital costs, the cost to operate these systems can be high due to their characteristically low sorbent utilization and expensive lime sorbent. A levelized cost analysis can be used to combine capital and operating costs.

TABLE 2-1

DESIGN BASIS FOR ECONOMIC ANALYSES

Item	DOE Base Center	
Plant Size (Net)	250 MW	
Capacity Factor	55%	
Coal Type	Bituminous	
Coal Sulfur	2.6% (3.0% Design)	
Plant Location	Ohio	
Discount Rate (MAR)	11.53%	
1st Year Fixed Charge Rate	24.5%	
Levelized Fixed Charge Rate	19.7%	
Remaining Plant Life	15 Years	
Retrofit Difficulty	Medium	
Item	DSD, DSI, FSI	LSFO
Construction Time	< 1 Year	2 Years
SO ₂ Removal	50%	95%
Ca/S	DSD = 1.1 DSI, FSI = 2.0	1.1
Recycle	DSD, DSI = Yes FSI = N/A	N/A
L/G	N/A	140
Sorbent Receiving	Pneumatic Trucks	Pneumatic Trucks
Sorbent Storage	7 Days	15 Days
Sorbent Type	Quicklime (95% Available)	Limestone
Sorbent Cost (FOB Mine)	\$62/Ton	\$16.50/Ton
Sorbent Transportation Distance	100 Miles	100 Miles
Hydration for DSI, FSI	At Plant	N/A
Waste Disposal	\$8/Ton	\$8.15/Ton
Reaction Vessel--Type/Quantity	DSD, DSI = Duct--2 @ 50% FSI = Boiler--1 @ 100%, Duct--2 @ 50%	Spray Tower--1 @100%

CAPITAL COSTS of DUCT INJECTION*

Total Capital Required

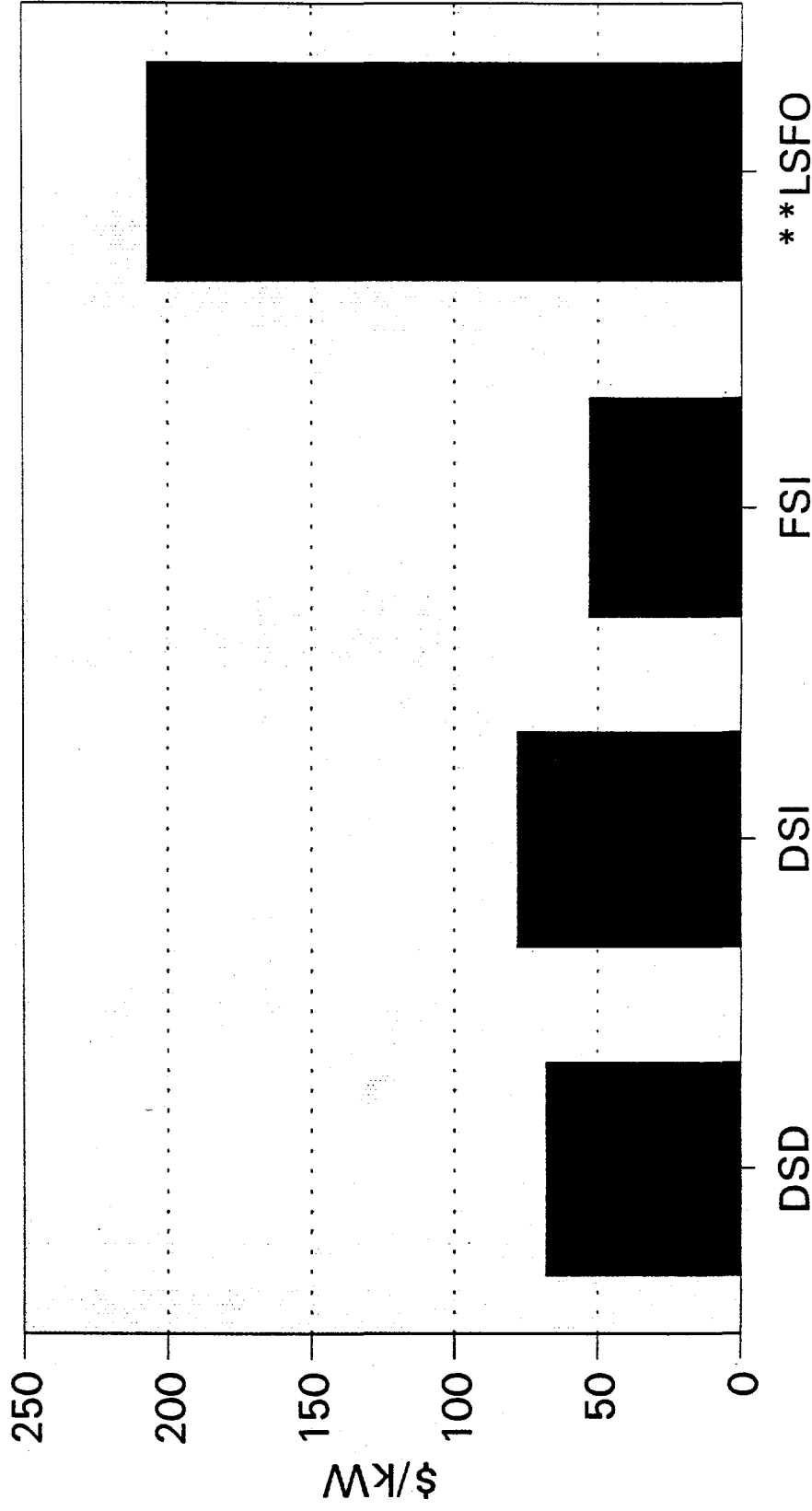


Figure 2-1

* 1992 Dollars

** Acid Rain Scrubber, Single Absorber, 95% Removal

Levelized control costs are presented in terms of dollars per ton of SO₂ removed. The levelized values incorporate both fixed capital, fixed operating and variable operating costs. The levelized values represent a convenient measure for comparing alternatives which have different capital and operating costs. Levelized annual costs are a hypothetical equal annual series of costs, which have the same present worth as the projections of annual costs which vary from year to year. Therefore, levelized annual costs will lead to the same decision as present worth values since the two parameters vary only by a constant (the capital recovery factor).

Figure 2-2 presents the levelized control costs for the four processes for the 15 year remaining plant life. A major factor in this type of levelized cost comparison is the total annual tons of SO₂ removed. Higher efficiency technologies such as LSFO at 95% SO₂ removal will, in many cases, have lower levelized control costs than 50% removal technologies such as DSI and DSD. However, in this comparison, DSD is the least costly followed by approximately equal levelized costs for FSI and LSFO. DSI is the most costly. DSI levelized costs are high because of the very low sorbent utilization of this process.

2.3.2 Cost Sensitivity Analysis

The capital and levelized control costs described above illustrate one hypothetical example application. This section presents the cost sensitivity of a few important design parameters in order to illustrate how some key variables, such as major plant equipment upgrades, plant size, coal sulfur, SO₂ removal level, and air to liquid ratio, affect the cost of duct injection processes. This information should provide the user with some relative comparison points to evaluate the economic viability for a given application.

For simplicity, these sensitivity analyses all start with the same set of base design, operating and economic parameters shown in Table 2-1. Each sensitivity analysis involves varying one parameter (e.g., plant size) while all other parameters remain at their base value.

Cost of Plant Upgrades. Retrofit of a duct injection process at some utility sites may require major plant upgrades. These upgrades might include adding a second ESP and installing a new, acid resistant lined chimney. Many existing ESPs may be too small to maintain current or future particulate emissions levels and/or opacity with the increased solids from duct injection. A new chimney may be required at older plants that do not have an acid resistant liner in their existing stack.

The major plant upgrade required for the LSFO process is the construction of a new stack. The new stack requirement philosophy is the same as for the duct injection processes. For this example evaluation, it is assumed that no ESP upgrades are required for the LSFO Case.

Figure 2-3 presents the capital costs for the base SO₂ removal system (as included in Figure 2-1) plus the major plant upgrades described above. For the DSI, DSD and FSI cases, a second 200 SCA ESP of modern design, with interconnecting ductwork and new ash handling system, was installed downstream of the existing ESP. The capital cost for the LSFO process is still the most costly but, rather than being almost three times the cost of the other three processes, it is only approximately 1.5 times the capital required for the duct injection processes.

Figure 2-4 presents the levelized control costs for the remaining plant life, including the major plant upgrades described above. With the inclusion of the new ESP and acid resistant

chimney, the levelized control costs of the DSI and DSD processes, and the FSI process with a new ESP, are higher than the LSFO levelized cost. The DSI levelized cost is approximately 1.2 times greater than FSI, and 1.6 times greater than that for LSFO. The DSD levelized cost is approximately equal to FSI, and 1.4 times greater than that for LSFO. These differences are due to the increased capital and operating cost requirements of the new ESP.

Plant Size. Figure 2-5 presents a sensitivity of DSD, DSI, FSI, and LSFO process levelized control costs versus gross unit size. The data show that, for plants with gross unit capacities of less than 420 MW, DSD is the least cost process in terms of \$/ton SO₂ removed. LSFO is the least expensive for plants with greater than 420 MW gross capacity.

Coal Sulfur. Figure 2-6 presents the cost sensitivities to the percent sulfur in the coal. The data show that DSD is the most economical choice up to 4% coal sulfur. DSD and DSI are not proven on higher than 4% sulfur coals. Coal sulfur content greater than 4% shows LSFO being the favored process.

SO₂ Removal. Figure 2-7 presents the DSD, DSI, and FSI process cost sensitivities to percent SO₂ removal. The range of SO₂ removal evaluated ranges from 25% to 75%. Costs take into account the reagent requirements and sorbent utilization at each SO₂ removal rate. All three processes have nearly equal levelized costs for 25% SO₂ removal, but at higher removals the FSI process becomes significantly less expensive than both the DSD and DSI processes. LSFO was not included on this sensitivity curve because the LSFO process is typically designed for SO₂ removals 90% or greater.

Air to Liquid Ratio. Figure 2-8 presents the DSD and DSI process cost sensitivities to the air to liquid ratio for slurry injection into the duct. The data shows that the DSD process is slightly more sensitive to changes in the air to liquid ratio. However, DSD is consistently the most economical in varying the air to liquid ratio due to the reduced amount of slurry required, compared to the DSI process.

The variables that must be considered when choosing a SO₂ removal system include capital and levelized cost expenditures as well as site feasibility and the modifications that must be made to accommodate a particular system. When considering a duct injection technology, the user of this handbook should consider the overall feasibility of the technology compared to other options based on capital and levelized costs, and on cost sensitivities for the processes. Duct injection processes are typically desirable on smaller generating capacity units firing low to medium sulfur coal, with low to medium SO₂ removal requirements.

2.4 Plant Data Requirements

The selection of an SO₂ reduction technology requires a thorough assessment of technical, regulatory, economic and site issues. To determine the feasibility of duct injection as a compliance strategy, it is necessary to collect some specific information from the candidate plant(s). Table 2-2 is a summary of the basic information required for the evaluation. This information can be recorded on Worksheet 2-1 located at the end of this section. This worksheet should be photocopied in order to evaluate various cases.

LEVELIZED CONTROL COSTS of DUCT INJECTION*

15 Year Costs

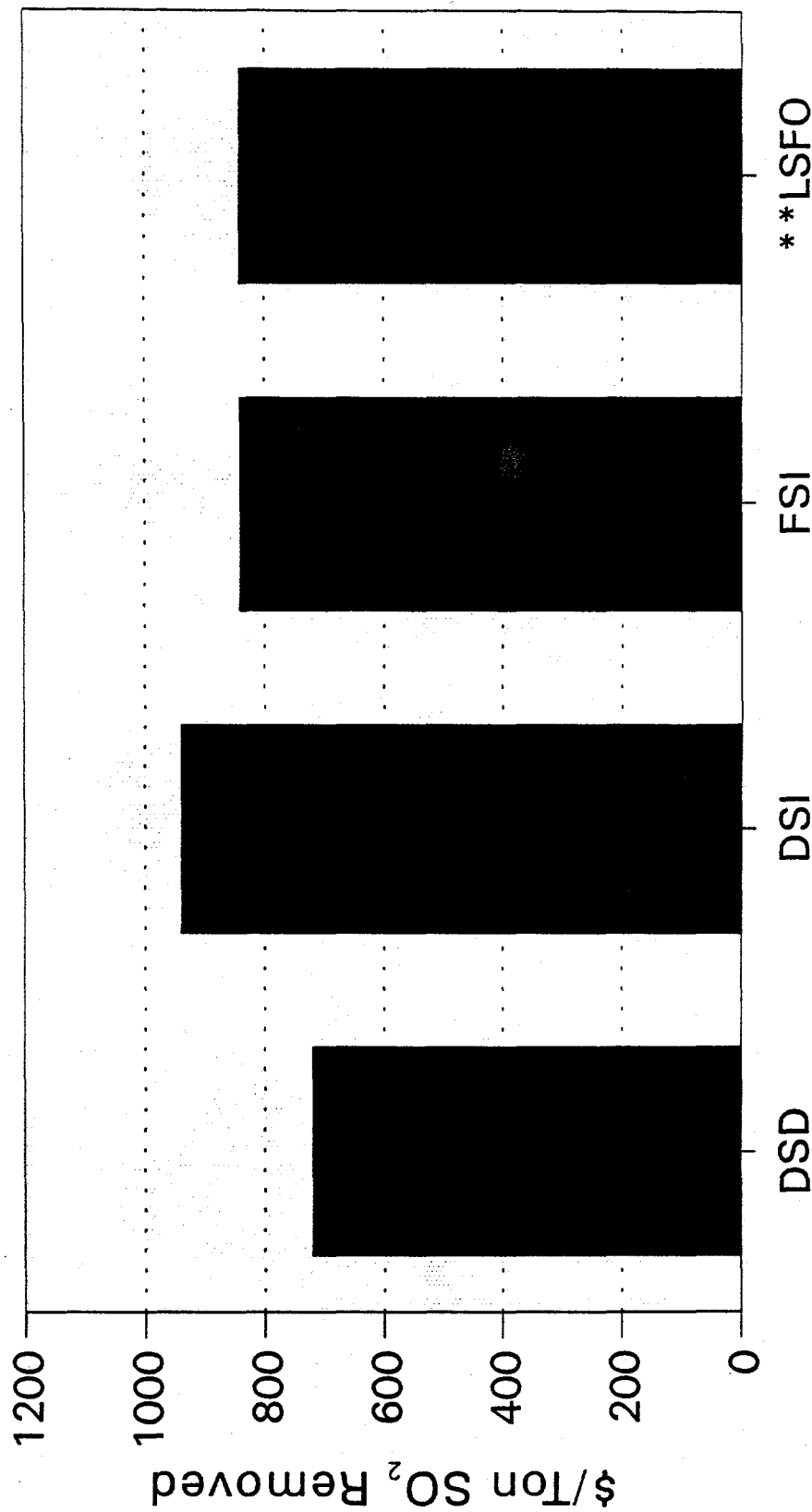


Figure 2-2

* 1992 Dollars

** Acid Rain Scrubber, Single Absorber, 95% Removal

CAPITAL COSTS of DUCT INJECTION*

Impacts of Major Plant Upgrades

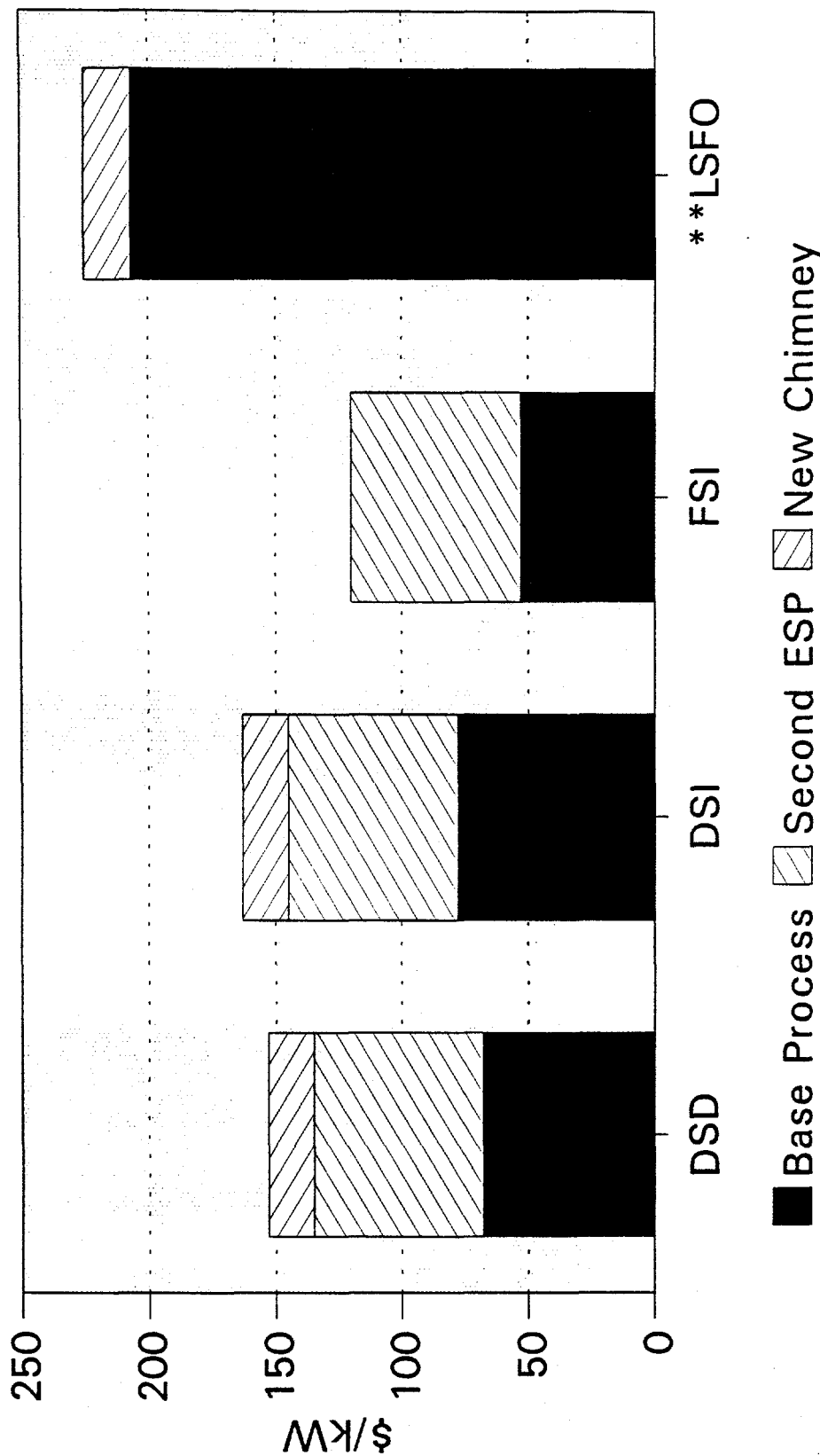


Figure 2-3

* 1992 Dollars

** Acid Rain Scrubber, Single Absorber, 95% Removal

LEVELIZED CONTROL COSTS of DUCT INJECTION* Impacts of Major Plant Upgrades

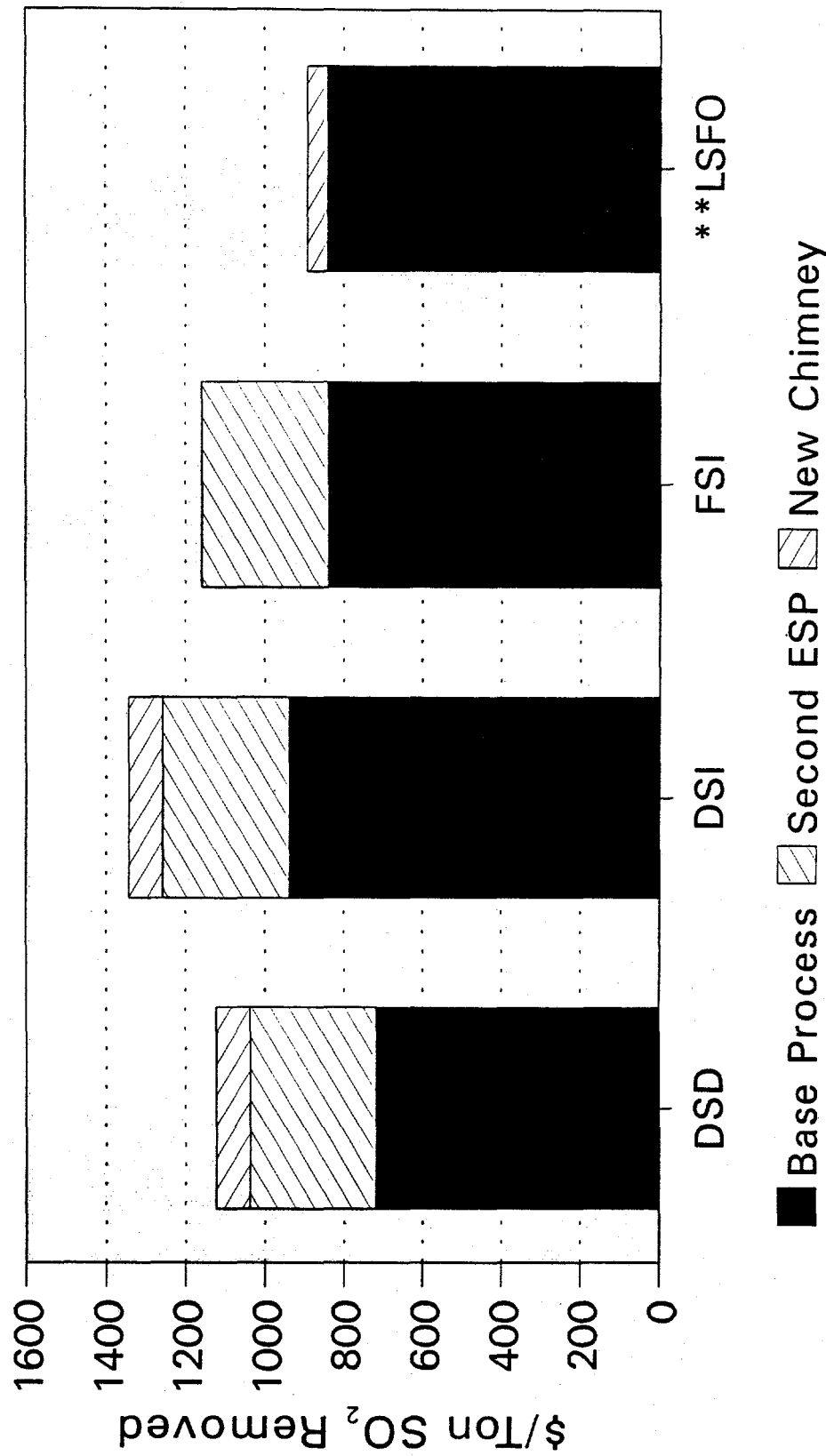


Figure 2-4

* 1992 Dollars

** Acid Rain Scrubber, Single Absorber, 95% Removal

LEVELIZED CONTROL COSTS* vs. GROSS UNIT SIZE DSD, DSI, FSI, LSFO

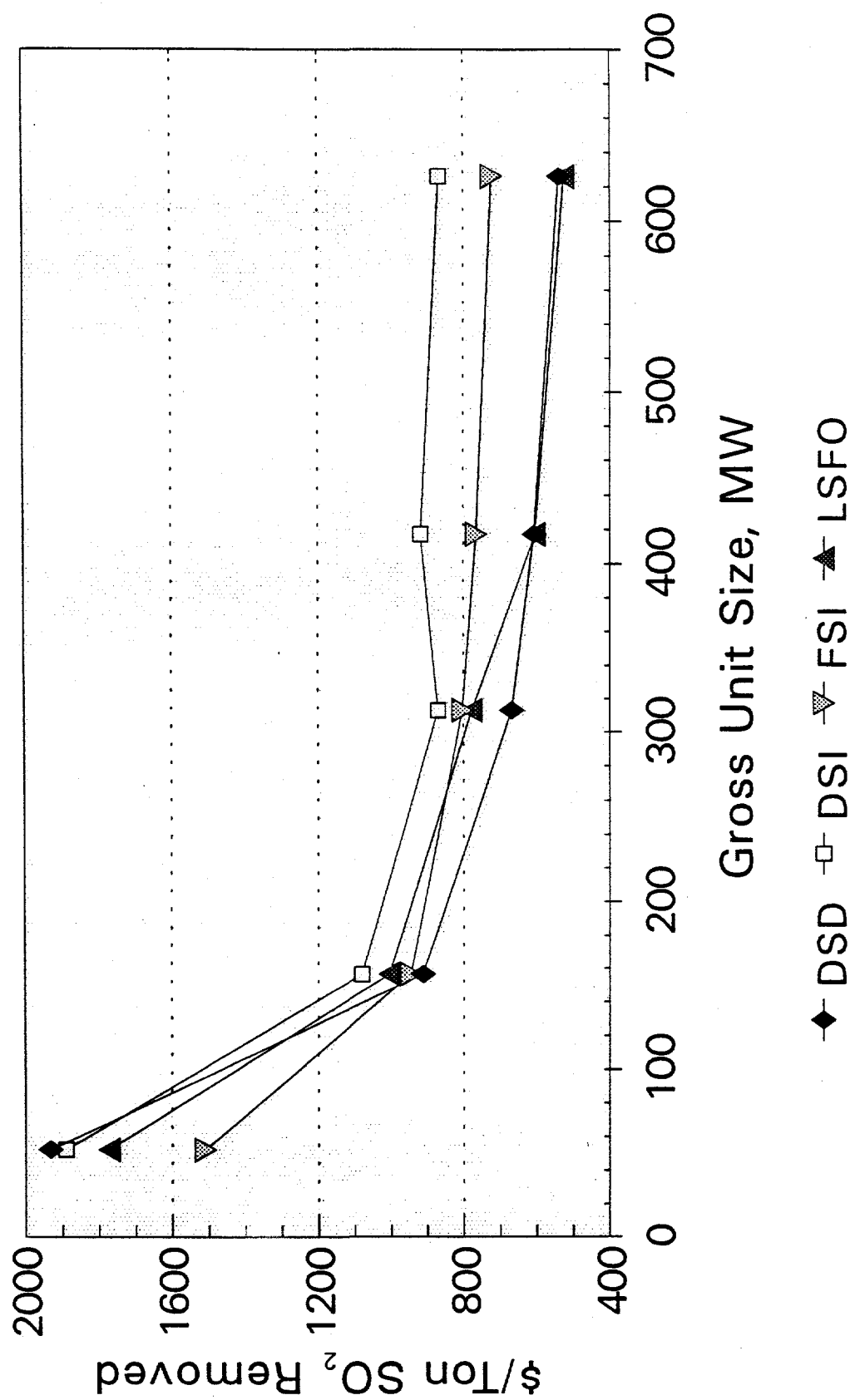


Figure 2-5

* 15 Year Levelized Costs, \$1992

LEVELIZED CONTROL COSTS* vs. COAL SULFUR % DSD, DSI, FSI, LSFO

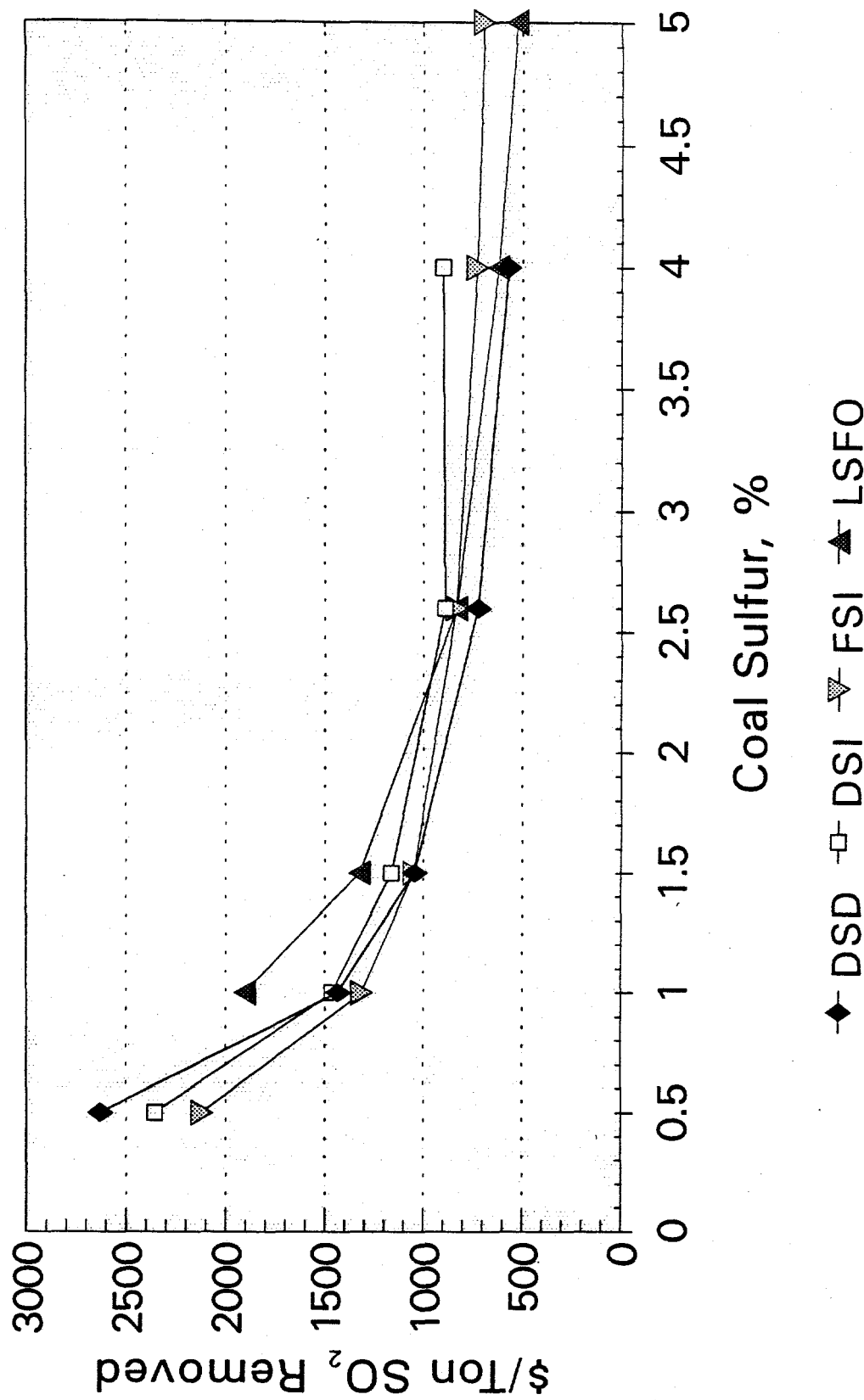


Figure 2-6

* 15 Year Levelized Costs, \$1992

LEVELIZED CONTROL COSTS* vs. % SO₂ REMOVED DSD, DSI, FSI

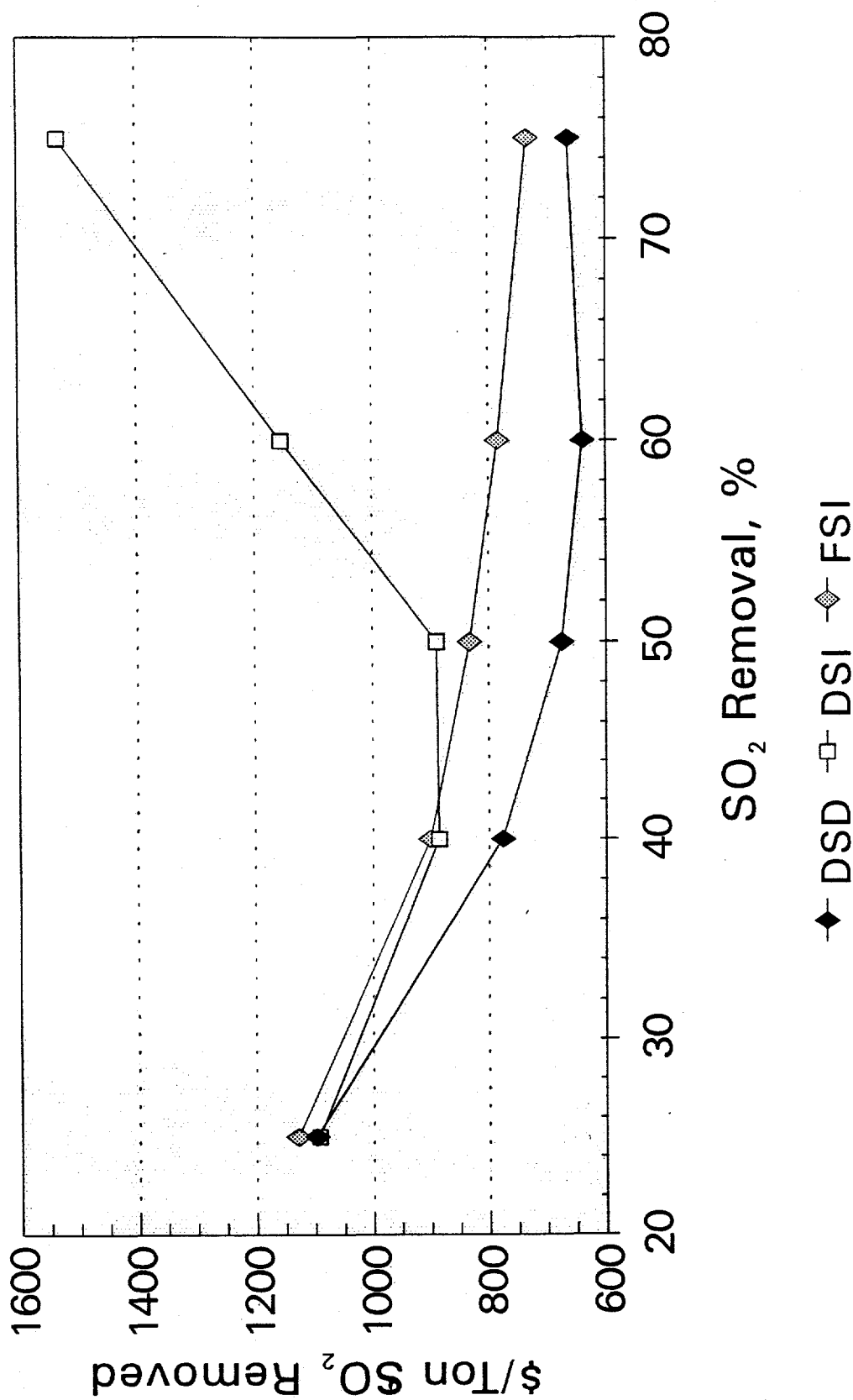


Figure 2-7

* 15 Year Levelized Costs, \$1992

LEVELIZED CONTROL COSTS* vs. AIR/LIQUID RATIO

DSD, DSI

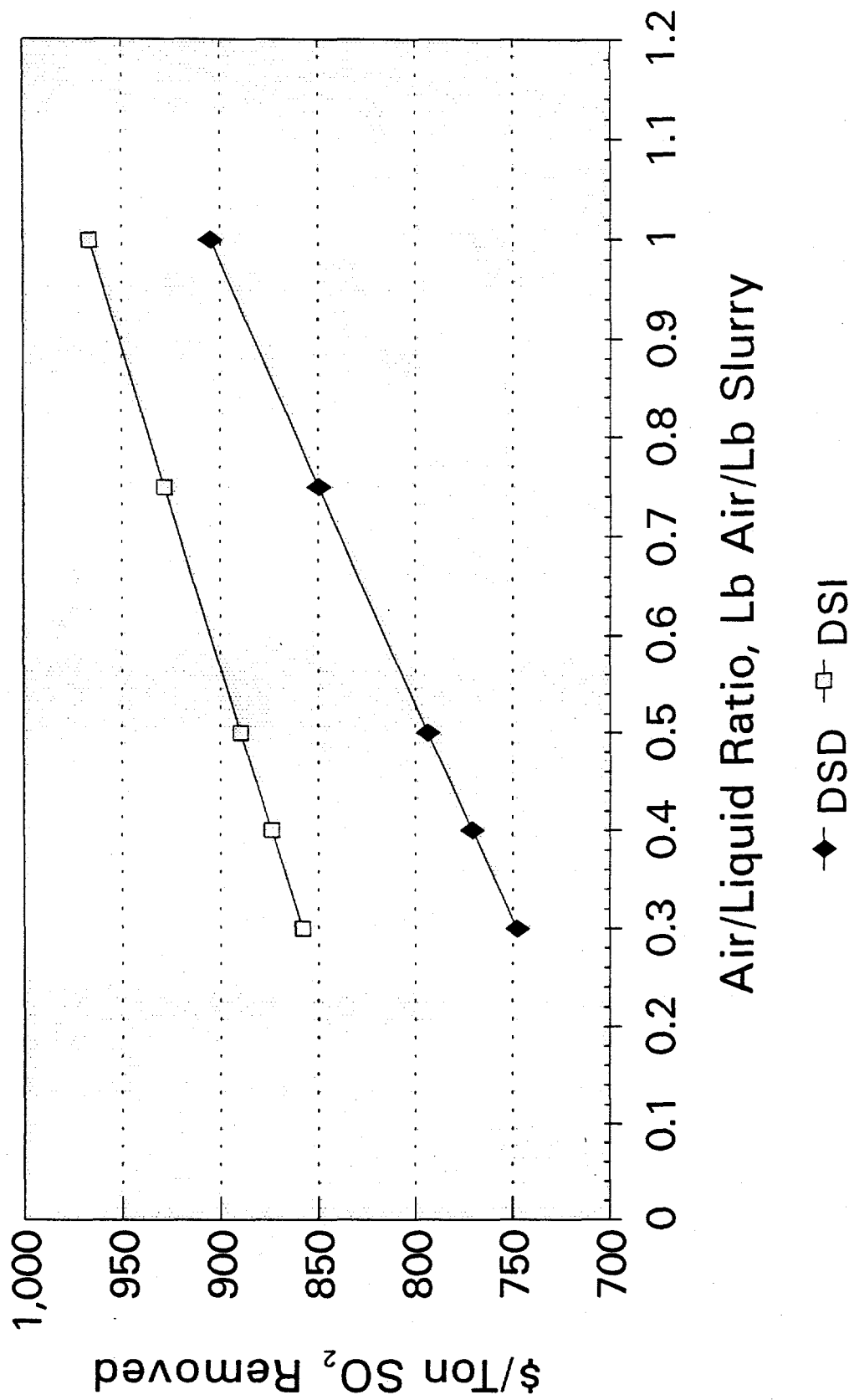


Figure 2-8

* 15 Year Levelized Costs, \$1992

TABLE 2-2
PLANT DATA REQUIREMENTS

Description		Units
1	SO ₂ Removal Required	%
2	Plant Size (Net or Gross)	MW
3	Capacity Factor	%
4	Coal Sulfur	%
5	Flue Gas Flow Rate	acfm
6	Longest Straight Run of Duct (LSR)	ft
7	Dimensions of LSR	ft x ft
8	Residence Time in LSR	sec
9	Ductwork Obstructions	Yes/No
10	ESP SCA	ft ² /1000 acfm
11	Space Available to Enlarge ESP?	Yes/No
12	ESP Velocity	ft/sec
13	ESP Collection Efficiency (Design or Measured)	%
14	ESP Outlet Emissions	lb/MM Btu
15	Particulate Emissions Limit	lb/MM Btu
16	Current Opacity	%
17	Opacity Limit	%
18	Ash Removal System Type	N/A
19	Is Ash Removal System Capacity Limited?	Yes/No
20	Ash Disposal/Utilization Method	N/A
21	Years Remaining to Reach Capacity of Ash Disposal Site	Yrs
22	Stack/Chimney Liner Type	N/A
23	Does Unit share a Common Flue?	Yes/No

2.4.1 Required SO₂ Removal

Duct injection processes are medium level SO₂ removal technologies. The upper limit is approximately 70% SO₂ removal, and a more typical economic SO₂ removal is 50%. As with all SO₂ reduction technologies, the level of SO₂ removal strongly affects process capital and operating costs. The user must determine what level of SO₂ removal is necessary for the candidate unit.

2.4.2 Plant Size (MW)

Although a duct injection system could be retrofit to any size plant, there are limits as to the economic viability compared to other technologies. Larger units favor high efficiency SO₂ removal technologies such as wet scrubbers.

2.4.3 Unit Capacity Factor

The total annual operating output of a unit also has a strong influence on the economical viability of these processes.

2.4.4 Coal Sulfur Content (%S)

This value is found in the as-received coal proximate analyses. It is advisable to use the high end of the range found in the representative coal analysis records. In the case of a planned coal switch, an additional margin of safety should be added to the prospective coal sulfur content for the design value.

2.4.5 Flue Gas Flow Rate

Flue gas flow rate (measured in actual cubic ft/min) downstream of the air heater is a very important parameter for sizing duct injection equipment as well as for determining several limiting factors. A measured value is preferred over a design value. A recent ESP performance test or boiler performance test will typically contain these data. If a significant fuel switch is planned, an estimated value based on combustion calculations may be better.

2.4.6 Longest Straight Run (LSR) of Ductwork between Air Heater and ESP

The user needs to determine the length (ft) of the longest straight run of flue gas ductwork between the air heater and ESP. This will be the most likely location for duct injection and humidification and can be vertical or horizontal. This length may be found from plant drawings or actual measurements.

2.4.7 Dimensions of LSR (ft x ft)

From plant drawing or actual measurements, the user will need to determine the inside dimensions of the LSR: Width (ft) x Height (ft).

2.4.8 Residence Time in LSR

The residence time of the flue gas within the LSR is critical to the duct injection processes. The water or slurry droplets which are sprayed into the duct need adequate time to dry before impacting duct walls or downstream bends, etc. The residence time, in seconds, is calculated as follows:

$$\text{Residence Time} = \text{LSR (ft)} \times (W \times H) / \text{Flue Gas Flow Rate (acfm)} \times \frac{60 \text{ sec}}{\text{min}} \quad (2-1)$$

where, $W \times H$ = Width (ft) of LSR x Height (ft) of LSR

2.4.9 Internal Obstructions in LSR

Internal obstructions in the flue gas path will be sites for wet solids build up and must be removed. These include stiffeners and turning vanes. Costs and time requirements to modify ductwork for external bracing and stiffeners must be considered.

2.4.10 Existing ESP SCA

The specific collection area of an ESP is an indicator of ESP size. SCA is measured as collection surface (ft²) per 1,000 acfm of flue gas flow rate. It is, therefore, a function both of ESP size and flue gas flow rate. In many cases, the actual SCA will be significantly different from the original design SCA as specified by the ESP manufacturer. The ESP Design Manual should list the total collection area (ft²). If there have been modifications to the ESP which altered the original collection area, these must be included. The SCA can be calculated by:

$$SCA = \text{Total Collection Area (ft}^2\text{)}/\text{acfm of flue gas}/1,000 \quad (2-2)$$

2.4.11 Is there Space Available to Enlarge the Existing ESP?

If the existing ESP is determined to be inadequate for duct injection service, it may be possible to enlarge the existing casings (new fields), or add new boxes in serial or parallel. The user should evaluate the space around the existing ESP not only for possible locations of additional equipment, but for constructability.

2.4.12 Existing ESP Face Velocity

The same considerations affecting SCA pertain to ESP face velocity. The ESP Design Manual may list the total cross-sectional area available for gas flow (ft²), or this area available to gas flow may have to be calculated based on number of gas passages, gas passage width and plate height. To determine actual ESP face velocity:

$$\text{ESP Velocity (ft/s)} = \frac{\text{Gas Flow (acfm)}}{\text{total gas flow area (ft}^2\text{)}} \times \frac{1 \text{ min}}{60 \text{ sec}} \quad (2-3)$$

The ESP design gas velocity can usually be found in the specification summary in the ESP operating manual.

2.4.13 ESP Collection Efficiency

Since duct injection impacts the particulate collection efficiency of the ESP, it is necessary to determine the current (or most recent) efficiency. These data are found in ESP performance test reports. If no performance tests have been conducted since unit start-up, the acceptance tests can be used.

2.4.14 Particulate Emissions

In addition to ESP efficiency, it is necessary to determine most recent particulate mass emission test data. These data are found in the latest emissions compliance test report.

2.4.15 Particulate Emission Limit

This limit is set by the regulatory agency with jurisdiction. State and local regulations usually must be as stringent or more stringent than the federal limits. It is recommended that both current and near future limits be considered to ensure that compliance is maintained over the life of the proposed system.

2.4.16 Typical Opacity

Opacity is the continuous measure of ESP performance and must be considered equally with particulate mass emissions. The user should select an opacity value averaged over an extended period at full load representative of normal operation.

2.4.17 Opacity Limit

The regulatory limit of integrated opacity should be used.

2.4.18 Ash Removal System Type

Duct injection processes change the amount and properties of the solids collected in the ESP. These changes will likely affect the operation of the ash handling and storage systems. The user should indicate the type of ash removal system at the candidate plant (i.e., pressure pneumatic, vacuum pneumatic, mechanical or wet sluice).

2.4.19 Is Existing Ash Removal System Capacity Limited?

Duct injection systems result in a substantial increase in solids. The additional burden on the ash handling system will likely require both equipment and operation modifications. If the existing ash handling system is operating at or near its capacity under fly ash only service, the system may require significant upgrade or replacement.

2.4.20 Ash Disposal/Utilization Method

The chemical, mineralogical and physical properties of the waste solids from duct injection are different from those of fly ash. These differences may affect current permitting, landfilling and/or waste by-product utilization practices.

2.4.21 Years Remaining to Reach Capacity of Existing Waste Disposal Site

The additional solids generated by the duct injection process will accelerate the rate of disposal site use.

2.4.22 Stack or Chimney Liner Type

Indicate existing stack or chimney liner material: steel, concrete, acid resistant brick, FRP or other. Duct injection flue gas properties may require modifications and/or material upgrades to the liner to prevent corrosion.

2.4.23 Does Unit Share a Common Flue?

Units sharing a common stack flue may require modifications and/or material upgrades to prevent problems resulting from the mixing of cool humidified duct injection flue gas with hot dry flue gases from a nontreated unit.

WORKSHEET 2-1
PLANT DATA REQUIREMENTS

	Description	Case No. _____
1	SO ₂ Removal Required, %	
2	Plant Size, MW	
3	Capacity Factor, %	
4	Coal Sulfur, %	
5	Flue Gas Flow Rate, acfm	
6	Longest Straight Run of Duct (LSR), ft	
7	Dimensions of LSR WxH, ft x ft	
8	Residence Time in LSR, sec	
9	Significant Internal Obstructions in LSR?, (Yes/No)	
10	ESP Size (SCA), ft ² /1,000 acfm	
11	Space Available to Enlarge ESP? (Yes/No)	
12	ESP Design Velocity, ft/sec	
13	ESP Collection Efficiency (Measured or Design), %	
14	Particulate Emissions (Measured), lb/MMBtu	
15	Particulate Emission Limit, lb/MMBtu	
16	Typical Opacity, %	
17	Opacity Limit, %	
18	Ash Removal System Type	
19	Is Ash Removal System Capacity Limited? (Yes/No)	
20	Ash Disposal/Utilization Method	
21	Years to Reach Capacity of Existing Disposal Site	
22	Stack/Chimney Liner Type	
23	Does Candidate Unit Share Common Stack Liner? (Yes/No)	

3.0 DESIGN CRITERIA

3.1 Specific Plant Information

Table 3-1 lists the plant design and operating data required for the conceptual design of a retrofit duct injection system. The following sections will guide the user in obtaining these data. The subsections in this Section 3.1 are numbered in the same order as the items are listed in Table 3-1. For instance, the text which suggests how the fly ash/bottom ash split may be obtained (Item 8 in Table 3-1) is given in Section 3.1.8. Some data will simply come from design manuals and operating logs, while other values must be calculated or obtained from field tests or measurements. The abbreviations for each item given in Table 3-1 will be used in the equations presented throughout this section.

TABLE 3-1
DATA REQUIREMENTS FOR THE CONCEPTUAL DESIGN
OF A RETROFIT DUCT INJECTION SYSTEM

Item	Description	Abbreviation	Units
1	Flue Gas Velocity	Vg	ft/sec
2	Flue Gas Volumetric Flow Rate	Qg	acfm
3	Flue Gas Mass Flow Rate	Mg	lb/hr
4	Flue Gas Temperature	Tg	°F
5	Flue Gas Saturation Temperature (Wet Bulb)	Twb	°F
6	Coal Firing Rate	MCoal	lb/hr
7	Coal Ash Content	%Ash	%
8	Fly Ash/Bottom Ash Split	N/A	Ratio
9	Fly Ash Mass Loading	Mfa	lb/hr
10	Coal Sulfur Content	%S	%
11	SO ₂ Mass Flow Rate	MSO ₂	lb/hr
12	Desired SO ₂ Removal Efficiency	N/A	%
13	Particulate Emissions Limit	N/A	lb/hr
14	Existing ESP SCA	SCA	ft ² /kacfm
15	Existing ESP Face Velocity	Vesp	ft/sec
16	ESP Design Type (WW or RDE)	N/A	N/A
17	Longest Straight Run of Ductwork Between AH & ESP	LSR	ft
18	Dimensions of LSR	WxH	ftxft
19	Residence Time in LSR	REZ	sec
20	Ash Removal System Type	N/A	N/A
21	Ash Removal System Capacity (Actual)	ARC	ton/hr
22	Ash Storage Capacity	ASC	ft ³ or ton
23	Stack or Chimney Liner Type	N/A	N/A

As values are determined for each of the above items, the user should enter the values on Worksheet 3-1, which is located at the end of Section 3.1. This worksheet should be photocopied so it can be used for different cases.

3.1.1-

3.1.3 Flue Gas Velocity, Volumetric Flow Rate, and Mass Flow Rate (Vg,Qg,Mg)

The flue gas flow rate exiting the air heater must be determined. This should include all in-leakage across the air heater. If possible, this gas flow should be measured using EPA Reference Methods 1 through 4, or similar procedures. These EPA Reference Methods are located in 40 CFR Part 60, Appendix A.

It is not advisable to use design flow rates (such as from original boiler specs) or dated test results since these data may not be representative of the actual current operating conditions. Boiler performance or particulate collector efficiency test data normally include flue gas flow rate measurements, and these results can be used provided they are recent (less than two years old) and the boiler operating conditions were representative. Full load test data are necessary for design purposes, but it is advisable to have gas flow measurements across a range of boiler operating conditions (boiler load, excess air, etc.). Minimum boiler load conditions typically yield the low end of the flue gas flow rate range, and these data are important to consider for atomizer placement, as well as solids and droplet settling tendencies.

The user should consider the condition of the unit when making measurements or reviewing historical data. Many plant/operating modifications can potentially affect flue gas flow rate. Among the most significant are fuel quality, combustion modifications, burner management, excess air, and air heater in-leakage (conditions of seals).

EPA Method 1 should be used to determine traverse points for pitot tube measurements in the ductwork downstream of the air heater. EPA Method 2 or equivalent should be used to determine flue gas velocity (Vg) and volumetric flow rate (Qg). EPA Methods 3 and 4 should be used to determine flue gas molecular weight and moisture content, respectively. From these data, the flue gas mass flow rate (Mg) can be calculated:

$$Mg \text{ (lb/hr)} = Qg(\text{acfm}) \times \frac{Pg}{Tg} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{MWW}{10.73} \quad (3-1)$$

Where: P_g = Flue gas pressure (psia)
 T_g = Flue gas temperature ($^{\circ}R$ which is $^{\circ}F + 460$)
 MWW = Molecular weight of wet flue gas (lb/lb mole)
10.73 = Gas constant [psia-ft³/($^{\circ}R$ -lb mole)]

This value of Mg does not include the fly ash.

After the maximum flue gas flow rate has been determined, the user may wish to add an additional safety margin, but no more than 10% is advised.

3.1.4 Flue Gas Temperature (Tg)

The flue gas temperature downstream of the air heater must be determined. Temperature measurements are made as part of the EPA Method 2 velocity determination test procedure. These measurements will provide a flue gas temperature profile across the duct at the

measurement point(s). The average flue gas temperature can then be calculated from the traverse data.

3.1.5 Flue Gas Saturation Temperature (Twb)

Typically, a duct injection process is controlled so that the treated flue gas is cooled to a certain temperature above the saturation or wet bulb temperature of the gas. This difference between operating temperature and saturation temperature is called the "approach" temperature, i.e., it indicates how close the operation approaches the saturation temperature. In order to determine the approach temperature, it is necessary to measure the flue gas saturation temperature (Twb). The most common method to measure saturation temperature is with a wet bulb thermocouple. The measurement should be made in the flue gas ductwork between the air heater and the particulate collector, at a representative full load condition. A simultaneous flue gas dry bulb temperature measurement should be made at the same location within the duct.

3.1.6 Coal Firing Rate (MCoal)

If no fuel change is planned, nor any major operational changes that would affect the plant heat rate, the coal firing rate can be obtained from representative full load historical operating data. If a coal change is planned, the firing rate must be estimated based on heating value, volatiles, combustion characteristics, etc.

3.1.7 Coal Ash Content (%Ash)

Coal ash content data can be found in the as-received proximate analyses. If the records indicate a range, the user should select the high side of the range. If a coal change is planned, it is advisable to add a margin of safety to the ash content indicated in the proximate analysis of the prospective coal.

3.1.8 Fly Ash/Bottom Ash Split (Fly ash fraction)

Of the total ash in the coal fired in a boiler, a portion forms slag and heavy bottom ash, and the remaining portion is entrained with the flue gas as fly ash. The ratio of fly ash to bottom ash varies with boiler type, operation, and, to some extent, fuel quality. The fly ash fraction is used to calculate fly ash mass loading. The split can be estimated by the number of truckloads of dewatered bottom ash, if dewatering bins are used, compared to truckloads of conditioned fly ash. If bottom ash is sluiced directly to ash ponds, the amount of fly ash to the ash silo can be estimated based on the number of truckloads of conditioned fly ash (subtracting out the conditioning water) to disposal, and this fly ash amount can be compared to the total estimated ash production based on the amount of coal fired and the ash content in the coal. If these data cannot be found, 80% fly ash/20% bottom ash can be used as an estimate for PC boilers.

3.1.9 Fly Ash Mass Loading (Mfa)

Fly ash mass loading is measured upstream of the particulate collector during particulate collector efficiency tests. EPA Method 5 or 17 is typically used. These data are typically reported as grains of ash per dry standard cubic feet (gr/dscf). These units may be converted to lb/hr by multiplying by the dry standard cubic feet per minute (dscfm) of gas flow rate calculated from EPA Method 2 (based on 68°F, 29.92 in.Hg), dividing by 7,000 gr per lb, and multiplying by 60 min/hr. If these data are dated or unavailable, it is advisable to conduct new tests or calculate the value as follows:

$$M_{fa} \text{ (lb/hr)} = M_{\text{Coal}} \times (\% \text{Ash}/100) \times \text{Fly ash fraction} \quad (3-2)$$

Note that, in many plants, a portion of the carbon from the coal is carried over with the flyash as unburned carbon. A value of 0.5% unburned carbon is typical.

3.1.10 Coal Sulfur Content (%S)

This value is found in the as-received coal proximate analyses. As with fly ash, it is advisable to use the high end of the range found in the representative coal analysis records. In the case of a planned coal switch, an additional margin of safety should be added to the prospective coal sulfur content for the design value.

3.1.11 SO₂ Mass Flow Rate (MSO₂)

For the purpose of this design effort, all fuel sulfur will be assumed to form SO₂. In part for simplicity, but more for design conservatism, SO₃ and pyritic sulfur will be included in the SO₂ value. Therefore, SO₂ mass flow rate (lb/hr) can be calculated as follows:

$$MSO_2 \text{ (lb/hr)} = M_{\text{Coal}} \times (\%S/100) \times \frac{1.998 \text{ lb SO}_2}{\text{lb S}} \quad (3-3)$$

3.1.12 Desired SO₂ Removal Efficiency

This value must be determined in order to proceed with the design effort. Generally, a specific stack SO₂ emission rate is desired either in lb/hr or lb/10⁶ Btu heat input. It is advisable to base the required removal efficiency on the design, untreated SO₂ mass flow rate determined in Eq. 3-3 (Section 3.1.11). If the stack SO₂ emission rate is in lb/10⁶ Btu heat input, the required percent removal of SO₂ is calculated by:

$$\frac{MSO_2 \text{ (from Eq. 3-3)} \times 10^6}{M_{\text{Coal}} \times \text{HHV of Coal}} - \frac{\text{Required Stack SO}_2 \text{ Emission Rate in lb SO}_2/10^6 \text{ Btu Input}}{\frac{MSO_2 \text{ (from Eq. 3-3)} \times 10^6}{M_{\text{Coal}} \times \text{HHV of Coal}}} \times (100) \quad (3-4)$$

where: HHV of Coal = Higher heating value of coal (Btu/lb)

A typical maximum percent SO₂ removal for duct injection technology is 50-70%.

3.1.13 Particulate Emissions Limit

The particulate emissions limit is ultimately set by the regulatory agency with jurisdiction. In most cases, this is set on a lb of particulate per 10⁶ Btu basis. For duct injection design purposes, it will be necessary to convert this to lb/hr at maximum load:

$$\begin{aligned} \text{Particulate Emissions Limit (lb/hr)} &= \\ \text{Particulate Emissions Limit} &\times M_{\text{Coal}} \times \text{HHV of Coal}/10^6 \\ \text{(In lb/10}^6 \text{ Btu Input)} & \end{aligned} \quad (3-5)$$

where: HHV of Coal = Higher heating value of coal (Btu/lb)

The user should take into consideration any pending regulatory changes which could subject a given unit to more restrictive emission limits. Also, the user should determine if increases in emissions above current emission levels, but below the compliance limit, are acceptable. In some cases, increases over a proven emission rate have been considered violations.

3.1.14 Existing ESP SCA (SCA)

The specific collection area of an ESP is an indicator of ESP size. SCA is measured as collection surface (ft²) per 1,000 acfm of flue gas flow rate. It is, therefore, a function both of ESP size and flue gas flow rate. In many cases, the actual SCA will be significantly different from the original design SCA as specified by the ESP manufacturer. The ESP Design Manual should list the total collection area (ft²). If there have been modifications to the ESP which altered the original collection area, these must be included. The SCA can be calculated by:

$$SCA = \text{Total Collection Area (ft}^2\text{)} / (Q_g / 1,000) \quad (3-6)$$

3.1.15 Existing ESP Face Velocity (Vesp)

The same considerations affecting SCA pertain to ESP face velocity. The ESP Design Manual may list the total cross - sectional area available for gas flow (ft²), or this area available to gas flow may have to be calculated based on number of gas passages, gas passage width, and plate height. To determine actual ESP face velocity:

$$V_{esp} \text{ (ft/s)} = \frac{Q_g}{\text{Total gas flow area (ft}^2\text{)}} \times \frac{1 \text{ min}}{60 \text{ sec}} \quad (3-7)$$

3.1.16 ESP Design Type

The user should indicate if the ESP is of weighted wire (WW) design or rigid discharge electrode (RDE) design. This information is found in the ESP Design Manual.

3.1.17 Longest Straight Run of Ductwork between Air Heater and ESP (LSR)

The user needs to determine the length (ft) of the longest straight run of flue gas ductwork between the air preheater and ESP. This will be the most likely location for duct injection and humidification. This length may be found from plant drawings or actual measurements.

3.1.18 Dimensions of LSR (WxH)

From plant drawing or actual measurements, the user will need to determine the inside dimensions of the LSR: Width (ft) x Height (ft).

3.1.19 Residence Time in LSR (REZ)

The residence time of the flue gas within the LSR is critical to the duct injection processes. The water or slurry droplets which are sprayed into the duct need adequate time to dry before impacting duct walls or downstream bends, etc. The residence time, in seconds, is calculated as follows:

$$REZ = \text{LSR (ft)} \times (W \times H) / Q_g \times \frac{60 \text{ sec}}{\text{min}} \quad (3-8)$$

Note that, this value of residence time is based on existing flue gas conditions before duct injection. The residence time of the flue gas in the duct will change after duct injection begins. However, all references in this handbook are based on flue gas conditions before duct injection is installed.

3.1.20 Ash Removal System Type

Indicate type of ash removal system: vacuum pneumatic, pressure pneumatic, mechanical, wet sluice, or other.

3.1.21 Ash Removal Capacity (ARC)

Indicate capacity of existing fly ash removal system. Actual test data should be used if available. It is recommended that tests be conducted to determine the maximum rate achievable, because design capacities (such as from original specs or design manuals) are usually not achievable.

It is difficult (at best) to test for conveying capacity. Listed below are four possible means.

1. Conveying capacity test - Ash will be accumulated in the silo for a known period of time during the test. The accumulated volume of ash in the silo and associated ash weight will be determined at the end of the test. Before the test begins, the ash silo should be unloaded to some minimum level, and the fluidizing air flow allowed to continue for 15 min after unloading has stopped. After the fluidizing air has been shut off for another 15 min, this minimum ash silo level needs to be measured via the yo-yo type level indicator (if it exists) or manually with a tape from the silo roof access door. After the ash level has been recorded, the fluidizing air flow shall be restarted and allowed to continue for the entire test period.

With the boiler operating at or near full load and with the ESP hoppers at or near high level, the conveying capacity test may begin. The time that the test begins and ends should be noted. The ash handling system should be run continuously for at least 4 hr. and preferably for 8 hr. For a pneumatic system, the pressure or vacuum chart recorder should be examined, and any conveying time associated with conveying from an empty hopper should be deducted from the total conveying time of the test. No silo unloading should occur during the test.

At the end of the test, the silo fluidizing air should be run for 15 min longer and then shut off for 15 min. The new ash level should then be measured as before. The quantity of ash conveyed to the silo should be determined by calculating the increase in volume of ash in the silo multiplied by the actual density of the ash. The ash density should be determined by collecting dry ash samples while the silo is being unloaded. The unloading may begin immediately after the final ash silo level has been measured.

At least three ash samples should be collected while loading three separate trucks. The samples should be placed in containers having known internal dimensions and know tare weight. Each sample should be allowed to sit undisturbed for 15 min. Density values can then be determined by using the height of the ash in the container, internal dimensions of the container, total weight of the container plus ash, and the tare weight of the container. The average of the three density values should be considered the density of the ash in the silo.

The ash handling system conveying capacity is equal to the tons of ash conveyed to the silo divided by the time the system was pulling from hoppers with ash in them.

ARC (ton/hr) =

$$\frac{(\text{Final Silo Level} - \text{Initial Silo Level, ft}) \pi D^2 \times \text{Density}}{(2000 \text{ lb/ton}) (\text{Time the System was Pulling Ash, hr})} \quad (3-9)$$

where: D = Internal diameter of ash silo (ft)
Density = Actual measured density of ash (lb/ft³)

2. A more simple test is to determine the time required to evacuate full ESP hoppers. This is not as accurate as the test described above since ash is constantly falling into the hoppers from the ESP, but it would give at least a rough check on conveyor capacity.
3. Permanently installed mass flow monitors are available for pneumatic and mechanical conveyors. Such monitors are available from Endress & Hauser Instruments of Greenwood, IN.
4. External load cells or strain sensors (such as Microcell Sensors manufactured by Kistler-Morse of Redmond, WA) are available. These devices would be mounted on each ash silo main vertical support member to measure the increase in ash weight over time.

3.1.22 Ash Storage Capacity (ASC)

Indicate the capacity of the existing fly ash storage silo(s). Please provide both storage area (ft³) and maximum load rating (tons).

3.1.23 Stack or Chimney Liner Type

Indicate existing stack or chimney liner material: steel, concrete, acid resistant brick, FRP, or other.

WORKSHEET 3-1

DATA REQUIREMENTS FOR THE CONCEPTUAL DESIGN
OF A RETROFIT DUCT INJECTION SYSTEM

Item	Description	Case No. _____	Case No. _____
1	Flue Gas Velocity (Vg), ft/sec		
2	Flue Gas Volumetric Flow Rate (Qg), acfm		
3	Flue Gas Mass Flow Rate (Mg), lb/hr		
4	Flue Gas Temperature (Tg), °F		
5	Flue Gas Saturation Temperature (Wet Bulb) (Twb), °F		
6	Coal Firing Rate (MCoal), lb/hr		
7	Coal Ash Content (%Ash), %		
8	Fly Ash/Bottom Ash Split (N/A), Ratio		
9	Fly Ash Mass Loading (Mfa), lb/hr		
10	Coal Sulfur Content (%S), %		
11	SO ₂ Mass Flow Rate (MSO ₂), lb/hr		
12	Desired SO ₂ Removal Efficiency (N/A), %		
13	Particulate Emissions Limit (N/A), lb/hr		
14	Existing ESP SCA (SCA), ft ² /kacfm		
15	Existing ESP Face Velocity (Vesp), ft/sec		
16	ESP Design Type (WW or RDE), N/A		
17	Longest Straight Run of Ductwork Between AH & ESP (LSR), ft		
18	Dimensions of LSR (WxH), ft x ft		
19	Residence Time in LSR (REZ), sec		
20	Ash Removal System Type, N/A		
21	Ash Removal System Capacity (Actual) (ARC), ton/hr		
22	Ash Storage Capacity (ASC), ft ³ or ton		
23	Stack or Chimney Liner Type, N/A		

3.2 Process Design Criteria

In order to determine reagent requirements, the size and design of the duct injection process equipment, and the required modifications to existing plant equipment, it is necessary to perform some process material balance calculations. Sections 3.2.1 and 3.2.2 provide material balance calculation guidelines for the DSI and DSD processes, respectively. If the user has already selected a duct injection process, then you should proceed to the appropriate section. It may be necessary to run through both cases in order to select the best process.

There are several critical duct injection process streams for which flow rates must be determined. For many parameters, design values will vary from more typical operating values to ensure that the duct injection process is conservatively sized and designed to operate at full load conditions and to be capable of being turned down over the full range of operating conditions.

Results from these calculations will also provide the necessary information to assess the impact of a duct injection process on existing major plant equipment. Section 3.2.3 describes the criteria used to determine the modifications and/or upgrades required for existing plant equipment. The major plant equipment discussed in Section 3.2.3 includes the ductwork downstream of sorbent injection, the particulate collection device, the ash handling system equipment, and the stack/chimney liner.

3.2.1 Dry Sorbent Injection

The major DSI process stream flow rates to be determined are:

1. Fresh sorbent requirements
2. Fresh sorbent conveying air requirements
3. Recycle material requirements
4. Recycle material conveying air requirements
5. Humidification water flow requirements
6. Atomizing air flow requirements
7. Solid waste handling, storage, and disposal requirements
8. ESP inlet flue gas conditions
9. Fresh CaO and hydration water requirements (for on-site hydration only)

The following sections will guide the user in determining flow rates for each of these streams. Worksheet 3-2, which is located at the end of this Section 3.2.1, is a simplified DSI Process Flow Diagram with the major process streams indicated. This worksheet should be photocopied so it can be used for different cases.

3.2.1.1 Fresh Sorbent Requirements

The DSD process introduces a considerable quantity of additional particulate into the flue gas which enters the ESP. The accompanying humidification of the flue gas, however, can increase the collection efficiency of the existing ESP such that the existing particulate emissions limit may still be achievable. It is very important to determine the ability of the ESP to handle the duct injection conditions before final process design can be completed. If it is determined that the ESP is inadequate, either ESP upgrades will be required or the duct injection feed rates will be limited by ESP performance. Refer to Section 3.2.3.2 for guidelines on ESP performance and upgrade strategies.

In DSI, hydrated lime $[\text{Ca}(\text{OH})_2]$ is the fresh sorbent (reagent) utilized. The first step in determining fresh sorbent requirements is to estimate the necessary calcium to sulfur stoichiometric ratio (Ca/S ratio) to achieve the desired SO_2 removal efficiency determined in Section 3.1.12. Figure 3-1 is a graph of SO_2 removal as a function of Ca/S ratio for DSI with lime-only operation (no recycle). Curves are shown for three approach to saturation temperatures which may be selected. Since it is likely that operation below a 25°F approach to saturation will not be practical at most plants unless additional duct work or absorbers are added, it is advisable to design the process based on calcium requirements at the 30°F to 50°F approach temperature curves. For conservatism, the 40°F to 50°F approach curves may be a good choice. For lime-only operation, the fresh sorbent requirement is calculated as follows:

$$\frac{\text{lb Ca}(\text{OH})_2}{\text{hr}} = \text{MSO}_2 \times \text{Ca/S Ratio} \times \frac{74.10}{64.06} \quad (3-10)$$

If the purity of the hydrated lime reagent is known, the total reagent flow (including impurities) can be calculated by dividing the $\text{Ca}(\text{OH})_2$ flow rate from Eq. 3-10 by the fractional purity. If the fresh sorbent requirement (calculated from Eq. 3-10 and divided by the fractional purity) is greater than the maximum particulate loading which can be tolerated at the ESP inlet under DSI conditions, then the amount of fresh sorbent must be reduced to be equal to or less than the maximum tolerable particulate loading. This will also reduce the SO_2 removal efficiency attainable.

If the fresh sorbent requirement is equal to or just less than the maximum tolerable particulate loading at the ESP inlet, lime-only operation may be more practical at the selected Ca/S ratio and desired SO_2 removal efficiency.

If the fresh sorbent requirement is significantly less than the maximum tolerable particulate loading at the ESP inlet, lime-only operation or lime plus recycle operation is feasible.

Correction for Recycle

The re-injection of solids collected in the particulate control device can reduce the fresh sorbent requirements by providing additional contact of unreacted lime with the flue gas. Predicting the level of improvement is complicated because it is affected by approach temperature, fresh sorbent reagent ratios, once-through sorbent utilization and fly ash characteristics.

For simplicity as well as design conservatism, Figure 3-2 allows the user to make a rough estimate of the effect of recycle on fresh Ca/S Requirements. Figure 3-2 shows the fractional reduction of fresh Ca/S as a function of approach temperature for two recycle ratios. This adjustment factor can be used to determine the corrected Ca/S ratio as follows:

$$\text{Ca/S}_{\text{ratio}} (\text{corr}) = \text{Ca/S}_{\text{ratio}} \times \text{Recycle Adjustment Factor} \quad (3-11)$$

If recycle is to be used, the fresh sorbent requirements should be estimated using the corrected Ca/S ratio.

3.2.1.2 Fresh Sorbent Conveying Air Requirements

A dilute phase pressure pneumatic conveying system to inject hydrated lime will require about 0.5-0.1 lb of conveying air per lb of solids depending on the distance conveyed.

SO₂ Removal vs. Ca/S Ratio

DSI - No Recycle

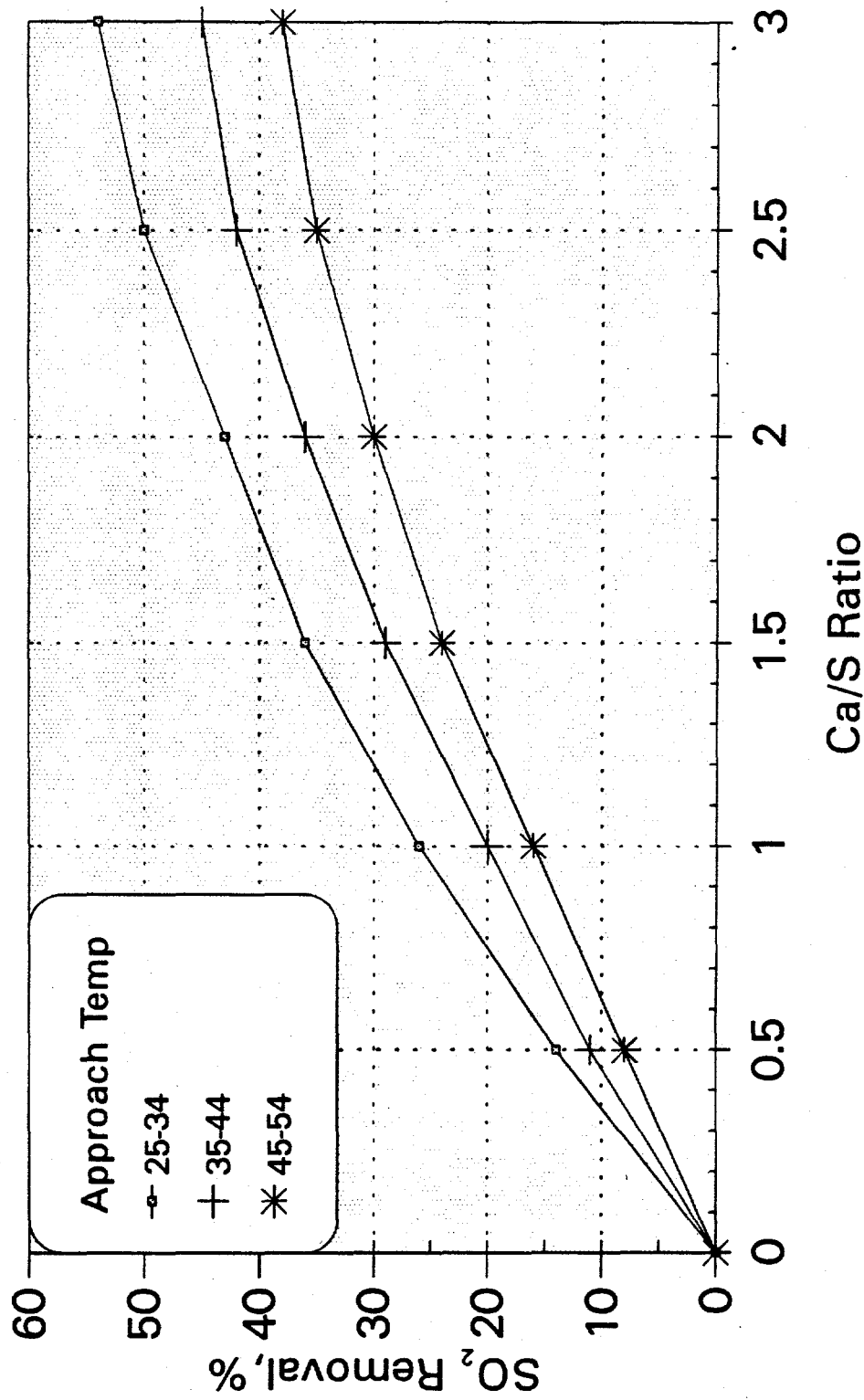
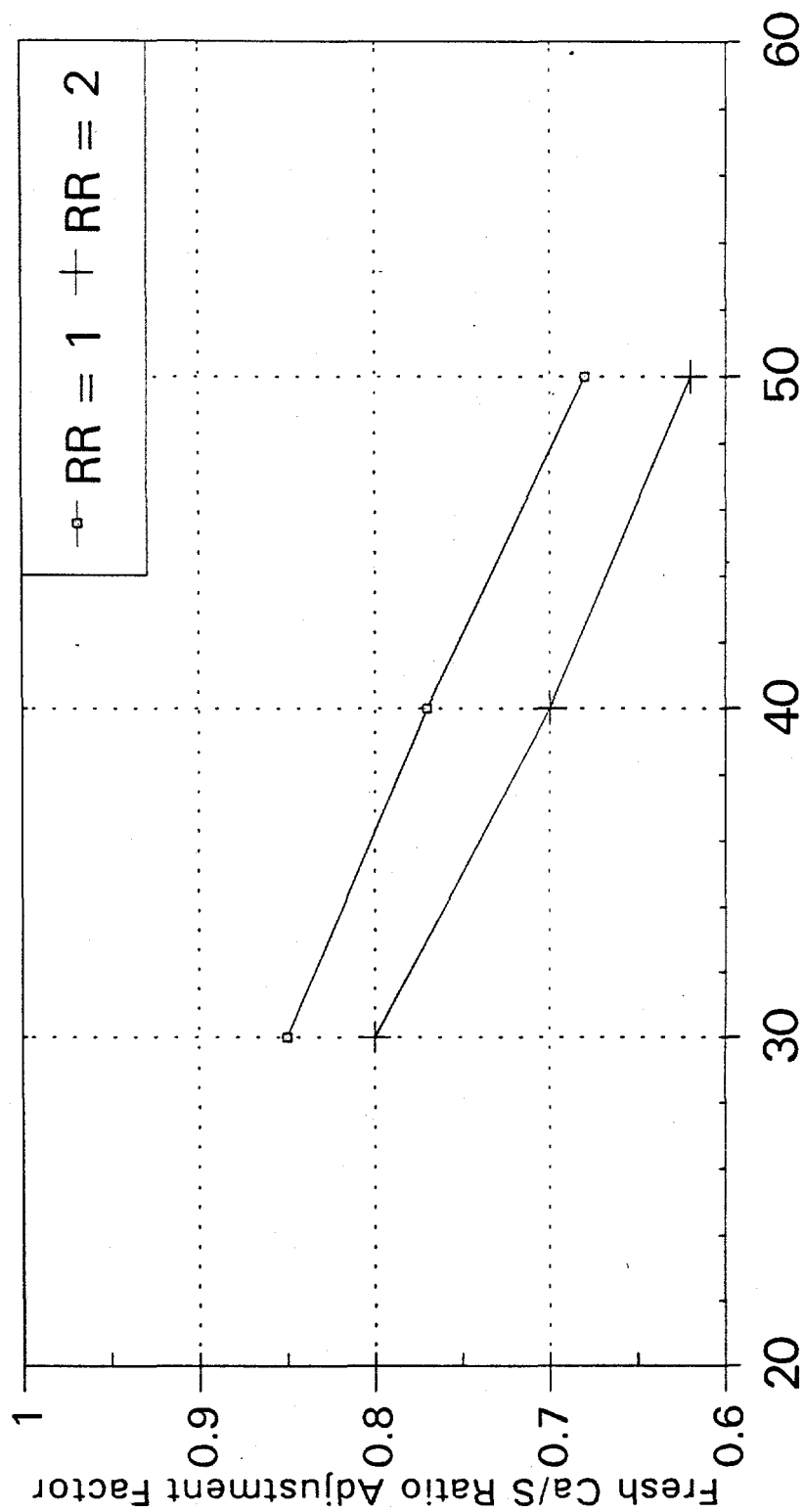


Figure 3-1

Source: Beverly DITF, Meredosia, EPRI, Coolside (no recycle, no additive)

Effect of Recycle on DSI Fresh Sorbent Requirements

RR = Recycle Ratio, Lb Recycle / Lb Ca(OH)_2



Approach to Saturation Temp, deg F

Figure 3-2

Source: Meredosa, EPRI

3.2.1.3 Recycle Material Requirements

Spent sorbent and fly ash collected in the particulate collection device can be re-injected into the flue gas to reduce fresh reagent requirements. Since the reagent is poorly utilized in duct injection processes, there is a considerable amount of unreacted reagent collected in the particulate collector. In the DSI process, recycle is injected into the duct on a mass ratio based on the fresh reagent injection rate. Figure 3-2 shows the potential reduction in fresh sorbent requirements by using recycle. This benefit is difficult to predict since it is impacted by several case specific parameters (i.e., one-through utilization, etc.). There is also a practical limit to the amount of solids that can be injected due to the capacities of the ESP and ash removal system. In addition, some pilot-plant data indicate that the marginal effectiveness of recycle drops dramatically above recycle ratios of 3:1. For a first cut in sizing recycle equipment, a recycle ratio of 1:1 is suggested.

$$\text{Recycle Rate (lb/hr)} = \text{Recycle Ratio} \times \text{Fresh Ca(OH)}_2 \text{ Rate} \quad (3-12)$$

When considering recycle ratios, it is important to keep in mind the impact on the particulate collection device. See the guidelines in Section 3.2.3.2.

3.2.1.4 Recycle Material Conveying Air Requirements

A dilute phase pressure pneumatic conveying system to inject recycle material will require about 0.20 lb of conveying air per lb of solids.

3.2.1.5 Humidification Water Flow Requirements

Among the most critical criterion to be determined is the approach to saturation temperature at which the duct injection process should be operated. SO₂ removal and calcium utilization increase with decreasing approach to saturation; however, so does the potential for operational problems such as wall wetting and solids deposition. For design purposes, it is recommended that equipment (pumps, etc.) be sized to allow operation at a 20°F approach even though it may not be practical to operate at this low approach temperature. The humidification water requirements can be calculated as follows:

$$\text{Humidification Water (lb/hr)} = \frac{M_g \times C_p \times (T_g - T_d)}{H_{vap}} \quad (3-13)$$

Where:

M _g	=	Flue gas mass flow rate (lb/hr)
C _p	=	Specific heat of flue gas (Btu/lb-°F)
T _g	=	Flue gas temperature downstream of air heater (°F)
T _d	=	Flue gas temperature downstream of duct injection (°F)
	=	Twb + target approach to saturation temperature
H _{vap}	=	Heat of vaporization (Btu/lb)

For design purposes, the user can use a C_p value of 0.25 Btu/lb-°F which is appropriate for typical flue gas compositions and temperatures downstream of the air heater. This value also includes a 3% margin for water required to cool the sulfation reactions, water of hydration for reaction products, etc. A value of 1,040 Btu/lb can be used for the heat of vaporization which is a standard in the boiler industry.

