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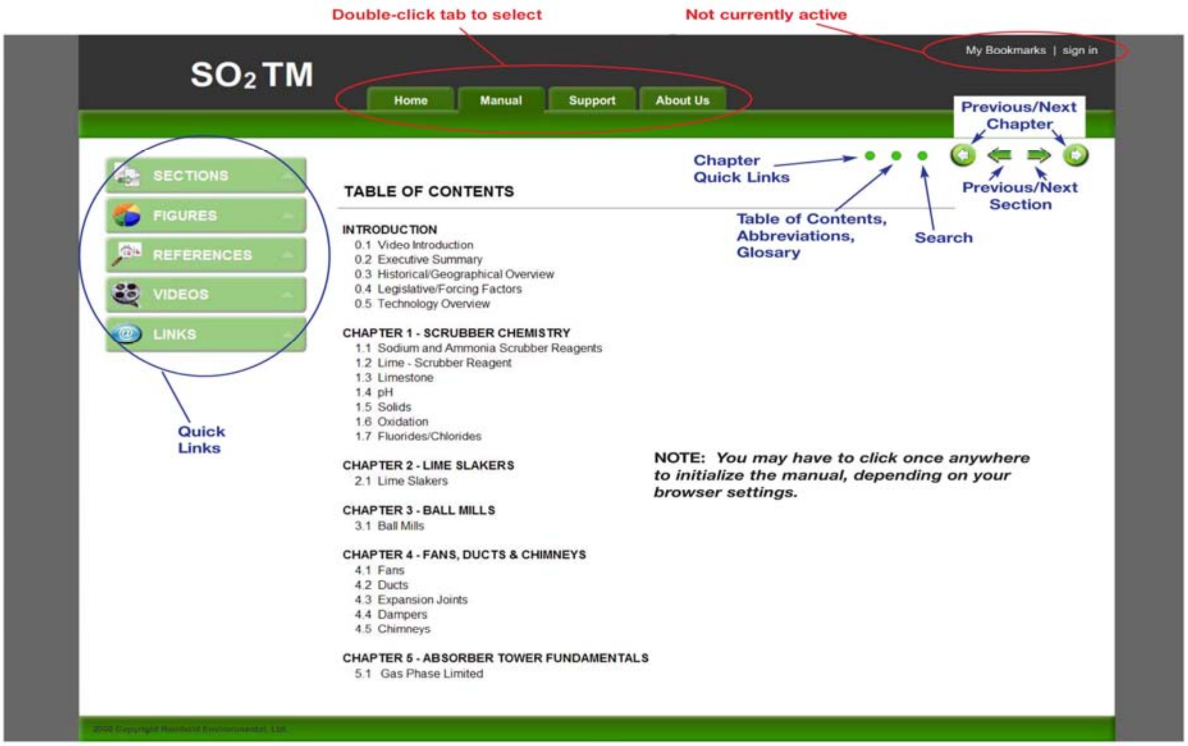
NAVIGATION HELP SCREEN



EXECUTIVE SUMMARY

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Acknowledgements

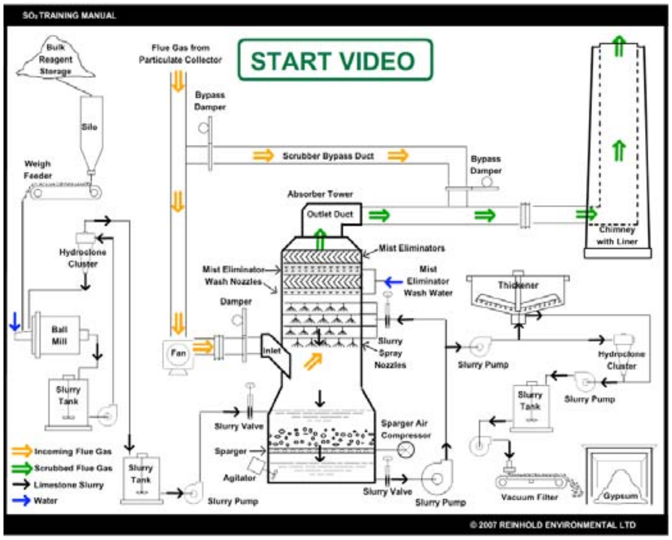
I wish to express my deepest gratitude to all the persons who have contributed to creation of this training manual including the following

- Ron Richard, RE Consulting, for his major contribution to the technical content,
- Suzi Reinhold, Deadline Drafting & Graphics, for her creative development of the graphic look for this manual using some very complex Flash code,
- The worldwide group of companies and individuals who supplied technical content for the manual,
- Jerry Presley, Dominion; Steve Wolsiffer, Consultant and the group of engineers and utility operators who participated in the comprehensive peer review,
- William Armiger, EMA and Susan Reinhold, CEO of Reinhold Environmental, without whose dreams and visions for ways to improve communications and training in the utility industry this manual would have never been written.

Gary

Gary D. Reinhold - President
Reinhold Environmental, Ltd.

0.1 Video Introduction



Introduction
(Narrated by Ron Richard, RE Consulting)

Please click on the green START VIDEO button in the Scrubber Flow Diagram on the left to hear a brief video introduction by Ron Richard, RE Consulting.

You may click on the green Introduction caption to enlarge the Scrubber Flow Diagram and video in a separate window.

You also click on any of the symbols in the Scrubber Flow Diagram for a list of the Chapters and Sections where that piece of equipment appears in the this training manual.

0.2 Executive Summary

Flue gas desulfurization (FGD) is the process of removing sulfur oxides, primarily SO_2, from the combustion gases exiting coal fired boilers.

In wet process FGD systems, flue gases are contacted with an absorbent in a vessel called either an absorber or a scrubber. The SO_2 reacts with the absorbent or dissolves into the solution to produce a slurry or liquid that contains dissolved or solidified sulfur compounds.

In a dry absorption system, only 60% of the water used by a wet scrubber is required to dissolve or suspend the reacting chemical. The advantages of a dry system is the potential of cost and energy savings, however, it may require higher chemical consumption and result in lower efficiencies.

Wet scrubbers have been in more common use then dry scrubbers. Wet FGD is most prevalent with high-sulfur fuel and/or high removal efficiency applications. There are several types of wet scrubber technology. The most common type in use is the spray tower design. In wet scrubbers, the flue gas enters a large vessel (spray tower or absorber), where it is sprayed with water slurry (approximately 10% to 30% lime or limestone). The calcium in the slurry reacts with the SO_2 to form calcium sulfite or calcium sulfate. The calcium sulfite waste product is usually mixed with fly ash (approximately 1:1) and fixation lime (approximately 5%) and disposed of in landfills. Alternatively, in forced-oxidation FGD processes gypsum can be produced from the FGD waste.

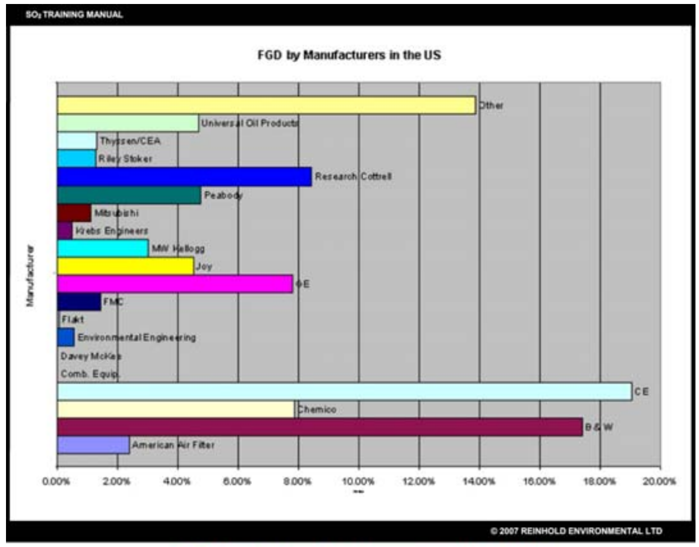
Early FGD systems relied heavily upon multiple absorbers and major equipment redundancy to meet required SO_2 removal and availability levels. As operating problems were resolved and process-control knowledge was gained, the need for new and higher quality materials became increasingly important. Alloys gradually replaced linings in the severe wet/dry zones and eventually came into widespread use in the absorber and outlet ductwork. Improved reliability and reduced redundancy has been achieved in recent installations.

The term "Dry Scrubber" refers to the condition of the waste material leaving the scrubber. In the dry process, the dry waste material produced and the flue gas leaving the scrubber is not saturated with moisture. Dry scrubber systems using lime spray drying are generally limited to the control of SO_2 emissions from sources that burn low to medium sulfur coal. Some issues that limit the use of spray dryers with high-sulfur coals include the potential impact of chloride contained in the coal on the spray dryer performance, and the ability of the existing particulate control device to handle the increased loading.

William J. Armiger, Jr., EMA

0.3 Historical Overview

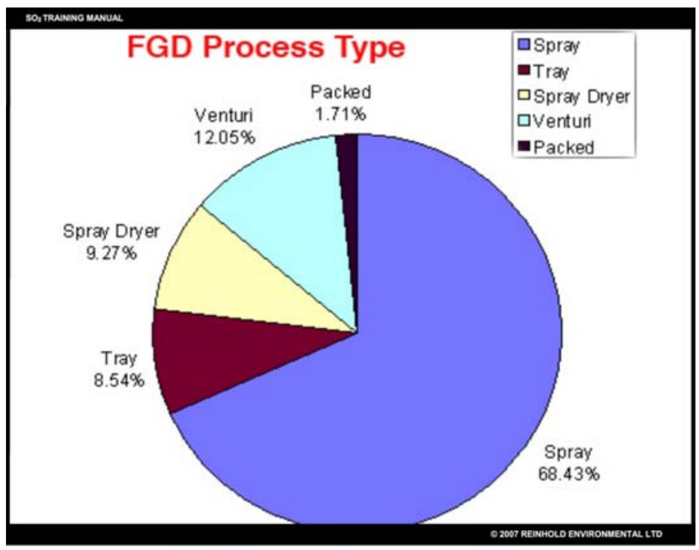
In the late 1960s power plant operators in the USA began to place orders with Research Cottrell, Peabody and others for FGD systems. Shortly thereafter Babcock & Wilcox and Combustion Engineering entered the FGD market and by January of 2000, they had the largest market share as can be seen in the figure to the right. Several mergers, acquisitions and name changes have occurred in this industry over the years.



FGD by Manufacturers in the U.S.
Used with permission

Outside the US, FGD systems were installed extensively in countries such as Germany and Japan where substantial experience was gained by companies such as Lurgi, Mitsubishi, and others.

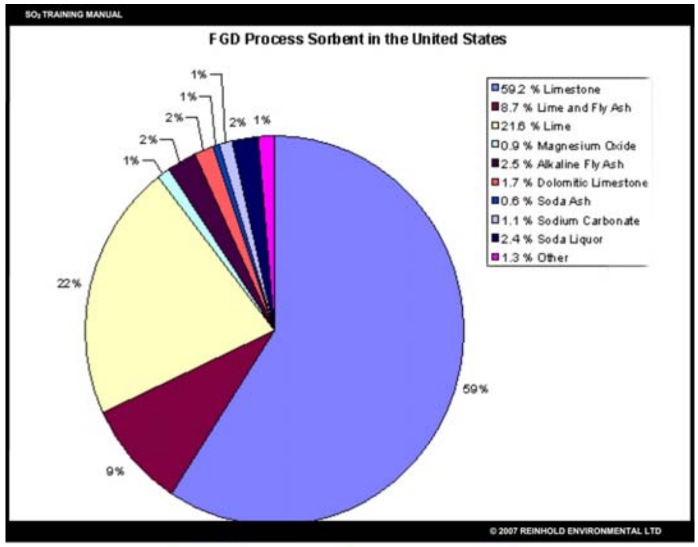
The 1990 Clean Air Act and its subsequent amendments mandated the reduction of power plant SO_2 emissions. Title IV of the act created a two phase plan administered by the U.S. Environmental Protection Agency to reduce acid rain in the U.S. Phase I has run from 1995 through 1999 and Phase II, which is more stringent was begun in 2000. A total of 435 boilers were considered Phase I units. More than 2000 were affected by phase II.