3.2.1.6 Atomizing Air Flow Requirements

The air flow requirements for atomizing the humidification water in the spray nozzles will vary considerably among the available commercial atomizers. The air-to-liquid ratio required to generate the droplet size distribution necessary for adequate evaporation must be obtained from the nozzle supplier. A conservative estimate for preliminary design purposes is 0.5 lb air/lb H₂O. Required air pressure at the atomizer also varies depending on the atomizer chosen, but it usually varies from 60 psig to 120 psig. These data are necessary to properly size and design air compressors and compressed air piping systems.

3.2.1.7 Solid Waste Handling, Storage, and Disposal Requirements

The DSI process will cause a drastic increase in solid waste generation over the baseline fly ash only operation. The new waste will consist of fly ash, calcium-sulfur reaction products, unreacted reagent, other calcium compounds (CaCO₃) and reagent inerts. The amounts of each of these components will vary with operation, SO₂ removal, load, etc.

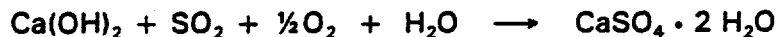
To determine the lbs/hr of reaction products, first calculate the sorbent utilization as follows:

$$\frac{\text{lbs utilized sorbent}}{\text{hr}} = \frac{\% \text{ SO}_2 \text{ Removal}}{\text{Ca/S}} \times \frac{\text{lbs Ca(OH)}_2 \text{ injected}}{\text{hr}}$$

Then, for estimating purposes, assume 70% of the utilized sorbent reacted with SO₂ to form calcium sulfite,



and 30% of the utilized sorbent reacted with SO₂ to form calcium sulfate.



$$\begin{aligned} \frac{\text{lbs Reaction Products}}{\text{hr}} = & \left(\frac{\text{lbs utilized sorbent}}{\text{hr}} \times 0.7 \times \frac{129.15 \text{ lbs CaSO}_3 \cdot \frac{1}{2} \text{H}_2\text{O}}{74.10 \text{ lbs Ca(OH)}_2} \right) + \\ & \left(\frac{\text{utilized sorbent}}{\text{hr}} \times 0.3 \times \frac{172.17 \text{ lbs CaSO}_4 \cdot 2 \text{H}_2\text{O}}{74.10 \text{ lbs Ca(OH)}_2} \right) \end{aligned}$$

The unreacted lime is determined as follows:

$$\frac{\text{lbs unreacted lime}}{\text{hr}} = \frac{\text{lbs Ca(OH)}_2 \text{ injected}}{\text{hr}} - \frac{\text{lbs utilized sorbent}}{\text{hr}}$$

3.2.1.8 ESP Inlet Flue Gas Conditions

Duct injection processes result in substantial changes in flue gas properties. The most significant changes are the increase in particulate loading due to injected sorbent and recycle, decreased temperature and increased moisture due to humidification. These new flue gas characteristics will affect the operation and performance of the particulate control device, ash handling and waste disposal systems, and alter the stack plume rise.

The total solids entering the particulate control device can be estimated by adding the injected sorbent and recycle streams to the fly ash leaving the boiler. It is necessary to account for calcium and sulfur reaction products based on the estimated SO_2 removal and calcium utilization.

$$\begin{aligned} \text{Total Solids Entering the ESP (lbs/hr)} = & \text{Mfa} + \text{reaction products} \\ & + \text{unreacted lime including inerts} \\ & + \text{recycle solids} \end{aligned} \quad (3-14)$$

The mass of fly ash leaving the boiler (Mfa) is determined by Eq. 3-2 in Section 3.1.9. The reaction products and unreacted lime are calculated from the equations in Section 3.2.1.7 above, and the inerts must also be added in. The amount of recycle (if used) is calculated using Eq. 3-12.

The flue gas temperature entering the ESP is the saturation temperature as determined in Section 3.1.5 plus the selected approach to saturation temperature (ΔTapp).

The flue gas mass flow rate entering the ESP is the gas flow rate exiting the air heater (Mg) plus the humidification water added (Eq. 3-13), minus the mass of SO_2 removed ($\text{MSO}_2 \times \text{SO}_2$ Removal Efficiency), plus the atomizing air and fresh sorbent and recycle conveying air.

3.2.1.9 Fresh CaO and Hydration Water Requirements (for on-site hydration only)

If the user is planning to hydrate quicklime on-site, the hydration water flow must be calculated. This is the water necessary for stoichiometric hydration, plus evaporation and other process losses.

$$\frac{\text{lb CaO Required}}{\text{hr}} = \frac{\text{lb Ca(OH)}_2}{\text{hr}} \times \frac{56.08}{74.10} \quad (3-15a)$$

If the purity of the quicklime reagent is known, the total reagent flow (including impurities) can be calculated by dividing the CaO flow rate from Eq. 3-15a by the fractional purity.

$$\text{Hydration Water Flow Rate (lb/hr)} = \text{lb CaO/hr} \times \frac{18.02}{56.08} \quad (3-15b)$$

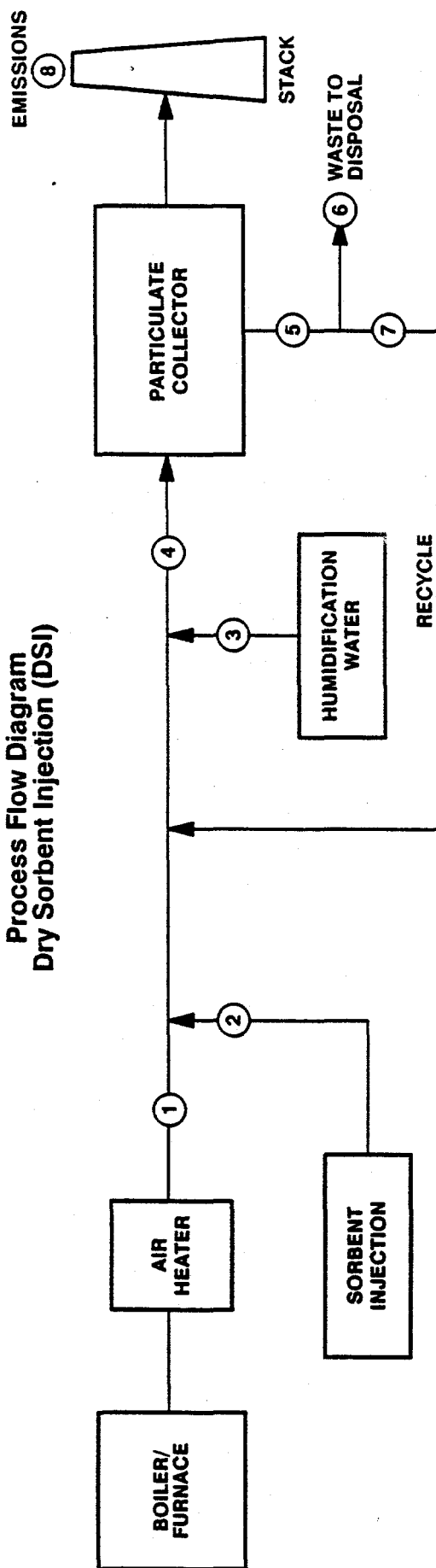
3.2.2 Duct Spray Drying

The major DSD process stream flow rates to be determined are:

1. Humidification water flow requirements
2. Slurry injection requirements
3. Atomizing air flow requirements
4. Fresh sorbent requirements
5. Lime slurry requirements
6. Recycle material requirements
7. Recycle slurry requirements
8. Dilution water requirements
9. Solid waste handling, storage, and disposal requirements
10. ESP inlet flue gas conditions

WORKSHEET 3-2

Process Flow Diagram Dry Sorbent Injection (DSI)



1. FLUE GAS DOWNSTREAM OF AIR HEATER

Flue Gas _____ lbs/hr
Fly Ash _____ lbs/hr
SO₂ _____ lbs/hr
Temperature _____ °F
Wet bulb _____ °F

2. SORBENT INJECTION

Ca(OH)₂ _____ lbs/hr
Inerts _____ lbs/hr
H₂O _____ lbs/hr
Conveying Air _____ lbs/hr

3. HUMIDIFICATION WATER

H₂O _____ lbs/hr
Atomizing Air _____ lbs/hr

5. COLLECTED SOLIDS

Total Solids _____ lbs/hr

7. RECYCLE

Solids _____ lbs/hr
Conveying Air _____ lbs/hr

6. WASTE TO DISPOSAL

Flue Gas _____ lbs/hr
Solids _____ lbs/hr
Temperature _____ °F
Δ T App _____ °F

8. EMISSIONS

Solids _____ lbs/hr
H₂O _____ lbs/hr
Total _____ lbs/hr
SO₂ _____ lbs/hr
Particulate _____ lbs/hr

The following sections will guide the user in determining flow rates for each of these streams. Worksheet 3-3, which is located at the end of this Section 3.2.2, is a simplified DSD Process Flow Diagram with the major process streams indicated. This worksheet should be photocopied so it can be used for different cases.

3.2.2.1 Humidification Water Flow Requirements

The humidification water requirements include the combination of three separate water streams:

1. Water in the Lime Slurry
2. Water in the Recycle Slurry
3. Dilution Water to the Atomizer Feed Tank

These three streams combine to make up the total available water in the atomizer feed slurry, which evaporates to cool the gas to the desired approach to saturation temperature.

Among the most critical factors to be determined is the approach to saturation temperature at which the duct injection process should be operated. SO_2 removal and calcium utilization increase with decreasing approach to saturation; however, so does the potential for operational problems such as wall wetting and solids deposition. For design purposes, it is recommended that equipment (pumps, etc.) be sized to allow operation at a 20°F approach, even though it may not be practical to operate at this low approach temperature. The humidification water requirements can be calculated as follows:

$$\text{Humidification Water (lb/hr)} = \frac{M_g \times C_p \times (T_g - T_d)}{H_{\text{vap}}} \quad (3-16)$$

where:	M_g	=	Flue gas mass flow rate (lb/hr)
	C_p	=	Specific heat of flue gas (Btu/lb- $^\circ\text{F}$)
	T_g	=	Flue gas temperature downstream of air heater ($^\circ\text{F}$)
	T_d	=	Flue gas temperature downstream of duct injection ($^\circ\text{F}$)
		=	$T_{\text{wb}} + \text{target approach to saturation temperature}$
	H_{vap}	=	Heat of vaporization (Btu/lb)

For design purposes, the user can use a C_p value of 0.25 Btu/lb- $^\circ\text{F}$ which is appropriate for typical flue gas compositions and temperatures downstream of the air heater. This value also includes a 3% margin for water required to cool the sulfation reactions, water of hydration for reaction products, etc. A value of 1,040 Btu/lb can be used for the heat of vaporization, which is a standard in the boiler industry.

3.2.2.2 Slurry Injection Requirements

In spray drying processes, it is beneficial to operate the atomizers at the highest feasible slurry solids content. The maximum slurry solids content is usually limited by atomizer design and/or maximum particulate loading to the ESP. Dual-fluid atomizers, as used in DSD, may vary widely in maximum slurry solids limits. It is important to obtain this performance data from the atomizer manufacturer. With these data, the slurry mass flow rate to the atomizers can be determined. Generally, the feed slurry solids content will vary between 30-40%.

$$\frac{\text{lb Slurry to Atomizer}}{\text{hr}} = \frac{\text{lb Humidification Water}}{\text{hr}} \times \frac{100}{100\text{-}\% \text{ Feed Slurry Solids}} \quad (3-17)$$

The total solids to the atomizer can then be calculated:

$$\frac{\text{lb Total Solids to Atomizer}}{\text{hr}} = \frac{\text{lb Slurry to Atomizer/hr-Humidification Water/hr}}{\text{hr}} \quad (3-18)$$

3.2.2.3 Atomizing Air Flow Requirements

The air flow requirements for atomizing the slurry in the spray nozzles will vary considerably among the available commercial atomizers. The air-to-liquid ratio required to generate the droplet size distribution necessary for adequate evaporation must be obtained from the nozzle supplier. A conservative estimate for preliminary design purposes is 0.5 lb air/lb slurry. Required air pressure at the atomizer also varies depending on the atomizer chosen, but it usually varies from 60 psig to 120 psig. These data are necessary to properly size and design air compressors and compressed air piping systems.

3.2.2.4 Fresh Sorbent Requirements

The DSD process introduces a considerable quantity of additional particulate into the flue gas which enters the ESP. The accompanying humidification of the flue gas, however, can increase the collection efficiency of the existing ESP such that the existing particulate emissions limit may still be achievable. It is very important to determine the ability of the ESP to handle the duct injection conditions before final process design can be completed. If it is determined that the ESP is inadequate, either ESP upgrades will be required or the duct injection feed rates will be limited by ESP performance. Refer to Section 3.2.3.2 for guidelines on ESP performance and upgrade strategies.

In DSD, pebble lime (CaO) is the sorbent utilized. The first step in determining fresh sorbent requirements is to estimate the necessary calcium to sulfur stoichiometric ratio (Ca/S ratio) to achieve the desired SO₂ removal efficiency determined in Section 3.1.12. Figure 3-3 is a graph of SO₂ removal as a function of Ca/S ratio for DSD. Curves are shown for two approach to saturation temperatures which may be selected. Since it is likely that operation at below a .25°F approach to saturation will not be practical at many plants, it is advisable to size equipment based on calcium requirements at the 30°F or 40°F approach temperature curves. The curves in Figure 3-3 are based on the use of recycle. Recycle operation is considered the baseline configuration for DSD for better reagent utilization, and to maintain a high slurry solids concentration to enhance droplet drying. Using the Ca/S from Figure 3-3, the CaO requirements can be calculated as follows:

$$\frac{\text{lb CaO}}{\text{hr}} = \text{MSO}_2 \times \text{Ca/S ratio} \times \frac{56.08}{64.06} \quad (3-19)$$

If the purity of the pebble lime reagent is known, the total fresh reagent flow (including impurities) can be calculated by dividing the CaO flow rate from Eq. 3-19 by the fractional purity.

SO₂ Removal vs. Ca/S Ratio

DSD w/Recycle

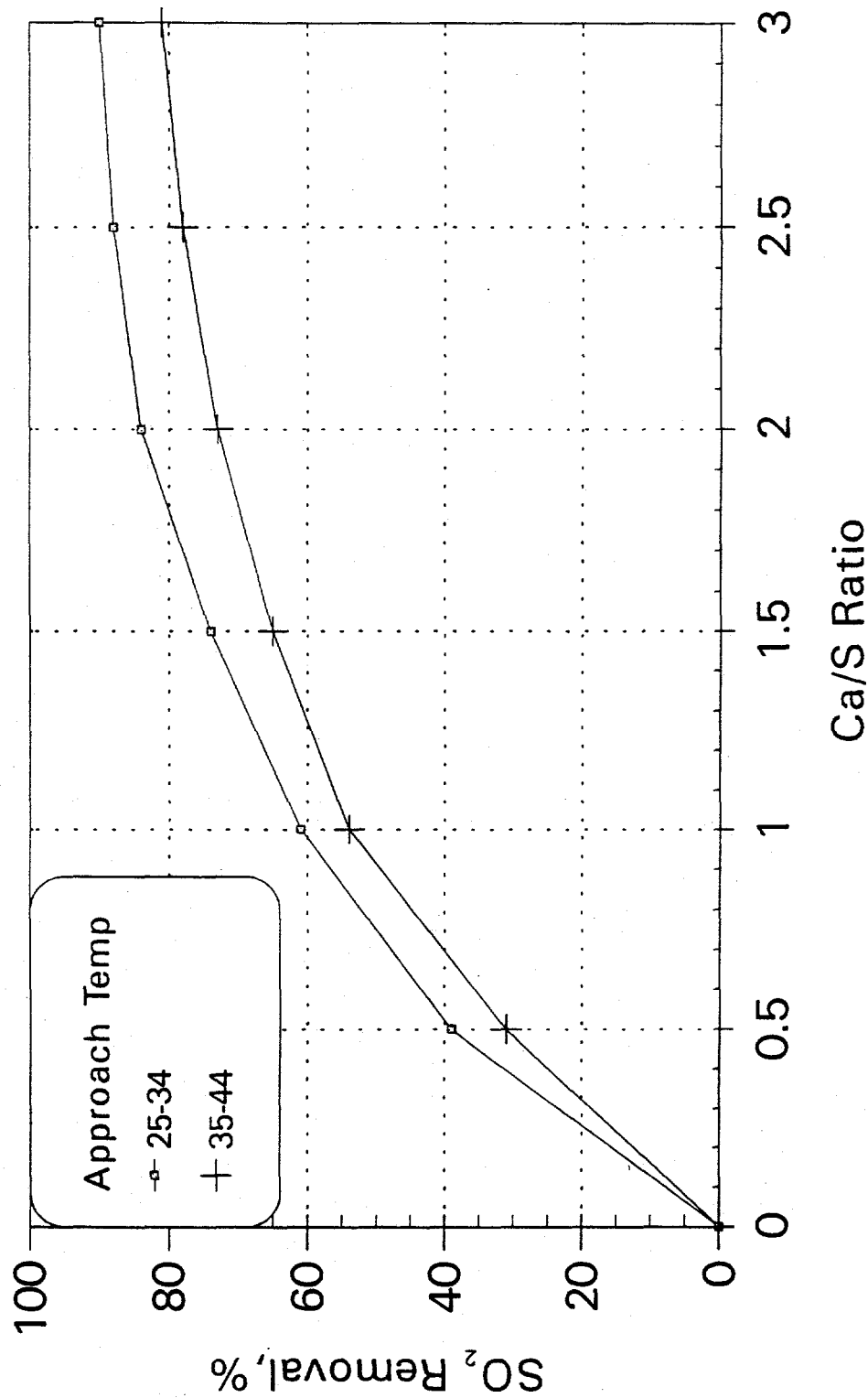


Figure 3-3

Source: Beverly DITF

If the fresh sorbent requirement is equal to or just less than the maximum tolerable particulate loading at the ESP inlet, lime-only operation may be more practical at the selected Ca/S ratio and desired SO₂ removal efficiency.

If the fresh sorbent requirement is significantly less than the maximum tolerable particulate loading at the ESP inlet, lime-only operation or lime plus recycle operation is feasible.

3.2.2.5 Lime Slurry Requirements

Water requirements and resulting lime slurry concentration are a function of slaker type. A ball mill slaker, for example, may produce a lime slurry which contains 25% solids. Paste slakers and detention slakers may produce more dilute slurries. To calculate the slurry mass flow rate out of the slaker, determine the product slurry solids content specified by the slaker manufacturer.

$$\text{Fresh Lime Slurry (lb/hr)} = \left[\frac{\text{lb CaO}}{\text{hr}} \times \frac{74 \text{ lb Ca(OH)}_2 + \text{Inerts (for ball mill)}}{56 \text{ lb CaO}} \right] \times \frac{100}{\% \text{ Solids in Slurry}} \quad (3-20)$$

Note that the lime slurry solids are in the form of slaked lime: Ca(OH)₂. The water requirements for slaking can then be calculated:

$$\frac{\text{lb Water to Slaker}}{\text{hr}} = \frac{\text{lb Fresh Lime Slurry}}{\text{hr}} - \frac{(\text{lb CaO} + \text{Inerts}) \text{ to Slaker}}{\text{hr}} \quad (3-21)$$

3.2.2.6 Recycle Material Requirements

To determine the amount of dry solids to be recycled from the particulate collector back to the DSD process, subtract the solids in the lime slurry from the total solids in the slurry to the atomizer (Eq. 3-18). This should be calculated for the maximum feed slurry solids content which can be accommodated by the ESP:

$$\frac{\text{lb Recycle Solids}}{\text{hr}} = \frac{\text{lb Total Solids to Atomizer}}{\text{hr}} - \quad (3-22)$$

$$\left[\frac{\text{lb Fresh CaO}}{\text{hr}} \times \frac{74 \text{ lb Ca(OH)}_2}{56 \text{ lb CaO}} + \text{Inerts (if included in lime slurry)} \right]$$

3.2.2.7 Recycle Slurry Requirements

To determine the water requirements for the recycle slurry, assume 45% recycle solids in the recycle slurry:

$$\frac{\text{lb Recycle Slurry Water}}{\text{hr}} = \frac{\text{lb Recycle Solids}}{\text{hr}} \times \frac{0.55}{0.45} \quad (3-23)$$

3.2.2.8 Dilution Water Requirements

The dilution water stream is used to make up the required water for flue gas humidification when the combined water flow rates in the lime slurry and recycle slurry are insufficient. This can occur during unusual operational conditions (e.g., unusual combinations of approach temperature and Ca/S ratio) or when there are equipment problems with the fresh lime or recycle systems. It is advised to size the dilution water process equipment for the same flow rates as the recycle water equipment. Dilution water requirements may be calculated as follows:

$$\begin{aligned} \text{Dilution water (lb/hr)} &= \\ &\text{Humidification Water} - \left[\frac{\text{lb/CaO}}{\text{hr}} \times \frac{74.10}{56.08} + \text{Inerts} \right] \times \\ &\left[\frac{100\% \text{ Solids in Lime Slurry}}{\% \text{ Solids in Lime Slurry}} \right] - \text{Recycle Slurry Water} \end{aligned}$$

3.2.2.9 Solid Waste Handling, Storage, and Disposal Requirements

The DSD process will cause a drastic increase in solid waste generation over the baseline fly ash only operation. The new waste will consist of fly ash, calcium-sulfur reaction products, unreacted reagent, other calcium compounds (CaCO_3) and reagent inerts. The amounts of each of these components will vary with operation, SO_2 removal, load, etc.

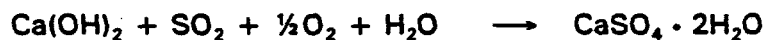
To determine the lbs/hr of reaction products, first calculate the sorbent utilization as follows:

$$\frac{\text{lbs utilized sorbent}}{\text{hr}} = \frac{\text{Fractional } \text{SO}_2 \text{ Removal}}{\text{Ca/S (Fresh)}} \times \frac{\text{lbs Ca(OH)}_2 \text{ injected}}{\text{hr}}$$

Then, for estimating purposes, assume 70% of the utilized sorbent reacted with SO_2 to form calcium sulfite,



and 30% of the utilized sorbent reacted with SO_2 to form calcium sulfate.



$$\begin{aligned} \frac{\text{lbs Reaction Products}}{\text{hr}} &= \left(\frac{\text{lbs utilized sorbent}}{\text{hr}} \times 0.7 \times \frac{129.15 \text{ lbs CaSO}_3 \cdot \frac{1}{2} \text{H}_2\text{O}}{74.10 \text{ lbs Ca(OH)}_2} \right) + \\ &\quad \left(\frac{\text{lbs utilized sorbent}}{\text{hr}} \times 0.3 \times \frac{172.17 \text{ lbs CaSO}_4 \cdot 2 \text{H}_2\text{O}}{74 \text{ lbs Ca(OH)}_2} \right) \end{aligned}$$

The unreacted lime is determined as follows:

$$\frac{\text{lbs unreacted lime}}{\text{hr}} = \frac{\text{lbs Ca(OH)}_2 \text{ injected}}{\text{hr}} - \frac{\text{lbs utilized sorbent}}{\text{hr}}$$

3.2.2.10 ESP Inlet Flue Gas Conditions

Duct injection processes result in substantial changes in flue gas properties. The most significant changes are the increase in particulate loading due to injected sorbent and recycle, decreased temperature and increased moisture due to humidification. These new flue gas characteristics will affect the operation and performance of the particulate control device, ash handling and waste disposal systems, and alter the stack plume rise.

The total solids entering the particulate control device can be estimated by adding the injected sorbent and recycle solids to the fly ash leaving the boiler. It is necessary to account for calcium and sulfur reaction products based on the estimated SO₂ removal and calcium utilization.

$$\text{Total Solids Entering the ESP (lbs/hr)} = \text{Mfa} + \text{reaction products} + \text{unreacted lime (including inerts)} + \text{recycle solids} \quad (3-24)$$

The mass of fly ash leaving the boiler (Mfa) is determined by Eq. 3-2 in Section 3.1.9. The reaction products and unreacted lime are calculated from the equations in Section 3.2.2.9 above, and the inerts must also be added in. The amount of recycle is calculated using Eq. 3-22.

The flue gas temperature entering the ESP is the saturation temperature as determined in Section 3.1.5 plus the selected approach to saturation temperature (ΔT_{app}).

The flue gas mass flow rate entering the ESP is the gas flow rate exiting the air heater (Mg) plus the humidification water added (Eq. 3-16) minus the mass of SO₂ removed (MSO₂ × SO₂ Removal Efficiency), plus the atomizing air.

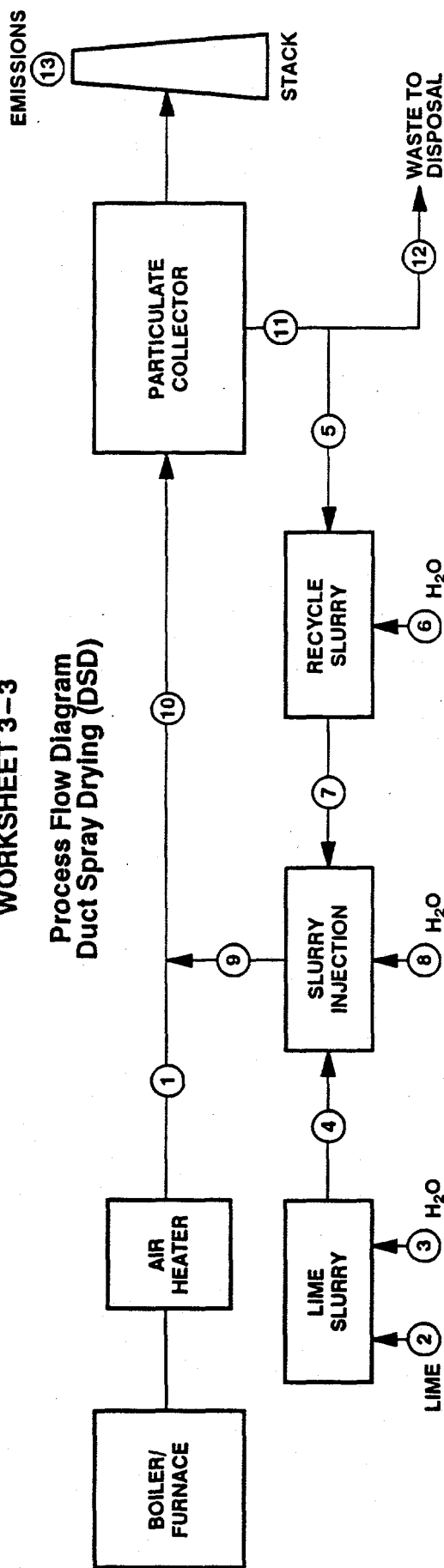
3.2.3 Criteria for Existing Plant Equipment Upgrades

3.2.3.1 Duct Residence Time Requirements For Droplet Evaporation

Residence time for adequate evaporation of humidification water or slurry droplets is a critical parameter for atomizer placement and atomizer selection. Factors affecting droplet evaporation include droplet size distribution, percent solids in droplet, inlet temperature and total amount of liquid injected (determining final temperature). The three graphs in Figure 3-4 show the relationship between droplet size and drying time as predicted by mathematical modeling. A commercial dual fluid atomizer generating droplets with a 40 micron sauter mean diameter and with a large droplet fraction of 112 microns was selected. This represents the type of atomizers considered necessary for duct injection. The user must use care in interpreting droplet size data. The Sauter mean diameter is a good representation of average droplet size; however, the large drop-size fraction (112 micron) of the distribution is of the most concern for evaporation. Figure 3-4 indicates that in order to adequately evaporate the large droplet fraction, nearly 2 seconds residence time are needed. The information in Figure 3-4 can be compared to the residence time in the longest straight run (LSR) as determined in Section 3.1.17. A much more accurate prediction of the users application can be accomplished with DIAN1D, the 1 dimensional computer model of duct injection processes. The user can input specific flue gas conditions and atomizer drop size data to generate predictions of drying time. DIAN1D is described in Section 4 of this handbook.

If residence time in the longest straight run is inadequate, duct injection should not be retrofit, unless duct modifications are installed to achieve the required residence time.

WORKSHEET 3-3

Process Flow Diagram
Duct Spray Drying (DSD)1. FLUE GAS DOWNSTREAM OF
AIR HEATER

Flue Gas _____ lbs/hr

Fly Ash _____ lbs/hr

SO₂ _____ lbs/hr

Temperature _____ °F

Wet bulb _____ °F

2. LIME TO SLAKER

CaO _____ lbs/hr

Inerts _____ lbs/hr

3. WATER TO SLAKER

H₂O _____ lbs/hr

4. FRESH SLURRY

Slurry _____ lbs/hr

_____ % solids

5. RECYCLE ASH TO SLURRY

Recycle Solids _____ lbs/hr

6. H₂O TO RECYCLE SLURRYH₂O _____ lbs/hr

7. RECYCLE SLURRY

Slurry _____ lbs/hr

_____ % solids

8. DILUTION WATER

H₂O _____ lbs/hr

9. SLURRY INJECTION

Solids _____ lbs/hr

H₂O _____ lbs/hr

Atomizing Air _____ lbs/hr

10. ESP INLET

Flue Gas _____ lbs/hr

Solids _____ lbs/hr

Temperature _____ °F

Δ T App _____ °F

11. COLLECTED SOLIDS

Total Solids _____ lbs/hr

12. WASTE TO DISPOSAL

Solids _____ lbs/hr

H₂O _____ lbs/hr

Total _____ lbs/hr

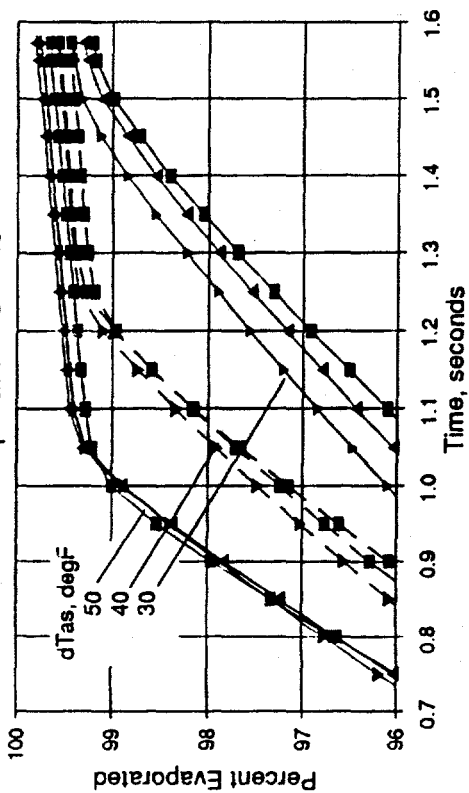
13. EMISSIONS

SO₂ _____ lbs/hr

Particulate _____ lbs/hr

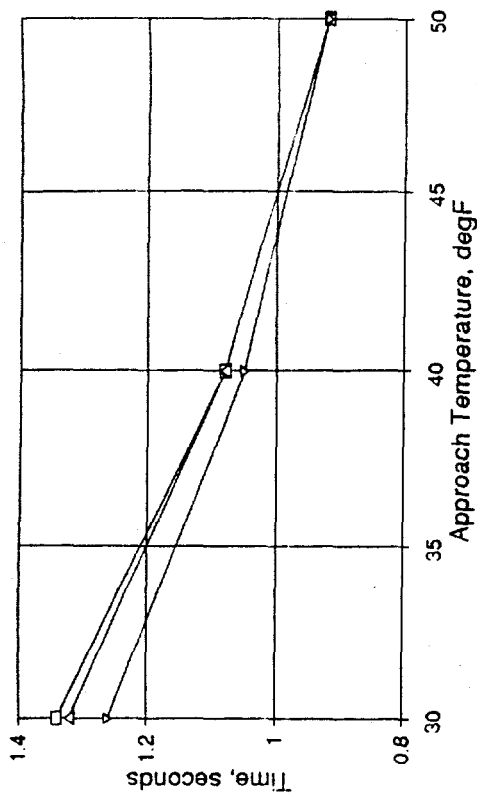
DIAN1D Reference Plant Predictions

Overall Evaporation vs Time



DIAN1D Reference Plant Predictions

Time Required to Evaporate 98% H₂O



DIAN1D Predictions

DOE Reference Plant, Drying Time

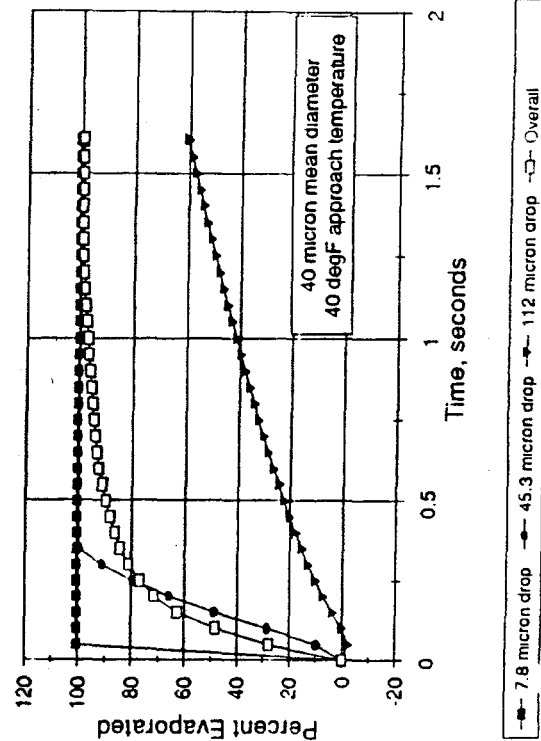


FIGURE 3-4

**DIAN1D Model
Predictions of Droplet Drying Time**

3.2.3.2 Effects on Particulate Collection Device

To determine the suitability of the existing particulate collection device, the user must determine the required particulate removal efficiency when operating under duct injection flue gas conditions. The particulate emissions rate limit was determined in Section 3.1.13. The user may wish to reduce this rate further as a safety measure, to compensate for particulate collection device operational problems such as ESP fields out of service. The solids loading to the ESP was calculated in Section 3.2.1.8 for DSI or 3.2.2.10 in the case of DSD. The required ESP efficiency is calculated as follows:

$$\text{Required ESP Efficiency (\%)} = \frac{\text{Total Solids Entering ESP-Particulate Emissions Limit}}{\text{Total Solids Entering ESP}} \quad (3-25)$$

Collection efficiency measured from recent performance tests is the best source of determining the existing ESP efficiency. If these data are not available, existing efficiency may be estimated by comparing the particulate emissions limit (in lb/hr from Section 3.1.13) to the fly ash mass loading at the ESP inlet (in lb/hr from Section 3.1.9).

In order to maintain the current particulate emissions rate, the required ESP efficiency after duct injection must be greater than the existing efficiency (due to increased solids loading). Because humidification can potentially improve the ESP electrical conditions, a significant increase in collection efficiency is possible. To determine if an ESP is capable of operating at higher efficiencies, and can be made to perform at the required level after duct injection, the user must evaluate the size and design of the ESP, its mechanical and electrical condition, and operating characteristics.

This manual can only provide the user with general information on how a duct injection system will affect an ESP. Determining the suitability of a particular ESP for duct injection service is among the most critical issues that will determine the feasibility of the project. The information in this section highlights the major parameters to consider, but the user is advised to consult an ESP expert to best determine if a particular ESP can meet the users requirements under duct injection conditions. The user is also advised to use ADAPCESP, a computer model for predicting the performance of ESPs downstream of duct injection processes (see Section 4 of this Handbook). This model can also be used to estimate the additional collection surface required to provide the desired collection efficiency or outlet emissions if the users ESP is found to be undersized.

ESP Size

Because the science of electrostatic precipitation is very complex and application specific, it is very difficult to form generalized correlations of ESP size to performance. For applications to duct injection processes, there are very limited empirical data for comparison. Utility lime based spray dryer technology which generates flue gas and particulate very similar to duct injection has been installed upstream of fabric filters or very large ($\text{SCA} > 500 \text{ ft}^2/1000 \text{ ACFM}$) ESPs. ESP vendor information suggests that to maintain particulate emissions below 0.03 lbs/MMBTU from spray dryers, a minimum of 400 SCA is required. If emissions limits are above 0.03 lbs/MMBTU, less collection surface may be required. The ESP Performance Model ADAPCESP can be used to estimate the ESP size requirement for a given ESP/duct injection case. Decisions as to the suitability of an ESP must be based on a variety of other parameters in addition to size.

ESP Face Velocity

The flue gas velocity through the ESP has a strong influence on performance. The face velocity not only determines treatment time in the energized sections, but is directly related to reentrainment emissions. Higher inlet loading from duct injection results in more particles subject to all reentrainment mechanisms including rapping, plate scouring, and hopper sweepage. In addition to these well known reentrainment mechanisms, very low resistivity (typically only a problem at very close ($< 25^{\circ}\text{F}$) approach temperatures) can lead to electrical reentrainment where the collected dust is actually repelled from the plates. For these reasons, ESPs with face velocities greater than 6 ft/second may require enlargement or other upgrades.

Mechanical/Electrical Condition

A prerequisite to the installation of duct injection is a detailed internal inspection to identify and repair all major mechanical problems within the ESP. Plate and electrode misalignment due to warped or bowed plates, damaged suspension or anti-sway devices should be repaired to provide the proper electrical clearances. Broken wires and insulators should be replaced. Obstructed or damaged gas flow distribution devices such as perforated plates and flow baffles should also be repaired. It is very important to identify and repair any leaks in the ESP casing and replace failed door seals to minimize air inleakage. Air inleakage reduces the effective ESP size, increases the face velocity and creates spots for condensation and corrosion. If the internal inspection reveals structural problems, a full structural analysis may be required before the decision to proceed with duct injection is made.

Operating Characteristics

Humidification through duct injection can improve ESP performance in several ways (reduced gas volume, increased gas density, reduced resistivity), but if the ESP is currently operating at near optimum levels, there may be little room for improvement in efficiency. ESPs in good mechanical condition, and which are operating at high ($> 20\text{mA}/\text{Ft}^2$) current densities (from high sulfur coal) may show only slight improvements in electric field strength and collection due to humidification. In these instances, if the required collection efficiency is significantly higher than the current performance level, then ESP upgrades (see Section 6) may be necessary.

If however, the existing ESP is not working at its full potential due to low ($< 10\text{mA}/\text{Ft}^2$) current densities, high fly ash resistivity, back corona, or excessive sparking, then the collection efficiency could improve dramatically. Humidification will affect the electrical conditions within the ESP and particle surface resistivity much as is accomplished through flue gas conditioning with SO_3 . The extent to which humidification can help is a function of the precipitator size, baseline electrical conditions, temperature, particulate size, gas velocity, etc. These variables are interdependent and their individual and cumulative effects are difficult to predict without ESP models.

If analyses indicate an ESP is undersized or unable to perform at the required level, there are a variety of ESP upgrade strategies to consider:

1. Correcting gas velocity distribution
2. Digital Controls
3. Increasing the size/treatment time of the ESP
4. Special discharge electrodes
5. Calcium chloride addition
6. Operational modifications

3.2.3.3 Effects on Existing Ash Handling and Storage Systems

Duct injection results in a substantial increase in solids collected in the particulate collection device. The solids collected in the particulate collector are equal to the total solids entering (Section 3.2.1.8 or 3.2.2.10, as applicable) multiplied by the ESP removal efficiency (Eq. 3-25). This value should be compared to the ash removal system capacity as determined in

Section 3.1.21. Undersized systems may have to be upgraded or replaced to accommodate the solids increase. In addition to capacity concerns, the physical and chemical properties of the duct injection waste solids may require other upgrades to the ash handling system. These properties include increased moisture, increased cohesivity, low temperature, and increased alkalinity. The most significant potential problems are a general decrease in flowability, and moisture/condensation which can lead to plugging.

3.2.3.4 Effects on Stack/Chimney Liner

The effects of a duct injection retrofit on the existing stack/chimney liner depend a great deal on the composition of the liner. With limited full-scale duct injection experience to draw upon, conventional lime spray dryer installations were investigated. Most of these installations included new stacks with acid resistant brick or FRP Liners. These materials, when properly installed and maintained, have performed well.

It is likely that plants that are candidates for duct injection retrofits will be older units with carbon steel or non acid resistant brick liners. The impacts of duct injection or spray dryer processes on these older stacks is largely unknown. An engineering evaluation of the adequacy of the existing chimney for duct injection flue gas conditions is recommended. The low temperature, high moisture flue gas will increase the potential for corrosion. It is therefore necessary to keep the flue gas safely above the water dew point by preventing cold spot condensation and inleakage. Commercial spray dryer experience has underscored the importance of adequate insulation over all duct and breaching surfaces including flanges and expansion joints. Metal expansion joints should be replaced with fabric or viton, and all leaks should be repaired.

Although duct injection processes operate well below typical acid dew point temperatures, this is not a major concern. Dry and semi-dry SO_2 removal processes like duct injection essentially eliminate the acid dew point by removing the SO_3 . However, application on units which share a common stack flue present a special problem.

If duct injection flue gas mixes with hot untreated flue gas from another unit, even small concentrations of SO_3 will likely result in the formation of H_2SO_4 droplets which can cause severe corrosion and a possible visible acid plume.

These gases may require the installation of an acid resistant liner (brick, FRP, gunnite) or a flue gas reheat system downstream of the ESP. It may, however, be more economical in many cases to erect a new chimney (with acid resistant materials) on units retrofit with duct injection systems, due to the outage requirements for re-lining a chimney or the high operating cost of a flue gas reheat system.

3.2.4 Sorbent Selection

The selection of a sorbent for a duct injection process will likely be based on economics. Although differences in sorbent characteristics have shown significant effects on SO_2 removal and sorbent utilization in laboratory tests, these effects have not been realized in pilot-scale test projects. The effects of scavenging appear to override particle size, surface area and porosity when the sorbent is injected upstream of humidification in DSI systems. These physical characteristics have shown a much greater effect in furnace sorbent injection, economizer sorbent injection, and in dry sorbent injection in non-scavenging configurations.

However, the scavenging mode of DSI has shown the capacity for much higher SO_2 removal. These data indicate selecting the least expensive sorbent based on available calcium content.

3.2.4.1 On-Site vs. Off-Site Hydration for DSI

In the dry sorbent injection process, dry hydrated lime $[\text{Ca}(\text{OH})_2]$ is injected to remove SO_2 . A major economic and process design issue will be whether to purchase hydrated lime or purchase quicklime (CaO) and hydrate it at the plant site. Although quicklime and hydrated lime are offered at similar prices, one lb of quicklime produces 1.32 lbs of $\text{Ca}(\text{OH})_2$ when hydrated on-site. There are a number of factors involved in making this decision. These include overall sorbent requirements, price and availability of each sorbent, transportation costs and distances, available plant space for a lime hydrator, etc. A lime hydrator will likely require additional O&M personnel and add a level of complexity to the DSI process. Preliminary economic evaluations conducted by UE&C using very generic criteria resulted in a break point of approximately 100 MW plant size. At plants larger than 100 MW, on-site lime hydration is less expensive on a levelized control cost basis; however, this is a site specific determination.

3.2.4.2 Truck vs. Rail Unloading

Another very important economic and process design issue concerns reagent receiving. Lime reagent can be delivered by truck, rail or barge. This discussion will focus primarily on truck and rail receiving. Lime reagent suppliers and transportation companies should be contacted to determine the price and availability of both truck and rail delivery. The delivered price/ton may vary considerably among the various suppliers. The user should consider the following in making its decision:

1. Maximum lime usage rate - This will determine the maximum amount of trucks or rail cars/day. Self unloading trucks typically require about 1 hour to unload. Six trucks per shift are a realistic maximum unloading rate per silo fill tube.
2. The number of shifts the plant will permit sorbent truck traffic and unloading.
3. Access space for multiple truck unloading. These trucks are quite large; adequate space to park the truck(s), turn around, waiting, etc. must be considered.
4. Operator(s) for rail unloading. A plant operator will be required to operate and monitor the unloading system, position rail cars, etc.
5. Rail access and clearance - Rail unloading systems require considerable space, and pose many potential access and retrofit difficulties in older plants.

Table 3-2 summarizes other considerations.

TABLE 3-2

TRUCK VS. RAIL UNLOADING

	Truck	Rail
Capital cost for unloading	Minimal-trucks are self-loading	Expensive, site specific - usually involves rail spur, pit area beneath tracks, pneumatic system.
Manpower requirements	Little or none - truck operator usually unloads	Manpower required for rail car management, unloading system operation, etc.
Unloading rate	Much slower (15-20 tons/hr) than rail system - 6 trucks/shift/system - could potentially have logistics problems	Have greater capacity - can typically be unloaded faster (30-40 ton/hr). Easier to manage logistically.

This information indicates that plants requiring over 300 tons/day of sorbent (12 trucks @ 25 ton/truck) should select rail unloading. Those plants requiring less than 300 tons/day should base their decision on the criteria discussed above.

4.0 DUCT INJECTION PREDICTIVE MODEL

This section describes the development of several computer-driven mathematical models designed to be optional companion tools to this handbook. These computer programs (DIAN1D, DIAN3D, and ADA PC-ESP) described below, will aid the user in predicting the performance and establishing design criteria for duct sorbent injection technology at a specific plant. This section describes the features of these models, but is not intended to be a "user's guide". The models and user's guides are available through the U.S. Department of Energy's (DOE) Energy Science and Technology Software Center.

Energy Science and Technology Software Center
P.O. Box 1020
Oak Ridge, TN 37831-1020
(615) 576-2606
Fax, (615) 576-2865

4.1 Model Description

4.1.1 DIAN1D

DIAN1D, a one-dimensional model, along with its user interface DIANUI are designed to be used on a personal computer (PC) to provide information on energy and mass transfer for slurry droplets injected into a flue gas stream using dual-fluid atomizers. It is an easy to use tool that can provide the user with quantitative information about the effect of drop size distribution and duct inlet conditions on slurry droplet evaporation and SO₂ absorption. However, droplet dispersion and wall deposition cannot be predicted with this 1D model.

4.1.2 DIAN3D

The computer model, DIAN3D, can solve three-dimensional equations of mass, momentum, and energy for both the flue gas and the sorbent and also models three modes of operation: humidification followed by dry sorbent injection, dry sorbent injection followed by water injection, and sorbent injection in slurry form. Emphasis has been placed on slurry injection because of its higher sorbent utilization rate and fewer operational problems compared to dry sorbent injection. The dry injection modes have not been tested. The output of the model can be presented in graphical form using the DIAN3D postprocessor and commercially available graphics computer programs. Users of DIAN3D should be experienced in running complex mathematical models, while DIAN1D can be run with only cursory knowledge of mathematical models. DIAN3D was designed to run on a Work Station or similar computer operating under the UNIX operating system and involves long (several hours) computing times for each execution of the program. Thus, its application is limited to instances where a preliminary analysis has been completed and a decision has been made to install a duct injection process. This sophisticated model can then be used to prepare detailed design information.

4.1.3 ADA PC-ESP

A third mathematical model, ADA PC-ESP, predicts the performance of an ESP operating under duct sorbent injection conditions (low temperature, high grain loading). This model, that can be run on a PC, provides information that is essential to understanding the detrimental effects (space charge effects, electrical reentrainment) that duct injection could have on a specific ESP. It also allows the user to develop strategies to improve ESP performance.

4.2 Model Input/Output

4.2.1 DIAN1D

The DIAN1D (one-dimensional Duct Injection Analysis model) user interface, DIANUI, is used to set up one-dimensional models of a duct injection system from plant design specifications and process requirements. DIANUI incorporates an SO₂ removal correlation and interactively calculates energy and material balances, allowing the user to estimate how different combinations of process variables affect SO₂ removal and calcium utilization. This capability is particularly useful for investigating the effects of calcium to sulfur ratio, approach to adiabatic saturation temperature and recycle prior to running DIAN1D.

DIANUI can write DIAN1D input files for single and multiple DIAN1D runs. Multiple runs are used by DIAN1D to perform parametric analyses for up to five variables.

DIANUI is interactive and menu driven. The user is presented with a menu from which specific data entry screens can be selected. Each screen contains data with a common functional relationship. Figure 4-1 illustrates the screens available for data entry. The screens are sequenced in a logical order and are automatically selected as the user proceeds with data entry. However, the user can override the default selection and select any screen.

FIGURE 4-1
MAIN MENU

DIAN User Interface

0	:	Read Case File
1	:	Duct Geometry
2	:	Duct Inlet Conditions
3	:	SO ₂ Removal Parameters
4	:	Atomizer Characteristics
5	:	DIAN Model Parameters
6	:	Write Case File
7	:	Write DIAN1D Input File
8	:	Material Balance Table
9	:	Exit Program

Figures 4-2 and 4-3 illustrate the input screens. Calculated values are underlined. However, these entries are displayed in yellow on the screen.

FIGURE 4-2
DUCT GEOMETRY

DUCT GEOMETRY			
DUCT		Quarter Symmetry?	: No
Height	: 11.000 ft		
Width	: 11.000 ft		
Length	: 90.000 ft		
Area	: <u>121.000</u> sq. ft		
ATOMIZERS		ATOMIZER SPACING	
Number of Rows	: 7	Top Row to Ceiling	: 2.000 ft
Number of Columns	: 7	Row to Row	: 1.000 ft
		Bottom Row to Floor	: <u>3.000</u> ft
		Column to Column	: 1.000 ft
		Side Wall Spacing	: <u>2.500</u> ft

<F1> Help <ESC> Accept Data

FIGURE 4-3
PLANT OPERATING CONDITIONS AND FUEL CHARACTERISTICS

PLANT DATA			
PLANT DATA		ULTIMATE ANALYSIS	
Net output	: 125.0 MWe	Moisture	: 5.99 wt %
Heat Rate	: 9722.0 Btu/kw-hr	Carbon	: 71.21 wt %
Excess Air	: 20.00 %	Hydrogen	: 4.79 wt %
Air in leakage	: 15.00 %	Nitrogen	: 1.40 wt %
Ash carry over	: 80.00 %	Sulfur	: 2.60 wt %
COMBUSTION AIR		Oxygen	: 4.80 wt %
Pressure	: 29.400 in_Hg	Chlorine	: 0.12 wt %
Temperature	: 70.00 degF	Ash	: 9.09 wt %
Humidity	: 50.00 %	<u>Total</u>	: <u>100.00</u> wt %
Oxygen	: 21.00 %	DuLong HHV	: <u>13061.1</u> Btu/lb
Nitrogen	: <u>79.00</u> %	HHV	: 13084.0 Btu/lb
Coal Type : User Supplied			
Description : Economic Study Base Coal			
Fuel Flow	: 92880.6 lb/hr	Ash	: <u>5.558</u> #/mil. Btu
Flue gas flow	: <u>1343298.6</u> lb/hr		: <u>6754.3</u> lb/hr

<F1> Help <ESC> Accept Data

For the most part the input required is included in the data collected in sections 3 and 4 of this handbook. Supplemental external calculations to convert data are usually not required. Default values are presented for every input field. Tables of properties for representative coals and typical two-fluid atomizers are provided as a convenience. The values in the tables can be replaced by the user in a table of user supplied values which is stored with the data file by DIANUI.

Input data is checked to determine if valid characters have been entered. Range checking is performed for input variables which have restricted valid ranges. Mass fractions are summed and displayed to allow the user to check that species concentrations total 100%. Access to the DOS file directory is provided when the user is asked to provide a name for an input or output file.

The input data can be saved in a case file and recalled later for additional processing. DIANUI writes all the input files required by DIAN1D for single runs or multiple parametric runs. The files are standard DOS ASCII text files and can be converted to UNIX format if DIAN1D is being run on a UNIX system.

Energy and mass balance calculations are performed each time a data input is changed. All calculated values displayed on the screen are immediately updated.

4.2.2 DIAN3D

DIAN3D is a three-dimensional model that describes the momentum, energy and mass transfer occurring in the duct injection process. The three-dimensional model allows DIAN3D to calculate the effect of atomizer spacing and wall clearance on deposition. Again, DIAN3D is a very complex computer model and should be used only when a preliminary analysis has been completed and a decision has been made to install a duct injection process. DIAN3D has the ability to model

- Multi-dimensional (2D or 3D) gas flow.
- Cartesian or cylindrical polar coordinate systems.
- Laminar or turbulent flow.
- Droplet dynamics using a Lagrangian approach.
- Heat and mass transfer between the gas phase and slurry droplets or inert particles.
- SO₂ removal.

DIAN3D allows individual atomizers to be represented as point sources of mass, momentum and energy, eliminating the need for detailed atomizer models requiring a large number of control volumes. The momentum source term must be determined by a separate calculation or from thrust measurements on an actual atomizer.

The user must use the DIAN3D preprocessor to prepare the input file required by DIAN3D. The user is required to generate an input file for the DIAN3D preprocessor of the form prefix.in which will contain all the necessary commands to set up a particular problem. The preprocessor will read-in the input file prefix.in, execute the given commands and generate an output file DIAN3D which is the input data file of the main code DIAN3D. Most of the input data are defaulted to useful values so that the user needs only specify necessary data for a particular problem. This significantly speeds up the process of setting up a specific problem.

The DIAN3D postprocessor provides a user with the ability to interactively view DIAN3D variables stored in the data files. The data can be plotted in a variety of formats and displayed at a graphics terminal or work station, or the output can be directed to a graphics file for subsequent output to a hardcopy device such as a PostScript or LaserJet compatible printer. The postprocessor can also convert DIAN3D data to a spreadsheet format or to the format required by TECPLOT, a commercial flow visualization program specifically designed to display the output from Computational Fluid Dynamics (CFD) codes (developed by Amtec Engineering). The postprocessor input/output is based on the GKS (developed by Advanced Technology Center) graphics standard and the user must provide a GKS library with device drivers.

The postprocessor has the following capabilities:

- interactive menu and prompt driven input,
- unit conversion for displaying variables in units other than the mks units used by DIAN3D,
- model boundary outline,
- session replay for repeating a postprocessor run, and
- page layout allowing multiple plots per page.

4.2.3 ADA PC-ESP

The data handling module for creating an input file for the ADA PC-ESP creates a full screen, menu driven interface to simplify data entry for the model. The data handling module isolates the user from the complexity of the ESP input formats (which vary depending on the values of the data). The module also validates input data, performs all necessary unit conversions, and allows the user to change default values. The data handling module leads the user via a series of menus and input screens through the entry of all information necessary to run the model. Thus the user is required to have only cursory understanding of computer models, on the level of any user of a simple software package. The user must be knowledgeable in the technical operation of an ESP in order to properly select the values for input to the model and interpret the results. However, the values to be input by the user are limited to the more commonly available parameters such as plate height, plate length, number of gas passages, plate spacing, mass loading, etc. The values for such parameters as the dielectric constant and effective ion mobility are automatically selected by the program based upon particle and gas stream characteristics, with the capacity for user override.

The following is a list of the data entry screens that will be seen by the user during the construction of a data set. Figure 4-4 is an example of one of these screens.

- SETUP screen
- EDITOR screen
- Particle size distribution screens *
- ESP geometry screens
- ESP operating conditions
- Non-ideal effects screen
- ESP inlet conditions

* (defaults can be selected based on mass median diameter)

FIGURE 4-4
ESP Operating Conditions

ADA Technologies PC ESP Model V3.00 Wednesday January 23, 1991 9:04 am				
File Description				
ESP Unit Name				
Director				
	Inlet	Outlet	Unit (F10 to switch)	
Temperature	0.000000	0.000000	deg C	
Differential Pressure	0.000000	0.000000	inH2O	
Barometric Pressure	0.000000		inH2O	
Flow Rate	0.000000	0.000000	Cuft/Min	
Percent Oxygen	0.000000	0.000000		
Percent Carbon Dioxide	0.000000	0.000000		
Percent Carbon Monoxide	0.000000	0.000000		
Percent Water Vapor	0.000000	0.000000		
(Remaining gas is considered to be Nitrogen)				
Operating voltages and currents are presented on the next screen				
No file selected				
Move cursor to desired field, simply type new value or press <F3> to edit				
Help <F1> Exit <esc> Edit <F3> Switch Units <F10>				

ADA PC-ESP allows the user to select between three levels of output with each level divided into several sections. Level 1 contains the following sections:

- 1) Printout of the files used in the model run.
- 2) Printout of all input data.
- 3) Cumulative percent mass and DM/DLOG mass distributions at the ESP inlet and outlet.
- 4) Summary table of precipitator operating conditions and performance.

The Level 2 output file contains the following sections:

- 1) Printout of the files used in the model run.
- 2) Printout of all input data.
- 3) Incremental analysis of precipitator performance.
- 4) Preliminary migration velocities and penetrations.
- 5) Outlet migration velocities and penetrations.
- 6) Particle size range statistics.
- 7) Cumulative percent mass and DM/DLOG mass distributions at the ESP inlet and outlet.
- 8) Summary table of precipitator operating conditions and performance.

The Level 3 output file contains the following sections:

- 1) Printout of the files used in the model run.
- 2) Printout of all input data.
- 3) Incremental analysis of precipitator performance.
- 4) Charge accumulated on different particle sizes in each increment.
- 5) Fraction of saturation charge in each increment for different size particles.
- 6) Preliminary migration velocities and penetrations.
- 7) Outlet migration velocities and penetrations.
- 8) Particle size range statistics.
- 9) Cumulative percent mass and DM/DLOG mass distributions at the ESP inlet and outlet.
- 10) Summary table of precipitator operating conditions and performance.

The program also provides the user with the option of preparing data for use in a graphics package. Either the Level 2 or 3 output options must be selected for the program to generate data for plotting. The data generated are in the correct format for direct input into the "GRAPHER" software package from Golden Software, Inc. There are five different plot data sets that can be generated by the program.

- 1) Inlet cumulative size distribution.
- 2) Inlet differential size distribution.
- 3) Outlet cumulative size distribution.
- 4) Outlet differential size distribution.
- 5) Efficiency vs. size.

4.3 Utilizing the Model Results

These computer-driven mathematical models were designed to be used as optional companion tools to this handbook. They will help the user predict the performance of duct sorbent injection technology at a specific plant. DIAN1D will provide the user with quantitative information about the effect of drop size distribution and duct inlet conditions on slurry droplet evaporation and SO₂ absorption. DIAN3D should be used to prepare detailed design information only after a decision has been made to install a duct injection process. DIAN3D can help determine atomizer location and spacing, and predict wall wetting and deposition in complex 3-dimensional geometries. ADA PC-ESP should be used to predict the performance of an ESP operating under duct sorbent injection conditions.

5.0 ENGINEERING DRAWINGS

Typical drawings have been prepared for a DSI and DSD duct injection system. These drawings are based on two ducts and two separate ESPs downstream of the boiler air heaters. The user will need to modify the drawings to account for the site-specific aspects of its plant.

Detailed electrical and instrumentation drawings were not part of the scope of this project, and, therefore, they have not been developed. General control loop philosophy for controlling a DSI or DSD system is contained in Section 8.1. No general arrangement, mechanical equipment, or structural drawings have been prepared due to the site-specific nature of these drawings. Ideas on general equipment configurations and retrofit considerations are given in Section 7.0.

5.1 Process Flow Diagrams

The following process flow diagrams (PFDs) have been developed and are located at the end of Section 5:

Sheet 01	Dry Sorbent Injection, Off-Site Hydration PFD
Sheet 02	Dry Sorbent Injection, On-Site Hydration PFD
Sheet 03	Duct Spray Drying PFD

Each PFD has a material balance outline built into the drawing which can be used to develop the material balance for a specific application. The prefix "K" denotes "thousands"; e.g., KLB/HR indicates thousands of pounds per hour. Sample material balances have been developed for a specific plant using these PFDs in the DSI and DSD Case Studies, Appendix A. Suggestions to the user for developing the material balances and stream conditions are given in Section 5.2.

The PFDs are all based on two ducts/ESP's for injection because (from the Duct Configuration Survey) that is most typical of candidate plants, but they can be readily modified to reflect one or three ducts/ESP's. This is true because streams representing the overall quantities of reagent, compressed air, etc. are included before they split and branch out to the duct(s).

A positive pressure rail car unloading system is shown in the PFDs. This is only one type of rail car unloading system available, and it is shown for simplicity only - not as a recommendation.

The PFDs show an existing vacuum ash handling system. If a positive pressure or mechanical system will be used, the recycle material may be conveyed directly to the recycle bin, and modifications to the existing ash silo may not be required. If a wet sluicing system will be used, recycle of collected material back to the process will not be possible.

The PFDs do not reflect equipment details or redundancy. These are shown on the P&IDs in Section 5.3.

5.1.1 Dry Sorbent Injection

On the two DSI PFDs, the hydrated lime and recycle material injectors are shown upstream of the dual-fluid humidification nozzles. Although sorbent injection upstream of humidification (scavenging mode) is generally considered to result in superior SO₂ removal, it can cause

material deposition. Locating the injectors and the humidification nozzles in the same vertical plane (for horizontal ducts) may give better operability. In that case, there would be no separate gas Stream No. 3 on the DSI PFD.

For DSI, the decision to use on-site or off-site hydration has a significant effect on the PFD. That is why a PFD has been developed for both options. The criteria to make this decision are given in Section 3.0.

For off-site hydration (PFD 01), the hydrate silo may be located either right next to the injection point(s) or remote from it as space and unloading constraints permit. However, the most reliable and economical feed rate control of the hydrated lime will be achieved if the silo is located close to the injection point(s). If the silo cannot be located near the injection point(s), the user may want to consider pneumatically transferring the lime from the remote silo to a hydrate day bin located close to the injection points. This case is not shown on the PFD.

For the on-site hydration option (PFD 02), the pebble lime silo, hydrators, and hydrate bin may be located either right next to the injection point(s) or remote from it as space and unloading constraints permit. However, to achieve the most reliable feed rate control of the hydrated lime, the hydrate bin should be located as close to the injection point(s) as possible, even if the silo and hydrators are located remotely.

5.1.2 Duct Spray Drying

For the DSD PFD, both a pebble lime silo and day bin are shown. This equipment arrangement reflects a conservative configuration in which the silo has to be located relatively far away from the injection ductwork due to rail car unloading or other site-specific constraints. For this equipment arrangement, it is considered more feasible to pneumatically convey lime from the silo to a small day bin located near the injection point (and have the slurry preparation accomplished close to the injection point) than to prepare the slurry near the remote silo and transport it a long distance to the injection point. This is especially true because a slurry return to the atomizer feed tank is normally required to keep slurry pipeline velocities high. If the day bin can be located close to the duct injection point, a separate lime day bin is not required.

A ball mill slaker is shown on the DSD PFD. A detention-type or paste-type slaker could also be used. These options are included in the detailed P&IDs in Section 5.3.

5.2 Material Balances

Material balance calculations have been developed for the major process streams for both duct injection systems described in Section 3.0 of this handbook. In order to develop a detailed equipment list, all of the process streams listed on the PFDs need to be calculated. The first step in completing the material balances is to transfer the results of Worksheets 3-2 and 3-3 on to the material balance boxes included in the applicable PFD. Next, the streams that are not evaluated in Section 3.0 need to be calculated. These streams are listed below. Note that the streams are not in sequential order due to the interdependency of the streams.

Appendix A of this handbook provides detailed examples of how the material balance calculations are developed for a specific duct injection system.

5.2.1 Dry Sorbent Injection - On-Site Hydration

Stream 2 - Flue Gas Downstream of the Air Heater: Refer to Section 3.0 of this handbook.

Stream 1 - Flue Gas Downstream of Economizer: The flue gas conditions of this stream can be calculated by knowing the conditions of stream 2 and the percent in leakage of the air heater. The following equation can be used to calculate the volumetric flow rate of this stream:

$$Q_1 = \text{Volumetric flow rate of stream 1} = \frac{Q_2 (\text{scfm})}{(1 + \% \text{ in-leakage})} \quad (5-1)$$

$$M_1 = \text{Mass flow rate of stream 1} = Q_1 \times \frac{P_1}{T_1} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{MW}{10.73} \quad (5-2)$$

Stream 10 - Hydrated Lime from Hydrate Bin: Refer to Section 3.0 of this handbook.

Stream 11 - Hydrated Lime to Injectors Per Duct: This stream is equivalent to stream 10 divided by the number of ducts.

Stream 16 - Recycle Solids from Recycle Bin: Refer to Section 3.0 of this handbook.

Stream 17 - Recycle Solids to Injectors Per Duct: This stream is equivalent to stream 16 divided by the number of ducts.

Stream 12 - Humidification Water to Atomizers: Refer to Section 3.0 of this handbook.

Stream 13 - Humidification Water to Atomizers: This stream is equivalent to stream 12 divided by the number of ducts.

Stream 25 - Atomizing Air from Compressors: To atomize the humidification water in the spray nozzles, 0.5 lb air/lb H₂O is required. The following equations can be used to calculate the flow rates of this stream:

$$M_{25} = \text{Mass flow rate of stream 25} = M_{12} \times 0.5 \text{ lb air/lb H}_2\text{O} \quad (5-3)$$

$$M_{\text{Water}_{25}} = \text{Mass flow rate of water} = M_{25} \times \% \text{ moisture in air} \times 0.6 \quad (5-4)$$

Note that the 0.6 factor in Equation 5-3, and others, defines the quantity of water in the ambient air that passes through the air compressors into the duct.

Stream 14 - Atomizing Air to Atomizers Per Duct: This stream is equivalent to stream 25 divided by the number of ducts.

Stream 15 - Solids from ESP to Ash Silo: Refer to Section 3.0 of this handbook.

Stream 18 - Waste Solids to Pug Mill: The waste solids to the pugmill can be calculated from the calcium sulfite and calcium sulfate reaction products, amount of calcium hydroxide utilized, flyash content of the gas, and the amount of recycled solids. The total particulate removed in the ESP is calculated as follows:

$$\begin{aligned} \text{Total Particulate Removed} &= (\text{Ca(OH)}_2 \text{ remaining} + \text{CaSO}_3 \cdot \frac{1}{2} \text{H}_2\text{O} \text{ produced} + \text{CaSO}_4 \cdot 2\text{H}_2\text{O} \text{ produced} + \\ &\text{(Wet basis)} \quad \text{Flyash and Inerts} + \text{Recycle-Particulate Emissions}) / \\ &\quad (1 - \% \text{ interstitial water}) \end{aligned} \quad (5-5)$$

The waste solids to the pugmill are calculated by subtracting the recycled solids (stream 16) from the total particulate removed, both on a wet basis.

Stream 19 - Waste Conditioning Water: The flow rates of this stream can be determined by knowing the mass flow rate of stream 18 and percent solids of streams 18 and 20. The following equation should be used:

$$M_{19} = \text{Mass flow rate of stream 19} = \frac{M_{18} \cdot x_{20} \cdot (x_{20} - x_{18})}{(1 - x_{20})} \quad (5-6)$$

$$\begin{aligned} \text{Where: } M_{18} &= \text{Mass flow rate of stream 18} \\ x_{18} &= \text{fraction of water in stream 18} \\ x_{20} &= \text{fraction of water in stream 20} \end{aligned}$$

Stream 20 - Waste to Disposal: This stream can be calculated from the flow rates of streams 18 and 19. The following equation can be used:

$$M_{20} = \text{Mass flow rate of stream 20} = M_{18} + M_{19} \quad (5-7)$$

Stream 8 - Lime to Hydrator: Refer to Section 3.0 of this handbook.

Stream 9 - Hydration Water to Hydrator: Refer to Section 3.0 of this handbook.

Stream 21 - Raw Water: This stream is identical to stream 9.

Stream 24 - Cooling Tower blowdown Water: This stream can be calculated from the flow rates of streams 12 and 19. The following equation can be used:

$$M_{24} = \text{Mass flow rate of stream 24} = M_{12} + M_{19} \quad (5-8)$$

Stream 22 - Air Compressor Cooling Water In: The mass flow rate of this stream can be calculated from the inlet and outlet air flows of the compressors. The following equations can be used:

$$\begin{aligned} Q_{in} &= \text{Inlet volumetric flow of compressors} \\ &= [((M_{25} - M_{\text{Water}_{25}})/\text{MW Air}) + (M_{\text{Water}_{25}}/(0.6 \times \text{MW H}_2\text{O}))] \\ &\quad \times (0.7302/60) \times (T_{in} + 460) \times (14.7/P_{in}) \end{aligned} \quad (5-9)$$

$$\begin{aligned} \text{HP} &= \text{Operating hp of the air compressors} \\ &= 0.0068 \times Q_{in} \times P_{in} \times \ln(P_{25}/P_{in}) \end{aligned} \quad (5-10)$$

$$\begin{aligned} M_{22} &= \text{Mass flow rate of stream 22} \\ &= (\text{HP} \times 2544.434 - (((M_{25} - M_{\text{Water}_{25}}) \times 0.241 + \\ &\quad M_{\text{Water}_{25}} \times 0.46) \times (T_{25} - 60)) + M_{\text{Water}_{25}}/0.6 \times 0.4 \\ &\quad \times 1034.2)) / (T_{23} - T_{22}) \end{aligned} \quad (5-11)$$

Stream 23 - Air Compressor Cooling Water Out: The mass flow rate of this stream is identical to that of stream 22. The higher temperature causes the volumetric flow rate of this stream to be slightly higher than that of stream 22.

Stream 3 - Flue Gas After Solids Injection: The flue gas conditions of this stream can be calculated by knowing the conditions of streams 2, 11, and 17.

Stream 4 - Flue Gas After Water Injection: The flue gas conditions of this stream can be calculated by knowing the conditions of streams 3, 13, and 14 and the approach to saturation temperature.

Stream 5 - Flue Gas Downstream of ESP: The flue gas conditions of this stream can be calculated by knowing the conditions of streams 4 and 15 and also the temperature drop across the ESP.

Stream 6 - Flue Gas Downstream of ID Fan: The flue gas conditions of this stream can be calculated by knowing the conditions of stream 5 and also the temperature drop and pressure rise across the ID fan.

Stream 7 - Stack Gas: This stream is identical to stream 6 multiplied by the number of ducts.

5.2.2 Dry Sorbent Injection - Off-Site Hydration

This system is identical to the on-site hydration system except that three process streams are eliminated when off-site hydration is chosen. These streams are:

- Stream 8 - Lime to Hydrator
- Stream 9 - Hydration Water to Hydrator
- Stream 21 - Raw Water

Therefore, this system will have the same material balance calculations minus these three streams. Note, the stream numbers for the two DSI processes are not identical because of the elimination of these three streams.

5.2.3 Duct Spray Drying

Stream 2 - Flue Gas Downstream of the Air Heater: Refer to Section 3.0 of this handbook.

Stream 1 - Flue Gas Downstream of Economizer: The flue gas conditions of this stream can be calculated by knowing the conditions of stream 2 and the percent in leakage of the air heater. The following equation can be used to calculate the volumetric flow rate of this stream:

$$Q_1 = \text{Volumetric flow rate of stream 1} = \frac{Q_2 (\text{scfm})}{(1 + \% \text{ in-leakage})} \quad (5-12)$$

$$M_1 = \text{Mass flow rate of stream 1} = Q_1 \times \frac{P_1}{T_1} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{\text{MWW}}{10.73} \quad (5-13)$$

Stream 14 - Diluton Water to Atomizer Feed Tank: Refer to Section 3.0 of this handbook.

Stream 13 - Recycle Solids to Recycle Slurry Tank: Refer to Section 3.0 of this handbook.

Stream 7 - Lime to Ball Mill: Refer to Section 3.0 of this handbook.

Stream 16 - Slurry from Atomizer Feed Tank: Refer to Section 3.0 of this handbook.

Stream 17 - Slurry to Atomizers Per Duct: This stream is equivalent to stream 16 divided by the number of ducts.

Stream 28 - Atomizing Air from Compressors: To atomize the feed slurry in the spray nozzles 0.5 lb air/lb slurry is required. The following equations can be used to calculate the flow rates of this stream:

$$M_{28} = \text{Mass flow rate of stream 28} = M_{16} \times 0.5 \text{ lb air/lb slurry} \quad (5-14)$$

$$M_{\text{Water}_{28}} = \text{Mass flow rate of water} = M_{28} \times \% \text{ moisture in air} \times 0.6 \quad (5-15)$$

Note that the 0.6 factor in Equation 5-14 defines the quantity of water in the ambient air that passes through the air compressors into the duct.

Stream 21 - Atomizing Air to Atomizers Per Duct: This stream is equivalent to stream 28 divided by the number of ducts.

Stream 12 - Solids from ESP to Ash Silo: Refer to Section 3.0 of this handbook.

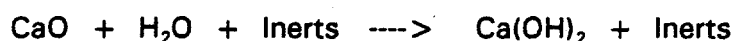
Stream 18 - Waste Solids to Pug Mill: The waste solids to the pugmill can be calculated from the calcium sulfite and calcium sulfate reaction products, amount of calcium hydroxide utilized, flyash content of the gas, and the amount of recycled solids. The total particulate removed in the ESP is calculated as follows:

$$\begin{aligned} \text{Total Particulate Removed} &= (\text{Ca(OH)}_2 \text{ remaining} + \text{CaSO}_3 \cdot \frac{1}{2} \text{H}_2\text{O} \text{ produced} + \text{CaSO}_4 \cdot 2\text{H}_2\text{O} \text{ produced} + \\ &\text{(Wet basis)} \quad \text{Flyash and Inerts} + \text{Recycle-Particulate Emissions}) / \\ &\quad (1\% \text{ interstitial water}) \end{aligned} \quad (5-16)$$

The waste solids to the pugmill are calculated by subtracting the recycled solids (stream 13) from the total particulate removed, both on a wet basis.

Stream 9 - Lime Slurry to Atomizer Feed Tank: Refer to Section 3.0 of this handbook.

Stream 8 - Slaking Water to Ball Mill: This stream can be calculated by evaluating the slaking reaction, and then performing some simple calculations as follows:



$$\begin{aligned} \text{MWater}_8 &= \text{Mass flow rate of water} \\ &= (\text{Ca(OH)}_2 + \text{Inerts}) \times [(1 - \text{fraction solids exiting}) / \\ &\quad \text{\% solids exiting}] + \text{Reaction H}_2\text{O} \end{aligned} \quad (5-17)$$

Stream 11 - Water to Ball Mill Sump: This stream can be calculated from stream 9 and the results of the slaking reaction. The following equation can be used:

$$\begin{aligned} \text{MWater}_{11} &= \text{Mass flow rate of water} \\ &= \text{M}_9 - \text{M}_8 - \text{M}_7 \end{aligned} \quad (5-18)$$

Stream 22 - Raw Water: This stream can be calculated from the flow rates of streams 8 and 11. The following equation can be used:

$$\text{M}_{22} = \text{Mass flow rate of stream 22} = \text{M}_8 + \text{M}_{11} \quad (5-19)$$

Stream 15 - Recycle Slurry to Atomizer Feed Tank: Refer to Section 3.0 of this handbook.

Stream 19 - Waste Conditioning Water: The flow rates of this stream can be determined by knowing the mass flow rate of stream 18 and percent solids of streams 18 and 20. The following equation should be used:

$$\text{M}_{19} = \text{Mass flow rate of stream 19} = \frac{\text{M}_{18} \times (\text{x}_{20} - \text{x}_{18})}{(1 - \text{x}_{20})} \quad (5-20)$$

$$\begin{aligned} \text{Where: } \text{M}_{18} &= \text{Mass flow rate of stream 18} \\ \text{x}_{18} &= \text{fraction of water in stream 18} \\ \text{x}_{20} &= \text{fraction of water in stream 20} \end{aligned}$$

Stream 20 - Waste to Disposal: This stream can be calculated from the flow rates of streams 18 and 19. The following equation can be used:

$$\text{M}_{20} = \text{Mass flow rate of stream 20} = \text{M}_{18} + \text{M}_{19} \quad (5-21)$$

Stream 10 - Water to Recycle Slurry Tank: This stream can be calculated from the flow rates of streams 13 and 15. The following equation can be used:

$$M_{10} = \text{Mass flow rate of stream 10} = M_{15} - M_{13} \quad (5-22)$$

Stream 27 - Cooling Tower Blowdown Water: This stream can be calculated from the flow rates of streams 10, 14, and 19. The following equation can be used:

$$M_{27} = \text{Mass flow rate of stream 27} = M_{10} + M_{14} + M_{19} \quad (5-23)$$

Stream 25 - Air Compressor Cooling Water In: The mass flow rate of this stream can be calculated from the inlet and outlet air flows of the compressors. The following equations can be used:

$$\begin{aligned} Q_{in} &= \text{Inlet volumetric flow of compressors} \\ &= [((M_{28} - M_{\text{Water}_{28}})/MW_{\text{Air}}) + (M_{\text{Water}_{28}}/(0.6 \times MW_{\text{H}_2\text{O}}))] \\ &\quad \times (0.7302/60) \times (T_{in} + 460) \times (14.7/P_{in}) \end{aligned} \quad (5-24)$$

$$\begin{aligned} HP &= \text{Operating hp of the air compressors} \\ &= 0.0068 \times Q_{in} \times P_{in} \times \ln(P_{28}/P_{in}) \end{aligned} \quad (5-25)$$

$$\begin{aligned} M_{25} &= \text{Mass flow rate of stream 25} \\ &= (HP \times 2544.434 - (((M_{28} - M_{\text{Water}_{28}}) \times 0.241 + \\ &\quad M_{\text{Water}_{28}} \times 0.46) \times (T_{28} - 60)) + M_{\text{Water}_{28}}/0.6 \times 0.4 \\ &\quad \times 1034.2))/(T_{28} - T_{25}) \end{aligned} \quad (5-26)$$

Stream 26 - Air Compressor Cooling Water Out: The mass flow rate of this stream is identical to that of stream 25. The higher temperature causes the volumetric flow rate of this stream to be slightly higher than that of stream 25.

Stream 23 - Steam to Slaking Water Heater: The mass flow rate of this stream can be calculated by knowing the mass flow rate of stream 8 and the initial and final temperature of stream 8. The following equations can be used:

$$\begin{aligned} T_i &= \text{Makeup water temperature} = 60^\circ\text{F} \\ T_F &= \text{Temperature of stream 8} = 90^\circ\text{F} \\ H_i &= \text{Enthalpy of entering water stream} = 28.06 \text{ Btu/lb} \\ H_F &= \text{Enthalpy of exiting water stream} = 57.99 \text{ Btu/lb} \\ E_8 &= \text{Energy of stream 8} \\ &= M_{\text{Water}_8} \times (H_F - H_i) \end{aligned} \quad (5-27)$$

$$\begin{aligned} M_{23} &= \text{Mass flow rate of stream 23} \\ &= E_8/857.01 \end{aligned} \quad (5-28)$$

where: 857.01 = Heat of vaporization of saturated steam at 150 psig.

Stream 24 - Condensate to Condenser:

The mass flow rate of this stream is identical to that of stream 23. The volumetric flow rate of this stream can be calculated with the following equation:

$$\begin{aligned} Q_{24} &= \text{Volumetric flow rate of stream 24} \\ &= M_{24} \times \frac{7.481 \text{ gal}}{\text{ft}^3} \times \frac{\text{hr}}{60 \text{ min}} \times \frac{\text{ft}^3}{55.0 \text{ lb}} \end{aligned} \quad (5-29)$$

where: 55 lb/ft³ = Density of water at 366°F.

Stream 3 - Flue Gas After Slurry Injection:

The flue gas conditions of this stream can be calculated by knowing the conditions of streams 2, 17, and 21 and the approach to saturation temperature.

Stream 4 - Flue Gas Downstream of ESP:

The flue gas conditions of this stream can be calculated by knowing the conditions of streams 3 and 12 and also the temperature drop across the ESP.

Stream 5 - Flue Gas Downstream of ID Fan:

The flue gas conditions of this stream can be calculated by knowing the conditions of stream 4 and also the temperature drop and pressure rise across the ID fan.

Stream 6 - Stack Gas:

This stream is identical to stream 5 multiplied by the number of ducts.

5.3 Piping and Instrumentation Diagrams

Piping and instrumentation diagrams (P&IDs) have been developed for both the DSI and DSD duct injection systems and are located after the PFDs at the end of Section 5. For each set of diagrams, a cover sheet is included which identifies the various symbols used in the drawings and describes the equipment numbering system utilized. These P&IDs were developed from three sources: 1) a review of the design of duct injection pilot plants/demonstration units, 2) existing lime spray dryer installations, and 3) good engineering practice for water, air, slurry, and flue gas systems.

The major components in each system have been assigned equipment numbers, and these numbers are listed at the top of the P&ID in which the equipment appears. An equipment list has been developed for each system which summarizes all of the major equipment and their corresponding numbers, and which identifies the sheet of the P&IDs that that equipment appears. These equipment lists are included in Section 5.4.

Similar to the PFDs in Section 5.1, the P&IDs for both systems are based on two ducts/ESPs for injection. They will need to be modified if the candidate plant has a different number of injection points.

The P&IDs are also based on a positive pressure rail car unloading system. This was used for reference only. A vacuum unloading system or combination vacuum-pressure system could be used as noted in the rail car unloading system bid specification (reference Appendix E). The P&IDs will need to be modified to reflect the unloading system selected for service.

The P&IDs for both systems give two options for recycling material collected in the ESP: 1) vacuum conveying from the ESP to the existing ash silo and, from there, positive pressure conveying to a recycle bin, or 2) positive pressure or mechanical conveying from the ESP directly to a recycle bin utilizing a diverter valve. The unused arrangement should be deleted from the production set of P&IDs.

For both the DSI and DSD system P&IDs, inlet SO_2/O_2 analyzers are shown in the ductwork upstream of the sorbent injection point. These are normally only required for two reasons: 1) if the SO_2 percent removal across the system is required to be reported (not just the outlet emission), or 2) if a feed-forward SO_2 signal is utilized in the process control. If neither of these two requirements exist, the inlet SO_2/O_2 analyzers may be deleted.

In the design presented in the miscellaneous utilities P&ID for both DSI and DSD, service and instrument air are assumed to be available from the existing plant compressors; new service and/or instrument air compressors are not shown.

5.3.1 Dry Sorbent Injection

The following P&IDs have been developed for the DSI system and are attached:

Sheet A	Legend & Symbols
Sheet 1	Flue Gas Duct Controls
Sheet 2	Flue Gas Duct Controls
Sheet 3A	Hydrate Unloading & Storage
Sheet 3B	Pebble Lime Unloading & Storage
Sheet 4	Pebble Lime Hydration & Hydrate Storage

Sheet 5A	Used Sorbent Recycle from Fly Ash Silo
Sheet 5B	Used Sorbent Recycle from Pressure Pneumatic or Mechanical Conveyor
Sheet 6	Miscellaneous Utilities

In addition, the DSI equipment list is included in Section 5.4.

Sheet 1 of the DSI P&IDs indicates that the sorbent is injected upstream of the humidification water. Although sorbent injection upstream of humidification (scavenging mode) is generally considered to result in superior SO₂ removal, it can cause material deposition. Locating the injectors and the humidification nozzles in the same vertical plane (for horizontal ducts) may give better operability. In that case, the P&ID would need to be modified to show coplanar injection.

If off-site hydration is chosen for DSI, hydrated lime will be unloaded and stored at the plant, and only Sheet 3A will be required. Sheets 3B and 4 should be deleted from the production set of P&IDs. Conversely, if on-site hydration is chosen, Sheet 3A should be deleted, and Sheets 3B and 4 included in the production set.

Sheet 3A of the DSI P&IDs reflects one silo for both hydrated lime storage and feeding of the duct injection points. As mentioned in Section 5.1.1, if this silo cannot be located near the injection points, the user may want to consider pneumatically transferring the lime from the remote silo to a hydrate day bin located close to the injection points. In this case, the P&IDs would have to be revised accordingly.

On Sheet 5A, waste material is shown to be transferred from the existing plant ash silo to a recycle bin. From the recycle bin, the waste material is recycled back through two separate feeders to the injection points. This was done because it is difficult to split pneumatically conveyed material evenly between two ducts. If only one duct exists at the plant site, a variable speed rotary feeder can be installed upstream of the fly ash silo rotary air lock (F401), and the recycle material injected directly from the ash silo to the injection point. In this case, the recycle bin may be deleted.

5.3.2 Duct Spray Drying

The following P&IDs have been developed for the DSD system and are attached:

Sheet A	Legend & Symbols
Sheet 1A	Flue Gas Duct Controls - Dual-Fluid Atomizer
Sheet 2	Flue Gas Duct Controls
Sheet 3	Pebble Lime Unloading & Storage
Sheet 4A	Ball Mill Slaker
Sheet 4B	Detention Slaker
Sheet 4C	Paste Slaker
Sheet 5	Reagent Dilution & Storage
Sheet 6A	Used Sorbent Recycle from Fly Ash Silo
Sheet 6B	Used Sorbent Recycle from Pressure Pneumatic or Mechanical Conveyor
Sheet 7	Miscellaneous Utilities

In addition, the DSD equipment list is included in Section 5.4.

Both a pebble lime silo and day bin are shown in the DSD P&IDs (Sheet 3). This equipment arrangement reflects a conservative configuration in which the silo has to be located relatively far away from the injection ductwork due to rail car unloading or other site-specific constraints. For this equipment arrangement, it is considered more feasible to pneumatically convey lime from the silo to a small day bin located near the injection point (and have the slurry preparation accomplished close to the injection point) than to prepare the slurry near the remote silo and pump it a long distance to the injection point. This is especially true because a slurry return line to the atomizer feed tank is normally required to keep slurry pipeline velocities high. If the silo can be located close to the duct injection point, a separate lime day bin is not required.

Three options are given in the P&IDs for slaking the pebble lime: 1) ball mill (Sheet 4A), 2) detention slaker (Sheet 4B), or 3) paste slaker (Sheet 4C). The P&ID sheets corresponding to the two methods not chosen for inclusion need to be deleted from the production set.

In the slurry lines, no flush or drain connections are shown so as to simplify the P&ID. However, flush and drain connections are required for each slaker and slurry pump and for flushing all long runs of slurry lines. Also, atomizer flushing is required periodically. The flush system may be "hard piped" or manual using flexible hoses and pipe stub connections.

All slurry pumps show recirculation lines back to the tank from which they take suction. This helps to keep slurry velocities high and minimize line pluggage. A back pressure valve is shown in each recirculation line. These are typically manual pinch valves; restriction orifices are not recommended for slurry service. Valves in slurry service are specified in the slurry valve bid specification (Appendix E).

5.4 Equipment Lists

The following documents are attached to this section:

Equipment Numbering System

Dry Sorbent Injection Equipment List

Duct Spray Drying Equipment List

EQUIPMENT NUMBERING SYSTEM

The first part of the equipment letter-number designation is a letter describing the type of equipment:

- A - Agitator
- B - Blower, Fan
- C - Conveyor, Compressor
- D - Dust Collector, Dryer
- F - Feeder, Air Lock, Diverter Valve
- H - Heat Exchanger
- M - Bin Activator, Slaker, Hydrator
- P - Pump
- S - Strainer, Screen, Scrubber
- T - Tank
- V - Bin, Silo, Miscellaneous Vessel
- W - Weighing Device
- X - Injector Assembly/Atomizer

The next part of the letter-number designates in what area the equipment is located and the sequence. For example, A101 designates an agitator in Area 100 and is the number one agitator in that area. The area codes are as follows:

<u>AREA CODE</u>	<u>AREA NAME</u>
100	Sorbent Storage and Preparation System
200	Humidification/Sorbent Injection System
300	Flue Gas System
400	Recycle System
500	Waste Handling System
600	General Support Equipment
700	Miscellaneous

If there is more than one item in the same service, they are identified by suffix alphabetically. For example, if there are redundant pumps in parallel, the pumps may be identified as P201A and P201B.

DRY SORBENT INJECTION EQUIPMENT LIST

<u>Equipment No.</u>	<u>Description</u>	<u>P&ID Sheet No.</u>
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AREA 100 - SORBENT STORAGE AND PREPARATION SYSTEMHydrate Unloading & Storage

B101	Rail Car Unloading Blower	3A
B102	Hydrate Silo Aeration Blower	3A
B103A,B,C	Hydrate Injection Blower	3A
C101A,B	Hydrate Screw Feeder	3A
D101	Hydrate Silo Dust Collector	3A
D104	Aeration Air Dryer	3A
F101	Rail Car Unloading Feeders	3A
F102A,B	Hydrate Rotary Air Lock	3A
V101	Hydrate Silo	3A

Pebble Lime Unloading & Storage/Hydration & Hydrate Storage

B104	Rail Car Unloading Blower	3B
B105A,B	Hydrate Transfer Blower	4
B106	Hydrate Bin Aeration Blower	4
B107A,B,C	Hydrate Injection Blower	4
B108A,B	Hydrator Scrubber Fan	4
C102A,B	Hydrate Screw Feeder	4
D102	Pebble Lime Silo Dust Collector	3B
D103	Hydrate Bin Dust Collector	4
D105	Hydrate Bin Aeration Air Dryer	4
F103	Rail Car Unloading Feeders	3B
F104	Lime Diverter Valve	3B
F105A,B	Lime Weigh Belt Feeder	3B
F106A,B	Hydrator Discharge Rotary Air Lock	4
F107A,B	Hydrate Rotary Air Lock	4
M101	Pebble Lime Silo Bin Activator	3B
M102A,B	Hydrator	4
S101A,B	Hydrator Scrubber	4
V102	Pebble Lime Silo	3B
V103	Hydrate Bin	4

AREA 200 - HUMIDIFICATION/SORBENT INJECTION SYSTEM

X201A,B	Fresh Reagent Injection Manifold	1
X202A,B	Recycle Reagent Injection Manifold	1
X203A,B	Dual-Fluid Atomizing Nozzle Assembly	1

DRY SORBENT INJECTION EQUIPMENT LIST

<u>Equipment No.</u>	<u>Description</u>	<u>P&ID Sheet No.</u>
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AREA 400 - RECYCLE SYSTEM

Used Sorbent Recycle from Fly Ash Silo

B401	Recycle Transfer Blower	5A
F401	Fly Ash Silo Rotary Air Lock	5A

Common to Both Sorbent Recycle Systems

B402	Recycle Bin Aeration Blower	5A&B
B403A,B	Recycle Injection Blower	5A&B
D401	Recycle Bin Dust Collector	5A&B
F402A,B	Recycle Bin Rotary Feeder	5A&B
F403A,B	Recycle Bin Rotary Air Lock	5A&B
V401	Recycle Bin	5A&B

AREA 600 - GENERAL SUPPORT EQUIPMENT

C601A,B,C	Atomizing Air Compressor	6
P601A,B	Hydration Water Pump	6
P602A,B	Humidification Water Pump	6
P603A,B	Waste Conditioning Water Pump	6
S601	Humidification Water Filter	6
T601	Raw Water Tank	6
T602	Blowdown Water Tank	6
V601	Atomizing Air Receiver	6

DUCT SPRAY DRYING EQUIPMENT LIST

<u>Equipment No.</u>	<u>Description</u>	<u>P&ID Sheet No.</u>
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AREA 100 - SORBENT STORAGE AND PREPARATION SYSTEM

Pebble Lime Unloading & Storage

B101	Rail Car Unloading Blower	3
B102	Pebble Lime Transfer Blower	3
D101	Pebble Lime Silo Dust Collector	3
D102	Pebble Lime Day Bin Dust Collector	3
F101	Rail Car Unloading Feeders	3
F102	Pebble Lime Rotary Air Lock	3
F103	Lime Diverter Valve	3
F104A,B	Lime Weigh Belt Feeder	3
M101	Pebble Lime Silo Bin Activator	3
M102	Pebble Lime Day Bin Activator	3
V101	Pebble Lime Silo	3
V102	Pebble Lime Day Bin	3

Ball Mill Slaker

A101A,B	Ball Mill Sump Agitator	4A
F105A,B	Diverter Valve	4A
H101A,B	Slaking Water Heater	4A
M103A,B	Ball Mill Slaker	4A
P101A,B,C,D	Ball Mill Sump Pump	4A
S101A,B	Lime Grit Screen	4A
T101A,B	Ball Mill Sump	4A

Detention Slaker

H102A,B	Slaking Water Heater	4B
M104A,B	Detention Slaker	4B
S102A,B	Lime Grit Screen	4B
V103A,B	Grit Bin	4B

Paste Slaker

H103A,B	Slaking Water Heater	4C
M105A,B	Paste Slaker	4C
S103A,B	Lime Grit Screen	4C
V104A,B	Grit Bin	4C

DUCT SPRAY DRYING EQUIPMENT LIST

<u>Equipment No.</u>	<u>Description</u>	<u>P&ID Sheet No.</u>
<u>Reagent Dilution & Storage</u>		
A102	Lime Slurry Storage Tank Agitator	5
A103	Atomizer Feed Tank Agitator	5
P102A,B	Lime Slurry Pump	5
P103A,B	Atomizer Feed Pump	5
T102	Lime Slurry Storage Tank	5
T103	Atomizer Feed Tank	5

AREA 200 - HUMIDIFICATION/SORBENT INJECTION SYSTEM

Dual-Fluid Atomization

X201A,B	Dual-Fluid Atomizing Nozzle Assembly	1A
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AREA 400 - RECYCLE SYSTEM

Used Sorbent Recycle from Fly Ash Silo

B401	Recycle Transfer Blower	6A
F401	Fly Ash Silo Rotary Air Lock	6A

Common to Both Sorbent Recycle Systems

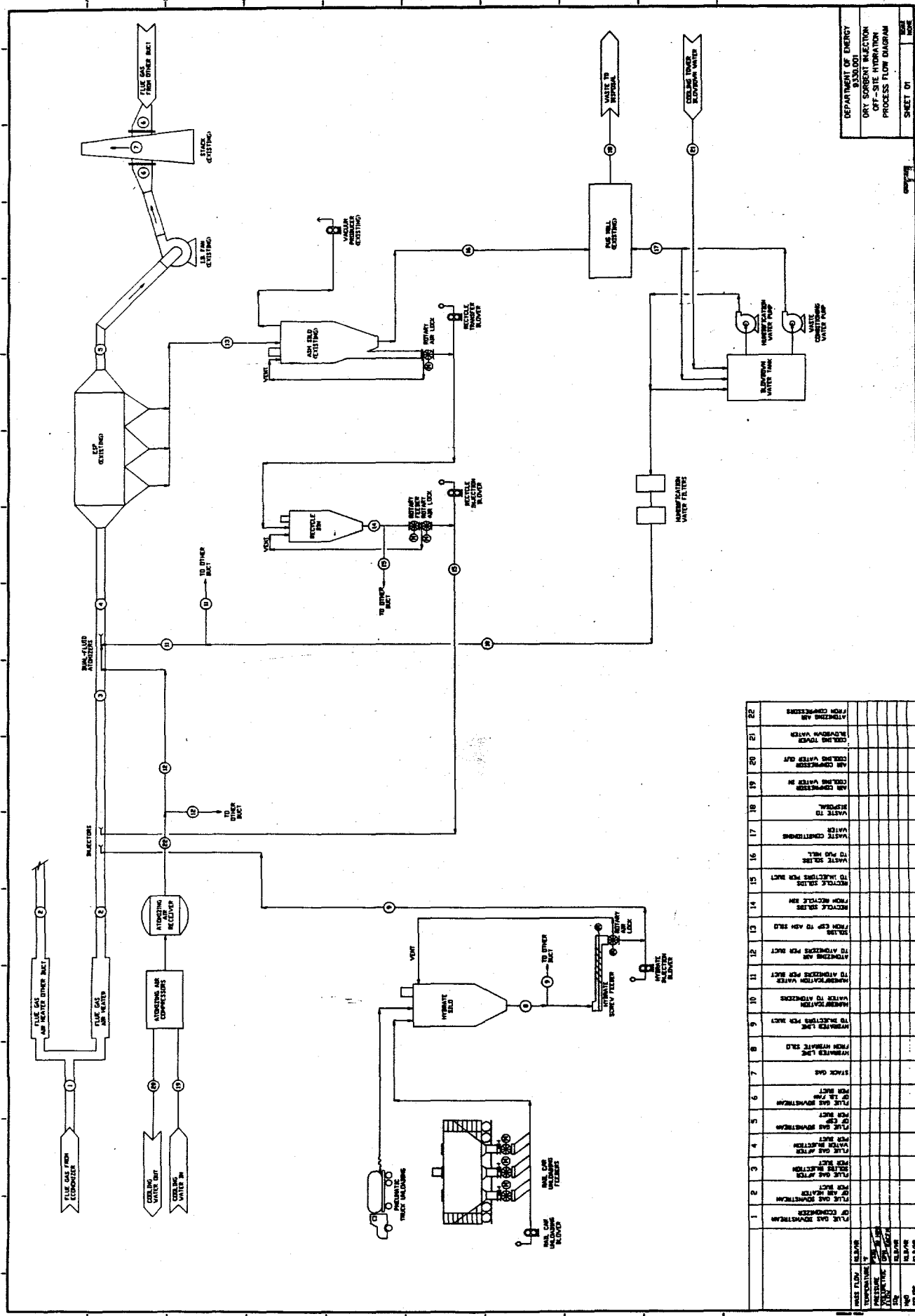
A401	Recycle Slurry Tank Agitator	6A&B
B402	Recycle Bin Aeration Blower	6A&B
D401	Recycle Bin Dust Collector	6A&B
F402	Recycle Bin Rotary Feeder	6A&B
P401A,B	Recycle Slurry Pump	6A&B
S401	Recycle Grit Screen	5
T401	Recycle Slurry Tank	6A&B
V401	Recycle Oversize Bin	5
V402	Recycle Bin	6A&B

DUCT SPRAY DRYING EQUIPMENT LIST

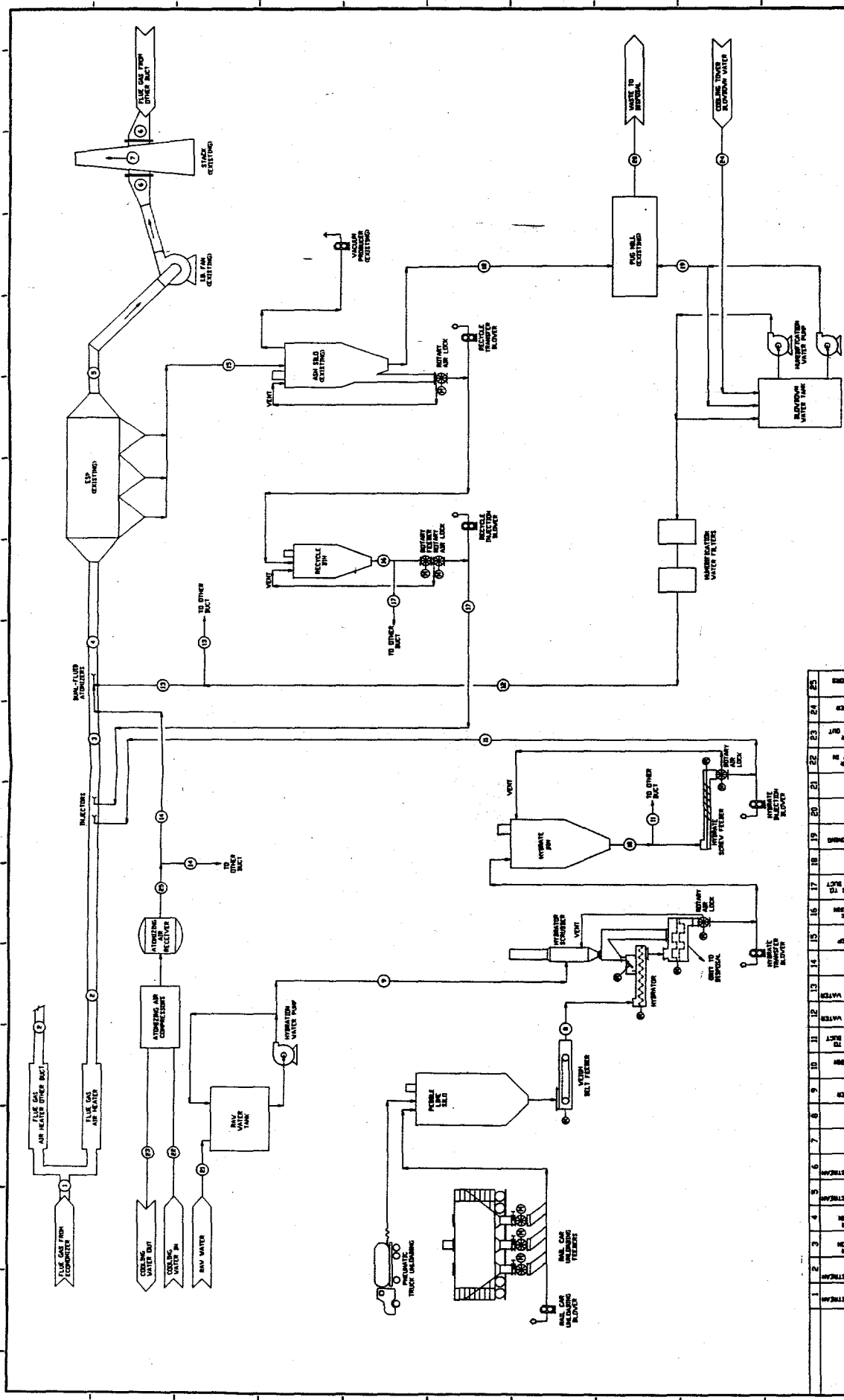
<u>Equipment No.</u>	<u>Description</u>	<u>P&ID Sheet No.</u>
<u>AREA 600 - GENERAL SUPPORT EQUIPMENT</u>		
C601A,B,C	Atomizing Air Compressor	7
P601A,B	Slaking Water Pump	7
P602A,B	Dilution Water Pump	7
P603A,B	Recycle Ash Water Pump	7
P604A,B	Waste Conditioning Water Pump	7
T601	Raw Water Tank	7
T602	Blowdown Water Tank	7
V601	Atomizing Air Receiver	7

DEPARTMENT OF ENERGY	DATE
WASH DC 20545	NOV 1994
DRY CURRENT INJECTION	SHEET 01
OFF-SITE HYDRATION	NOV 1994
PROCESS FLOW DIAGRAM	

RECEIVED
AUG 28 1995
OSTI



NO.	DESCRIPTION	UNIT	QTY	UNIT PRICE	TOTAL PRICE
1	WASTE TO REMOVAL	1	1	1	1
2	WASTE TO REMOVAL	1	1	1	1
3	WASTE TO REMOVAL	1	1	1	1
4	WASTE TO REMOVAL	1	1	1	1
5	WASTE TO REMOVAL	1	1	1	1
6	WASTE TO REMOVAL	1	1	1	1
7	WASTE TO REMOVAL	1	1	1	1
8	WASTE TO REMOVAL	1	1	1	1
9	WASTE TO REMOVAL	1	1	1	1
10	WASTE TO REMOVAL	1	1	1	1
11	WASTE TO REMOVAL	1	1	1	1
12	WASTE TO REMOVAL	1	1	1	1
13	WASTE TO REMOVAL	1	1	1	1
14	WASTE TO REMOVAL	1	1	1	1
15	WASTE TO REMOVAL	1	1	1	1
16	WASTE TO REMOVAL	1	1	1	1
17	WASTE TO REMOVAL	1	1	1	1
18	WASTE TO REMOVAL	1	1	1	1
19	WASTE TO REMOVAL	1	1	1	1
20	WASTE TO REMOVAL	1	1	1	1
21	WASTE TO REMOVAL	1	1	1	1
22	WASTE TO REMOVAL	1	1	1	1



NO.	DESCRIPTION	UNIT	QTY	REMARKS
1	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
2	FLUE GAS AFTER HEATING	PER SEC		
3	FLUE GAS AFTER WATER HEATING	PER SEC		
4	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
5	FLUE GAS AFTER HEATING	PER SEC		
6	FLUE GAS AFTER WATER HEATING	PER SEC		
7	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
8	FLUE GAS AFTER HEATING	PER SEC		
9	FLUE GAS AFTER WATER HEATING	PER SEC		
10	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
11	FLUE GAS AFTER HEATING	PER SEC		
12	FLUE GAS AFTER WATER HEATING	PER SEC		
13	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
14	FLUE GAS AFTER HEATING	PER SEC		
15	FLUE GAS AFTER WATER HEATING	PER SEC		
16	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
17	FLUE GAS AFTER HEATING	PER SEC		
18	FLUE GAS AFTER WATER HEATING	PER SEC		
19	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
20	FLUE GAS AFTER HEATING	PER SEC		
21	FLUE GAS AFTER WATER HEATING	PER SEC		
22	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
23	FLUE GAS AFTER HEATING	PER SEC		
24	FLUE GAS AFTER WATER HEATING	PER SEC		
25	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
26	FLUE GAS AFTER HEATING	PER SEC		
27	FLUE GAS AFTER WATER HEATING	PER SEC		
28	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
29	FLUE GAS AFTER HEATING	PER SEC		
30	FLUE GAS AFTER WATER HEATING	PER SEC		
31	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
32	FLUE GAS AFTER HEATING	PER SEC		
33	FLUE GAS AFTER WATER HEATING	PER SEC		
34	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
35	FLUE GAS AFTER HEATING	PER SEC		
36	FLUE GAS AFTER WATER HEATING	PER SEC		
37	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
38	FLUE GAS AFTER HEATING	PER SEC		
39	FLUE GAS AFTER WATER HEATING	PER SEC		
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46	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
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48	FLUE GAS AFTER WATER HEATING	PER SEC		
49	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
50	FLUE GAS AFTER HEATING	PER SEC		
51	FLUE GAS AFTER WATER HEATING	PER SEC		
52	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
53	FLUE GAS AFTER HEATING	PER SEC		
54	FLUE GAS AFTER WATER HEATING	PER SEC		
55	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
56	FLUE GAS AFTER HEATING	PER SEC		
57	FLUE GAS AFTER WATER HEATING	PER SEC		
58	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
59	FLUE GAS AFTER HEATING	PER SEC		
60	FLUE GAS AFTER WATER HEATING	PER SEC		
61	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
62	FLUE GAS AFTER HEATING	PER SEC		
63	FLUE GAS AFTER WATER HEATING	PER SEC		
64	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
65	FLUE GAS AFTER HEATING	PER SEC		
66	FLUE GAS AFTER WATER HEATING	PER SEC		
67	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
68	FLUE GAS AFTER HEATING	PER SEC		
69	FLUE GAS AFTER WATER HEATING	PER SEC		
70	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
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76	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
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88	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
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91	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
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96	FLUE GAS AFTER WATER HEATING	PER SEC		
97	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		
98	FLUE GAS AFTER HEATING	PER SEC		
99	FLUE GAS AFTER WATER HEATING	PER SEC		
100	FLUE GAS FROM COMBUSTION OF COAL	PER SEC		

LINES

PROCESS

INSTRUMENT (ELECTRICAL
OR FILLED CAPILLARY)INDICATES FLOW SPLIT
INTO MULTIPLE STREAMS

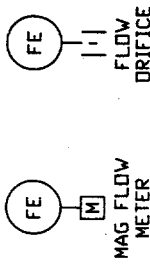
INSTRUMENTS

XX LOCALLY MOUNTED

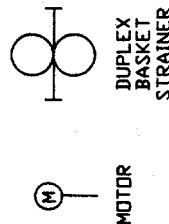
XX LOCAL PANEL MOUNTED

XX CONTROL ROOM

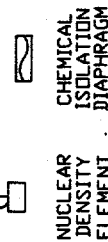
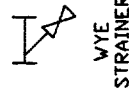
INSTRUMENT SYMBOLS

MAG FLOW
METERFLOW
DRIFICE

TE



MOTOR

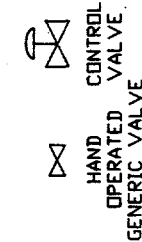
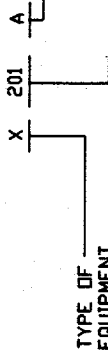
NUCLEAR
DENSITY
ELEMENTCHEMICAL
ISOLATION
DIAPHRAGM

WYE

STRAINER

UNSHIELDED
THERMOCOUPLESHIELDED
THERMOCOUPLE

VALVES

HAND
OPERATED
VALVECONTROL
VALVESOLENOID
OPERATED
VALVEBACK
PRESSURE
REGULATED
VALVEPRESSURE
SAFETY
VALVEBALL
VALVEGLOBE
VALVE

- A - AGITATOR
B - BLOWER, FAN
C - CONVEYOR, COMPRESSOR
D - DUST COLLECTOR, DRYER
F - FEEDER, AIR LOCK, DIVERTER VALVE
H - HEAT EXCHANGER
M - BIN ACTIVATOR, HYDRATOR
P - PUMP
S - STRAINER, SCREEN, SCRUBBER
T - TANK
V - BIN, SILD, MISCELLANEOUS VESSEL
W - WEIGHING DEVICE
X - INJECTOR ASSEMBLY/ATOMIZER

- 100
200
300
400
500
600
700

- SORBENT STORAGE AND PREPARATION SYSTEM
HUMIDIFICATION/SORBENT INJECTION SYSTEM
FLUE GAS SYSTEM
RECYCLE SYSTEM
WASTE HANDLING SYSTEM
GENERAL SUPPORT EQUIPMENT
MISCELLANEOUS

INSTRUMENT IDENTIFICATION INDEX

FIRST LETTER	SECOND LETTER	THIRD LETTER
A	ANALYSIS	ALARM
B		
C	DENSITY	CONTROLLER
D	DIFFERENTIAL ELEMENT	
E		
F	FLOW	
G		
H	HAND	HIGH
I	CURRENT	INDICATOR
J	INDICATOR SCAN	
K		
L	LEVEL	LOW
M	MOISTURE	
N		
O	PRESSURE	
P		
Q	RESTRICTION	RECORD SWITCH
R	SPEED	TRANSMITTER
S	TEMPERATURE	
T		
U	VIBRATION	VALVE
V	WEIGHT	
W		
X	TEST CONNECTION RELAY/COMPUTE	
Y	POSITION	
Z		

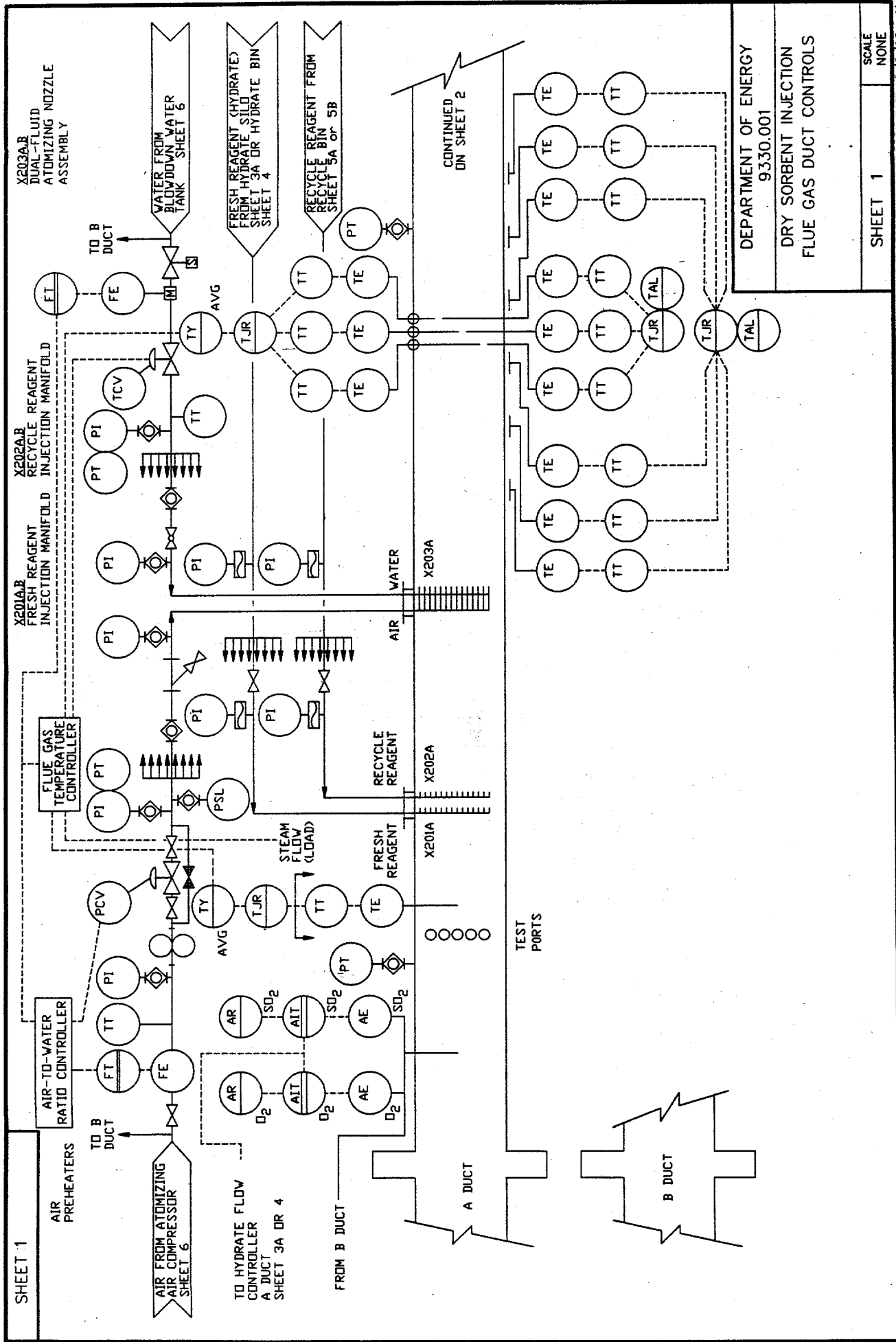
EQUIPMENT NUMBERING SYSTEM

DEPARTMENT OF ENERGY
9330.001DRY SORBENT INJECTION
LEGEND
&
SYMBOLS

SHEET A

SCALE
NONE

CAD NO. A90P000A DATE 02/22/91 DRW



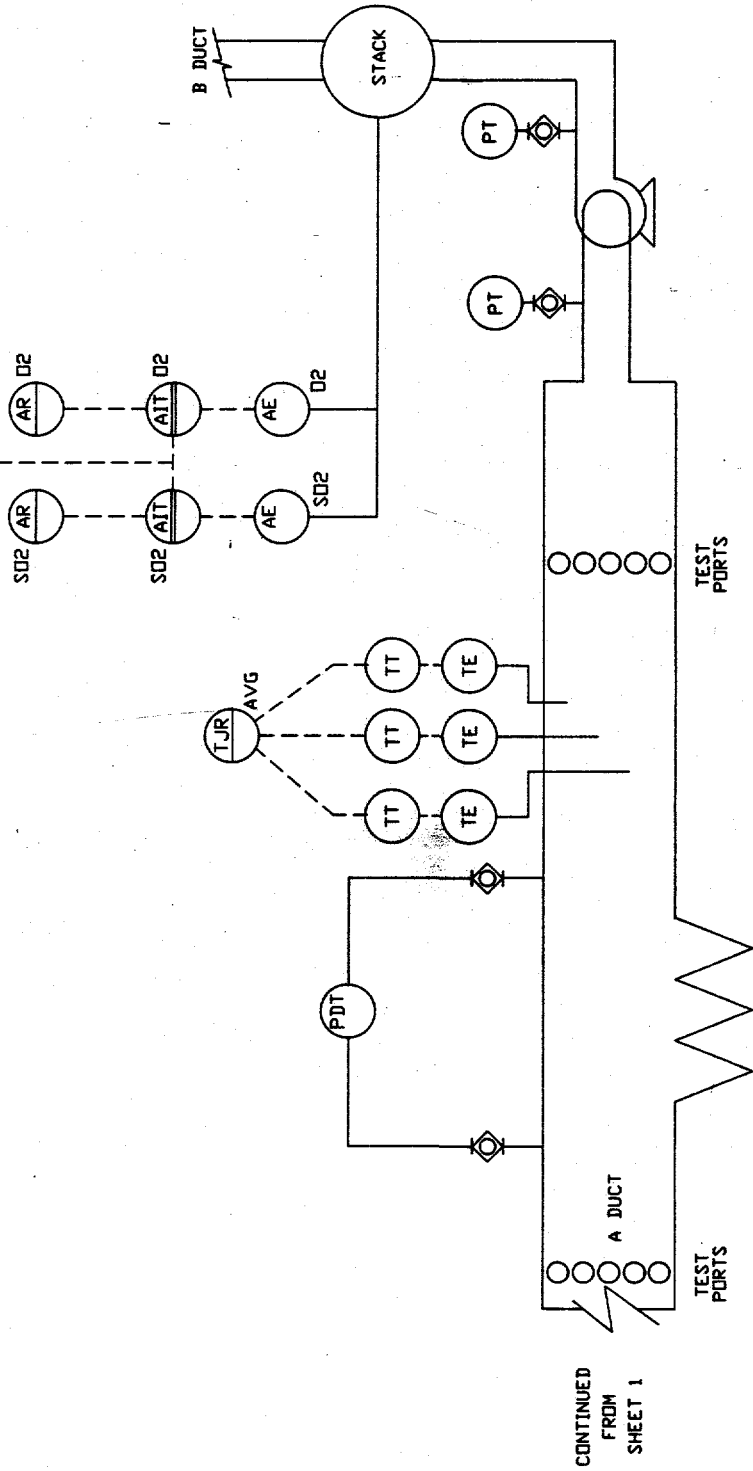
CAD NO. A90P0001 DATE 12/2/92 ALO

DEPARTMENT OF ENERGY	SHEET 1	SCALE NONE
9330.001		
DRY SORBENT INJECTION		
FLUE GAS DUCT CONTROLS		

ELECTROSTATIC
PRECIPITATOR
(EXISTING)

INDUCED
DRAFT FAN
(EXISTING)

TO HYDRATE FLOW
CONTROLLERS
A & B DUCTS
SHEET 3A OR 4

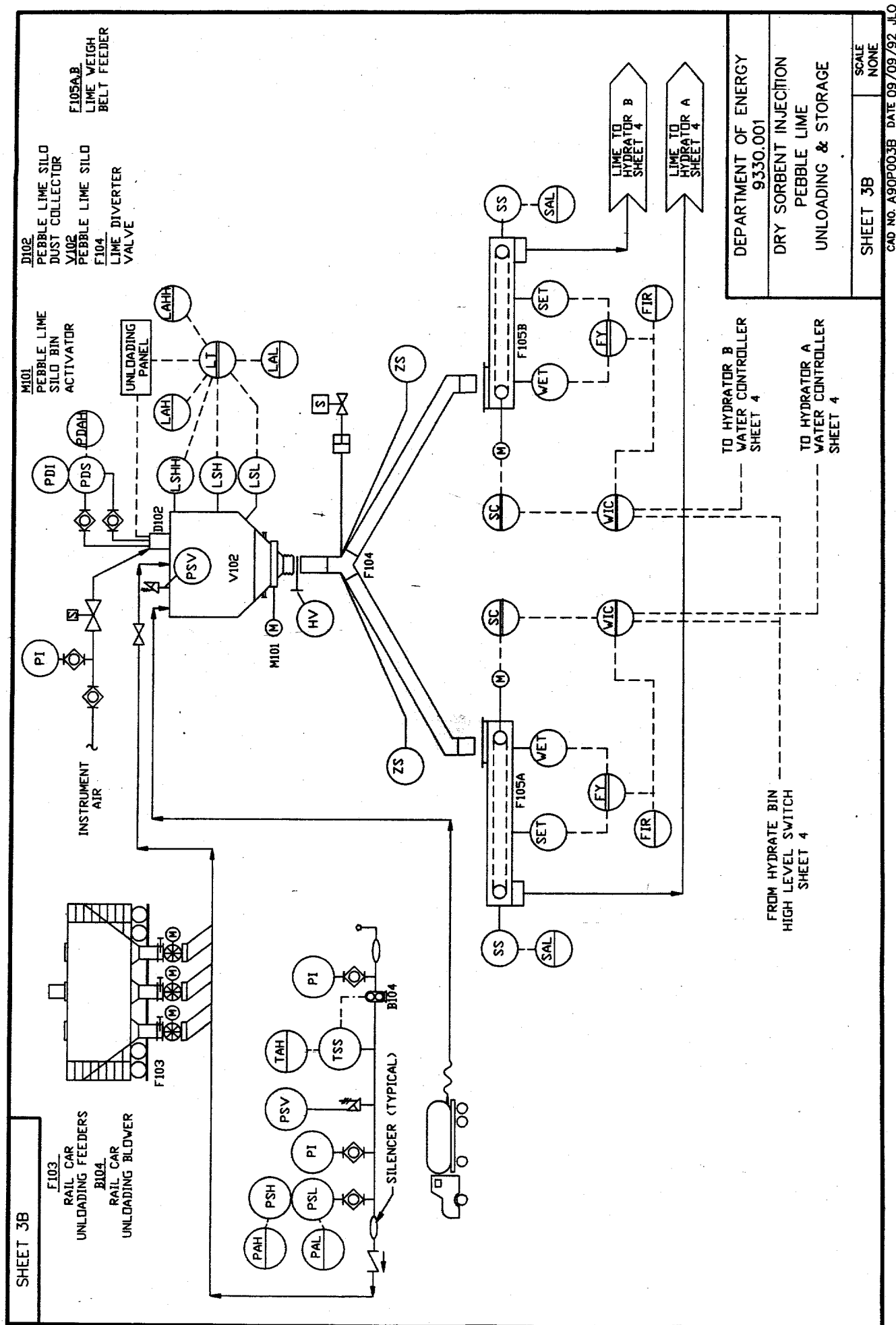


DEPARTMENT OF ENERGY
9330.001

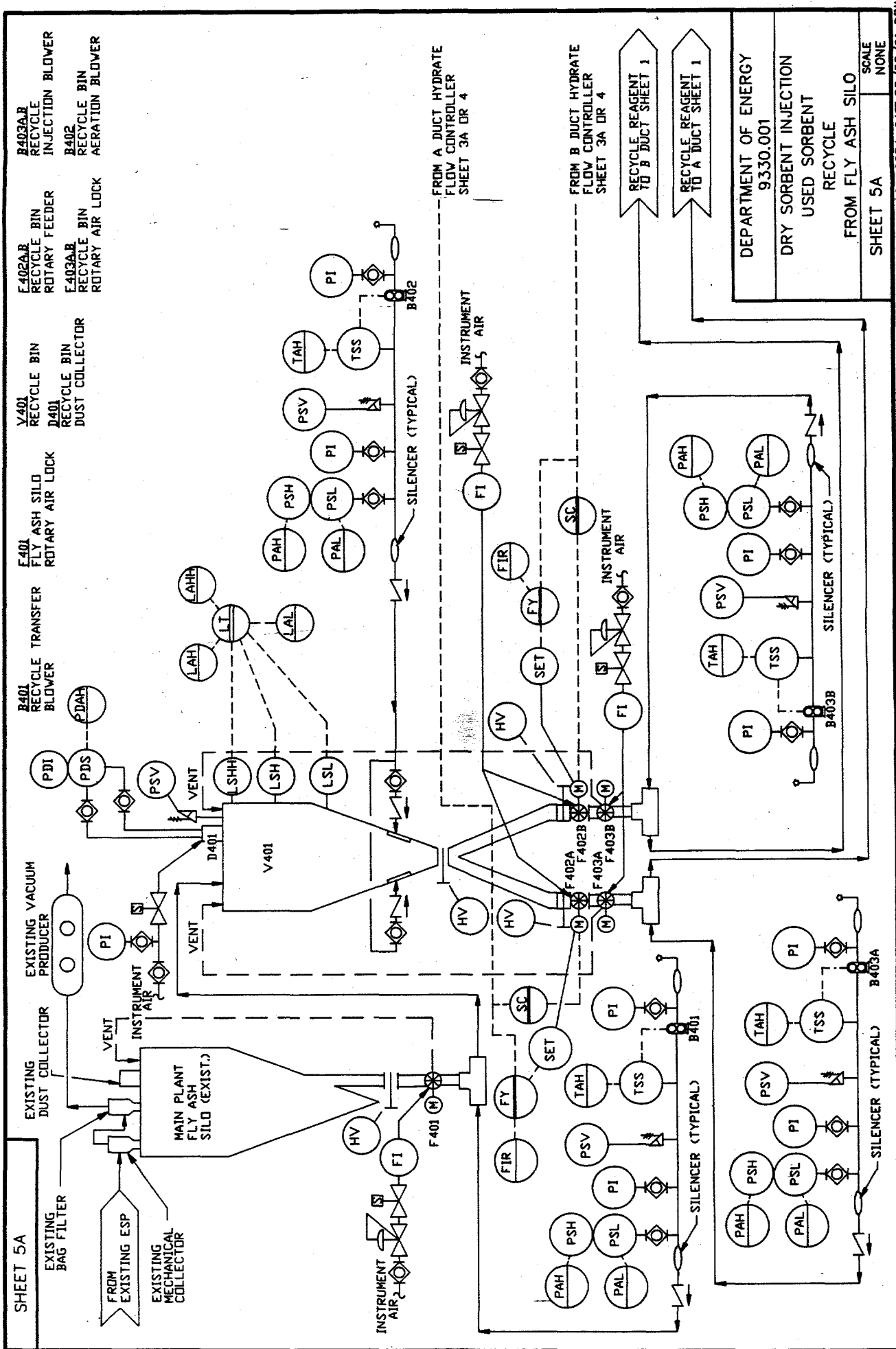
DRY SORBENT INJECTION
FLUE GAS DUCT CONTROLS

SHEET 2
SCALE
NONE

CAD NO. A90P0002 DATE 12/07/90 DRW

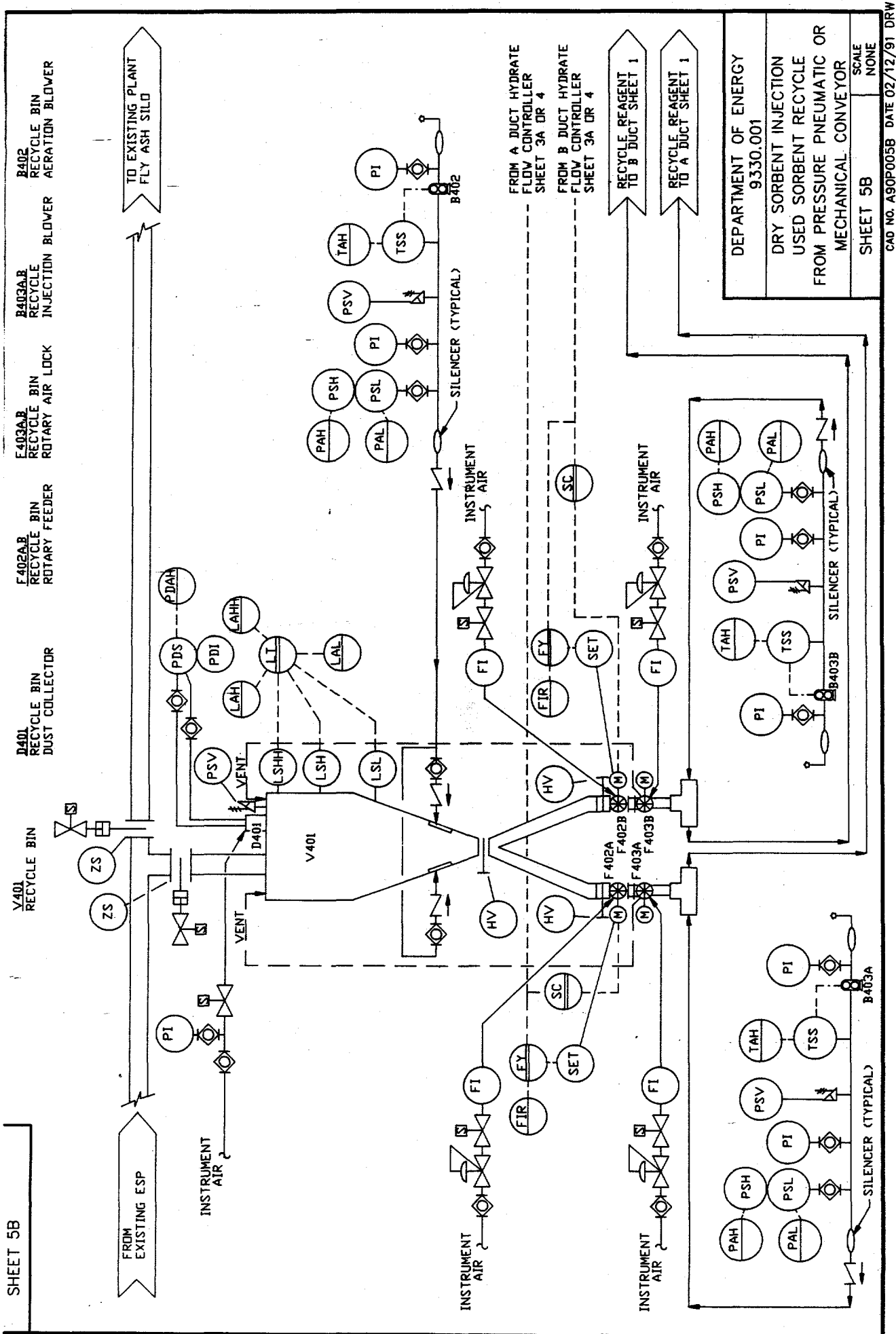


SHEET 5A



DEPARTMENT OF ENERGY	SCALE	NONE
9330.001		
DRY SORBENT INJECTION		
USED SORBENT		
RECYCLE		
FROM FLY ASH SILO		
SHEET 5A		

CAD NO. A90P005A DATE 02/22/91 DRW



SHEET 6

T601
RAW
WATER TANK

C601A,B,C
ATOMIZING AIR
COMPRESSOR

COOLING WATER IN

COOLING WATER OUT

COMPRESSOR
LUBRICATION
SYSTEM

LSLL LSL LSH LSHH

COOLING TOWER
BLOWDOWN WATER

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T602

BLOWDOWN
WATER TANK

FROM
C601B

FROM
C601C

PSV

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V601

ATOMIZING
AIR RECEIVER

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P601A,B

HYDRATION
WATER PUMP

PSV

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S601

HUMIDIFICATION
WATER FILTER

PSV

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P603A,B

WASTE CONDITIONING
WATER PUMP

PSV

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S601

HUMIDIFICATION
WATER FILTER

PSV

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SHEET 1A

X201AB
DUAL-FLUID ATOMIZING
NOZZLE ASSEMBLY

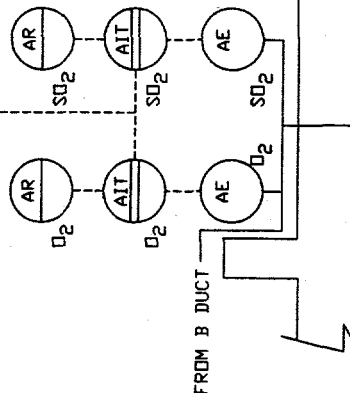
AIR
PREHEATERS

B DUCT

STEAM FLOW (LOAD)

FLUE GAS
TEMPERATURE
CONTROLLER

TO MASS RATIO
CONTROLLER
SHEET 5



DEPARTMENT OF ENERGY
9330.001

DUCT SPRAY DRYING
FLUE GAS DUCT CONTROLS
DUAL-FLUID ATOMIZER

SHEET 1A

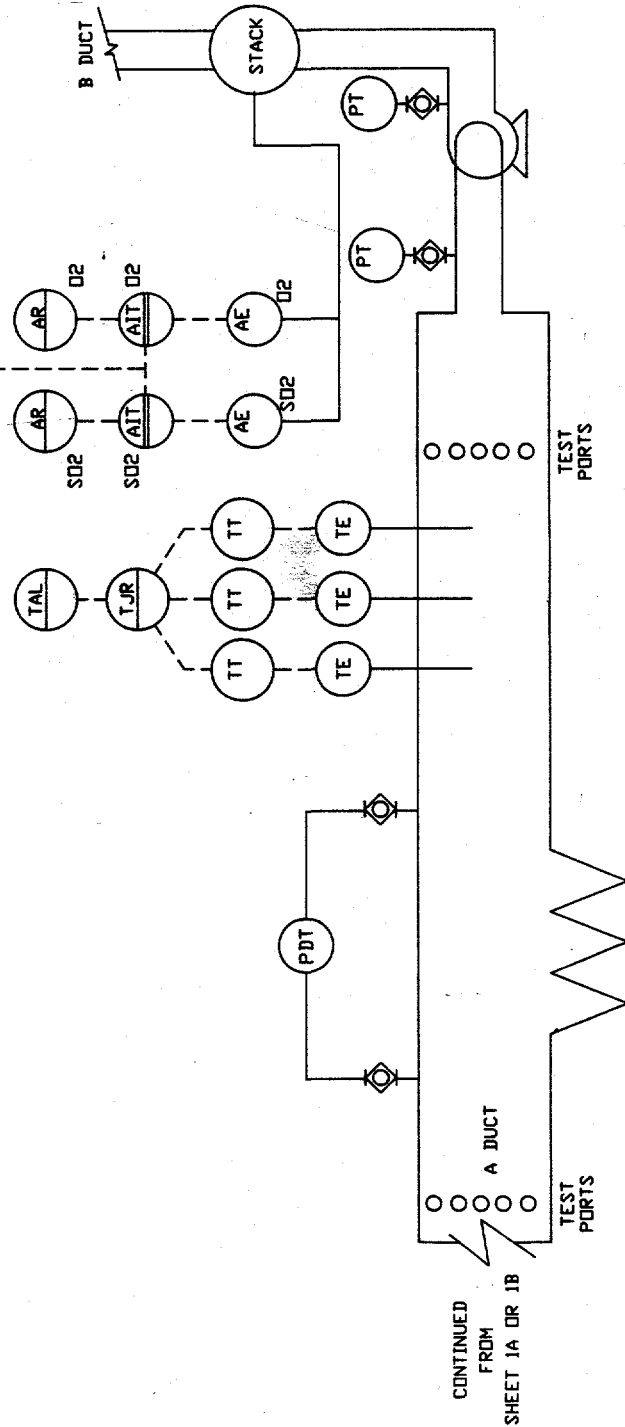
SCALE
NONE

CAD NO. A90P101A DATE 12/2/92 ALO

ELECTROSTATIC
PRECIPITATOR
(EXIST)

INDUCED
DRAFT FAN
(EXIST)

TO MASS
RATIO CONTROLLER
SHEET 5



DEPARTMENT OF ENERGY
9330.001

DUCT SPRAY DRYING
FLUE GAS DUCT CONTROLS

SHEET 2

SCALE
NONE

CAD NO. A90P1002 DATE 11/28/90 DRW

SHEET 3

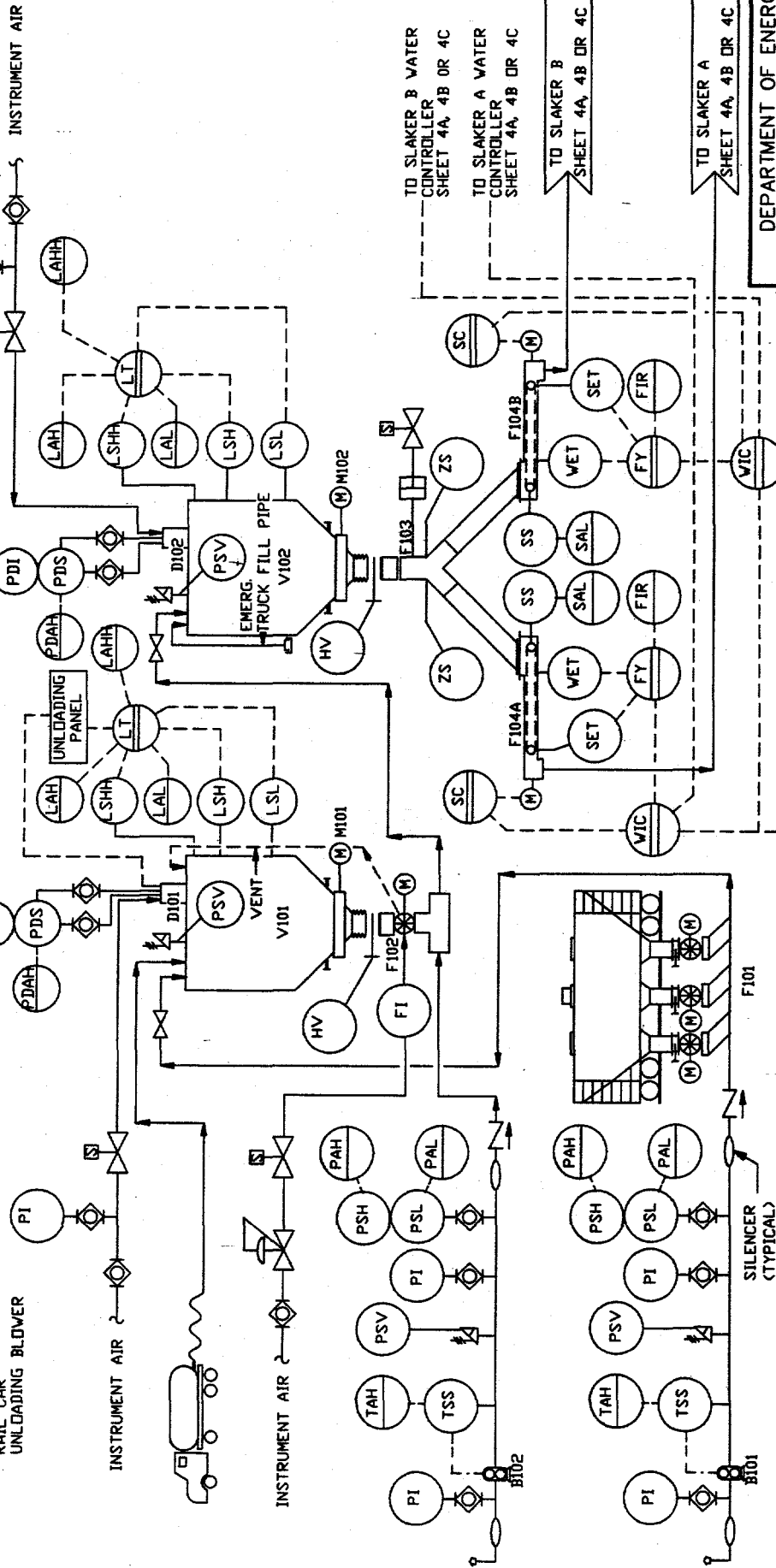
F101
RAIL CAR
UNLOADING
FEEDERS
B101
RAIL CAR
UNLOADING
BLOWER

D101
PEBBLE LIME SILO
DUST COLLECTOR
V101
PEBBLE LIME SILO
VENT
M101
PEBBLE LIME SILO
BIN ACTIVATOR

F102
PEBBLE LIME
ROTARY AIR LOCK
B102
PEBBLE LIME
TRANSFER BLOWER

D102
PEBBLE LIME DAY BIN
DUST COLLECTOR
V102
PEBBLE LIME DAY BIN
VENT
M102
PEBBLE LIME DAY BIN
BIN ACTIVATOR

F103
LINE DIVERTER VALVE
F104A,B
LINE WEIGH
BELT FEEDER



FROM LIME
SLURRY STORAGE
TANK LEVEL
CONTROLLER
SHEET 5

DEPARTMENT OF ENERGY
9330.001

DUCT SPRAY DRYING
PEBBLE LIME UNLOADING
& STORAGE

SHEET 3 SCALE NONE

CAD NO. A90P1003 DATE 09/09/92 JLO

SHEET 4B

FROM LIME WEIGH BELT
FEEDER A SHEET 3

NOTES:

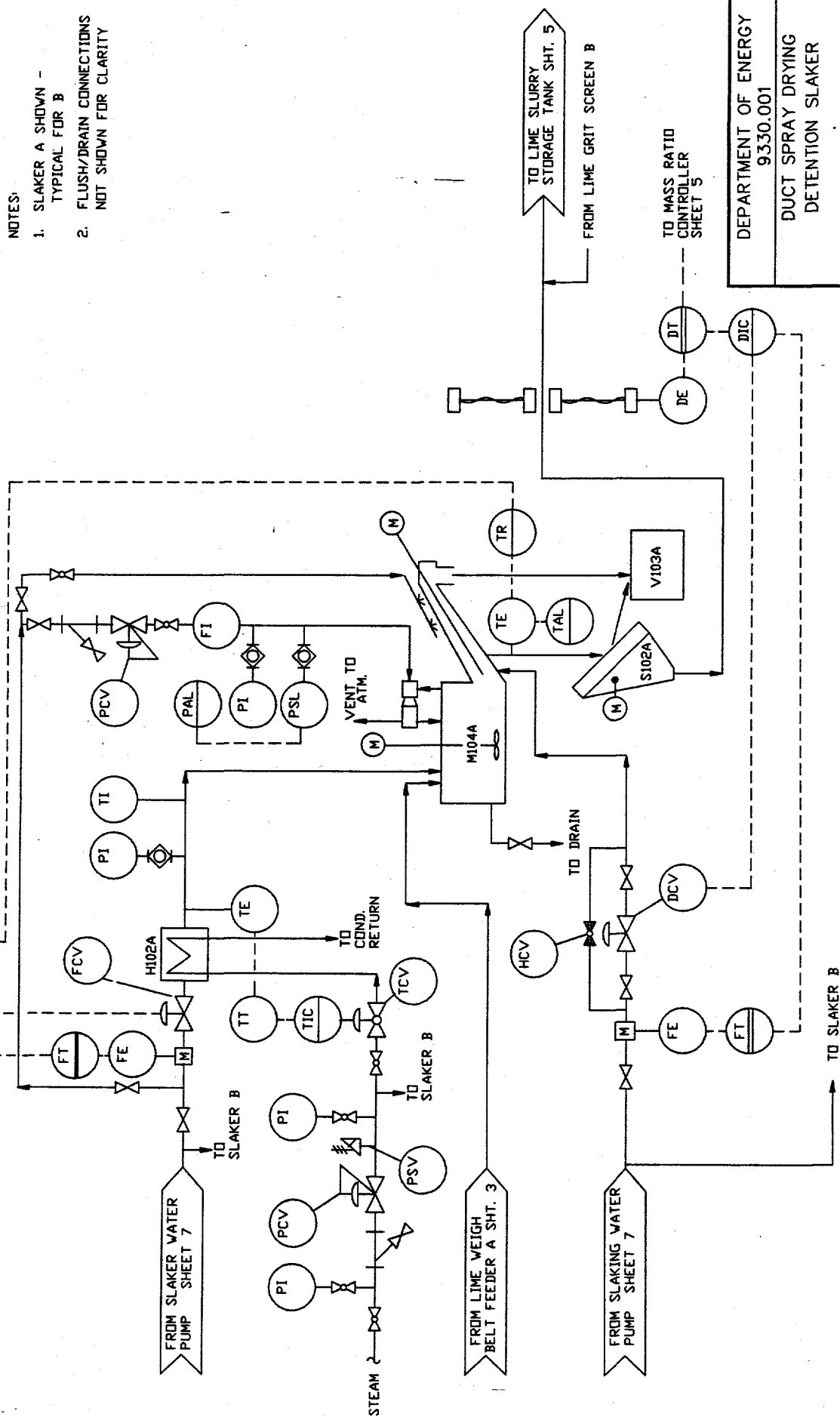
1. SLAKER A SHOWN -
TYPICAL FOR B
2. FLUSH/DRAIN CONNECTIONS
NOT SHOWN FOR CLARITY

H102AB
SLAKING
WATER
HEATER

M104AB
DETENTION
SLAKER

V103AB
GRIT
BIN

S102AB
LIME GRIT
SCREEN



DEPARTMENT OF ENERGY
9330.001

DUCT SPRAY DRYING
DETENTION SLAKER

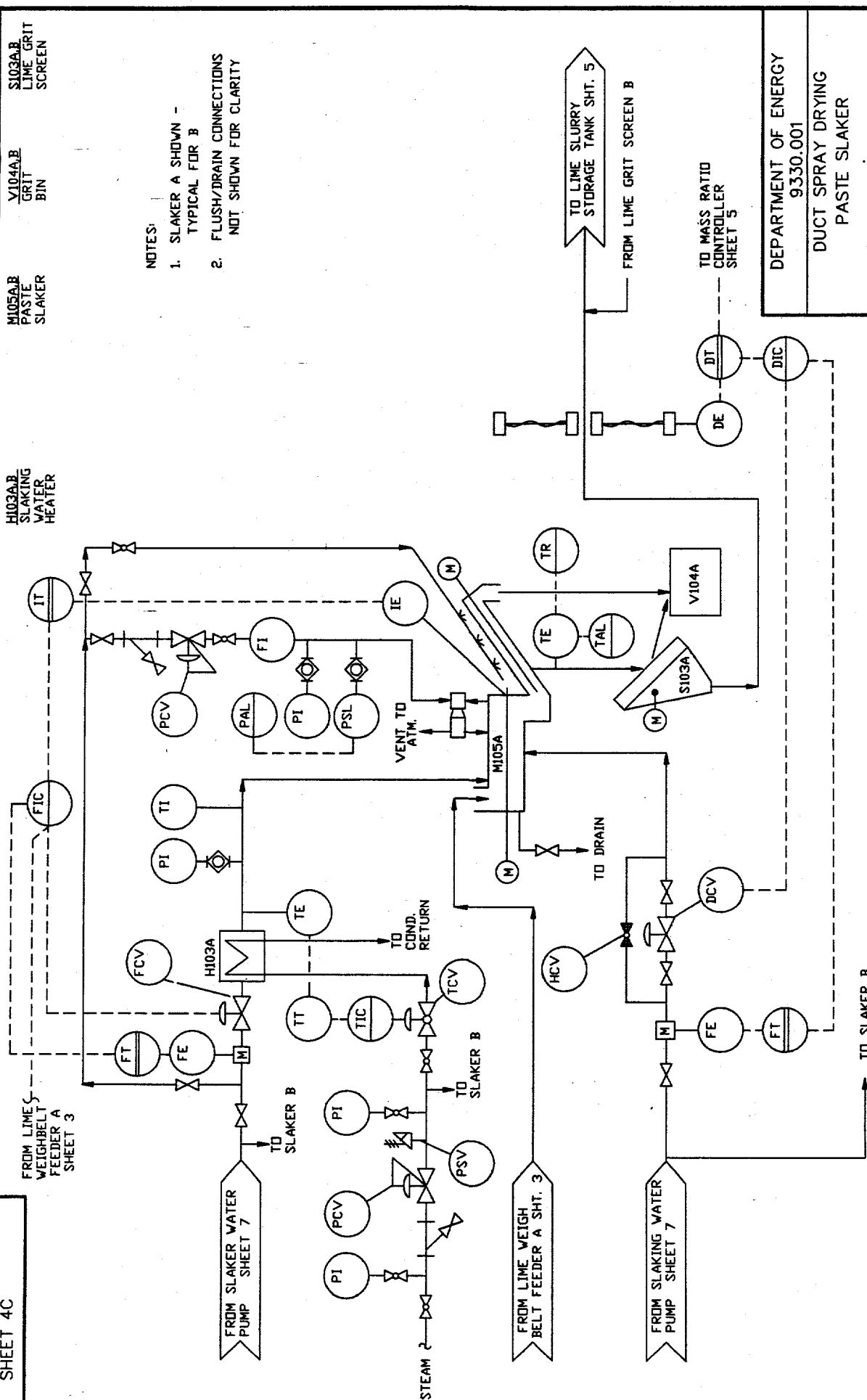
SHEET 4B

SCALE
NONE

CAD NO. A90PT04B DATE 09/09/92 JLO

NOTES:

1. SLAKER A SHOWN -
TYPICAL FOR B
2. FLUSH/DRAIN CONNECTIONS
NOT SHOWN FOR CLARITY



DEPARTMENT OF ENERGY

9330.001

DUCT SPRAY DRYING

PASTE SLAKER

SHEET 4C

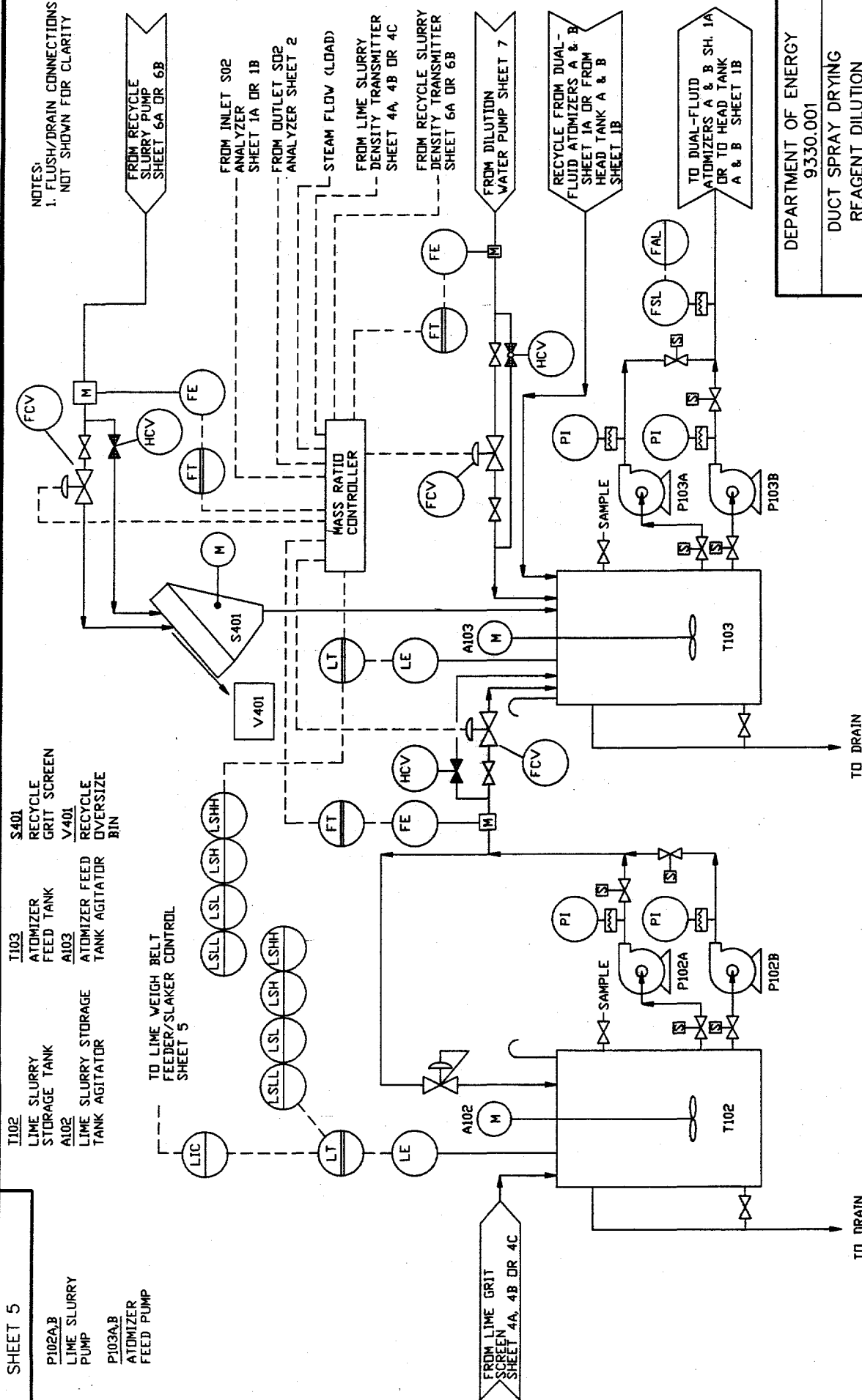
SCALE
NONE

SHEET 5

P102A,B
LIME SLURRY
PUMP
P103A,B
ATOMIZER
FEED PUMP

T102
LIME SLURRY
STORAGE TANK
A102
LIME SLURRY STORAGE
TANK AGITATOR
T103
ATOMIZER
FEED TANK
A103
ATOMIZER FEED
TANK AGITATOR
S401
RECYCLE
GRIT SCREEN
V401
RECYCLE
OVERSIZE
BIN

TO LIME WEIGH BELT
FEEDER/SLAKER CONTROL
SHEET 5

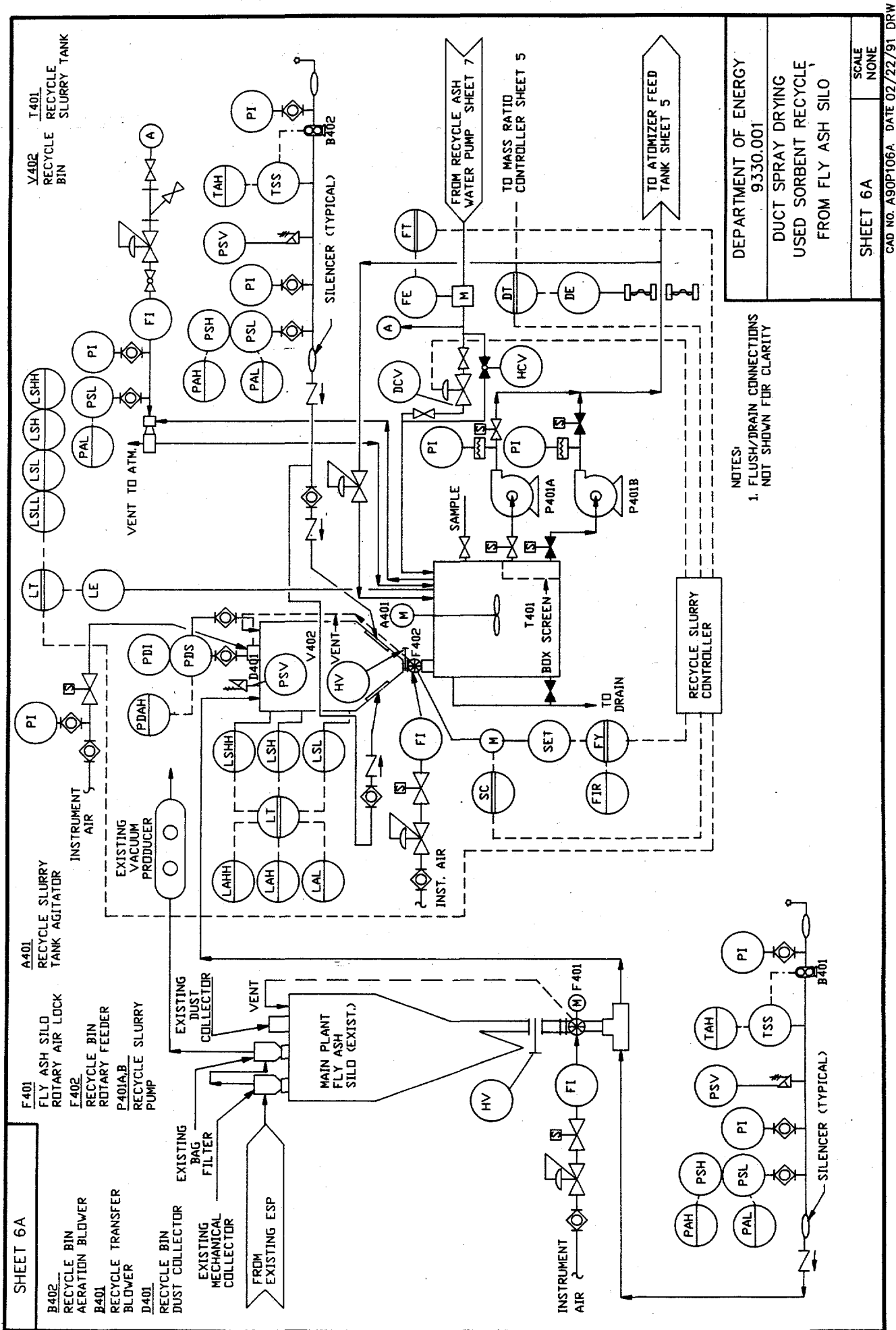


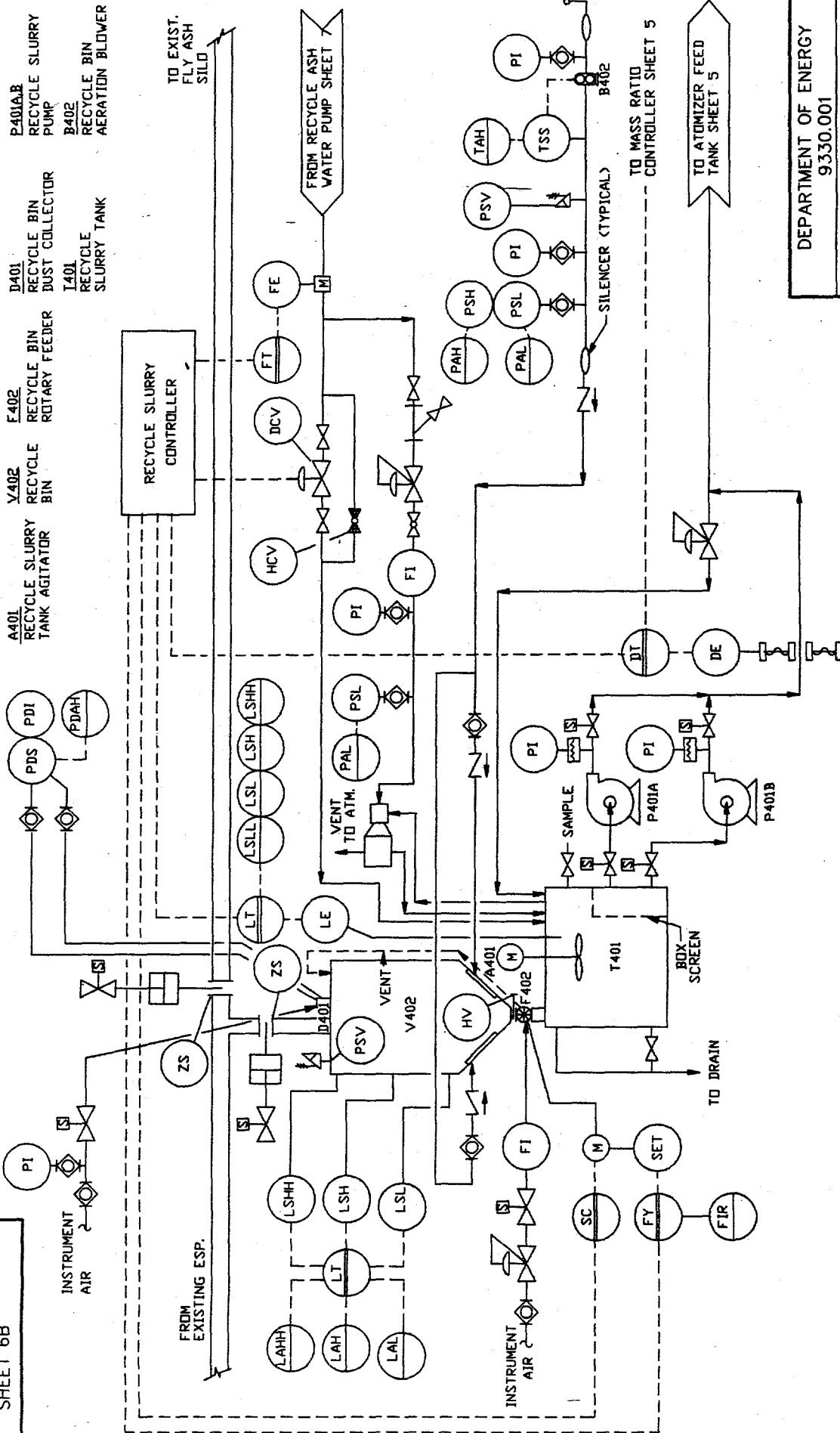
DEPARTMENT OF ENERGY
9330.001

DUCT SPRAY DRYING
REAGENT DILUTION
& STORAGE

SHEET 5
SCALE
NONE

CAD NO. A90P1005 DATE 09/09/92 J.L.O.





NOTES:
1. FLUSH/DRAIN CONNECTIONS
NOT SHOWN FOR CLARITY

DEPARTMENT OF ENERGY
9330.001

DUCT SPRAY DRYING
USED SORBENT RECYCLE FROM
PRESSURE PNEUMATIC OR
MECHANICAL CONVEYOR

SHEET 6B
SCALE
NONE

TO SLAKERS
SHEET 4A, 4B OR 4C

TO BALL MILL SUMPS
SHEET 4A OR
SLAKERS
SHEET 4B OR 4C

T601
RAW WATER TANK

P601A,B
SLAKING WATER
PUMP

T602
BLOWDOWN
WATER TANK

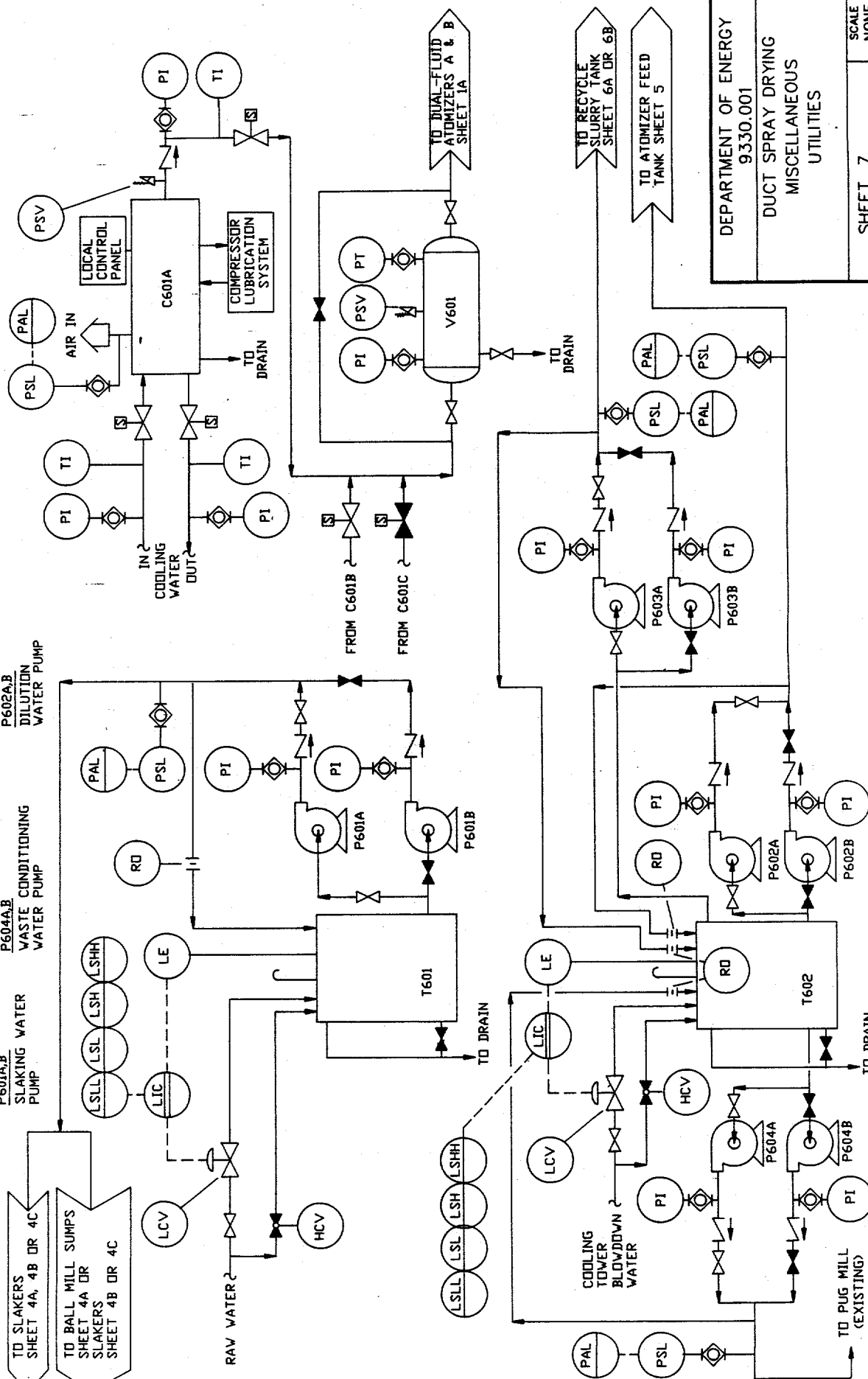
P602A,B
WASTE CONDITIONING
WATER PUMP

P603A,B
RECYCLE ASH
WATER PUMP

P602A,B
DILUTION
WATER PUMP

C601A,B,C
ATOMIZING
AIR COMPRESSOR

V601
ATOMIZING
AIR RECEIVER



DEPARTMENT OF ENERGY
9330.001

DUCT SPRAY DRYING
MISCELLANEOUS
UTILITIES

SHEET 7

SCALE
NONE

6.0 EQUIPMENT SIZING AND DESIGN

This section gives sizing and design criteria for specific equipment. Once the material balances have been developed per the discussions in Sections 3.0 and 5.2, individual pieces of equipment and other components of the duct injection system retrofit may be sized and designed. Examples of equipment sizing and design, using the criteria in this section, are given in Appendix A.