FGD Process Types in the U.S.
Used with permission

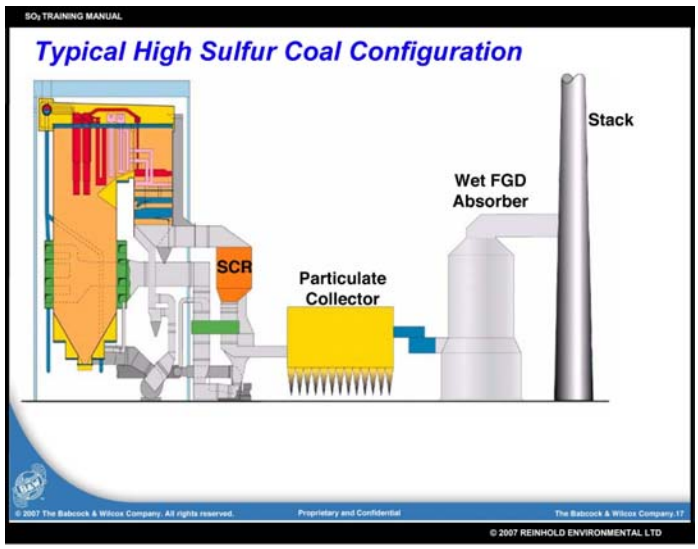
Today there is a rapidly growing market and there are more than a dozen suppliers with substantial experience in meeting the industry requirement. Wet process FGD systems have been to date the most widely used technology in the US with the spray tower design representing about 70% of the total installed base as of January 2000. (See figure to the right)

A wide variety of process sorbents have been used prior to January 1, 2000 with limestone selected for approximately 59% of the installed base. (see figure to the right)



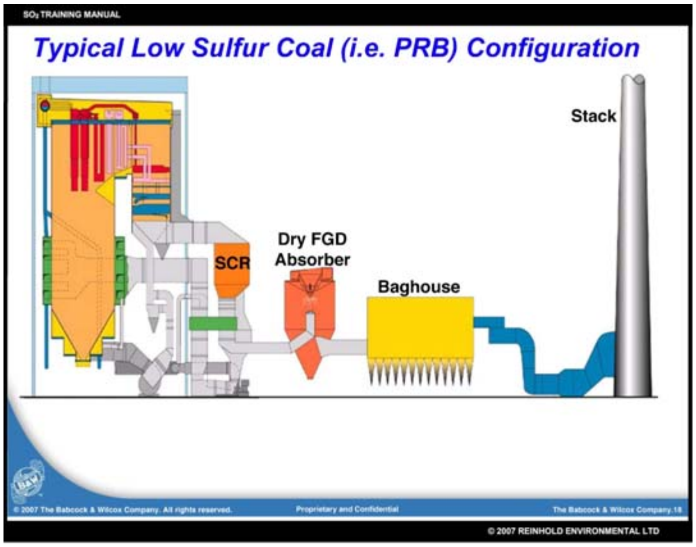
FGD Sorbent Types in the U.S.
Used with permission

A typical Wet FGD Configuration for use in high sulfur applications is shown in the figure to the right.



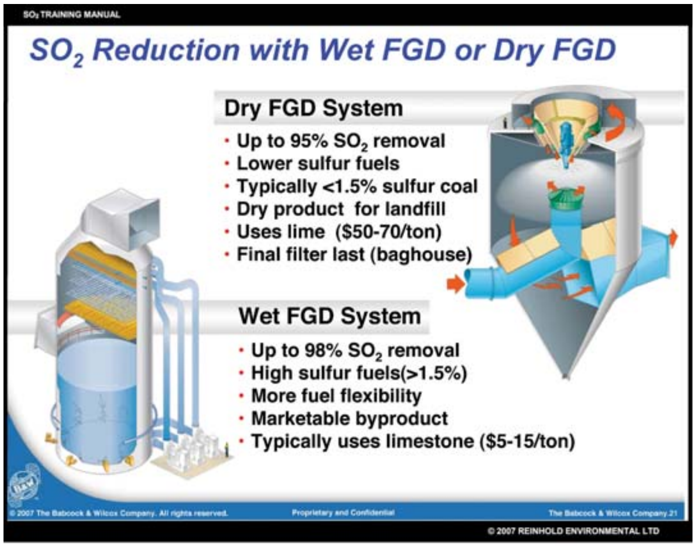
Typical High Sulfur Coal Configuration
Used with permission from Babcock and Wilcox

A typical Dry FGD Configuration used in low sulfur applications is shown in the figure to the right



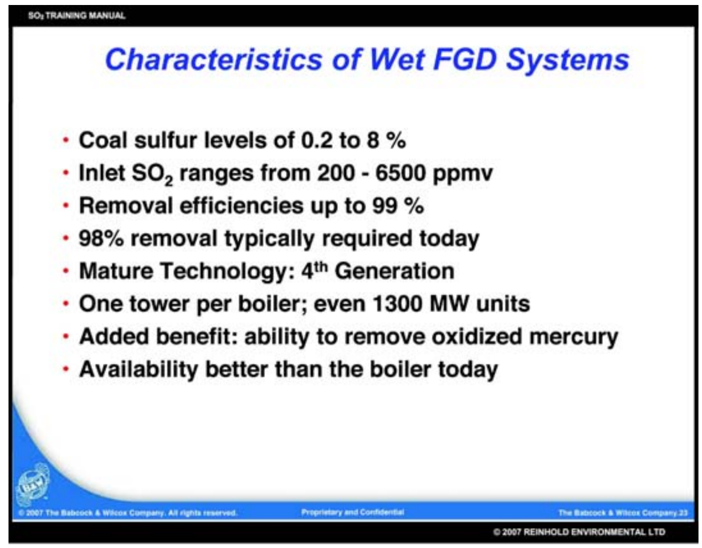
Typical Low Sulfur Coal Configuration
Used with permission from Babcock and Wilcox

The characteristics of a typical Wet FGD are and a typical Dry FGD are shown in the figure to the right.



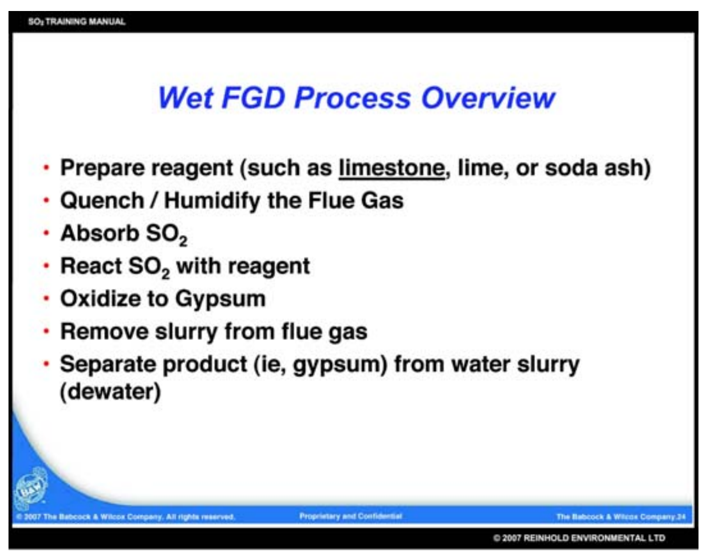
SO2 Reduction with Wet FGD or Dry FGD
Used with permission from Babcock & WIlcox

The design characteristics of a typical Wet FGD are shown to the right.



Wet FGD System Characteristics
Used with permission from Babcock and Wilcox

The process characteristics of a typical Wet FGD are shown in the figure to the right.



Wet FGD Process Overview
Used with permission from Babcock and Wilcox

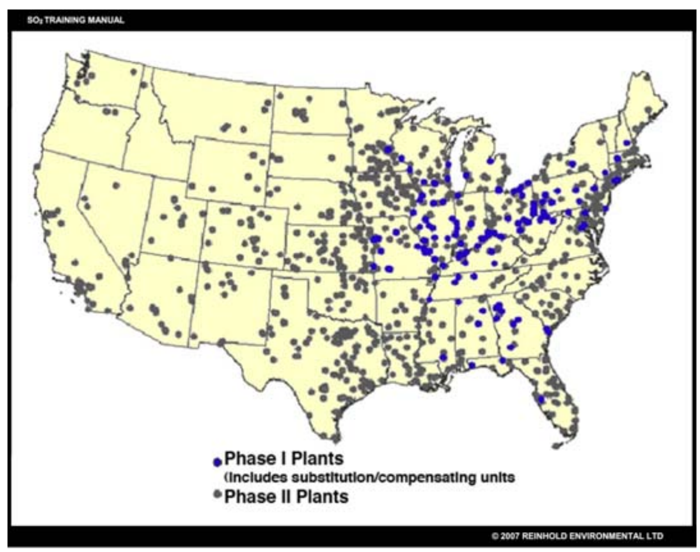
0.4 Legislative/Forcing Factors

Title IV

The Clean Air Act Amendments of 1990 address air quality concerns in the United States that were not covered in earlier legislation. The purpose of this program was to reduce Acid Rain, by reducing the SO_2 (sulfur dioxide) emissions from power plants. NOx emissions are also regulated as part of the Clean Air Act.

Title IV of the Act created a two-phased plan, administered by the U.S. Environmental Protection Agency (EPA), to reduce acid rain in the United States. Phase I ran from 1995 through 1999, and Phase II, which is more stringent than Phase I, began in 2000. A total of 435 units are considered Phase I units. More than 2,000 units have been affected by Phase II.

The acid rain program allocated "emissions allowances" to Phase I units, allowing them to emit one ton of SO_2 for each allowance. Some utilities have obtained additional allowances from auctions and trade or purchase provisions in the Act. All 435 Phase I generating units had sufficient allowances to comply with Title IV in 1995. By complying with Title IV, Phase I units significantly reduced their SO_2 emissions compared to previous years; they emitted 4.5 million tons of SO_2 in 1995, 48% less than the 8.7 million tons emitted in 1990, and approximately 39 percent lower than the 7.4 million tons emitted in 1994. All Title IV units emitted approximately 10.63 million tons of SO_2 in 2001, while the Phase I units emitted 3.6 million tons of SO_2.



Affected Sources under the Acid Rain Program
Reference
http://www.epa.gov/airmarkets/cmap/mapgallery/mg_so2_before_aft.html

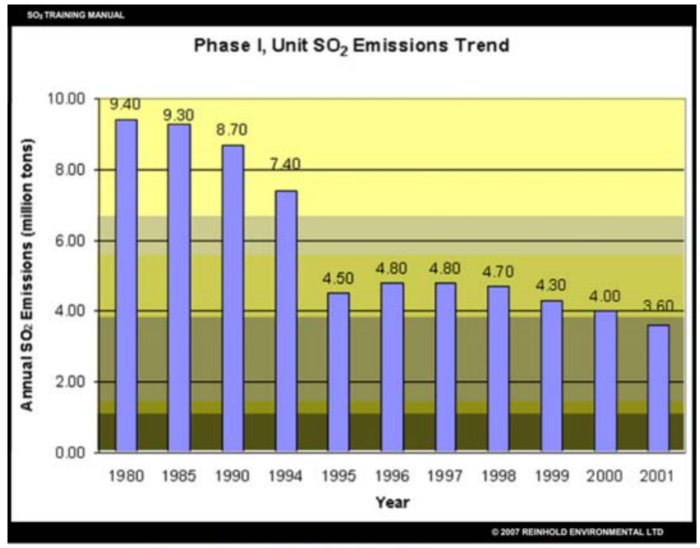
Allowances

The allowance trading system, under which affected utility units are allocated "allowances" is based on past fuel consumption and emission rates.

An allowance authorizes a unit within a utility or industrial source to emit one ton of SO_2 during a given year or any year thereafter. At the end of each year, the unit must hold an amount of allowances at least equal to its annual emissions. For example, a unit that emits 5,000 tons of SO_2 must hold at least 5,000 allowances for the year. Regardless of how many allowances a unit holds, it is never entitled to exceed the limits set under Title I of the Act to protect public health.

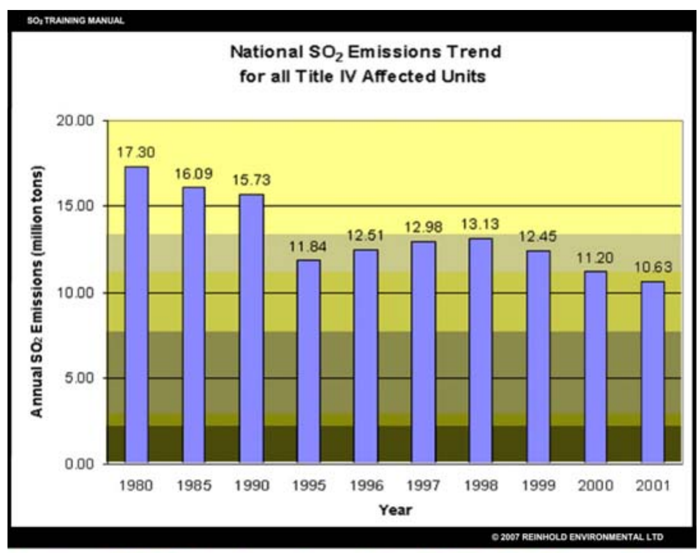
Allowances can be sold as commodities. Once the allowances are given to a utility, allowances may be bought, sold, traded, or saved for use in future years. Allowances may not be used prior to the year for which they are allocated.

Allowances are allocated by year beginning in 1995. EPA decided to grant allowances at an emission rate of 2.5 pounds of SO_2/mmBtu of heat input, multiplied by the unit's baseline mmBtu (the average fossil fuel consumed from 1985 through 1987), for all Title IV Phase I Units. The allowances granted are listed in Table A of the Clean Air Act and codified in the Allowance System Regulations (Part 73, Table 1). Alternative or additional allowance allocations were made for various units, including affected units in Illinois, Indiana, and Ohio, which were allocated a pro rata share of 200,000 additional allowances each year from 1995 to 1999.



Phase I - Unit SO2 Emissions Trends
Reference http://www.epa.gov/airmarkets/emissions/score01/index.html

In Phase II, which began in the year 2000, EPA expanded the group of affected sources to include virtually all units over 25 megawatts, and lowered the allowance allocation. Allowance allocation calculations were made for various types of units, such as units with low and high emissions rates or low fuel consumption. The EPA has allocated allowances to each unit at an emission rate of 1.2 pounds of SO_2/mmBtu of heat input, multiplied by the unit's baseline. During Phase II, the Act places a cap at 8.95 million on the number of allowances issued to units each year. The goal is to require continuing decreases in SO_2 emissions.



National SO2 Emissions Trend for All TItle IV Affected Units
Reference http://www.epa.gov/airmarkets/emissions/score01/index.html

Allowances are also available from three EPA sources. During Phase I, units could apply for and receive extra allowances by:

- Installing a technology that removed at least 90 percent of the unit's SO_2 emissions or by reassigning their reduction requirements among other units that had installed such equipment,
- Receiving incentives for units achieving SO_2 emissions reductions through customer-oriented conservation measures or renewable energy generation,

- From yearly EPA auctions.

Units that began operating in 1996 or later (Phase II) are not given allowances, but must purchase allowances from:

- EPA,
- Commodities, or
- Sales from other utilities

EPA has established accounts for all Phase I and Phase II utility units. Records are kept of what allowances are used in each year, and any allowances that are transferred to another year. If allowances are bought or sold, each must be transferred to the subject account. The system used is called the "Allowance Tracking System" (ATS).

Each year the total SO_2 emissions are added up and compared to the number of SO_2 allowances in the ATS for each power plant unit. If there are not enough emission allowances the utility must purchase additional allowances. The transactions must be final by March 1 of the following year. If SO_2 allowances are not used, the allowances will be deferred to the next year. If the unit's emissions exceed the allowances the unit may pay a penalty or take allocated emission allowances from the next year. There is a $2000 per ton cash penalty for SO_2 non compliance.

To make sure that the allowances are consistently valued and to ensure that all of the projected emission reductions are in fact achieved, it is necessary that actual emissions from each affected utility unit be determined. Title IV requires that affected units continuously measure and record their:

- SO_2,
- NOx,
- CO_2 emissions
- Flue gas flow,
- Opacity, and
- Other flue gas properties

Most plants will meet these requirements by using continuous emission monitoring systems (CEMS). The initial regulations for an Acid Rain Program continuous emission monitoring (CEM) requirements were published at 40 CFR Part 75 on January 11, 1993 (58 FR 3590) and has written other rule and technical revisions to Part 75.

Compliance Equipment and Methods

A utility could use one or more of the following compliance methods for Title IV:

- Fuel switching and/or fuel blending with lower sulfur coal,
- Purchasing additional allowances,
- Installing flue gas desulfurization (FGD) equipment,

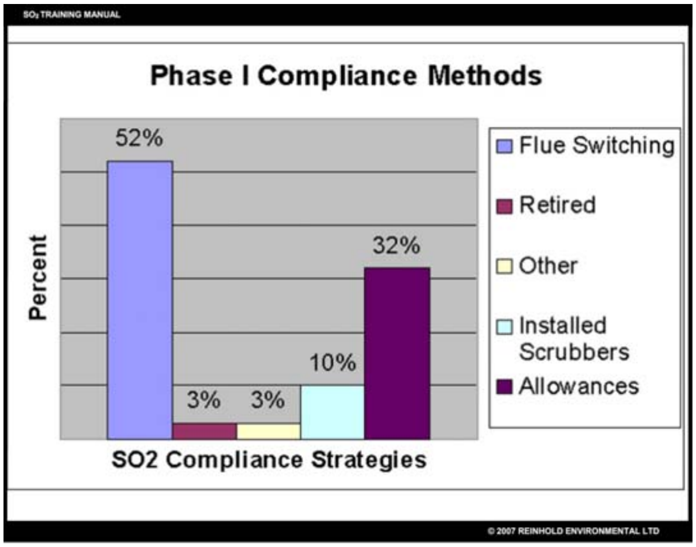
- Using previously implemented emissions controls,
- Retiring units,
- Boiler repowering,
- Substituting Phase II units for Phase I units, or
- Compensating Phase I units with Phase II units.

The chart below indicates the methods used to achieve compliance in Phase I of Title IV. From the chart it can be observed that 52% of the Phase I units used fuel switching as the most economical method for SO_2 control. The second most popular method for SO_2 control was the use of allowances. Installation of new scrubbers (FGD equipment) was the third most used option at 10 %.

Phase II compliance methods were expected to be similar but because of more stringent emission limits for SO_2 and the new mercury regulations in several plants, scrubbers became the most-economical viable option.

Regional Haze

In 1977 the Clean Air Act amendments set a national goal to improve visibility in certain mandatory Class I Federal Areas that include national parks and wilderness areas. This amendment required the EPA to issue regulations to protect the Class I areas from the negative effect of manmade pollution. In total there are now 156 areas in the country that have Class I status.



Phase I - Compliance Methods
Reference: The Effects of Title IV of the Clean Air Act Amendments of 1999 on Electric Utilities: An Update March 1997 DOE/IEA-0582(97) Distribution Category UC-950

A Chronology of the Regional Haze Regulations is as follow:

- In 1980, the EPA issued regulations concerning visibility problems that were attributed to a single source or a small group of sources. This was considered the first phase of the regulation.
- In 1988, various government agencies and EPA began monitoring fine particulate and visibility in 30 national parks and wilderness areas throughout the United States. The data gathered was analyzed to determine what portion of the fine particulate could be attributed to what pollutants. Some of these pollutants were nitrates, sulfates, carbon, and soil dust.
- In 1990, Congress amended the Clean Air Act. The amendment required EPA to establish the Grand Canyon Visibility Commission, and work with several western states to study and address visibility in the Grand Canyon national park. Congress also required EPA to take action on regional haze within 18 months of receiving the recommendations from the Commission.
- In 1997, EPA proposed regional haze regulations, while at the same time issuing new National Ambient Air Quality Standards (NAAQS) for fine particulate. Because of evidence that fine particles can be transported hundreds of miles, all 50 states are required to participate in planning and analysis of regional haze data. Even though a state does not have a Class I area, the state may be required to install pollution

control equipment to minimize a visual impairment in a Class I area. The regulation requires States to develop long-term strategies to improve visibility. According to EPA, without the effects of pollution a natural visual range is 140 miles in the west and 90 miles in the eastern United States. However, in certain parts of the US, fine particulates have reduced the visual range to a maximum of 90 miles in the west and a maximum of 24 miles in the east.

- In 1999, the EPA issued regulations to improve visibility. States are required to submit their plans following action by EPA to designate areas for the NAAQS for PM 2.5. (PM 2.5 are those particles less than 2.5 microns in diameter.) Those areas designated by EPA as attainment states have one year to submit regional haze plans (2004 to 2006). Those areas in non attainment states will have three years to submit plans (2006 to 2008). Also, expanded monitoring was required in 1999. The locations requiring visibility improvements increased from 30 to 108, and representative data has to be provided from all 156 Class I areas.

The first long term strategies developed by states will cover 10 to 15 years. Review of the States strategies are scheduled to be done in 2018. A State's strategy review is scheduled every 10 years after 2018.

BART (Best Available Control Technology) is one of the main components of a Regional Haze state plan. The regional haze rules require the following to be part of the state's plans:

- A regional analysis of the total emission reductions that can result from the installation of BART,
- A list of sources that can improve visibility if BART is installed, and
- The BART emission limit from each source.

Reference:
http://www.epa.gov/ttn/oarpg/t1/fact_sheets/hazefs2.pdf- Final Regional Haze Regulations for Protection of Visibility in National Parks and Wilderness Areas-6/2/99

PM 2.5

Congress directed Environmental Protection Agency to set National Ambient Air Quality Standards (NAAQS) for the six most common air pollutants. The Clean Air Act requires that NAAQS be set at levels that protect the public, regardless of the cost. One of the main pollutants of concern is fine particulate. Fine particulate is a mixture of liquid droplets and fine solids. SO_2 is part of the fine particulate mixture.

SO_2 TRAINING MANUAL

POLLUTANT	STANDARD VALUE *		STANDARD TYPE
Carbon Monoxide (CO)			
8-hour Average	9 ppm	(10 mg/m^3)	Primary
1-hour Average	35 ppm	(40 mg/m^3)	Primary
Nitrogen Dioxide (NO_2)			
Annual Arithmetic Mean	0.053 ppm	(100 μg/m^3)	Primary & Secondary
Ozone (O_3)			
1-hour Average	0.12 ppm	(235 μg/m^3)	Primary & Secondary
8-hour Average **	0.08 ppm	(157 μg/m^3)	Primary & Secondary
Lead (Pb)			
Quarterly Average	1.5 μg/m^3		Primary & Secondary
Particulate (PM 10) *Particles with diameters of 10 micrometers or less*			
Annual Arithmetic Mean	50 μg/m^3		Primary & Secondary
24-hour Average	150 μg/m^3		Primary & Secondary
Particulate (PM 2.5) *Particles with diameters of 2.5 micrometers or less*			
Annual Arithmetic Mean **	15 μg/m^3		Primary & Secondary
24-hour Average **	65 μg/m^3		Primary & Secondary
Sulfur Dioxide (SO_2)			
Annual Arithmetic Mean	0.03 ppm	(80 μg/m^3)	Primary
24-hour Average	0.14 ppm	(365 μg/m^3)	Primary
3-hour Average	0.50 ppm	(1300 μg/m^3)	Secondary

National Ambient Air Quality Standards for Fine Particulates
Reference: National Ambient AIr Quality Standards-
http://www.epa.gov/airs/criteria.html

EPA is adding new fine particle standards (PM2.5) to the existing PM10 standards. The numbers, 2.5 and 10 refer to the particle size measured in microns.

The figure to the right contains a list of the National Ambient Air Quality Standards.

Clear Skies Initiative

The Clear Skies Act of 2002 (Clear Skies Act) amends Title IV and Title I of the Clean Air Act to establish new programs requiring reductions of sulfur dioxide, nitrogen oxides, and mercury emissions from electric generating facilities.

The Clear Skies Act establishes a cap and a trading program for sulfur dioxide, mercury, and NOx, which are modeled after the existing Acid Rain Program. The trading programs must be established with allowances that hold emission level to less than or equal to existing levels, and the new trading programs must be referenced in the new Title V permits. Continuous Emission Monitors (CEM) and reporting are also required. An automated excess emission penalty replaces the existing single penalty. Fossil fueled boilers, not originally in the program, may be required to participate in the Clear Skies program if certain requirements are met. Once a unit is governed by the Clear Skies Initiative it is not allowed to withdraw. A program may be established that allows EPA to recommend adjustment of the number allowances available to Congress.