6.1 Sorbent Storage and Preparation System

6.1.1 Dry Sorbent Injection

One of the first steps in designing the equipment in a DSI duct injection system is determining whether the hydrated lime will be produced off-site or on-site. The criteria to make this decision are given in Section 3.2.4.1. If off-site hydration is selected, commercial grade hydrated lime will be received at the plant site, and Section 6.1.1.1 below is applicable. If on-site hydration is selected, 1/4 in. minus pebble lime (quicklime) will be received and hydrated at the plant, and Section 6.1.1.2 below is applicable.

6.1.1.1 Off-Site Hydration (Ref. DSI P&ID Sheet 3A)

Table 6-1 is a summary of the equipment sparing and sizing criteria for DSI with off-site hydration.

Rail Car Unloading

Each rail car will hold about 50 tons of hydrated lime. Each rail car will have two to four compartments/hoppers, each with a bottom discharge gate. The options for pneumatically unloading the car, and the corresponding equipment required, are discussed in detail in the rail car unloading system specification (Spec. No. M101) in Appendix E.

The unloading system capacity should be determined with two primary factors in mind: 1) the unloading rate should be high enough to unload the rail cars quickly, thereby minimizing demurrage on the rail cars and minimizing the operating labor required to "keep an eye" on the unloading, and 2) the unloading rate should be high enough such that, optimally, unloading may be accomplished Monday through Friday during the day shift.

Using the second criterion above, the design lime consumption [injected into the duct(s)] in ton/hr, multiplied by 168 hr in a week, gives the maximum tons for a week's supply of lime. These maximum tons divided by 19.2 hr gives a good estimate of the required lime unloading rate. The time available for actually unloading this tonnage of lime using the unloading equipment is based on four 8-hr day shifts (after a three-day weekend) at an assumed unloading equipment operating percentage of 60%. The assumed value of 60% accounts for the time for normal car spotting, operator break times, etc. This percentage will vary from plant to plant.

TABLE 6-1

**DRY SORBENT INJECTION - OFF-SITE HYDRATION
EQUIPMENT SPARING AND SIZING CRITERIA**

Equipment	Sparing/Capacity	Sizing Criteria
Rail Car Unloading System	1 @ 100% (unless 2 or more are required to achieve the required unloading rate - no spare blowers)	168 of hydrated lime @ the design hydrated lime consumption divided by 19.2 hr; 30-40 ton/hr for each system
Hydrate Silo(s)	1 @ 100% (unless 2 are required to achieve 7 days of storage)	7 days @ the design hydrated lime consumption
Screw Feeder	1 @ 100% for each duct	One times the design hydrate consumption for that duct adjusted for the lowest available calcium in the hydrated lime received
Hydrate Pneumatic Injection Conveyor	1 @ 100% for each duct (including a spare blower)	One times the design hydrate consumption for that duct adjusted for the lowest available calcium in the hydrated lime received
Recycle Pneumatic Transfer Conveyor	1 @ 100% (no spare blower)	Two times the design recycle material consumption (but in the range of 25-40 ton/hr)
Recycle Bin	1 @ 100%	8 hr @ the design recycle material consumption
Recycle Rotary Feeder	1 @ 100% for each duct	One times the design recycle material consumption for that duct
Recycle Pneumatic Injection Conveyor	1 @ 100% for each duct (no spare blower)	One times the design recycle material consumption for that duct (but in the range of 25-40 ton/hr)
Waste Conveying System to Ash Silo(s) (if required)	1 @ 100% for each ESP (including a spare blower)	Two times the maximum expected waste collection rate in the ESP

Equipment	Sparing/Capacity	Sizing Criteria
Ash Silo(s) (existing plus new)	1 @ 100% (unless 2 are required to achieve 90 hr of waste storage)	90 hr @ the maximum expected ESP waste collection rate
Pug Mill(s) (existing plus new)	1 @ 100% (unless 2 are required to achieve the specified rate)	7 days (168 hr) of waste @ the maximum expected ESP collection rate divided by 19.2 hr
Atomizing Air Compressor	3 @ 50%	0.5 design air-to-water ratio; 125 psig discharge pressure
Atomizing Air Receiver	1 @ 100%	10 sec @ total design air requirement (acfm)
Blowdown Water Tank	1 @ 100%	1 hr retention
Water Pumps	2 @ 100% for each service	1.2 times the design water consumption for each service

Typical capacities for a rail car unloading system range from 30 - 40 ton/hr. If the required capacity, as estimated above, is significantly greater than 30 - 40 ton/hr, one or more of the following will have to be considered: 1) unloading during evening and/or graveyard shifts, 2) increasing the capacity of the rail car unloading system above 40 ton/hr (through discussions with system suppliers), and 3) the use of two or more unloading systems to allow unloading two or more hoppers at a time.

Typical pneumatic unloading conveying velocities range from 2,500 to 3,000 ft/min for hydrated lime. The air required for conveying the lime is somewhat dependent on conveying distance. For an unloading conveying distance of 100 ft, about 0.05 lb air per lb lime is required compared to 0.075 lb air per lb lime for 400 ft of conveying distance. Blowers are normally rated at just less than 15 psig discharge pressure to stay below the ASME pressure code requirements.

Additional design criteria are contained in the rail car unloading system specification.

Redundant blowers for either positive or negative pressure systems are typically not required; only one blower per service is suggested as shown on DSI P&ID Sheet 3A in Section 5.3. This is recommended because 1) the blowers should only operate 30-40% of the time allowing time for routine maintenance, and 2) as discussed below, provisions for truck unloading should be included in the storage silo - this will allow lime to be unloaded directly into the silo by truck-mounted blowers if one of the rail car unloading blowers is unavailable.

Truck Unloading

Even if rail is to be the principal mode of lime delivery, truck shipments will probably be needed from time to time to compensate for railroad strikes, problems with the rail car unloading system, etc. The storage silo should be fitted with a truck fill pipe as noted in DSI

P&ID Sheet 3A. If lime delivery by truck is the only mode utilized, two truck fill pipes per silo are recommended. Material, size, and fittings for this pipe are given in the silo/day bin specification (Spec. No. M102) in Appendix E.

If a rail car and truck fill line are connected to a silo, they each will require some way of being isolated. Otherwise, conveying air/lime will discharge from the truck fill pipe when the rail car unloading conveyor is used, and/or the rail car unloading line could become plugged with lime dust when the truck fill pipe is used. The truck fill pipe can be isolated simply by using a cap at the quick coupling at grade. When the truck fill pipe is used, the rail car unloading line should be blanked off to prevent lime dust from possibly filling up and plugging this line. If the truck fill pipe is to be sparingly used, a manual gate in the rail car unloading line is adequate. If the truck fill line is to be used frequently, a pneumatically operated isolation gate in the rail car unloading line would be more appropriate. Regardless of the type of operator, the gate in the rail car unloading line should be located as close as possible to the silo inlet connection. If two truck unloading lines are the only means of filling the silo, each should be furnished with a cap at the quick coupling at grade.

A pneumatic lime truck will hold about 20 tons of hydrated lime. Because of the truck-mounted blower, the truck is essentially self-unloading, requiring only that the storage silo be equipped with a bin vent filter and pressure relief device. Hydrated lime can be blown up to 200 ft vertically and 300 ft combined vertical and horizontal run with the truck-mounted blower. The intake end of the fill pipe should be mounted vertically, with the bottom about 4 ft above ground. The truck fill pipe should run vertically first, then horizontally. Normally, a truck can be unloaded in about 1 hr. If faster unloading is desired, a high capacity truck unloading stationary blower can be installed at grade near the base of the silo. Associated flex hose and truck connection fittings should be included. This truck unloading blower could be operated by plant personnel or the truck operator.

Hydrate Silo

Minimum lime storage capacity for a continuously operating facility is generally considered to be either 150% of the normal delivery quantity (e.g., enough capacity to hold 9 rail cars worth of lime if 6 rail cars is the normal delivery) or 7 days of storage at the design lime consumption [injected into the duct(s)], whichever is greater. A bulk density of 30 lb per cu ft may be used for capacity of hydrated lime. The straight wall height should be 2.5-4.0 times the silo diameter, and a freeboard (unused volume above the level of a full silo) of 4 ft should be assumed.

Whether to use one or more hydrate silos depends on the design lime consumption, silo construction economy, and also on silo height. Since hydrated lime can be unloaded 200 ft vertically using a truck-mounted blower, and allowing 25 ft for the process equipment located underneath the silo cone, the silo straight wall height plus cone height is limited to about 175 ft. At a straight wall height to diameter ratio of 2.5 and a 60° cone angle, the maximum silo diameter is 56 ft, and the storage capacity (at a bulk density of 30 lb per cu ft) is about 5,200 tons. This is a huge silo and is the largest that should be considered. Construction economy will likely limit silo diameter to 30 - 40 ft (800 - 1900 tons of hydrated lime storage at a 2.5 aspect ratio). These calculations assume that the silo freeboard volume is approximately equal to the silo cone volume. Therefore, the approximate silo capacity can be calculated using the total straight wall height and ignoring the cone volume.

Hydrated lime tends to form rat holes and craters which can cause arching or bridging in storage. The silo cone angle for hydrated lime should be 70° from the horizontal if no flow aid is utilized, or 60° if fluidizing pads are installed. A bin activator or vibrator is not recommended on hydrated lime silos as they tend to pack the material rather than enhance the flow. Fluidizing pads are recommended in conjunction with a dedicated hydrate silo aeration blower. As noted in DSI P&ID Sheet 3A, a spare aeration blower is not recommended. However, a tie-in from a plant service air line (with pressure reducing station) should be used as a back-up when the aeration blower is not available. If an air dryer is not installed downstream of the service air tie-in, instrument air should be used instead.

A minimum of four fluidizing pads should be installed starting at about 1-2 ft above the hopper outlet. The pads should be mounted directly to the hopper wall. The pads should be 8 in. to 12 in. wide and about 8 ft long depending on the silo size. The fluidizing pads should be porous stone or polyester fabric with a permeability rating of about 10 cfm per sq. ft. at 2 in. H_2O differential pressure. Although not shown on the P&IDs, a manually operated butterfly or ball valve should be installed in the line to each fluidizing pad for trimming air flow.

Fluidizing air pressure should be 3-5 psig, and the air flow should be 10 scfm per sq ft of fluidizing pad area. The aeration (fluidizing) blower should be sized at 10 scfm per sq ft and enough discharge pressure to overcome losses and still maintain 3-5 psig at the fluidizing air pads.

In areas of high humidity, an air dryer (desiccant type) is recommended for the fluidizing air as shown in DSI P&ID Sheet 3A. Hydrated lime is quite hygroscopic, and moisture in the fluidizing air could cause agglomeration and flowability problems within the silo. The air dryer should be sized for the full fluidizing blower discharge flow.

An alternative to fluidizing pads is aeration flow cones. These devices are mounted directly to the hopper walls and use compressed air to aerate along the inside of hopper walls. The compressed air is released in a circular pattern, and the aeration results in undercutting and flowability of the lime. Such aeration flow cones are the Vibra-Jet Bin Aerator manufactured by Dynamic Air Conveying Systems of St. Paul, MN.

The hopper flow design for the hydrate silo should be mass flow, i.e., first in - first out. This eliminates an annular portion of the lime that remains in the silo until the level is drawn down very low. Any stagnant areas will likely form hard deposits over time due to the affinity of water to hydrated lime. An exception to mass flow design may be required if the silo location limits the available head room; mass flow design requires a relatively tall silo. In this case, expanded flow - with minimal dead areas in the silo - should be used.

The pressure relief device on top of the hydrate silo may be simply a hinged manhole cover or a device designed specifically to relieve pressure at a certain setpoint.

Additional design criteria are contained in the silo/day bin specification.

The hydrate silo dust collector must be sized to filter the transport air from a positive pressure rail car unloading system and/or a truck-mounted blower. Normally, the rail car unloading system will not operate concurrent with the unloading of a truck, so the collector should be sized for the larger flow of the two which is usually the rail car unloading system. If truck unloading is the only means of filling the silo, and two truck fill pipes are installed, the dust collector should be sized for two trucks unloading concurrently (2 @ 800 cfm per truck gives

1,600 cfm). If a vacuum rail car unloading system is employed with the filter receiver located on top of the silo, a dust collector is still required, but it may be much smaller as it only needs to filter the air displaced from the silo as it fills with lime and/or filter the conveying air from a truck-mounted blower. In this case, the air from a truck-mounted blower (about 800 cfm) is used to size the dust collector.

The use of an exhaustor fan on the dust collector is optional. However, the slight negative pressure in the silo air space, created by the exhaustor, will result in air in-leakage through any small openings in the silo roof instead of lime dust out-leakage, and it will minimize the possibility of lime dust filling and plugging an idle silo fill line. For silos/bins located indoors, an exhaustor fan is normally used to blow the air exiting the dust collector outside of the building.

The outlet dust loading from the dust collector is often specified by the State or local regulatory agency with jurisdiction. With no other guidance, a removal efficiency of 99.9% should be specified.

Other design criteria for the dust collector are contained in the bin vent dust collector specification (Spec. No. M103) in Appendix E.

If more than one silo is required to achieve the 7 days of storage capacity, a rotary vane feeder would be attached to each silo cone. The feeders would discharge to a common screw conveyor. The flow from each silo would be controlled either by blending the flows together or by total flow from each silo in sequence. The common screw conveyor would feed a hopper or bin (probably requiring a bucket elevator); the hopper or bin would discharge to the downstream process equipment. If only one silo is used (as shown in DSI P&ID Sheet 3A), the silo would discharge directly to the downstream process equipment.

Sheet 3A of the DSI P&IDs reflects one silo for both hydrated lime storage and feeding of the duct injection points. As noted in Section 5.3.1, if this silo cannot be located near the injection points, due to space and/or unloading constraints, the user may want to consider pneumatically transferring the lime from the remote silo to a hydrate day bin located close to the injection points. In this case, the design criteria for both the pneumatic transfer conveyor and the day bin will be essentially the same as those given in Section 6.1.1.2. Whether the hydrated lime, which is injected into the duct(s), is fed from a silo or a day bin, the hydrated lime injection equipment, as described below, would be the same.

Hydrated Lime Injection Equipment

Although there are a number of ways of metering the injected lime, the P&IDs show the lime being discharged from the silo through a variable speed screw feeder and into a dilute phase, positive pressure pneumatic conveying system through a constant speed air lock valve. The screw speed is controlled to maintain a specified SO_2 emission based on SO_2 monitor signal or coal sulfur and boiler load. Controls are discussed in Section 8.0.

The injection conveyor should be a dilute phase pressure conveying system to provide a constant flow at the required pressure to the injectors. A single pipe would convey the lime to a distribution bottle near the flue gas duct where it is split into smaller, balanced loss pipes to each injector. Injector design is discussed in Section 6.2.1.

The conveyor piping should be routed either vertically or horizontally with no more than a 15° deviation from vertical or horizontal to minimize particle drop out in the pipe.

One hydrate screw feeder/rotary air lock should be provided per duct. Each hydrate screw feeder and hydrate rotary air lock should be sized for at least 100% of the design hydrated lime usage rate for that duct as adjusted for the lowest available calcium in the hydrated lime received. For example, if the suppliers of hydrated lime closest to the plant indicate that the range of $\text{Ca}(\text{OH})_2$ in their hydrate is 95-98%, the screw feeders and air locks should be sized for the design $\text{Ca}(\text{OH})_2$ required (reference Eq. 3-10 in Section 3.2.1.1) divided by 0.95 to account for the inerts.

Variable speed rotary feeders can be purchased, but they are typically not as accurate as screw feeders. For good lime feed control, screw feeders in series with constant speed rotary air locks are recommended. The additional advantage of this arrangement is that any blowback of pressurized conveying air which leaks through the air lock will not prevent the lime from flowing out of the silo - it will dissipate through the screw feeder casing. A vent should be installed from the rotary air lock to the top of the silo to vent off this pressurized air (reference the P&IDs), but this vent line is prone to pluggage.

The hydrate injection pneumatic conveying system capacity for each duct should be at least 100% of the design hydrated lime usage rate for that duct as adjusted for the lowest available calcium in the hydrated lime received. The hydrate injection blowers should be sized for conveying velocities ranging from 2,500 to 3,000 ft/min. The air required for conveying the lime is somewhat dependent on conveying distance. For a conveying distance of 100 ft, about 0.05 lb air per lb lime is required compared to 0.075 lb air per lb lime for 400 ft of conveying distance. Blowers are normally rated at just less than 15 psig discharge pressure to stay below the ASME pressure code requirements.

Additional design criteria are contained in the pneumatic transfer/ injection conveyors specification and the screw feeders specification (Spec. Nos. M105 and M107, respectively) in Appendix E.

A spare injection blower should be available when an in-service machine requires maintenance. For the two duct case shown in the P&IDs, a total of three blowers would be required - one dedicated to each duct with a common spare. A spare set of screw feeder/rotary air lock is not shown in the P&IDs. A third set is not recommended because of the complexity of tying in a common spare to the other two sets. In addition, with three chutes from the lime silo, it is more uncertain that lime will fill each chute properly compared to two chutes. Instead of a "hard piped" spare set of feeders, it is recommended that spares be available to replace the in-line screw feeder and/or rotary air lock in a minimum amount of time.

If only one duct requires lime injection, two 100% systems would be recommended.

6.1.1.2 On-Site Hydration (Ref. DSI P&ID Sheets 3B & 4)

Table 6-2 is a summary of the equipment sparing and sizing criteria for DSI with on-site hydration.

TABLE 6-2

**DRY SORBENT INJECTION - ON-SITE HYDRATION
EQUIPMENT SPARING AND SIZING CRITERIA**

Equipment	Sparing/Capacity	Sizing Criteria
Rail Car Unloading System	1 @ 100% (unless 2 or more are required to achieve the required unloading rate - no spare blowers)	168 hr of pebble lime required @ the design hydrated lime consumption divided by 19.2 hr; 30-40 ton/hr for each system
Pebble Lime Silo(s)	1 @ 100% (unless 2 are required to achieve 7 days of storage)	7 days of pebble lime required @ the design hydrated lime consumption
Lime Hydrator & Weigh Belt Feeder	2 @ 100%	One to three times the design hydrated lime consumption (depending on plant operating philosophy) adjusted for the lowest available calcium in the hydrated lime produced
Hydrate Pneumatic Transfer Conveyor	1 @ 100% (including a spare blower)	One times the design capacity of each hydrator (but in the range of 25-45 ton/hr)
Hydrate Bin	1 @ 100%	24 hr @ the design hydrate consumption
Screw Feeder	1 @ 100% for each duct	One times the design hydrate consumption for that duct adjusted for the lowest available calcium in the hydrated lime produced
Hydrate Pneumatic Injection Conveyor	1 @ 100% for each duct (including a spare blower)	One times the design hydrate consumption for that duct adjusted for the lowest available calcium in the hydrated lime produced
Recycle Pneumatic Transfer Conveyor	1 @ 100% (no spare blower)	Two times the design recycle material consumption (but in the range of 25-40 ton/hr)

Equipment	Sparing/Capacity	Sizing Criteria
Recycle Bin	1 @ 100%	8 hr @ the design recycle material consumption
Recycle Rotary Feeder	1 @ 100% for each duct	One times the design recycle material consumption for that duct
Recycle Pneumatic Injection Conveyor	1 @ 100% for each duct (no spare blower)	One times the design recycle material consumption for that duct (but in the range of 25-40 ton/hr)
Waste Conveying System to Ash Silo(s) (if required)	1 @ 100% for each ESP (including a spare blower)	Two times the maximum expected waste collection rate in the ESP
Ash Silo(s) (existing plus new)	1 @ 100% (unless 2 are required to achieve 90 hr of waste storage)	90 hr @ the maximum expected ESP waste collection rate
Pug Mills (existing plus new)	1 @ 100% (unless 2 are required to achieve the specified rate)	7 days (168 hr) of waste @ the maximum expected ESP collection rate divided by 19.2 hr
Atomizing Air Compressor	3 @ 50%	0.5 design air-to-water ratio; 125 psig discharge pressure
Atomizing Air Receiver	1 @ 100%	10 sec @ total design air requirement (acfm)
Water Tanks	1 @ 100% for each service	1 hr retention
Water Pumps	2 @ 100% for each service	1.2 times the design water consumption for each service

Rail Car Unloading

Each rail car will hold about 100 tons of pebble quicklime. Each rail car will have two to four compartments/hoppers, each with a bottom discharge gate. The options for pneumatically unloading the car, and the corresponding equipment required, are discussed in detail in the rail car unloading system specification (Spec. No. M101) in Appendix E.

The unloading system capacity should be determined with two primary factors in mind: 1) the unloading rate should be high enough to unload the rail cars quickly, thereby minimizing demurrage on the rail cars and minimizing the operating labor required to "keep an eye" on the unloading, and 2) the unloading rate should be high enough such that, optimally, unloading may be accomplished Monday through Friday during the day shift.

Using the second criterion above, the design lime consumption [injected into the duct(s)] in ton/hr, multiplied by 168 hr in a week, gives the maximum tons for a week's supply of lime. These maximum tons divided by 19.2 hr gives a good estimate of the required lime unloading rate. The time available for actually unloading this tonnage of lime using the unloading equipment is based on four 8-hr day shifts (after a three-day weekend) at an assumed unloading equipment operating percentage of 60%. The assumed value of 60% accounts for the time for normal car spotting, operator break times, etc. This percentage will vary from plant to plant. Note: The design lime consumption injected into the duct(s) will be based on hydrated lime; the lime unloading capacity will be based on pebble lime; a conversion will have to be made between the two.

Typical capacities for a rail car unloading system range from 30 - 40 ton/hr. If the required capacity, as estimated above, is significantly greater than 30 - 40 ton/hr, one or more of the following will have to be considered: 1) unloading during evening and/or graveyard shifts, 2) increasing the capacity of the rail car unloading system above 40 ton/hr (through discussions with system suppliers), and 3) the use of two or more unloading systems to allow unloading two or more hoppers at a time.

Typical pneumatic unloading conveying velocities range from 4,000 to 5,000 ft/min for pebble quicklime. The air required for conveying the lime is somewhat dependent on conveying distance. For an unloading conveying distance of 100 ft, about 0.10 lb air per lb lime is required compared to 0.15 lb air per lb lime for 400 ft of conveying distance. Blowers are normally rated at just less than 15 psig discharge pressure to stay below the ASME pressure code requirements.

Additional design criteria are contained in the rail car unloading system specification.

Redundant blowers for either positive or negative pressure systems are typically not required; only one blower per service is suggested as shown on DSI P&ID Sheet 3B in Section 5.3. This is recommended because 1) the blowers should only operate 30 - 40% of the time allowing time for routine maintenance, and 2) as discussed below, provisions for truck unloading should be included in the storage silo - this will allow lime to be unloaded directly into the silo by truck-mounted blowers if one of the rail car unloading blowers is unavailable.

Truck Unloading

Even if rail is to be the principal mode of lime delivery, truck shipments will probably be needed from time to time to compensate for railroad strikes, problems with the rail car unloading system, etc. The storage silo should be fitted with a truck fill pipe as noted in DSI P&ID Sheet 3B. If lime delivery by truck is the only mode utilized, two truck fill pipes per silo are recommended. Material, size, and fittings for this pipe are given in the silo/day bin specification (Spec. No. M102) in Appendix E.

If a rail car and truck fill line are connected to a silo, they each will require some way of being isolated. Otherwise, conveying air/lime will discharge from the truck fill pipe when the rail car unloading conveyor is used, and/or the rail car unloading line could become plugged with lime dust when the truck fill pipe is used. The truck fill pipe can be isolated simply by using a cap at the quick coupling at grade. When the truck fill pipe is used, the rail car unloading line should be blanked off to prevent lime dust from possibly filling up and plugging this line. If the truck fill pipe is to be sparingly used, a manual gate in the rail car unloading line is adequate. If the truck fill line is to be used frequently, a pneumatically operated isolation gate

in the rail car unloading line would be more appropriate. Regardless of the type of operator, the gate in the rail car unloading line should be located as close as possible to the silo inlet connection. If two truck unloading lines are the only means of filling the silo, each should be furnished with a cap at the quick coupling at grade.

A pneumatic lime truck will hold about 25 tons of pebble quicklime. Because of the truck-mounted blower, the truck is essentially self-unloading, requiring only that the storage silo be equipped with a bin vent filter and pressure relief device. Pebble lime can be blown up to 150 ft vertically and 200 ft combined vertical and horizontal run with the truck-mounted blower. However, it takes almost 2 hr to unload a 25 ton truck against 150 ft of vertical height compared to about 1 hr to unload a truck against 100 ft of vertical height. The intake end of the fill pipe should be mounted vertically, with the bottom about 4 ft above ground. The truck fill pipe should run vertically first, then horizontally. If faster unloading is required, a high capacity truck unloading stationary blower can be installed at grade near the base of the silo. Associated flex hose and truck connection fittings should be included. The truck unloading blower could be operated by plant personnel or the truck operator.

Pebble Lime Silo

Minimum lime storage capacity for a continuously operating facility is generally considered to be either 150% of the normal delivery quantity (e.g., enough capacity to hold 9 rail cars worth of lime if 6 rail cars is the normal delivery) or 7 days of storage at the design lime consumption [injected into the duct(s)], whichever is greater. Note (again): The design lime consumption injected into the duct(s) will be based on hydrated lime; the 7 days of lime storage capacity will be based on pebble lime; a conversion will have to be made between the two. A bulk density of 55 lb per cu ft may be used for capacity of pebble lime. The straight wall height should be 2.5-4.0 times the silo diameter, and a freeboard (unused volume above the level of a full silo) of 4 ft should be assumed.

Whether to use one or more pebble lime silos depends on the design lime consumption, silo construction economy, and also on silo height. Since pebble lime can be unloaded a maximum of 150 ft vertically using a truck-mounted blower, and allowing 50 ft for the process equipment located underneath the silo cone, the silo straight wall height plus cone height is limited to about 100 ft. At a straight wall height to diameter ratio of 2.5 and a 60° cone angle, the maximum silo diameter is about 32 ft, and the storage capacity (at a bulk density of 55 lb per cu ft) is about 1,800 tons. These calculations assume that the silo freeboard volume is approximately equal to the silo cone volume. Therefore, the approximate silo capacity can be calculated using the total straight wall height and ignoring the cone volume.

Pebble lime tends to form rat holes and craters which can cause arching or bridging in storage. The silo cone angle for pebble lime should be 60° from the horizontal. A bin activator or vibrator is recommended on pebble lime silos to promote flow. The diameter of the hopper outlet to the bin activator should be at least 1/3 the diameter of the silo.

The hopper flow design for the pebble lime silo can be mass flow, expanded flow, or funnel flow as long as the hopper angle is 60°. The pressure relief device on top of the pebble lime silo may be simply a hinged manhole cover or a device designed specifically to relieve pressure at a certain setpoint.

Additional design criteria are contained in the silo/day bin specification and bin activator specification (Spec. No. M104) in Appendix E.

The pebble lime silo dust collector must be sized to filter the transport air from a positive pressure rail car unloading system and/or a truck-mounted blower. Normally, the rail car unloading system will not operate concurrent with the unloading of a truck, so the collector should be sized for the larger flow of the two which is usually the rail car unloading system. If truck unloading is the only means of filling the silo, and two truck fill pipes are installed, the dust collector should be sized for two trucks unloading concurrently (2 @ 800 cfm per truck gives 1,600 cfm). If a vacuum rail car unloading system is employed with the filter receiver located on top of the silo, a dust collector is still required, but it may be much smaller as it only needs to filter the air displaced from the silo as it fills with lime and/or filter the conveying air from a truck-mounted blower. In this case, the air from a truck-mounted blower (about 800 cfm) is used to size the dust collector.

The use of an exhaust fan on the dust collector is optional. However, the slight negative pressure in the silo air space, created by the exhaust fan, will result in air in-leakage through any small openings in the silo roof instead of lime dust out-leakage, and it will minimize the possibility of lime dust filling and plugging an idle silo fill line. For silos/bins located indoors, an exhaust fan is normally used to blow the air exiting the dust collector outside of the building.

The outlet dust loading from the dust collector is often specified by the State or local regulatory agency with jurisdiction. With no other guidance, a removal efficiency of 99.9% should be specified.

Other design criteria for the dust collector are contained in the bin vent dust collector specification (Spec. No. M103) in Appendix E.

If more than one silo is required to achieve the 7 days of storage capacity, a rotary vane feeder would be attached to each silo cone. The feeders would discharge to a common screw conveyor. The flow from each silo would be controlled either by blending the flows together or by total flow from each silo in sequence. The common screw conveyor would feed a hopper or bin (probably requiring a bucket elevator); the hopper or bin would discharge to the downstream process equipment. If only one silo is used (as shown in DSI P&ID Sheet 3B), the silo would discharge directly to the downstream process equipment.

Hydration Equipment

Although there are a number of ways of metering pebble lime into the hydrators, the P&IDs show the lime being discharged from the silo to two, redundant weigh belt feeders. Each 100% capacity weigh belt feeder feeds a 100% capacity lime hydrator. Redundancy is recommended in this equipment due to its historically high maintenance; therefore, two 100% capacity trains are suggested.

The weigh belt feeder is a short belt conveyor equipped with a weigh deck which measures the weight of lime carried on a section of the belt. Instrumentation adjusts a vertical gate and the speed of the belt so that only a set weight of material is allowed out of the pebble lime silo and into the hydration chamber of the hydrator. Weigh belt feeders are suggested in lieu of screw feeders because they are generally more accurate. Good control of the pebble lime and water feed rates to the hydrator is required to produce a product with the proper characteristics.

The hydrator consists of a hydration chamber followed by a seasoning chamber. The premixer introduces just enough water into the pebble lime to cause the formation of a dry hydrate. No further grinding would be required for this process. The commercial hydrators available range in size from 2 to 45 ton/hr of hydrated product at 30 lb per cu ft.

The capacity of the hydrators should be at least 100% of the design hydrated lime usage [injected into the duct(s)] as adjusted for the lowest available calcium in the hydrated lime produced. The minimum available Ca(OH)_2 in the hydrated lime product should be about 95% if a high calcium quicklime is used. Therefore, the hydrators should be sized for the design Ca(OH)_2 required (reference Eq. 3-10 in Section 3.2.1.1) divided by 0.95 to account for the inerts. Note: The design lime consumption injected into the duct(s) will be based on hydrated lime; the lime feeding capacity of the weigh belt feeders will be based on pebble lime; a conversion will have to be made between the two. For example, if the suppliers of pebble lime closest to the plant indicate that the range of CaO in their lime is 88-93%, the weigh belt feeders should be sized for the design CaO required (reference Eq. 3-15a in Section 3.2.1.9) divided by 0.88 to account for the inerts.

The hydrators can be operated either continuously, or on a batch basis, depending on plant operating philosophy. If the plant chooses to operate the hydrators continuously, or at least several hours each shift, then the capacity of the weigh belts and hydrators only needs to be based on the design hydrated lime usage in the duct(s) as suggested above. If the plant prefers that all of the hydrated lime for 24 hr of operation be generated on the day shift (or enough hydrated lime for 8 hr of operation be generated in 2 or 3 hr) and stored in the hydrate bin, the capacity of the weigh belts/hydrators needs to be based on three times the design hydrated lime usage.

Other design criteria for the weigh belt feeders and hydrators are contained in Spec. Nos. M106 and M108, respectively, in Appendix E.

The hydrator discharges into a surge chamber feeding a pneumatic conveyor that transfers the hydrate to a day bin (hydrate bin) located near the injection points. The rotary feeder which feeds the hydrate into the hydrate transfer conveyor and the pneumatic transfer conveyor itself would be sized to handle at least the design capacity of each hydrator; however, the capacity of this pneumatic transfer conveyor should normally range from 25-45 ton/hr. One dedicated rotary feeder with downstream isolation gate should be provided for each hydrator.

One hydrate pneumatic transfer conveyor should be provided to service both hydrators. The hydrate transfer blowers should be sized for conveying velocities ranging from 2,500 to 3,000 ft/min. The air required for conveying the lime is somewhat dependent on conveying distance. For a conveying distance of 100 ft, about 0.05 lb air per lb lime is required compared to 0.075 lb air per lb lime for 400 ft of conveying distance. Blowers are normally rated at just less than 15 psig discharge pressure to stay below the ASME pressure code requirements.

Additional design criteria are contained in the pneumatic transfer/injection conveyors specification (Spec. No. M105) in Appendix E.

A spare blower for the transfer conveyer is typically included. This is recommended because 1) both hydrators are serviced by this one conveyer - the hydrators should not be limited by want of a spare blower, and 2) even though provisions for emergency truck unloading should

be included in the hydrate bin, the capacity of the bin (24 hr if it is full) may be insufficient to supply the duct(s) until a truckload of hydrated lime can be brought on-site.

Hydrate Bin

The hydrate bin should be fitted with a truck fill pipe as noted in DSI P&ID Sheet 4. This will allow truck delivery of hydrated lime to the plant in the event interruptions in the pebble lime supply are experienced, both hydrators are out of service, etc. Material, size, and fittings for this pipe are given in the silo/day bin specification in Appendix E.

Since there will be two fill lines to the hydrate bin (from the hydrators and the emergency truck fill pipe), they each will require some way of being isolated. Otherwise, conveying air/lime will discharge from the truck fill pipe when the hydrate transfer conveyer is used, and/or the hydrate transfer line could become plugged with lime dust when the truck fill pipe is used. Since the truck fill pipe will likely be used only sparingly, it can be isolated simply by using a cap at the quick coupling at grade. The hydrate transfer conveying line should be fitted with a manual isolation gate located as close as possible to the bin inlet connection; it should be closed any time truck unloading will be accomplished.

The hydrate bin storage capacity should generally be 24 hr worth of hydrate at the design hydrated lime usage. This gives plant maintenance enough time to repair the pneumatic transfer conveyor when it breaks down. A bulk density of 30 lb per cu ft may be used for capacity of hydrated lime. The straight wall height should be 2.5-4.0 times the bin diameter, and a freeboard (unused volume above the level of a full bin) of 3 ft should be assumed.

Hydrated lime tends to form rat holes and craters which can cause arching or bridging in storage. The hydrate bin cone angle should be 70° from the horizontal if no flow aid is utilized, or 60° if fluidizing pads are installed. A bin activator or vibrator is not recommended on hydrated lime bins as they tend to pack the material rather than enhance the flow. Fluidizing pads are recommended in conjunction with a dedicated hydrate bin aeration blower. As noted in DSI P&ID Sheet 4, a spare aeration blower is not recommended. However, a tie-in from a plant service air line (with pressure reducing station) should be used as a back-up when the aeration blower is not available. If an air dryer is not installed downstream of the service air tie-in, instrument air should be used instead.

A minimum of four fluidizing pads should be installed starting at about 1-2 ft above the hopper outlet. The pads should be mounted directly to the hopper wall. The pads should be 8 in. to 12 in. wide and about 8 ft long depending on bin size. The fluidizing pads should be porous stone or polyester fabric with a permeability rating of about 10 cfm per sq ft at 2 in. H₂O differential pressure. Although not shown on the P&IDs, a manually operated butterfly or ball valve should be installed in the line to each fluidizing pad for trimming air flow.

Fluidizing air pressure should be 3-5 psig, and the air flow should be 10 scfm per sq ft of fluidizing pad area. The aeration (fluidizing) blower should be sized at 10 scfm per sq ft and enough discharge pressure to overcome losses and still maintain 3-5 psig at the fluidizing air pads.

In areas of high humidity, an air dryer (desiccant type) is recommended for the fluidizing air as shown in DSI P&ID Sheet 4. Hydrated lime is quite hygroscopic, and moisture in the fluidizing air could cause agglomeration and flowability problems within the silo. The air dryer should be sized for the full fluidizing blower discharge flow.

An alternative to fluidizing pads is aeration flow cones. These devices are mounted directly to the hopper walls and use compressed air to aerate along the inside of hopper walls. The compressed air is released in a circular pattern, and the aeration results in undercutting and flowability of the lime. Such aeration flow cones are the Vibra-Jet Bin Aerator manufactured by Dynamic Air Conveying Systems of St. Paul, MN.

The hopper flow design for the hydrate bin should be mass flow, i.e., first in - first out. This eliminates an annular portion of the lime that remains in the bin until the level is drawn down very low. Any stagnant areas will likely form hard deposits over time due to the affinity of water to hydrated lime. An exception to mass flow design may be required if the bin location limits the available head room; mass flow design requires a relatively tall bin. In this case, expanded flow - with minimal dead areas in the bin - should be used.

The pressure relief device on top of the hydrate bin may be simply a hinged manhole cover or a device designed specifically to relieve pressure at a certain setpoint.

Additional design criteria are contained in the silo/day bin specification.

The hydrate bin dust collector must be sized to filter the transport air when the positive pressure hydrate transfer conveyor is in operation.

The use of an exhaust fan on the dust collector is optional. However, the slight negative pressure in the bin air space, created by the exhaust fan, will result in air in-leakage through any small openings in the bin roof instead of lime dust out-leakage, and it will minimize the possibility of lime dust filling and plugging an idle bin fill line. For silos/bins located indoors, an exhaust fan is normally used to blow the air exiting the dust collector outside of the building.

The outlet dust loading from the dust collector is often specified by the State or local regulatory agency with jurisdiction. With no other guidance, a removal efficiency of 99.9% should be specified.

Other design criteria for the dust collector are contained in the bin vent dust collector specification.

Hydrated Lime Injection Equipment

Although there are a number of ways of metering the injected lime, the P&IDs show the lime being discharged from the bin through a variable speed screw feeder and into a dilute phase, positive pressure pneumatic conveying system through a constant speed air lock valve. The screw speed is controlled to maintain a specified SO₂ emission based on SO₂ monitor signal or coal sulfur and boiler load. Controls are discussed in Section 8.0

The injection conveyor should be a dilute phase pressure conveying system to provide a constant flow at the required pressure to the injectors. A single pipe would convey the lime to a distribution bottle near the flue gas duct where it is split into smaller, balanced loss pipes to each injector. Injector design is discussed in Section 6.2.1.

The conveyor piping should be routed either vertically or horizontally with no more than a 15° deviation from vertical or horizontal to minimize particle drop out in the pipe.

One hydrate screw feeder/rotary air lock should be provided per duct. Each hydrate screw feeder and hydrate rotary air lock should be sized for at least 100% of the design hydrated lime usage for that duct as adjusted for the lowest available calcium in the hydrated lime produced. For example, if the suppliers of hydrators indicate that the range of Ca(OH)_2 in the hydrate produced from the pebble lime is 95-98%, the screw feeders and air locks should be sized for the design Ca(OH)_2 required (reference Eq. 3-10 in Section 3.2.1.1) divided by 0.95 to account for the inerts.

Variable speed rotary feeders can be purchased, but they are typically not as accurate as screw feeders. For good lime feed control, screw feeders in series with constant speed rotary air locks are recommended. The additional advantage of this arrangement is that any blowback of pressurized conveying air which leaks through the air lock will not prevent the lime from flowing out of the hydrate bin - it will dissipate through the screw feeder casing. A vent should be installed from the rotary air lock to the top of the bin to vent off this pressurized air (reference the P&IDs), but this vent line is prone to pluggage.

The hydrate injection pneumatic conveying system capacity for each duct should be at least 100% of the design hydrated lime usage rate for that duct as adjusted for the lowest available calcium in the hydrated lime produced. The hydrate injection blowers should be sized for conveying velocities ranging from 2,500 to 3,000 ft/min. The air required for conveying the lime is somewhat dependent on conveying distance. For a conveying distance of 100 ft, about 0.05 lb air per lb lime is required compared to 0.075 lb air per lb lime for 400 ft of conveying distance. A conveying distance of 600 ft. requires about 0.1 lb air per lb lime. Blowers are normally rated at just less than 15 psig discharge pressure to stay below the ASME pressure code requirements.

Additional design criteria are contained in the pneumatic transfer/injection conveyors specification and the screw feeders specification (Spec. Nos. M105 and M107, respectively) in Appendix E.

A spare injection blower should be available when an in-service machine requires maintenance. For the two duct case shown in the P&IDs, a total of three blowers would be required - one dedicated to each duct with a common spare. A spare set of screw feeder/rotary air lock is not shown in the P&IDs. A third set is not recommended because of the complexity of tying in a common spare to the other two sets. In addition, with three chutes from the hydrate bin, it is more uncertain that lime will fill each chute properly compared to two chutes. Instead of a "hard piped" spare set of feeders, it is recommended that spares be available to replace the in-line screw feeder and/or rotary air lock in a minimum amount of time.

If only one duct requires lime injection, two 100% systems would be recommended.

6.1.2 Duct Spray Drying (Ref. DSD P&ID Sheets 3-5)

In DSD, 3/4 in. minus pebble lime (quicklime) will be received at the plant and stored in a pebble lime silo(s). From the silo(s), the lime will be fed to a slaking system which converts the pebble lime to a lime slurry; the lime slurry will then be pumped to dual-fluid nozzles in the flue gas duct(s). The equipment required would be essentially the same as that used in existing utility spray dryer installations except that no spray dryer vessels would be required. Table 6-3 is a summary of the equipment sparing and sizing criteria for DSD.

TABLE 6-3

**DUCT SPRAY DRYING
EQUIPMENT SPARING AND SIZING CRITERIA**

Equipment	Sparing/Capacity	Sizing Criteria
Rail Car Unloading System	1 @ 100% (unless 2 or more are required to achieve the required unloading rate - no spare blowers)	168 hr of pebble lime @ the design lime consumption divided by 19.2 hr; 30-40 ton/hr for each system
Pebble Lime Silo(s)	1 @ 100% (unless 2 are required to achieve 7 days of storage)	7 days @ the design lime consumption
Pebble Lime Pneumatic Transfer Conveyor	1 @ 100% (no spare blower)	Three times the design lime consumption (but in the range of 25-40 ton/hr)
Pebble Lime Day Bin	1 @ 100%	24 hr @ the design lime consumption
Lime Slaker & Weigh Belt Feeder	2 @ 100%	One to three times the design lime consumption (depending on plant operating philosophy) adjusted for the lowest available calcium in the pebble lime received
Slaking Water Heater	2 @ 100%	Heat up the slaking water (from 35-120°F) required when the slaker is operating at design capacity
Tanks	1 @ 100% for each service	Lime slurry storage tank - 8 or 24 hr Recycle slurry tank - 2.5 or 8 hr Atomizer feed tank - 30 min Water tanks - 1 hr each service
Pumps	2 @ 100% for each service	1.2 times the design capacity for each service

Equipment	Sparing/Capacity	Sizing Criteria
Recycle Pneumatic Transfer Conveyor	1 @ 100% (no spare blower)	Two times the design recycle material consumption (but in the range of 25-40 ton/hr)
Recycle Bin	1 @ 100%	8 hr @ the design recycle material consumption
Recycle Rotary Feeder	1 @ 100%	One times the design recycle material consumption
Waste Conveying System to Ash Silo(s) (if required)	1 @ 100% for each ESP (including a spare blower)	Two times the maximum expected waste collection rate in the ESP
Ash Silo(s) (existing plus new)	1 @ 100% (unless 2 are required to achieve 90 hr of waste storage)	90 hr @ the maximum expected ESP waste collection rate
Pug Mill(s) (existing plus new)	1 @ 100% (unless 2 are required to achieve the specified rate)	7 days (168 hr) of waste @ the maximum expected ESP collection rate divided by 19.2 hr
Atomizing Air Compressor	3 @ 50%	0.5 design air-to-slurry ratio; 125 psig discharge pressure
Atomizing Air Receiver	1 @ 100%	10 sec @ total design air requirement (acfm)

Rail Car Unloading

Each rail car will hold about 100 tons of pebble quicklime. Each rail car will have two to four compartments/hoppers, each with a bottom discharge gate. The options for pneumatically unloading the car, and the corresponding equipment required, are discussed in detail in the rail car unloading system specification (Spec. No. M101) in Appendix E.

The unloading system capacity should be determined with two primary factors in mind: 1) the unloading rate should be high enough to unload the rail cars quickly, thereby minimizing demurrage on the rail cars and minimizing the operating labor required to "keep an eye" on the unloading, and 2) the unloading rate should be high enough such that, optimally, unloading may be accomplished Monday through Friday during the day shift.

Using the second criterion above, the design lime consumption [injected into the duct(s)] in ton/hr, multiplied by 168 hr in a week, gives the maximum tons for a week's supply of lime. These maximum tons divided by 19.2 hr gives a good estimate of the required lime unloading rate. The time available for actually unloading this tonnage of lime using the unloading equipment is based on four 8-hr day shifts (after a three-day weekend) at an assumed unloading equipment operating percentage of 60%. The assumed value of 60% accounts for

the time for normal car spotting, operator break times, etc. This percentage will vary from plant to plant.

Typical capacities for a rail car unloading system range from 30-40 ton/hr. If the required capacity, as estimated above, is significantly greater than 30-40 ton/hr, one or more of the following will have to be considered: 1) unloading during evening and/or graveyard shifts, 2) increasing the capacity of the rail car unloading system above 40 ton/hr (through discussions with system suppliers), and 3) the use of two or more unloading systems to allow unloading two or more hoppers at a time.

Typical pneumatic unloading conveying velocities range from 4,000 to 5,000 ft/min for pebble quicklime. The air required for conveying the lime is somewhat dependent on conveying distance. For an unloading conveying distance of 100 ft, about 0.10 lb air per lb lime is required compared to 0.15 lb air per lb lime for 400 ft of conveying distance. Blowers are normally rated at just less than 15 psig discharge pressure to stay below the ASME pressure code requirements.

Additional design criteria are contained in the rail car unloading system specification.

Redundant blowers for either positive or negative pressure systems are typically not required; only one blower per service is suggested as shown on DSD P&ID Sheet 3 in Section 5.3. This is recommended because 1) the blowers should only operate 30-40% of the time allowing time for routine maintenance, and 2) as discussed below, provisions for truck unloading should be included in the storage silo - this will allow lime to be unloaded directly into the silo by truck-mounted blowers if one of the rail car unloading blowers is unavailable.

Truck Unloading

Even if rail is to be the principal mode of lime delivery, truck shipments will probably be needed from time to time to compensate for railroad strikes, problems with the rail car unloading system, etc. The storage silo should be fitted with a truck fill pipe as noted in DSD P&ID Sheet 3. If lime delivery by truck is the only mode utilized, two truck fill pipes per silo are recommended. Material, size, and fittings for this pipe are given in the silo/day bin specification (Spec. No. M102) in Appendix E.

If a rail car and truck fill line are connected to a silo, they each will require some way of being isolated. Otherwise, conveying air/lime will discharge from the truck fill pipe when the rail car unloading conveyor is used, and/or the rail car unloading line could become plugged with lime dust when the truck fill pipe is used. The truck fill pipe can be isolated simply by using a cap at the quick coupling at grade. When the truck fill pipe is used, the rail car unloading line should be blanked off to prevent lime dust from possibly filling up and plugging this line. If the truck fill pipe is to be sparingly used, a manual gate in the rail car unloading line is adequate. If the truck fill line is to be used frequently, a pneumatically operated isolation gate in the rail car unloading line would be more appropriate. Regardless of the type of operator, the gate in the rail car unloading line should be located as close as possible to the silo inlet connection. If two truck unloading lines are the only means of filling the silo, each should be furnished with a cap at the quick coupling at grade.

A pneumatic lime truck will hold about 25 tons of pebble quicklime. Because of the truck-mounted blower, the truck is essentially self-unloading, requiring only that the storage silo be equipped with a bin vent filter and pressure relief device. Pebble lime can be blown up to 150

ft vertically and 200 ft combined vertical and horizontal run with the truck-mounted blower. However, it takes almost 2 hr to unload a 25 ton truck against 150 ft of vertical height compared to about 1 hr to unload a truck against 100 ft of vertical height. The intake end of the fill pipe should be mounted vertically, with the bottom about 4 ft above ground. The truck fill pipe should run vertically first, then horizontally. If faster unloading is required, a high capacity truck unloading stationary blower can be installed at grade near the base of the silo. Associated flex hose and truck connection fittings should be included. The truck unloading blower could be operated by plant personnel or the truck operator.

Pebble Lime Silo

Minimum lime storage capacity for a continuously operating facility is generally considered to be either 150% of the normal delivery quantity (e.g., enough capacity to hold 9 rail cars worth of lime if 6 rail cars is the normal delivery) or 7 days of storage at the design lime consumption [injected into the duct(s)], whichever is greater. A bulk density of 55 lb per cu ft may be used for capacity of pebble lime. The straight wall height should be 2.5-4.0 times the silo diameter, and a freeboard (unused volume above the level of a full silo) of 4 ft should be assumed.

Whether to use one or more pebble lime silos depends on the design lime consumption, silo construction economy, and also on silo height. Since pebble lime can be unloaded a maximum of 150 ft vertically using a truck-mounted blower, and allowing 50 ft for the process equipment located underneath the silo cone, the silo straight wall height plus cone height is limited to about 100 ft. At a straight wall height to diameter ratio of 2.5 and a 60° cone angle, the maximum silo diameter is about 32 ft, and the storage capacity (at a bulk density of 55 lb per cu ft) is about 1,800 tons. These calculations assume that the silo freeboard volume is approximately equal to the silo cone volume. Therefore, the approximate silo capacity can be calculated using the total straight wall height and ignoring the cone volume.

Pebble lime tends to form rat holes and craters which can cause arching or bridging in storage. The silo cone angle for pebble lime should be 60° from the horizontal. A bin activator or vibrator is recommended on pebble lime silos to promote flow. The diameter of the hopper outlet to the bin activator should be at least 1/3 the diameter of the silo.

The hopper flow design for the pebble lime silo can be mass flow, expanded flow, or funnel flow as long as the hopper angle is 60°. The pressure relief device on top of the pebble lime silo may be simply a hinged manhole cover or a device designed specifically to relieve pressure at a certain setpoint.

Additional design criteria are contained in the silo/day bin specification and bin activator specification (Spec. No. M104) in Appendix E.

The pebble lime silo dust collector must be sized to filter the transport air from a positive pressure rail car unloading system and/or a truck-mounted blower. Normally, the rail car unloading system will not operate concurrent with the unloading of a truck, so the collector should be sized for the larger flow of the two which is usually the rail car unloading system. If truck unloading is the only means of filling the silo, and two truck fill pipes are installed, the dust collector should be sized for two trucks unloading concurrently (2 @ 800 cfm per truck gives 1,600 cfm). If a vacuum rail car unloading system is employed with the filter receiver located on top of the silo, a dust collector is still required, but it may be much smaller as it only needs to filter the air displaced from the silo as it fills with lime and/or filter the

conveying air from a truck-mounted blower. In this case, the air from a truck-mounted blower (about 800 cfm) is used to size the dust collector.

The use of an exhaust fan on the dust collector is optional. However, the slight negative pressure in the silo air space, created by the exhaust fan, will result in air in-leakage through any small openings in the silo roof instead of lime dust out-leakage, and it will minimize the possibility of lime dust filling and plugging an idle silo fill line. For silos/bins located indoors, an exhaust fan is normally used to blow the air exiting the dust collector outside of the building.

The outlet dust loading from the dust collector is often specified by the State or local regulatory agency with jurisdiction. With no other guidance, a removal efficiency of 99.9% should be specified.

Other design criteria for the dust collector are contained in the bin vent dust collector specification (Spec. No. M103) in Appendix E.

If more than one silo is required to achieve the 7 days of storage capacity, a rotary vane feeder would be attached to each silo cone. The feeders would discharge to a common screw conveyor. The flow from each silo would be controlled either by blending the flows together or by total flow from each silo in sequence. The common screw conveyor would feed a hopper or bin (probably requiring a bucket elevator); the hopper or bin would discharge to the downstream process equipment. If only one silo is used (as shown in DSD P&ID Sheet 3), the silo would discharge directly to the downstream process equipment.

Both a pebble lime silo and day bin are shown in the DSD P&IDs (Sheet 3). This equipment arrangement reflects a conservative configuration in which the silo has to be located relatively far away from the injection ductwork due to rail car unloading or other site-specific constraints. For this equipment arrangement, it is considered more feasible to pneumatically convey lime from the silo to a small day bin located near the injection point (and have the slurry preparation accomplished close to the injection point) than to prepare the slurry near the remote silo and pump it a long distance to the injection point. This is especially true because a slurry return line to the atomizer feed tank is normally required to keep slurry pipeline velocities high. From a practical standpoint, slurry should be prepared within 200 ft of the point of use. If the silo can be located close to the duct injection point, a separate lime day bin is not required.

If a separate pebble lime day bin is required, a positive pressure transfer conveyor will be required to pneumatically convey the lime from the silo to the day bin. A rotary air lock is attached to the silo cone to feed the lime into the transfer conveyor. The capacity of the rotary air lock/transfer conveyor should be three times the design lime consumption in the duct injection process. That way, a 24 hr capacity day bin can be filled in one shift (likely the day shift).

Typical capacities for a pneumatic transfer conveyor range from 25-40 ton/hr. If the required capacity, as estimated above, is significantly greater than 25-40 ton/hr, one or more of the following will have to be considered: 1) conveying for longer periods of time such as during the evening and/or graveyard shifts, 2) increasing the capacity of the transfer conveying system above 40 ton/hr (through discussions with conveyor suppliers), and 3) the use of two conveying systems to increase total conveying rate.

Typical pneumatic conveying velocities range from 4,000 to 5,000 ft/min for transfer of pebble lime. The air required for conveying the lime is somewhat dependent on conveying distance. For a conveying distance of 100 ft, about 0.10 lb air per lb lime is required compared to 0.15 lb air per lb lime for 400 ft of conveying distance. Blowers are normally rated at just less than 15 psig discharge pressure to stay below the ASME pressure code requirements.

Additional design criteria are contained in the pneumatic transfer/ injection conveyors specification (Spec. No. M105) in Appendix E.

A spare blower for the transfer conveyor is typically not required; only one blower is suggested as shown on DSD P&ID Sheet 3. This is recommended because 1) the blower should only operate 30-40% of the time allowing time for routine maintenance, and 2) as discussed below, provisions for emergency truck unloading should be included in the day bin - this will allow lime to be unloaded directly into the day bin by truck-mounted blowers if the transfer blower is unavailable.

A proven alternative to the dilute-phase transfer system described above is a dense-phase pneumatic conveying system. Dense-phase systems require compressed air, but typically use only 1/10 the air volume of dilute-phase systems. Dense-phase systems are capable of much longer conveying distances.

Pebble Lime Day Bin

The pebble lime day bin should be fitted with a truck fill pipe as noted in DSD P&ID Sheet 3. This will allow truck delivery of pebble lime to the plant in the event there are problems with the silo unloading system, the silo itself, and/or the transfer conveyor from the silo to the day bin. Material, size, and fittings for this pipe are given in the silo/day bin specification in Appendix E.

Since there will be two fill lines to the day bin (from the transfer conveyor and the emergency truck fill pipe), they each will require some way of being isolated. Otherwise, conveying air/lime will discharge from the truck fill pipe when the transfer conveyor is used, and/or the transfer conveying line could become plugged with lime dust when the truck fill pipe is used. Since the truck fill pipe will likely be used only sparingly, it can be isolated simply by using a cap at the quick coupling at grade. A manual gate in the transfer conveying line is adequate; this gate should be located as close as possible to the day bin inlet connection. It should be closed any time truck unloading will be accomplished.

The pebble lime day bin storage capacity should generally be 24 hr worth of pebble lime at the design lime usage. This gives plant maintenance enough time to repair the pneumatic transfer conveyor when it breaks down. A bulk density of 55 lb per cu ft may be used for capacity of pebble lime. The straight wall height should be 2.5-4.0 times the bin diameter, and a freeboard (unused volume above the level of a full bin) of 3 ft should be assumed.

Pebble lime tends to form rat holes and craters which can cause arching or bridging in storage. The day bin cone angle for pebble lime should be 60° from the horizontal. A bin activator or vibrator is recommended on pebble lime day bins to promote flow. The diameter of the hopper outlet to the bin activator should be at least 1/3 the diameter of the bin.

The hopper flow design for the pebble lime day bin can be mass flow, expanded flow, or funnel flow as long as the hopper angle is 60°. The pressure relief device on top of the pebble lime day bin may be simply a hinged manhole cover or a device designed specifically to relieve pressure at a certain setpoint.

Additional design criteria are contained in the silo/day bin specification and bin activator specification in Appendix E.

The pebble lime day bin dust collector must be sized to filter the transport air from the positive pressure transfer conveyor and/or a truck-mounted blower. Normally, the transfer conveyor will not operate concurrent with the unloading of a truck, so the collector should be sized for the larger flow of the two which is usually the transfer conveyor.

The use of an exhaustor fan on the dust collector is optional. However, the slight negative pressure in the bin air space, created by the exhaustor, will result in air in-leakage through any small openings in the bin roof instead of lime dust out-leakage, and it will minimize the possibility of lime dust filling and plugging an idle bin fill line. For silos/bins located indoors, an exhaustor fan is normally used to blow the air exiting the dust collector outside of the building.

The outlet dust loading from the dust collector is often specified by the State or local regulatory agency with jurisdiction. With no other guidance, a removal efficiency of 99.9% should be specified.

Other design criteria for the dust collector are contained in the bin vent dust collector specification.

Slaking Equipment

Although there are a number of ways of metering pebble lime into the slakers, the P&IDs show the lime being discharged from the day bin to two, redundant weigh belt feeders. Each 100% capacity weigh belt feeder feeds a 100% capacity lime slaker. Redundancy is recommended in this equipment due to its historically high maintenance; therefore, two 100% capacity trains are suggested.

The weight belt feeder is a short belt conveyor equipped with a weigh deck which measures the weight of lime carried on a section of the belt. Instrumentation adjusts a vertical gate and the speed of the belt so that only a set weight of material is allowed out of the pebble lime day bin and into the slaker. Weigh belt feeders are suggested in lieu of screw feeders because they are generally more accurate. Good control of the pebble lime and water feed rates to the slaker is required to produce a slurry with the proper characteristics.

The capacity of the weigh belt feeders and slakers should be at least 100% of the design pebble lime usage as adjusted for the lowest available calcium in the pebble lime received. For example, if the suppliers of pebble lime closest to the plant indicate that the range of CaO in their lime is 88-93%, the weigh belt feeders and slakers should be sized for the design CaO required (reference Eq. 3-19 in Section 3.2.2.4) divided by 0.88 to account for the inerts.

The slakers can be operated either continuously, or on a batch basis, depending on plant operating philosophy. If the plant chooses to operate the slakers continuously, or at least several hours each shift, then the capacity of the weigh belts and slakers only needs to equal

the design pebble lime usage as suggested above. If the plant prefers that all of the lime slurry for 24 hr of operation be generated on the day shift (or enough lime slurry for 8 hr of operation be generated in 2 or 3 hr) and stored in the lime slurry storage tank, the capacity of the weigh belts/slakers needs to be three times the design pebble lime usage.

Other design criteria for the weigh belt feeders are contained in the gravimetric feeder specification (Spec. No. M106) in Appendix E.

Three options are given in the P&IDs for slaking the pebble lime: 1) ball mills (Sheet 4A), 2) detention slakers (Sheet 4B), or 3) paste slakers (Sheet 4C).

Ball Mill Slakers

Ball mill slakers operate on the principle of a grinding ball mill (ref. DSD P&ID Sheet 4A). The ball mill slaker consists of a ball mill, an agitated ball mill sump, sump pumps, and a recycle cyclone or screen. Any core or grit which may be in the lime is effectively ground up and its lime value recovered. A separate grit removal system is not required. The lime and water are fed into the ball mill where they are mixed. Iron balls in the mill pulverize the larger particles and produce a finer particle size slurry. The slurry overflows the ball mill discharge into a sump tank that is agitated to keep the slurry in suspension. The slurry is pumped to either a cyclone separator or a vibrating screen where the larger particles are removed and recycled to the ball mill for further grinding. The undersize portion flows to an agitated lime slurry storage tank and then to the process. Because extremely fine grinding is not the primary function of the mill, fewer balls are added to the drum than in a typical grinding application. Only enough balls are added to ensure removal of the layers of unreactive scale which may form on the lime particles and to grind the grit material. The mill drum is sized to provide adequate retention time for the slaking reaction, usually 5-10 min. Typically, the solids content of the lime slurry from a ball mill slaker is 25-30% (specific gravity of 1.18-1.21).

The design solids content of the lime slurry from the ball mill slakers should range from 20-35% (specific gravity of 1.14 - 1.25). A 35% lime slurry is very viscous and is physically the upper limit. All of the non-inert solids in the slurry will be assumed to be in the form of Ca(OH)_2 if a high calcium pebble lime is used. The lime slurry should have 99% passing through 200 mesh and 90% passing through 400 mesh. It is anticipated that grit particles as large as 1/4 in. in size will occasionally discharge from the ball mill. Depending on the percent solids in the discharged lime slurry and on the temperature of the inlet slaking water, the temperature of the lime slurry which will discharge from the ball mill will range from 170-190°F. The pH of the lime slurry will be 12 plus. The chloride range will be the same range as in the slaking water as diluted due to the lime addition.

It is recommended that good quality raw water (less than 500 mg/l of sulfite, sulfate, or bisulfate ions, less than 100 mg/l of chlorides, and less than 1,000 mg/l of total dissolved solids) be used for dilution in the sump as well as for slaking.

The lime slurry which exits the ball mill discharges to a small ball mill sump. This tank gives time for slurry stabilization - for completion of all chemical reactions - before the slurry passes through pumps, small-bore piping, and valves. The storage capacity of this tank should provide a retention time of 5-10 min at the design lime consumption. The slurry from the ball mill is typically diluted in the ball mill sump to 20-25% solids. However, the design solids content of the lime slurry from the ball mill sumps should range from 20-30%.

It is recommended that ball mill slakers be mounted on concrete pedestals at grade - not on elevated floors. The ball mill sump height must be short enough such that the slurry can discharge from the ball mill to the sump by gravity. This requirement adds another criterion for the design and size of the ball mill sumps.

Ball mill sumps should have a minimum of 1-1/2 ft of freeboard (non-wetted wall height). These tanks should be designed such that their wetted wall height is approximately equal to the tank diameter. These tanks are vented to atmosphere, so the design pressure is atmospheric pressure plus the fluid static height. A design temperature at 250°F is adequate. These tanks will likely require personnel protection insulation or other means of protecting personnel because the tank walls will likely exceed 140°F at times. An internal coating or lining is not required.

The agitator in each sump will be required to keep the lime and grit solids in suspension as well as blend the dilution water with the lime slurry from the ball mill discharge. The agitator will be required to achieve complete off-bottom suspension. The agitator must be capable of handling slurries ranging from 20-30% solids.

Two 100%, redundant ball mill sump pumps should be provided per ball mill sump to transfer lime slurry to the lime slurry storage tank. These pumps should be designed to accommodate the 1/4 in. inerts that will be in the lime slurry from the ball mill. The capacity (in gpm) of each pump should be at least 120% of the lime slurry produced by the ball mill slaker, diluted to 20% solids, when the ball mill slaker is operating at its design capacity. The additional 20% capacity is recommended for pump wear and also to provide a minimum recirculation back to the ball mill sump even at design capacity. The pumps must be capable of handling slurries ranging from 20-30% solids. The design head and available NPSH for these pumps will depend on equipment layout.

Lime slurry piping may be unlined schedule 80 carbon steel. The piping should be designed as a loop system with recirculation back to the sump. The piping would be periodically flushed with water to remove any build-up that occurred.

The lime grit screen should have a 20 mesh screen. All slurry solids greater than 20 mesh will be recycled back to the ball mill inlet. The capacity (in gpm) of the lime grit screen should be equal to the capacity of each ball mill sump pump. The grit screen must be capable of handling slurries ranging from 20-30% solids. The slurry should have 99% of the slurry particles passing through 200 mesh. A cyclone classifier with the same design criteria listed above could be used instead of the vibrating screen.

Other design criteria for the ball mill slakers, ball mill sumps, agitators, sump pumps, and lime grit screens are contained in Spec. Nos. M109, M113, M114, M115, and M112, respectively, in Appendix E.

A slaking water heater is recommended to preheat the slaking water during one or more of the following situations: 1) slaker start-up, 2) when the slaking water is very cold resulting in a lime slurry temperature out of the ball mill of less than 170°F, and/or 3) when the lime quality is poor resulting in a lime slurry temperature out of the ball mill of less than 170°F. The slaking water heater will typically be rated for 150 psig saturated auxiliary steam on the shell side. The exchanger should be rated to heat up 100% of the required slaking water flow from 35°F to 120°F when the ball mill slaker is operating at its design capacity.

Detention Slaker

The detention slaker is probably the simplest of the three slakers. It consists of a slaking compartment and a classifier compartment (ref. DSD P&ID Sheet 4B). The slaking section is comprised of a steel tank and an impeller type mixer(s) supported by tank spanning beams. It is designed to promote rapid, intimate contact. The flared tank classifier compartment is connected to the slaker by submerged slurry passage ports. It consists of heavy duty reciprocating rakes or a classifying screw, and a washed grit discharge section. Lime and slaking water are fed into the slaker through openings in the cover. After slaking, the slurry passes into the classifier where it is diluted and grit is settled. The classifier moves the grit up an inclined deck for a final water spray and then to the discharge container. The degritted milk of lime flows into a launder, which spans the classifier, and then to a vibrating grit screen. Slurry is retained in a detention slaker for 10-30 min. Quicklime and water are fed to the slaker in specific proportions. Typically, the ratio is adjusted in order to produce a slurry containing 20-25% solids.

The design solids content of the lime slurry from the detention slakers should range from 20-30%. The optimum water to lime ratio and resulting solids content varies somewhat among vendors' designs. All of the non-inert solids in the slurry will be assumed to be in the form of $\text{Ca}(\text{OH})_2$ if a high calcium pebble lime is used. The lime slurry should have 99% passing through 200 mesh and 90% passing through 400 mesh. It is anticipated that grit particles as large as 1/4 in. in size will occasionally discharge from the detention slaker. Depending on the percent solids in the discharged lime slurry and on the temperature of the inlet slaking water, the temperature of the lime slurry which will discharge from the detention slaker will range from 170-190°F. The pH of the lime slurry will be 12 or greater. The chloride range will be the same range as in the slaking water as diluted due to the lime addition.

It is recommended that good quality raw water (less than 500 mg/l of sulfite, sulfate, or bisulfate ions, less than 100 mg/l of chlorides, and less than 1,000 mg/l of total dissolved solids) be used for dilution in the classifier as well as for slaking.

The detention slakers should optimally be located on an elevated floor. In this arrangement, the slurry which overflows from the slaker flows by gravity through the lime grit screen and into the lime slurry storage tank. No pumping would be required.

The lime grit screen should have a 20 mesh screen. All slurry solids greater than 20 mesh will discharge into the same grit bin as the grit removed in the slaker classifier. The grit bin should be a dumpster capable of being removed through a roll-up door using existing plant equipment. The capacity (in gpm) of the lime grit screen should be equal to the lime slurry produced by the detention slaker, diluted to 20% solids, when the detention slaker is operating at its design capacity. The grit screen must be capable of handling slurries ranging from 20-30% solids. The slurry should have 99% of the slurry particles passing through 200 mesh.

Other design criteria for the detention slakers and lime grit screens are contained in Spec. Nos. M110 and M112, respectively, in Appendix E.

A slaking water heater is recommended to preheat the slaking water during one or more of the following situations: 1) slaker start-up, 2) when the slaking water is very cold resulting in a lime slurry temperature out of the slaker of less than 170°F, and/or 3) when the lime quality is poor resulting in a lime slurry temperature out of the slaker of less than 170°F. The slaking water heater will typically be rated for 150 psig saturated auxiliary steam on the shell

side. The exchanger should be rated to heat up 100% of the required slaking water flow from 35°F to 120°F when the slaker is operating at its design capacity.

Paste Slaker

The paste slaker consists of a slaking compartment with two sets of counter-rotating paddles acting as a pug mill for mixing. Water and quicklime are fed continuously and automatically by a torque-actuated water inlet valve (ref. DSD P&ID Sheet 4C). Increasing torque indicates that the lime paste is too thick so additional water is added to reduce the viscosity of the paste to the desired level. As the paste is discharged over a weir into a dilution compartment, a continuous water spray dilutes the paste to a slurry. The grit settles and moving rakes on the same shaft as the mixing paddles maintain proper agitation of the lime suspension to remove the grit to a classifier for discharge into an external enclosed elevator. The slurry then flows over a weir and out the discharge port. The grit is washed free of lime in the elevator, and the recovered lime water is returned to the dilution chamber. The washed grit exits the elevator into the discharge container. Slurry is retained in a paste slaker for about 5 to 10 min. Quicklime and water are fed to the slaker at a 2:1 ratio resulting in about a 44% solids paste. In the dilution compartment, the paste is typically diluted to 20-25% solids.

The design solids content of the lime slurry from the paste slakers should range from 20-30%. The optimum water to lime ratio and resulting solids content varies somewhat among vendors' designs. All of the non-inert solids in the slurry will be assumed to be in the form of Ca(OH)_2 if a high calcium pebble lime is used. The lime slurry should have 99% passing through 200 mesh and 90% passing through 400 mesh. It is anticipated that grit particles as large as 1/4 in. in size will occasionally discharge from the paste slaker. Depending on the percent solids in the discharged lime slurry and on the temperature of the inlet slaking water, the temperature of the lime slurry which will discharge from the paste slaker will range from 170-190°F. The pH of the lime slurry will be 12 or greater. The chloride range will be the same range as in the slaking water as diluted due to the lime addition.

It is recommended that good quality raw water (less than 500 mg/l of sulfite, sulfate, or bisulfate, less than 100 mg/l of chlorides, and less than 1,000 mg/l of total dissolved solids) be used for dilution in the dilution compartment as well as for slaking.

The paste slakers should optimally be located on an elevated floor. In this arrangement, the slurry which overflows from the slaker flows by gravity through the lime grit screen and into the lime slurry storage tank. No pumping would be required.

The lime grit screen should have a 20 mesh screen. All slurry solids greater than 20 mesh will discharge into the same grit bin as the grit removed in the slaker classifier. The grit bin should be a dumpster capable of being removed through a roll-up door using existing plant equipment. The capacity (in gpm) of the lime grit screen should be equal to the lime slurry produced by the paste slaker, diluted to 20% solids, when the paste slaker is operating at its design capacity. The grit screen must be capable of handling slurries ranging from 20-30% solids. The slurry should have 99% of the slurry particles passing through 200 mesh.

Other design criteria for the paste slakers and lime grit screens are contained in Spec. Nos. M111 and M112, respectively, in Appendix E.

A slaking water heater is recommended to preheat the slaking water during one or more of the following situations: 1) slaker start-up, 2) when the slaking water is very cold resulting in a lime slurry temperature out of the slaker of less than 170°F, and/or 3) when the lime quality is poor resulting in a lime slurry temperature out of the slaker of less than 170°F. The slaking water heater will typically be rated for 150 psig saturated auxiliary steam on the shell side. The exchanger should be rated to heat up 100% of the required slaking water flow from 35°F to 120°F when the slaker is operating at its design capacity.

Choosing a Slaker

All three slakers described above have advantages and disadvantages. The discussion which follows will give the user some basis for choosing the slaker type to be used in a specific application. The best basis for making such a decision is on previous plant experience with one or more of the slaker types. Barring that, the discussion below (paraphrased from EPRI's Lime FGD Systems Data Book, 2nd ed., EPRI CS-2781, January 1983) may be useful.

The range of slaking conditions is limited in any type of slaker by the occurrence of drowning or burning conditions that produce low-quality slurry. Drowning is caused by the presence of too much water in proportion to lime and is indicated by a sharp drop in slaking temperature when the flow of water is increased slightly. The result is that the calcium hydroxide being produced adheres to the quicklime particles. Each quicklime particle is surrounded by a layer of relatively impervious and unreactive calcium hydroxide. Because of its grinding action, ball mill slakers are less susceptible to this type of problem than detention or paste slakers. At the other extreme, burning also produces particles of unreacted quicklime surrounded by a hard impervious layer of hydrate. In burning, insufficient water causes localized overheating at the surface of the quicklime particles. The very high temperatures that develop cause formation of unreactive oxide and hydrate crystals. Burning usually produces steam, which removes water from the mixture and causes a further increase in temperature when the flow of slaking water is decreased slightly. If not controlled, it will cause serious overheating that may damage the equipment.

A detention or paste slaker must include provisions for removing grit from the slurry. Grit consists of sand and similar impurities, plus the carbonate cores of quicklime pebbles that were not calcined during lime manufacture. Good-quality quicklime contains 1 to 2% grit; poor grades may contain up to 5%. The grit is usually discarded in a sludge pond or land fill. Grit particles that remain in the slurry cause abrasive damage to slurry handling equipment. Properly slaked slurry of pure hydrated lime can be considered nonabrasive, since the lime particles are soft, lightweight solids that do not scratch or erode metals. Ball mill slakers grind the grit to a fine size and do not produce a separate grit stream. The finely ground grit particles are included in the slaked lime slurry. The lime slurry from a ball mill may be somewhat abrasive.

None of these slaker types have proved superior for all applications. Each type offers certain advantages. Characteristics of these slakers are listed in Table 6-4.

Both high slaking temperature and long retention time are required to slake some poor quality grades of quicklime. It is uneconomical to slake poor quality quicklime with paste slakers if it is necessary to operate several slakers at reduced capacity in order to provide adequate retention time. In a detention slaker, poor quality quicklime can be processed by heating the feed water, thereby providing both high temperature and longer retention time. Preheated water can also be used with a paste slaker, but the technique is less effective since the lower

TABLE 6-4
SLAKER CHARACTERISTICS

CHARACTERISTICS	BALL MILL SLAKER	DETENTION SLAKER	PASTE SLAKER
Size of equipment for equal capacity	Smallest for large capacity	Large equipment	Intermediate equipment
Capacity of available equipment	Can be built in any capacity	Can be built in any capacity	Available only in standard capacities, limited to about 8,000 lb quicklime/hr
Quality of quicklime	High quality or poor quality quicklime	High quality or medium quality quicklime	High quality quicklime
Lime size range	Can handle any size which can be handled by feeder	Can handle any size up to 2 in. lumps	Should be limited to particles smaller than 3/4 in.
Mechanical complexity	Moderately complex	Very simple	Moderately complex
Water-to-lime ratio	Needs less slaking water	Needs more slaking water	Needs less slaking water
Slurry quality	Smaller particles	Larger particles	Usually slightly smaller particles
Initial cost of equipment of equal capacity	Intermediate cost	Least cost	Highest cost

water-to-lime ratio limits the amount of preheat that can be used without causing burning. Ball mill slakers can economically slake poor quality quicklime by proper sizing of the reaction time. Preheating the slaking water would be beneficial but is not required.

Slakers must be ventilated to prevent condensation of vapor inside the weigh belt feeder. If the vapor is not allowed to escape, it condenses and reacts with lime dust to form hard deposits on the feeder surface. A slaker ventilation system must remove the hot, humid air. However, it should also be designed to prevent discharge of lime dust into the atmosphere. A ventilation system is shown for all of the slakers in the DSD P&IDs. A water operated eductor is shown that uses a portion of the dilution water to exhaust a small amount of air from the slaking chamber.

When quicklime is slaked in either a detention or a paste slaker, the quality of the resulting lime slurry is affected by the slaking water used. Impurities reduce the slaking rate and cause the production of large, dense particles of partially hydrated lime. The slurry may be more abrasive, thereby increasing the maintenance requirement for the system. As discussed earlier, ball mill slakers are less sensitive to water quality because the grinding action removes the coatings on the lime particles.

Reagent Storage and Injection Equipment

Regardless of which slaking method is employed, the lime slurry is stored in an agitated lime slurry storage tank (reference DSD P&ID Sheet 5). Only one tank is recommended to keep capital costs low and because of the historically high availability of such tanks. Two tanks would be recommended for increased reliability if adequate space and capital are available. The pump cross-ties and control system for two, redundant tanks, however, are complex.

This tank gives time for slurry stabilization - for completion of all chemical reactions - before the slurry passes through pumps, small-bore piping, and valves. The storage capacity of this tank should be either 8 or 24 hr worth of lime slurry at the design lime usage. The decision to select 8 or 24 hr of capacity is based on whether the slakers will be operated only during the day shift or during all shifts as discussed above. Another consideration in deciding on the number of hours of lime storage is the size of the resulting lime slurry tank.

Slurry storage tanks generally are 20 ft or less in diameter. Although slurry tanks larger than 20 ft in diameter have been used (up to 42 ft in diameter), they tend to be harder to agitate and keep clean. The space requirements of larger tanks can also be a problem in retrofit situations. Typically, the solids content of the lime slurry will vary from 20-25%. However, the design solids content of the lime slurry should range from 20-30%.

The lime slurry storage tank should have a minimum of 3 ft of freeboard (non-wetted wall height). This tank should be designed such that its wetted wall height is approximately equal to the tank diameter. This tank is vented to atmosphere, so the design pressure is atmospheric pressure plus the fluid static height. A design temperature of 250°F is adequate. This tank will likely require personnel protection insulation or other means of protecting personnel because the tank walls will likely exceed 140°F at times. An internal coating or lining is not required.

The lime slurry storage tank agitator will be required to keep the lime solids (and ground grit if a ball mill slaker is used) in suspension. The agitator will be required to achieve complete off-bottom suspension. The agitator must be capable of handling slurries ranging from 20-30% solids.

Two 100%, redundant lime slurry pumps should be provided to transfer lime slurry to the atomizer feed tank. These pumps should pump only screened slurry with a maximum particle size of 20 mesh. The capacity (in gpm) of each pump should be at least 120% of the design lime slurry consumption required for injection into the duct(s), diluted to 20% solids. The additional 20% capacity is recommended for pump wear and also to provide a minimum recirculation back to the lime slurry storage tank even at design capacity. The pumps must be capable of handling slurries ranging from 20-30% solids. The design head and available NPSH for these pumps will depend on equipment layout.

Lime slurry piping may be unlined schedule 80 carbon steel. The piping should be designed as a loop system with recirculation back to the storage tank so that flow to the atomizer feed tank can vary from minimum to maximum flow and still maintain enough velocity in the piping to minimize lime build-up inside the pipes. The piping would be periodically flushed with water to remove any build-up that occurred.

The lime slurry is pumped to an agitated atomizer feed tank. Only one tank is recommended to keep capital costs low and because of the historically high availability of such tanks. Two tanks would be recommended for increased reliability if adequate space and capital are available. The pump cross-ties and control system for two redundant tanks however, is complex.

This tank mixes the lime slurry, recycle slurry, and (possibly) dilution water before injection into the ductwork. The storage capacity of this tank must be small in order to allow rapid changes in slurry concentration as fluctuations in sulfur dioxide occur. A capacity of 30 min at the design lime consumption, at 40% feed solids content, plus design water required for cooling the flue gas to a 20°F approach to saturation is recommended. Typically, the solids content of the feed slurry will vary from 30-40% (specific gravity of 1.21 - 1.29). However, the solids content could be as low as 20% (specific gravity of 1.14) with lime slurry only when the recycle system is unavailable.