A new part of the Clear Skies Act establishes new lower caps on the total sulfur dioxide emissions and allowance procedures beginning on January 1, 2010. The Clear Skies Initiative covers existing fossil fuel electricity generating boilers and turbines and integrated gasification combined cycle plants greater than 25 megawatts. The owner or operator must hold allowances for all the units at a plant at least equal to the sulfur dioxide emissions for that unit for the year. The Clear Skies Act (CSA), annual sulfur dioxide emissions for affected units are:

- Capped at 4.5 million tons starting in 2010, and
- Capped at 3.0 million tons starting in 2018.

The Title IV cap is 9.0 million tons. The reductions represent a 50% reduction by 2010, and a further 66.7% reduction by 2018, meaning the 2018 sulfur dioxide emission level will be required to be 1/3 that of the Title IV cap.

For the first year that the CSA is effective, 99% of the allowances will be allocated to the units, and the remaining 1% sold at auction. Every year after that for the next 20 years the amount of sulfur dioxide allowances to be sold will increase by 1% per year. After that initial 20 year period has passed the amount of allowances to be auctioned off will increase by 2.5% per year. Eventually, all allowances will be sold at auction. A separate emission limitation and allowance program will be established for the states of the Western Regional Air Partnership. This program goes into effect in 2018, or later when the emission for these electricity generating units exceed 271,000 tons.

Mercury emissions are also addressed by the Clear Skies Initiative. Compliance will be determined on a facility basis. Annual mercury emissions are capped at:

- 26 tons per year starting 2010, and

- 15 tons per year starting in 2018.

The allowance percentages will be the same as allocated for sulfur dioxide.

New coal fired units that begin operation after the date of enactment of the Clear Skies initiative are subject to the following emission limits:

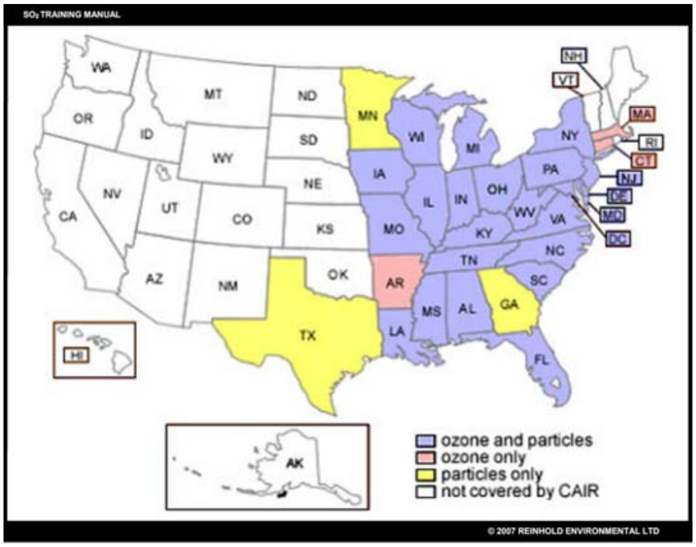
- 2.0 lb/MWh for sulfur dioxide,
- 1.0 lb/ MWh for nitrogen oxide,
- 0.2 lb/ MWh for particulate emissions, and
- 0.015 lb/GWh for mercury.

It should be noted that alternate standards may apply in certain situations. Affected units are exempted from the requirements of the New Source Review and exempted from the requirement to install the Best Available Control Technology. To quality for exemption from New Source Review and Best Available Control Technology, an existing unit must meet the Clear Skies emission standards. But, for an existing unit to quality for this exemption it must meet the existing NSPS limit of particulate of .03 lb/MMBtu, or commit within three years to do so. Other requirements also apply.

EPA is allowed to designate areas as transitional, if EPA or the state can perform modeling that demonstrates that the area will attain the 8 hour ozone or PM 2.5 National Ambient Air Quality Standards through a combination of controlled reductions. The Utility MACT (emission of hazardous air pollutants) standards will be eliminated. The restrictions on regional transport requirements would be limited under the Clean Skies Initiative.

Reference: Summary of Clear Skies Act of 2002, from http://www.epa.gov.

Clean Air Interstate Rule (CAIR)



States Affected by Clean Air Intestate Rule (CAIR)
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On March 10, 2005, the Environmental Protection Agency (EPA) announced the Clean Air Interstate Rule (CAIR), a rule that will achieve the largest reduction in air pollution in more than a decade. This action, called the "Interstate Air Quality Rule" when it was proposed in January 2004, offers steep and sustained reductions in air pollution as well as dramatic health benefits at more than 25 times greater than the cost by 2015.

Through the use of the proven cap-and-trade approach, CAIR achieves substantial reductions of sulfur dioxide (SO_2) and nitrogen oxides (NOx) emissions and is a powerful component of the Administration's plan to help over 450 counties in the eastern U.S. meet EPA's protective air quality standards for ozone or fine particles.

CAIR covers 28 eastern states and the District of Columbia. In this rule EPA finds that SO_2 and NOx emissions from 25 states and the District of Columbia contribute to unhealthy levels of fine particles in downwind states. In addition, NOx emissions in 25 eastern states and the District of Columbia contribute to unhealthy levels of 8-hour ozone in other downwind states.

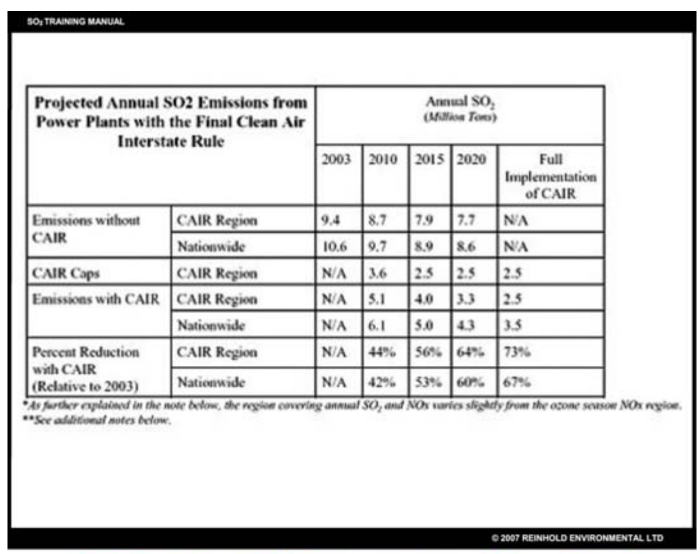
Based on an assessment of the emissions contributing to interstate transport of air pollution and available control measures, EPA has determined that achieving required reductions in the identified states by controlling emissions from power plants is highly cost effective.

- States must achieve the required emission reductions using one of two compliance options: 1) meet the state's emission budget by requiring power plants to participate in an EPA-administered interstate cap and trade system that caps emissions in two stages, or 2) meet an individual state emissions budget through measures of the state's choosing.
- CAIR provides a Federal framework requiring states to reduce emissions of SO_2 and NOx. EPA anticipates that states will achieve this primarily by reducing emissions from the power generation sector. These reductions will be substantial and cost-effective, so in many areas, the reductions are large enough to meet the air quality standards. The Clean Air Act requires that states meet the new national, health-based air quality standards for ozone and PM2.5 standards by requiring reductions from many types of sources. Some areas may need to take additional local actions. CAIR reductions will lessen the need for additional local controls.

If states choose to meet their emissions reductions requirements by controlling power plant emissions through an interstate cap and trade program, EPA's modeling shows that:

- In 2010, CAIR will reduce SO_2 emissions by 4.3 million tons -- 45% lower than 2003 levels, across states covered by the rule. By 2015, CAIR will reduce SO_2 emissions by 5.4 million tons, or 57%, from 2003 levels in these states. At full implementation, CAIR will reduce power plant SO_2 emissions in affected states to just 2.5 million tons, 73% below 2003 emissions levels.
- In 1990, national SO_2 emissions from power plants were 15.7 million tons compared to 3.5 million tons that will be achieved with CAIR. In 1990, national NOx emissions from power plants were 6.7 million tons, compared to 2.2 million tons that will be achieved with CAIR.

In upcoming but closely related action, EPA will impose the first ever federally-mandated requirements that coal-fired electric utilities reduce their emissions of mercury. Together the Clean Air Mercury Rule and the Clean Air Interstate Rule create a multi-pollutant strategy to reduce emissions throughout the United States.


SO_2 TRAINING MANUAL

Projected Annual SO2 Emissions from Power Plants with the Final Clean Air Interstate Rule		Annual SO_2 (Million Tons)				
		2003	2010	2015	2020	Full Implementation of CAIR
Emissions without CAIR	CAIR Region	9.4	8.7	7.9	7.7	N/A
	Nationwide	10.6	9.7	8.9	8.6	N/A
CAIR Caps	CAIR Region	N/A	3.6	2.5	2.5	2.5
Emissions with CAIR	CAIR Region	N/A	5.1	4.0	3.3	2.5
	Nationwide	N/A	6.1	5.0	4.3	3.5
Percent Reduction with CAIR (Relative to 2003)	CAIR Region	N/A	44%	56%	64%	73%
	Nationwide	N/A	42%	53%	60%	67%

*As further explained in the note below, the region covering annual SO_2 and NOx varies slightly from the ozone season NOx region.
**See additional notes below.

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CAIR Projected SO2 Emissions from Power Plants

Reference:
http://www.epa.gov/air/interstateairquality/charts_files/cair_emissions_costs.pdf

Cap and Trade Basics, SO_2 & NOx

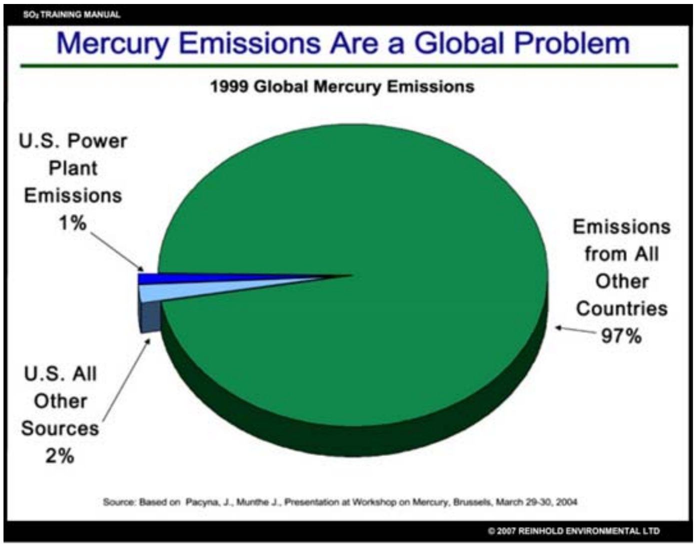
EPA already allocated emission "allowances" for SO_2 to sources subject to the Acid Rain Program. These allowances will be used in the CAIR model SO_2 trading program. For the model NOx trading programs, EPA will provide emission "allowances" for NOx to each state, according to the state budget. The states will allocate those allowances to sources (or other entities), which can trade them. As a result, sources are able to choose from many compliance alternatives, including: installing pollution control equipment; switching fuels; or buying excess allowances from other sources that have reduced their emissions.

CAIR Timeline

- 2005 - Promulgate CAIR Rule
- 2006 - State Implementation Plans Due
- 2009 - Phase I Cap in Place for NOx
- 2010 - Phase I Cap in Place for SO_2
- 2015 - Phase II Cap in Place for NOx and SO_2

HAPS- Mercury

Under Title III of the Clean Air Act, EPA is responsible for determining the hazards to public health posed by 189 hazardous air pollutants (HAP's). Title III directed EPA to perform a study of the HAP's (also known as air toxics) to determine which hazards are likely to occur as a result of emissions by electric utility steam generating units, and to report the results to Congress.



1999 Global Mercury Emissions
Reference: http://www.epa.gov/air/mercuryrule/pdfs/slide3.pdf

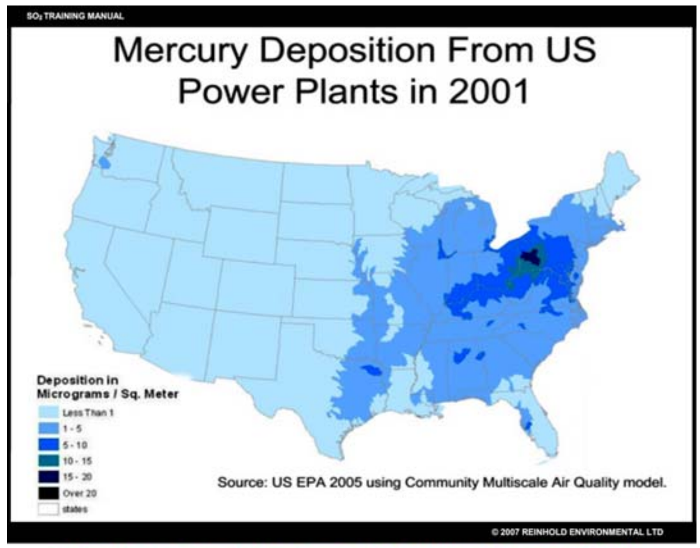
The Clean Air Act also required EPA to recommend whether to control 189 air toxics, including mercury, by November 15, 1995. However, this deadline was delayed.

For a complete list of EPA's Air Toxics see
Reference 0.4.e. EPA Air Toxics Table

On December 14, 2000, the EPA announced that it had found that the regulation of mercury and other air toxics is warranted. A project to develop emission regulations was begun. Emission standards were scheduled to be developed by December 15, 2003. Two reports have been submitted to congress by the EPA. The first in 1997 was the Mercury Study Report to Congress, which identified fossil-fired power plants as the largest single source of mercury in the country. The second report to Congress in 1998, Utility Air Toxics Report to Congress, recorded and analyzed the air toxics emission from power plants. Mercury was identified as the toxic of greatest concern.

According to EPA research, coal-fired power plants are the largest source of mercury emissions. However, municipal waste incinerators, medical waste incinerators, and hazardous waste incinerators also emit mercury.

On March 15, 2005, EPA issued the first-ever federal rule to permanently cap and reduce mercury emissions from coal-fired power plants. The Clean Air Mercury Rule will build on EPA's Clean Air Interstate Rule (CAIR) to significantly reduce emissions from coal-fired power plants -- the largest remaining sources of mercury emissions in the country. When fully implemented, these rules will reduce utility emissions of mercury from 48 tons a year to 15 tons, a reduction of nearly 70 percent.

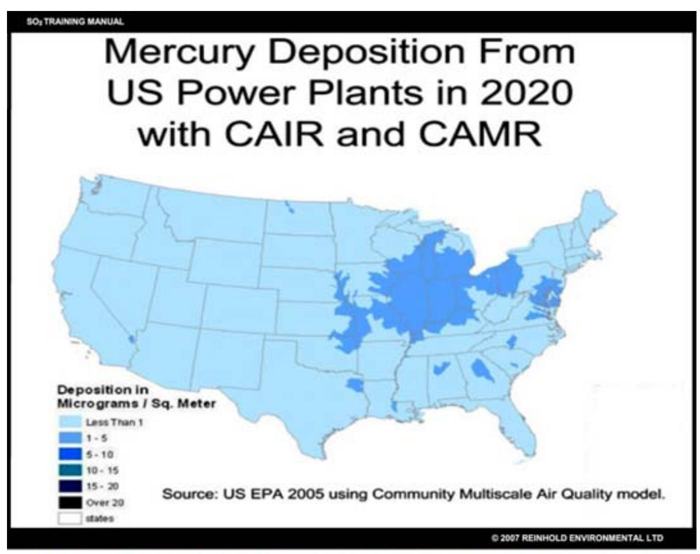


Mercury Deposition from U.S. Power Plants in 2001
Reference:
http://www.epa.gov/air/mercuryrule/pdfs/nationaldepositionmaps3.pdf

EPA believes it makes sense to address mercury, SO_2 and NOx emissions simultaneously through CAIR and the Clean Air Mercury Rule. These rules will protect public health and the environment without interfering with the steady flow of affordable energy for American consumers and business.

The Clean Air Mercury Rule establishes "standards of performance" limiting mercury emissions from new and existing coal-fired power plants and creates a market-based cap-and-trade program that will reduce nationwide utility emissions of mercury in two distinct phases.

- The first phase cap is 38 tons and emissions will be reduced by taking advantage of "co-benefit" reductions – that is, mercury reductions achieved by reducing sulfur dioxide (SO_2) and nitrogen oxides (NOx) emissions under CAIR.
- In the second phase, due in 2018, coal-fired power plants will be subject to a second cap, which will reduce emissions to 15 tons upon full implementation.



Mercury Deposition from U.S. Power Plants in 2020 with CAIR and CAMR
Reference: http://www.epa.gov/air/mercuryrule/pdfs/nationaldepositionmaps4.pdf

New coal-fired power plants ("new" means construction starting on or after Jan. 30, 2004) will have to meet stringent new source performance standards in addition to being subject to the caps.

EPA's modeling shows that CAIR will significantly reduce the majority of the coal-fired power plant mercury emissions that deposit in the United States, and those reductions will occur in areas where mercury deposition is currently the highest. The Clean Air Mercury Rule is expected to make additional reductions in emissions that are transported regionally and deposited domestically, and it will reduce emissions that contribute to atmospheric mercury worldwide.

Mercury Emissions - A Global Problem

Mercury emitted from coal-fired power plants comes from mercury in coal, which is released when the coal is burned. While coal-fired power plants are the largest remaining source of human-generated mercury emissions in the United States, they contribute very little to the global mercury pool. Recent estimates of annual total global mercury emissions from all sources -- both natural and human-generated -- range from roughly 4,400 to 7,500 tons per year. Human-caused U.S. mercury emissions are estimated to account for roughly 3 percent of the global total, and U.S. coal-fired power plants are estimated to account for only about 1 percent.

EPA has conducted extensive analyses on mercury emissions from coal-fired power plants and subsequent regional patterns of deposition to U.S. waters. Those analyses conclude that regional transport of mercury emission from coal-fired power plants in the U.S. is responsible for very little of the mercury in U.S. waters. That small contribution will be significantly reduced after EPA's Clean Air Interstate Rule and Clean Air Mercury Rule are implemented.

U.S. coal-fired power plants emit mercury in three different forms: oxidized mercury (likely to deposit within the U.S.); elemental mercury, which travels hundreds and thousands of miles before depositing to land and water; and mercury that is in particulate form. Because mercury can be transported thousands of miles in the atmosphere, and because many types of fish are caught and sold globally, effective exposure reduction will require reductions in global emissions.

Revision of December 2000 Finding

- Also on March 15, 2005, in a separate but related action, EPA revised and reversed its December 2000 finding that it was "appropriate and necessary" to regulate coal- and oil-fired power plants under section 112 of the Clean Air Act. We are taking this action because we now believe that the December 2000 finding lacked foundation and because recent information demonstrates that it is not appropriate or necessary to regulate coal- and oil-fired utility units under section 112.
- EPA nevertheless believes it is important to regulate mercury emissions from coal-fired power plants. For that reason EPA has signed two complementary rules – CAIR and the Clean Air Mercury Rule, issued

under sections 110(a)(2)(D) and 111 of the law, respectively. These rules will allow us to more effectively limit mercury emissions from these plants.

Cap and Trade Basics Hg

- The March 15, 2005 rule establishes a cap-and-trade system for mercury that is based on EPA's proven Acid Rain Program. The Acid Rain Program has produced remarkable and demonstrable results, reducing SO_2 emissions faster and at far lower costs than anticipated, and resulting in wide-ranging environmental improvements.
- In the Clean Air Mercury Rule, EPA has assigned each state and two tribes an emissions "budget" for mercury, and each state must submit a State Plan revision detailing how it will meet its budget for reducing mercury from coal-fired power plants. Two tribes that have coal-fired power plants that will be affected by this rule also have been assigned a mercury emissions budget.
- Although states and tribes are not required to adopt the EPA-administered cap-and-trade program, the Agency believes most will do so. The state and tribal emission budgets are permanent, regardless of growth in the electric sector.

The Benefits of Cap-and-Trade Regulation over MACT

- For both a cap-and-trade system and a MACT, emissions limits are established and must be achieved.
- However, under a cap-and-trade system reductions and caps emissions are capped permanently and nationwide emissions can only go down. The ability to bank unused allowances for future use can lead to early reductions of mercury. A trading approach is forward-looking in its assessment of technology because it provides a continuous incentive for technology innovation.
- A traditional Section 112(d) MACT approach sets standards based on technology performance. Each plant subject to a MACT must meet a specific emissions limit. However, benefits of MACT are not always permanent: With shifts in coal use and with economic growth, nationwide emission reductions could erode over time. In addition, a MACT approach would not create as much continuous incentive for the development of new mercury control technology.

On May 31, 2006, Administrator Johnson signed the Federal Register notice that completes the Agency's action on the petitions to reconsider the Clean Air Mercury Rule.

In response to the petitions for reconsideration, EPA reaffirmed its approach for regulating mercury emissions from power plants and made technical changes and clarifications to the Clean Air Mercury Rule. Today's action responds to petitioners' requests for changes to certain aspects of two mercury-related actions:

- EPA's decision that it is neither necessary nor appropriate to regulate power plant mercury emissions under section 112 of the Clean Air Act (called the Section 112(n) Revision Rule) and
- the cap-and-trade Clean Air Mercury Rule.

After carefully considering the petitions and the information that was submitted during the public comment period, EPA has determined that its original determination as presented in the final Section 112(n) Revision Rule was correct and is reaffirming the March 29, 2005 action.

With regard to Clean Air Mercury Rule, EPA is making two technical changes to the rule and finalizing language reaffirming that municipal waste combustors and certain industrial boilers are not covered under this rule.

0.5 Technology Overview

FGD Technology

Wet Limestone Scrubber at a German Power Plant
Used with permission

Flue gas desulfurization (FGD) is the process of removing sulfur oxides, primarily SO_2, from the combustion gases. In wet process FGD systems, flue gases are contacted with an absorbent in a vessel called either an absorber or a scrubber. The SO_2 reacts with the absorbent or dissolves into the solution to produce a slurry or a liquid that contains dissolved or solidified sulfur compounds. The systems are grouped into two categories: regenerable and non-regenerable, depending on whether the sulfur is separated from the absorbent as waste. Nonregenerable processes produce a sludge that requires disposal, while the regenerable system includes additional steps to convert the sulfur into a by-product. Examples of non-regenerable wet FGD systems are lime scrubbing, limestone scrubbing, sodium carbonate scrubbing, and dual alkali systems. The magnesium oxide scrubbing and Wellman-Lord systems are classified as regenerable processes.

The term "Dry Scrubber" refers to the condition of the waste material leaving the scrubber. In the dry process, the dry waste material produced and the flue gas leaving the scrubber is not saturated with moisture.

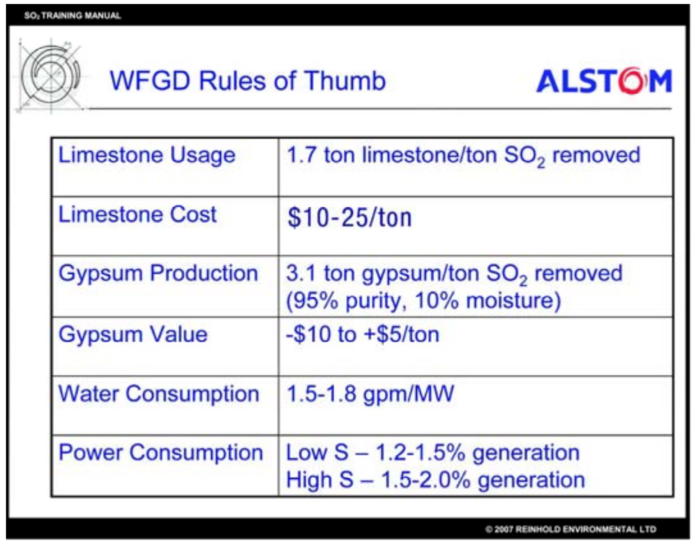
Various types of FGD technology have been designed for various applications. Scrubbers are constructed with such a multiplicity of designs that no simple type can be considered representative of the category as a whole. This manual only will address wet lime and limestone scrubbers. Dry scrubbers will be addressed in a separate manual.

Wet Scrubber Overview

The term "wet scrubber" indicates that a wet slurry is utilized in the absorber to saturate the process and a liquid waste product is produced. The flue gas leaving the process is saturated with moisture. Wet scrubbers have been in more common use than dry scrubbers.

There are several types of wet scrubber technology. The most common type in use is the spray tower design. There is also a packed-bed tower design and an impingement plate design. The fourth main type is a venturi scrubber.