The atomizer feed tank should have a minimum of 1-1/2 ft of freeboard (non-wetted wall height). This tank should be designed such that its wetted wall height is approximately equal to the tank diameter. This tank is vented to atmosphere, so the design pressure is atmospheric pressure plus the fluid static height. A design temperature of 200°F is adequate. No personnel protection is necessary on this tank. An internal coating or lining is not required.

The atomizer feed tank agitator will be required to keep the solids in suspension as well as blend the lime slurry, recycle slurry, and dilution water. The agitator will be required to achieve complete off-bottom suspension. The agitator must be capable of handling slurries ranging from 20% (lime slurry only) to 40% (lime plus recycle slurry) solids.

Two 100%, redundant atomizer feed pumps should be provided to pump the feed slurry from the feed tank to the atomizers at the required pressure. These pumps should pump only screened slurry with a maximum particle size of 20 mesh. The capacity (in gpm) of each pump should be at least 120% of the design lime consumption, at 40% feed solids content, plus design water required for cooling the flue gas to a 20°F approach to saturation. The additional 20% capacity is recommended for pump wear and also to provide a minimum recirculation back to the atomizer feed tank even at design capacity. The pumps must be capable of handling slurries ranging from 20% to 40% solids. The design head and available NPSH for these pumps will depend on equipment layout and required slurry pressure at the atomizers.

Feed slurry piping may be unlined schedule 80 carbon steel. The piping should be designed as a loop system with recirculation back to the feed tank so that flow to the atomizers can vary from minimum to maximum flow and still maintain enough velocity in the piping to minimize build up inside the pipes. The piping would be periodically flushed with water to remove any build-up that occurred.

Other design criteria for the lime slurry and atomizer feed tanks, agitators, slurry pumps, and slurry valves are contained in Spec. Nos. M113, M114, M115, and M116, respectively, in Appendix E.

6.2 Humidification/Sorbent Injection System

6.2.1 Dry Sorbent Injection

In DSI, separate injection of the dry hydrated lime sorbent and humidification water are required. The humidification water is sprayed into the ductwork utilizing some kind of atomizer. At the time of publication of this handbook, dual-fluid nozzles have been developed for spraying the humidification water in DSI processes more extensively than rotary atomizers. In addition, the 180° spray angle of rotary atomizers will be too large for most retrofit applications. Therefore, only dual-fluid nozzles are discussed in detail in this handbook. The hydrated lime sorbent is injected into the ductwork via injector pipes. The design and placement of both the humidification nozzles and sorbent injectors are discussed below and in Topical Report 8, Atomizer Specifications for Duct Injection Technology by Babcock & Wilcox.

6.2.1.1 Humidification Nozzle Design

Nozzles used for humidifying the flue gas are among the most critical components in a DSI process. Poor performance of the nozzles can lead to wall wetting, wet solids deposition, and frequent and costly equipment maintenance and downtime. Atomizer capacity, performance, and arrangement are critical in eliminating material deposition while maximizing SO₂ capture.

Nozzle Droplet Size

For successful duct injection of humidification water, the nozzles must be capable of providing a spray in which the largest droplets formed in the atomization process are sufficiently small to completely evaporate in the available residence time. The droplet size of the atomized sprays is a key parameter for a successful DSI application.

The largest acceptable drop sizes can be estimated based on the available gas residence time, the inlet flue gas temperature, and the approach to saturation temperature. For in-duct atomization of humidification water in applications with less than 1 sec of residence time, the amount of spray mass above 100 microns should be limited to 1% or less, and the mass percent of droplets over 80 microns should be limited to less than 5% so that complete dryout of the droplets is attained. The Sauter Mean Diameter (defined as the diameter of a droplet whose surface-to-volume ratio is the same as that of the entire spray) of a spray that meets the above large droplet criteria will generally be less than 25 microns.

Nozzle Air Consumption

Each commercially available dual-fluid nozzle will require a certain amount and pressure of compressed air to produce the water droplet size distribution consistent with available residence time. The compressed air requirements may vary considerably among commercially available nozzles. Droplet size is the desired product of atomization, while the air-to-water mass ratio required to generate the drop size distribution is a measure of the cost. For dual-fluid nozzles, the air-to-water ratio is the most important parameter affecting droplet size. For a given type of dual-fluid nozzle, droplet size is inversely proportional to air-to-water ratio. An estimate of the maximum acceptable air-to-water ratio is 0.5 lb air/lb water.

Given the high costs to produce the quantities of compressed air required for duct injection applications, it is beneficial to operate at the lowest possible air-to-water ratio. A comparison of available nozzles based on the compressed air consumption alone, however, does not

account for differences in required atomizing air pressure; required air pressure also affects the cost of the compressed air. Commercially available nozzles have operating air pressures that range from 60 to 120 psig. Nozzles should be selected based on a power consumption analysis: which nozzle produces the required drop size distribution at the lowest total power consumption (considering the quantity and pressure of the required compressed air).

Nozzle Liquid Capacity

The liquid capacity required for a specific duct injection application is determined based on the flue gas flow rate and temperature and on the desired approach to saturation temperature. The liquid capacities of nozzles providing acceptable atomization (in terms of producing a spray with sufficient fineness as noted above) are usually small--on the order of 0.08-2.0 gpm.

The results of past and on-going projects indicate that multiple small nozzles perform better than fewer, larger nozzles even when the droplet size distribution is the same for both cases. This appears to be the result of small nozzles causing less disturbance to the gas flow. Also, many smaller nozzles promote better initial mixing between the droplets and the flue gas. However, all of the projects to date have used a trial and error approach to specify the number and capacity of nozzles in the array. At this time, the only known methodology for specifying the nozzle capacity and the geometry of the nozzle array is detailed numerical or physical modeling.

Droplet Trajectory/Spray Angle

Nozzles of different designs provide sprays with widely varying spray patterns and droplet trajectories. Droplet trajectory influences nozzle performance because the initial direction of the high velocity spray can result in direct impingement of liquid on internal surfaces. In contrast, it is imperative that the spray adequately mix with the surrounding flue gas so that complete drying of the droplets can occur in the limited time available. Better performance has been achieved in tests with nozzles that provide a spray trajectory with a smaller included spray angle. Nozzles with a single discharge hole or with multiple holes oriented with a small included angle have achieved the highest success.

The maximum tolerable spray angle for a given DSI application will depend on the clearances between the nozzles and the walls. In the flue region close to the nozzle plane, droplet trajectory and spray angle may determine the available residence time for evaporation. Narrow spray angles are important for humidification in ducts with small cross sections or for arrays with close wall clearances. Spray angle is not a "stand-alone" parameter; successful humidification and sorbent injection without deposition in the near field will depend on wall clearances as well as spray angle. Further downstream of the nozzle plane, wall deposition is more likely to be a function of turbulence rather than direct impingement.

A lower limit in spray angle is about 14° which represents the expansion of a free jet. A 30° spray angle is a maximum.

Nozzle Hydraulic Characteristics

For successful DSI, uniform profiles of temperature and velocity across the duct cross section have been shown to be important. Likewise, the mass flux of injected water must be uniform across the duct cross section. A poor distribution of gas temperature, gas velocity, and/or

liquid mass flux (as droplets) will result in localized regions of saturated gas that can lead to wetting and solids deposition. Several factors influence the ability to control the droplet size and water flow distribution over the duct cross section. These factors include the sensitivity of individual nozzles to changes in operating water and/or air pressure, the nozzle-to-nozzle uniformity in operating characteristics, and the effect of variable water pressure with vertical elevation in the duct.

The pressure-flow characteristics of a single nozzle or an array of just a few nozzles are usually not critical because it is possible to monitor and control the air and water flow rates to each individual nozzle. With a large array of nozzles, however, individual control of flow to each nozzle is not practical. Rather, multiple nozzles are manifolded into a parallel array and controlled from a single source of air and water. The control of flow is to the manifold, and the flow to the individual nozzles is dependent on the water pressure distribution in the manifold and the pressure-flow characteristics of the individual nozzles. The uniformity of flow across an array will, in part, depend on the sensitivity of each individual nozzle to water pressure at the nozzle inlet.

A measure of nozzle sensitivity is the change in water flow that results from a change in water pressure at a constant air pressure. This change is the slope of the water flow-water pressure curve. The more sensitive the nozzles (or steeper the slope), the more likely a nozzle array will have flow maldistribution during normal process variations. Acceptable sensitivity will depend on both the geometry of the manifold and the type of process control. For large arrays of nozzles, an estimate of maximum acceptable nozzle sensitivity is 5% or less change in water flow per psi change in water pressure at full load.

If the sensitivity of a candidate nozzle is unacceptably high, then it can be modified by increasing the liquid flow resistance between the nozzle and the manifold. One method for increasing the hydraulic resistance is to install one or more orifices immediately upstream of the nozzle. It is important that the addition of orifices does not change the spray droplet size distribution.

Another factor that will affect the uniformity of the mass flux and droplet size distribution across the duct is the part-to-part uniformity of the nozzles. Arrays of nozzles require good part-to-part uniformity in hydraulic and droplet size distribution characteristics. Since a large number of nozzles will be controlled by a single source of air and liquid, if the pressure-flow characteristics of the nozzles are not identical, the water flow to each nozzle could be substantially different. Variations in air or water flow can affect the droplet size distribution because of the effect these variations will have on air-to-water ratio. Nozzle-to-nozzle variability can arise solely from slight differences in the size, shape, angle, and location of the holes in the components that make up the nozzle.

The third factor that affects the duct cross-sectional mass flux and droplet size uniformity is the differences in vertical location of nozzles in large arrays. Nozzles in a duct that are located at different elevations and are supplied by a common water source are subject to flow maldistributions. The maldistribution is caused by variations in the static pressure in the water lines. The nozzles at lower elevations will "see" a higher supply pressure and flow rate than nozzles at upper elevations.

One solution to this potential elevational flow maldistribution is to measure and control the water flow to each level of nozzles in an array. For arrays with a large number of nozzles, this approach could require a multitude of flow meters and control valves in an active control loop.

This type of scheme is susceptible to flow instabilities and is costly and complex. Passive control with simple instrumentation is more desirable. Based on the operating characteristics of internal mix, dual-fluid nozzles, the effect of variable water pressure on flow rate can be offset with air pressure that also varies with height. This type of solution will require knowledge of the pressure-flow characteristics of the nozzles in a given array.

Materials of Construction and Wear

Wear, corrosion, deposition, and pluggage of individual nozzles in an array can lead to degradations in flow characteristics. Stainless steel (316) humidification nozzles will wear due to erosion caused by the air and water. Replaceable, hardened inserts for the high wear areas are recommended. To minimize wear in humidification nozzles, the materials of construction should be stainless steel 316 or better with ceramic or silicon carbide inserts at the wear points. The wear points are typically the mixing points of the water and compressed air and the discharge points from the nozzle.

Corrosion may occur when sulfurous and chlorine constituents of the flue gas condense on exposed metal surfaces. Low-grade stainless steel (304) has been found to corrode in duct injection environments. For corrosion protection, nozzles fabricated from 316 stainless steel (minimum) are recommended.

Another factor that can negatively influence nozzle performance is build-up of material on the nozzles themselves. Condensation of moisture on the relatively cold nozzles become sites for solids in the flue gas (sorber plus fly ash) to adhere. Flow patterns within the duct may also deposit material on the nozzle tips. Turbulent eddies or recirculation zones may force solids to the wet surfaces of the nozzles. Material build-up on the nozzle tip can alter the spray pattern, partially or completely plug a nozzle, and cause dripping. A recommended method to reduce deposition on the nozzle tip is through the use of shielding devices (reference Figure 6-1). The nozzles should be installed within shields. Air lances and/or rappers may also be installed to control deposition on the nozzle and manifold surfaces (also reference Section 6.3.3).

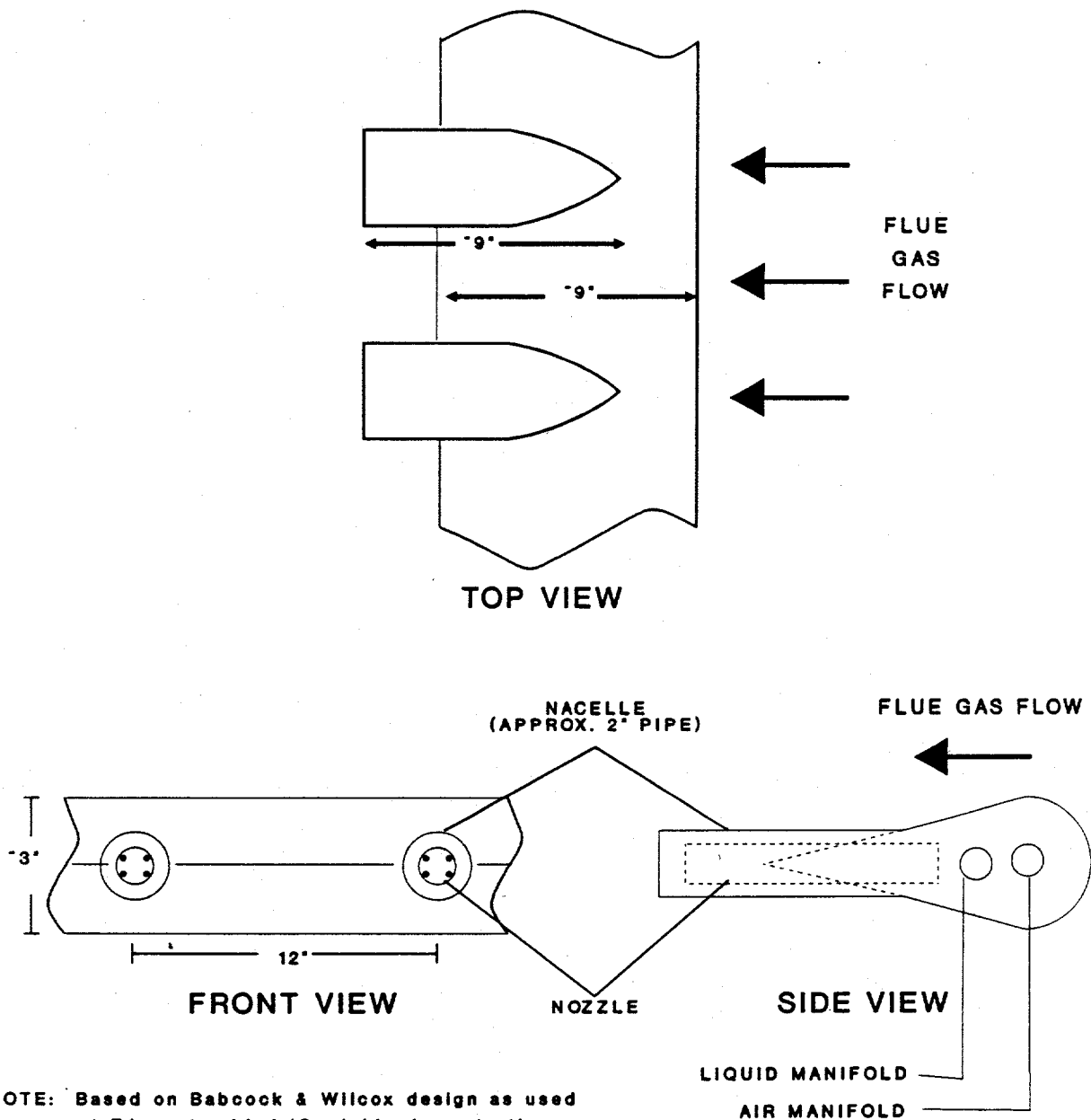
Pluggage of the internal air and/or water passages of nozzles by solids in the humidification water and compressed air may be a problem. If the water quality is questionable (containing high suspended solids, a filtering system should be provided (reference Section 6.6.1). The compressed air should be filtered before entering the manifolds. Nozzles with very small diameter internal passages should not be used.

6.2.1.2 Humidification Nozzle Placement

The humidification nozzle headers should be aerodynamic (in the form of an airfoil) to reduce build-up on the upstream edge of surfaces.

The most successful duct injection projects have utilized arrays (totaling 10 to 100 nozzles) of small capacity nozzles to achieve atomization with acceptable amounts of deposition. The geometry of nozzle arrays that provides good performance without deposition is difficult to determine without detailed modeling. Required nozzle-to-nozzle spacing and wall clearance will, in part, be a function of nozzle capacity and spray angle. Suggested clearances are 1 ft between nozzles (both horizontally and vertically) and 2 ft between the outer-most nozzles and the duct walls and ceiling. For horizontal ducts, the spacing between the lower-most nozzles and duct floor should be about 3 ft.

FIGURE 6-1
SHIELDING NOZZLES
IN AN AERODYNAMIC MANIFOLD



NOTE: Based on Babcock & Wilcox design as used at Edgewater Limb/Coolside demonstration.

Nozzle alignment can have a significant effect on humidification and sorbent injection performance. Nozzles placed in a duct, whether singly or in a multi-nozzle array, must be aligned so as to prevent jet impingement on the duct walls, minimize ash deposition on the nozzles, and maximize the mixing between the spray and the flue gas. Nozzle alignment will be somewhat specific to the application, and will depend on the spray angle of the nozzle and the distance from the wall. However, the required wall clearance may be reduced by tilting the nozzles closest to the walls inward by 2-5°.

6.2.1.3 Sorbent Injector Design

The dry sorbent injector designs fall in two basic categories:

1. Cross Duct Lances
2. Parallel Flow Injectors

Cross Duct Lances

The cross duct lances consist of several pipes that extend the full width (or height) of the flue duct. There are holes in the pipes that disperse the sorbent parallel to the gas stream (reference Figure 6-2).

Cross duct lances typically consist of 6 in. pipes connected to a header. Each pipe is drilled with 2-3 in. diameter injection nozzles (holes) spaced every 3 ft along the pipe. The nozzles point downstream, concurrent with the direction of flue gas flow.

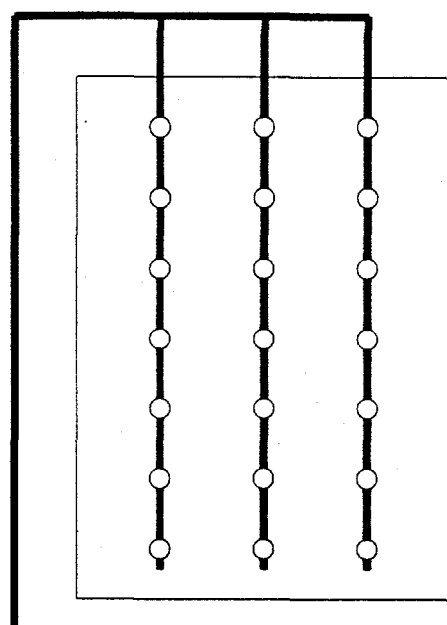
Due to the geometry of the injection system, vertical pipes tend to fill from the bottom with settled reagent. As the level increases, the lower injection nozzles along the pipe would become obscured and rendered inoperative. Therefore, horizontally-oriented pipes are recommended.

Cross duct lances give good dispersion with low conveying pressure. The main concerns with this type of injector are that the lances cause a significant obstruction to the gas flow and that pluggage of the holes is possible.

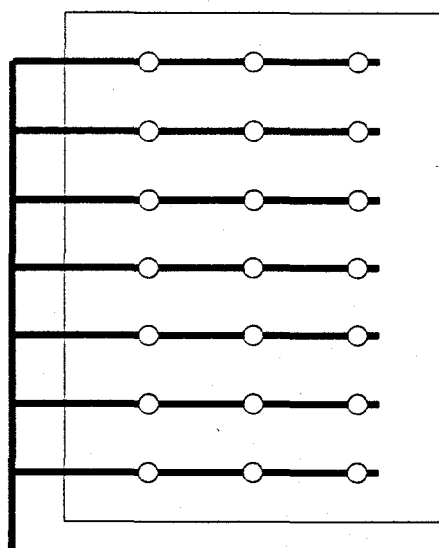
Parallel Flow Injectors

An alternative to the cross duct lances is a series of single point parallel flow injectors. Each injector would consist of a 1 ½ - 2 in. diameter pipe installed across the duct cross section. The pipes would enter from the top of the duct (for horizontal ducts) and are of varying length. Each pipe ends in an elbow that turns the sorbent stream so that it is injected parallel to the gas flow (Figure 6-3). The pipes would be spaced about 3 ft apart horizontally and would be of varying lengths so that the vertical spacing (for horizontal ducts) is also about 3 ft. The pneumatic blower system used to transport the fresh sorbent (and recycle material) should be designed to produce velocities of 40-80 ft/sec at the injector outlet.

Recycle material injection may be used to reduce fresh lime consumption (reference section 6.4.1). Although combining the recycle material with the fresh sorbent would likely result in the best distribution within the duct, this is not recommended so as to preserve operation if the recycle system is not available.



VERTICAL LANCES



HORIZONTAL LANCES

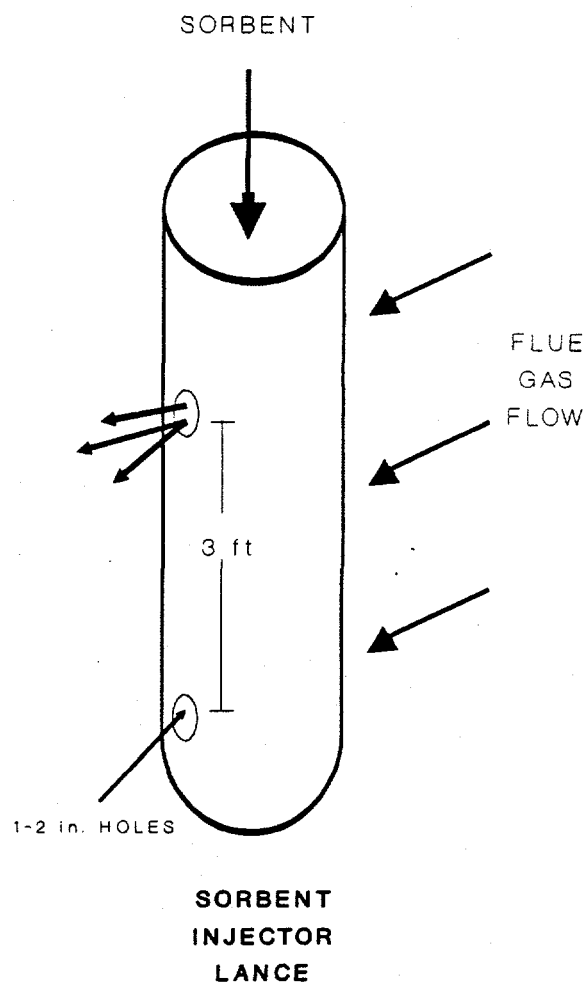


FIGURE 6-2
CROSS DUCT INJECTION LANCE DESIGN

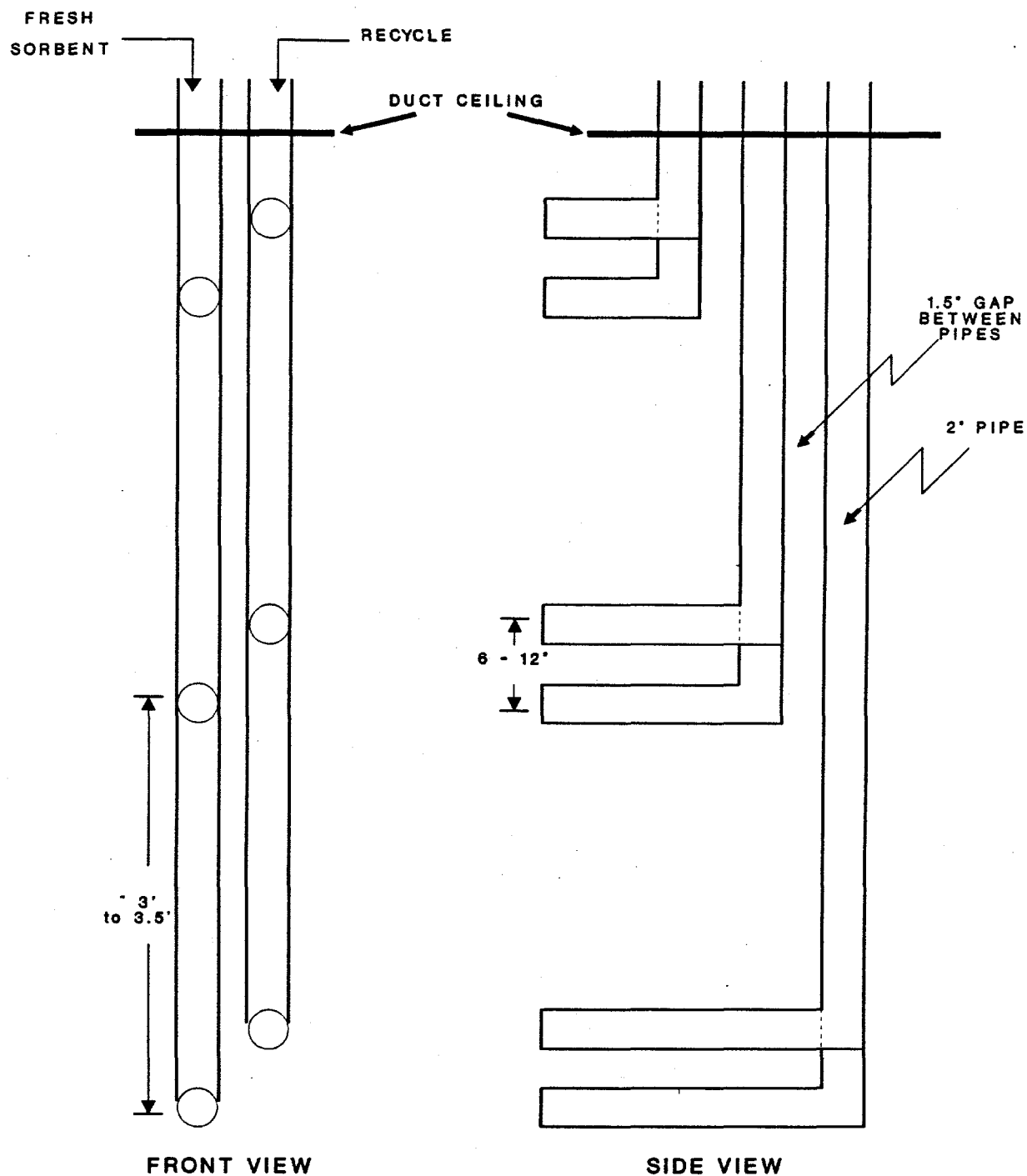


FIGURE 6-3
PARALLEL FLOW INJECTOR DESIGN

6.2.1.4 Sorbent Injector Placement

In DSI, the hydrated lime must be dispersed in such a manner as to obtain rapid mixing, uniform distribution, and maximum utilization of the sorbent. The location of the sorbent injectors within the existing ductwork is critical for two major reasons. First, adequate retention time is required for SO_2 removal by the hydrate before the gas enters the ESP. Second, proper mixing and distribution of the sorbent across the duct cross section is required to promote optimum SO_2 removal and minimize wall deposition. The sorbent injection point should be in a straight duct section for proper mixing and distribution, and it should be upstream of the ESP as far as possible to maximize retention time.

Operation with sorbent injection downstream of humidification may result in significant build-up of fly ash on duct walls just downstream of the humidification nozzle array. In addition, severe corrosion to the sorbent and ductwork immediately downstream of the water nozzles may result due to high levels of SO_3 in the humidified flue gas.

In upstream sorbent injection, sorbent particles come in direct contact with, and are encapsulated by, water droplets sprayed into the duct downstream of the sorbent injection point (scavenging), and the sorbent utilization is significantly higher. It is believed that wall wetting deposition problems will not be severe in the full-scale duct since the humidification nozzles can be adequately spaced. In addition, corrosion potential is reduced because, with upstream sorbent injection, the alkaline sorbent will remove most of the SO_3 before it contacts the humidification section.

Upstream hydrate injection is decidedly more beneficial from an SO_2 removal standpoint than downstream injection. Therefore, sorbents should be injected upstream of, or in the same plane as, the humidification water. Injection of the sorbent in the coplanar configuration minimizes the build-up of sorbent on the upstream edge of the nozzle array. Also, there is some indication that coplanar injection results in entrainment of the dry sorbent and flue gas by the high velocity atomization air which may help distribute the dry sorbent more evenly throughout the duct cross section. Therefore, it is recommended that the sorbent injection system be located in the same plane as the humidification system.

If used, each recycle injector would be located about 6 in. to 1 ft away from its corresponding fresh sorbent injector.

6.2.2 Duct Spray Drying

For DSD, the lime reagent, humidification water, and recycle material are mixed together before injection into the duct. The resulting slurry is sprayed into the ductwork utilizing some kind of atomizer. At the time of publication of this handbook, dual-fluid nozzles have been developed for spraying the slurry in DSD processes more extensively than rotary atomizers. In addition, the 180° spray angle of rotary atomizers will be too large for most retrofit applications. Therefore, only dual-fluid nozzles are discussed in detail in this handbook. The design and placement of the slurry nozzles are discussed below.

6.2.2.1 Slurry Nozzle Design

Nozzles used for spraying slurry are among the most critical components in a DSD process. Poor performance of the nozzles can lead to wall wetting, wet solids deposition, and frequent and costly equipment maintenance and downtime. Atomizer capacity, performance, and arrangement are critical in eliminating material deposition while maximizing SO_2 capture.

Nozzle Droplet Size

For successful duct injection of slurry, the nozzles must be capable of providing a spray in which the largest droplets formed in the atomization process are sufficiently small to almost completely dry in the available residence time. The droplet size of the atomized sprays is a key parameter for a successful DSD application.

The largest acceptable drop sizes can be estimated based on the available gas residence time, the inlet flue gas temperature, and the approach to saturation temperature. For in-duct atomization of slurry in applications with less than 1 sec of residence time, the amount of spray mass above 100 microns should be limited to 1% or less, and the mass percent of droplets over 80 microns should be limited to less than 5% so that complete dryout of the droplets is attained. The Sauter Mean Diameter (defined as the diameter of a droplet whose surface-to-volume ratio is the same as that of the entire spray) of a spray that meets the above large droplet criteria will generally be less than 25 microns.

Nozzle Air Consumption

Each commercially available dual-fluid nozzle will require a certain amount and pressure of compressed air to produce the slurry droplet size distribution consistent with available residence time. The compressed air requirements may vary considerably among commercially available nozzles. Droplet size is the desired product of atomization, while the air-to-slurry mass ratio required to generate the drop size distribution is a measure of the cost. For dual-fluid nozzles, the air-to-slurry ratio is the most important parameter affecting droplet size. For a given type of dual-fluid nozzle, droplet size is inversely proportional to air-to-slurry ratio. An estimate of the maximum acceptable air-to-slurry ratio is 0.5 lb air/lb slurry.

Given the high costs to produce the quantities of compressed air required for duct injection applications, it is beneficial to operate at the lowest possible air-to-slurry ratio. A comparison of available nozzles based on the compressed air consumption alone, however, does not account for differences in required atomizing air pressure; required air pressure also affects the cost of the compressed air. Commercially available nozzles have operating air pressures that range from 60 to 120 psig. Nozzles should be selected based on a power consumption analysis: which nozzle produces the required drop size distribution at the lowest total power consumption (considering the quantity and pressure of the required compressed air).

Nozzle Liquid Capacity

The liquid capacity required for a specific duct injection application is determined based on the flue gas flow rate and temperature and on the desired approach to saturation temperature. The liquid capacities of nozzles providing acceptable atomization (in terms of producing a spray with sufficient fineness as noted above) are usually small--on the order of 0.08-2.0 gpm.

The results of past and on-going projects indicate that multiple small nozzles perform better than fewer, larger nozzles even when the droplet size distribution is the same for both cases. This appears to be the result of small nozzles causing less disturbance to the gas flow. Also, many smaller nozzles promote better initial mixing between the droplets and the flue gas. However, all of the projects to date have used a trial and error approach to specify the number and capacity of nozzles in the array. At this time, the only known methodology for specifying the nozzle capacity and the geometry of the nozzle array is detailed numerical or physical

modeling.

Droplet Trajectory/Spray Angle

Nozzles of different designs provide sprays with widely varying spray patterns and droplet trajectories. Droplet trajectory influences nozzle performance because the initial direction of the high velocity spray can result in direct impingement of liquid on internal surfaces. In contrast, it is imperative that the spray adequately mix with the surrounding flue gas so that near complete drying of the droplets can occur in the limited time available. Better performance has been achieved in tests with nozzles that provide a spray trajectory with a smaller included spray angle. Nozzles with a single discharge hole or with multiple holes oriented with a small included angle have achieved the highest success.

The maximum tolerable spray angle for a given DSD application will depend on the clearances between the nozzles and the walls. In the flue region close to the nozzle plane, droplet trajectory and spray angle may determine the available residence time for evaporation. Narrow spray angles are important for slurry injection in ducts with small cross sections or for arrays with close wall clearances. Spray angle is not a "stand-alone" parameter; successful slurry injection without deposition in the near field will depend on wall clearances as well as spray angle. Further downstream of the nozzle plane, wall deposition is more likely to be a function of turbulence rather than direct impingement.

A lower limit in spray angle is about 14° which represents the expansion of a free jet. A 30° spray angle is a maximum.

Nozzle Hydraulic Characteristics

For successful DSD, uniform profiles of temperature and velocity across the duct cross section have been shown to be important. Likewise, the mass flux of injected slurry must be uniform across the duct cross section. A poor distribution of gas temperature, gas velocity, and/or liquid mass flux (as droplets) will result in localized regions of saturated gas that can lead to wetting and solid deposition. Several factors influence the ability to control the droplet size and slurry flow distribution over the duct cross section. These factors include the sensitivity of individual nozzles to changes in operating slurry and/or air pressure, the nozzle-to-nozzle uniformity in operating characteristics, and the effect of variable slurry pressure with vertical elevation in the duct.

The pressure-flow characteristics of a single nozzle or an array of just a few nozzles are usually not critical because it is possible to monitor and control the air and slurry flow rates to each individual nozzle. With a large array of nozzles, however, individual control of flow to each nozzle is not practical. Rather, multiple nozzles are manifolded into a parallel array and controlled from a single source of air and slurry. The control of flow is to the manifold, and the flow to the individual nozzles is dependent on the slurry pressure distribution in the manifold and the pressure-flow characteristics of the individual nozzles. The uniformity of flow across an array will, in part, depend on the sensitivity of each individual nozzle to slurry pressure at the nozzle inlet.

A measure of nozzle sensitivity is the change in slurry flow that results from a change in slurry pressure at a constant air pressure. This change is the slope of the slurry flow-slurry pressure curve. The more sensitive the nozzles (or steeper the slope), the more likely a nozzle array will have flow maldistribution during normal process variations. Acceptable sensitivity will

depend on both the geometry of the manifold and the type of process control. For large arrays of nozzles, an estimate of maximum acceptable nozzle sensitivity is 5% or less change in slurry flow per psi change in slurry pressure at full load.

If the sensitivity of a candidate nozzle is unacceptably high, then it can be modified by increasing the liquid flow resistance between the nozzle and the manifold. One method for increasing the hydraulic resistance is to install one or more orifices immediately upstream of the nozzle. It is important that the addition of orifices does not change the spray droplet size distribution.

Another factor that will affect the uniformity of the mass flux and droplet size distribution across the duct is the part-to-part uniformity of the nozzles. Arrays of nozzles require good part-to-part uniformity in hydraulic and droplet size distribution characteristics. Since a large number of nozzles will be controlled by a single source of air and liquid, if the pressure-flow characteristics of the nozzles are not identical, the slurry flow to each nozzle could be substantially different. Variations in air or slurry flow can affect the droplet size distribution because of the effect these variations will have on air-to-slurry ratio. Nozzle-to-nozzle variability can arise solely from slight differences in the size, shape, angle, and location of the holes in the components that make up the nozzle.

The third factor that affects the duct cross-sectional mass flux and droplet size uniformity is the differences in vertical location of nozzles in large arrays. Nozzles in a duct that are located at different elevations and are supplied by a common slurry source are subject to flow maldistributions. The maldistribution is caused by variations in the static pressure in the slurry lines. The nozzles at lower elevations will "see" a higher supply pressure and flow rate than nozzles at upper elevations.

One solution to this potential elevational flow maldistribution is to measure and control the slurry flow to each level of nozzles in an array. For arrays with a large number of nozzles, this approach could require a multitude of flow meters and control valves in an active control loop. This type of scheme is susceptible to flow instabilities and is costly and complex. Passive control with simple instrumentation is more desirable. Based on the operating characteristics of internal mix, dual-fluid nozzles, the effect of variable slurry pressure on flow rate can be offset with air pressure that also varies with height. This type of solution will require knowledge of the pressure-flow characteristics of the nozzles in a given array.

Materials of Construction and Wear

Wear, corrosion, deposition, and pluggage of individual nozzles in an array can lead to degradations in flow characteristics. Stainless steel (316) slurry nozzles will wear due to erosion caused by the abrasiveness of the solids in the slurry. Replaceable, hardened inserts for the high wear areas are recommended. To minimize wear in slurry nozzles, the materials of construction should be stainless steel 316 or better with ceramic or silicon carbide inserts at the wear points. The wear points are typically the impingement points of the slurry prior to mixing with the atomizing air, the mixing points of the slurry and compressed air, and the discharge points from the nozzle.

Corrosion may occur when sulfurous and chlorine constituents of the flue gas condense on exposed metal surfaces. Low-grade stainless steel (304) has been found to corrode in duct injection environments. For corrosion protection, nozzles fabricated from 316 stainless steel (minimum) are recommended.

Another factor that can negatively influence nozzle performance is build-up of material on the nozzles themselves. Build-up on the nozzle tips can be caused by the expansion of the air-slurry mixture leaving the nozzle. Condensation of moisture on the relatively cold nozzles become sites for solids in the flue gas (sorber plus fly ash) to adhere. Flow patterns within the duct may also deposit material on the nozzle tips. Turbulent eddies or recirculation zones may force solids to the wet surfaces of the nozzles. Material build-up on the nozzle tip can alter the spray pattern, partially or completely plug a nozzle, and cause dripping. A recommended method to reduce deposition on the nozzle tip is through the use of shielding devices (reference Figure 6-1). The nozzles should be installed within shields. Air lances and/or rappers may also be installed to control deposition on the nozzle and manifold surfaces (also reference Section 6.3.3).

Pluggage of the internal air and/or slurry passages of nozzles by solids in the slurry and compressed air may be a problem. The slurry and compressed air should be filtered before entering the manifolds. Nozzles with very small diameter internal passages should not be used.

6.2.2.2 Slurry Nozzle Placement

The slurry nozzle headers should be aerodynamic (in the form of an airfoil) to reduce build-up on the upstream edge of surfaces.

The most successful duct injection projects have utilized arrays (totaling 10 to 100 nozzles) of small capacity nozzles to achieve atomization with acceptable amounts of deposition. The geometry of nozzle arrays that provides good performance without deposition is difficult to determine without detailed modeling. Required nozzle-to-nozzle spacing and wall clearance will, in part, be a function of nozzle capacity and spray angle. Suggested clearances are 1 ft between nozzles (both horizontally and vertically) and 2 ft between the outer-most nozzles and the duct walls and ceiling. For horizontal ducts, the spacing between the lower-most nozzles and duct floor should be about 3 ft.

Nozzle alignment can have a significant effect on slurry injection performance. Nozzles placed in a duct, whether singly or in a multi-nozzle array, must be aligned so as to prevent jet impingement on the duct walls, minimize ash deposition on the nozzles, and maximize the mixing between the spray and the flue gas. Nozzle alignment will be somewhat specific to the application, and will depend on the spray angle of the nozzle and the distance from the wall. However, the required wall clearance may be reduced by tilting the nozzles closest to the walls inward by 2-5°.

6.3 Flue Gas System Modifications

6.3.1 Ductwork Internals

This section provides suggestions for modifications to existing ductwork internals to facilitate the retrofit and operation of a duct injection system. These discussions and resulting modifications will hopefully minimize material build-up. Section 6.3.3 deals with specific design considerations that will likely be required to accommodate material deposition if it occurs.

6.3.1.1 Gas Velocity and Temperature Profile to the Injection Point

Since this project involves scrubbing the flue gas by injecting sorbent into existing ducts, it is necessary to know the flue gas velocity and temperature profiles inside the duct upstream and downstream of the injection location. Knowledge of the velocity profiles is necessary because a proper profile can stop the sorbent from directly impacting the wall, maintain sorbent entrainment, ensure proper residence time for chemical reaction and drying, and maximize sorbent and flue gas mixing to promote maximum contact with SO_2 . The temperature profiles must be known so that it can be determined whether the flue gas temperature will remain above the water dew point and the acid dew point to prevent condensation on, and corrosion of, the duct walls; in addition to corrosion, wet walls will result in material deposition and wall build-up. Also, knowing the temperature profile facilitates control of the amount of humidification necessary to hold the desired approach temperature for chemical reaction.

The velocity profile at the exit of the air heater heat transfer surface is generally considered to be uniform. There is usually sufficient pressure drop in the air heater heat transfer surface to dampen out most flow nonuniformities that may have been present upstream of the air heater. However, at the air heater outlet, the temperature profile can be nonuniform and independent of the velocity profile. As the flue gas flows from the air heater outlet to the injection location, either profile can become more or less uniform depending upon the duct configuration. It is in this section of the ductwork that distribution devices may be necessary to correct the velocity and/or temperature profiles to provide the required distribution prior to the injection location.

Turning vanes used to correct a velocity profile will not necessarily correct a temperature profile. When using turning vanes, if there is a maldistribution in temperature upstream of the vanes, the same temperature maldistribution will exist downstream because the vanes do not increase gas mixing. Only gas mixing can correct an uneven temperature distribution, which would require additional pressure drop that may not be available in a retrofit application. Therefore, it is imperative that criteria be established for acceptable velocity and temperature profiles at the injection location.

The Industrial Gas Cleaning Institute (IGCI) has set criteria for the velocity profile entering an electrostatic precipitator. The IGCI standards state that a fixed percentage of the velocity data points at a given location cannot be greater than the average value by a fixed amount:

- 85% of the measured velocities less than 1.15 times the average velocity
- 99% of the measured velocities less than 1.40 times the average velocity

These type of criteria ensure that there are few local velocity high spots in the velocity profile.

The Air Movement and Control Association (AMCA) has established criteria (AMCA Standard 803) for the velocity profile entering a fan. Their criteria ensure that the velocity profile is uniform for both high and low values of local velocity by recommending that the standard deviation of the velocity data be within a specified limit: neither the width nor height velocity distortion parameter (for horizontal ducts) should exceed 10% of the mean of all velocities measured in a plane. The velocity distortion parameters are calculated as follows for a horizontal, rectangular duct:

The mean of all velocities measured in a plane is

$$V_{ave} = (\sum_W \sum_H V_{h,w}) / (W \times H)$$

The mean velocity along each height level in the duct is

$$V_{w, ave} = (\sum_W V_{h,w}) / W$$

The mean velocity along each width partition is

$$V_{h, ave} = (\sum_H V_{h,w}) / H$$

The width velocity distortion parameter is

$$VD_w = \frac{[\sum_W (V_{w, ave} - V_{ave})^2 / W]^{0.5} \times 100}{V_{ave}}$$

The height velocity distortion parameter is

$$VD_h = \frac{[\sum_H (V_{h, ave} - V_{ave})^2 / H]^{0.5} \times 100}{V_{ave}}$$

where: W = Number of width partitions traversed (reference Figure 6-5)

H = Number of height levels traversed (reference Figure 6-5)

These AMCA conditions are slightly more strict than those of the IGCI, but either set of criteria can be used as a guideline for duct injection.

The velocity and temperature profiles at the injection point need to be measured to determine if corrective devices are needed. The recommended minimum number of traverse points for rectangular ducts is indicated in Figure 6-4. For rectangular ducts with cross-sectional areas of 24 sq ft and less, the recommended minimum number is 24. For cross-sectional areas greater than 24 sq ft, the minimum number of points increases as indicated in Figure 6-4. The points are to be located in the centers of equal areas with the areas as nearly square as practical (see Figure 6-5). Fewer points may be used if the flow is very uniform; however, the maximum area covered per point should not exceed 3 sq ft.

Once the velocity profile at the injection point is determined, it must be compared to the IGCI or AMCA criteria noted above. If the existing velocity profile is poorer than these criteria, turning vanes and/or distribution plates must be installed upstream to achieve these minimum

FIGURE 6-4
RECOMMENDED MINIMUM NUMBER OF TRAVERSE
POINTS FOR RECTANGULAR DUCTS

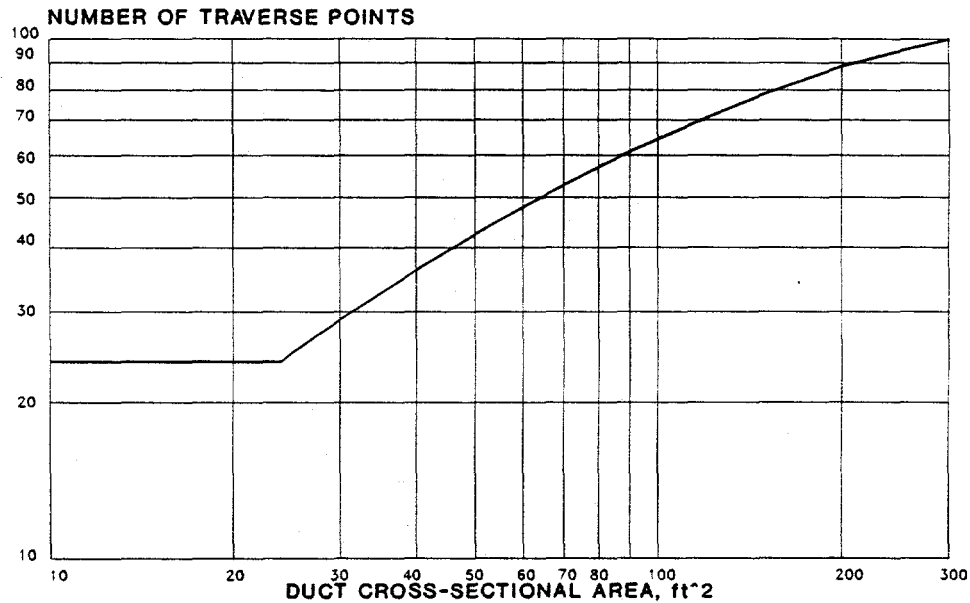
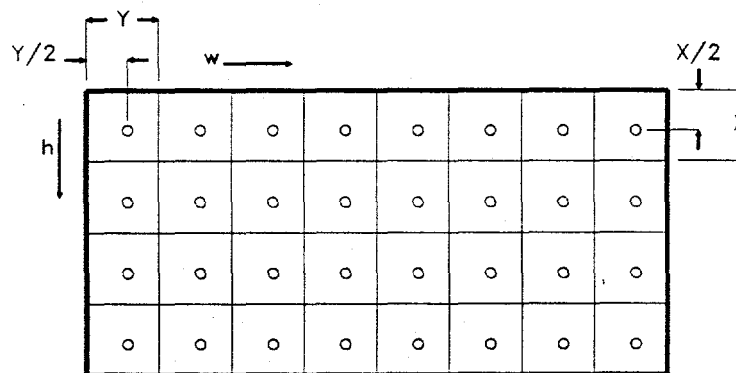


FIGURE 6-5
DISTRIBUTION OF TRAVERSE POINTS
FOR RECTANGULAR DUCTS



$V_{h,w}$ = velocity at any point h,w
 $h = 1,2,...H$ (4 in this illustration)
 $w = 1,2,...W$ (8 in this illustration)

criteria. These modifications should be implemented per ASHRAE or AMCA Standard 210 recommendations.

If the existing temperature profile is poorer than the criteria given above, devices must be installed upstream to increase gas mixing.

A scale flow model can be used to determine the internal corrective devices in the duct to provide the required velocity and temperature profiles upstream of the injection location before installing these devices in the full size unit. The flow model can also be used to minimize the system pressure drop for the retrofit application.

6.3.1.2 Modifications to Duct Internals Downstream of the Injection Point

The physical layout of the ductwork downstream of the injection point is important in minimizing material deposition. The ideal arrangement would be a straight duct without any internals such as stiffeners, bracing, turning vanes, etc. This is rarely the case.

It is recommended that all internal bracing and/or stiffeners be removed and replaced with external stiffeners. This is typically an expensive and involved changeout because it requires removal and reinstallation of duct insulation. It is considered necessary, however, to eliminate potential sites for material deposition.

Thermocouples located downstream of water or slurry injection but upstream of the particulate control device should be shielded from the wet solids and/or water droplets. Unshielded thermocouples may be used downstream of the humidification zone if they are located far enough downstream that evaporation is complete. Thermocouple number, location, and design are discussed in more detail in Section 8.0 and are shown in the P&IDs, Section 5.3.

If turning vanes are located in the ductwork downstream of water or slurry injection, build-up will occur on them unless evaporation is complete before the solids reach the vanes. Typically, this build-up will necessitate shutdown and manual cleaning. Therefore, duct injection retrofit is not recommended in a section of ductwork containing turning vanes unless sufficient residence time exists to completely dry all droplets. Even then, coating the vanes with a non-stick surface coating, such as Teflon, and installing rappers on the vanes is recommended.

6.3.2 Ductwork Externals

This section provides suggestions for modifications to existing ductwork externals to facilitate the retrofit and operation of a duct injection system.

6.3.2.1 Support Steel

The design of the existing ductwork support structural steel must be evaluated to determine if it can accommodate normal levels of solids build-up and large amounts of material deposition in an upset condition. In an upset condition, several feet of material @ 100 lb per cu ft could build up on the duct floor.

6.3.2.2 Access Doors/Viewports

Access doors (24 in. x 30 in. high) should be added in the duct to allow access to the duct injection equipment and to facilitate cleanout. Two access doors should be available on each side of the duct - one at the spray injection equipment, and one about 20 ft downstream. To aid in visual inspection and troubleshooting, viewports should be provided at the water nozzle grid and at the sorbent injection location for DSI or at the slurry nozzle grid for DSD. A minimum of the two such viewports should be provided on each side of the duct.

6.3.2.3 Test Ports

Test ports are recommended upstream and downstream of the duct injection location to facilitate performance testing and troubleshooting/diagnostics. The number and location of the test ports should be determined per 40 CFR Part 60, Appendix A, Reference Method 1.

6.3.2.4 Access Platforms

Permanent access platforms with toeplate and handrail should be provided to the new access doors, viewports and test ports. For the access platforms at the test ports, the handrail should be removable to facilitate test probe handling.

6.3.2.5 Load Cells/Strain Sensors

Detecting the start of material build-up is important in order to take immediate corrective action. External load cells or strain sensors (such as Microcell Sensors manufactured by Kistler-Morse of Redmond, WA) may be used for this purpose. These devices should be mounted on each main vertical support member for the ductwork between the injection point and ESP. The output signals can be sent to stand-alone displays or can be tied into the duct injection control system. The control room indication should be alarms as a minimum.

6.3.2.6 Insulation

Ductwork insulation is important to minimize corrosion of internal duct surfaces downstream of humidification. A minimum of 4 in. of insulation should be installed on all duct surfaces. 6 in. have been necessary in some commercial lime spray drying systems located in cold weather climates. Insulation is also required over all flanges, expansion joints, damper housings, and any other exposed surfaces downstream of humidification. Severe corrosion has been experienced in these areas on commercial spray drying installations. This applies to the ductwork between the ESP and chimney as well.

6.3.3 Deposition Control Modifications

Some level of material deposition is likely inevitable, under certain operating conditions, no matter how well the duct injection system is designed. Poor nozzle performance, nozzle erosion, load swings, and unsatisfactory ductwork geometry and/or unsatisfactory gas velocity or temperature profiles can be major causes of material deposition.

Most power plant ductwork is rectangular, contains several turns, and may lack flow straightening devices. Rarely does it contain the long, square, straight sections needed to eliminate material deposition. Therefore, the sorbent and water injection scheme will be heavily dependent on the particular ductwork layout and geometry.

Deposition occurs by several mechanisms, depending on the specific technology being applied. The two main mechanisms are direct impingement of slurry or water sprays on duct surfaces, and incomplete evaporation of droplets that impact with duct walls or other internals. Deposition may range from a thin coating to thick layers that choke off almost the entire cross section of the duct. Material deposition can lead to boiler downtime and increased maintenance costs. Therefore, any successful commercial application of duct injection technology must limit material deposition to manageable levels.

Material deposition is typically progressive, i.e., wall deposits lead to greater impingement and accelerated growth. Methods need to be employed to remove the deposits quickly after they form. Research has shown that material deposition is usually confined to a small area within the duct. Installation of appropriate solids handling equipment is recommended in this "affected zone" where deposition can be expected. One or more of the following suggestions should be implemented to minimize solids build-up.

6.3.3.1 Sootblowers

Sootblowers are effective at removing wall and floor deposits in a localized area. They are usually used in conjunction with a hopper(s) to collect the material which is dislodged from the walls. The sootblowers should be rated at about 74 scfm each and use 100 psig air. They should be mounted horizontally across the bottom of the affected zone. The sootblowers should be mounted flush with the duct wall or recessed a fraction of an inch so as not to create any projection into the gas stream.

6.3.3.2 Floor Puffers

A technique applicable to dry, fluid ash build-ups on horizontal surfaces is the use of floor puffers. The concept is to periodically pulse or fluidize the dry solids back into the flue gas stream. Floor puffers can vary in configuration and equipment detail depending on the type of duct application.

One method is to periodically (5 to 6 time/hr) introduce a pulse of compressed air through a grid of pipes or wide angle duck-bill nozzles in areas where dry solids settle out due to particle size and/or low gas velocity. The pipes or nozzles may be pulsed individually or in banks. These pipes/nozzles are typically 2-3 in. in diameter to supply sufficient volume of air to clean a section of duct floor. A dedicated air receiver is usually required since this type of approach requires a relatively large volume of air.

Floor puffers are only effective on dry, fluffy solids. If material is damp or clumpy, another technique is advised.

6.3.3.3 Droplet Impingement Devices

Droplet impingement devices (DIDs), patented by Babcock & Wilcox, consist of two staggered rows of heated pipes installed just before a duct bend, the perforated plate at the ESP inlet, or other location which cannot tolerate unevaporated droplets. Water or slurry droplets which

are not evaporated are forced to impact the DIDs. The deposits that form on the pipes are removed by periodic rapping and fall into a hopper installed underneath. DIDs are normally not required unless a residence time of less than 0.5 seconds is available to the bend, perforated plate, or other flow disturbance.

Each row of pipes should be 1 in. diameter on 2 in. centers (50% open area for each row). The two rows should be placed in a arrangement similar to the Babcock and Wilcox DID design. The pipes may be heated by low quality steam.

6.3.3.4 Sonic Horns

Sonic horns have been tested in duct injection systems, but it is not clear how effective they are at minimizing duct wall deposition. When used, they have been mounted upstream of the nozzles/injectors with the bell pointing downstream. This arrangement minimizes solids building up in the bell.

6.3.3.5 Air Lances

The humidification nozzles in DSI or slurry nozzles in DSD are relatively cold during operation as they have "cold" water or slurry flowing through them. It is likely that fly ash will build up on their upstream surfaces. In addition, if sorbent injection is located upstream of the humidification nozzles in the DSI process, significant build-up of sorbent will occur on the upstream surfaces of the humidification nozzles.

Air lances may be installed, either fixed or moving type to blow compressed air on upstream surfaces of the nozzles and support structure. Nominal air pressure should be 100 psig.

6.3.3.6 Rappers

Rappers are recommended to dislodge solids build-up on nozzles and the nozzle support structure. The vertical support beams of the nozzle array may be extended through the top of the duct roof plate (or through the side of vertical ducts). Rappers may be installed to rap the protruding support beams.

6.3.3.7 Hoppers

As noted in several previous sections, installation of a hopper(s) is recommended to collect dislodged materials in the affected zone in horizontal ducts. In vertical ducts, installation of a hopper is recommended at the bottom of the vertical run.

For hoppers located in horizontal ducts, material tends to build up at the point where the downstream side of the hopper is attached to the duct floor. Therefore, it is recommended that a sootblower be installed near the duct floor just downstream of the hopper. This sootblower would consist of a 2 to 2 1/2 in. pipe with 1/4 in. holes drilled in it on 3 1/4 in. centers. The holes are located so that the sootblowing air is injected upstream (into the on-coming flue gas) to blow any material build-up into the hopper.

The hopper should have a minimum of 24 in. diameter (if round) or 24 in. by 24 in. opening at the bottom. It should be fitted with a crusher or lump breaker of some kind to grind the lumps before the material enters the ash handling system. The hopper valley angle should be at least 60° with the horizontal.

The hopper should be provided with hopper heaters on at least the bottom third of the vertical height of the hopper, including the hopper outlet throat. The entire hopper should be insulated. Each hopper shall be provided with one solid steel strike bar that shall protrude through the insulation to be used as a striking anvil to relieve hopper plugging. Two 4 in. pipe nipples fitted with pipe caps (or equivalent removable cover), extending 4 in. beyond all adjacent insulation and lagging, shall be located near each hopper outlet flange to permit emergency rodding.

Each hopper shall be equipped with a high dust level alarm device, consisting of a nuclear level sensor. This device shall include one source and detector attachment per hopper and two normally closed contacts.

6.3.3.8 Non-Stick Coatings

The duct walls and ceiling (for horizontal ducts) may be lined with a non-stick coating to minimize material deposition. The coating would require a temperature rating of the normal air heater outlet temperature plus at least 50°F to account for upsets. These types of coatings have not been tested in duct injection applications, and their usefulness has not been verified.

6.3.4 Electrostatic Precipitator

One of the most important issues to be addressed in the retrofit of a duct injection system is the ability of an existing electrostatic precipitator (ESP) to maintain emission levels after the retrofit. Depending on the desired SO₂ removal and coal sulfur content, duct injection will increase the mass loading to an ESP by 5-15 gr/acf; this corresponds to an increase in loading to the ESP by a factor of 3-12. An ESP basically operates on an efficiency basis which means that, at any set operating condition, an increase in inlet mass loading will result in an increase in outlet emissions. Therefore, in order to maintain particulate outlet loading and opacity levels while the inlet loading increases, ESP efficiency must increase.

6.3.4.1 Effects of Duct Injection on ESP Performance

Flue Gas Effects

The retrofit of a DSI or DSD process causes the following changes to the flue gas entering the ESP:

- Increase in particulate loading
- Decrease in temperature
- Increase in density
- Decrease in gas volume with corresponding decrease in velocity
- Increase in humidity
- Decrease in SO₂/SO₃ content

The decrease in flue gas volume flow rate results in a higher net ESP specific collection area (SCA) and a lower velocity. The increase in gas density allows the ESP to operate at higher power levels without back corona (sparking). These effects may allow better performance to offset the increase in particulate loading.

Low-Resistivity Dust

Humidification also results in a decrease in particulate resistivity. Tests indicate that, although calcium-based sorbents have very high (10^{13} to 10^{14} ohm-cm) resistivities at 300°F, the surface conditioning due to humidification and cooling reduces the resistivities of the ash/sorbent wastes from duct injection processes to extremely low (10^7 to 10^9 ohm-cm) values. This is primarily due to the low temperature, high humidity conditions in ESPs downstream of these processes.

Although reduced resistivity allows the particulate to be collected more easily, ESPs operating on low-resistivity dusts can experience rapping and scouring reentrainment of the collected solids due to reduced holding forces. When reentrainment is a problem, the emissions can increase by a factor of 10 or more. Scouring reentrainment is strongly influenced by velocity.

Electrical reentrainment may also occur when low-resistivity particles on the ESP collecting plates reverse their polarity and are repelled from the plates. To complicate this, electrical reentrainment may result in a reduction in particle size of the repelled solids making them more difficult to recollect. ESPs with large SCAs may have enough excess collecting area to compensate for reentrainment problems.

Space Charge Corona Quenching

Another potential effect of a duct injection retrofit upstream of an ESP is space charge corona quenching due to high concentrations of fine particles in the ESP inlet field. This current density reduction may be sufficient to reduce the strength of the electric field to the point of reduced ESP collection efficiency. Because DSD results in larger particles, it may not result in such severe quenching effects.

Electrode Design

One retrofit concern is the cleanability of deposits from weighted wire type discharge electrodes when operating under duct injection conditions. Increased quantities, as well as physical properties of the ash/sorbent waste solids, may lead to increased wire deposits. If wire deposits increase with duct injection, they could lead to potential degradation of precipitator electrical conditions if the deposits cannot be easily removed by the existing rapper system. The weight of the deposits combined with increased rapping intensity can lead to more wire failures which result in reduced collection efficiency and higher maintenance cost.

6.3.4.2 Potential Options for Upgrading ESP Performance

As noted in Section 6.3.4.1, the retrofit of a duct injection system will cause both positive and negative effects on ESP performance. The net change in performance for a particular ESP is site specific and very difficult to determine in advance.

Several methods exist for increasing the efficiency of an existing ESP. Unfortunately, not all of these methods are applicable after the retrofit of duct injection technology. Many of these techniques for improving precipitator performance were developed to overcome problems associated with difficult to collect, high resistivity (10^{11} to 10^{13} ohm-cm) fly ash. As previously mentioned, the particulate resistivity will decrease with the application of a duct injection system.

Among the upgrade options not considered to be effective for duct injection retrofits are: SO₃ conditioning, NH₃ conditioning cooled electrode precharging, wide plate spacing, pulsed energization, and intermittent energization. There are a number of strategies that have the potential to improve ESP performance in a duct injection system application.

1. Correcting gas velocity distribution
2. Digital Controls
3. Increasing SCA/treatment time
4. Special discharge electrodes
5. Calcium chloride addition

These options may have to be implemented individually or in combination. Application criteria are site specific.

Correcting Gas Velocity Distribution

Industrial Gas Cleaning Institute (IGCI) guidelines for ESP gas distribution recommend that 85% of velocity readings fall within 25% of the average velocity and no readings be more than 40% from the average value. The velocity distribution at the ESP inlet should be measured. It may be necessary to modify the inlet section by adding turning vanes or perforated plates to create an even gas flow per IGCI guidelines and by adding baffles to prevent sneakage.

Many existing ESPs, even if started up within the last few years, can benefit from remedial gas flow distribution improvements. It has been found that adherence to more stringent and widely encompassing flow distribution requirements than conventionally used in the past can be applied to drastically improve precipitator performance and thus reduce outlet emissions.

The conventional criteria used today by ESP manufacturers are much more stringent than those used fifteen years ago. The additional cost to remodel an existing installation and to retrofit gas flow distribution devices to achieve these more stringent criteria is often easily justifiable for a marginally performing ESP.

A modern ESP built to meet current gas flow distribution standards, which are accepted in the industry, will have extensive gas flow distribution devices included in the design. Typical devices at the inlet to a precipitator with a conventional pyramidal nozzle would usually include a minimum of two perforated plates with quite often a third. The rows of perforated plates would vary in average porosity, depending on the distance to the precipitator inlet at which the plate is placed. When there is a complicated inlet duct arrangement, various portions of the perforated plates may have blockages applied to produce, in effect, a variable porosity across the face of the precipitator. In addition, flow straightening devices, such as "egg crates" or other straightening lattices, vanes and "kicker plates" may be applied at various places or across the entire face of the perforated plate to promote straight flow through the precipitator box.

A modern precipitator will include some kind of distribution device(s) across the outlet of the precipitator box. This might be a perforated plate or some type of "distribution channels" which can be arranged to provide a variable porosity across the outlet of the precipitator. Modern ESP designs have outlet porosities of 20 to 30 percent open area without a marked pressure drop penalty. If complicated outlet duct runs are involved, turning vanes and other devices may be included in the precipitator's outlet nozzle.

Modern design practices keep gas flow out of the precipitator's hoppers to reduce reentrainment of ash from hoppers; an especially prevalent problem if filled hoppers are common. Note that, just because a precipitator has hopper baffles, does not mean that hopper flow and thus reentrainment does not occur. Many early hopper-baffle designs actually promote hopper flows.

Digital Controls

Modern, digital T-R set controls are far superior to the conventional analog automatic voltage controls and may offer significant improvements over early vintage digital controls. Modern digital controls have the capability to be programmed to recognize more varied and complicated protocol in their operation. For example, controls would detect the effects of duct injection (increased current densities due to low-resistivity conditions), and optimize ESP operation by adjusting the T-R sets accordingly. In so doing, these controls not only can improve precipitator performance but actually save energy by reducing excessive powers levels which otherwise would be wasted when TR sets are operating at current or voltage limit. An option for many of these controls is the capability to include an "energy management system". Such systems interface with the unit's opacity monitor to allow backing off of power levels without increasing outlet opacity. Also, modern digital controls are capable of more effectively detecting power arcs and quenching excessive arcing and sparking to prolong the life of discharge electrodes.

Another capability of modern digital controls is "power-off rapping". High resistivity fly ash can be difficult to dislodge from the collecting plates. In "power-off" rapping, the TR set is de-energized very briefly as the plates are rapped, removing the electrical holding force.

Increasing Specific Collection Area (SCA)/Treatment Time

Some ESPs may need to be enlarged to meet the required emission levels. Although expensive, 20% additional SCA can be created by increasing only the height of many ESPs. Larger SCA increases would require additional precipitator fields which add to the space occupied by the ESP and would involve a significant capital cost. Nevertheless, increasing the SCA of an existing ESP is an option that should be evaluated if the duct injection process results in increased emissions.

Many existing ESPs are marginally sized for the current service conditions, and significantly undersized to meet more stringent particulate emission limits or to operate downstream of duct injection.

Increasing Plate Height - Can add as much as 20% to SCA but may not be practical due to poor gas flow distribution, long outage requirements, and structural support problems common to many older ESPs.

Adding Collecting Fields in Series - Additional fields can be added either as an extension of the existing box or as a new box in series. The major draw backs of this arrangement are space requirements.

Adding Collecting Fields in Parallel - The addition of a second ESP in parallel with the existing ESP to increase SCA has some special advantages. Reentrainment due to low resistivity is a strong function of velocity. In these cases, a small decrease in velocity can cause a large decrease in emissions. A second ESP in parallel with the existing ESP will allow both ESPs

to operate at lower gas velocities while providing an increase in SCA. An additional advantage of adding a parallel ESP is that the boiler does not have to be taken off-line during construction; only a short outage is necessary for tie-in.

Special Discharge Electrodes

Space charge quenching is often found in high dust loading applications such as cement kilns or applications with large amounts of submicron particles such as smelters. For these applications, ESP vendors recommend corona electrodes designed with barbs, pins or other points to create localized corona zones to produce more current at a given voltage. If corona quenching in the first ESP section is found to be a limiting factor, a discharge electrode designed for increased current may be installed in the first section.

High current discharge electrodes may have another advantage. As previously mentioned, low-resistivity material may be repelled from the ESP plates induced by the high potential gradient in the ESP. Increasing the voltage would aggravate this problem, but increasing the current density would help to hold particles to the plates. Limited tests of high current density electrodes at the dry injection pilot plant were inconclusive. More research is needed across a broader range of operating conditions to determine at what conditions, if any, that high current density discharge electrodes are practical in duct injection.

Calcium Chloride Addition

Reentrainment accounts for the majority of particulate emissions from ESPs which are in good electrical and mechanical condition, and which are not operating on high resistivity dusts. Reentrainment can occur from rapping, hopper sweepage and the velocity scouring of the ash off the collecting plates. In addition, electrical reentrainment has been observed on ESPs operating downstream of spray dryers and duct injection processes. The flue gas velocity has a strong influence on reentrainment. Reentrainment can be severe on older ESPs with design gas velocity above 5 ft/second or those ESPs treating larger than design gas volumes (due to in-leakage, fuel changes, etc.).

Additives have been demonstrated to reduce reentrainment emissions by increasing the cohesivity of the collected particles. Increased particle cohesivity or "stickiness" cause the particles to agglomerate into large particles or sheets which will fall into the collection hopper or be easily recollected rather than be carried out of the ESP with the flue gas.

Calcium chloride (CaCl_2) has been demonstrated as a cohesivity aid on ESPs operating downstream of lime spray dryer pilot plants. CaCl_2 is an inorganic deliquescent salt which slows the drying rate of slurry droplets, effectively resulting in wetter and more cohesive solids.

Calcium chloride is typically added as a dry powder, in the case of dry sorbent injection (DSI), to the humidification water, and in the case of duct spray drying (DSD) to the recycle slurry. Additive rates vary with each potential application due to differences in coal and ash properties, approach to saturation, etc. Based on spray dryer pilot plant results, the CaCl_2 should be added at a rate to achieve 2.0% by weight concentration of CaCl_2 in the recycle solids.

Despite these promising results, there is insufficient application history at the time of this publication to recommend CaCl_2 addition as an ESP upgrade strategy. More testing and long

term commercial operation will be required. There are several potential problems associated with CaCl_2 additives. First, chloride addition is most effective at very close approach to saturation temperatures (approximately 20°F) which may be outside the practical operating range for duct injection.

There are also potential side effects related to the use of CaCl_2 . The deliquescent nature of the additive slows the rate of drying and may lead to increased duct wall wetting and solids deposition. Wet solids can build up on perforated plates and discharge electrodes as well as create problems with solids removal and conveying systems. Elevated chloride levels in the waste solids may impact waste disposal and by-product utilization decisions. High chlorides can lead to stress corrosion cracking in lower grade stainless steel. These issues should be evaluated carefully when considering the use of calcium chloride additives.

6.3.4.3 ESP Operating and Maintenance Considerations

Rapping Cycle Modifications

Optimizing rapping intensity and frequency can improve ESP performance. A portion of the emissions from all ESPs is the result of rapping reentrainment. The rapping frequency and intensity should be adjusted for the fly ash and flue gas conditions specific to each ESP application. When these conditions are altered, as in the case of a duct injection retrofit, the rappers must be readjusted. In many cases, optimizing rapping frequency and intensity can significantly improve the performance of an ESP.

For ESPs operating with low-resistivity ash, rapper adjustments can generally minimize opacity spiking, but they may not result in significant reductions in overall mass emissions. In these cases, mass emissions from velocity scouring far outweigh the contribution of rapper related reentrainment. Since opacity is generally the day to day indicator of ESP emissions compliance, however, rapper optimization is a very necessary task.

Power-Off Rapping

Extended operation of sorbent injection may result in a long-term residual build-up of particulate on the ESP collecting plates. This would result in severe ESP power degradations and increased opacity. Intermittent power-off rapping should be generally successful in removing these long-term plate build-ups and in restoring stack opacity to acceptable levels. This is typically accomplished by de-energizing the electrical field and manually initiating the rapping. However, this sometimes results in high opacity excursions. While this practice in its crude form may not be suitable for normal power plant operations, it may be possible to automate the procedure. Several manufacturers offer microprocessor based programmable rapper controllers and automatic precipitator power controllers. By initiating power-off rapping field by field at carefully timed intervals, opacity excursions may be avoided. This option is considered feasible in conjunction with the retrofit of a duct injection system.

6.3.4.4 Miscellaneous ESP Modifications

A complete review and inspection of the electrical and mechanical conditions of the ESP should be performed. The following items are recommended:

Access Doors

Many existing access doors will be corroded and/or their seals shot. All doors, including hot and cold roof access doors, side access doors, access doors at high voltage rapper insulator compartments, and hopper access doors, should be inspected. If corroded, the doors should be sandblasted and coated with a vinyl ester resin or epoxy based coating.

If the seal is shot, replace it. If the door is corroded, replace it and then add an insulated door cover. Corrosion will be worse after the duct injection retrofit.

Insulation

If not already in place, install an insulator compartment heating and ventilation system. Install insulation in the insulator compartment area.

If not already in place, install throat heaters on the hopper outlets.

If not already in place, insulate the high voltage rapper compartments.

Blow in additional insulation on each outside wall of the ESP. This will fill all of the voids caused by the stiffeners. Add insulation to the outlet nozzle of the ESP.

Fluidizing Air Provisions

It is recommended that two fluidizing stones per hopper be added to the first two rows of the ESP.

The fluidizing pads should be porous stone with a permeability rating of about 10 cfm per sq ft at 2 in. H₂O differential pressure. A manually operated butterfly or ball valve should be installed in the line to each fluidizing pad for trimming air flow.

Fluidizing air pressure should be 3-5 psig, and the air flow should be 10 scfm per sq ft of fluidizing pad area. The fluidizing blower(s) should be sized at 10 scfm per sq ft and enough discharge pressure to overcome losses and still maintain 3-5 psig at the fluidizing air pads.

Installation of hopper fluidizing stones will require removal and reinstallation of existing insulation and lagging. It will also likely require removal of existing hopper heaters and possibly replacing certain sections in the affected area with new heaters due to the mounting collars required. As a minimum, the new hopper heaters should have a heating capability equal to or greater than the existing hopper heaters.

6.4 Recycle System

Recycle in a duct injection system consists of returning a portion of the waste solids (fly ash, calcium-sulfur salts, and unreacted lime) to the flue gas stream. By providing multiple exposures of sorbent to the flue gas, recycling increases the opportunity for a given sorbent particle to react with SO_2 . For a given level of SO_2 removal, increased utilization of the reagent will result in less unreacted sorbent in the waste product. Thus, recycle of ash/sorbent waste material will reduce the total quantity of waste which must be disposed.

If the user chooses to utilize the recycle of ash/sorbent waste material collected in the particulate collection device [usually an electrostatic precipitator (ESP)], the equipment configuration to accomplish this is fairly site specific. The type of existing ash handling system, the ease at which an existing ash silo may be modified to incorporate recycle provisions, and the number of ducts for injection of the recycle material are all considerations.

6.4.1 Dry Sorbent Injection Recycle

In DSI, the recycle material is maintained dry, and the important design considerations are the same as for the waste material: dry conveying and storage. After storage, the recycle material is injected into the duct utilizing injectors separate from, but near, the fresh lime injectors.

Vacuum Pneumatic Ash Handling System

It is expected that many candidate plants for DSI retrofit will employ an existing vacuum pneumatic system to convey ash from the ESP to an existing ash silo. Because of the nature of vacuum ash handling systems, the ash has to be conveyed to the ash silo first before it can be recycled. It may be possible to modify the discharge equipment underneath the existing ash silo to allow a portion of the ash to either be blown directly back into the duct or conveyed to a recycle storage bin for subsequent injection into the duct (see DSI P&ID Sheet 5A).

For units where injection will occur in a single duct, the ash may be metered and then dilute-phase conveyed (using a variable speed rotary feeder and constant speed rotary air lock underneath the ash silo) directly back to the duct distribution header. For this design, the need for a separate recycle storage bin is eliminated. For larger units, especially units with more than one duct/ESP, ash will normally be dilute-phase or dense-phase conveyed from the existing ash silo to a recycle bin; from the recycle bin, it will be metered and dilute-phase conveyed using rotary feeders/rotary air locks to the various injection points - one dedicated set of rotary valves and blower per duct.

If a separate recycle bin is required (as shown in the P&IDs), a positive pressure transfer conveyor will be required to pneumatically convey the waste from the ash silo to the recycle bin. A rotary air lock is attached to the silo discharge to feed the waste material into the transfer conveyor. The capacity of the rotary air lock/transfer conveyor should be two times the design recycle material consumption in the duct injection process as calculated by the criteria in Section 3.0. This margin allows for lost time due to system warm-up, interruptions in waste flow to the pipeline, purging of conveyor prior to shutdown, and downtime for maintenance.

Typical capacities for a pneumatic transfer conveyor range from 25-40 ton/hr. If the required capacity, as estimated above, is significantly greater than 25-40 ton/hr, one or more of the following will have to be considered: 1) conveying for longer periods of time such as during the evening and/or graveyard shifts, 2) increasing the capacity of the transfer conveying system above 40 ton/hr (through discussions with conveyor suppliers), and 3) the use of two conveying systems to increase total conveying rate.

Typical pneumatic conveying velocities range from 4,000 to 6,000 ft/min for transfer of waste material. The air required for conveying the waste is somewhat dependent on conveying distance. For a conveying distance of 100 ft, about 0.12 lb air per lb waste is required compared to 0.17 lb air per lb waste for 400 ft of conveying distance. Blowers are normally rated at just less than 15 psig discharge pressure to stay below the ASME pressure code requirements.

Additional design criteria are contained in the pneumatic transfer/injection conveyors specification (Spec. No. M105) in Appendix E.

A spare blower for the transfer conveyor is typically not required; only one blower is suggested as shown on DSI P&ID Sheet 5A. This is recommended because 1) the blower should only operate 50-60% of the time allowing time for routine maintenance, and 2) the recycle system is not critical to the operation of the duct injection system, i.e., the required SO₂ removal can be achieved without recycle solids.

A proven alternative to the dilute-phase transfer system described above is a dense-phase pneumatic conveying system. Dense-phase systems require compressed air, but typically use only 1/10 the air volume of dilute-phase systems. Dense-phase systems are capable of much longer conveying distances.

Pressure Pneumatic/Mechanical Ash Handling System

If a positive pressure or mechanical ash handling system exists at the plant, a diverter gate may be installed in the ash line(s) to the existing ash silo to direct the ash/sorbent waste to a recycle bin for a portion of the time (reference DSI P&ID Sheet 5B). This design eliminates the need to convey the recycle solids out to the ash silo and then back to the process. In addition, no modifications to the existing ash silo discharge equipment would be necessary. It may be possible to direct ash from only the hoppers nearest the ESP inlet to the recycle bin. Inlet fields collect the majority of the solids, including most of the unreacted lime.

Wet Sluicing Ash Handling System

As noted in Section 6.5.1.1, wet sluicing of waste from the ESP will not allow recycle operation.

Recycle Bin

The recycle bin storage capacity should generally be 8 hr worth of waste material at the design recycle material usage. Since recycle is not critical to the SO₂ removal process, a smaller bin (in terms of hours of storage) is recommended compared to the hydrate bin. A bulk density of 50 lb per cu ft may be used for capacity of waste material. The straight wall height should be 1.5-2.2 times the bin diameter, and a freeboard (unused volume above the level of a full bin) of 3 ft should be assumed.

Ash/sorbent waste tends to form rat holes and craters which can cause arching or bridging in storage. Either a 60° conical hopper or flat-bottom bin may be used, but fluidizing air is required for either design. The flat-bottom design generally is recommended because of its lower cost and its traditional acceptance for conventional fly ash applications. A bin activator or vibrator is not recommended on recycle bins as they tend to pack the material rather than enhance the flow. Fluidizing is recommended in conjunction with a dedicated recycle bin aeration blower. As noted in DSI P&ID Sheets 5A and 5B, a spare aeration blower is not recommended since the recycle system is not critical to the operation of the duct injection system. However, a tie-in from a plant service air line could be used as a back-up when the aeration blower is not available as was recommended for the hydrate lime silos and bins in Section 6.1.1.1.

Experience has shown that uniform surface coverage (fluidized bottoms) is better than concentrated local fluidization (fluidizing pads). Fluidized bottoms should be porous stone with a permeability rating of about 10 cfm per sq ft at 2 in. H₂O differential pressure. Although not shown on the P&IDs, a manually operated butterfly or ball valve should be installed in the line to each section of the fluidized bottom for trimming air flow.

Fluidizing air pressure should be 3-5 psig, and the air flow should be 10 scfm per sq ft of fluidizing stone area. The aeration (fluidizing) blower should be sized at 10 scfm per sq ft and enough discharge pressure to overcome losses and still maintain 3-5 psig at the fluidizing air stones.

The hopper flow design for the recycle bin should be funnel flow. The pressure relief device on top of the recycle bin may be simply a hinged manhole cover or a device designed specifically to relieve pressure at a certain setpoint.

Additional design criteria are contained in the silo/day bin specification (Spec. No. M102) in Appendix E.

The recycle bin dust collector must be sized to filter the transport air from the positive pressure recycle transfer conveyor.

The use of an exhaust fan on the dust collector is optional. However, the slight negative pressure in the bin air space, created by the exhaust fan, will result in air in-leakage through any small openings in the bin roof instead of waste dust out-leakage, and it will minimize the possibility of waste dust filling and plugging the vent lines from the rotary feeders. For silos/bins located indoors, an exhaust fan is normally used to blow the air exiting the dust collector outside of the building.

The outlet dust loading from the dust collector is often specified by the State or local regulatory agency with jurisdiction. With no other guidance, a removal efficiency of 99.9% should be specified.

Other design criteria for the dust collector are contained in the bin vent dust collector specification (Spec. No. M103) in Appendix E.

Recycle Injection Equipment

Although there are a number of ways of metering the injected recycle material, the P&IDs show the material being discharged from the bin through a variable speed rotary feeder and into a dilute phase, positive pressure pneumatic conveying system through a constant speed air lock valve. The rotary feeder speed is controlled to maintain a specified recycle ratio. Controls are discussed in Section 8.0.

The injection conveyor should be a dilute phase pressure conveying system to provide a constant flow at the required pressure to the recycle injectors. A single pipe would convey the material to a distribution bottle near the flue gas duct where it is split into smaller, balanced loss pipes to each injector. Injector design is discussed in Section 6.2.1.1. From a flexibility and reliability standpoint, fresh sorbent and recycle material should be injected separately. This would allow the recycle system to be shut down without interrupting the fresh sorbent system.

The conveyor piping should be routed either vertically or horizontally with no more than a 15° deviation from vertical or horizontal to minimize particle drop out in the pipe.