In general wet scrubbers can be categorized by pressure drop (or energy consumption). Low energy scrubbers are those with typical pressure drops less than 5 in. of water, medium-energy scrubbers are those with typical pressure drops from 5-15 in. of water; and high-energy scrubbers are those with typical pressure drops greater than 15 in. of water. Spray towers provide the lowest pressure drop. Certain packed-bed scrubbers are medium-energy consumers, while venturi-type scrubbers are an example of high-energy scrubbers.



Limestone Usage	1.7 ton limestone/ton SO_2 removed
Limestone Cost	$10-25/ton
Gypsum Production	3.1 ton gypsum/ton SO_2 removed (95% purity, 10% moisture)
Gypsum Value	-$10 to +$5/ton
Water Consumption	1.5-1.8 gpm/MW
Power Consumption	Low S – 1.2-1.5% generation High S – 1.5-2.0% generation

Wet FGD Rules of Thumb
Used with permission from Alstom

Wet Scrubber Chemistry

The chemical reactions that occur in a wet scrubber are:

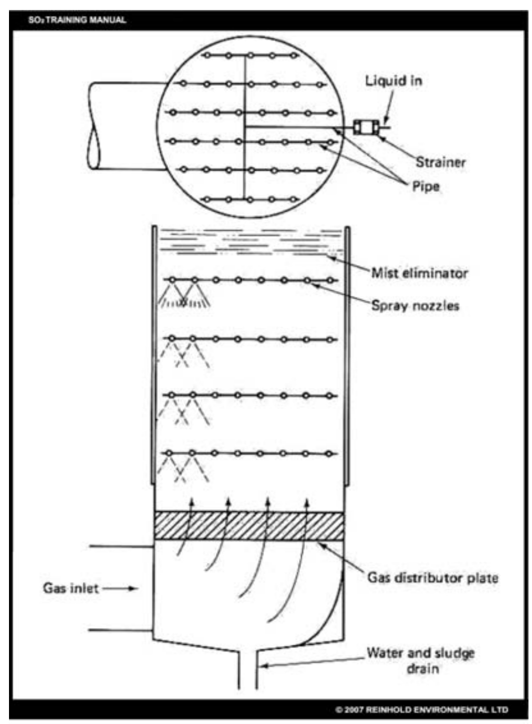
$$SO_2 + CaCO_3 + 1/2H_2O \rightarrow CaSO_3\bullet 1/2\ H_2O + CO_2$$

$$SO_2 + 1/2O_2 + CACO_3 + 2H_2O \rightarrow CaSO_4\bullet 2H_2O + CO_2$$

Wet Scrubber Performance

Wet scrubbers are usually designed for efficiency of 80 to 98 percent SO_2 removal. Additives (e.g., magnesium-enhanced lime or adipic acid) have also been utilized to enhance the base design and improve the process efficiency by 5 to 10 %, raising it to a total 95 to 99%. These performance levels have been proven for both high and low sulfur coals in many commercial applications in Europe, Japan, and the United States.

Energy must be used to capture SO_2 from the flue gas and approximately 1 to 2 % of the unit's generating capacity is consumed to meet the power requirements of the scrubber, usually in some form of pressure drop within the absorber. An additional 1% is consumed for gas reheating (when available). When gas-to-gas heating is used, there is no additional efficiency penalty.



Gravity Spray Tower
Used with permission

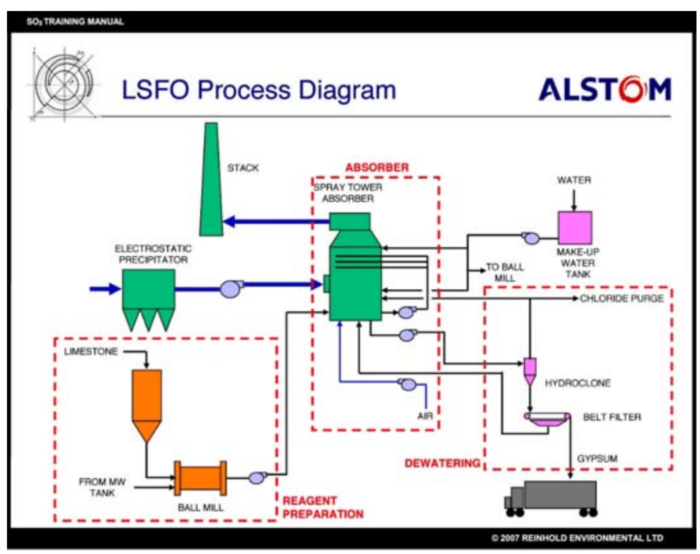
Types of wet scrubbers

Spray Tower Wet Scrubbers

A simplified process flow diagram of a spray tower design wet scrubber is shown in the LSFO Process Diagram figure below. In this scrubber design, after leaving the particulate removal device, which can be either an ESP or a fabric filter, the flue gas enters a large vessel (spray tower or absorber), where it is sprayed with calcium-based water slurry (approximately 10-20 percent lime or limestone). The calcium in the slurry reacts with the SO_2 to form calcium sulfite or calcium sulfate. A portion of the slurry from the reaction tank is pumped into the thickener, where the solids settle before going to a filter for final dewatering to about 50 percent solids. The calcium sulfite waste product is usually mixed with fly ash (approximately 1:1) and fixative lime (approximately 5 percent) and disposed of in landfills. Alternatively, gypsum can be produced from FGD waste, which is a useful by-product.

Gravity spray towers, in which fine-size liquid droplets are made to fall through rising exhaust gases and are drained at the bottom of the chamber, are the most common spray towers. In a vertical tower the relative velocity between fine-size droplets and the gas is eventually the terminal settling velocity of the droplets. However, to avoid spray droplet re-entrainment, the terminal settling velocity of the droplets must be greater than the velocity of the rising gas stream. In practice, the vertical gas velocity typically ranges from 2 to 5 ft/sec. For higher velocities, a mist eliminator must be used in the top of the tower to remove the moisture from the flue gas.

In some installations (especially in Germany), the flue gas is reheated to avoid corrosion downstream in the power plant. Many scrubbers have gas-bypassing capability, which can be used for gas reheating. Also, gas-to-gas reheating may be used, which does not have a penalty on plant efficiency.



LSFO Process Diagram
Used with permission from Alstom

In the early years of introduction of FGD technology, a spare absorber was included to allow full-load operation with one absorber out of service. Recent improvements in reliability have contributed to the elimination of the spare module in most installations. Presently, large capacity scrubber modules can handle flue gas approximately equivalent to that of a 1,000 MW coal power plant. Wet scrubbers are generally designed for a maximum flue gas flow rate.

Limestone Forced Oxidation is a variation of the above scrubbers. In the LSFO process, the calcium sulfite initially formed in the spray tower absorber is nearly 100 percent oxidized to form gypsum (calcium sulfate) by bubbling air through the sulfite slurry in the tower re-circulation tank or in a separate vessel.

Because of their larger size and structure, gypsum crystals settle and dewater better than calcium sulfite crystals, reducing the required size of by-product handling equipment. The high gypsum content also permits disposal of the dewatered waste without fixation. Gypsum also has a potential commercial value, and this needs to be incorporated into the overall assessment of the FGD processes.

By controlling the gypsum quality in the dewatering step, wallboard-grade gypsum can be produced. The majority of scrubber installations in Europe and Japan generate gypsum for reuse. In the United States, sale of gypsum depends on local markets for wallboard, cement, and agricultural soil amendments.

The LSFO process with throwaway by-product is the standard process against which other FGD processes are compared.

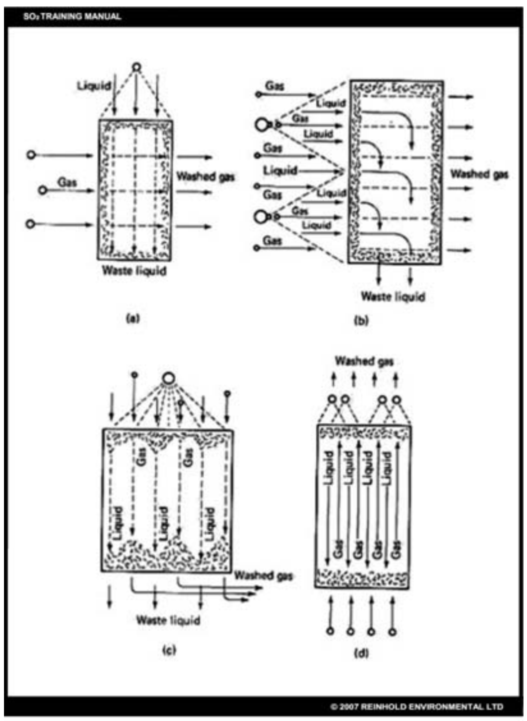
The advantages of a spray tower wet scrubber are:

- Relatively low gas side pressure drop,
- Can handle flammable and explosive dusts,
- Relatively free from plugging, thus capable of treating relatively high dust concentrations.
- Relatively small space requirements,
- Collects particles, as well as, gases.

The disadvantages of a spray tower wet scrubber are:

- Creates water disposal problems since the liquid requirements range from 3 to 20+ gal/1000 ft3 of gas treated.
- Low mass transfer efficiencies,
- Inefficient in removing fine particulate in the range of 0-5 micron. Particles larger than 10 microns can typically be removed with efficiencies around 70% or greater
- When fiberglass construction is used, sensitivity to temperature changes,
- High operating cost.
- Liquid slurry nozzle wear

Packed-bed Tower Wet Scrubbers



Packed Bed Scrubbers
Used with permission

The figure to the right illustrates the typical designs for packed-bed Scrubbers.

In vertical-flow packed-bed scrubbers, liquid is introduced above the packing and flows down through the bed.

The advantages of a packed-bed tower scrubber are:

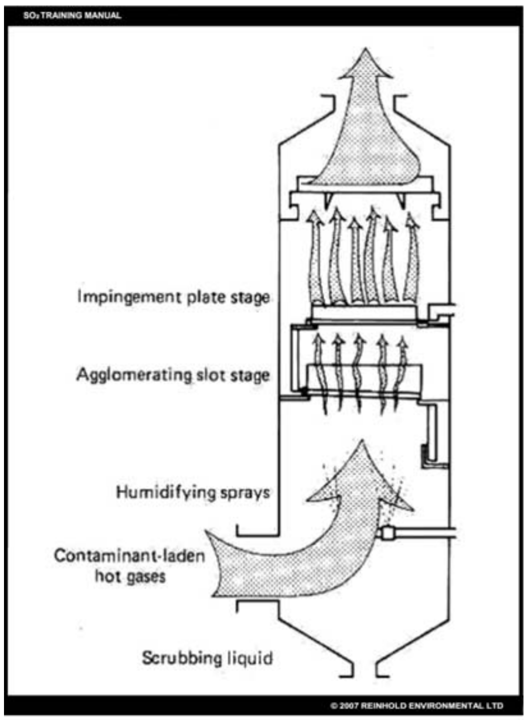
- Low to medium pressure drop for the liquid slurry stream,

- High mass-transfer efficiencies,
- Mass transfer can be improved with change in packing design,
- Relatively low capital cost,
- Small space requirements,
- Collects particulate and gases.

The disadvantages of a packed-bed tower scrubber are:

- High pressure drop on the gas side which at the flood point can result in the formation of a layer above the packing.
- Water disposal issues,
- Waste is collected wet,
- Particulate may cause plugging of the packing media since the design is for removal of pollutant gases and vapors not particulate matter.
- Cross flow, co-current-flow and countercurrent-flow packed scrubbers are not capable of achieving a high-enough gas velocity to effectively remove particulates smaller than 3-5 microns in diameter.
- Relatively high maintenance cost.
- Packing replacement

Impingement Plate Wet Scrubber



Impingement Plate Scrubber
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Impingement plate scrubbers utilize perforated plates with an impingement baffle over each perforation. The intention is to expand the surface area of the liquid through use of the gas stream's kinetic energy. Gas velocities of 15-20 ft/sec through the orifices are common. Overall collection efficiencies for a single plate may range from 90-98% for 1 micron particles with a pressure drop from 1-4 in. of water per plate.

The advantages of an impingement plate scrubber are:

- Handle flammable and explosive dust,
- Provides gas absorption and dust collection in a single unit. Handles mist,
- Collection efficiency can be varied by design,
- Cools hot gas,
- Corrosive gas and dust can be neutralized,
- More efficient gas-slurry contact for SO_2 removal

The disadvantages are:

- Waste product is collected wet,
- Water disposal issues. Typically water requirements usually range from 3-5 gal/1000 ft3 of gas.
- High potential for corrosion,

- Protection against freezing required,
- Off-gas may required reheating to avoid a visible steam plume from the stack,
- Collected particulate may be contaminated, and may not be recyclable,
- Disposal of waste sludge may be very expensive.

Venturi Wet Scrubbers

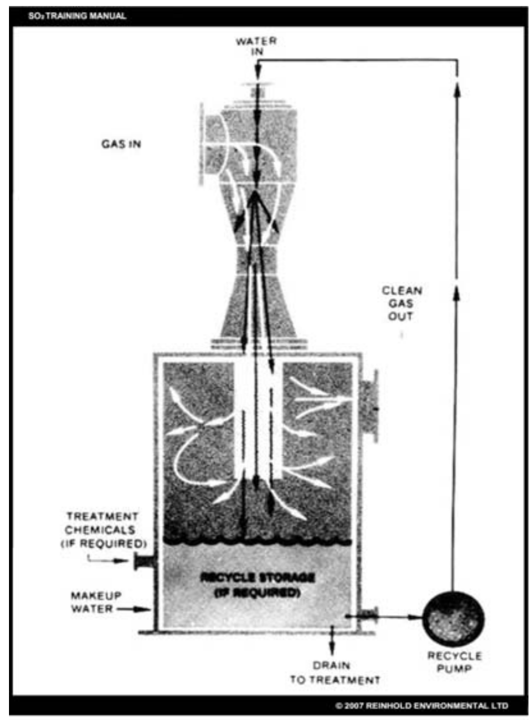
In a venturi scrubber, the scrubbing liquid is introduced at an angle to a high velocity gas flow in the venturi throat. Very small droplets are formed and high relative velocities are maintained until the droplets are accelerated to their terminal velocity. Gas velocities through a venturi throat typically range from 12,000 to 24,000 ft/min. The velocity of the gases alone causes the atomization of the liquid. The energy expended in the scrubber is almost completely accounted for by the gas stream pressure drop through the scrubber.

The advantages of a venturi scrubber are:

- Can handle mists,
- Relatively low maintenance,
- Simple design and easy to install,
- Collection efficiency can be varied,
- Provides cooling of hot gases, and
- Corrosive gases are neutralized.

The disadvantages are:

- Effluent liquid can create water disposal issues,
- Waste product is collected wet. Water injected into the venturi in quantities ranging from 5-15 gal/1000 ft3 of gas.
- High potential for corrosion
- Have not been located in optimal locations and had to be relocated after operation began.



Venturi Wet Scrubber
Used with permission

<u>Wet Scrubber Operational Concerns</u>

It is necessary to establish equilibrium between the SO_2, CO_2, H_2O, limestone slurry, and sulfite/sulfate in order to create a proper reaction. Normally, the wet limestone system varies from 1.01 to 1.1 moles of CaCO3 per mole of SO_2. The pH range must be kept in the 5.0 to 6.0 range. A gradual decrease in operating pH requires a fresh limestone feed.

The spent sorbent from the reaction tank is dewatered and disposed of, usually in a waste slurry pond or landfill.

Wet scrubber process variables include:

- Flue gas flow rate,
- Recycle slurry pH,
- Flue gas SO_2 concentrations,
- Liquid-to-gas ratio,
- Retention time.

Assuming that the proper unit was selected for the given application, most scrubber problems usually involve spray nozzle plugging, liquid circuit restrictions, and/or entrainment of droplets from the vessel. Typical FGD operational issues often include:

- The pH is likely to be the most important control variable for absorber operation. The pH is used to determine the amount of limestone added to the system. Increasing the amount of limestone added increases the amount of SO_2 removal.
- Increasing the concentration of SO_2 (or sulfur content in the fuel) will decrease SO_2 removal efficiency of the absorber.
- The amount of surface system available for reaction with SO_2 is determined by the liquid-to-gas ratio. For a counter flow absorber the liquid-to-gas ratio approximates the surface area of droplets and is one of the main design variables available to obtain a desired SO_2 removal.
- Solids concentration and retention time affect the performance and reliability of wet scrubber operation. Solid concentration is usually maintained at 10 to 15 percent by weight. Proper solids concentration in the slurry is necessary to ensure scale-free operation of the absorber. Correct solid retention time is required to achieve high utilization of limestone, and maintain correct properties of the solids. The typical solids retention time for a wet scrubber is 12 to 14 hours.
- Agitators - There are agitators in the reactant tanks. There are cases where the agitator material was redesigned due to the erosive nature of the slurry. Also agitator failures in the reaction tank have occurred. Agitator shafts have failed.
- Flow transmitters are often located on the exterior of the towers. In the winter lines to the flow transmitters will freeze if not properly protected.
- Differential pressure transmitters are used to determine if pluggage exists in various parts of the tower. Often these must be relocated to prevent large fluctuation in delta p.
- Mist eliminators have deformed during temperature excursions, and had to be replaced. Plugging has occurred at the mist eliminators. Mist eliminator wash valves which have not closed properly must be replaced with different valves.
- Mist eliminator tie rods have been installed made of inadequate materials. These often break are usually upgraded or replaced.
- Y strainers have been installed in service water lines to prevent algae and pipe scale from blocking the flow of water into the agitator and pump seal water lines.
- The large slurry re-circulation pumps have had a minor amount of oil leaking past the oil seals. There is also noted failure of re-circulation pumps as well are slurry recycle pumps.
- Improperly directed slurry spray nozzles have caused holes in the tower sidewalls due to direct impingement.
- Excessive oil leakage out of journal bearings during ball mill startups.

- Often packing in the small pumps on the scrubber is replaced by mechanical seals to reduce maintenance and seal water usage.
- Pneumatic air lines controlling the re-circulation pump drain valves have been known to break due to high vibration of the pumps. There are frequent maintenance concerns with re-circulation pump operations.
- Often the original design of access and maintenance platforms are located in improper areas.
- High ball wear in the limestone ball mill is a common problem. There are also cases when the limestone ball mill would not meet design requirements. Outage time has also been caused by broken belts to the limestone ball mill slurry pumps.
- There are occasionally failures in the limestone feed pipelines and material must be replaced. There have also been piping failures in the slurry re-circulation lines.
- Outage time has been caused by various pump malfunctions and valve sticking.
- FGD systems have been in outage due to circuit breaker and other electrical malfunctions.
- Failure of the flue gas bypass damper has caused outage time. On occasion these have been replaced with alloy dampers. Damper drives have failed.
- System pluggage is often an operational problem for FGD. It may be necessary to change the system's pH to decrease plugging within the system.
- The disposal systems have experienced some filter belt problems. Also breaks have been found in fiberglass pipe to disposal ponds.
- Scale has accumulated on various instrumentation probes, which leads to malfunctions.

Trends in Wet Scrubbers

Design Trends

- No stand-by spare absorber unit – one huge absorber to scrub the flue gases from the entire, or multiple, generating units or boilers.
- No bypass, indirect or direct reheat of scrubbed gases resulting in wet outlet duct and wet stack
- 100% scrubbing of flue gases.
- Design life of 40 years plus – therefore "reliability" will become a very critical issue and take on added importance.
- Shift towards a total metallic concept with alloys like 317LMN, 6Mo SS, C-276 and alloy 59 for different FGD components.
- Depending on economics, some shifting will occur towards use of 0.187" or 0.250" solid alloy C-276 / alloy 59 plate material as opposed to wallpapering or roll clad for new construction.
- Use of wider and longer sheet/plates up to 96" wide for better fabrication due to less weldments which increases quality.
- In places where "wallpapering" will be used, use of heavier sheet such as 5/64" (2 mm), 3/32" (2.4 mm) or 1/8" (3 mm) as opposed to 1/16" (1.6 mm). Compartmentalization techniques for better inspection and repair.
- Use of improved fabrication and inspection techniques and greater emphasis on quality control and quality assurance during construction.
- The concept of insurability especially in Europe for FGDs.

- Investigations to improve fabrication and installation techniques (FRP materials, pre-assembled modular units, standardized designs).

Materials of Construction

Early FGD systems relied heavily on multiple absorbers and major equipment redundancy to meet SO_2 removal and availability levels that, by today's standards, are quite modest. As operating problems were resolved and process knowledge was gained, the need for new and higher quality materials became increasingly important, if overall reliability was also to be improved. Alloys gradually replaced linings in the severe wet/dry zones and eventually came into widespread use in the absorber and outlet ductwork. Early absorber linings over carbon steel exhibited a useful life of 8 to 14 years for rubber or polymer applications and required periodic maintenance attention.

Alloy	UNS#	Fe	Ni	Cr	Mo	Others	PRE*
317LMN	S31726	Bal	14	18	4.2	N	32
1925hMo	N08926	Bal	25	21	6.5	Cu, N	48
31	N08031	Bal	31	27	6.5	Cu, N	54
625	N06925	3	61	22	9	Cb	52
22	N06022	3	58	21	13	W	65
C-276	N10276	5	57	16	16	W	69
59	N06059	<1	59	23	16		76

Nominal Chemical Composition of Some Current FGD Alloys
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As a general rule for absorbers, 317LM or 317MN stainless steel, with a minimum of 4.25% molybdenum has proved to be the minimum quality for most applications, and indeed, has become the most cost effective alloy for systems up to 12,000-14,000 ppm chlorides. The duplex (24,000 ppm chlorides) or 6-7% molybdenum superaustenitic (30,000 ppm chlorides) stainless steels are suitable for intermediate ranges, while the nickel based alloys are the best choice for chlorides over 30,000 ppm.

Property	(Unoxidized) Calcium Sulfite	(Oxidized) Calcium Sulfate
Particle Sizing (%)		
Sand Size	1.3	16.5
Silt Size	90.2	81.3
Clay Size	8.5	2.2
Specific Gravity	2.57	2.36

Typical Physical Properties of FGD Scrubber Material
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Outlet ductwork conditions are always severe, even for a relatively low chloride system. The prudent material selection is one of the higher nickel based alloys, such as C22 or C276, using wallpaper or clad plate construction.

Retrofit site conditions have served to emphasize the need for high reliability. Because of the use of fewer and larger absorbers, extended outages for major repairs will not be possible without the risk of affecting annual SO_2 emissions unfavorably. Utilities would be wise to consider a conservative approach to material selection, recognizing that the cost differential between lower and a higher grade alloys is not as significant as it was a few years ago.

Alloy Trends

- Alloy C-276 and alloy 59 continue to be the preferred alloys for the critical areas of coal fired power plant FGD systems (wet/dry zone, outlet duct, mixing zone, damper seals, stack breaching, stack liner) and municipal and hazardous waste incinerator scrubbers.
- For less critical areas the increasing trend will be to use 6Mo alloys (absorbers and absorber internals, dampers) such as the standard 21% Cr, 6.5 Mo (1925hMo) alloys and the advanced 27 Cr, 6.5 Mo alloy (alloy 31).
- Alloy 317LMN will continue to have a greater share for the absorber tower, although the 6Mo alloys will begin to replace alloy 317LMN for higher reliability and assurance.
- Alloy 22 and alloy 625 will gradually fade away from the FGD industry, being replaced by alloy 59 & alloy C-276.

Physical Property	Dewatered	Stabilized	Fixated
Solids Content (%)	40 - 65	55 - 80	60 - 80
Specific Gravity	2.25 - 2.60	2.25 - 2.60	2.25 - 2.60
Wet Density (kg/m³)	1,460 - 1,780	1,460 - 1,780	1,540 - 1,860
Wet Density (lb/ft³)	90 - 110	90 - 110	95 - 115
Dry Density (kg/m³)	970 - 1,280	1,210 - 1,540	970 - 1,650
Dry Density (lb/ft³)	60 - 80	75 - 95	80 - 102

Physical Characteristics of Typical Calcium Sulfite FGD Scrubber Material
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<u>Dewatered Wet FGD material - sulfite sludge</u>

Physical Properties

FGD scrubber sludge is the wet solid residue generated by a wet scrubber. The scrubber absorber discharge is an off-white slurry with a solids content in the range of 10 to 20 percent.

Because FGD systems are usually accompanied by or combined with a fly ash removal system, fly ash is often incorporated into the FGD sludge.