One recycle rotary feeder/rotary air lock should be provided per duct. Each rotary feeder and rotary air lock should be sized for at least 100% of the design recycle material consumption for that duct based on the design Ca(OH)_2 consumption and recycle ratio. Recycle ratio is defined as lb recycle material per lb Ca(OH)_2 (excluding inerts) injected into the duct.

For good recycle feed control, rotary feeders in series with constant speed rotary air locks are recommended. The additional advantage of this arrangement is that any blowback of pressurized conveying air which leaks through the air lock will not prevent the material from flowing out of the recycle bin. A vent should be installed from the rotary air lock to the top of the bin to vent off this pressurized air (reference the P&IDs).

The recycle injection pneumatic conveying system capacity for each duct should be at least 100% of the design recycle material consumption for that duct. The recycle injection blowers should be sized for conveying velocities ranging from 4,000 to 6,000 ft/min. The air required for conveying the material is somewhat dependent on conveying distance. For a conveying distance of 100 ft, about 0.12 lb air per lb material is required compared to 0.17 lb air per lb material for 400 ft of conveying distance. Blowers are normally rated at just less than 15 psig discharge pressure to stay below the ASME pressure code requirements.

Additional design criteria are contained in the pneumatic transfer/injection conveyors specification in Appendix E.

A spare injection blower is not recommended to keep capital costs low and because the recycle system is not critical to the operation of the duct injection system. A spare set of rotary feeder/rotary air lock is also not shown in the P&IDs for the same reasons.

6.4.2 Duct Spray Drying Recycle

For the DSD process, the recycle material is conveyed and stored dry as in the DSI system, but then it is slurried with water and combined with the fresh lime slurry before injection into the duct.

Vacuum Pneumatic Ash Handling System

It is expected that many candidate plants for DSD retrofit will employ an existing vacuum pneumatic system to convey ash from the ESP to an existing ash silo. Because of the nature of vacuum ash handling systems, the ash has to be conveyed to the ash silo first before it can be recycled. It may be possible to modify the discharge equipment underneath the existing ash silo to allow a portion of the ash to be conveyed to a recycle storage bin for subsequent reslurrying and injection into the duct (see DSD P&ID Sheet 6A).

A positive pressure transfer conveyor will be required to pneumatically convey the waste from the ash silo to the recycle bin. A rotary air lock is attached to the silo discharge to feed the waste material into the transfer conveyor. The capacity of the rotary air lock/transfer conveyor should be two times the design recycle material consumption in the duct injection process as calculated by the criteria in Section 3.0. This margin allows for lost time due to system warm-up, interruptions in waste flow to the pipeline, purging of conveyor line prior to shutdown, and downtime for maintenance.

Typical capacities for a pneumatic transfer conveyor range from 25-40 ton/hr. If the required capacity, as estimated above, is significantly greater than 25-40 ton/hr, one or more of the following will have to be considered: 1) conveying for longer periods of time such as during the evening and/or graveyard shifts, 2) increasing the capacity of the transfer conveying system above 40 ton/hr (through discussions with conveyor suppliers), and 3) the use of two conveying systems to increase total conveying rate.

Typical pneumatic conveying velocities range from 4,000 to 6,000 ft/min for transfer of waste material. The air required for conveying the waste is somewhat dependent on conveying distance. For a conveying distance of 100 ft, about 0.12 lb air per lb waste is required compared to 0.17 lb air per lb waste for 400 ft of conveying distance. Blowers are normally rated at just less than 15 psig discharge pressure to stay below the ASME pressure code requirements.

Additional design criteria are contained in the pneumatic transfer/ injection conveyors specification (Spec. No. M105) in Appendix E.

A spare blower for the transfer conveyor is typically not required; only one blower is suggested as shown on DSD P&ID Sheet 6A. This is recommended because 1) the blower should only operate 50-60% of the time allowing time for routine maintenance, and 2) the recycle system is not critical to the operation of the duct injection system, i.e., the required SO₂ removal can be achieved without recycle solids.

A process alternative to the dilute-phase transfer system described above is a dense-phase pneumatic conveying system. Dense-phase systems require compressed air, but typically use only 1/10 the air volume of dilute-phase systems. Dense-phase systems are capable of much longer conveying distances.

Pressure Pneumatic/Mechanical Ash Handling System

If a positive pressure or mechanical ash handling system exists at the plant, a diverter gate may be installed in the ash line(s) to the existing ash silo to direct the ash/sorbent waste to a recycle bin for a portion of the time (reference DSD P&ID Sheet 6B). This design eliminates the need to convey the recycle solids out to the ash silo and then back to the process. In

addition, no modifications to the existing ash silo discharge equipment would be necessary. It may be possible to direct ash from only the hoppers nearest the ESP inlet to the recycle bin. Inlet fields collect the majority of the solids, including most of the unreacted lime.

Wet Sluicing Ash Handling System

As noted in Section 6.5.1.1, wet sluicing of waste from the ESP will not allow recycle operation.

Recycle Bin

The recycle bin storage capacity should generally be 8 hr worth of waste material at the design recycle material usage. Since recycle is not critical to the SO_2 removal process, a smaller bin (in times of hours of storage) is recommended compared to the lime day bin. A bulk density of 50 lb per cu ft may be used for capacity of waste material. The straight wall height should be 1.5-2.2 times the bin diameter, and a freeboard (unused volume above the level of a full bin) of 3 ft should be assumed.

Ash/sorbent waste tends to form rat holes and craters which can cause arching or bridging in storage. Either a 60° conical hopper or flat-bottom bin may be used, but fluidizing air is required for either design. The flat-bottom design generally is recommended because of its lower cost and its traditional acceptance for conventional fly ash applications. A bin activator or vibrator is not recommended on recycle bins as they tend to pack the material rather than enhance the flow. Fluidizing is recommended in conjunction with a dedicated recycle bin aeration blower. As noted in DSD P&ID Sheets 6A and 6B, a spare aeration blower is not recommended since the recycle system is not critical to the operation of the duct injection system. However, a tie-in from a plant service air line could be used as a back-up when the aeration blower is not available as was recommended for the hydrate lime silos and bins in Section 6.1.1.1.

Experience has shown that uniform surface coverage (fluidized bottoms) is better than concentrated local fluidization (fluidizing pads). Fluidized bottoms should be porous stone with a permeability rating of about 10 cfm per sq ft at 2 in. H_2O differential pressure. Although not shown on the P&IDs, a manually operated butterfly or ball valve should be installed in the line to each section of the fluidized bottom for trimming air flow.

Fluidizing air pressure should be 3-5 psig, and the air flow should be 10 scfm per sq ft of fluidizing stone area. The aeration (fluidizing) blower should be sized at 10 scfm per sq ft and enough discharge pressure to overcome losses and still maintain 3-5 psig at the fluidizing air stones.

The hopper flow design for the recycle bin should be funnel flow. The pressure relief device on top of the recycle bin may be simply a hinged manhole cover or a device designed specifically to relieve pressure at a certain setpoint.

Additional design criteria are contained in the silo/day bin specification (Spec. No. M102) in Appendix E.

The recycle bin dust collector must be sized to filter the transport air from the positive pressure recycle transfer conveyor.

The use of an exhauster fan on the dust collector is optional. However, the slight negative pressure in the bin air space, created by the exhauster, will result in air in-leakage through any small openings in the bin roof instead of waste dust out-leakage, and it will minimize the possibility of waste dust filling and plugging the vent lines from the rotary feeders. For silos/bins located indoors, an exhauster fan is normally used to blow the air exiting the dust collector outside of the building.

The outlet dust loading from the dust collector is often specified by the State or local regulatory agency with jurisdiction. With no other guidance, a removal efficiency of 99.9% should be specified.

Other design criteria for the dust collector are contained in the bin vent dust collector specification (Spec. No. M103) in Appendix E.

Recycle Injection Equipment

A rotary feeder is located below the recycle bin to meter the recycle material into a recycle slurry tank (reference DSD P&ID Sheets 6A and 6B). Since preparation of recycle slurry can be done continuously (compared to "batch" slaking of the lime slurry), the capacity of the rotary feeder only needs to be at least 100% of the design recycle material consumption. Generally, the design recycle consumption for DSD will occur when a 40% solids feed slurry is being injected into the duct(s), at maximum gas flow, at the minimum expected lime consumption. The design recycle consumption may be limited from the above calculated value due to the maximum solids loading the ESP is capable of treating while still being in compliance.

The dry recycle material is wetted in an agitated recycle slurry tank. Only one tank is recommended to keep capital costs low and because the recycle system is not critical to the operation of the duct injection system. The storage capacity of this tank should be either 2.5 or 8 hr worth of recycle slurry at the design recycle usage. Since recycle is not critical to the SO₂ removal process and because the rotary feeder can operate continuously, a smaller tank (in terms of hours of storage) is recommended compared to the lime slurry storage tank. The decision to select 2.5 or 8 hr of capacity is based on whether recycle slurry will be generated only once per shift or continuously. Typically, the solids content of the recycle slurry will vary from 40-45% (specific gravity of 1.29-1.33), but the design of the tank should be based on a range of 30-50% solids (specific gravity of 1.21-1.36).

The recycle slurry tank should have a minimum of 3 ft of freeboard (non-wetted wall height). This tank should be designed such that its wetted wall height is approximately equal to the tank diameter. This tank should be supplied with a venturi scrubber to pull a slight negative at the top of the tank. The design pressure should be atmospheric plus the fluid static height. A design temperature of 200°F is adequate. No personnel protection is necessary on this tank. A coating is not required, but a 3/8 in. carbon steel blast plate on the tank floor (in addition to the 1/4 in. floor plate) is recommended to resist erosion due to agitation of the abrasive ash. To be conservative, the 3/8 in. carbon steel liner should be extended 4 ft up the walls of the tank.

The recycle slurry tank agitator will be required to blend the recycle material with dilution water as well as keep the solids in suspension. The agitator will be required to achieve complete off-bottom suspension. The agitator must be capable of handling slurries ranging from 30-50% solids. This agitator should have two levels of blading.

Two 100%, redundant recycle slurry pumps should be provided to transfer recycle slurry to the atomizer feed tank. These pumps must be designed to accommodate the "clumps" from the recycle slurry tank. Box screens should be provided in the recycle slurry tanks over the pump suctions, but it is expected that 3/4-1 in. clumps will occasionally enter the pumps. The capacity (in gpm) of each pump should be at least 120% of the design recycle material consumption required for injection into the duct(s), diluted to 30% solids. The additional 20% capacity is recommended for pump wear and also to provide a minimum recirculation back to the recycle slurry tank even at design capacity. The pumps must be capable of handling slurries ranging from 30-50% solids. The design head and available NPSH for these pumps will depend on equipment layout.

Recycle slurry piping may be unlined schedule 80 carbon steel. The piping should be designed as a loop system with recirculation back to the recycle slurry tank so that flow to the atomizer feed tank can vary from minimum to maximum flow and still maintain enough velocity in the piping to minimize build-up inside the pipes. The piping would be periodically flushed with water to remove any build-up that occurred.

A recycle grit screen should be located above the atomizer feed tank to screen the recycle slurry (reference DSD P&ID Sheet 5). The recycle grit screen should have a 20 mesh screen. All slurry solids greater than 20 mesh will be rejected to a recycle oversize bin. The oversize bin should be a dumpster capable of being removed through a roll-up door using existing plant equipment. The capacity (in gpm) of the recycle grit screen should be equal to the capacity of each recycle slurry pump. The grit screen must be capable of handling slurries ranging from 30-50% solids.

Other design criteria for the rotary feeder, recycle slurry tank, agitator, slurry pumps, grit screen, and slurry valves are contained in Spec. Nos. M105, M113, M114, M115, M112, and M116, respectively, in Appendix E.

6.5 Waste Handling System

6.5.1 Waste Handling System Modifications

The physical, chemical, and mineralogical properties of the waste generated from a duct injection system will be different from fly ash. Several of these properties can affect the conveyance and storage of this material. To some extent, ash/sorbent waste from duct injection processes is similar to that from spray dryer scrubbers although there is considerably more unreacted $\text{Ca}(\text{OH})_2$ in the duct injection waste because of its inherently lower sorbent utilization.

In addition to a change in waste properties, the quantity of waste generated is the other most important factor in evaluating the effects of a duct injection retrofit on an existing waste handling system. Depending on the desired SO_2 removal, coal ash and sulfur content, and recycle rate, duct injection will increase the particulate loading to the particulate collection device by a factor of 2-12.

A waste handling system consists of five principle subsystems: conveying, storage, conditioning, transportation to the disposal site, and final disposal. The conveying, storage, conditioning of wastes produced by the DSI and DSD processes are addressed in this Section 6.5.1; the transportation and disposal of these wastes are covered separately in Section 6.5.2.

6.5.1.1 Conveying System

After the fly ash/sorbent waste is collected in the particulate collection device [usually an electrostatic precipitator (ESP)], a waste conveying system removes the waste from the collection hoppers and conveys it to a temporary storage area (bin or silo). The conveying equipment may consist of both feeders and conveyors.

There are several types of waste conveying systems:

1. Vacuum Pneumatic
2. Pressure Pneumatic
3. Mechanical
4. Wet Sluicing

Vacuum Pneumatic Conveying

The dilute phase, vacuum pneumatic system is probably the most widely used in the utility industry. However, after retrofit of DSI or DSD, this conveying system can potentially experience one or more of the following problems:

1. Plugging in ash intake valves
2. Build-up of material in conveying lines
3. Insufficient conveying capacity

Plugging in ash intake valves is the result of damp solids from the duct injection process and/or condensation caused by the reduced operating temperature in the ESP. Heat tracing

and insulating these intake valves should solve this problem. Fluidizing pads may be required in ESP hoppers to get DSI or DSD waste to flow into the conveying system. Two fluidizing stones per hopper are recommended.

Build-up and subsequent plugging in the conveying system is a result of the relatively poor flowability and hygroscopic nature of these wastes. Compared to fly ash only, a significant amount of waste may settle out of the air stream in vacuum conveying lines; most of these deposits will consist of calcium products. This is of special concern in areas of high ambient humidity. Such problems can be minimized by using dry, heated air for transporting the solids and/or heat tracing/insulating of the conveying lines. Extending the air inlets into heated enclosures may also be used. Retrofitting wide-angle elbows can reduce the plugging problems at bends. A regular inspection and maintenance program is recommended to minimize plugging of lines and elbows.

Insufficient conveying capacity is the result of increased solids loading to the ESP, especially in cases where recycle is used. A revision of the ash pulling schedule is the most straightforward and cost-effective solution. In cases where this is insufficient or impossible, increasing conveying air capacity and/or system component size may be necessary (conveying lines, blowers, bin receivers, etc.). Discussions with the supplier of the existing ash conveying system are the best way to evaluate increases in capacity.

If the existing system is currently at or near operational capacity, the best solution may be to replace a portion of, or the entire system with a new system designed to accommodate the full duct injection solids capacity. If adequate clearance exists, a pressure pneumatic ash handling system should be considered as the replacement if recycle of the collected waste will be utilized. This is discussed further in the pressure pneumatic subsection.

One method of increasing the conveying capacity, while continuing to utilize much of the existing equipment, is to replace the conveying system for the first field or first two fields of the ESP with a new, dedicated system while continuing to utilize the existing system for the last fields. As a rule of thumb, it is suggested that only the first field ash handling system could be replaced for a two or three field ESP; for four fields or more, the ash handling system in the first two fields could be replaced by a new system.

When installing a new system, the design waste conveying rate should include approximately a 100% margin over the maximum expected ESP waste collection rate to account for lost time due to system warm-up, interruptions in ash flow to the pipeline, gate changeover time, dump time of separating equipment, purging of conveyor line prior to shutdown, and downtime for maintenance.

In vacuum systems, the waste must first be transferred to the existing plant ash silo. If recycle of a portion of these solids is required, the recycle waste would then be conveyed from the ash silo directly to the duct or to a recycle bin as shown in DSI P&ID Sheet 5A and DSD P&ID Sheet 6A (this is discussed more in Section 6.4). In some cases, it will not be possible to modify the existing ash silo to convey material from it back to the process. In these cases, either recycle would not be possible, or a new ash silo would have to be constructed. The new silo would be capable of receiving waste from the ESP, and allowing it to be pneumatically conveyed back to the process as well as discharged to trucks, etc. This is discussed more in the storage discussion below (Section 6.5.1.2).

Pressure Pneumatic Conveying

Pressure pneumatic conveying systems are subject to the same potential operating problems and limitations (plugging/build-up in ash intakes and conveying lines) as vacuum pneumatic systems. The same solutions as discussed above apply to pressure pneumatic systems as well.

As with vacuum ash conveying systems, a revision of the ash pulling schedule is the most straightforward and cost-effective solution to insufficient conveying capacity after a duct injection retrofit. In cases where this is insufficient or impossible, increasing conveying air capacity and/or system component size may be necessary (conveying lines, blowers, pressure tanks, etc.). Discussions with the supplier of the existing ash conveying system are the best way to evaluate increases in capacity.

If the existing system is currently at or near operational capacity, the best solution may be to replace a portion of, or the entire system with a new system designed to accommodate the full duct injection solids capacity. One method of increasing the conveying capacity, while continuing to utilize much of the existing equipment, is to replace the conveying system for the first field or first two fields of the ESP with a new, dedicated system while continuing to utilize the existing system for the last fields. As a rule of thumb, it is suggested that only the first field ash handling system could be replaced for a two or three field ESP; for four fields or more, the ash handling system in the first two fields could be replaced by a new system.

When installing a new system, the design waste conveying rate should include approximately a 100% margin over the maximum expected ESP waste collection rate to account for lost time due to system warm-up, interruptions in ash flow to the pipeline, gate changeover time, purging of conveyor line prior to shutdown, and downtime for maintenance.

Pressure pneumatic ash handling systems allow recycle solids to be periodically diverted directly into a recycle bin for subsequent injection into the duct (reference DSI P&ID Sheet 5B and DSD P&ID Sheet 6B).

Mechanical Conveying

When considering the retrofit of DSI or DSD to plants that use a mechanical ash conveying system, the primary concern is conveying capacity. Since many mechanical conveying systems are designed to operate continuously, increasing cycle frequency may not apply. It may be possible to increase this capacity by increasing feeder or conveyor speed, increasing motor size, gearing changes, increasing screw flight diameters, etc. Discussions with the supplier of the existing ash conveying system are the best way to evaluate increases in capacity.

If the existing system cannot be modified to meet the expected increase in solids from duct injection, it may be necessary to replace a portion of, or the entire system with a new system designed to accommodate the full duct injection solids capacity. One method of increasing the conveying capacity while continuing to utilize much of the existing equipment, is to replace the conveying system for the first field or first two fields of the ESP with a new, dedicated system while continuing to utilize the existing system for the last fields. As a rule of thumb, it is suggested that only the first field ash handling system could be replaced for a two or three field ESP; for four fields or more, the ash handling system in the first two fields could be replaced by a new system.

When installing a new system, the design waste conveying rate should include approximately a 100% margin over the maximum expected ESP waste collection rate to account for lost time due to interruptions in ash flow to the conveyor, gate changeover time, and downtime for maintenance.

Mechanical ash handling systems allow recycle solids to be diverted directly into a recycle bin for subsequent injection into the duct - similar to a pressure pneumatic conveyor (reference DSI P&ID Sheet 5B and DSD P&ID Sheet 6B). However, the modifications required to achieve this would likely be extensive. It would likely be more cost-effective to continue to convey mechanically to the existing plant ash silo, and then convey the solids pneumatically from the ash silo back to the process (similar to vacuum ash conveying systems). In some cases, it will not be possible to modify the existing ash silo to convey material from it back to the process. In these cases, either recycle would not be possible, or a new ash silo would have to be constructed. The new silo would be capable of receiving waste from the ESP, and allowing it to be pneumatically conveyed back to the process as well as discharged to trucks, etc. This discussed more in the storage discussion below (Section 6.5.1.2).

In addition to capacity limitations, the physical properties of the ash/sorbent waste material may cause operational problems. As previously mentioned, these wastes are hygroscopic and exhibit poor flowability characteristics. They tend to be sticky and bridge over easily. In addition, the material will likely be easily aerated (similar to spray dryer waste), and this limits the speed at which it can be conveyed using mechanical conveyors without being wetted or enclosed.

The following discussion, paraphrased from EPRI's Calcium Spray Dryer Waste Management Design Guidelines, EPRI CS-5312, September 1987, describes potential modifications to mechanical conveying equipment after the retrofit of a duct injection system.

Belt Conveyors - The material to be transported may have to be wetted on the belt conveyor to minimize dusting problems. However, if the material is wetted, it may become sticky and special belt cleaners or scrapers may have to be installed to prevent material from accumulating on the belt. Wetting duct injection wastes also increases their potential to cause corrosion; therefore, special corrosion resistant materials of construction should be used.

Screw Conveyors - The typical screw conveyor consists primarily of a standard pitch helix (pitch equal to its outside diameter) supported within a U-shaped trough. These standard components may be modified, however, to improve operations and thereby broaden the range of useful applications.

The flight configuration (shape and/or pitch) can be varied to promote mixing, improve feed control or to improve the conveyability of sticky, lumpy or very free flowing materials. Almost any degree of mixing can be achieved with screw-conveyor flights which have been cut, cut and folded or replaced by a series of paddles. The use of ribbon flights allows sticky materials to be handled. Variable-pitch, tapered-flight, or stepped-flight units can provide precise control of the transport rate. Short-pitch screws retard flushing.

As stated previously, the conveyor screw is supported within a trough that typically is U-shaped. Alternate trough shapes also are available to improve conveyor operation. Rectangular troughs (with or without a detachable bottom) are frequently used for handling

hot or abrasive materials. During transfer in this type of trough, the material forms a layer on the bottom and partially up the side forcing the material in transit to travel on itself. Thus, abrasion is reduced and internal insulation is provided by the material itself. Tubular troughs are used for outdoor applications and for loading full cross-sections.

Standard materials of construction for screw fighting, flight mounting, troughs, trough ends, covers, hanger straps, feed/discharge spouts, gates, and shafting are generally satisfactory for most screw conveyor applications. However, when any of the following conditions are encountered, special construction materials are required.

1. Solids pack and build on the trough
2. Corrosive or abrasive materials are to be conveyed
3. The material to be conveyed is very wet

For conveyor applications involving duct injection waste, abrasion and possibly corrosion of the conveyor components should be considered. Solids may tend to build up on the trough if moisture is encountered; consequently, the first item listed above also may require consideration. The last item is not expected to be a concern with duct injection wastes.

Stainless steel or mild steel coated with epoxy resin, plastic, rubber ceramic or galvanizing is recommended for trough construction if solids build-up is expected to occur. Constructing most remaining conveyor components with coated mild steel will minimize the effects of abrasive and slightly to mildly corrosive materials during transfer.

Chain Conveyors - The primary component of all chain conveyors is the chain. Selection of the appropriate construction material for a given application generally is dependent on the required strength, expected travel speed and needed attachments (if any). To minimize excessive wear, chain material hardness (based on the Brinell Scale) also must be compatible with the abrasive and corrosive properties of the material to be conveyed (based on the Mohs Index). When severely abrasive materials are handled, special localized hardening can be applied to the areas subjected to wear. The resulting Brinell hardness generally is 180 to 200. Tables and/or graphs presenting acceptable Mohs Index values for materials of specified hardnesses are available to provide guidance during chain material selection.

Drag chain conveyors frequently are equipped with a Type "H" or "C" chain. These chain types are relatively wide, have broad, flat sliding surfaces, and range in pitch (length of one complete unit of chain) from 5 to 8 in. One of the primary differences between the two chains is working strength. Type "C" drag chains are available with working strengths of 7,000 to 9,300 pounds whereas Type "H" chains have lower strengths ranging from 3,500 to 6,500 pounds. Type "C" chains also have a greater wearing surface for sliding on both carrying and return runs. The welded steel chain is a relatively new development. This chain type is available as a drag chain and has a working strength that generally ranges from 10,000 to 15,000 pounds. A fourth type of drag chain, the "SD" chain, is often used when abrasive materials such as cement clinkers, slag and ashes are handled. This type of chain is similar to the first two types ("H" and "C") except it is fabricated from heavy, heat-treated cast alloy steel and has wide, flat Z-section sidebars. "SD" chains are available with a 6- or 9-in. pitch and working strengths of 16,700 to 23,400 pounds.

A standard en-masse conveyor is provided with straight flights. When some materials are conveyed vertically or even up a steep incline with a chain having this configuration, particles may tend to fall through the chain rather than travel with it. Consequently, the straight flights

are replaced with "U"- or "O"-shaped flights to increase the chain surface area in contact with the material and thereby enhance the ability of material particles to interlock with each other. These "U"- or "O"-shaped flights are covered with solid plates at calculated intervals when fine powdery materials are conveyed.

Bucket Conveyors - The primary components of a bucket elevator consist of:

1. Buckets
2. Carrying medium
3. Terminals
4. Casing

Presented below is a brief discussion of design considerations associated with each of these components.

Buckets - When relatively abrasive materials are handled and extra protection of the digging lip is required, style AA buckets are provided. Styles SC and C buckets are used to convey sticky materials that tend to pack in the bottom of the bucket. The style AC bucket, originally developed for cement plants, is primarily used for fine solids with fluid-like characteristics where large capacities are required or for highly abrasive free-flowing materials. This type of bucket is provided with a high front lip to increase capacity.

Carrying Medium - Two types of conveying medium are available for bucket elevators -- chain and belt. Belts generally are limited to centrifugal discharge type elevators. Belt and bucket elevators are well adapted to handling abrasive materials that would produce excessive wear on chains. They also are more suitable for high speed applications. However, belt type elevators are sensitive to elevated temperatures. Consequently, when temperatures in excess of 300°F are anticipated, chain elevators are used. Chain and bucket elevators also are equipped frequently with perforated buckets when handling wet materials, to drain surplus water.

Terminals - Chain elevators operate over head sprockets or traction wheels. Using traction wheels at the head-end of an elevator greatly increases both chain and wheel life. The traction wheel can be used on all centrifugal elevators except when handling materials of a lubricating nature. To operate successfully, the traction wheel requires a high coefficient of friction between the chain bushing and wheel surface. Properly applied, a traction wheel operates without slip, thereby eliminating the relative angular movement or scrubbing action between the chain and steel surface, which is typical of a sprocket and chain combination. The benefit derived from using a traction wheel in lieu of a head sprocket (increased chain and wheel life) is not as significant with continuous elevators because of the lower speeds. However, when used, care must be taken in the selection to eliminate the possibility of slip. Sprockets rather than traction wheels generally are used at the foot-end of an elevator. Engagement between the wheel and chain tends to be loose, resulting in poor guiding of the chain and buckets through the loading zone. Pulleys are used with belts. Elevator pulleys are either cast iron or welded steel with a nominal crown face for tracking. Head pulleys sometimes are covered with rubber belting, vulcanized rubber or non-skid fabric to provide a higher coefficient of friction between the belt and pulley.

Casing - Elevator casing usually is sectional, dust-tight and is fabricated with structural steel, sheet steel or aluminum. The boot section typically is of heavier gauge. Doors are provided for accessing elevator machinery.

Wet Sluicing Conveying

Very little is known about the potential effects of DSI or DSD wastes on a wet sluicing ash removal system. There are concerns regarding the cementitious properties of calcium-based materials that can potentially lead to plugging and scaling of venturies and conveying lines. The calcium in DSI and DSD wastes, however, has been hydrated prior to entering the process; the potential for any additional hydration in the sluice line is minimal. It is possible that periodic pigging of these lines or cleaning with high pressure water lances may be required to remove scale and deposits. Water addition to the waste material may increase environmental concerns by requiring wet disposal (the unreacted lime in the waste will likely raise the pH of the sluice to as high as 12).

As with vacuum ash conveying systems, a revision of the ash pulling schedule is the most straightforward and cost-effective solution to insufficient conveying capacity after a duct injection retrofit. In cases where this is insufficient or impossible, increasing conveying capacity and/or system component size may be necessary (conveying lines, venturies, tanks, etc.). Discussions with the supplier of the existing ash conveying system are the best way to evaluate increases in capacity.

If the existing system is currently at or near operational capacity, the best solution may be to replace a portion of, or the entire system with a new system designed to accommodate the full duct injection solids capacity. One method of increasing the conveying capacity, while continuing to utilize much of the existing equipment, is to replace the conveying system for the first field or first two fields of the ESP with a new, dedicated system while continuing to utilize the existing system for the last fields. As a rule of thumb, it is suggested that only the first field ash handling system could be replaced for a two or three field ESP; for four fields or more, the ash handling system in the first two fields could be replaced by a new system.

When installing a new system, the design waste conveying rate should include approximately a 100% margin over the maximum expected ESP waste collection rate to account for lost time due to system warm-up, interruptions in ash flow to the pipeline, gate changeover time, purging of conveyor line prior to shutdown, and downtime for maintenance.

Ash sluicing systems wet the ash to a dilute slurry. Therefore, this type of ash handling system is not conducive to recycling the material back to the process. In DSI, the recycle material needs to be dry, so wet sluicing will not allow recycle operation. For DSD, the waste material is slurried with water, but usually to a 40-45% solids slurry - not 20% solids typical of a wet sluicing system. Therefore, wet sluicing will generally not be compatible with recycle of material back into the duct.

Recommended Testing

The waste properties are expected to vary with different plant designs and operating conditions. Therefore, tests to assess accurate waste characteristics should be performed for each DSI or DSD installation as part of the selection and equipment design process. If testing is performed at laboratory-scale, field conditions must be duplicated to give as-conveyed conditions (e.g., ambient conditions at the plant must be considered).

6.5.1.2 Storage

An ash silo or bin is usually in place to provide surge capacity between ash production and transport to disposal. The increased volume of waste solids resulting from a duct injection retrofit will reduce the surge capacity. To compensate for this reduction:

1. the frequency of discharging the waste solids for disposal must be increased; expanding the ash hauling schedule over a longer period, or increasing the number of trips (or trucks) may be necessary, and/or
2. additional storage capacity may be required; additional waste solids silos may be added to maintain the number of hours or days of storage.

A new storage silo may be desired for two reasons: 1) to increase surge capacity, and 2) to allow waste to be recycled back to the process - the existing ash silo may not be physically capable of being modified to allow material to be recycled.

If another silo(s) is desired, it should be large enough so that, between the existing and new silo(s), 90 hr of surge capacity is provided. This provides surge capacity over a three-day weekend from 3:00 p.m. Friday afternoon to 9:00 a.m. Tuesday morning. The new silo(s) should be fitted with a dry unloading spout to accommodate the recycle system rotary feeders, etc., as shown in DSI P&ID Sheet 5A and DSD P&ID Sheet 6A, as well as the traditional rotary unloader or pug mill for unloading into trucks, etc. A bulk density of 50 lb per cu ft may be used for capacity of waste material. The straight wall height should be 1.5-2.2 times the silo diameter, and a freeboard (unused volume above the level of a full silo) of 5 ft should be assumed.

If a new, dedicated ash handling system is installed on the first field(s) of the ESP, the waste conveyed from these fields should empty into the new silo fitted with recycle system provisions. This should be done because the material in the first field(s) would likely have the largest percentage of unreacted lime; therefore, this would be the material of choice to be recycled.

Discharge of waste from an ash silo after DSI or DSD retrofit can be different from that with fly ash only. Due to the physical properties mentioned above, the potential for bridging and rat-holing is much greater. Existing ash silos can likely be utilized after duct injection retrofit, but fluidization (if not already existing) will likely be required to effect material discharge. A bin activator or vibrator is not recommended on ash silos as they tend to pack the material rather than enhance the flow. Fluidizing is recommended in conjunction with a dedicated ash silo aeration blower. A spare aeration blower is not recommended; however, a tie-in from a plant service air line could be used as a back-up when the aeration blower is not available as was recommended for the hydrate lime silos and bins in Section 6.1.1

Experience has shown that uniform surface coverage (fluidized bottoms) is better than concentrated local fluidization (fluidizing pads). Fluidizing bottoms should be porous stone with a permeability rating of about 10 cfm per sq ft at 2 in. H₂O differential pressure. A manually operated butterfly or ball valve should be installed in the line to each section of the fluidized bottom for trimming air flow.

Fluidizing air pressure should be 3-5 psig, and the air flow should be 10 scfm per sq ft of fluidizing stone area. The aeration (fluidizing) blower should be sized at 10 scfm per sq ft and

enough discharge pressure to overcome losses and still maintain 3-5 psig at the fluidizing air stones.

In addition to fluidizing, hopper modifications such as air cannons, poke holes, or strike plates may be required when using existing silos for storage.

New ash silos may utilize either 60° conical hoppers or flat-bottoms, but fluidizing air is required for either design. The flat-bottom design generally is recommended because of its lower cost and its traditional acceptance for conventional fly ash applications.

New ash silos should be designed similarly to the requirements given above for modifications to existing silos with regard to fluidizing system, air cannons, poke holes, strike plates, etc.

The hopper flow design for new ash silos should be funnel flow. The pressure relief device on top of new ash silos may be simply a hinged manhole cover or a device designed specifically to relieve pressure at a certain setpoint.

Additional design criteria are contained in the silo/day bin specification (Spec. No. M102) in Appendix E.

Recommended Testing

To predict flow from storage vessels, flow properties should be determined by conducting special direct shear, controlled strain tests. The flow properties obtained from these tests are bulk density, effective internal angle of friction during flow, internal angle of friction in incipient flow, kinematic angle of wall friction, and unconfined yield strength. To obtain an accurate assessment of these flow properties, test procedures must reflect the conditions expected to occur within a storage vessel such as compaction pressure and moisture content.

6.5.1.3 Conditioning

Conditioning can be used to make DSI or DSD wastes more amenable for transport and disposal. The alternatives are:

1. Conditioning the waste with water
2. Blending the waste with sludge
3. Pelletizing or sintering the waste

The technique of pelletizing or sintering the waste is used primarily for utilizing the waste product instead of disposing of it. But pelletizing or sintering also may be useful prior to disposal. This process reduces and controls the waste volume, prevents dusting problems, and reduces leaching potential in the landfill. However, the costs associated with these processes are typically very high.

Blending the dry waste with dewatered FGD sludge is another alternative for waste conditioning. The advantages of this method over separate disposal of these wastes are easier handling and stabilizing of the sludge.

The most common method of conditioning dry waste is the addition of water prior to disposal. The proper amount of water must be added to control dust generation during truck loading

and transport without causing the waste to harden or set up. Generally this will require about 15-25% water, by weight, but this value should be verified by appropriate testing for specific applications.

An existing pug mill or rotary unloader is usually in place to condition the ash for transportation to disposal. As with the conveying and storage systems, additional equipment may be required to handle the increased waste solids volume. If another ash silo is erected, then another pug mill or rotary unloader will be required. Regardless, between the existing and any new conditioners, the recommended feed rate to the conditioners is:

$$\frac{7 \text{ days (168 hr) of waste @ max ESP collection rate (in tons)}}{19.2 \text{ hr}}$$

The rationale behind this equation is that the full ash silo(s) needs to be emptied after a three-day weekend (actually 90 hr of collection as noted in Section 6.5.1.2) from Tuesday morning through Friday afternoon of the following week. While the silo is being emptied, however, waste continues to be conveyed into it; from 9:00 a.m. Tuesday morning to 3:00 p.m. Friday afternoon adds another 78 hr worth of waste. The total tons of waste to be conditioned is 168 hr worth. The time available for actually feeding this tonnage of waste to the unloader is assumed to be 19.2 hr: four 8-hr day shifts at an assumed unloader operating percentage of 60%. The assumed value of 60% of actual unloader operation accounts for the time interval between trucks, time for normal truck spotting, operator break times, etc. This percentage will vary from plant to plant. Ready access of conditioning equipment is important for daily wash-down.

As an alternative to water, specialty chemicals including surfactants and foam are commonly used to suppress dust from solids handling systems. The advantages of these specialty chemicals are that they reduce water requirements.

6.5.2 Waste Disposal

The physical, chemical, and mineralogical properties of the waste generated from a duct injection system will be different from fly ash. Several of these properties can affect the transportation, utilization, and final disposal of this material. To some extent, ash/sorbent waste from duct injection processes is similar to that from lime spray dryer scrubbers although there is considerably more unreacted Ca(OH)_2 in the duct injection waste because of its inherently lower sorbent utilization.

The most significant concerns about the disposal of wastes from calcium-based duct sorbent injection processes have been identified as:

1. Possible human health and operating effects associated with handling very powdery, alkaline materials.
2. The corrosive nature of very alkaline solutions.
3. The calcium content of the solids may lead to cementitious reactions when exposed to moisture.
4. The possibility of highly alkaline discharges (pH greater than 12) from storage areas.

In addition to a change in waste properties, the quantity of waste generated is the other most important factor in evaluating the effects of a duct injection retrofit on an existing waste disposal system. Depending on the desired SO_2 removal and coal ash and sulfur content, duct injection will increase the disposal waste quantity by a factor of 1.8 to 5.0.

6.5.2.1 Transportation Methods

After the fly ash/sorbent waste has been conveyed from the ESP to the ash storage silo and conditioned, the transportation subsystem transports the waste material from the plant area to the disposal site. Likely existing transport systems include:

1. Trucks
2. Belt Conveyors
3. Pneumatic Conveyors
4. Wet Sluicing
5. Rail Cars
6. Barges

Trucks

The primary advantages of truck transport are flexibility and reliability. The capacity of the system can be increased by simply increasing the number of trucks and/or operating shifts. They are typically the most flexible and practical alternative when considering the nature of landfill operations. Also, they often are the most practical alternative when considering surface mine disposal at mine mouth stations.

After new waste production rates have been determined, the number of trucks and operating shifts which must be provided in order to transport the increased material quantity can be estimated. Different truck sizes and numbers of shifts should be investigated in order to satisfy the increased demand on the waste transport subsystem.

The potential corrosivity (high pH) and dust problems associated with duct injection wastes should be considered when an existing truck transport system is being utilized. Corrosion may cause deterioration of truck bodies faster than for fly ash only. Special liners or materials of truck construction may be used and/or trucks can be cleaned regularly to minimize this problem. Dust problems can be minimized by either wetting the material, covering open trucks with tarps, or using enclosed truck trailers.

Belt Conveyors

The speed of the existing belt conveyor(s) may have to be increased to accommodate the greater throughput after the duct injection retrofit. However, this may not be practical because, since DSI and DSD wastes are easily aerated, this limits the speed at which they can be conveyed using belt conveyors without being wetted or enclosed. The material to be transported may have to be wetted on the belt conveyor to minimize dusting problems. However, if the material is wetted, it may become sticky and special belt cleaners or scrapers may have to be installed to prevent material from accumulating on the belt. Wetting duct injection wastes also increases their potential to cause corrosion; therefore, special corrosion resistant materials of construction may be required.

Pneumatic Conveyors

Pneumatic conveying has seen only limited applications in the transport of utility wastes. Pneumatic conveying systems are not economically efficient at distances greater than approximately 7,500 ft.

After retrofit of a DSI or DSD system, a pneumatic conveying system can potentially experience one or more of the following problems:

1. Plugging in ash intake valves
2. Build-up of material in conveying lines
3. Insufficient conveying capacity

Plugging in ash intake valves is the result of damp solids from the duct injection process and/or conditioning. Heat tracing and insulating these intake valves should solve this problem.

Build-up and subsequent plugging in the conveying system is a result of the relatively poor flowability and hygroscopic nature of these wastes. Compared to fly ash only, a significant amount of waste may settle out of the air stream in vacuum conveying lines; most of these deposits will consist of calcium products. This is of special concern in areas of high ambient humidity. Such problems can be minimized by using dry, heated air for transporting the solids and/or heat tracing/insulating of the conveying lines. Extending the air inlets into heated enclosures may also be used. Retrofitting wide-angle elbows can reduce the plugging problems at bends. A regular inspection and maintenance program is recommended to minimize plugging of lines and elbows.

Insufficient conveying capacity is the result of increased waste production rate. A revision in the waste conveying schedule is the most straightforward and cost-effective solution. In cases where this is insufficient or impossible, increasing conveying air capacity and/or system component size may be necessary (conveying lines, blowers, etc.). Discussions with the supplier of the existing conveying system are the best way to evaluate increases in capacity. If the existing system is currently at or near operational capacity, the best solution may be to replace the entire system with a new system designed to accommodate the full duct injection waste disposal rate.

Wet Sluicing

Very little is known about the potential effects of DSI or DSD wastes on a wet sluicing transport system. There are concerns regarding the cementitious properties of calcium-based materials that can potentially lead to plugging and scaling of venturiers and conveying lines. The calcium in DSI and DSD wastes, however, has been hydrated prior to entering the process; the potential for any additional hydration in the sluice line is minimal. It is possible that periodic pigging of these lines or cleaning with high pressure water lances may be required to remove scale and deposits.

Water addition to the waste material may increase environmental concerns by requiring wet disposal (the unreacted lime in the waste will likely raise the pH of the sluice to as high as 12). A liquid separation and reclaim water system or other special modifications may be required at the disposal area similar to mineral tailings systems.

Rail Cars

The same comments regarding increase in waste quantity, dustiness, and corrosivity apply to a railroad transport system as were discussed above for a truck system.

Barges

If analyses of the DSI or DSD waste indicate no major problems with corrosivity and dusting, standard barges can be used. More frequent hauling will be required due to the increase in waste to disposal.

6.5.2.2 Final Disposal Methods

Waste disposal is the final placement of the waste in a permanent location. The three most common disposal methods in use for fly ash are landfill, mine disposal, and wet impoundment (pond).

Water conditioning to control dusting during transport and to achieve the optimum moisture content for disposal is a critical factor in the handling characteristics of DSI and DSD waste material. Too much water causes the material to become sticky and hard to handle and to possibly set up in the transport equipment. Not enough water results in ineffective dust control. Optimum moisture appears to be 30-40% by weight. A properly mixed fly ash/sorbent waste product will, in most cases, enhance the landfill operation due to the pozzolanic action of the lime portion. This will tend to decrease the permeability of the waste and form a cementitious crust that will deter erosion of the exposed surface. In addition, it can significantly reduce the leachability of potentially problematic elements (As, Ba, Cd, Pb, Se, etc.).

In general, the potential environmental risks posed by DSI/DSD wastes appear to be minimal. The moisture content, dry density, strength, and permeability of these wastes are such that landfill without a liner should be generally adequate. The leachability of the RCRA-regulated elements are below current RCRA standards. However, certain State and/or local regulations may pose restrictions on the disposal of the waste from these processes. These regulations need to be considered when applying this technology.

If additives are used in the duct injection process, testing will be required to determine their effect on disposal properties such as strength, permeability, and leachate properties.

Modification of Existing Disposal Areas

If there is capacity remaining in the existing disposal area which is currently accepting coal combustion wastes, it should be considered for duct injection wastes. Because the site already is being used for waste disposal, information should be available for the site including geotechnical data and permitting information. This information will provide a basis upon which to begin analyses of any required disposal area modifications. Disposal modification may require only modifying existing permits as opposed to repeating the entire permitting process.

Any modifications to existing disposal areas should consider embankment stability and possible contamination of surface water and ground water. The following discussion,

paraphrased from EPRI's Calcium Spray Dryer Waste Management Design Guidelines, EPRI CS-5312, September 1987, describes the evaluations required after the retrofit of a duct injection system.

Embankment Stability - Physical instability is a potential problem for all coal combustion by-product disposal areas. Stability is influenced by: physical waste properties such as waste density, strength, degree of saturation, effective cohesion, effective angle of shearing resistance, and behavior during shearing (dilatant versus densifying); site conditions including geotechnical characteristics of the in-place foundation material; and geometric factors such as the heights and outslopes (or slope angles) of embankments. In general, for a given material, the maximum safe embankment height decreases with increasing slope angle. The effective slope angle of the embankment may be flattened by either lowering the slope angle (outslope) itself or by constructing benches. Benches also aid in the control of surface runoff and in providing access to all areas of the landfill face. In fact, many State regulations require benches on embankments and dictate minimum spacing and sizes. Benches are usually placed every 20 to 50 ft in vertical height and typically vary in width from 10 to 30 ft. However, flattening the outslope and/or constructing benches reduces the capacity of a landfill. Foundation material also should be analyzed; weak underlying material can lead to instability and slope failure. Design measures should be taken to minimize any potential problems with weak foundation material. Surface water and ground water controls influence the amount of moisture in the waste material and, therefore, effect the stability of embankments.

Surface Water - The potential for surface water contamination depends upon the amount of water that passes through, or is in contact with, the waste material. Therefore, in order to reduce contamination, the amount of surface water entering the landfill should be minimized. This is usually done by constructing diversion channels at the perimeter of the landfill to divert runoff from adjacent areas away from the site. Diversion of this water will reduce the amount of leachate generated, reduce erosion of the landfill, and decrease the amount of runoff from the site that must be controlled, collected or treated. All surface runoff from the active area of the site should be collected. At a minimum, this water should be passed through a sedimentation pond. In addition, it should be tested for possible contamination and treated if necessary. The site should be staged so that only runoff from the disturbed, uncovered area is collected. Limiting the drainage area to only the disturbed area reduces the amount of runoff entering the pond and reduces its size and associated cost. Therefore, landfill staging is important in sizing sedimentation ponds.

Ground Water - The potential for ground water contamination is related to the amount of water passing through the waste material, the quality of the leachate produced, and existing geologic and ground water conditions. Measures can be taken to reduce the potential for degradation of ground water aquifers. These measures are instituted because of specific site conditions, waste material characteristics and regulatory requirements. The amount of water passing through the waste material and subsequent leachate generation can be reduced by constructing diversion channels at the perimeter of the landfill and grading the waste material to drain both during construction and after reclamation. The quality of leachate varies with different DSI or DSD wastes depending on many process factors. Whether or not the leachate is a potential problem is also a function of both site location and regulatory requirements (i.e., more control measures probably will be required if a landfill is located over an area with a shallow, high-quality aquifer than if it is located in an isolated area). If the leachate contains contaminants exceeding the EPA drinking water standards, hazardous waste criteria, or other appropriate limitations, measures may be required to reduce potential adverse ground water impacts. These measures could include: installing a liner under the disposal area to minimize

leachate entering the ground water aquifer, constructing a leachate collection system to collect leachate, installing an under-drain for the landfill to collect springs and seeps thereby preventing this water from contacting the wastes, constructing diversion channels and grading the landfill to minimize surface water which can enter the landfill and generate leachate, and constructing a leachate treatment facility to treat this leachate before discharging it to the environment. Existing geologic conditions also can affect the ground water at the site. The site should ideally be located over an area with a deep, low-quality, ground water aquifer containing low permeability soils. However, most sites do not involve ideal conditions and require at least some limited measures to minimize leachate.

Design conditions will vary depending on whether the existing disposal area is a landfill, surface mine, or wet impoundment.

Modifying Existing Landfill Disposal Areas

Conventional landfill disposal areas currently receiving other combustion wastes may be able to receive duct injection wastes without significant modifications to the landfill. Because of the additional waste quantities generated with duct injection, however, the storage capacity of the disposal area will be expended over a shorter time period, shortening the life of the disposal site in general. Expansion of the landfill may extend its life; expansion can be accomplished by either horizontally or vertically enlarging the landfill.

In designing modifications for an existing landfill disposal area, the first step is to compare properties of DSI or DSD wastes with the properties of those wastes currently placed in the disposal area. The new waste properties should be used to verify the original design and develop new designs if required.

As discussed above, DSI and DSD wastes should be placeable in landfills with few potential impacts due largely to their inherently cementitious properties which reduce permeabilities and leachate quantities as well as constituent leachability. These properties also increase the strength of the wastes generally as compared to conventional fly and bottom ash, thereby improving their engineering performance.

Waste disposal at a landfill site will be subjected to numerous passes of earth-moving equipment and trucks. Because of this, the structural integrity of the waste is very important. Permeability is greatly affected by the amount of landfill compaction. It is therefore recommended that all DSI and DSD waste material landfill operations incorporate a layered compaction procedure.

Modifying Existing Mine Disposal Areas

Existing mine disposal areas currently receiving other coal combustion wastes may be able to receive duct injection wastes without major modifications to disposal operations. However, the final grades of the reclaimed mine have to be raised to allow for increased waste quantities.

Leachate and strength properties of DSI and DSD wastes should be compared to like properties for wastes currently being placed in the mine. In many cases, the new wastes will have greater strength and, therefore, will not affect mine disposal adversely. If questionable, stability and leachate analyses for mine disposal of the wastes should be performed.

Modifying Existing Wet Disposal Areas

There are two basic approaches to utilizing existing wet impoundments for disposal of duct injection wastes. The first is to continue impoundment disposing of the wastes in slurry form. The second is to drain the impoundment, stabilize the existing wastes, and landfill dry DSI or DSD wastes upon the drained impoundment wastes.

If the impoundment will continue to be used for wet disposal, duct injection wastes can be pumped to the impoundment in slurry form. However, due to the increased quantities of wastes, the slurry line to the impoundment may have to be increased in size, and the remaining life of the impoundment will be shortened. Also, due to the high pH of the slurry and the tendency of these wastes to "set-up", steps must be taken to prevent associated problems with the waste transport system (e.g., sufficiently dilute slurry, line maintenance, etc.).

New Disposal Areas

If it becomes necessary to build a new landfill, State and/or local permitting requirements may be much more stringent than Federal regulations. Site selection will be based upon transportation and economic considerations as well as technical and environmental criteria.

Because the landfill disposal option is so common, state-of-the-art environmental protection techniques have been developed and are becoming commonplace in the industry. Clay liners, impermeable synthetic liners, leachate collection/detection, ground water monitoring, and runoff/leachate collection, settling, and treatment systems are examples of this technology which are being used to meet today's stringent environmental protection requirements.

6.6 General Support Equipment

6.6.1 Dry Sorbent Injection (Ref. DSI P&ID Sheet 6)

Atomizing Air Compressors/Receiver

In the design presented in the P&IDs, service and instrument air are assumed to be available from the existing plant compressors; new service and/or instrument air compressors are not shown.

Centrifugal air compressors are suggested to provide atomizing air to the humidification nozzles. Three, 50% capacity compressors are recommended to supply the total air required. A spare compressor is recommended because of the high maintenance historically required for these machines.

The discharge pressure and total air capacity required will depend on the specific nozzles utilized (reference Section 6.2); however, as a conservative approximation, a 125 psig discharge pressure and an air-to-water ratio of 0.5 lb air per lb humidification water are appropriate. This 0.5 design air-to-water ratio should be applied to the design humidification water requirement as calculated in Section 3.0.

If an aftercooler is included in the compressor package (which is how the air compressor specification in Appendix E is written), the discharge temperature of the compressed air should be 20-25°F above the cooling water inlet temperature. Normally, compressor capacity is rated in ICFM (inlet cubic ft per minute); therefore, the total compressed air in lb/hr, as calculated using the suggested air-to-water ratio given above, has to be converted to ICFM. In the compressor industry, ICFM is typically based on intake pressure (barometric pressure minus 0.3 psi for inlet air filter losses), 60°F, and prevailing relative humidity.

For simplicity, a value of 60% relative humidity may be chosen to calculate ICFM and moisture content entering the compressor. A dry bulb temperature of 60°F and 60% relative humidity result in about 0.0065 lb water per lb dry air (at 14.696 psia). The molecular weight of air with this humidity is 28.74 lb/lb mole.

There is one complication in making these air requirement calculations: a portion of the water vapor in the compressor inlet air condenses out in the intercoolers/aftercooler. Based on a 125 psig compressor discharge pressure and a 105°F discharge temperature, about 40% of the inlet water vapor will condense. Therefore, the air which discharges the compressor will have a specific humidity of about 0.0039 lb water per lb dry air and a molecular weight of 28.78 lb/lb mole.

The air requirement at the compressor discharge in X lb/hr may be converted to ICFM as follows:

$$\text{ICFM} = \frac{(X \text{ lb/hr})(1.0065)(520^\circ\text{R})[10.73 \text{ psia}\cdot\text{ft}^3/(\text{lb mole})]}{(1.0039)(28.74 \text{ lb/lb mole})(P_b - 0.3 \text{ psia})(60 \text{ min/hr})}$$

Where: P_b = Barometric pressure in psia

Each of the 50% capacity compressors should be sized for 1/2 of the total air required for all of the duct injection points.

All of the air compressors should discharge to a common air receiver. This vessel would provide a small amount of surge capacity and would provide air to the nozzles for a short time in case of an emergency shutdown or power loss to the air compressors. The air receiver should have a design pressure of 150 psig in accordance with Section VIII, Div. 1 of the ASME Boiler and Pressure Vessel Code. The capacity of the receiver should be about 10 sec of reserve air consumption based on the total design air requirement. The 10 sec capacity should be based on actual air volume at the compressor discharge (ACFM @ 125 psig and 100-115°F).

$$\text{ACFM (at compressor discharge)} = \frac{(X \text{ lb/hr})(T_D + 460^\circ\text{R})[10.73 \text{ psia-ft}^3/(\text{lb mole})]}{(28.78 \text{ lb/lb mole})(P_B + 125)(60 \text{ min/hr})}$$

Where: T_D = Compressed air discharge temperature in °F
 P_B = Barometric pressure in psia

Other design criteria for the atomizing air compressors and air receiver are contained in the air compressor specification (Spec. No. M601) in Appendix E.

Water Tanks

A raw water tank and blowdown water tank should be provided for surge capacity and to facilitate water pump suction. Only one tank is needed for each service to keep capital costs low and because there are few problems with water tanks. The raw water tank would hold the "good" quality water to be used for hydrating, etc. The blowdown water tank would hold the poorer quality water to be used for flue gas humidification, waste conditioning, etc. Typically, this water is comprised largely of cooling tower blowdown, ash pond return water, etc. If ash pond return water is used, a duplex strainer should be located in the water inlet line to the blowdown water tank.

The storage capacity of these tanks should be about 1 hr at their respective design water consumptions. The raw water and blowdown water tanks should have a minimum of 3 ft of freeboard (non-wetted wall height) unless the required diameter is less than 10 ft; in that case, the freeboard may be 1.5 ft. These tanks are vented to atmosphere, so the design pressure should be atmospheric plus the fluid static height. A design temperature of 200°F is adequate. No personnel protection is necessary on these tanks unless the source water is very hot for some reason. A lining is not required, but an epoxy coating should be used on the internal surfaces. Other design criteria for the water tanks are contained in the tank specification (Spec. No. M113) in Appendix E.

Water Pumps

Two 100%, redundant water pumps should be provided for each water service noted on the P&IDs. The capacity (in gpm) of each pump should be at least 120% of the design water consumption for each service. The additional 20% capacity is recommended for pump wear and also to provide a minimum recirculation back to the respective water tank even at design capacity. The hydration water pumps (for on-site hydration of pebble lime) need to have sufficient capacity to supply water to the hydrators while operating at their design rating. For the humidification water pumps, the capacity of each pump should be at least 120% of the design water required for cooling the flue gas to a 20°F approach to saturation. The waste conditioning water pumps need to have sufficient capacity to supply water to the pug mill or rotary unloader while operating at its design rating. The design head and available NPSH for

these pumps will depend on equipment layout. Water piping may be schedule 40 carbon steel.

A duplex humidification water filter is recommended (reference DSI P&ID Sheet 6). This equipment will filter the humidification water sprayed into the duct to minimize nozzle wear. The filter should have 40 micron elements. The capacity of the filter should be equal to the capacity of each humidification water pump.

6.6.2 Duct Spray Drying (Ref. DSD P&ID Sheet 7)

Atomizing Air Compressors/Receiver

In the design presented in the P&IDs, service and instrument air are assumed to be available from the existing plant compressors; new service and/or instrument air compressors are not shown.

Centrifugal air compressors are suggested to provide atomizing air to the slurry nozzles. Three, 50% capacity compressors are recommended to supply the total air required. A spare compressor is recommended because of the high maintenance historically required for these machines.

The discharge pressure and total air capacity required will depend on the specific nozzles utilized (reference Section 6.2); however, as a conservative approximation, a 125 psig discharge pressure and an air-to-slurry ratio of 0.5 lb air per lb slurry are appropriate. This 0.5 design air-to-slurry ratio should be applied to the design slurry flow requirement as calculated in Section 3.0.

If an aftercooler is included in the compressor package (which is how the air compressor specification in Appendix E is written), the discharge temperature of the compressed air should be 20-25°F above the cooling water inlet temperature. Normally, compressor capacity is rated in ICFM (inlet cubic ft per minute); therefore, the total compressed air in lb/hr, as calculated using the suggested air-to-slurry ratio given above, has to be converted to ICFM. In the compressor industry, ICFM is typically based on intake pressure (barometric pressure minus 0.3 psi for inlet air filter losses), 60°F, and prevailing relative humidity.

For simplicity, a value of 60% relative humidity may be chosen to calculate ICFM and moisture content entering the compressor. A dry bulb temperature of 60°F and 60% relative humidity result in about 0.0065 lb water per lb dry air (at 14.696 psia). The molecular weight of air with this humidity is 28.74 lb/lb mole.

There is one complication in making these air requirement calculations: a portion of the water vapor in the compressor inlet air condenses out in the intercoolers/aftercooler. Based on a 125 psig compressor discharge pressure and a 105°F discharge temperature, about 40% of the inlet water vapor will condense. Therefore, the air which discharges the compressor will have a specific humidity of about 0.0039 lb water per lb dry air and a molecular weight of 28.78 lb/lb mole.

The air requirement at the compressor discharge in X lb/hr may be converted to ICFM as follows:

$$\text{ICFM} = \frac{(X \text{ lb/hr})(1.0065)(520^\circ\text{R})(10.73 \text{ psia}\cdot\text{ft}^3/(\text{lb mole}))}{(1.0039)(28.74 \text{ lb/lb mole})(P_b - 0.3 \text{ psia})(60 \text{ min/hr})}$$

Where: P_b = Barometric pressure in psia

Each of the 50% capacity compressors should be sized for 1/2 of the total air required for all of the duct injection points.

All of the air compressors should discharge to a common air receiver. This vessel would provide a small amount of surge capacity and would provide air to the nozzles for a short time in case of an emergency shutdown or power loss to the air compressors. The air receiver should have a design pressure of 150 psig in accordance with Section VIII, Div. 1 of the ASME Boiler and Pressure Vessel Code. The capacity of the receiver should be about 10 sec of reserve air consumption based on the total design air requirement. The 10 sec capacity should be based on actual air volume at the compressor discharge (ACFM @ 125 psig and 100-115°F).

$$\text{ACFM (at compressor discharge)} = \frac{(X \text{ lb/hr})(T_D + 460^\circ\text{R})(10.73 \text{ psia}\cdot\text{ft}^3/(\text{lb mole}))}{(28.78 \text{ lb/lb mole})(P_b + 125)(60 \text{ min/hr})}$$

Where: T_D = Compressed air discharge temperature in °F
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Other design criteria for the atomizing air compressors and air receiver are contained in the air compressor specification (Spec. No. M601) in Appendix E.

Water Tanks

A raw water tank and blowdown water tank should be provided for surge capacity and to facilitate water pump suction. Only one tank is needed for each service to keep capital costs low and because there are few problems with water tanks. The raw water tank would hold the "good" quality water to be used for slaking, etc. The blowdown water tank would hold the poorer quality water to be used for flue gas humidification and waste conditioning, etc. Typically, this water is comprised largely of cooling tower blowdown, ash pond return water, etc. If ash pond return water is used, a duplex strainer should be located in the water inlet line to the blowdown water tank.

The storage capacity of these tanks should be about 1 hr at their respective design water consumptions. The raw water and blowdown water tanks should have a minimum of 3 ft of freeboard (non-wetted wall height) unless the required diameter is less than 10 ft; in that case, the freeboard may be 1.5 ft. These tanks are vented to atmosphere, so the design pressure should be atmospheric plus the fluid static height. A design temperature of 200°F is adequate. No personnel protection is necessary on these tanks unless the source water is very hot for some reason. A lining is not required, but an epoxy coating should be used on the internal surfaces. Other design criteria for the water tanks are contained in the tank specification (Spec. No. M113) in Appendix E.

Water Pumps

Two 100%, redundant water pumps should be provided for each water service noted on the P&IDs. The capacity (in gpm) of each pump should be at least 120% of the design water consumption for each service. The additional 20% capacity is recommended for pump wear and also to provide a minimum recirculation back to the respective water tank even at design capacity. The slaking water pumps need to have sufficient capacity to supply water to the slakers while operating at their design rating. The dilution water pumps should be designed to supply the required dilution water for cooling the flue gas to a 20°F approach to saturation. The recycle ash water pumps should be sized to wet the design recycle material consumption to a 30% solids slurry. The waste conditioning water pumps need to have sufficient capacity to supply water to the pug mill or rotary unloader while operating at its design rating. The design head and available NPSH for these pumps will depend on equipment layout. Water piping may be schedule 40 carbon steel.

7.0 PLANT AND EQUIPMENT ARRANGEMENT CONSIDERATIONS

7.1 Equipment Configurations

Individual pieces of new equipment should be sized and designed in accordance with the suggestions of Section 6.0. This section gives suggestions and ideas to consider when selecting a duct injection equipment configuration and while laying out the new equipment.

7.1.1 Lime Unloading Arrangement and Silo Location

Normally, lime shipments (whether hydrated lime or pebble lime) will be by enclosed truck or rail car. Lime shipments by covered barge are also a possibility, but barge shipment is not covered in this handbook.

For off-site hydration in the DSI process, the hydrate silo may be located either right next to the injection point(s) or remote from it as space and unloading constraints permit. However, the most reliable and economical feed rate control of the hydrated lime will be achieved if the silo is located close to the injection point(s). If the silo cannot be located near the injection point(s), the user may want to consider pneumatically transferring the lime from the remote silo to a hydrate day bin located close to the injection point(s). This case is not shown on the PFDs or P&IDs in Section 5.0.

For the on-site hydration option in DSI, the pebble lime silo, hydrators, and hydrate bin may be located either right next to the injection point(s) or remote from it as space and unloading constraints permit. However, to achieve the most reliable feed rate control of the hydrated lime, the hydrate bin should be located as close to the injection point(s) as possible, even if the silo and hydrators are located remotely.

For the DSD process, the pebble lime silo may be located either right next to the injection point(s) or remote from it as space and unloading constraints permit. Locating the silo close to the injection point(s) is preferable; however, if the silo cannot be located near them, it is considered more feasible to pneumatically convey lime from the silo to a small day bin located near the injection point(s) [and have the slurry preparation accomplished close to the injection point(s)] than to prepare the slurry near the remote silo and pump it a long distance to the injection point(s). This is especially true because a slurry return line to the atomizer feed tank is normally required to keep slurry pipeline velocities high. From a practical standpoint, slurry should be prepared within 200 ft of the point of use. If the silo can be located close to the duct injection point(s), a separate lime day bin is not required.

7.1.1.1 Truck Delivery

For truck delivery, the lime is typically unloaded by the driver using the truck-mounted blower. No additional equipment is required. If lime delivery by truck is the only mode utilized, two truck fill pipes per silo are recommended. They should be located far enough apart to allow spotting of two trucks concurrently. On the other hand, two lines located close together will facilitate installation and reduce costs, and this arrangement may be used if space around the silo will allow two trucks to back up to the silo side-by-side. A concrete slab (or pavement as a minimum) in the area around the lime silo(s) is recommended to aid in vacuuming/washdown and general housekeeping. If faster unloading is required, a high capacity stationary blower can be installed near the base of the storage silo. Associated flex hose and

truck connection fittings should be included. The truck unloading blower could be operated by plant personnel or the truck operator.

7.1.1.2 Rail Car Delivery

For rail car delivery, a separate rail spur is necessary to store the cars while waiting to be unloaded or picked up. An insulated unloading shed should be located over the spur which is long enough to completely enclose at least one rail car so that the doors at each end may be closed. This allows the shed to be heated in the winter and controls the dusting. At least 12 ft of clearance is required above the car. Permanent building heat should be provided. A dust collector with suction fan should be installed on the shed to control the dusting. A concrete floor (or pavement as a minimum) should be provided within the shed to aid in vacuuming/ washdown and general housekeeping. All blowers, local electrical equipment, and local controls associated with the unloading equipment should be located within the unloading shed.

The rail car unloading equipment may be vacuum only, combined vacuum-pressure, or positive pressure only (reference Spec. No. M101 in Appendix E). If vacuum unloading is utilized, the vacuum hose needs to be long enough and oriented in such a way as to reach all of the hoppers on the rail car without moving the car once it is spotted within the shed. If vacuum unloading is used, the elevation of the finished floor between the tracks should be lower than the top of the tracks by about 2 in. to aid in locating the rail car connectors which clamp to the rail car hopper outlets. In a vacuum-only rail car unloading system, the filter receiver(s) is located on top of the lime storage silo(s) and the silo(s) must be located near the rail car unloading point (typically within 100-250 ft). Vacuum blowers (depending on site elevation and corresponding barometric pressure) can convey lime only a few hundred feet.

If a combined vacuum-pressure or positive pressure-only unloading system is selected, the silo(s) may be located remote from the unloading point. This is true because pressure blowers can convey the lime up to 1500 ft. Longer distances than 1500 ft are possible, but the conveying horsepower required becomes very high. In a combined vacuum-pressure system, the filter receiver is typically located inside the unloading shed.

7.1.2 Sorbent Injector Placement in DSI

As discussed in Section 6.2.1.4, sorbent injection in the DSI process should be upstream of, or in the same plane as, humidification water injection.

7.1.3 Slaking/Slurry Handling in DSD

If ball mill-type slakers are selected, they need to be supported on concrete pedestals at grade. The resulting slurry flows by gravity into the relatively small ball mill sump tanks and is then pumped to the lime slurry storage tank. Detention and paste slakers are typically mounted on the second floor of the process equipment building, and they overflow through screens to the lime slurry storage tank mounted below at grade.

The atomizer feed tank should be located as close as practical to the injection point(s) to minimize the slurry pumping distance. This distance should be no more than 200 ft.

7.1.4 General Equipment Arrangement Considerations

A general statement can be made that most of the equipment associated with a duct injection system is fairly maintenance intensive. Therefore, the entire system should be designed and laid out to allow ready access for operation and maintenance of all components. **Sufficient area around all equipment including tanks, slakers, hydrators, feeders, vibrating screens, compressors, blowers, and pumps should be provided for operation and maintenance laydown: 3ft-6in. clear as a minimum.**

Silo/bin hoppers and all process equipment including blowers, feeders, and conveyors should be located inside insulated buildings with heating and ventilation. This is recommended for freeze protection, to minimize weather contamination of the sorbent, and to make it more convenient and comfortable for operations and maintenance personnel to perform their duties. Whether a DSI or DSD process is selected, the sorbent will quickly be everywhere; containing it to a building is aesthetically useful.

Hydrated lime can be particularly fine and lime slurry particularly messy; housekeeping will be a major effort. Fine lime particles have been known to penetrate sealed NEMA 4 electrical cabinets. All electrical cabinets and controls should be centralized in pressurized "clean" rooms. Due to excessive dusting in DSI systems with on-site hydration, it is recommended that the hydrators be located in their own "room" within the process equipment building.

Sloping floor trenches (18 in. wide, 6-18 in. deep) and a 7 ft cube (minimum) sump should be located in the process equipment building to facilitate washdown and general housekeeping. The sump should be accessible for muck-out by vacuum truck. Equipment, process, and other contaminated drainage should be hard-piped to the sump (or trench). Floor drains in elevated floors where washdown will occur should include permanently installed piping from the drains to the sump (or trench). A sump agitator and sump pump should be provided to pump the collected drainage to an ash pond or other drain system.

All instruments, lighting, local electrical equipment, and internal building siding panels must be of a sealed design such that periodic washdown will not damage them.

A weather enclosure should be constructed next to the duct where the nozzle array manifolds and distribution headers extend from the duct. This enclosure will make it more convenient and comfortable to monitor air and liquid pressures, temperatures, and flow rates to each nozzle array and sorbent injector array (for DSI only). The enclosure will also facilitate change-out of nozzle arrays, strainer maintenance, etc.

7.2 Retrofit Considerations

Existing plant equipment modifications should be accomplished in accordance with the suggestions of Section 6.0. This section gives suggestions and ideas to consider when interfacing the duct injection equipment into the existing plant. Interface with existing plant controls are discussed separately in Section 8.0.

7.2.1 Plant Utility Interfaces

A single point of supply for the following utilities will normally be required to be furnished by the user from the plant.

- Make-up water
- Raw water
- Cooling water
- Potable water
- Fire protection water
- Auxiliary steam
- Condensate return
- Service air (excluding atomizing air)
- Instrument air

Make-up water is used for flue gas humidification, slurry dilution (if applicable), hose down, and flushing. It is typically cooling water blowdown/clarifier underflow. Make-up water should be used to the greatest extent possible. A complete washdown water distribution system including piping, valves, pressure reliefs, and connections with hoses should be installed in the retrofit buildings/areas at a maximum of 100 ft intervals.

Raw water should be used only where absolutely necessary. It may be used for slaking, hydration, cooling water, and slurry pump seals. If raw water is not suitable for cooling water purposes (such as compressor cooling), a separate source of plant cooling water should be provided. Potable water should be used for emergency eye wash, shower facilities, and domestic uses only. If replaceable, non-piped emergency shower and eye wash stations are provided, potable water may not be required. Fire protection water is required depending on the design and insurance requirements of the fire protection system within the retrofit buildings/areas.

Auxiliary steam required for use in slaking water preheat and building heating is typically 150 psig saturated.

Service air will be required for pneumatic tools, maintenance, etc. Separate, new compressors would normally be required to supply the compressed air for the operation of the humidification or slurry nozzles, whichever are applicable. A complete service air distribution system including piping, valves, pressure reliefs, and connections with hoses should be installed in the retrofit buildings/areas at a maximum of 100 ft intervals.

Instrument quality air (-40°F dewpoint) would normally be required from the plant for the control valves, etc.

7.2.2 Waste Handling and Recycle System

7.2.2.1 Existing Vacuum Pneumatic System

If the existing vacuum system is currently at or near operational capacity, it may be necessary to replace a portion of, or the entire system with a new system designed to accommodate the full duct injection solids capacity. If adequate clearance exists, a pressure pneumatic ash handling system should be considered as the replacement if recycle of the collected waste will be utilized.

One method of increasing the conveying capacity, while continuing to utilize much of the existing equipment, is to replace the conveying system for the first field or first two fields of the ESP with a new, dedicated system while continuing to utilize the existing system for the last fields. As a rule of thumb, it is suggested that only the first field ash handling system could be replaced for a two or three field ESP; for four fields or more, the ash handling system in the first two fields could be replaced by a new system.

In vacuum systems, the waste must first be transferred to the existing plant ash silo. If recycle of a portion of these solids is required, it may be possible to modify the discharge equipment underneath the existing ash silo to allow a portion of the waste to be conveyed from the ash silo directly to the duct, or to a recycle bin for subsequent injection into the duct. One possibility is to tie in to an existing dry unloading spout. In some cases, it will not be possible to modify the existing ash silo to convey material from it back to the process. In these cases, either recycle would not be possible, or a new ash silo would have to be constructed. The new silo would be capable of receiving waste from the ESP, and allowing it to be pneumatically conveyed back to the process as well as discharged to trucks, etc.

For units where injection will occur in a single duct, the recycle solids may be metered and then dilute-phase conveyed (using a variable speed rotary feeder and constant speed rotary air lock underneath the ash silo) directly back to the duct distribution header. For this design, the need for a separate recycle storage bin is eliminated. For larger units, especially units with more than one duct/ESP, ash will normally be dilute-phase or dense-phase conveyed from the existing or new ash silo to a recycle bin; from the recycle bin, it will be metered and dilute-phase conveyed using rotary feeders/rotary air locks to the various injection points. The recycle bin, if used, should be located near the injection points.

7.2.2.2 Existing Pressure Pneumatic System

If the existing pressure system is currently at or near operational capacity, it may be necessary to replace a portion of, or the entire system with a new system designed to accommodate the full duct injection solids capacity. One method of increasing the conveying capacity, while continuing to utilize much of the existing equipment, is to replace the conveying system for the first field or first two fields of the ESP with a new, dedicated system while continuing to utilize the existing system for the last fields. As a rule of thumb, it is suggested that only the first field ash handling system could be replaced for a two or three field ESP; for four fields or more, the ash handling system in the first two fields could be replaced by a new system.

Pressure pneumatic ash handling systems allow recycle solids to be periodically diverted directly into a recycle bin for subsequent injection into the duct. A diverter gate may be installed in the ash line(s) to the existing ash silo to direct the ash/sorbent waste to a recycle

bin for a portion of the time. This design would eliminate the need to convey the recycle solids out to the ash silo and then back to the process. In addition, no modifications to the existing ash silo discharge equipment would be necessary. The recycle bin should be located near the injection point(s).

7.2.2.3 Existing Mechanical System

If the existing mechanical system is currently at or near operational capacity, it may be necessary to replace a portion of, or the entire system with a new system designed to accommodate the full duct injection solids capacity. One method of increasing the conveying capacity while continuing to utilize much of the existing equipment, is to replace the conveying system for the first field or first two fields of the ESP with a new, dedicated system while continuing to utilize the existing system for the last two fields. As a rule of thumb, it is suggested that only the first field ash handling system could be replaced for a two or three field ESP; for four fields or more, the ash handling system in the first two fields could be replaced by a new system.

Mechanical ash handling systems allow recycle solids to be periodically diverted directly into a recycle bin for subsequent injection into the duct - similar to a pressure pneumatic conveyor. However, the modifications required to achieve this would likely be extensive. It would likely be more cost-effective to continue to convey mechanically to the existing plant ash silo, and then convey the solids pneumatically from the ash silo back to the process (similar to vacuum ash conveying systems). It may be possible to modify the discharge equipment underneath the existing ash silo to allow a portion of the waste to be recycled. One possibility is to tie in to an existing dry unloading spout. In some cases, it will not be possible to modify the existing ash silo to convey material from it back to the process. In these cases, either recycle would not be possible, or a new ash silo would have to be constructed. The new silo would be capable of receiving waste from the ESP, and allowing it to be pneumatically conveyed back to the process as well as discharged to trucks, etc.

If a diverter gate can be installed in the ash line(s) to the existing ash silo, a new conveyor could direct the ash/sorbent waste to a recycle bin for a portion of the time. This design would eliminate the need to convey the recycle solids out to the ash silo and then back to the process. In addition, no modifications to the existing ash silo discharge equipment would be necessary. The recycle bin should be located near the injection point(s).

7.2.3 Special Cases

Numerous site-specific duct designs and plant arrangements will be encountered when retrofitting a duct injection process. Specific examples of special design considerations for retrofitting this technology are presented below.

7.2.3.1 Two Existing ESPs in Series

Two ESPs in series often result due to a retrofit of a second ESP to improve overall particulate collection efficiency. Two ESPs in series introduce options with regards to the point at which humidification water and sorbent may be injected. These options affect the potential for downstream material deposition and ductwork corrosion.

Since current data indicate lime injection upstream of, or in the same plane as, humidification water spray provides superior sorbent utilization for the DSI process, injecting the lime and water in this manner into the duct just downstream of the first ESP may be the most effective configuration. This arrangement is similar to the HYPAS process developed by EPRI. Adding a portion of the humidification water upstream of the first ESP would be attractive since it would improve the performance of that ESP; however, the potential for corrosion from SO_3 makes this option unacceptable. In addition, modeling suggests that the fraction of water unevaporated at the inlet of the second ESP is not improved significantly by introducing some of the humidification water upstream of the first ESP.

Injecting the sorbent just upstream of, or in the same plane as, the humidification array is expected to protect the downstream ductwork from SO_3 corrosion. The two ESPs in series may allow for operating at higher net utilization since most of the fly ash is removed by the first ESP.

7.2.3.2 Two Existing ESPs in Parallel

Two ESPs in parallel often result due to a retrofit of a second ESP to improve overall particulate collection efficiency. In many instances, the original ESP will have been "close coupled" to the boiler air preheater allowing almost no residence time for a duct injection retrofit. The ductwork to the second ESP may be more amenable to retrofit of duct injection. However, three issues must be considered if nozzles are installed upstream of one ESP, but not the other: 1) entrainment of flue gas causing maldistribution, 2) corrosion of downstream ductwork, and 3) low overall SO_2 removal.

The very high velocity of the spray exiting the nozzle causes the flue gas to become entrained - significantly altering the flue gas velocity profile. Much higher flue gas velocities would result in the vicinity of the nozzles. Depending on where the nozzles are located, this may disrupt the distribution of flue gas between the two ESPs.

If duct injection is retrofitted to one of the ESP trains, but not the other, the mixing of the humidified, cool gas from one ESP with the hot, SO_2/SO_3 laden gas from the other could cause the combined gas temperature to fall below the acid dew point of the mixed stream. This could result in severe corrosion to ductwork and the stack liner downstream of the mix point.

The third issue to consider if duct injection is applied to only one train is that 50-60% SO_2 removal across one train may result in only 20-35% overall SO_2 removal for the unit as a whole (depending on the gas flow rate split between the two ESPs).

7.2.3.3 Possibility of Stack Lean

Recent experience in the FGD industry has shown that mixing of a hot, dry gas with a cool, saturated gas in a stack may result in differential expansion and the ultimate leaning of a brick and mortar stack liner. A similar condition could exist with a retrofit project wherein duct injection is applied to only one of two duct trains which discharge to a common stack. At power stations where two or more units feed into a common flue, this situation could also occur.

In all observed cases of liner lean, the liners have been constructed of brick and mortar. In several of the stack lean cases observed, a scrubbed gas breeching has been located above the hot bypass gas breeching. This gradient has caused the differential expansion

experienced. In cases where two flue streams of different temperature enter a common chimney, the cool and hot gas breechings should be located opposite of each other at the same elevation. There should be no turning vanes located inside the stack so that the mixing of these two gas streams will occur quite rapidly and violently. The opposite breeching arrangement is believed to present a lower risk of stack lean. For retrofits of duct injection at existing plants, this potential problem would require careful analysis.

7.2.3.4 Excessive Length of ESP Outlet Ductwork

If the outlet ductwork from the ESP to stack is exceptionally long (greater than 300 ft), the heat loss through this ductwork would limit the humidification approach temperature because of concerns that downstream condensation might cause ductwork corrosion. The approach temperature which would minimize the potential for corrosion would depend on the length of the outlet duct run. The primary design criterion is to achieve a minimum 20°F approach temperature at the stack inlet. For a 300 ft ESP outlet duct run, the required approach temperature at the ESP inlet is estimated to be about 50°F. However, this high of an approach temperature at the ESP inlet would limit SO₂ removal. To operate at closer approach temperatures may require the application of protective coatings or linings to the outlet duct and stack, or adding a reheat system. All of these modifications will have significant capital cost impacts.

7.2.3.5 Effect of Sloped Ducts/Duct Bends

Some units may have adequate duct residence time only if two duct sections with an inclusive bend are considered. These units would be considered marginal from a humidification viewpoint. Similarly, sloped duct runs are present at some plants. With no field experience to draw upon, it should be assumed that bends in ducts and sloped ducts could present some special concerns for the placement of sorbent injectors and atomizer arrays. Flow models should be used to determine the need for additional turning vanes or gas flow distribution devices. Any wall deposition in sloped ducts could pose special problems. Deposited solids could slide down the duct and create large localized build-ups. This could, however, simplify an on-line solids removal system if a single hopper could be installed at the point of build-up.

7.2.3.6 Ash Silo Common to Several Units

It is quite possible that a duct injection system will be retrofit onto a unit which shares a common ash silo with one or more other units at the station. This would not be a major concern (other than the fact that the silo will fill more quickly than before the retrofit), but the effectiveness of any waste material recycled back to the duct from the ash silo would be diminished. This would be due to the "dilution effect" of the non-calcium containing fly ash from the unaffected unit(s).

As noted previously in Sections 6.4 and 7.2.2, if an existing pressure pneumatic or mechanical system is used to convey ash/sorbent waste from the unit being retrofitted to the ash silo, the system should be modified to convey solids directly to a recycle bin for a portion of the time. This design would eliminate the need to convey the recycled solids out to the ash silo and then convey "diluted" solids back to the process. The recycle bin would then contain undiluted material which would be recycled back to the duct injection point(s).

If an existing or modified vacuum pneumatic system is used, all of the solids must first be transferred to the ash silo, and then conveyed back to the process. For the DSI process,

recycle of diluted solids with a large percentage of fly ash will not increase utilization significantly. Therefore, if the DSI process is selected for a unit which would utilize a vacuum pneumatic waste handling system and which shares an ash silo with an unmodified unit, recycle of the collected waste material is not suggested. The one exception to this recommendation is if a new ash silo will be built. Then, waste handling systems could be designed such that all or most of the material entering the new silo would be duct injection ash/sorbent waste. In that case, recycle of this material directly back to the duct, or to a recycle bin for subsequent injection into the duct, would increase utilization and SO_2 removal.

If the DSD process is selected for a unit which would utilize a vacuum pneumatic waste handling system and which shares an ash silo with an unmodified unit, recycle of the collected waste material is recommended whether or not a new ash silo is erected. This recommendation is based on the fact that recycle material is needed to keep the feed slurry solids content high for drying purposes. If the recycle solids contain significant unreacted calcium, so much the better; but, whether or not recycle solids contain significant calcium, they are necessary. Slurries with 30-40% solids dry much easier than 10-20% solids slurries. The recycle material is needed to add to the lime slurry to increase the feed slurry solids content.

7.2.3.7 Positive Pressure ESP

If the ESP(s) is located downstream of the ID fans, there would be a greater potential for dust leakage into the penthouse with the increased solids loading resulting from a duct injection system. This would increase the possibility of shorting out a field. If not already pressurized, the penthouse would require a pressurization system to minimize this potential problem.

8.0 PROCESS CONTROL

This section provides suggestions for the control of a duct injection system including overall control system philosophy and hardware requirements. Specific and detailed control system design is outside of the scope of this handbook.

8.1 Process Control System Philosophy

8.1.1 Dry Sorbent Injection

Because there are so many sheets and control logic lines to track, the suggested DSI process control scheme given in the P&IDs in Section 5.3.1 can be somewhat difficult to follow. Therefore, a simplified version of the overall DSI control philosophy is given in Figure 8-1. Basically, there are two main control loops: 1) a flue gas temperature control loop, and 2) an SO₂ control loop. For DSI, these two loops are essentially independent.

Flue Gas Temperature Control Loop

Flue gas temperature downstream of the injection point in the DSI process is controlled by evaporative cooling. Humidification water is sprayed into the ductwork to humidify the gas to the desired approach to adiabatic saturation temperature. Since approach to saturation directly affects sorbent utilization and SO₂ removal, maintaining the desired approach is extremely important. This is more critical in processes such as DSI with inherently low sorbent utilization. Ideally, a DSI process should be operated at the closest approach to saturation possible without incurring operational problems such as deposition of wet solids. This critical balance requires accurate measurement and control of the flue gas temperature.

The primary objective of the temperature control loop is to maintain the desired approach to saturation temperature at the ESP inlet. However, this requires measurement of the saturation temperature of the flue gas (also called the wet bulb temperature). This can be measured upstream of the sorbent and humidification water injection point or downstream of the ESP. Ideally, it is preferable to measure wet bulb upstream of the ESP to minimize the effects of in-leakage and thermal inertia in the ESP which tend to dampen process changes. However, measuring the wet bulb upstream of the ESP is very difficult due to the high particulate loading at that point. Even in areas of low particulate loading, there are few continuous wet bulb monitors that are commercially offered and even fewer that are reliable. Currently, the most reliable method of wet bulb temperature determination is a manual measurement in which a thermocouple covered with a wetted cotton wick is inserted into the flue gas stream.

Since air heater outlet flue gas conditions of temperature and humidity tend to change with load, fuel quality, and boiler operations, the flue gas wet bulb temperature tends to fluctuate. Therefore, an "ideal" operating temperature is difficult to maintain. The development of a reliable continuous wet bulb monitor will improve this capability, but until this technology is perfected, a more conservative control approach is recommended: the temperature control loop should maintain a setpoint flue gas dry bulb temperature at the ESP inlet. The dry bulb temperature setpoint chosen should be established at the desired approach to saturation temperature (see Section 3.2.1) based on the flue gas saturation temperature at normal boiler operating conditions (see Section 3.1.5). This control scheme will result in fluctuating approach temperatures as wet bulb temperature fluctuates. This somewhat conservative practice is typical in spray dryer scrubbing.

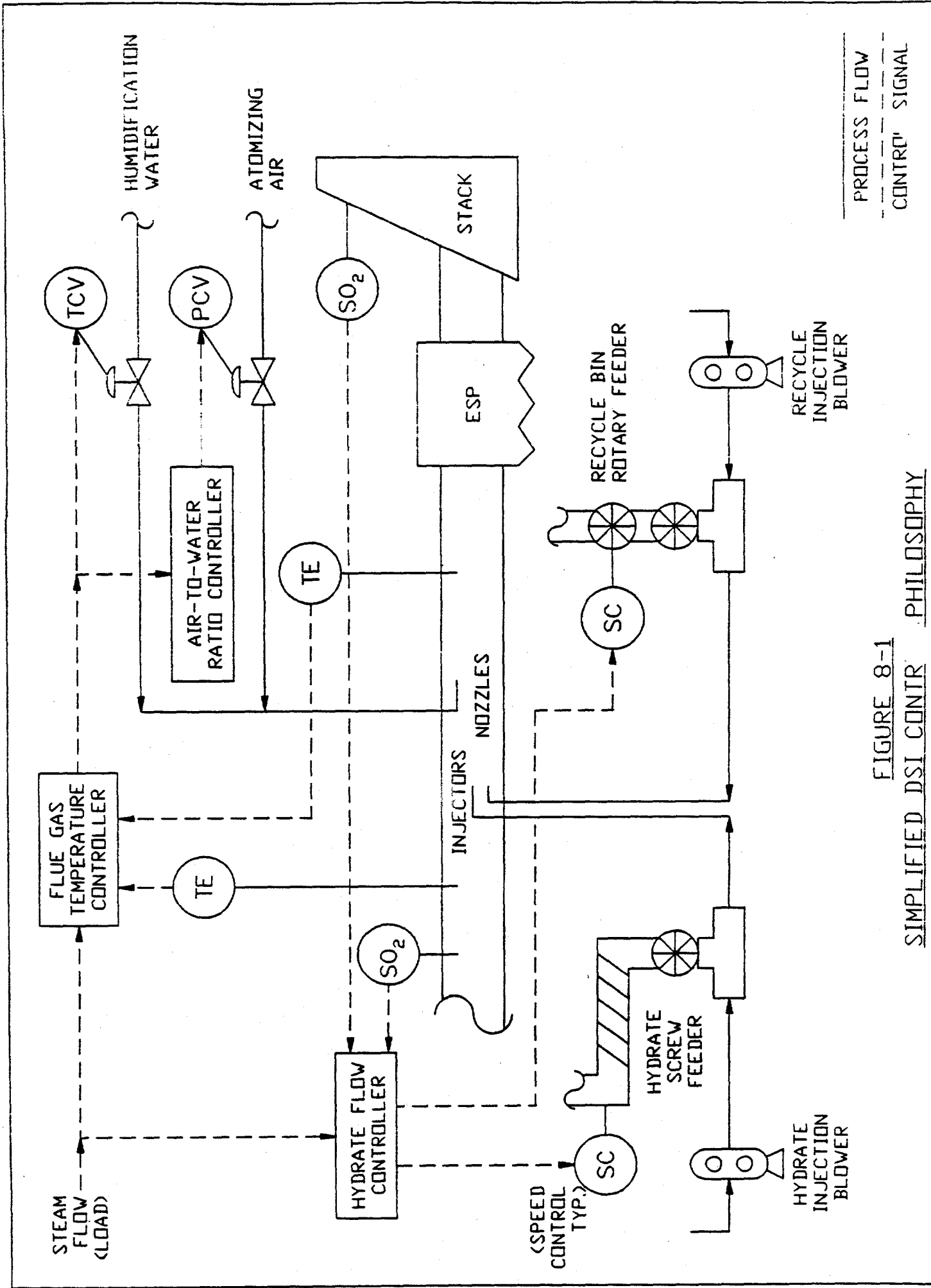


FIGURE 8-1
SIMPLIFIED DSI CONTR PHILOSOPHY

The use of a distributed control system, programmable logic controller, or similar automatic feed-forward/feedback control system is desirable. The temperature controller should be programmed for the proper response time/rate to changes in measured duct temperature caused by system dynamics. This will help prevent overspraying episodes. The temperature data acquisition device should have the capability of indicating average temperature in the grid as well as individual thermocouple probes. Alarms can be attached to the thermocouple probe outputs to indicate water injection problems.

For best control, the flue gas temperature controller should operate in a feed-forward/feedback loop. A steam flow signal will be input to the controller to give a feed-forward indication of flue gas flow which will exit the air heater; the temperature of this flue gas will also be input to the controller (reference Figure 8-1). Shielded thermocouples in the duct downstream of the injection point will provide the feedback input to the controller. Based on this combination of feed-forward and feedback signals, the controller will adjust the humidification water flow rate to maintain a desired flue gas temperature setpoint (dry bulb) at the ESP inlet. This is actually accomplished by modulating the temperature control valve in the water line feed to the injection point.

Although controlling the approach to saturation temperature at the ESP inlet is of primary importance, the temperature controller must also monitor and maintain an adequate flue gas temperature at the ESP outlet. This is important because of the corrosion potential in this region of ductwork. Typically, the temperature downstream of the ESP should be at least 20°F above saturation for corrosion protection.

DSI systems have the potential for operational swings, and upstream conditions can change rapidly. Some causes of these changes could be boiler load swings, sootblowing, tube leaks, steam coil operation, etc. Therefore, it is advisable to have feed-forward capability so that sudden changes in upstream conditions will not cause DSI process upsets. A sudden drop in air heater outlet flue gas temperature, for example, would be sensed by the controller and the humidification water flow rate reduced accordingly, rather than waiting for the ESP inlet temperature to drop before reducing water flow.

Other safety interlocks should be part of the temperature control scheme. A minimum of three thermocouples should provide signals to the controller at the ESP inlet. The average of these three values is used to determine the feedback control. If one of the measurements is more than 4°F from the average, it should be considered to be erroneous and not included in the average calculation. If all three of the temperature measurements are more than 4°F apart, the controller should control to a default, safe setpoint. Another interlock which should be provided to prevent loss of control is that, if the approach temperature drops to less than 25°F, the controller would automatically revert to the default setpoint.

Another useful alarm or interlock would be a signal from the powerhouse when sootblowers are activated. A maximum humidification water flow rate switch (not shown on the P&IDs) should be added in the water feed line to ensure that an approach temperature of less than 20°F cannot be achieved. Water valves should fail shut; atomizing air valves should fail open. The difference between the atomizing air pressure and the water feed pressure to the nozzles should be interlocked to maintain adequate spray formation.

SO₂ Control Loop

The heart of the SO₂ control loop will be the hydrate flow controller. For best control, the hydrate flow controller should operate in a feed-forward/feedback loop. A steam signal will be input to the controller to give a feed-forward indication of flue gas flow which will exit the air heater; the SO₂ concentration of this flue gas will also be input to the controller (reference Figure 8-1). This latter signal is provided by an inlet SO₂ analyzer located in the ductwork just downstream of the air heater. An outlet SO₂ analyzer (typically located in the stack) will provide the feedback input to the controller. Based on this combination of feed-forward and feedback signals, the controller will adjust the hydrated lime flow rate to maintain either a constant percent removal of SO₂ or required emission limit (lb/10⁶ Btu, lb/hr, etc.). This is actually accomplished by adjusting the speed of the hydrate variable speed screw feeders. The hydrate flow controller also adjusts the speed of the recycle material rotary feeders to maintain the desired recycle ratio setpoint.

The controller logic will need to include calculation of the current Ca/S ratio and an estimation of the change in this ratio required to achieve a different level of SO₂ removal. Recycle ratios may also need to be changed at different operating conditions such as different required SO₂ removals and different boiler loads.

Miscellaneous DSI Control Loops

Two other control loops required in a DSI system are an air-to-water controller and a hydrator water controller if the hydrated lime is produced on-site. The air-to-water controller will maintain the desired air flow to the humidification nozzles based on the water flow allowed by the flue gas temperature controller. This will be accomplished by modulating the pressure control valve in the air feed line from the atomizing air compressors (reference DSI P&ID Sheet 1 in Section 5.3). Generally, a constant air-to-water ratio will be maintained at the nozzles unless a higher value is desired at low water flows as boiler load reduces.

If on-site hydration of pebble lime is chosen, a pebble lime/water control scheme will be required for the hydrator. The water-to-lime ratio is critical to produce a usable product. The operators will typically set the lime weigh belt feeder speed at a certain ton/hr, and the hydrator water controller will adjust the raw water into the hydrator to produce the desired product. This will be accomplished by automatically modulating the flow control valve in the raw water feed line from the raw water tank. This scheme will typically utilize feed-forward/feedback control: the signal from the lime weigh belt feeder is the feed-forward indication, while the temperatures from the thermocouples located in the hydrator seasoning chamber provide the feedback control signals (reference DSI P&ID Sheet 4 in Section 5.3).

8.1.2 Duct Spray Drying

Because there are so many sheets and control logic lines to track, the suggested DSD process control scheme given in the P&IDs in Section 5.3.2 can be somewhat difficult to follow. Therefore, a simplified version of the overall DSD control philosophy is given in Figure 8-2. Basically, there are two main control loops: 1) a flue gas temperature control loop, and 2) an SO₂ control loop. For DSD, these two loops are interrelated.

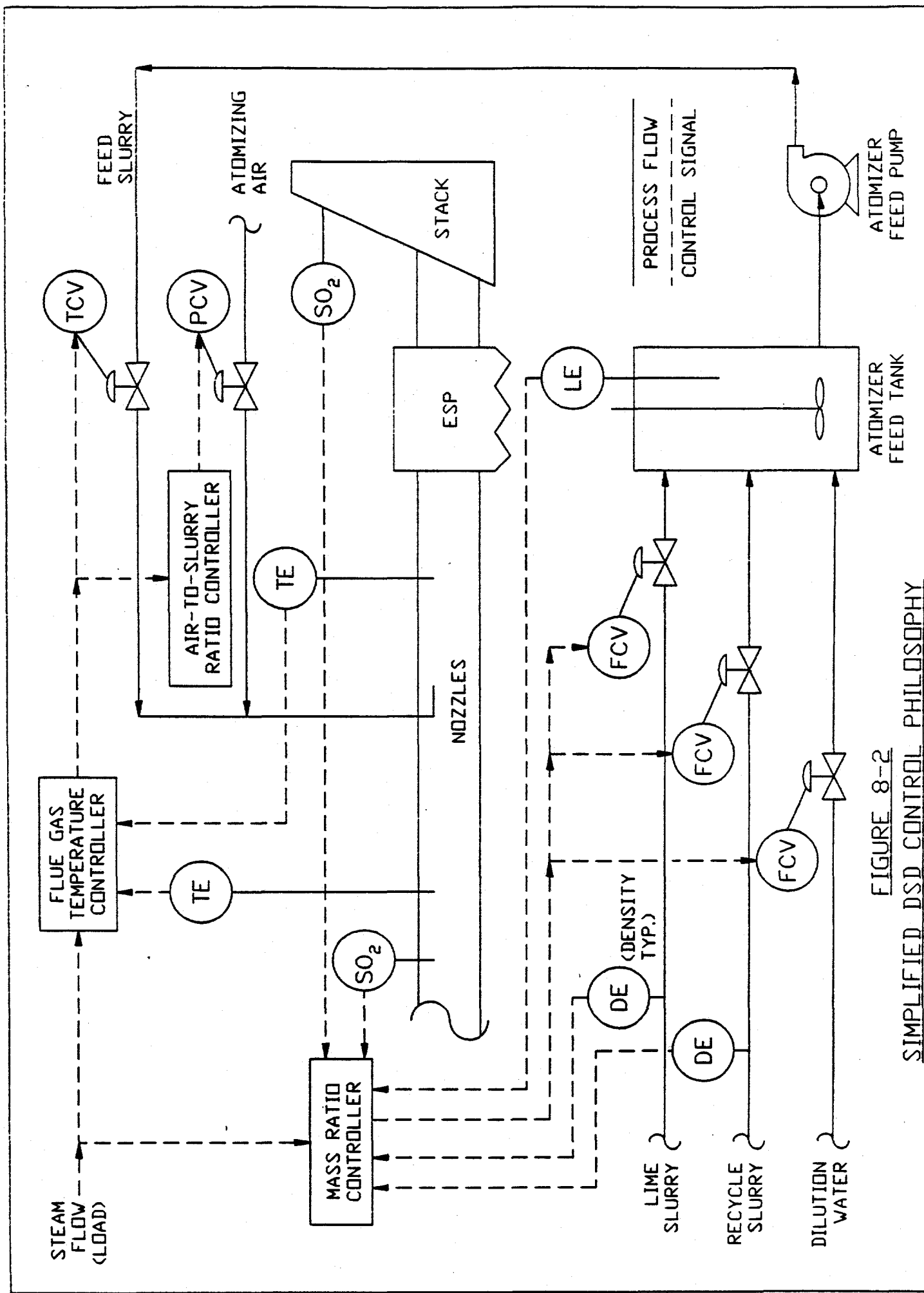


FIGURE 8-2
SIMPLIFIED DSD CONTROL PHILOSOPHY

Flue Gas Temperature Control Loop

Flue gas temperature downstream of the injection point in the DSD process is controlled by evaporative cooling. Feed slurry solids content and flow rate into the ductwork are both controlled to humidify the gas to the desired approach to adiabatic saturation temperature. Since approach to saturation directly affects sorbent utilization and SO_2 removal, maintaining the desired approach is extremely important. This is more critical in processes such as DSD with inherently low sorbent utilization. Ideally, a DSD process should be operated at the closest approach to saturation possible without incurring operational problems such as deposition of wet solids. This critical balance requires accurate measurement and control of the flue gas temperature.

The primary objective of the temperature control loop is to maintain the desired approach to saturation temperature at the ESP inlet. However, this requires measurement of the saturation temperature of the flue gas (also called the wet bulb temperature). This can be measured upstream of the slurry injection point or downstream of the ESP. Ideally, it is preferable to measure wet bulb upstream of the ESP to minimize the effects of in-leakage and thermal inertia in the ESP which tend to dampen process changes. However, measuring the wet bulb upstream of the ESP is very difficult due to the high particulate loading at that point. Even in areas of low particulate loading, there are few continuous wet bulb monitors that are commercially offered and even fewer that are reliable. Currently, the most reliable method of wet bulb temperature determination is a manual measurement in which a thermocouple covered with a wetted cotton wick is inserted into the flue gas stream.

Since air heater outlet flue gas conditions of temperature and humidity tend to change with load, fuel quality, and boiler operations, the flue gas wet bulb temperature tends to fluctuate. Therefore, an "ideal" operating temperature is difficult to maintain. The development of a reliable continuous wet bulb monitor will improve this capability, but until this technology is perfected, a more conservative control approach is recommended: the temperature control loop should maintain a setpoint flue gas dry bulb temperature at the ESP inlet. The dry bulb temperature setpoint chosen should be established at the desired approach to saturation temperature (see Section 3.2.2) based on the flue gas saturation temperature at normal boiler operating conditions (see Section 3.1.5). This control scheme will result in fluctuating approach temperatures as wet bulb temperature fluctuates. This somewhat conservative practice is typical in spray dryer scrubbing.

The use of a distributed control system, programmable logic controller, or similar automatic feed-forward/feedback control system is desirable. The temperature controller should be programmed for the proper response time/rate to changes in measured duct temperature caused by system dynamics. This will help prevent overspraying episodes. The temperature data acquisition device should have the capability of indicating average temperature in the grid as well as individual thermocouple probes. Alarms can be attached to the thermocouple probe outputs to indicate slurry injection problems.

For best control, the flue gas temperature controller should operate in a feed-forward/feedback loop. A steam flow signal will be input to the controller to give a feed-forward indication of flue gas flow which will exit the air heater; the temperature of this flue gas will also be input to the controller (reference Figure 8-2). Shielded thermocouples in the duct downstream of the injection point will provide the feedback input to the controller. Based on this combination of feed-forward and feedback signals, the controller will adjust the slurry flow rate to maintain a desired flue gas temperature setpoint (dry bulb) at the ESP inlet.

This is actually accomplished by modulating the temperature control valve in the slurry line feed to the injection point.

Although controlling the approach to saturation temperature at the ESP inlet is of primary importance, the temperature controller must also monitor and maintain an adequate flue gas temperature at the ESP outlet. This is important because of the corrosion potential in this region of ductwork. Typically, the temperature downstream of the ESP should be at least 20°F above saturation for corrosion protection.

DSD systems have the potential for operational swings, and upstream conditions can change rapidly. Some causes of these changes could be boiler load swings, sootblowing, tube leaks, steam coil operation, etc. Therefore, it is advisable to have feed-forward capability so that sudden changes in upstream conditions will not cause DSD process upsets. A sudden drop in air heater outlet flue gas temperature, for example, would be sensed by the controller and the slurry flow rate reduced accordingly, rather than waiting for the ESP inlet temperature to drop before reducing slurry flow.

Other safety interlocks should be part of the temperature control scheme. A minimum of three thermocouples should provide signals to the controller at the ESP inlet. The average of these three values is used to determine the feedback control. If one of the measurements is more than 4°F from the average, it should be considered to be erroneous and not included in the average calculation. If all three of the temperature measurements are more than 4°F apart, the controller should control to a default, safe setpoint. Another interlock which should be provided to prevent loss of control is that, if the approach temperature drops to less than 25°F, the controller would automatically revert to the default setpoint.

Another useful alarm or interlock would be a signal from the powerhouse when sootblowers are activated. A maximum slurry flow rate switch (not shown on the P&IDs) should be added in the slurry feed line to ensure that an approach temperature of less than 20°F cannot be achieved. Slurry valves should fail shut; atomizing air valves should fail open. The difference between the atomizing air pressure and the slurry feed pressure to the nozzles should be interlocked to maintain adequate spray formation.

SO₂ Control Loop

The heart of the SO₂ control loop will be a mass ratio controller. This controller utilizes feed-forward and feedback signals to adjust the lime solids content, recycle material solids content, and water content of the feed slurry pumped to the injection nozzles. For best control, the mass ratio controller should operate in a feed-forward/feedback loop. A steam signal will be input to the controller to give a feed-forward indication of flue gas flow which will exit the air heater; the SO₂ concentration of this flue gas will also be input to the controller (reference Figure 8-2). This latter signal is provided by an inlet SO₂ analyzer located in the ductwork just downstream of the air heater. An outlet SO₂ analyzer (typically located in the stack) will provide the feedback input to the controller. Based on this combination of feed-forward and feedback signals, the controller will adjust the relative composition of lime slurry, recycle material slurry, and water in the atomizer feed slurry. It will maintain either a constant percent removal of SO₂ or required emission limit (lb/10⁶ Btu, lb/hr, etc.).

The actual control methodology will be to adjust the lime slurry feed rate into the atomizer feed tank as the SO₂ fluctuates; this will be accomplished by modulating the feed control valve in the lime slurry feed line from the lime slurry storage tank. The recycle slurry and

dilution water flow rates will be modulated (utilizing their respective flow control valves) to maintain a relatively constant percent solids in the atomizer feed tank as well as a constant level in this tank. As the amount of fresh lime slurry required for SO_2 removal increases, for example, the flow rate of recycle material slurry will be decreased in order to maintain a fairly constant feed slurry solids content.

In order for the controller to calculate the relative flow rates of recycle slurry and dilution water to the atomizer feed tank to maintain a constant feed slurry percent solids, the solids content of the lime slurry and recycle slurry will have to be known. These data can be input by the operators from periodic grab sample measurements, or they can be input continuously from density meters as shown in the P&IDs. The size of the atomizer feed tank will be small (only about 30 min capacity) to facilitate reasonably rapid changes in the lime content of the feed slurry as the SO_2 content of the flue gas fluctuates.

Interrelationship Between DSD Temperature and SO_2 Control Loops

As mentioned above, these two primary control loops are not independent; the approach temperature and SO_2 control loops are interrelated. The temperature controller will adjust the feed slurry flow rate to the nozzles to maintain a constant setpoint flue gas temperature. However, such an adjustment would also change the Ca/S ratio and consequently the SO_2 removal efficiency. This would then require the SO_2 controller to respond accordingly.

Miscellaneous DSD Control Loops

Other control loops required in a DSD system are an air-to-slurry ratio controller, a slaker water controller, and a recycle slurry controller. The air-to-slurry controller will maintain the desired air flow to the slurry nozzles based on the slurry flow allowed by the flue gas temperature controller. This will be accomplished by modulating the pressure control valve in the air feed line from the atomizing air compressors (reference DSD P&ID Sheet 1 in Section 5.3). Generally, a constant air-to-slurry ratio will be maintained at the nozzles unless a higher value is desired at low slurry flows as boiler load reduces.

A pebble lime-water control scheme will be required for the slaker regardless of which type is selected. The water-to-lime ratio is important in producing a usable product slurry. The operators will typically set the lime weigh belt feeder speed at a certain ton/hr, and the slaker water controller will adjust the raw water into the slaker to produce the desired product. This will be accomplished by automatically modulating the flow control valve in the raw water feed line from the raw water tank. This scheme will typically utilize feed-forward/feedback control: the signal from the lime weigh belt feeder is the feed-forward indication, while the temperatures from the thermocouples located at the slaker discharge provide the feedback control signals. This type of feedback control based on slurry discharge temperature works for the ball mill or detention type slakers; however, for the paste slaker, the feedback signal is from the torque on the pug mill paddle shafts (reference DSD P&ID Sheets 4A, 4B, and 4C in Section 5.3).

The recycle slurry controller (reference DSD P&ID Sheet 6A or 6B) maintains a constant percent solids in the recycle slurry pumped to the atomizer feed tank. This solids content is typically around 40–45%. The dry recycle material is fed from the recycle bin to the wetting tank utilizing a rotary feeder. The speed of the rotary feeder is the feed-forward signal to the

controller which adjusts the density control valve in the water feed line to this tank. The density of the resulting recycle slurry from this tank is the feedback control signal to the controller.

8.1.3 Control System Functional Requirements

8.1.3.1 General

All equipment start and stop functions would be performed via work stations, which would have the capability of displaying the various process loops in real time. The control system should be able to respond to fluctuations in inlet SO₂ concentration, gas temperature, and gas flow rate, and also allow process or equipment upset conditions to be detected and corrected without process shutdown.

All of the equipment should be controllable from the work stations. Most equipment should have a "HAND" and an "AUTO" mode of operation. In the "HAND" mode, the selected device would operate on command, taking into account any safety interlocks. In the "AUTO" mode, the device is enabled and would operate when called upon by the logic of the operation.

The DSI or DSD should be broken into logical process areas or loops, with each area/loop being shown on one or two status screens on the work station. The status screen should show process flow and equipment status for the area/loop. Display of current value, setpoint, and alarm limits for each process parameter should be shown on the status screens or other screens. The status of each piece of equipment should be indicated by the color of the device. Process alarm conditions should also be shown on these screens.

All of the "HAND-OFF-AUTO" controls for a specific area/loop should be located on process control screens. The screen display should show the status of each device. In addition, any equipment fault should be shown on the screen. Setting the process parameters should be possible from control screens. These screens should show the current value, setpoint, and alarm limits, and the setpoint and alarm limits should be modifiable by the operator as needed.

Any alarm condition detected by the control system should cause the central alarm system light and horn to be activated. The alarm condition should be displayed on the screen and logged on the alarm printer. The alarm system should be "ACKNOWLEDGED" with a push button or a "SILENCE ALARM" key. The "ACKNOWLEDGE" is also logged.

The control system should operate with complete stability under all conditions of dynamic load change. It should quickly and accurately respond to load changes. It should also be designed to require a minimum amount of operator participation, and should include all necessary logic to change the operating mode of the final control element safely under various operating conditions. During steady state load conditions, the control system should not cause the furnace pressure to vary by more than 0.1 in. water, and during load changes, this variation should not be more than 0.2 in. water.

Sufficient alarm points including equipment failure and trip alarms should be provided to ensure that the operator is alerted to any abnormal condition or equipment failure. Equipment should be interlocked and automatically tripped, as required, to protect the equipment. Interlocks should be provided to ensure an orderly shutdown of the DSI or DSD system in the event of operation of a protective device or equipment failure. Neither a shutdown of the DSI or DSD system nor any malfunction of the system should cause a boiler trip.

The DSI or DSD system should function automatically over the entire turndown range of the system, although operator action may be necessary for start-up or shutdown. Transfer between manual and automatic operation should be bumpless, with automatic tracking while in the manual mode. Reset windup on loss of water or slurry source should be eliminated in order to prevent overshooting on restart of these sources.

Where dual pumps or other equipment are provided for lead-lag operation, provision should be included to select either pump or other equipment for lead operation.

8.1.3.2 Dry Sorbent Injection

Lime Unloading Control System

Local control of the lime unloading system should be supplied in the vicinity of the delivery point. The controls should be weatherproof and dust proof. The lime unloading control system would likely consist of a simple, locally mounted control panel with manual selector switches, push buttons, and indicator lights for each blower, valve, and motor controlled.

The dust collector of a hydrate or pebble lime silo or bin should be automatically activated whenever a blower is started which will fill the silo or bin with lime. Diagnostic instrumentation should be provided for each blower in the lime unloading system to alarm high temperature or low developed pressure conditions (reference DSI P&ID Sheets 3A, 3B, & 4 in Section 5.3).

SO₂ Removal Control System

For off-site hydration, the functional control requirements for the hydrate feed to the injectors are described in Section 8.1.1 above. Similarly to the lime unloading system described above, diagnostic instrumentation should be provided for each blower in the hydrate feed system to alarm high temperature or low developed pressure conditions (reference DSI P&ID Sheet 3A in Section 5.3).

In the case of on-site hydration, the lime feeding and hydrating equipment should be capable of being controlled automatically once the operator has selected which hydrating train will be used and what the lime feed rate will be on the lime weigh belt feeder. The hydrating water flow rate should be automatically controlled to produce the desired product; this will be accomplished using a magnetic flow meter in series with the hydrating water flow control valve (also reference Section 8.1.1 above).

Typically, lime hydrating will be performed on a batch basis: hydrating will continue until the hydrate bin high level is reached. The hydrate bin level controller should be able to shut off lime feed to the hydrator when the high-high level is reached. From the hydrate bin, control of the hydrated lime feed rate to the duct(s) would be as described in Section 8.1.1 above.

The turndown capability of the duct injection system is critical. As flue gas flow rate fluctuates, the control system must vary the sorbent and (especially) humidification water flow rates. The flow rates of these injected materials must be capable of "following" flue gas flow rate reductions, or material build-ups will likely result. The following turndown strategies are suggested:

- For dry sorbent injection, the sorbent conveying air flow should normally be maintained at a constant rate at all sorbent and flue gas flows. If the DSI control system is sophisticated enough, and sufficient operator attention is available to the DSI, a different turndown philosophy may be utilized: the sorbent and conveying air flows should both be turned down to maintain a constant air-to-solids mass ratio down to 50% load (as long as minimum conveying velocities are maintained); below 50% load, the sorbent conveying air flow should be maintained at a constant rate regardless of the sorbent rate.
- For humidification water injection, the water and atomizing air flows should both be turned down at a constant air-to-water mass ratio down to 50% load (as long as the minimum pressure differential between the air and water streams to the nozzles is maintained). Below 50% load, the water flow should continue to be turned down to maintain the approach temperature while the atomizing air flow (pressure) to the nozzles remains constant.

The dust collector of the recycle bin should be automatically activated whenever a blower is started which will fill the bin with recycled material. Diagnostic instrumentation should be provided for each blower in the recycle system to alarm high temperature or low developed pressure conditions (reference DSI P&ID Sheets 5A & 5B in Section 5.3). The control system should initiate transfer of recycled material to the recycle bin when the low level in this bin is reached, and the transfer should terminate when the high level is reached. The functional control requirements for the recycle material feed to the injectors are described in Section 8.1.1 above.

As a minimum, the following control and monitoring functions should be provided:

- Hydrate silo level/aeration air dryer/blower status (off-site hydration only)
- Pebble lime silo level/bin activator status (on-site hydration only)
- Lime diverter valve status (on-site hydration only)
- Lime feed rate to operating hydrator (on-site hydration only)
- Hydrating water feed rate to operating hydrator (on-site hydration only)
- Temperature of hydrated lime exiting hydrator (on-site hydration only)
- On/off status of each lime weigh belt feeder/hydrator (on-site hydration only)
- Hydrator discharge rotary air lock status (on-site hydration only)
- Hydrate transfer blower status (on-site hydration only)
- Hydrate bin level/aeration air dryer/blower status (on-site hydration only)
- Hydrate bin dust collector status (on-site hydration only)
- Hydrated lime feed rate to duct(s)
- On/off status of each hydrate screw feeder/rotary air lock
- On/off status of each hydrate injection blower
- Fly ash silo rotary air lock status
- Recycle transfer blower status
- Recycle bin level/aeration blower status
- Recycle bin dust collector status
- Recycle material feed rate to duct(s)
- On/off status of recycle bin rotary feeder/rotary air lock
- On/off status of each recycle injection blower
- Humidification water feed rate/temperature/pressure to atomizers (nozzles) for each duct
- Compressed air feed rate/temperature/pressure to atomizers (nozzles) for each duct

- Pressure difference between humidification water and atomizing air to the nozzles
- Flue gas flow rate to each duct (from boiler steam signal)
- Air heater outlet flue gas temperature/pressure for each duct
- Air heater outlet SO₂ concentration for each duct
- ESP inlet/outlet flue gas temperature/pressure for each duct
- Duct wall temperatures downstream of the injection point for each duct
- Stack SO₂ concentration

8.1.3.3 Duct Spray Drying

Lime Unloading Control System

Local control of the lime unloading system should be supplied in the vicinity of the delivery point. The controls should be weatherproof and dust proof. The lime unloading control system would likely consist of a simple, locally mounted control panel with manual selector switches, push buttons, and indicator lights for each blower, valve, and motor controlled.

The dust collector of a pebble lime silo or bin should be automatically activated whenever a blower is started which will fill the silo or bin with lime. Diagnostic instrumentation should be provided for each blower in the lime unloading system to alarm high temperature or low developed pressure conditions (reference DSD P&ID Sheet 3 in Section 5.3).

SO₂ Removal Control System

A pebble lime day bin may be utilized in addition to the lime silo. If it is, the control of the lime transfer conveyor from the pebble lime silo to the day bin should be included in the SO₂ removal control system. The control system should automatically initiate transfer of lime to the lime bin when the low level in this bin is reached, and the transfer should terminate when the high level is reached.

The lime feeding and slaking equipment should be capable of being controlled automatically once the operator has selected which slaking train will be used and what the lime feed rate will be on the lime weigh belt feeder. The slaking water flow rate should be automatically controlled to achieve the setpoint lime slurry solids content; this will be accomplished using a magnetic flow meter in series with the slaking water flow control valve. Dilution water should be controlled to the lime slurry exiting a ball mill-type slaker (it should be controlled to the slaker for a detention or paste-type slaker). The flow rate of dilution water should be automatically controlled to achieve the setpoint lime slurry solids content; again, this should be accomplished with a magnetic flow meter in series with the density control valve (dilution water flow control valve).

If the slaking water requires heating to produce a good quality lime slurry, steam flow should be automatically controlled based on the temperature of the slaking water to the slaker. The steam flow rate should be adjusted utilizing the temperature control valve.

Typically, lime slaking will be performed on a batch basis: slaking will continue until the lime slurry storage tank is filled. The lime slurry storage tank level controller should be able to shut off lime feed to the slaker when the high-high level is reached.

The turndown capability of the duct injection system is critical. As flue gas flow rate fluctuates, the control system must vary the slurry flow rate. The slurry flow rate must be capable of "following" flue gas flow rate reductions, or material build-ups will likely result. The following turndown strategies are suggested:

- For slurry injection, the slurry and atomizing air flows should both be turned down at a constant air-to-slurry mass ratio down to 50% load (as long as the minimum pressure differential between the air and slurry streams to the nozzles is maintained). Below 50% load, the slurry flow should continue to be turned down to maintain the approach temperature while the atomizing air flow (pressure) to the nozzles remains constant.

The dust collector of the recycle bin should be automatically activated whenever a blower is started which will fill the bin with recycled material. Diagnostic instrumentation should be provided for each blower in the recycle system to alarm high temperature or low developed pressure conditions (reference DSD P&ID Sheets 6A & 6B in Section 5.3). The control system should initiate transfer of recycled material to the recycle bin when the low level in this bin is reached, and the transfer should terminate when the high level is reached.

The functional control requirements for the recycle slurry preparation and slurry feed to the injection nozzles are described in Section 8.1.2 above.

As a minimum, the following control and monitoring functions should be provided:

- Pebble lime silo level/bin activator status
- Pebble lime rotary air lock status
- Pebble lime transfer blower status
- Pebble lime day bin level/bin activator status
- Pebble lime day bin dust collector status
- Lime diverter valve status
- Lime feed rate to operating slaker
- Slaking water feed rate/temperature to operating slaker
- Steam control valve position
- Dilution water feed rate to operating slaker
- Temperature of lime slurry exiting slaker
- On/off status of each lime weigh belt feeder/slaker/lime grit screen
- Lime slurry storage tank level/agitator status
- Density of lime slurry
- Lime slurry feed rate to atomizer feed tank
- On/off status of each lime slurry pump
- Fly ash silo rotary air lock status
- Recycle transfer blower status
- Recycle bin level/aeration blower status
- Recycle bin dust collector status
- Recycle material feed rate to recycle slurry tank
- Water feed rate to recycle slurry tank
- On/off status of recycle bin rotary feeder/recycle grit screen
- Recycle slurry tank level/agitator status
- Density of recycle slurry
- Recycle slurry feed rate to atomizer feed tank
- On/off status of each recycle slurry pump

- Dilution water feed rate to atomizer feed tank
- Atomizer feed tank level/agitator status
- Feed slurry feed rate/temperature/pressure to atomizers (nozzles) for each duct
- Compressed air feed rate/temperature/pressure to atomizers (nozzles) for each duct
- Pressure difference between feed slurry and atomizing air to the nozzles
- On/off status of each atomizer feed pump
- Flue gas flow rate to each duct (from boiler steam signal)
- Air heater outlet flue gas temperature/pressure for each duct
- Air heater outlet SO₂ concentration for each duct
- ESP inlet/outlet flue gas temperature/pressure for each duct
- Duct wall temperatures downstream of the injection point for each duct
- Stack SO₂ concentration

8.2 Control Instrumentation Requirements

Two major alternatives for the DSI or DSD process control system are 1) a distributed control system, or 2) a programmable logic control system. These alternatives are both described below; instrumentation and other devices required for control are also discussed.

8.2.1 Distributed Control System

If a distributed control system (DCS) is currently in use at the plant, this control system should be extended to the new control system for the DSI or DSD system. This extension to the DCS would typically apply only to the SO₂ removal-related reagent preparation and feed equipment. The control of the existing/modified ash handling system would likely be an extension of whatever system is already in use. The new lime unloading control system would likely consist of a simple, locally mounted control panel with selector switches, push buttons, and indicator lights.

The DCS control system would typically be a microprocessor-based distributed control system and include analog control (PID), digital control, sequential control, and data acquisition capabilities. The control system hardware would generally consist of a minimum of two free-standing output/input unit consoles, each with one 19 in. CRT, associated keyboard, one mass storage device, and all electronics to interface this equipment with the DCS. Only one of the consoles would be required to operate the SO₂ removal equipment. A free-standing printer should also be provided for alarm logs, reports, etc.

Controller and input/output (I/O) cabinets to support the DCS and consoles would be required. All DCS process inputs and outputs would terminate at I/O cabinets located near the SO₂ removal system consoles. A redundant data communication highway, complete with all cable, would be provided. Programming for a complete system would be necessary in order to control, display, trend, alarm, store, and log all control and instrumentation parameters.

The SO₂ control system would have the capability of starting up, normal operation, and shutting down of the SO₂ removal-related equipment by a single operator. Process control loops should be functionally and physically divided from one another in order to prevent a failure of any one component causing the shutdown of the entire SO₂ control system.

The DCS should allow full manual control of a control loop when it is transferred to manual control for replacement of a defective module (e.g., a logic or control card).

8.2.2 Programmable Logic Control System

If the plant has no existing distributed control system, a programmable logic controller (PLC) should probably be used for DSI or DSD system overall control. As noted for the DCS above, this PLC would typically apply only to the SO₂ removal-related reagent preparation and feed equipment. The control of the existing/modified ash handling system would likely be an extension of whatever system is already in use. The new lime unloading control system would likely consist of a simple, locally mounted control panel with selector switches, push buttons, and indicator lights.

The PLC control system would typically consist of several racks to provide processing, motor starting control and status, analog I/O, and digital I/O for field equipment and instrumentation. The processor should be interfaced through a data highway to a PLC programming computer and a minimum of two PLC operator interfaces or work stations. Each work station would generally consist of a free-standing console with 19 in. CRT, associated keyboard, and all electronics to interface this equipment with the PLC. Only one of the consoles would be required to operate the SO₂ removal equipment. A free-standing printer should also be provided for alarm logs, reports, etc.

The PLC programming computer would allow programming and documentation of the PLC, maintenance of an equipment data base, and preparation of reports printed out on the free-standing printer. Programming for a complete system would be necessary in order to control, display, trend, alarm, store, and log all control and instrumentation parameters.

The SO₂ control system would have the capability of starting up, normal operation, and shutting down of the SO₂ removal-related equipment by a single operator. Process control loops should be functionally and physically divided from one another in order to prevent a failure of any one component causing the shutdown of the entire SO₂ control system.

8.2.3 Other Control Instrumentation

In addition to the overall controller, other control devices/instrumentation are required for a DSI or DSD system.

Flow Meters/Flow Control Valves

Probably the most common control device in a DSI or DSD system is the flow meter in series with a flow control valve. This combination is used to control the flow rates of water, compressed air, and (for DSD only) slurry. The P&IDs are based on use of magnetic flow meters for these applications (except for compressed air flow metering). This type of flow meter has proven itself to be reliable and accurate even for slurry applications. Other types of flow meters are available including ultrasonic and mass flow meters, which measure the Coriolis force on electromagnetically vibrated tubes.

Water and compressed air control valves are standard power plant items, but slurry control valves tend to be more specialized. Functional and design criteria for slurry control valves are contained in Spec. No. M116 in Appendix E.

Solids Flow Control

Another common control device is the solids feeder. In DSI or DSD systems, this feeder is typically a rotary feeder, weigh belt (gravimetric) feeder, or screw feeder. Although these feeders are mechanically different, they all control using a similar technique: variable speed drive. Functional and design criteria for rotary feeders, weigh belt feeders, and screw feeders are contained in Spec. Nos. M105, M106, and M107, respectively, in Appendix E.

8.3 Monitoring Instrumentation Requirements

This subsection provides suggestions for selection of the type and application of process monitoring instrumentation for a duct injection system. The suggestions are generally applicable to both the DSI and DSD technologies except where specifically noted.

8.3.1 Flue Gas Temperature Monitoring

As discussed in Section 8.1 above, air heater outlet temperature (dry bulb) should be used as a feed-forward control parameter. Flue gas dry bulb temperature is typically measured with a grid of thermocouple probes located in the duct just downstream of the air heater. Since the flue gas temperature profile can be nonuniform at the air heater outlet (reference Section 6.3.1.1), care should be taken in determining the number and placement of thermocouple probes. In many plants, thermocouples will already exist at this location.

To achieve a constant approach to saturation temperature during DSI or DSD operation, accurate and reliable measurement of both dry bulb and wet bulb flue gas temperature is important. Dry bulb temperature can be measured by a combination of shielded and unshielded thermocouples. Thermocouples located in the humidification water or slurry injection zone should be shielded to prevent liquid droplets and wet solids deposition from affecting temperature measurement. The water or slurry flow rate control thermocouples should be shielded (reference DSI P&ID Sheet 1 and DSD P&ID Sheet 1). Alarm thermocouples should be unshielded and should be located just upstream of the ESP. Wet bulb should be periodically measured by hand upstream of humidification water or slurry injection until a reliable continuous monitor is developed.

Flue gas dry bulb temperature is typically measured with a grid of thermocouple probes located in the duct upstream of the ESP. Since flue gas can be maldistributed in ductwork downstream of DSI and DSD injection points, care should be taken in determining the number and placement of thermocouple probes. Complete temperature traverses should be conducted prior to and after humidification water or slurry nozzle installation to determine the duct cross-sectional temperature profile and to identify any cold spots. At least three or four thermocouples should be used at each measurement point.

The use of duct wall RTDs is suggested to provide early detection of wall wetting. These duct skin temperature measuring devices should be installed downstream of water or slurry injection. The exact location should be chosen at the point of most likely wall wetting, which can be determined by modeling or other means. When the temperature drops to nominally 145°F (or about 20°F above the saturation temperature), wall wetting is imminent, and water or slurry flow rate should be reduced immediately.

Finally, ESP outlet temperature should be measured with an array of unshielded thermocouples. These measurements should be taken to maintain the temperature at this

point safely above the flue gas saturation point. These temperature measurements can be monitored and recorded, but they typically will not be used as part of the feedback control loop. Since saturation temperature can be affected by in-leakage, it may also be advisable to periodically monitor the wet bulb temperature at this location.

8.3.2 Flue Gas SO₂ Concentration Monitoring

Measurement of SO₂ is necessary for continuous emissions monitoring for regulatory compliance, and it is vital for controlling the DSI or DSD process as well. The 1990 Clean Air Act Amendments have established stringent requirements for measuring and reporting pollutant gas emission levels. The user is assumed to have a Continuous Emissions Monitoring System (CEMS) in place prior to the design and retrofit of the duct injection system. The following discussion of SO₂ monitors is intended to provide information to aid the user in selecting additional SO₂ monitoring for the duct injection process. As discussed above in Section 8.1, an SO₂ monitor should be located at the ESP outlet duct or stack for emissions compliance and SO₂ feedback control. In addition, SO₂ monitors should be located at the air heater outlet(s) for feed-forward control if possible. A reference specification is included for SO₂/diluent monitors as Spec. No. C002 in Appendix E.

In order for SO₂ measurements to be expressed in units of most applicable emissions standards (lb/10⁶ Btu), measurement of a gas diluent usually is made concurrently and at the same location. The 1990 Clean Air Act Amendments also require a flow monitor as part of the CEMS. The P&IDs show O₂ as the diluent measured, but CO₂ may be used as well. Although appropriate for many monitoring applications, a wet basis system (one in which the SO₂ concentration is output in ppm, wet basis) may not be acceptable for applications downstream of a DSI or DSD system because a constant moisture content must be assumed.

There are two broad categories of commercially available SO₂ monitors: in situ and extractive. In situ systems measure SO₂ and diluent (either O₂ or CO₂) concentrations directly in the flue gas stream. In contrast, extractive systems extract and transport samples of flue gas to analyzers located outside the gas stream. There are inherent advantages and disadvantages to both types of systems. Selection of one over the other is site specific. Table 8-1 compares the advantages and disadvantages of in situ and extractive SO₂ monitoring systems as they apply to DSI and DSD. In addition, a technical description of each type follows.

8.3.2.1 In Situ Systems

Most in situ gas monitoring systems use light beams to detect and quantify SO₂ and diluent gas concentrations. The wavelength of the light depends on which gas is being monitored. Most in situ systems can be thought of as "in stack" spectrophotometers whose measurement path is some segment of the stack or duct cross section.

In situ systems may be classified as either path or point instruments. Path systems have a measurement path length that can be as long as the inside diameter of the duct or stack. Point in situ systems typically have a measurement path that is only a few centimeters in length. As with single-point extractive systems (discussed below), point in situ systems are more susceptible to questions of sample representativeness than are path systems. This is a particularly relevant concern for monitoring applications downstream of DSI or DSD systems where streamlines of sorbent and SO₂ removal may occur.

TABLE 8-1
COMPARISON OF IN SITU AND EXTRACTION
SO₂ MONITORING SYSTEMS

SYSTEM TYPE	ADVANTAGES	DISADVANTAGES
Path In Situ Systems	1) Fast response time. 2) No calibration gas needed. 3) No sample transport or conditioning. 4) Simple less expensive installation.	1) Potential interference by particulate or droplets. 2) Gas measured on wet basis, moisture content must be assumed - sometimes not possible downstream of DSI or DSD systems. 3) Vibration sensitive - potential difficulty in maintaining calibration.
Point In Situ Systems	1) Fast response time. 2) No sample transport or conditioning. 3) Simple less expensive installation.	1) Single point, representative sample difficult if SO₂ is stratified. 2) Gas measured on wet basis. 3) Vibration sensitive. 4) Access for maintenance can be difficult.
Conventional Extractive Systems	1) Most proven technology. 2) Multiprobe capability for representative sample. 3) Analyzer time share capability. 4) Analyzers can be installed in an accessible clean environment. 5) Gas measured on a dry basis.	1) Sample transport and conditioning system. Expensive to install and operate - high power requirements. 2) Sample transport and conditioning system has potential for pluggage, leaks, and condensation problems (both water and acid).
Dilution Extractive Systems	1) Heated sample lines and moisture removal system not necessary. 2) Multiprobe capability for representative sample. 3) Analyzer time share capability. 4) Analyzers can be installed in an accessible clean environment.	1) Questions concerning measurement and data precision with a highly diluted sample. 2) Dilution system may not work on high moisture flue gas, such as that encountered downstream of DSI or DSD. 3) Gas measured on a wet basis, this may not be a problem if CO₂ is used as the dilution gas.

Path In Situ Systems

Commercially available path in situ systems use a single-pass measurement technique. In this configuration, the light source (infrared for CO_2 and ultraviolet or infrared for SO_2) is mounted on one side of the duct or stack and the detector assembly on the opposite side. As with opacity transmissometers, precise alignment of the transmitter and detector assemblies is imperative to ensure accurate data.

Simplistically stated, photometric in situ gas monitors (both path and point) are based on the operational principle that the gas being monitored absorbs light of a given wavelength. The wavelength is carefully chosen to minimize absorption interference from other gases. Although sophisticated electronic techniques are used to monitor the desired gas in the presence of accompanying particulate matter, particulate interference constitutes a fundamental limitation of path in situ systems.

Path in situ systems cannot be calibrated in the same manner as point in situ or extractive systems. Because of the measurement path length, which extends across the duct or stack, it is usually impossible to zero or calibrate path in situ systems by introducing a known zero or calibration gas into the detector's complete measurement path. Therefore, path in situ systems are usually calibrated indirectly, either by incremental addition or by using auxiliary light sources.

Point In Situ Systems

The point in situ SO_2 monitoring system is designed to minimize the particulate interference problem typical of path systems through the use of a porous ceramic filter which surrounds a short (several centimeter) measurement cell located at the end of the sampling probe. The purpose of the probe is not to serve as a sample transport conduit, but rather to provide a sealed, clear path from the light source to the measurement cavity. The filter is used to prevent particulate matter and entrained moisture from entering the cell, while permitting an unobstructed flow of gas into the measurement cavity. Although most of these monitors are equipped with a high pressure "blow-back" for dislodging particulate matter which may tend to build up on the outside of the filter, gas streams with high particulate grain loadings and/or entrained moisture can clog the ceramic filter. More detrimentally, this material can provide a reaction substrate for sorbent/ SO_2 scrubbing to occur.

In a typical point in situ configuration, the light source/detector assembly is located outside the duct or stack at one end of the probe and a mirror is located at the other end in the measurement chamber. In the case of SO_2 monitoring, an ultraviolet light beam is projected down the probe, through the measurement chamber, to the mirror which reflects the light back to the detector assembly. The absorbance of ultraviolet light by the gas in the measurement chamber provides a measure of SO_2 concentration.

A point in situ system measures the SO_2 concentration at a single point. Obtaining a representative sample from a single point is not always possible, especially downstream of a DSI or DSD process. Most in situ monitor manufacturers offer multipoint systems, but, since each probe requires an analyzer, multipoint systems may be cost prohibitive.

Calibration of point in situ analyzers is performed by passing a sample of bottled calibration gas of known concentration through the detector cell. The instrument is adjusted electronically to compensate for any drift which may have occurred.

8.3.2.2 Extractive Systems

Extractive monitoring systems withdraw a sample from the flue gas for external analysis. All extractive systems have three common subsystems: 1) sample probes, 2) sample transport and conditioning, and 3) gas analyzers.

Sample Probes

Most extractive monitor probes are equipped with a filter to remove coarse particulate matter prior to transport of the gas sample to the analyzers. Filters can be located in the flue gas stream, or in a heated sample junction box just outside the duct or stack sample location. A variety of filters and filtering materials may be used, including sintered stainless steel, ceramic, glass, and quartz fiber filters. As with the ceramic filters discussed above for in situ systems, most extractive system probes are equipped with high-pressure "blow-back" to remove particulate matter or sorbent that collects in the probe and on the exterior surfaces of the filter. Problems similar to those discussed in relation to in situ system probes are common to these probes as well. In applications where reactive sorbent may deposit on the filter surface, it may be necessary to heat the filter above the reaction temperature of the sorbent.

Typically, sample probes are constructed of one of a variety of stainless steels and, in special sampling applications, may be lined with quartz or glass. Since the gas analyzers are separate, multipoint time-sharing sampling is possible. Probes can be sampled individually, or as a composite depending on site specific needs.

Sample Transport and Conditioning

Sample handling systems customarily begin at the junction of the probe and the sample transport line, usually just outside the duct or stack. Sample handling systems usually consist of heated and insulated Teflon sample transport lines and may include gas conditioning equipment. The purpose of the sample conditioning system is to provide a clean, dry sample to the analyzers without altering the gas concentrations. Sample conditioning equipment may include a primary or secondary particulate filter and a water removal apparatus.

The two types of water removal apparatus most frequently used in sample conditioning systems are refrigerated condensers and permeation dryers. Refrigerated condensers rapidly cool the sample, causing the moisture in the gas to condense. The condensed moisture is trapped and periodically removed from the condenser assembly. Precautions usually are taken in designing the condenser and trap to minimize contact between the condensate and the cooled sample to avoid absorption of the SO_2 by the condensed liquid.

Permeation dryers are an alternative to refrigerated coolers and offer some potential advantages. This type of drying system uses membranes that are selectively permeable to water vapor. The water vapor in the flue gas sample diffuses through the membranes into a dry purge air stream. This process occurs continuously as wet stack gas flows in one direction through the dryer while dry purge air flows countercurrently.

In addition to the coarse particulate filter usually located in, or just external to, the duct or stack, many sample conditioning systems include a secondary filter for fine particulate removal. Secondary filters are usually located downstream of the moisture removal system. For DSI or DSD applications, these may be undesirable due to potential for scrubbing if unreacted sorbent particles are deposited on the filter.

Gas Analyzers

The SO₂ analyzer is usually the most trouble-free and reliable component of extractive monitoring systems. Most analyzers are industrial adaptations of proven, laboratory gas analysis techniques. As with in situ systems, the operating principle of the analyzer in most extractive systems is the absorbance of light by the gas sample.

The most common type of SO₂ analyzer operates by ultraviolet light absorption. The instrument components typically include optical filters, photo multiplier tubes, and amplifiers. The concentration of SO₂ is based on the absorbance of ultraviolet light of a specific wavelength.

Other types of SO₂ analyzers, based on nondispersive infrared light absorption, flame photometry, and fluorescence, are also available, but less common.

Most regulations require that the SO₂ concentration be reported in units of mass of SO₂ per energy expended (e.g., lb/10⁶ Btu). To accomplish this, the excess O₂ or CO₂ must be monitored in order to "back out" the excess diluent air. The O₂ or CO₂ analyzer uses the same gas sample (arranged in parallel or in series) as the SO₂ analyzer. Most O₂ analyzers utilize an electrochemical cell (or fuel cell) to produce a linearized voltage signal that is proportional to the ratio of O₂ concentration of a reference gas (usually air) to the O₂ concentration of the sample. Most CO₂ analyzers operate on the absorption of infrared light.

Gas analyzers are required to be calibrated periodically as required by the appropriate regulations. Sample flow is interrupted or diverted and the data acquisition system flagged while bottled reference gases of known concentration are introduced through the sampling system to each analyzer. The data acquisition computer performs the necessary electronic adjustments to calibrate the instruments. Calibration and drift data are recorded to generate the proper reports. Alarms can be set if excessive drift or an invalid calibration has occurred. Calibration can also be initiated manually.

Dilution Extractive Systems

A recent trend in extractive monitoring systems is sample dilution. By using a critical orifice, the withdrawn sample is diluted to a known ratio using dry air, O₂, or CO₂. Therefore, the gases entering the analyzers are much lower in concentration. The advantage of a highly diluted sample is that the net dew point is extremely low. The need for heated sample lines and water removal is typically eliminated. There is an upper limit of flue gas moisture range in which a dilution system can be applied. This may limit its application in some DSI or DSD cases.

8.3.2.3 SO₂ monitoring System Controller and Data Acquisition

Most SO₂ monitoring systems offered commercially include an onboard computer control and data acquisition system. These may be separate components. The control system (many newer systems are PLC based) is responsible for all of the ongoing operations of the sampling system and gas analyzers. These include purging and blow-back of probes, purging and draining of refrigerated condenser units, calibration of analyzers, etc. In time-share or multipoint sampling, the control system automatically switches probes or sampling locations. The system is also responsible for setting status flags and alarms.

One of the most important functions of the SO₂ monitoring system is to record and document the SO₂ emissions to the environmental regulatory agency with jurisdiction. The data acquisition system records real time data from the analog or digital outputs of the analyzers, performs some time averaging, and provides limited data storage. Typically, regulatory agencies have specific requirements for data reporting and recordkeeping. The data acquisition system should be configured to comply with these requirements. Both hard copies along with disks may be required in standard format for the regulatory agency's use. These data can be accessed by a separate plant computer or datalogger, if desired. In addition to the computer data logging, most plants choose to record real time gas analyzer outputs on chart recorders.

8.3.2.4 Sampling Location

Gas sampling location(s) may depend on how the DSI or DSD process is to be regulated and controlled. If it is necessary to maintain a specified percent SO₂ removal, SO₂ and diluent sampling at the inlet and outlet of the DSI or DSD process may be required. Typically, this means one system upstream of sorbent or slurry injection and one system at the stack or ESP outlet. In some cases, one set of analyzers can be time-shared between the inlet and outlet sampling locations (for extractive systems only); however, regulatory agencies seldom allow this. If regulations require only a specified outlet SO₂ emission limit, a single sample location at the stack or ESP outlet may be sufficient. Process removal efficiency can still be estimated by sulfur balance calculations. This single sampling location arrangement, however, does not afford the feed-forward control signal that was discussed in Sections 8.1.1 and 8.1.2.

Sampling downstream of the sorbent or slurry injection, but upstream of the ESP is not practical. Unreacted wet or dry solids can deposit on or in the sampling system generating false SO₂ removal measurements.

Care must be taken in selecting probe (or probe grid) location downstream of particulate control due to potential streamlines of SO₂ caused by uneven sorbent distribution or flow stratification in ESPs.

8.3.3 Solids/Slurries Level Monitoring

There are many silos and bins in a DSI or DSD system, which will contain solids. Typical solids level measurement for these applications is provided by "point" probes as opposed to continuous level monitors. A "LOW", "HIGH", and "HIGH-HIGH" point measurement is generally adequate. These point probes may be either capacitance-type or nuclear point detector level probes.

Level measurement in slurry tanks in a DSD system is a difficult application. One type of instrument that seems to operate fairly reliably and accurately is the flexible cable capacitance-type probe (such as Drexelbrook level probes). These probes have a weighted signal cable which is contained within a stilling well inside the slurry tank.

8.3.4 Slurry Density Monitoring (DSD only)

In a DSD system, slurry density monitoring at several points is important to overall controllability. As noted in Section 8.1.2 above, in order for the SO₂ controller to calculate the relative flow rates of lime slurry, recycle slurry, and dilution water to the atomizer feed tank to maintain the required SO₂ removal and a constant feed slurry percent solids, the solids content of the lime slurry and recycle slurry will have to be known. These data can be input by the operators from periodic grab sample measurements, or they can be input continuously from density meters as shown in the P&IDs (DSD Sheets 4, 5, and 6).

Slurry density meters are typically nuclear-type such as manufactured by Kay-Ray of Mt. Prospect, IL or Texas Nuclear (TN Technologies) of Round Rock, TX. A nuclear source with accompanying receiver measures the amount of radiation which passes through the slurry. This is calibrated to slurry density in percent solids.

Other types of slurry density monitoring include measuring the vibration of an electrically excited U-tube through which the slurry is flowing. As the density of the slurry increases, it tends to increase the dampening of the vibration.

8.3.5 Test Ports/Connections

Test ports should be added upstream and downstream of the duct injection system and downstream of the ESP for conducting routine inspection and maintenance and for conducting performance tests (such test ports are shown in the P&IDs in Section 5.3). Permanent access platforms should be provided for these test ports.

8.4 Plant Monitoring and Control System Interfaces

The retrofit of a DSI or DSD system to a power plant will require interfacing the duct injection process control system to the existing boiler and auxiliary process control systems. This will likely entail both hardware and software modifications to transmit, interpret, and control the required analog and digital signals. This subsection provides some very general information to assist plant personnel in making control system interface decisions. The interface between new and old control systems is so site-specific, only limited suggestions are given below.

After the start-up and initial operation phases, normal control of the duct injection system will likely be accomplished from the main plant control room. Even so, a local control area near the duct injection equipment should probably be provided. This area will be used extensively during start-up and initial operation as well as during times of extensive or abnormal operation and maintenance. During normal operation, after the initial operation period is over, this local control area may not require permanent staffing. Sufficient control and monitoring functions need to be available from the main plant control room. This will require at least two work stations as described in Sections 8.2.1 and 8.2.2 above. A data highway will be required between the local control area and main plant control room.

Typical control signals from the existing boiler and burner control system, which are essential to the DSI or DSD control system are:

- Boiler trip signal
- Steam load analog signal for air heater outlet flue gas flow rate indication
- Sootblowing signals

Typical control signals from the DSI or DSD control system, which are essential to the boiler and burner control system are:

- Analog signals from the stack SO₂ analyzer/diluent analyzer
- All alarm points for the main plant control room annunciator

The retrofit of the duct injection system will increase the solids loading to the ESP and ash handling system. Modifications to the controls for this equipment will almost certainly be necessary. Upgrades of the ESP rapper controls and/or ash pulling sequence control are covered in Section 11.0, Operation and Maintenance Guidelines.

9.0 CORROSION PREVENTION GUIDELINES

Corrosion prevention must be taken into account when considering a duct injection process due to the low temperature, high humidity flue gas environment. In extreme cases, corrosion can result in holes in the ductwork, ESP wire failures, failures of expansion joints, as well as operational problems in the ESP and stack.

Typically, the acid dew-point is a major concern when considering SO₂ removal systems. One advantage of dry and semi-dry FGD processes over wet processes is that the SO₃ is removed by the sorbent, essentially eliminating the acid dew-point.

In duct injection processes, corrosion occurs by two primary mechanisms:

1. Cold spot condensation
2. Under-deposit environment(s)

Condensation can occur in cold-spots when metal surface temperatures fall below the water dew-point due to ambient air leaks into the system and/or inadequate insulation. These systems operate at close approach to saturation temperatures (30°-40°F) and require little cooling to bring the gas below saturation. Once the condensation has occurred, SO₂ can dissolve in the condensed moisture layer and lead to corrosion. Corrosion can also occur beneath wet solids deposits. The environment beneath the deposits can vary from extremely caustic to extremely acidic. Because the exposed metal beneath the deposit is isolated from the flue gas, any corrosive process can accelerate and become severe.

Because the duct injection system is retrofit into existing ductwork, the user does not have the option of selecting the ideal materials for equipment exposed to the flue gas. Most equipment in the path of the flue gas downstream of duct injection will be constructed of carbon steel or, in some cases, corten. Even if the user could select new materials, there are several practical limitations to his choices.

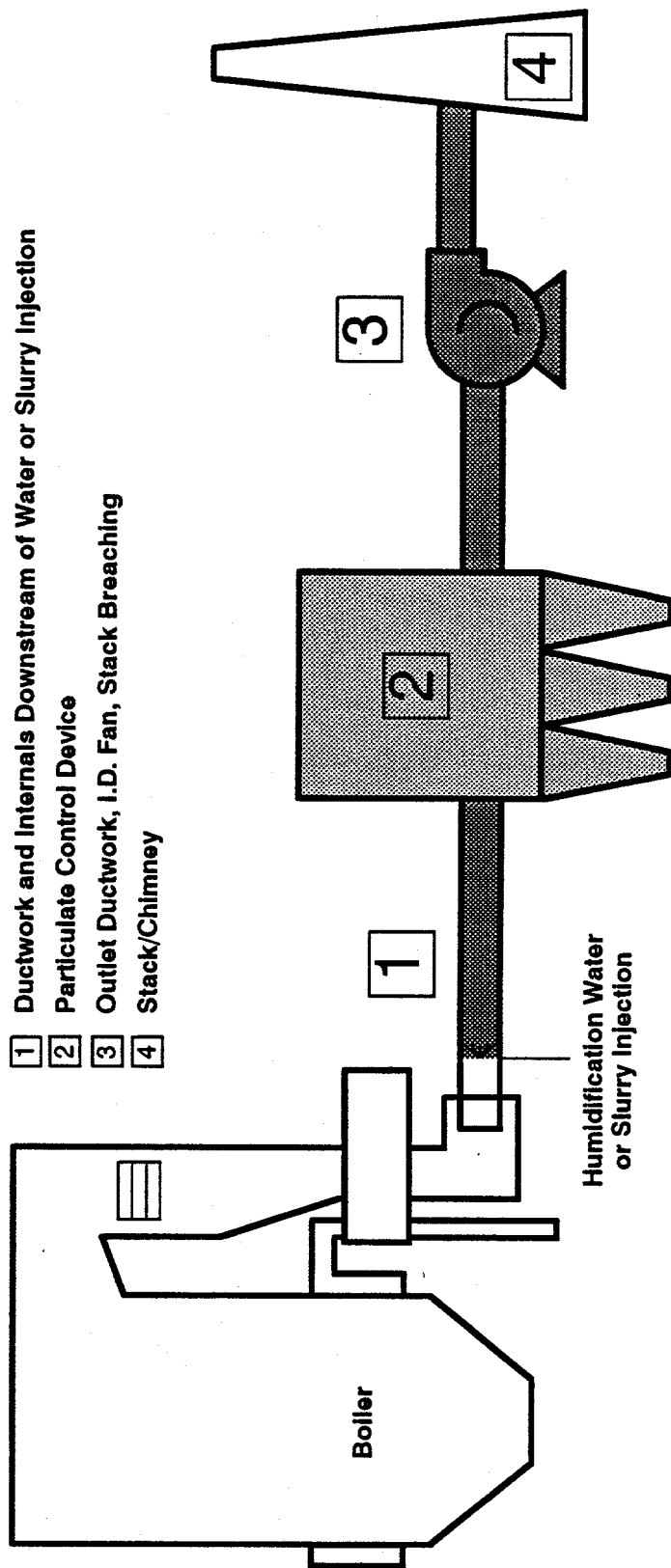
Hastelloys and Inconels are the most corrosion resistant materials, but replacing existing ductwork, ESP, etc., with these materials would be far too costly. Lower grade stainless steels are not recommended for these applications due to their susceptibility to chloride attack.

This section identifies the areas and equipment subject to corrosion as a result of a duct injection retrofit, and provides some recommendations to minimize these corrosion problems. For detailed information concerning corrosion rates and laboratory test results, refer to Reference 3, Materials Corrosion Report. This section is divided into four subsections based on the plant zones shown in Figure 9-1.

9.1 Humidification and Slurry Injection Ductwork

The ductwork located in the slurry or humidification water injection zone is subject to corrosion from condensation as well as corrosion under the wet solids deposits. When humidification water and sorbent are injected into the flue gas flow path, duct wall wetting may occur. Although the solid deposits may react with SO₂ in the flue gas, thereby increasing SO₂ removal, a severe environment may form beneath the deposit which can range from extremely acidic to extremely caustic. This under-deposit area can be subject to corrosion.

Figure 9--1
Potential Corrosion Zones
Duct Injection Retrofits



Ideally, the best way to avoid duct pluggage and under deposit corrosion is to prevent wet solids from depositing on duct surfaces. Unfortunately, this is unrealistic as some limited wall wetting solids deposition will occur even in the best designed and operated system. These problems, however, can be minimized by optimizing the location and design of the humidification nozzle array (see Section 6.2), and by maintaining tight control of system operation. Close monitoring of flue gas temperature and duct wall RTDs will provide early indications of problems. Section 8.0 of this report discusses process controls and deposition monitoring. Since some deposition will occur, it is very important to remove the deposits quickly to minimize the potential for under deposit corrosion. Deposition control techniques are described in Section 6.3.3.

It is anticipated that most plants will have carbon steel or corten ductwork in the humidification zone. It is not considered practical to replace this ductwork with corrosion resistant material. Corrosion resistant alloy clad on carbon steel or coated carbon steel provides effective protection from acid attack; however, alloy cladding or wallpapering of the duct may not be desirable due to the capital costs and downtime requirements associated with this type of corrosion protection. Vinyl ester resins and epoxy protective coatings on carbon steel have been tested as a corrosion inhibitor in ductwork, but the test results have been inconclusive. Since these coatings are relatively inexpensive compared to alloy cladding or wallpapering, the user may wish to further evaluate their use.

9.2 Particulate Collection Device

Electrostatic precipitators (ESP) are the most likely particulate collection devices to be installed at plants considering duct injection technologies. Corrosion has been a problem in most ESPs operating downstream of lime spray dryers, which produce a flue gas environment very similar to that in duct injection. Corrosion has been reported in several areas within the ESP.

Discharge electrode failures have been reported in the inlet most fields of at least one ESP operation downstream of a spray dryer. Corrosion under sorbent/ash deposits is suspected.

The outlet fields and outlet nozzles are especially subject to corrosion due in part to absence of sufficient alkali coating in these areas. The relatively low alkali solids loading in the gas in the outlet ESP fields is not sufficient to neutralize any acidic species which dissolve in the condensed moisture layer around the outlet fields and nozzle. This problem has been observed, in particular, in ESPs located in colder climates. The large surface area and thermal mass make it difficult to prevent moisture condensation when operating at duct injection temperatures. These problems are most severe during low load operation, start-up and shutdown. The most effective method for minimizing this type of condensation corrosion is to thoroughly insulate the ESP. A minimum of 4 in. of insulation is recommended; 6 in. have been necessary on some ESPs downstream of spray dryers in cold climates. The ESP OEM should be consulted as to any specifics on insulation detail. All exposed surfaces, such as flanges, damper housings, and expansions joints must also be well insulated. All access doors should be equipped with insulated door covers.

Air in-leakage must be minimized to prevent localized cold spots. The ESP doors and hopper connections are the primary source of air in-leakage to the unit. New, high grade gaskets will most likely be required to minimize the in-leakage through the doors. If the doors and surrounding areas currently show some corrosion, sandblast the corroded areas and paint the sandblasted area with a corrosion resistant coating, such as a vinyl ester resin or epoxy.

9.3 ESP Outlet Duct and Stack Breaching

The same precautions apply to the ESP outlet duct and stack breaching as for the ESP itself. Adequate insulation, and good seals at all connection points will minimize condensation and limit air in-leakage into the duct.

All areas of outlet ducting should be well insulated to minimize temperature loss. As with the ESP, 4 to 6 in. of insulation will be required. Any leaks in the ductwork should be patched to minimize cold spots. Corrugated metal expansion joints should be replaced with fabric or viton-type expansion joints. Corrugated metal expansion joints were found to corrode and fail in several utility spray dryer installations, and were replaced.

9.4 Stack and Chimney Liner

Stack corrosion and erosion could be a major concern for most plants suitable for a duct injection retrofit. Most of these plants will likely be older units with carbon steel or non-acid resistant brick liners. The impacts of a duct injection process on these types of stacks is largely unknown. The low temperature, high moisture flue gas will increase the potential for corrosion and erosion. Therefore, it is necessary to keep the flue gas safely above the water dew point by preventing cold spot condensation and in-leakage in the ESP and upstream ductwork. Commercial spray dryer experience has underscored the importance of adequate insulation over all duct and breaching surfaces including flanges and expansion joints. However, these precautions may not be sufficient to prevent corrosion and potential stack lean over long term operation. Application on units which share a common stack flue present a special problem. If duct injection flue gas mixes with hot untreated flue gas from another unit, even small concentrations of SO_3 will likely result in the formation of H_2SO_4 droplets which can cause severe corrosion and a possible visible acid plume. Relining the chimney with acid-resistant brick, flaked glass, FRP or other protective material may be required if upstream preventative measures are insufficient.

The most effective way to insure minimal corrosion in the stack is to construct a new chimney with an acid-resistant brick liner or a FRP liner. Building a new chimney is an alternative to relining the existing stack due to the outage requirements involved in relining the chimney. The new chimney can be erected while the unit is operation, requiring only a short outage for tie-in.

The flue gas can also be reheated to further minimize the possibility of acid condensation in the stack. The deterrent to reheating the flue gas is the high operating cost associated with reheat systems. Refer to Spec. No. M301, "Steam Coil Flue Gas Reheaters" (in Appendix E), for guidelines concerning reheat systems.

9.5 References

- 1) Brown, C.A., et al, "1.7 MW Pilot Results for the Duct Injection FGD Process Using Hydrated Lime Upstream of an ESP," presented at the 1991 SO_2 Control Symposium, December, 1991.
- 2) Felix, L.G., et al, "Scaleup Tests and Supporting Research for the Development of Duct Injection Technology," presented at the 1991 SO_2 Control Symposium, December, 1991.

- 3) "Materials Corrosion Report," Revision 1, DOE Duct Injection Prototype Development Program, Document No. RDD:91:4572-72-01:02, August, 1991.
- 4) Trip Report: Pacific Power Wyodak Station, United Engineers and Constructors, May 1992.

10.0 EQUIPMENT BID SPECIFICATION GUIDELINES

Bid specifications have been prepared for the major equipment required in a duct injection system retrofit. The list of specifications prepared is contained in Table 10-1. The specifications themselves are included in Appendix E. This section provides guidelines and suggestions to the user for customizing the specifications for a site-specific application.

Bid specifications are included for the major process components. Specifications for equipment which is "typical" to a power plant, such as heat exchangers, water pumps, etc., have not been included. The bid specifications are "furnish and deliver"; field erection specifications for mechanical, structural, electrical, or controls have not been included.

The specifications detail the performance and technical requirements for the equipment, but they are generic enough to allow customizing for a specific plant application. All of the equipment specifications have the same format and section numbering system. There are several standard sections in all of the specifications which contain requirements applicable to equipment in general; these requirements may require modification for procurement of specific equipment as noted below.

The equipment specification numbering system follows the Area Codes established in Section 5.4; e.g., Spec. No. M101 refers to a mechanical equipment specification (from the prefix "M") and is applicable to Area 100, Sorbent Storage and Preparation System. Since Spec. No. M101 is the rail car unloading bid specification, this equipment fits into Area 100. Similarly, Spec. No. M601 is a mechanical equipment specification applicable to Area 600, General Support Equipment. This is the air compressor bid specification, and compressors are considered general support equipment.

Three of the documents in Appendix E have a different format than the equipment specifications. These three documents were developed to be supplements to the equipment specifications - not stand-alone documents - and they are so referenced in Section 2 of each equipment specification. These three documents are:

Spec. No. E001	NEMA Frame Induction Motors
Spec. No. E002	Electrical Requirements for Packaged Mechanical Equipment
Spec. No. C001	Instrumentation and Controls for Packaged Mechanical Equipment

Specific comments and suggestions for customizing each section of the equipment specifications are given below:

Section 1 - This section briefly outlines the scope of the specification. A blank line or lines followed by a set of parentheses are included in the first paragraph for the user to specify the total number of items of that equipment to be purchased. For example, one (1) welded steel silo and two (2) day bins could be filled in Spec. No. M102, and three (3) bin vent dust collectors in Spec. No. M103.

As noted in this section, all of the equipment specifications were written to be furnish and deliver only, with the Owner providing unloading, storage, and erection.

Throughout all of the specifications, the term "Seller" is used for the vendor, and the term "Owner" is used for the buyer and/or owner and/or operator of the plant. The term "Bidder" is not used anywhere in any specification; this was done to make it easier to convert a bid specification into a purchase specification. Similarly, the words "bid" and "proposal" are not used anywhere in any specification. If the user has specific requirements for bidders, they can be included as an attachment.

Section 2 - This section lists any drawings or documents which supplement the specification. For most of the equipment specifications, the motor specification (E001), electrical requirements specification (E002), and instrumentation and controls specification (C001) are the only referenced supplements. For those specifications where the above supplemental equipment is not applicable - such as for bins or tanks - the above supplements are not referenced. The user should add any other "standard" specifications or documents that are normally used for equipment purchase.

Section 3 - This section lists the codes, standards, and regulations which apply for the design and fabrication of the subject equipment. The codes listed have been tailored for each specific piece of equipment, but the user may want to make deletions or additions based on its experience.

Section 4 - Paragraph A of this section provides a fairly detailed listing of what specific equipment the Seller is to provide. Blank lines are provided next to each piece of equipment and major auxiliary for the user to indicate the number of items to be furnished or just to indicate that item should be included. Continuing the example used above, the following could be entered for Spec. No. M102:

a.	<u>1</u>	silos
b.	<u>2</u>	day bins
c.	<u>2</u>	emergency truck fill pipes (for day bins only)
d.	<u>incl. for each</u>	roof hatches and shell manholes
e.	<u>incl. for each</u>	level indicator mountings
f.	<u>incl. for each</u>	ladders and platforms

And, for Spec. No. M103:

a.	<u>3</u>	enclosures
b.	<u>3 sets</u>	filter bags/bag cleaning system
c.	<u>2</u>	exhauster fans (for day bins only)
d.	<u>incl. for each</u>	controls

The other paragraphs in this section are fairly general in nature and will not normally require input or modification by the user. However, the user may want to delete certain requirements such as O&M manuals or a training program, depending on the complexity and nature of the equipment.

Section 5 - This section provides a fairly complete listing of related equipment, materials, and/or services that the Owner will provide. This section should be reviewed carefully by the user. Although it has been tailored for each specific piece of equipment, the user may need to make site-specific modifications or additions to this section.

This section also includes a release for fabrication requirement. This statement gives the Owner some assurance that fabrication will not start until the Owner is satisfied with the Seller's design and fabrication procedures. This statement may be deleted by the user under certain circumstances, e.g., standard equipment to be supplied, etc.

Section 6 - Paragraph A should be completed by the user to reflect the environmental conditions of the plant site. Some of the items may not be applicable to all of the equipment, e.g., ambient temperature, snow load, and wind load for equipment to be located indoors. However, this paragraph gives a good checklist for the user to specify the applicable plant conditions.

Paragraph B.a(2) also needs to be completed by the user to indicate whether the equipment will be located indoors or outdoors, and to give an approximate service or capacity factor for the equipment. Specific conditions of service for the equipment will be given by the user in the Design Data Sheet Completed by Owner (reference the write-up on Technical Data below).

Paragraph C.a gives general equipment design requirements. The user will need to complete Paragraph C.a(2) as appropriate for the expected life of the retrofit. Again, specific design parameters will be given by the user in the Design Data Sheet Completed by Owner.

Section 7 - This is a general section with regard to guarantees. It does, however, reference the Technical Data sheets to be completed by the Seller wherein items to be guaranteed are denoted by asterisks. If the user has other standard requirements regarding guarantees, these may be added to this section or added as a supplement to the specification.

Section 8 - This is the section which gives the details of design and construction for each piece of equipment. These requirements have been either taken from specifications which were used to buy similar equipment on actual projects, or they were generated based on the developmental work performed as part of this DOE program.

The user may have plant and/or system design requirements which conflict with, or supplement, the requirements given in this section; these will need to be included.

Section 9 - A standard welding requirements section has been included in every specification. For most standard, shop-fabricated equipment, the Seller has its own shop welding procedures in place, and these specification requirements are not necessary. These requirements may "scare" the vendors into putting more money into their bids and/or result in numerous exceptions. In these cases, these welding requirements may be deleted at the user's discretion. The specified requirements will be useful and applicable to large weldments such as tanks and silos.

Section 10 - A standard, conservative section on shop cleaning and painting has been included in each specification. Again, some of these requirements may cause the equipment price to increase unnecessarily and/or result in numerous exceptions. In these cases, the appropriate requirements may be deleted at the discretion of the user.

Section 11 - Standard identification requirements are included in each equipment specification. These requirements are fairly typical and general in nature; however, the user may need to modify the requirements as appropriate.

Section 12 - In specifications for rotating and other equipment which produces noise emissions, requirements are given for maximum sound levels. The requirements in the appropriate specifications are for 85 dBA at 3ft. If different levels apply to the specific plant site, the user should modify this section. A data sheet for noise emissions is included in each applicable specification for the Seller to document the noise levels. If the subject equipment does not cause noise emissions, this section has been deleted.

For applicable equipment, vibration requirements are also included in this section. The design requirement is for a vibration velocity of 0.2 in./sec. instead of a range of amplitudes. Again, if different levels apply to the specific plant, the user should modify this section. Since vibration monitoring for most process equipment of this size is seldom pursued, the Seller's scope is limited in the specifications to providing provisions for mounting the vibration monitoring equipment; the equipment itself would be supplied by the Owner.

Section 13 - A standard section giving requirements for packing and shipping is included in each specification. Some of the requirements may require modification or deletion by the user.

Section 14 - Paragraph A of this section gives general requirements for testing and inspections. This section is standard in all of the specifications. Paragraph B delineates the Seller's responsibilities and the Owner's rights for inspections of the equipment. In some of the specifications, mandatory hold points are specified beyond which the Seller may not proceed without the Owner's inspection or waiver.

Paragraph C provides the general and specific shop test requirements for the subject equipment. The general requirements are standard for all equipment. The user may have plant and/or system requirements which conflict with, or supplement, the specific requirements given in this section; these will need to be included.

Paragraph D is a standard subsection for all equipment which gives the Seller's and Owner's responsibilities with regard to field testing.

Section 15 - This is a standard section - almost identical in every specification - which lists the Seller's responsibilities for generating, filing, and/or submitting applicable documents during the design, fabrication, and testing of the equipment. The requirements given in this section are fairly extensive and detailed, but the user will need to add any site-specific requirements.

In Paragraph D, the user will need to fill in several blanks to identify the number of originals and copies of the documents to be submitted by the Seller.

Paragraph E is a listing of data and drawings to be submitted during the Seller's design phase. This list should be supplemented by the user as required. Paragraph E.f determines the Seller's requirements for O&M manuals. The user will need to specify the quantity of O&M manuals required in Paragraph E.f(1)(a).

Paragraph F.c(1) requires input from the user to specify the turnaround time required by the Owner for review of Seller's submittals. In Paragraph F.c(3), the user will specify the subsequent turnaround time allowed the Seller for submittal of revised documents after the Owner's comments are received. Finally, Paragraph F.c(5) requires the user to fill in the turnaround time required of the Seller for final certified drawings.

Section 16 - A schedule for receipt of documents and the equipment itself is included in each specification. A first review date is given in terms of days or weeks after award of purchase order for the documentation. These dates are subject to change based on the user's requirements and negotiations with the Seller. The delivery date of the equipment is left blank for the user to specify. A final issue date for applicable documentation is left open for the user to specify.

Technical Data - As mentioned above, a noise level data sheet is included in each applicable specification for the Seller to document the sound levels of its equipment both with and without sound attenuation.

Each specification contains a Design Data Sheet Completed by Owner and a Design Data Sheet Completed by Seller. The Owner's data sheets allow the user to specify the number and type of components, the specific service conditions under which the equipment will operate (e.g., slurry or solids composition, temperature, density, etc.), and the design parameters required (e.g., flow rate, capacity, design temperature and pressure, etc.).

The Design Data Sheet Completed by Seller provides the vendors (and ultimately, the Seller) with space to describe their equipment; blanks are included so the Seller can confirm its design and guaranteed performance (guaranteed items are denoted by asterisks).

Instructions at the top of the data sheet suggest that the user can reproduce the Design Data Sheet Completed by Owner so that a data sheet can be completed for each different application. Referring again to the silo/day bin example above, the Welded Steel Silos/Day Bins Design Data Sheet Completed by Owner can be reproduced so that one data sheet can be completed by the user to describe the silo and one to describe the two day bins (if the two day bins are identical - otherwise, a separate data sheet should be used for each day bin).

Similarly, instructions at the top of the data sheet suggest that the vendors (and ultimately, the Seller) should complete a separate Design Data Sheet Completed by Seller for each distinct application.

TABLE 10-1

EQUIPMENT BID SPECIFICATIONS*

<u>Spec. No.</u>	<u>Title</u>
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Mechanical Equipment Specifications

M101	Rail Car Unloading System
M102	Welded Steel Silos/Day Bins
M103	Bin Vent Dust Collectors
M104	Bin Activators
M105	Pneumatic Transfer/Injection Conveyors
M106	Gravimetric Feeders
M107	Screw Feeders
M108	Atmospheric Lime Hydrators
M109	Ball Mill Lime Slakers
M110	Detention-Type Lime Slakers
M111	Paste-Type Lime Slakers
M112	Vibrating Grit Screens
M113	Water and Slurry Tanks
M114	Agitators
M115	Horizontal Centrifugal Slurry Pumps
M116	Slurry Valves
M301	Steam Coil Flue Gas Reheaters
M601	Centrifugal Air Compressors

Controls and Instrumentation Equipment Specifications

C002	Continuous Emissions Monitoring System
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Supplements

E001	NEMA Frame Induction Motors
E002	Electrical Requirements for Packaged Mechanical Equipment
C001	Instrumentation and Controls for Packaged Mechanical Equipment

* All bid specifications included in Appendix E.

11.0 OPERATION AND MAINTENANCE GUIDELINES FOR DUCT INJECTION

Proper operation and maintenance (O&M) of a duct injection system is not only critical for maintaining SO₂ emission requirements, but also for ensuring overall unit availability. Duct injection processes utilize the existing plant ductwork, particulate collector, and ash handling systems, which cannot be bypassed in the event of major operating problems. If problems, such as severe buildups of wet solids in the ductwork or the loss of one or more ESP field occur, the unit may be forced to reduce load or shut down. These risks call for a conservative approach to the operation of a duct injection process and emphasize the importance of preventative maintenance.

This section provides general guidelines and recommendations for operating and maintaining duct injection processes (DSI and DSD) from a system or process standpoint. O&M guidelines for each duct injection process subsystem (reagent preparation, humidification/sorbent injection, flue gas system, etc.) are presented. The O&M considerations for new equipment unique to duct injection (such as dual-fluid atomizers, slurry pumps, lime slakers, and hydrators) are discussed. In addition, revised O&M procedures for existing plant equipment (ESP, ash handling, etc.) are given. However, new equipment common to power plants, such as compressors, pumps, valves, tanks, agitators, blowers, and feeders, are not covered.

Although this section gives numerous suggestions for operating and maintaining a duct injection system, it is not intended to serve as an O&M manual. It is strongly recommended that the user develop an O&M manual specific to the retrofitted duct injection process. The general operation and maintenance guidelines given in this section, combined with specific vendor O&M requirements and instrumentation and control requirements developed during detailed design, will form the basis for such an O&M manual.

11.1 Operational Guidelines

When starting up a piece of equipment or a subsystem of equipment, there should always be someone present locally at the equipment who is in voice contact with the control room to confirm equipment operation, valve positions, etc.

11.1.1 Sorbent Storage and Preparation System

The most important item of note in the sorbent storage and preparation area is SAFETY. Lime can be very dangerous if not handled properly. A discussion of safety precautions for bulk lime and lime slurry is contained in Section 11.4.

11.1.1.1 Dry Sorbent Injection

General

Lime, especially hydrated lime, tends to fluidize easily and can be difficult to control. Care will be required to prevent flooding and uncontrolled solids feed. Vent lines from rotary air locks need to be checked and cleaned periodically to ensure good lime feed to pressurized pneumatic conveyor lines. Otherwise, flow to the conveyor line may become erratic due to backflow of pressurized air from the pneumatic conveyor, impeding flow of solids into the air lock.

After pneumatically transferring lime from one area to another, make sure that the line is clear of material before the blower is shut down. Periodically, check the inlet air filters associated with blowers for pluggage.

Hydrator

The size of the pebble lime feed can have an effect on hydrator operation. Larger size pebbles require more retention time in the seasoning chamber compared to a fine, powder feed. Thus, the height of the weir in the seasoning chamber needs to be higher (providing a longer retention time) for larger size lime feed.

Turndown is difficult with a hydrator. Generally, it needs to be operated close to its design rating in a batch mode as opposed to trying to operate it continuously at some reduced load. Although automatic operation is preferable, manual operation of the hydrator may be required at times. Lime flow rate can be maintained constant, while water flow is varied based on temperature feedback.

Grit from the pebble lime will build up in the seasoning chamber. It must be removed periodically and disposed. Flushing out all of the equipment after each batch is imperative. Otherwise, very tenacious buildups may occur.

Start-up (Off-Site Hydration)

First, the hydrate silo aeration blower should be started and allowed to fluidize the hydrated lime for 10-15 min (this blower will be operated the entire time lime is fed to the ducts). Then, the hydrate injector blowers should be brought on-line, followed by the hydrate rotary air locks. Finally, the hydrate screw feeders should be initiated (all manual slide gates open).

Shutdown (Off-Site Hydration)

The hydrate silo aeration blower is shut down followed by the hydrate screw feeders. Then the hydrate rotary air locks should be de-energized, and, lastly (after the material clears the pneumatic injection lines), the hydrate injection blowers should be shut down.

After system shutdown, if the lime is still fluid and flows through the hydrate screw feeders, the manual gates will have to be closed each time the injection system is shut down.

Start-up (On-Site Hydration)

The hydration chamber of the hydrator is first filled about half full with water, and then the operator starts up the hydrator using the following steps: 1) the hydrator mixer paddles and scrubber fan are energized, 2) the hydrator discharge rotary air lock and hydrate transfer blower are energized, 3) hydration water flow is initiated by energizing the hydration water pump, 4) the pebble lime feed is initiated by energizing the selected lime weigh belt feeder, 5) the feeder "on" signal opens the appropriate side of the lime diverter valve, and 6) diverter valve fully open starts the pebble lime silo bin activator. The resulting hydrated lime is fed from the hydrate bin as described above for off-site hydration.

Shutdown (On-Site Hydration)

When the operator initiates hydrator stop, the equipment should shut down in the following order: 1) silo bin activator stops, 2) silo diverter valve closes, 3) lime weigh belt feeder stops, 4) operator initiates de-energization of the hydrator discharge rotary air lock and hydrate transfer blower, 5) the hydrator paddle and fan are stopped, and 6) after adequate flushing, operator initiates hydration water pump stop.

11.1.1.2 Duct Spray Drying

General

Lime tends to fluidize easily and can be difficult to control. Care will be required to prevent flooding and uncontrolled solids feed. Vent lines from rotary air locks need to be checked and cleaned periodically to ensure good lime feed to pressurized pneumatic conveyor lines. Otherwise, flow to the conveyor line may become erratic due to backflow of pressurized air from the pneumatic conveyor, impeding flow of solids into the air lock.

After pneumatically transferring lime from one area to another, make sure that the line is clear of material before the blower is shut down. Periodically, check the inlet air filters associated with blowers for pluggage.

It is important to monitor all slurry handling equipment for solids build-up, drop-out, or pluggage. Slurry line pressures should be checked frequently during each shift. Slurry tanks should be checked periodically for solids build-up on walls and floors. Tank agitator motor amps should be checked periodically; increasing amps may be a sign of buildup or too thick of a slurry. Abrasion potential of slurry pump internals, slurry piping, valves, and atomizer inserts will increase with increasing slurry solids.

Slurry in tanks should never remain stagnant. Two methods of movement (agitator and/or pumped loop) should be used continuously. No slurry should be left in any line when not in use. All lines, valves, pumps, and atomizers should always be flushed after isolation or shutdown.

As a minimum, the slurry flushing system should be capable of providing a complete four-volume flush of the entire slurry system. Flush velocities in lines should be 10 ft/sec. Each slurry pump and control valve should be flushable using equipment isolation valves to the greatest extent possible. Flushing points should be furnished for slurry pumps, valves, all slurry pipe bends, at the bottom of vertical risers, and every 100 ft in horizontal piping. Flushing points that are not part of a permanently piped system should be used for manual hose hookup and flushing. Flushing of piping should be downhill. Flushing water connections should be located on the top or side of slurry piping to avoid plugging.

It is essential to ensure periodic rotation of parallel slurry equipment if standby equipment is to remain operational. The pump in the standby train should be drained or completely flushed with water. It is not required to run this pump until the train is started up.

Lime Slaker

Turndown is difficult with a lime slaker. Generally, it needs to be operated close to its design rating in a batch mode as opposed to trying to operate it continuously at some reduced load.

Although automatic operation is preferable, manual operation of the slaker may be required at times. Lime flow rate can be maintained constant, while water flow is varied based on temperature feedback.

The bin activator associated with the bin or silo from which lime is fed into the lime slaker should only run during slaking operation. It should be interlocked with the weigh belt feeder. If it is turned on and allowed to run all the time, the lime would tend to pack too tightly in the bin or silo hopper.

Slurry Pumps

When two redundant slurry pumps are provided for the same service, slurry discharged from the operating pump can often build up in the discharge piping of the idle pump. This situation can be minimized using minimal "dead legs" in discharge piping between the discharge block valve and tee; however, operating personnel should be ready to flush and/or rod this section of piping before bringing the idle pump on line.

Slurry pumps should be operated such that more slurry will be pumped than is required in the downstream process. This operating condition ensures that the excess will recycle back to the originating tank to keep line velocities high even at low loads.

Slurry Density

A factor that can affect droplet drying and wet solids deposition is the percent solids in the atomized slurry. As a rule, the more solids in the slurry, the quicker the droplets will dry within the ductwork. Therefore, it is necessary to add recycle material to the lime slurry before feeding it to the atomizers. As a practical matter, slurries with less than 20% solids content will cause severe duct wall deposits because of poor drying. However, there are physical limits to the slurry solids content that can be pumped and atomized through dual-fluid atomizers. This limit varies with atomizer design and pump capacity, but 30-40% solids is the upper limit for many commercial dual-fluid atomizers.

As discussed in Sections 3.0 and 5.0 of this handbook, there are several interactive parameters that determine the necessary slurry density at any given operating condition. The atomized slurry is either slaked lime slurry or a mixture of slaked lime slurry and recycled solids. For the purpose of droplet drying, it is desirable to operate the atomizers at the maximum percent solids possible (as mentioned above). However, the particulate control device (especially in the case of an older, smaller ESP) and/or the ash handling system may limit the amount of solids that can be introduced into the gas stream. Within the physical limits and capacity of a particular DSD system, however, it is strongly recommended that the highest practical percent solids in the feed slurry be utilized.

Start-up

Depending on the slaker type installed, the slaking chamber is first filled about half full with water, and then the operator starts up the slaker using the following steps: 1) the slaker mechanical components, lime grit screen, and slaker vent system are energized, 2) slaking water flow is initiated by energizing the slaking water pump, 3) the pebble lime feed is initiated by energizing the selected lime weigh belt feeder, 4) the feeder "on" signal opens the appropriate side of the lime diverter valve, and 5) diverter valve fully open starts the pebble lime day bin activator.

Shutdown

When the operator initiates slaker stop, the equipment should shut down in the following order: 1) day bin activator stops, 2) silo diverter valve closes, 3) lime weigh belt feeder stops, 4) the slaker mechanical components, lime grit screen, and slaker vent system are stopped, and 5) after adequate flushing, operator initiates slaking water pump stop.

11.1.2 Humidification/Sorbent Injection System

11.1.2.1 Operating Temperature

The optimum flue gas temperature at which to control the duct injection process will achieve the desired level of SO₂ removal while avoiding wet solids from depositing on duct surfaces. Maintaining this balance is probably the single most important factor in the successful operation of any duct injection system.

A conservative approach is strongly recommended even if it requires slightly higher sorbent usage and operating costs. Although SO₂ removal and sorbent utilization improve with closer and closer approach to saturation temperature, there is a practical limit to how close to saturation any system may be operated without risking solids deposition and duct pluggage.

An example of why conservatism is warranted may be taken from operating experience of conventional lime spray dryers installed on utility boilers. These units were typically designed to operate at approach to saturation temperatures of 20 - 30°F; however, nearly all of these units actually operate at approaches of 30 - 40°F to avoid vessel wall build-ups, ash handling problems, and other operational difficulties. And these units have the luxury of 8 - 10 seconds of gas residence time for droplet drying.

Duct injection may require an even more conservative approach since there is much less time for droplet evaporation in the plant ductwork compared to that available in spray dryer vessels. Although this criterion is site specific, a rule of thumb is that duct injection systems should operate with an approach to saturation between 30 and 50°F. Operating below 30°F sharply increases the risk of duct deposition, while sorbent utilization drops off dramatically at approach temperatures above 50°F. As noted in Section 8.0, another parameter to consider when selecting the approach to saturation is the temperature at the ESP outlet. The temperature at this point should not be less than 20°F above saturation for corrosion protection.

Also noted in Section 8.0 is that flue gas temperature is controlled by humidification water or slurry injection. A temperature signal from an array of shielded thermocouples located just upstream of the ESP provides the feedback control point. In addition, an array of unshielded thermocouples should be installed at the same duct location as the shielded array. If unevaporated water or slurry droplets impinge on any of the unshielded thermocouples, they will indicate a lower temperature compared to the adjacent shielded thermocouple. Complete evaporation can be assumed if both the shielded and unshielded thermocouples are indicating the same temperature (and the temperature is above the saturation point). Conversely, if the temperature signal from any unshielded thermocouple is less than 10°F above the saturation temperature, an alarm should be indicated. Plant operators can switch the water or slurry injection to manual control, while an operator checks the thermocouples and the corresponding atomizer lances for problems, such as deposits or pluggage.

Along with the unshielded, alarm thermocouple array in the flue gas stream, duct wall thermocouples or RTDs may be located at several positions downstream of the atomizer array where wall wetting is most likely. These positions can be determined by cold-flow or computer modeling. An alarm status should be indicated if any of these wall thermocouples or RTDs read less than about 15°F above saturation (or more than 10°F below the bulk gas temperature). At this point, wall wetting is imminent, and operators should switch the duct injection system to manual control, while troubleshooting procedures are implemented.

Thermocouples and RTDs should be kept in good working order at all times due to the critical importance of temperature measurements. Flue gas thermocouples should be pulled and checked for, and cleaned of, deposits, if necessary. Plant I&C staff should check and maintain calibration of all temperature controllers, water or slurry flow meters, and control valves.

11.1.2.2 Atomizers

Dual-fluid atomizers should be kept in good working condition at all times. One major cause of wall wetting can be poor atomization that can result from:

1. Insufficient atomizing air pressure
2. Solids build-up on atomizer tip
3. Plugging of atomizer internals
4. Plugging of liquid manifold in atomizer lance
5. Wear on atomizer internals
6. Build-up of solids on upstream edges of nozzles and/or atomizer lances

Air and liquid pressures at each atomizer lance should be checked each shift. Alarms and interlocks should be provided to prevent water or slurry injection at insufficient air pressure. Nozzles and lances should be inspected frequently during operation to detect build-ups and/or dripping. Atomizer deposits will interfere with performance and can cause dripping and spray coalescence. Dripping will typically result in accumulations on duct floors. Spare lances should be maintained in ready mode at the injection location at all times for quick change out. All lance connections should be of the quick-disconnect type. Individual atomizers should be inspected periodically for wear and abrasion according to the manufacturer's recommendations.

Strainers in the atomizing air and humidification water or slurry lines are very important for minimizing wear and erosion of atomizer internals. These strainers should be checked regularly. Duplex strainers should be switched regularly and the off-line basket cleaned.

11.1.2.3 Humidification Water Atomizer/Sorbent Injector Arrangement

The sorbent injectors should be extended into the same injection plane as the water spray atomizers rather than injecting upstream or downstream of the atomizers. This arrangement will minimize build-ups on the humidifier lances.

Although not shown on DSI P&ID Sheet 1, each humidification water feed line to each lance may be equipped with a flow element (magnetic flowmeter) to enable the prompt detection of lance operating problems, such as atomizer plugging. In addition, an automatic water shutoff valve (shown as the ball valve in DSI P&ID Sheet 1) should be activated by loss of atomization air pressure. The manual globe valve in each line should be used to trim water flow among lances. These globe valves allow humidification water distribution between the

top and bottom spray lances to accommodate hydraulic gradients due to head differences.

11.1.2.4 Slurry Nozzle Arrangement

Although not shown on DSD P&ID Sheet 1A, each slurry feed line to each lance may be equipped with a flow element (magnetic flowmeter) to enable the prompt detection of lance operating problems, such as atomizer plugging. In addition, an automatic slurry shutoff valve (not shown in DSD P&ID Sheet 1A) should be activated by loss of atomization air pressure. The manual valve in each line should be used to trim slurry flow among lances. These valves allow slurry distribution between the top and bottom spray lances to accommodate hydraulic gradients due to head differences.

11.1.2.5 Process Turndown Considerations

Turndown of the humidification water or slurry injection system is addressed in Section 8.1.3.2 or 8.1.3.3, respectively. The dynamic and interdependent nature of the duct injection process streams can result in different operational concerns at different load conditions. For example, inlet flue gas temperature will vary with load, requiring changes in humidification water requirements or slurry composition and flow rate. These characteristics and trends are unique to each duct injection installation and cannot be easily generalized. It is vital to establish these trends and impacts on operation during start-up and performance testing. Conditions resulting in more dilute slurry, for example, require special attention to anticipate wall wetting, while conditions resulting in high slurry density should be closely monitored for pluggage and abrasion problems.

For humidification water or slurry injection, the liquid and atomizing air flows should both be turned down at a constant air-to-liquid mass ratio down to 50% load (as long as the minimum pressure differential between the air and liquid streams to the nozzles is maintained). Below 50% load, the liquid flow should continue to be turned down to maintain the desired approach temperature, while the atomizing air flow (pressure) to the nozzles remains constant.

11.1.2.6 Start-up

During start-up, humidification water or slurry should be injected into the flue gas at flow rates that achieve the following:

1. 30°F gas temperature drop every 15 min down to 200°F
2. 10°F gas temperature drop every 15 min down to 170°F
3. 5°F gas temperature drop every 15 min until target operating temperature is reached

For DSI start-up, dry sorbent should be pneumatically injected first with no accompanying water injection (reference Section 11.1.1.1). This mode of operation reduces the potential for acid condensation and can likely be accommodated for up to an hour before ESP efficiency begins to degrade. After sorbent injection steadies out, humidification water injection may commence by initiating the atomizing air compressors and then the humidification water pump.

11.1.2.7 Shutdown

During DSI shutdown, humidification water should be shut off first, followed by interruption of sorbent flow. Then the hydrate injection blowers and atomizing air compressors should be shut down.

11.1.3 Flue Gas System

Optimizing rapping intensity and frequency can improve ESP performance. A portion of the emissions from all ESPs is the result of rapping re-entrainment. The rapping frequency and intensity are normally adjusted for the fly ash and flue gas conditions specific to each ESP application. When these conditions are altered, as in the case of a duct injection retrofit, the rappers must be readjusted. In many cases, optimizing rapping frequency and intensity can significantly improve the performance of the ESP.

For ESPs operating with low-resistivity ash, rapper adjustments can generally minimize opacity spiking, but they may not result in significant reductions in overall mass emissions. In these cases, mass emissions from velocity scouring far outweigh the contribution of rapper-related re-entrainment. Since opacity is generally the day-to-day indicator of ESP emissions compliance, however, rapper optimization is a very necessary task.

Extended operation of sorbent injection may result in a long-term residual build-up of particulate on the ESP collecting plates. This would result in severe power degradations and increased opacity. Intermittent power-off rapping should be generally successful in removing these long-term plate build-ups and in restoring stack opacity to acceptable levels. This is typically accomplished by de-energizing the electrical field and manually initiating the rapping. However, this sometimes results in high opacity excursions. While this practice in its crude form may not be suitable for normal power plant operations, it may be possible to automate the procedure. Several manufacturers offer microprocessor-based programmable rapper controllers and automatic precipitator power controllers. By initiating field-by-field power-off rapping at carefully timed intervals, opacity excursions may be avoided. This option is considered feasible in conjunction with the retrofit of a duct injection system.

Deposits may build up on the ESP discharge wires. This situation may be caused by the stickiness of the lime/sorbent waste, as well as transformer/rectifier set voltage limitations. The latter phenomenon can promote wire deposit formation since sparking, which helps to clean wires, is limited initially. A 5 to 10 kV increase in required operating voltage would be expected for the change in operating conditions caused by lime injection and the increased water content of the flue gas.

To correct the wire deposit problem, new rappers may need to be added or existing ones replaced with more effective rapping intensity. For example, drop rods could be replaced with tumble hammer rappers.

11.1.4 Recycle System

11.1.4.1 General

The recycle system is generally provided to improve the economics of the duct injection system process, by returning a portion of the lime that was not utilized in the first pass. Therefore, it is not as critical of a subsystem as some other areas. However, adding recycle

material into the lime slurry before it is fed to the atomizers is important for proper drying, as discussed above.

Duct injection solids are generally high in moisture compared to typical boiler fly ash. This fact may result in significant operational difficulties when operating a duct injection system. Increased moisture in the duct injection solids can lead to:

1. Difficulty in removing solids from hoppers
2. Solids build-up and plugging of conveying piping
3. Solids setting up in a recycle bin

Due to the large volume of solids collected and the potential stickiness of this material, it may be difficult to extract the solids from storage bins. Operators should be prepared to utilize pokeholes and striking plates to re-establish flow if pluggage or bridging is detected by inspection.

Potential problem areas in recycle material conveying piping, such as elbows, should be identified. It may be helpful to provide extra flanged sections to help access these areas for clean-out.

Level detectors and fluidizing aids associated with recycle material bins should be closely monitored.

11.1.4.2 Dry Sorbent Injection

Start-up

First, the recycle bin aeration blower should be started and allowed to fluidize the ash/sorbent waste for 10-15 min (this blower will be operated the entire time recycle material is fed to the ducts). Then, the recycle injector blowers should be brought on-line, followed by the recycle bin rotary air locks. Finally, the recycle bin rotary feeders should be initiated (all manual slide gates open).

Shutdown

The recycle bin aeration blower is shut down, followed by the recycle bin rotary feeders. Then the recycle bin rotary air locks should be de-energized, and, lastly (after the material clears the pneumatic injection lines), the recycle injection blowers should be shut down.

After system shutdown, if the material is still fluid and flows through the recycle bin rotary feeders, the manual gates will have to be closed each time the injection system is shut down.

The feed rate of the recycled material can be estimated based on recycle bin rotary feeder speed, feeder pocket volume, and solids bulk density. However, this method is subject to error if feeder pockets do not fill completely, the feeder wears, and/or the solids bulk density changes. Another method of estimating recycle material flow rate is pressure drop in the transfer line from the pickup point to the distribution bottle.

11.1.4.3 Duct Spray Drying

Start-up

The recycle slurry tank is filled with water to just cover the upper agitator blade. Then, the agitator is energized and left on for as long as the liquid level in the tank is above minimum. To begin recycle material feed, the following steps are followed: 1) the recycle bin aeration blower should be started and allowed to fluidize the ash/sorbent waste for 10-15 min (this blower will be operated the entire time recycle material is fed to the recycle slurry tank), 2) ash wetting water is initiated by energizing the recycle ash water pump, 3) the recycle slurry tank vent system is brought on-line, and 4) the recycle bin rotary feeder is started (manual slide gate open).

Generally, the recycle material wetting in the recycle slurry tank is independent from transferring recycle slurry to the atomizer feed tank with the recycle slurry pumps.

Shutdown

The recycle bin aeration blower is shut down, followed by the recycle bin rotary feeder, the recycle slurry tank vent system, and the recycle ash water pump.

11.1.5 Waste Handling System

Duct injection solids are generally higher in moisture than typical boiler fly ash. This fact may result in more attention being given to the operation of the ash handling system than before the retrofit. Increased moisture in the duct injection solids can lead to:

1. Difficulty in removing solids from hoppers
2. Solids build-up and plugging of ash conveying piping
3. Solids setting up in ash storage silos

Due to the large volume of solids collected and the potential stickiness of this material, high hopper levels can develop rapidly. If left unchecked, this condition can lead to grounding of ESP electrical sections. Operators should be prepared to utilize pokeholes and striking plates to re-establish flow if high levels are indicated or detected by inspection.

After an ESP is shut down, the ash handling system should be kept in operation. At least two complete hopper cleaning cycles should be conducted after flue gas flow has ceased.

If a vacuum pneumatic fly ash handling system is installed on an ESP, it should not run continuously unless it is known that ash is building up in the hoppers. If the vacuum system pulls on hoppers with little or no ash in them, flue gas is sucked into the ash line which then passes through the receiver/separators and other equipment before being exhausted downstream of the vacuum blower. Flue gas contains moisture and acid that will condense out in the cold equipment on top of the ash silo. The moisture/acid condensation will likely cause corrosion of equipment and build-up of material in the separators, dump gates, etc.

Potential problem areas in ash conveying piping, such as elbows, should be identified. It may be helpful to provide extra flanged sections to help access these areas for clean-out.

As with ESP hoppers, level detectors, heaters (if applicable), and fluidizing aids associated with ash storage silos should be closely monitored.

11.1.6 General Support Equipment

Air compressors supplying atomizing air should be well maintained. Alarms and interlocks should be provided to prevent liquid or slurry injection at insufficient air pressure.

11.2 Maintenance Guidelines

11.2.1 Sorbent Storage and Preparation System

Housekeeping will be a major effort with lime systems. Due to its fineness, hydrate, especially, will tend to get everywhere, requiring frequent cleaning. Fine lime has been known to penetrate NEMA 4 enclosures. Therefore, controls, instruments, motor control centers, etc. should be isolated from the lime processing equipment. Lime dust can penetrate motor seals and gear boxes; frequent oil changes are necessary.

11.2.1.1 Dry Sorbent Injection

Hydrator

Mixing paddle wear can be significant in the hydrator seasoning chamber. They can wear as much as 2-4 in. in just a few months of operation. Entire paddle arms can break off. Changing the oil will be required frequently as lime will penetrate motor and gear lubrication seals.

11.2.1.2 Duct Spray Drying

Slurry handling tends to be inherently maintenance intensive. Abrasion and erosion from slurry solids (especially from recycled material containing fly ash) causes considerable equipment wear. Pluggage from solids that settle out in "dead legs" is another prevalent problem that will require maintenance. Spare pump impellers and liners will be necessary, even though two redundant pumps are typically provided for each service. Periodically, all slurry handling equipment must be shut down and thoroughly cleaned of all scale and build-up.

11.2.2 Humidification/Sorbent Injection System

Dual-fluid atomizers should be maintained in good working condition at all times. Spare lances should be maintained in ready mode at the injection location at all times for quick change out. All lance connections should be of the quick-disconnect type. Individual atomizers should be inspected periodically for wear and abrasion according to the manufacturer's recommendations. Cleaning scale build-up from individual nozzles will sometimes be required, utilizing mild acid solutions.

11.2.3 Flue Gas System

ESP and ductwork access doors and door seals should be maintained to minimize any air in-leakage. Damaged or insufficient insulation should be replaced immediately.

11.2.4 Recycle System

Even though the recycle system is generally not a critical component of a duct injection system, solids flow aids, such as fluidizing air systems, should be well maintained. Level detectors, and fluidizing aids associated with recycle bins should be well maintained.

11.2.5 Waste Handling System

Level detectors on ash collection hoppers beneath the particulate control device should be well maintained. Hopper heaters and other solids flow aids, such as fluidizing air systems, should also be well maintained. As with ESP hoppers, level detectors, heaters (if applicable), and fluidizing aids associated with ash storage silos should be well maintained.

11.2.6 General Support Equipment

Air compressors supplying atomizing air should be well maintained. Loss of atomizing air would result in also immediate build-up of material on the duct walls. Alarms and interlocks should be provided to prevent liquid or slurry injection at insufficient air pressure.

11.2.7 Monorails/Trolleys/Hoist

For proper removal and maintenance of all equipment, atomizers, and other applicable equipment, monorails, trolleys or lifting beams, and hoists should be supplied as follows:

Monorail/Electric Trolley/Electric Hoist

Ball mill or detention slakers
Atomizing air compressors

Monorail/Manual Trolley/Electric Hoist

All slurry tank agitators
Slurry pump
Sump pump/agitator
Paste slakers
Dust collectors/fans on top of silos/bins
Atomizer lances

Lifting Beam/Manual Trolley/Chain Hoist

Water pumps
Solids conveying/aerating blowers
Screw feeders

11.3 Preventive Maintenance Program

A preventive maintenance program will minimize equipment failures and downtime and ensure long life from the duct injection system. The preventive maintenance instructions, as presented in the manufacturers' O&M manuals for each piece of equipment in the duct injection process, should be reviewed and considered in developing a preventive maintenance program. This program should delineate the major tasks required for the preventive

maintenance of each piece of equipment and should also reference the appropriate manufacturer's O&M instructions for more detail.

In lieu of specific, manufacturer-recommended frequencies for each preventive maintenance task, the following frequencies may be used as a guideline. Frequencies are given as daily (once per shift), weekly, monthly, etc. The preventive maintenance program developed by the plant for the duct injection system should also include corresponding check lists for use by O&M personnel.

11.3.1 Sorbent Storage and Preparation System

<u>Equipment</u>	<u>Maintenance Tasks</u>	<u>Frequency</u>
Blowers	Check bearing temperature and vibration	Daily
	Check developed air pressure	Daily
	Grease drive-end bearings	Monthly
	Check oil level in opposite-end bearings and inspect breather for pluggage	Monthly
	Clean air filter element	Monthly
	Drain condensate from silencers	Monthly
	Inspect belt drive; check for noise, belt wear, and proper belt tension and sheave alignment	Quarterly
	Grease motor bearings	Quarterly
Screw Feeders	Change oil in blower	Annually
	Inspect screw for lime build-ups; clean out if necessary and inspect and clean feeder inlet and discharge chutes	Weekly
	Check oil level in gear box and check that breather is unclogged	Monthly
	Change oil in gear box	Annually

Weigh belt Feeders	Inspect belt for lime build-ups and clean off if lime is sticking to it; clean out lime underneath belt and inspect and clean feeder inlet and discharge chutes	Weekly
	Check oil level in gear box and check that breather is unclogged	Monthly
	Inspect feeder scrapers for wear and alignment	Monthly
	Check belt tension and tracking	Quarterly
	Change oil in gear box	Annually
Rotary Feeders/ Air Locks	Inspect pulse generator gears for wear; relube idler shaft	Annually
	Check and clear vents if plugged	Weekly
	Inspect blade seals for wear and sealing	Monthly
	Grease feeder bearings	Monthly
	Grease motor bearings	Monthly
Silo/Bin Dust Collectors	Check differential pressure across filter; if it is more than 4 in. water, increase frequency of air pulsing	Weekly
	Check timer and solenoid valves for proper operation	Weekly
	Inspect filter bags for wear and condition and that every bag clamp is tight	Quarterly
	Grease fan and fan motor	Quarterly
Bin Activators	Inspect rubber isolators for hanging orientation and material build-up; if the isolators are cocked to one side, the lime is probably stagnant on one side of the hopper	Monthly

Hydrator	Inspect rubber sock for cracking, leaks, or tears	Monthly
	Grease top and bottom motor bearings	Quarterly
	Flush hydrator and clean out grit from seasoning chamber	Daily
	Inspect hydrator scrubber and chutes underneath scrubber for lime build-up	Weekly
	Grease all bearings on paddle shafts; grease all gears	Monthly
	Check oil level in gear reducer and check that breather is unclogged	Monthly
	Grease hydrator scrubber fan shaft bearings	Monthly
	Inspect all belt drives; check for noise, belt wear, and proper belt tension and sheave alignment	Quarterly
	Grease all motor bearings	Quarterly
	Change oil in gear reducer	Annually
Slaker	Flush slaker and clean out	Daily
	Inspect slaker vent for lime build-up	Weekly
	Grease all bearings on paddle shafts and rake shafts; grease all gears	Monthly
	Check oil level in gear reducer and check that breather is unclogged	Monthly
	Inspect all belt drives; check for noise, belt wear, and proper belt tension and sheave alignment	Quarterly
	Grease all motor bearings	Quarterly

	Change oil in gear reducer	Annually
Vibrating Lime Grit Screen	Hose down screen	Daily
	Clean out any accumulation of scaled lime; inspect discharge and overflow parts for build-up or obstruction; inspect spray nozzle for plugging	Weekly
	Remove and clean the screen element with dilute acid	Weekly
	Grease the top motor bearing of the vibrating screen	Weekly
Agitators	Grease upper and lower output shaft bearings, motor, couplings, and seals	Monthly
	Check oil level in gear reducer and check that breather is not clogged	Monthly
	Grease motor bearings	Quarterly
	Check gear tooth condition and and contact pattern	Semi-Annually
	Change oil in gear reducer	Annually
Slurry Pumps	Ensure pump seal water flow is on to all slurry pumps	Daily
	Check developed slurry pressure	Daily
	Grease pump bearings	Monthly
	Inspect packing; verify that packing is leaking water during pump operation	Monthly
	Inspect belt drives; check for noise, belt wear, and proper belt tension and sheave alignment	Quarterly
	Grease motor bearings	Quarterly
	Inspect impeller and adjust impeller clearance	Quarterly

11.3.2 Humidification/Sorbent Injection System

<u>Equipment</u>	<u>Maintenance Tasks</u>	<u>Frequency</u>
Dual-Fluid Atomizers	Inspect all hose connections for tightness and for leaks	Daily
	Check the air and liquid pressures in each line supplying a manifold or lance	Daily
	Check atomizing air and liquid strainers for proper operation; switch baskets on Duplex strainers	Daily
	Scrape any deposits from atomizers; clean slurry nozzles in acid bath	Weekly
Dry Sorbent Injectors	Inspect all hose connections for tightness and leaks	Daily
	Check the air pressure in each line	Daily

11.3.3 Flue Gas System

<u>Equipment</u>	<u>Maintenance Tasks</u>	<u>Frequency</u>
Existing Ductwork	Inspect the walls, ceiling, and floor via access doors/viewports	Daily
	Check all gasketed and bolted areas for evidence of dust leakage or air in-leakage; reseal all areas of leakage	Weekly
Thermocouples	Verify thermocouples are reading properly and that they are not coated with build-up	Weekly
Expansion	Check for significant material loading on the bottom of the joint	Monthly
Existing ESP	Check hoppers for evidence of bridging or build-up of particulate	Daily
	Watch rapper cycle to verify proper sequence	Weekly

Check all gasketed and bolted areas for evidence of dust leakage or air in-leakage; reseal all areas of leakage

Weekly

11.3.4 Recycle System

<u>Equipment</u>	<u>Maintenance Tasks</u>	<u>Frequency</u>
Blowers	Check bearing temperature and vibration	Daily
	Check developed air pressure	Daily
	Grease drive-end bearings	Monthly
	Check oil level in opposite-end bearings and inspect breather for pluggage	Monthly
	Clean air filter element	Monthly
	Drain condensate from silencers	Monthly
	Inspect belt drive; check for noise, belt wear, and proper belt tension and sheave alignment	Quarterly
	Grease motor bearings	Quarterly
Rotary Feeders/ Air Locks	Change oil in blower	Annually
	Check and clear vents if plugged	Weekly
	Inspect blade seals for wear and sealing	Monthly
	Grease feeder bearings	Monthly
Recycle Bin Dust Collectors	Grease motor bearings	Monthly
	Check differential pressure across filter; if it is more than 4 in. water, increase frequency of air pulsing	Weekly
	Check timer and solenoid valves for proper operation	Weekly

Vibrating Recycle Grit Screen	Inspect filter bags for wear and condition and that every bag clamp is tight	Quarterly
	Grease fan and fan motor	Quarterly
	Hose down screen	Daily
	Clean out any accumulation of scaled material; inspect discharge and overflow parts for build-up or obstruction; inspect spray nozzle for plugging	Weekly
	Remove and clean the screen element with dilute acid	Weekly
Recycle Slurry Tank Agitator	Grease the top motor bearing of the vibrating screen	Weekly
	Grease upper and lower output shaft bearings, motor, couplings, and seals	Monthly
	Check oil level in gear reducer and check that breather is not clogged	Monthly
	Grease motor bearings	Quarterly
	Check gear tooth condition and and contact pattern	Semi-Annually
Recycle Slurry Pumps	Change oil in gear reducer	Annually
	Ensure pump seal water flow is on to all slurry pumps	Daily
	Check developed slurry pressure	Daily
	Grease pump bearings	Monthly
	Inspect packing; verify that packing is leaking water during pump operation	Monthly
	Inspect belt drives; check for noise, belt wear, and proper belt tension and sheave alignment	Quarterly

Grease motor bearings	Quarterly
Inspect impeller and adjust impeller clearance	Quarterly

11.3.5 Waste Handling System

If the existing ash handling system will be reused, the preventive maintenance requirements will be similar to those currently in place; however, these requirements may need to be implemented on a more frequent basis due to the increased volume of material handled. If a new system is installed, preventive maintenance will be as prescribed by the new equipment manufacturer.

11.3.6 General Support Equipment

<u>Equipment</u>	<u>Maintenance Tasks</u>	<u>Frequency</u>
Atomizing Air Compressors	Check bearing temperature and vibration	Daily
	Check developed air pressure	Daily
	Check cooling water flow, pressure, and temperature	Daily
	Grease drive-end bearings	Monthly
	Check oil level in opposite-end bearings and inspect breather for pluggage	Monthly
	Clean air filter element	Monthly
	Drain condensate from silencers	Monthly
	Inspect drive; check for noise and alignment	Monthly
	Grease motor bearings	Quarterly
Water Pumps	Change oil in compressor	Annually
	Check that oil for pump bearings is filled to oil level line	Weekly
	Inspect packing	Monthly
	Grease motor bearings	Quarterly
	Change oil in pump	Annually

Humidifi-
cation Water
Filter

Check pressure differential
across filter and switch to
other filter basket; clean
basket not in service

Daily

11.3.7 General Maintenance and Inspection Rounds

General preventive maintenance includes inspection rounds performed at least once per shift, while the duct injection system is operating. The rounds should include the following items as a minimum:

1. Visual inspection of all rotating equipment, checking for normal bearing temperatures (by hand or local temperature gauge), oil levels, grease cups, and local temperatures and pressures. Such rotating equipment includes weigh belt feeders, rotary feeders, screw feeders (if applicable), aeration and injection blowers/rotary air locks (if applicable), hydrators or slakers (as applicable), agitators (if applicable), slurry and water pumps (if applicable), and atomizing air compressors.
2. Visual inspection of all wet/dry interface areas, such as hydrator premixer or slaker throat (as applicable) where the lime first mixes with water and the recycle slurry tank powder chute. If build-up is occurring in these areas, rod it out.
3. Visual inspection of slurry vibrating screens (if applicable). If scaling is present, clean off with steel brush.
4. Visual confirmation of all flows to tanks (if applicable), cooling water flows, overflows, etc.
5. Visual confirmation of all tank and bin levels.
6. Overall inspection for leaks in dry and wet lines.
7. Reading of all local indicators.
8. Visual inspection of atomizer sprays and sorbent injection (if applicable). Verify water or slurry pressure and atomizing air pressure to each lance.
9. Confirmation of dry material flow out of the ESP hoppers.
10. Check all valve and damper positions.

11.4 Safety Concerns

11.4.1 Handling Lime

The primary safety concern when handling lime or any other highly alkaline solids is caustic burns due to skin contact. All personnel need to adequately protect themselves against skin contact with the lime to avoid burns. Adequate protection includes wearing gloves, safety goggles, dust masks, long-sleeved shirts, pants long enough to cover the tops of shoes or boots, and head covering.

Should a worker come into contact with lime, cleanse the affected area immediately with soap and warm water and then vinegar to remove all of the lime. After washing is complete, apply burn ointment, such as boric acid salve, and then bandage the area to prevent infection during the healing process. If the lime comes into contact with the eyes, flush thoroughly with cold water and then boric acid solution.

Slaked lime can also produce burns when the slurry is hot. When lime contacts water, an exothermic reaction takes place creating a very hot slurry. If the lime-to-water ratio gets too high, the resulting slurry can begin to boil due to steam formation and "burp" hot slurry everywhere. Maintaining a maximum lime-to-water ratio is critical. One means of accomplishing this is to install a thermostatic valve in the slaking system. Such a device prevents overheating and possible explosion by opening a safety valve to supply cold water to the slaker if the temperature increases past a setpoint. Alternatively, the lime feed could be interrupted if the setpoint temperature is reached.

Cool or cold slurry causes only minor problems when it comes into contact with the skin. Cool slurry can remove natural skin oils. This can be protected against by using gloves or some form of oil or petroleum jelly to help the skin retain oils, prevent chapping, and reduce infection.

Efficient dust collection and removal should be employed in slaking areas to vent lime dust and steam produced in the slaking reaction. Housekeeping is important to remove lime solids build-up around process equipment. Dry vacuums can be utilized for this purpose.

11.4.2 Emergency Shower/Eyewash Stations

Emergency shower and eyewash stations should be provided in the immediate vicinity of:

1. The lime hydrator or slaker
2. Any tank that stores lime or atomizer feed slurry
3. Any slurry vibrating screens
4. Slurry atomizers at duct level (eyewash station only)
5. The lime feeders on an elevated floor
6. The recycle material rotary feeder on an elevated floor

The emergency showers/eyewash stations should be hard piped, if possible; otherwise, replaceable, non-piped stations are acceptable.

11.5 Troubleshooting

11.5.1 Sorbent Storage and Preparation System

Abnormality	Probable Cause	Corrective Action
Hydrator temperature too high (DSI only)	Low hydration water flow	Check operation of hydration water flow control
	Lime feed rate too high	Check operation of lime weigh belt feeder

Abnormality	Probable Cause	Corrective Action
Hydrator temperature too low (DSI only)	High slaking water flow	Check operation of slaking water flow control
	Lime feed rate too low	Check operation of lime weigh belt feeder
	Lime pluggage	Inspect lime feed chutes for pluggage or restrictions
	Low lime reactivity or impure lime	Check lime reactivity and purity by proper analysis
Lime hydrating problems (DSI only)	Build-up of deposits or scale	Proper flushing of hydrator and associated scrubber and piping after shutdown; a good flush before start of hydrating
Slaker temperature too high (DSD only)	Low slaking water flow	Check operation of slaking water flow control
	Lime feed rate too high	Check operation of lime weigh belt feeder
Slaker temperature too low (DSD only)	High slaking water flow	Check operation of slaking water flow control
	Lime feed rate too low	Check operation of lime weigh belt feeder
	Lime pluggage	Inspect lime feed chutes for pluggage or restrictions
	Low lime reactivity or impure lime	Check lime reactivity and purity by proper analysis
Lime slaking problems (DSD only)	Build-up of deposits or scale	Proper flushing of slaker and associated pumps and piping after shutdown; a good flush before start of slaking
High or low slurry tank levels (DSD only)	Malfunctioning level probes/control valves	Check/repair level probes and control loops
	Malfunctioning water/slurry control valves	Check/repair valves
Slurry control valve problems (DSD only)	Gradual build-up of deposits or scale	Weekly line flushing
High solids in lime slurry storage tank (DSD only)	Malfunctioning slaker	Check operation of weigh belt feeder and slaker

Abnormality	Probable Cause	Corrective Action
	Low slaking water flow	Check operation of slaking water flow control
	Malfunctioning lime slurry storage tank agitator	Check agitator operation
Low solids in lime slurry storage tank (DSD only)	Malfunctioning slaker	Check operation of weigh belt feeder and slaker
	High slaking water flow	Check operation of slaking water flow control
	Plugged lime grit screen	Check and clean out screen
	High lime slurry pump and/or ball mill sump pump seal water flow	Check seal water flow
	Improper operation of slaker scrubber vent system	Check slaker scrubber vent system
High solids in atomizer feed tank (DSD only)	Low dilution water flow	Check operation of dilution water flow control
	Malfunctioning dilution water, lime slurry, or recycle slurry flow control valve	Check/repair valve
	Lime slurry storage tank density too high	Refer to "High solids in lime slurry storage tank" item above
	Recycle slurry tank density too high	Refer to "Recycle slurry tank percent solids too high" item in Section 11.5.4
	Malfunctioning atomizer feed tank agitator	Check agitator operation
Low solids in atomizer feed tank (DSD only)	High dilution water flow	Check operation of dilution water flow control
	Malfunctioning dilution water, lime slurry, or recycle slurry flow control valve	Check/repair valve
	Lime slurry storage tank density too low	Refer to "Low solids in lime slurry storage tank" item above

Abnormality	Probable Cause	Corrective Action
	Recycle slurry tank density too low	Refer to "Recycle slurry tank percent solids too low" item in Section 11.5.4
	Plugged recycle grit screen	Check and clean out screen
	High atomizer feed pump, lime slurry pump, and/or recycle slurry pump seal water flow	Check seal water flow

11.5.2 Humidification/Sorbent Injection System

Abnormality	Probable Cause	Corrective Action
Duct walls/floor wet or showing deposits/build-up	Outlet temperature too low	Verify proper outlet temperature setpoint
	Atomizer nozzle pluggage, damage, or misalignment	Inspect atomizers and clean, repair, replace, or realign; also, inspect water/slurry basket strainers
	Sorbent injector pluggage or misalignment (DSI only)	Inspect injectors and clean or realign
	Malfunctioning outlet temperature control	Check thermocouples and control loop
	High flue gas saturation temperature	Confirm/check wet bulb at ESP outlet
	Low air-to-water/slurry ratio or low air pressure	Check atomizing air system including pressure control valve and strainers
	Problems with atomizer flush	Improve atomizer flushing techniques
Low water/slurry flow in one atomizer lance	Malfunctioning temperature control	Check thermocouples and control loop
	Line pluggage	Inspect water/slurry piping for plugs or restrictions
	Malfunctioning slurry control valves	Check/repair valves

Abnormality	Probable Cause	Corrective Action
High gas temperature at ESP inlet	Malfunctioning temperature control	Check thermocouples and control loop
	Water/slurry flow line to atomizers plugged or block valve closed	Inspect water/slurry piping for plugs or restriction; check for block valve failed close
	Inlet temperature from boiler is too high	Check with boiler operations
Low gas temperature at ESP inlet	Malfunctioning temperature control	Check thermocouples and control loop
	Water/slurry valve failed open	Check for valve problems
	Inlet temperature from boiler is too low	Check with boiler operations
High SO ₂ removal efficiency	Malfunctioning temperature control	Check thermocouples and control loop
	Atomizer feed tank density too high (DSD only)	Refer to "High solids in atomizer feed tank" item in Section 11.5.1
	Incorrect ESP inlet temperature setpoint	Verify proper ESP inlet temperature setpoint
Low SO ₂ removal efficiency	Malfunctioning temperature control	Check thermocouples and control loop
	Atomizer feed tank density too low (DSD only)	Refer to "Low solids in atomizer feed tank" item in Section 11.5.1
	Incorrect ESP inlet temperature setpoint	Verify proper ESP inlet temperature setpoint
	Lime slurry storage tank density too low (DSD only)	Refer to "Low solids in lime slurry storage tank" item in Section 11.5.1
	Low flow to slurry atomizers (DSD only)	Check feed lines for pluggage or block valve failed closed

Abnormality	Probable Cause	Corrective Action
	Problems with hydrate feed system (DSI only)	Check hydrate feed system including screw feeders, hydrate rotary air locks, injection blowers, and pressure in distribution bottle and individual feed lines

11.5.3 Flue Gas System

Abnormality	Probable Cause	Corrective Action
Duct walls/floor wet or showing deposits/build-up	Build-up or pluggage on inlet vanes	Clear/clean inlet vanes
High pressure drop across injection ductwork	Substantial pluggage or build-up in injection zone	Check ductwork injection zone and clean out if necessary
	High flue gas flow	Check with boiler operations
	Pressure transmitter failure	Repair or replace transmitter

11.5.4 Recycle System

Abnormality	Probable Cause	Corrective Action
Recycle slurry tank percent solids too low (DSD only)	High recycle slurry pump seal water flow	Check seal water flow
	Improper recycle bin rotary feeder speed	Check operation and control of recycle bin rotary feeder
	High recycle ash water flow	Check operation of recycle ash water flow control
	Improper operation of recycle tank scrubber vent system	Check recycle tank scrubber vent system
Recycle slurry tank percent solids too high (DSD only)	Improper recycle bin rotary feeder speed	Check operation and control of recycle bin rotary feeder

Abnormality	Probable Cause	Corrective Action
	Low recycle ash water flow	Check operation of recycle ash water flow control
	Malfunctioning recycle slurry tank agitator	Check agitator operation

11.5.5 General Support Equipment

Abnormality	Probable Cause	Corrective Action
High or low water tank levels	Malfunctioning level probes/control valves	Check/repair level probes and control loops
High atomizing air temperature	Malfunctioning compressor cooling water loop	Check operation of cooling water loop
Low atomizing air pressure	Malfunctioning air compressor or not enough compressors on-line	Check operation of compressors
	Leak in compressed air piping/receiver	Inspect piping/receiver for leaks
	Open relief valve	Check relief valve operation and pressure at compressor discharge

11.6 Staffing

The proper staffing of a duct injection system is critical to its operation. The similarities between the DSI and DSD systems lead to similar operations and maintenance personnel requirements. DSI may require fewer operating personnel depending on the type of lime purchased. The staffing requirements can be separated into three categories:

1. Operations
2. Maintenance
3. Laboratory

The operations personnel include duct injection system operators and supervisors. The maintenance personnel are responsible for maintenance and upkeep of the FGD system. Finally, laboratory personnel are responsible for all sampling and testing to assure that the proper chemistry and mixing is occurring throughout the process.

11.6.1 Operations

The operations personnel are responsible for ensuring proper operation of the system so that the station stays in compliance with SO₂ emissions limits. The type of personnel included in this category are: superintendents, control room operators, outside operators, board (chief)

operators, and day operators. Descriptions for each of these positions is listed below.

Superintendent - The superintendent has full administrative control over the operations and maintenance personnel working in the duct injection area of the plant. The superintendent is also responsible for maintaining control of SO₂ emissions and compliance, and solving minor technical problems. The superintendent also serves as process engineer; however, large scale plants (>300MW) may require additional process engineering staff.

Control Room Operator - The control room operator monitors the control systems for the duct injection system and notifies the superintendent or on-site operators of any problems with operations or equipment failure.

Outside Operator - The outside operator is responsible for maintaining proper operation and control of the scrubbing system. The operator is also responsible for performing simple chemical analysis to maintain process control. Operators should route samples to the laboratory if the analytical work is time consuming, not urgent, or requires the use of sophisticated equipment.

Board (Chief) Operator - The board operator is the senior operator for the duct injection system and is the direct supervisor of the outside operators. The board operator also has technical responsibility and control over the process.

Day Operator - The day operator is being trained to be an outside operator. The day operator's responsibilities include work with the reagent unloading and storage and waste disposal, as well as filling in for the outside operators when they are unavailable.

Staffing philosophies for duct injection systems vary from utility to utility. Operating labor utility surveys show the general trend of operating labor per unit MW capacity decreasing with increasing generating capacity. Recommended operating labor requirements for the 250 MW case studies presented in Appendix A are based on the lime consumption rates. For lime usage less than 300 tpd, six operators should be used and, for usage greater than 300 tpd, seven operators are estimated to be required. If the user is evaluating the DSI process and is considering purchasing hydrated lime then, for hydrated lime usage less than 300 tpd, five operators should be used, otherwise six operators are required. These operator requirements include personnel to perform the operator tasks listed above. In some cases, depending on the plant size, individual operators are required to perform several job functions to avoid overstaffing.

Duct injection systems may need to be overstaffed at start-up to catch any design flaws and overcome any complications typically associated with plant start-up. After the system is fully operating and running smoothly, staffing can be decreased to minimum requirements.

11.6.2 Maintenance

The maintenance labor requirement for the duct injection system is necessary for general upkeep of the components such as pumps, blowers, etc. Maintenance labor varies widely depending on the type of system and equipment included.

11.6.3 Laboratory

Laboratory staffing for a duct injection system is only required during the day shift. DSI and DSD facilities will only require one laboratory technician (M-F, day shift only) to monitor the chemistry of the process. Weekend and backshift sampling and testing can be done by the operators.

A lab technician will be required to perform several tests on a daily basis. Some tests need to be done more than once a day. The tests conducted should determine slurry percent solids, available CaO in the ESP solids, Ca(OH)_2 content of the lime feed slurry, free moisture in the ESP solids, and daily stoichiometric ratio. The calcium content and reactivity of the lime should also be checked once per shipment.

Sample data sheets based on actual utility data sheets are provided in Tables 11-1 through 11-7. These data sheets are for daily lab reports, lime analysis, or ESP solids analysis, etc.

Standard laboratory procedures should be used for all tests and it is recommended that the quicklime reactivity test be done based on ASTM Standard C110-76a.

11.7 REFERENCES

1. Lime Handling, Application, and Storage, 4th ed., Published by the National Lime Association, Arlington, VA, 1982.

TABLE 11-1
LAB REPORT TO SCRUBBER OPERATOR (ONCE/SHIFT)

DSD FGD SYSTEM
DENSITY ANALYSIS

Date: _____

Time: _____

		Density		% Solids
Lime Slurry, Ball Mill Sump				
Lime Slurry, Storage Tank				
Lime Slurry, Atomizer Feed Tank				
Recycle Slurry Tank				
Adiabatic Saturation	Duct #1	(Dry)		(Wet)
Temp., °F	Duct #2	(Dry)		(Wet)

TECHNICIAN: _____

TABLE 11-2
DAILY LAB REPORT TO SCRUBBER SUPERVISOR (MON-FRI)
FOR DSI AND DSD

Date: _____

FLYASH INSOLUBLE IN HCl	
FLYASH AVAILABLE CaO	
ESP PRODUCT MOISTURE	
ESP AVAILABLE CaO	
ESP SULFITE, SO ₃	
ESP SULFATE, SO ₄	
LIME AVAILABLE Ca(OH) ₂	
STOICHIOMETRIC RATIO	
FEED TANK pH (DSD ONLY)	

TECHNICIAN: _____

TABLE 11-3
MANUALLY SAMPLING OF EVERY 10TH TRUCK ON CONTRACT
RAW LIME ANALYSIS

DATE:	LOAD NO.:
SUPPLIER:	TRUCK NO.:
CONTRACT NO.:	TRAILER NO.:

SIEVE ANALYSIS

	3/4 INCH	5/8 INCH	3/8 INCH	NO.#100
% PASS				
% RET.				

TOTAL INSOLUBLE MATTER:	
AVAILABLE CALCIUM OXIDE:	

TABLE 11-4
DSI/DSD SCRUBBER LAB ANALYSIS

<u>DAILY TESTING:</u>	<u>Specific Gravity/Percent Solids</u> on all process slurries (3 times per shift).
	<u>Available CaO</u> and <u>SO₃</u> content of processed ash leaving SDA.
	<u>Available Ca(OH)₂</u> in process lime slurries.
	<u>Free Moisture</u> on duct wall solids and processed ash leaving duct.
<u>WEEKLY ANALYSIS:</u>	<u>Percent Solids</u> content of process slurries using the oven dry method. (This is done to verify correct denominator used in the daily % solids determination.)
	<u>Available CaO</u> in untreated flyash to duct.
<u>RAW LIME ANALYSIS:</u>	A sample from the first and every subsequent tenth truck delivery is taken and tested for the following: 1) <u>SIZE</u> (under contract spec.) 2) <u>INSOLUBLE MATTER</u> 3) <u>AVAILABLE CaO</u> (under contract duct. 4) <u>REACTIVITY</u>
<u>OTHER TESTING PERFORMED PERIODICALLY:</u>	1) <u>Total SO₂ & SO₃</u>: Performed on slaking and dilution water. 2) <u>Total Alkalinity</u>: Of processed ash leaving duct. 3) <u>Setting Rate</u>: Of lime slurries to determine slaking efficiency. 4) <u>Available CaO</u>: Of lime on weight belt feeder. 5) Manual testing and determination of <u>Dew Point</u> of flue gas leaving particulate removal system. (To verify accuracy of on-line Adsorpt monitors.)

A Stoichiometric ratio, Ca/S, using the chemical compound makeup of processed ash is performed daily on a composite mixture collected once every eight hours. This provides insight as to how well the process is working over the previous 24 hours, and also to verify the computer calculated stoichiometry. This analysis is made once per day, Monday through Friday.

TABLE 11-5
DAILY REPORT FOR LAB CHLORIDE & SODIUM CONTENT OF ASH (ONCE/WEEK)
FGD PROCESS ANALYSIS

Date: _____

ESP PRODUCT	
Insoluble in HCl	%
Sulfate SO ₄	%
Free Moisture	%

STOICHIOMETRIC RATIO DETERMINATION	
FLY ASH:	%
A. Available CaO	%
B. Insoluble in HCl	%
C. Moisture free unburned carbon	%
ESP PRODUCT:	%
D. Available CaO	%
E. Available Ca(OH) ₂ (D X 1.32)	%
F. Sulfite, SO ₃	%
G. Calcium Sulfite, CaSO ₃ · ½H ₂ O (F X 1.61)	%
H. Sulfate, SO ₄ (F X 0.176)	%
I. Calcium Sulfate, CaSO ₄ · 2H ₂ O (H X 1.792)	%
J. Lime Inerts $\frac{100-AL}{AL} \left(\frac{17D+14F}{17} \right)$	%
K. Total Calcium Compounds (E + G + I + J)	%
L. Fly Ash Fraction (100-K)	%
M. Active Lime $D + (F \times 0.824) - (A \times \frac{L}{100})$	%
N. Sulfur Removed, SO ₂ + SO ₃ (F X 0.941)	%
Stoichiometric Ratio, SEC, $(\frac{M}{N} \times 1.143)$	%
Feed Tank pH	%

		Available Ca(OH) ₂ in Storage	%
Computer Calculated S.R.		Total Alkalinity, ESP Product	meg. OH/g
Sulfur Removal	%	Total SO ₂ + SO ₄ , Slaking Water	mg/L.

REMARKS		
	Cl ⁻	Na ⁺
Feed Tank		
Inlet Ash		
Baghouse Ash		
Basin "C"		

TECHNICIAN: _____

[illegible]

Sample Number	
Date/Time	
Lime Source	
Lime Type	
Batch No.	
Active Slaking Time	
Total Temperature Rise	

TABLE 11-7
DSD SLURRY DENSITY AND SOLIDS ANALYSIS
WEEKLY LAB LOG

Date: _____

TIME OF DAY																
Location																
Lime Slurry Base Mill Sump	D															
	%															
Lime Slurry Storage Tank	D															
	%															
Lime Slurry Atomizer Feed Tank	D															
	%															
Recycle Slurry Tank	D															
	%															

ADIABATIC SATURATION TEMPERATURE

Time																
Duct #1	Dry															
	Wet															
Duct #2	Dry															
	Wet															

12.0 ECONOMIC EVALUATION

This section will guide the user through the fundamental calculations required to conduct a rough estimate of the total capital requirement and levelized costs for DSI and DSD systems. The user will be given guidelines to predict installation factors, retrofit factors and miscellaneous charges leading to the total capital requirement for a duct injection system. The user will then develop operating costs and utilize guidelines to develop levelization factors to calculate levelized costs.

The cost estimating procedure generally follows the guidelines established by EPRI in estimating costs for FGD systems and has been generally accepted by the utility community. A detailed explanation of this procedure can be found in reference 1.

12.1 Total Capital Requirement

The total capital requirement calculation is based on the process equipment capital costs, retrofit factors, and miscellaneous charges such as contingency and engineering fees. Worksheet 12-1 is a summary table for the components involved in calculating the total capital requirement. Entries in this worksheet will be described in Sections 12.1.1-12.1.3.

12.1.1 Total Process Capital

The first step in performing an economic evaluation is assembling the vendor cost information for each piece of equipment (material only) needed in the process. Typically, adequate cost information is available for only the major equipment items such as slakers, silos and pumps; cost information for auxiliary equipment can be estimated as a percentage of the major equipment. After the user has assembled the equipment costs by equipment cost area, the user must determine appropriate equipment installation factors. Miscellaneous charges, if any, and appropriate retrofit factors are then applied to calculate the total process capital. The total process capital is the basis for the contingency and engineering fees, and other auxiliary fees that need to be added to obtain a total capital requirement for the process.

12.1.1.1 Installation Factor Adjustment

The installation factor is a composite number including labor, direct and indirect field costs such as sales tax, contractors fee, payroll taxes, insurance and bonds, construction equipment and supplies, temporary facilities, and vendor fees. Also included in the installation factor is the required earthwork, concrete, buildings, piping, electrical, painting, instrumentation and controls, and insulation. These factors were derived using standard, engineering cost estimating procedures and reflect average U.S. union wage rates. The users actual costs may vary slightly due to differences in actual construction labor rates. It is important to note that labor is only one component of the composite installation factor.

The installation factors are a function of the size of the equipment. Installation factors decrease for increasing equipment sizes. Table 12-1 lists some common ranges of equipment installation factors typical of equipment sizes found in the duct spray drying and duct sorbent injection processes for lime feed rates between 1 and 10 ton/hr.

TABLE 12-1

TYPICAL EQUIPMENT INSTALLATION FACTORS

Equipment Item	Lime Feed Rates (Tons Per Hour)		
	1.0-5.0	5.0-10.0	> 10.0
Air Compressor	2.2	2.1	2.1
Air Receiver	7.8	4.9	4.7
Bin Activator	3.9-3.2	3.2-2.8	2.7
Dual-Fluid Atomizing Assembly	1.7	1.7	1.7
Hydrate Screw Feeder	3.3-3.0	3.0-2.8	2.8
Hydrator*	3.7-1.3	1.3	1.3
Pneumatic Transfer Systems	2.7-2.4	2.4-2.1	2.1
Ball mill	1.4	1.4	1.4
Pumps			
- Cast Steel	9.5-8.0	8.0-7.0	6.5
- Rubber Lined Carbon Steel	6.2	6.1	6.0
Railcar Unloading System	3.0-2.0	2.0-1.8	1.8
Reagent Injection Manifold	1.7	1.7	1.7
Rotary Feeder/Airlock	3.3-3.0	3.0-2.8	2.8
Silos**			
- Carbon Steel	3.8-2.7	2.7-1.7	1.7
- Concrete	3.5-3.1	3.1-2.8	2.7
Slaker***	2.4-1.9	1.9-1.6	1.6
Boiling Water Heater	8.0	8.0	8.0
Tanks			
- Carbon Steel	5.2-4.7	4.7-4.0	3.5
- Rubber Lined Carbon Steel	3.7-2.7	2.7-2.1	2.0
(Storage)			
- Rubber Lined Carbon Steel	6.7-4.9	4.9-3.9	3.8
(Process)			
Waste Conveying System	2.4	2.3	2.1
Overall Installation Factor	3.0-2.0	2.0-1.8	1.8

* Hydrator cost installation factor (i.f.) includes the lime weigh belt feeder, hydrator scrubber, and the hydrator scrubber fan.

** Carbon steel and concrete bin and silo costs/i.f. include the dust collectors.

*** Slaker cost/i.f. includes the lime weigh belt feeder and ball mill sump and agitator.

To estimate the installation factor for a particular equipment item, refer to the fresh sorbent usage rate of your system as determined in Section 3. Find the equipment item and the installation factor in Table 12-1 for the proper range of lime feed rates. Simple linear interpolation is sufficient to obtain the required factor for those equipment items with a range of factors listed.

If the user does not wish to figure an installation factor for each piece of equipment, an overall installation factor may be applied to the bottom line uninstalled capital cost to calculate the installed capital cost. Again, linear interpolation can be used to determine installation factor as a function of lime feed rate.

Once the individual installation factors are found for the equipment items, simply multiply the factors by the uninstalled equipment cost to obtain the installed equipment cost. Add the installed costs for each plant area to get a total installed area cost. Plant areas are as defined in Section 5.4 of this handbook. Input the total installed capital costs in the respective installed capital cost row in Worksheet 12-1.

12.1.2 Retrofit Factors

Retrofit factors adjust for site specific conditions which may complicate installing the required equipment. Retrofit factors take into account underground obstructions, site access and congestion, and soil variances. An overall estimate of the retrofit factor can be used to adjust the total process capital cost. Three categories of retrofit factors can be defined as low retrofit difficulty, medium retrofit difficulty, and high retrofit difficulty. Suggested retrofit factors for these three categories are listed in Table 12-2. These categories are described below:

Low Retrofit Difficulty - There is some major underground obstruction, such as a duct bank, water line, or plant drainage line. Site access is somewhat limited. Access for large cranes is limited to two sides, and some equipment must be located in remote or unconventional areas.

Medium Retrofit Difficulty - More than one of the major underground obstructions listed above exists, as well as several minor pipes and trenches. Site access is limited by existing structures that cannot be relocated, which may force special designs for some components of the duct injection system. Access for large cranes is limited to one side, and the majority of the equipment must be located in remote or unconventional areas.

High Retrofit Difficulty - Several of the major underground obstructions described above exist including a possible gas main. Site access is severely limited with extremely crowded working conditions. Access for large cranes is blocked from all sides, and the majority of the equipment must be located in remote or unconventional areas.

TABLE 12-2
RETROFIT FACTORS

Low Retrofit Difficulty	1.1
Medium Retrofit Difficulty	1.3
High Retrofit Difficulty	1.5

The user should determine which degree of retrofit difficulty best describes the designated plant. This number should be transferred to Worksheet 12-1 and multiplied by the total installed capital cost to calculate the total process capital cost.

12.1.3 Miscellaneous Considerations

Several costs must be added to the total process capital cost to calculate the total capital requirement of a duct injection system. These costs include process and project contingency costs, and general facilities and engineering costs. Recommended cost adjustment factors for both the duct spray drying and duct sorbent injection processes are listed in Table 12-3. The user should transfer the area installed capital costs from Worksheet 12-1 to Worksheet 12-2 and multiply the capital cost by the respective cost adjustment factors to generate the appropriate charges. These charges should be added to the total process capital cost in Worksheet 12-1 to arrive at the total capital requirement. A description of each type of cost is given below:

Process Contingency - Process contingency accounts for the level of process development that has been achieved to date. Process contingency also attempts to account for any uncertainty in design that may be a risk in scaling the process to commercial scale from test-scale operation. Process contingency should be calculated separately for each process area, because the degree of development varies for each process area. Process contingency should be accounted for on an area-by-area basis. At the time of this publication, the areas considered to present the highest risk are the humidification/sorbent injection area and the flue gas areas due to unresolved concerns about wall wetting, solids deposition, corrosion, and ESP impacts which most adversely impact plant operation and ultimately result in increased cost.

Project Contingency - Project contingency accounts for any additional equipment that may be required as a result of an alteration to the original design. Lower factors are applied to standard design items, while higher factors are applied to specialized equipment that is specific to the process. Project contingency should be accounted for on an area-by-area basis.

General Facilities - General facilities accounts for roads, buildings, fabrication shops, etc. General facilities can be accounted for based on the total process capital cost for all equipment cost areas.

Engineering and Home Office Costs - Engineering and home office costs account for any required engineering and home office overhead. Engineering and home office costs can be accounted for based on the total process capital cost for all equipment cost areas.

TABLE 12-3
RECOMMENDED CAPITAL COST ADJUSTMENT FACTORS*

Equipment Cost Area	Process Contingency	Project Contingency
100 - Sorbent Storage and Preparation System	5%	15%
200 - Humidification/Sorbent Injection System	15%	15%
300 - Flue Gas System	15%	15%
400 - Recycle System	5%	15%
500 - Waste Handling System	5%	15%
600 - General Support Equipment	0%	15%
700 - Miscellaneous	0%	15%
General Facilities: 10% for all equipment cost areas.		
Engineering and Home Office Costs: 10% for all equipment cost areas.		

* All factors apply to both the DSD and DSI processes.

12.2 Operating And Maintenance Costs

Duct injection technologies typically have lower capital costs but higher operating costs when compared to other SO₂ removal technologies. Operating and maintenance costs must be considered when evaluating life cycle costs. These costs include all variable operating charges for consumable items such as sorbent, power, and water. Fixed operating and maintenance charges such as operating, maintenance, and administrative labor charges must also be included. Worksheet 12-3 is a summary worksheet for the operating and maintenance costs.

To calculate variable operating and maintenance costs, the user must first determine a unit capacity factor, typically available from a utility planning department. The capacity factor is defined as the actual kWh produced by a unit divided by the theoretical kWh if the unit operated at 100% capacity throughout the year. The user has already calculated the required mass flows and energy requirements needed to determine the variable operating costs in Section 5.2 of the handbook. The operating coal sulfur value, versus design sulfur, should be used to calculate the mass and energy requirements to correctly reflect the actual variable operating costs. To calculate variable operating costs in dollars per year, use the following generic equation:

$$\text{Variable operating costs (\$/yr)} = \text{flow rate} \times \text{unit cost} \times 8,760 \text{ hr/yr} \times \text{capacity factor} \quad (12-1)$$

To calculate fixed operating and maintenance costs, determine the number of operators required, assumed to be the number of 40 hour shifts per week required to operate the system, and the operating labor cost. The recommended number of operators is based on ton per day (tpd) of pebble lime consumption. For lime usage less than 300 tpd, six operators should be used and, for usage greater than 300 tpd, seven operators are estimated to be required. If the user is evaluating costs for the DSI process and is considering purchasing hydrated lime then, for hydrated lime usage less than 300 tpd, five operators should be used, otherwise six operators are required. To calculate the annual operating labor cost in dollars per year, use the following generic equation:

$$\text{Annual operating labor (\$/yr)} = \frac{\text{labor rate (\$/hr)} \times \text{number of operators} \times 40 \times 52}{\text{number of operators} \times 40 \times 52} \quad (12-2)$$

Maintenance costs are calculated per plant area, based on the total process capital costs calculated in Worksheet 12-1. The recommended maintenance factors in Worksheet 12-4 are based on knowledge of the maintenance schedule required for similar equipment in similar types of service. To calculate the maintenance costs for each plant area, transfer the area installed capital costs from Worksheet 12-1 to Worksheet 12-4 and multiply the capital costs by the maintenance factors. The maintenance cost is comprised of both labor and material charges. The recommended ratio between maintenance labor and materials is 40 percent labor and 60 percent materials. Multiply the total maintenance charge by 40 percent to obtain the labor portion of this charge. The maintenance labor is required to calculate the administrative labor charge.

Administrative labor is an estimate of the overhead required for managing plant personnel. Administrative labor is calculated based on 30 percent of the operating and maintenance labor. To calculate the annual administrative labor cost in dollars per year, use the following equation:

$$\text{Annual administrative labor (\$/yr)} = 0.3 \times (\text{annual administrative labor}) \times (\text{maintenance labor} + \text{operating labor}) \quad (12-3)$$

Transfer these calculated costs to Worksheet 12-3 to summarize the operating and maintenance charges. The sum of the various charges gives the total first year expenses that must be incurred due to the FGD system.

12.3 Levelized Costs

Levelized values represent a convenient measure for comparing alternatives which have different capital and operating costs. Levelized annual costs are a hypothetical equal annual series of costs. These costs have the same present worth as the projections of annual costs which vary from year to year. Therefore, levelized annual costs will lead to the same decision as present worth values since the two parameters vary only by a constant (the capital recovery factor).

12.3.1 Economic Factors

Levelized costs are based on several important economic factors which should be obtained from the economic or accounting department of the utility. The values of these factors may be interdependent and cannot be arbitrarily selected. These factors include the discount rate, first year and levelized fixed charge rates, inflation rate, and escalation rates. Definitions of these factors are listed below:

Discount Rate - The interest rate which is used to calculate the present worth of each alternative. A utility's minimum acceptable return (MAR) is often used as the discount rate.

Fixed Charge Rates (FCR) - The fixed charge rate is a multiplier on the capital investment which yields the magnitude of fixed costs that account for return on equity and debt, book depreciation, income taxes, property tax and insurance. Fixed costs typically decline over time because of the utility industry accounting

practices. A "first year" fixed charge rate accounts for these costs for the first year. A "levelized" fixed charge rate accounts for these costs on a levelized annual basis (i.e., an equal annual series of fixed costs which has the same present worth as the actual series which declines over time).

Inflation Rate - The inflation rate is an estimate of the average annual inflation for the plant life.

Escalation Rates - Escalation rates can be individually defined for consumables, power costs, and capital costs. The escalation rate for a current dollar analysis takes into account both inflation and real escalation.

12.3.2 First Year Costs

First year variable operating and maintenance costs were calculated in Section 12.2 in dollars per year. Fixed charges also need to be calculated and included in the total first year and levelized costs. Fixed charges are calculated by multiplying the total capital requirement (from Worksheet 12-1) by the first year fixed charge rate. The fixed charges should be added to Worksheet 12-5, First Year and Levelized Cost Table, as well as to all first year operating costs from Worksheet 12-3.

First year dollars can be converted to units that are often used to compare to other systems. These units are \$/kW, mils/kWh, and \$/ton SO₂ removed. To convert \$/yr to these units use the following equations:

$$\$/kW\text{-yr} = (\$/\text{yr})/(\text{net kW}) \quad (12-4)$$

$$\text{mils/kWh} = (\$/\text{yr}) \times (1000 \text{ mils}/\$)/(\text{net kW} \times 8,760 \text{ hr/yr} \times \text{capacity factor}) \quad (12-5)$$

$$\$/\text{ton SO}_2 = (\$/\text{yr}) \times (2,000 \text{ lb/ton})/[(\text{lb SO}_2/\text{hr removed}) \times (8,760 \text{ hr/yr}) \times (\text{capacity factor})] \quad (12-6)$$

These calculations should be done for every item listed in Worksheet 12-5.

12.3.3 Levelized Costs

The levelized costs are comprised of two major categories:

- Levelized fixed costs which can be calculated by multiplying the total capital requirement (from Worksheet 12-1) by the levelized fixed charge rate.
- Levelized variable costs which can be calculated by multiplying the first year operating and maintenance costs (which are considered at time = 0) by a "levelization factor". This factor represents the multiplication of a present worth factor which accounts for escalation ("P/AE" factor) and a capital recovery factor ("A/P" factor) which levelizes the present worth value. The derivation of these factors are provided below:

$$\text{Capital Recovery Factor (A/P)} = \frac{i \times (1+i)^n}{(1+i)^n - 1} \quad (12-7)$$

Present Worth of an Escalating

$$\text{Series Factor} = \frac{(1 + \text{esc}) \times [(1 + i)^n - (1 + \text{esc})^n]}{(i - \text{esc}) \times (1 + i)^n} \quad (12-8)$$

where: i = interest rate used as a discount rate
 esc = commodity escalation rate
 n = expected remaining plant life

Escalation rates can be separately defined for consumables, fuel, power, and capital costs prior to start-up. If the escalation rates vary for the different categories, a new P/AE factor must be calculated for each unique escalation rate. This evaluation of the levelized costs will only involve the consumables and power escalation rates. The fuel and capital cost escalation do not need to be considered for the purposes of this handbook.

The levelization factors for the variable costs and the levelized fixed cost data should be transferred to Worksheet 12-5. This measure can then be converted to other units (\$/kW, mils/kWh, and \$/ton of SO₂ removed) by following Equations 12-4, 12-5 and 12-6.

12.4 References

- 1) "Economic Evaluation of FGD Systems" Volumes 1&2, EPRI Report No. GS-7193, February, 1991 and January, 1992.
- 2) Lotus 1-2-3, Release 2.2, Reference Manual, Lotus Development Corporation, 1989.
- 3) "FGDCOST User's Manual", Version 1, EPRI Report No. GS-7525-L, August, 1991.

WORKSHEET 12-1

TOTAL CAPITAL REQUIREMENT

Installed Capital Cost:

100 - Sorbent Storage and Preparation System	\$ _____
200 - Humidification/Sorbent Injection System	\$ _____
300 - Flue Gas System	\$ _____
400 - Recycle System	\$ _____
500 - Waste Handling System	\$ _____
600 - General Support Equipment	\$ _____
700 - Miscellaneous	\$ _____

Total Installed Capital Cost	\$ _____
------------------------------	----------

Retrofit Factor	X _____
-----------------	---------

Total Process Capital	\$ _____
-----------------------	----------

Process Contingency	\$ _____
---------------------	----------

Project Contingency	\$ _____
---------------------	----------

General Facilities	\$ _____
--------------------	----------

Engineering/Home Office	\$ _____
-------------------------	----------

Total Capital Requirement	\$ _____
---------------------------	----------

WORKSHEET 12-2

CONTINGENCY AND FEE CALCULATIONS

Equipment Cost Area	Installed Capital Cost (\$)	Process* Contingency	Project* Contingency
100-Sorbent Storage/Preparation		x % =	x % =
200-Humidification/Sorbent Injection		x % =	x % =
300-Flue Gas System		x % =	x % =
400-Recycle System		x % =	x % =
500-Waste Handling System		x % =	x % =
600-General Support Equipment		x % =	x % =
700-Miscellaneous		x % =	x % =
TOTAL	\$	\$	\$
General Facilities = Total Process Capital Cost x Fee* = _____			
Engineering and Home Office Costs = Total Process Capital Cost x Fee* = _____			

* All contingency and fee allocations should be copied from Table 12-3. The user may substitute their own contingency and fee allocations for the recommended percentages.

WORKSHEET 12-3

FIRST YEAR OPERATING COSTS

Variable/Fixed Operating Parameters	\$/Year
Reagent	_____
Waste Disposal	_____
Steam	_____
Raw Water	_____
Blowdown Water	_____
Cooling Water	_____
FGD Power	_____
Operating Labor	_____
Maintenance Labor/Materials	_____
Administrative Labor	_____
Total First Year Operating Costs	\$ _____

WORKSHEET 12-4

MAINTENANCE LABOR/MATERIALS CHARGES

Equipment Cost Area	Process Capital (\$)	Maintenance Factor*	Maintenance Cost (\$/yr)
100-Sorbent Storage/Preparation		X 4% =	
200-Humidification/Sorbent Injection		X 8% =	
300-Flue Gas System		X 2% =	
400-Recycle System		X 4% =	
500-Waste Handling System		X 4% =	
600-General Support Equipment		X 1.5% =	
700-Miscellaneous		X 1.5% =	
TOTAL FIRST YEAR MAINTENANCE COST			\$ _____
Maintenance Labor = 40% of Total First Year Maintenance Cost =			\$ _____

* Maintenance factors apply to both the DSD and DSI processes.

WORKSHEET 12-5

FIRST YEAR AND LEVELIZED COSTS

	FIRST YEAR					LEVELIZED				
	\$/Year	\$/kW	mils/ kWh	\$/Ton SO ₂ Removed	Leveli- zation Factor	\$/Year	\$/kW	mils/ kWh	\$/Ton SO ₂ Removed	
Reagent										
Waste Disposal										
Steam										
Raw Water										
Blowdown Water										
Cooling Water										
FGD Power										
Operating Labor										
Maintenance Labor/Materials										
Administrative Labor										
Fixed Charges										
TOTAL										