Type of Coal	Sulfur Content	Type of Process	$CaSO_3$	$CaSO_4$	$CaCO_3$	Fly Ash
Bituminous	2.9 - 4.0	Lime	50 - 94	2 - 6	0 - 3	4 - 41
Bituminous	2.9	Limestone	19 - 23	15 - 32	4 - 42	20 - 43
Bituminous	1.0 - 4.0	Dual Alkali (Ca-Na)	65 - 90	5 - 25	2 - 10	0
Bituminous	2.0 - 3.0	Lime (Forced Oxidation)	0 - 3	52 - 65	2 - 5	30 - 40
Lignite	0.6	Fly Ash (Class C)	0 - 5	5 - 20	0	40 - 70
Subbituminous	0.5 - 1.0	Limestone	0 - 20	10 - 30	20 - 40	20 - 60

Major Components of FGD Scrubber Material from Different Coal Types and Scrubbing Processes (percent by weight)

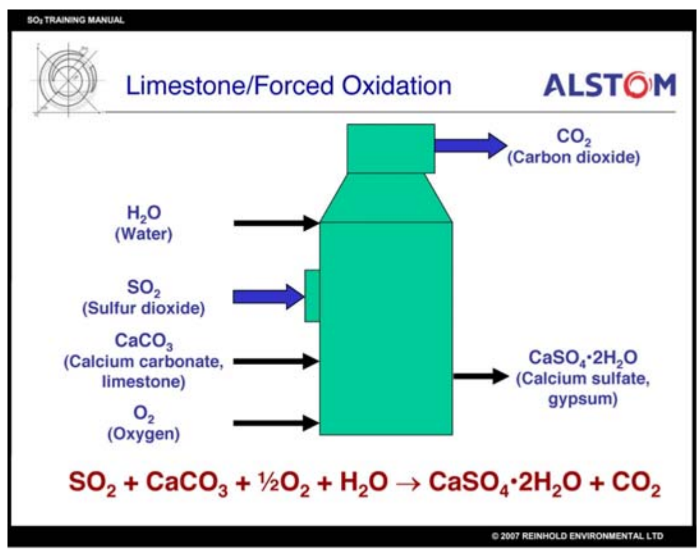
The relative proportion of the sulfite and sulfate constituents is very important in determining the physical properties of FGD sludges. Depending on the type of process and sorbent material used, the calcium sulfite (CaSO3) can contribute anywhere from 20 to 90 percent of the available sulfur, the remaining being calcium sulfate (CaSO4). FGD sludges with high concentrations of sulfite pose a significant dewatering problem. The sulfite sludges settle and filter poorly. They are thixiotropic and generally not suitable for land disposal or management without additional treatment (a thixiotropic material appears as a solid, but will liquify when vibrated or agitated). The degree to which FGD scrubber material is treated influences its physical properties. The basic physical properties of the FGD scrubber material include solids content, moisture content, specific gravity, and wet and dry density. When dewatered, the calcium sulfite FGD sludges become a soft filter cake with a solids content typically in the 40 to 65 percent range.

Calcium sulfate (gypsum) FGD sludges can be dewatered much more easily and may achieve solids contents up to as high as 90 percent after dewatering. Dewatered and unstabilized calcium sulfite FGD scrubber sludge consists of fine silt-clay sized particles with approximately 50 percent finer than 0.045 mm (No. 325 sieve). It has a dry density in the range of 960 to 1,280 kg/m3 (60 to 80 lbs/ft3), with a specific gravity of solids in the 2.4 range.

The figures to the right show the differences in typical physical properties (particle size and specific gravity) between calcium sulfite and calcium sulfate FGD scrubber material.

Forced oxidation

Forced oxidation, which is a separate step after the actual desulfurization process, involves blowing air into the tank that holds calcium sulfite sludge, and results in the oxidation of the calcium sulfite (CaSO3) to calcium sulfate (CaSO4). The calcium sulfate formed by this reaction grows to a larger crystal size than calcium sulfite. As a result, the calcium sulfate can be filtered or dewatered to a much drier and more stable material than the calcium sulfite sludge. Dewatering of FGD scrubber sludge is ordinarily accomplished by centrifuges, vacuum belt filters or filter presses.



Limestone/Forced Oxidation
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Stabilization and Fixation

Stabilization and fixation are terms that are often used interchangeably when referring to FGD sludge treatment. In general, stabilization of FGD scrubber material refers to the addition of a sufficient amount of dry material, such as fly ash, to the dewatered FGD filter cake so that the stabilized material can be handled and transported by construction equipment without water seepage and can also support normal compaction machinery when placed into a landfill. Stabilization is primarily the result of physical reactions between the FGD sludge cake and the added drying agent.

Fixation ordinarily refers to the addition of sufficient chemical reagent(s) to convert the stabilized FGD scrubber material into a solidified mass and produce a material of sufficient strength to satisfy applicable structural specifications. This can involve the addition of Portland cement, lime, and/or self-cementing fly ash to induce both physical and chemical reactions between the stabilized sludge filter cake and the added reagents. The majority of the fixation processes currently in operation involve the addition of quicklime and pozzolanic fly ash, resulting in a pozzolanic reaction that provides added strength to dewatered FGD scrubber material.

The solids contents of fixated FGD scrubber material ordinarily range from 60 to 80 percent. The specific gravity of fixated FGD sulfite scrubber material can range from 2.25 to 2.60, with an average of 2.38. Between 88 and 98 percent of the particles are in the silt size range. Depending on the amount of fly ash in the blend, maximum dry density values of fixated FGD scrubber material can range from 1,280 to 1,600 kg/m3 (80 to 102 lb/ft3) at optimum moisture contents ranging from 20 to 30 percent when tested using the standard Proctor (ASTM D698) test method.

Mechanical properties of typical calcium sulfite FGD scrubber material are shown in the figure to the right below.

Dewatered unstabilized calcium sulfite FGD scrubber sludges have a paste like consistency with low shear strength and little bearing capacity. They are thixiotropic, meaning that, when agitated, they revert to a liquid or slurry form. They have no unconfined compressive strength, an angle of internal friction around 20°, and a permeability in the range of 10-4 to 10-5 cm/sec.(9)

Stabilized or fixated calcium sulfite FGD scrubber material has unconfined compressive strength values in the range of 170 kPa (25 lb/in2) to 1380 kPa (200 lb/in2), an angle of internal friction of 35° to 45°, and coefficient of permeability values in the range of 10-6 to 10-7 cm/sec.(5)

SO_2 TRAINING MANUAL

Mechanical Property	Dewatered	Stabilized	Fixated
Shear Strength - Internal Friction Angle	20°	35° - 45°	35° - 45°
Permeability (cm/sec)	10^{-4} to 10^{-5}	10^{-6} to 10^{-7}	10^{-6} to 10^{-8}
28-Day Unconfined Compressive Strength (kPa)	- -	170 - 340	340 - 1,380
(lb/in^2)	- -	25 - 50	50 - 200

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Mechanical Properties of Typical Calcium Sulfite FGD Scrubber Material
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If stabilized or fixated FGD scrubber sludge is to be used for road base construction, then the unconfined compressive strength is more likely to be in the range of 1720 kPa (250 lb/in2) to as high as 6900 kPa (1,000 lb/in2), depending on specification requirements and reagent addition rates. The flexural strength of stabilized FGD sludge road base materials is normally in the 690 to 1,720 kPa (100 to 250 lb/in2) range. To achieve these strength ranges, additional fixation reagents (Portland cement, lime, fly ash, etc.) will usually be required.

Recycling

Stabilized or fixated calcium sulfite FGD scrubber material has been used as landfill liners and as an embankment and road base material. Stabilization or fixation of FGD scrubber material (especially calcium sulfite sludge) can be accomplished by the addition of quicklime and pozzolanic fly ash, Portland cement, or self-cementing fly ash. Other activators may be used in place of quicklime. The FGD scrubber sludge is dewatered before the addition of stabilization or fixation reagents. Additional fixation reagents may need to be added for stabilized base construction in order to meet compressive strength or durability requirements. Permeability values are critical for landfill liner applications

Oxidized (calcium sulfate) FGD scrubber material, once it has been dewatered, has been sold to wallboard manufacturers as by-product gypsum. This material has also been used as feed material, in place of gypsum, for the production of Portland cement. Oxidized FGD scrubber material (calcium sulfate) does not require fixation or stabilization for use as wallboard gypsum, but merely drying to a required solids content. Wallboard production represents the largest single market for forced oxidation FGD scrubber material.

Although there is significant interest in using calcium sulfate FGD scrubber material in wallboard construction and in Portland cement production (as a gypsum source), relatively small amounts of calcium sulfate FGD scrubber material are presently being recycled.

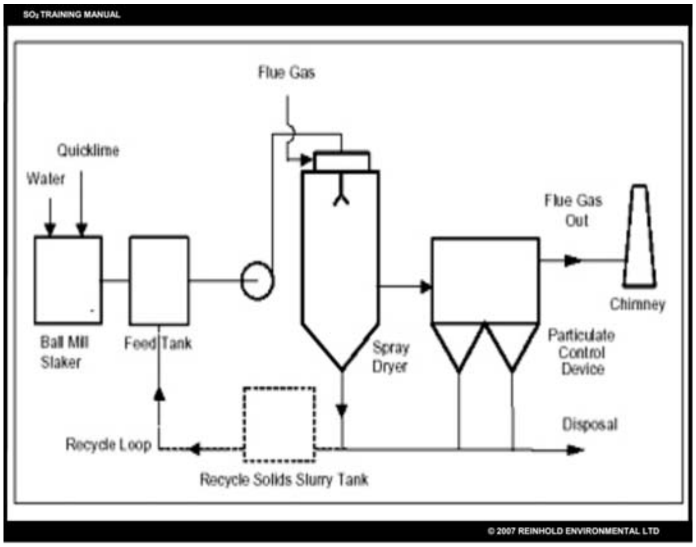
Disposal

FGD scrubber sludge can be disposed of in holding ponds or in landfills. Stabilization or fixation and placement in landfills are the most common methods of disposal. Stabilized or fixated calcium sulfite FGD sludge filter cake can have a solids content from 55 to 80 percent, depending on the amount of fly ash in the blend. The resultant fixated FGD sludge product is a damp, gray, silty, compactable material capable of supporting normal construction equipment and developing compressive strength.

Dry Scrubbers (Lime Spray Drying)

The term "Dry Scrubber" refers to the condition of the waste material leaving the scrubber. In the dry process, the dry waste material produced and the flue gas leaving the scrubber is not saturated with moisture.

Lime Spray Drying is typically used for the control of SO_2 emissions for sources that burn low to medium sulfur coal. Some issues that limit the use of spray dryers for high-sulfur coal applications include the potential impact of chloride contained in the coal on the spray dryer performance, and the ability of the existing particulate control device to handle the increased loading.



Dry Scrubber System Flow Diagram
Used with permission

Dry Scrubber Chemistry

The chemical reactions of the dry scrubber for SO_2 removal are:

$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 \bullet 1/2H_20 + 1/2H_20$

$Ca(OH)_2 + SO_3 + H_2O \rightarrow CaSO_4 \bullet 2H_2O$

$CaSO_3 + 1/2H_2O \rightarrow CaSO_4$

Dry Scrubber Operational Concerns

Quicklime is mixed with water in a ball mill slaker. This forms a slurry that can be in the range of 1 part lime to 4 parts water, for a 1% sulfur coal. However, the amount of lime to water ratio must be changed to compensate for changes in SO_2 levels in the flue gas. This particular piece of equipment requires a lot of attention from station operations, due to potential for overflow in the mixing bowls. After the slurry is mixed it is stored in a feed tank. The feed tank must be constantly agitated to prevent the slurry from solidifying.

Rotary atomizers are typically used to finely disperse the slurry into the flue gas. There have been problems with slurry buildup on the disperser vanes of the atomizers, which have caused forced outages to clean the disperser vanes. Also disperser motors often must be pulled for cleaning/ maintenance every few days, due to limitations on vibrations.

The amount of water fed into the spray dryer must be carefully controlled to avoid over saturation of the flue gas. There is a delicate balance required. If too much water is injected complete saturation of the flue gas occurs, which will affect the SO_2 removal process and complicate particulate collection downstream.

Some of the dry reaction product from the spray dryer is collected in the bottom of the spray dryer. From the bottom of the spray dryer this residue may be reused or disposed of. One concern is the hardening of any residue in the spray dryer hopper. In cases, this residue must be removed by extreme measures.

If an existing particulate control device is used on a dry scrubber it should be noted that the dry scrubbing process increases the amount of particulate in the flue gas. The downstream control device, (usually a baghouse), must be sized to accommodate the increased grain loading.

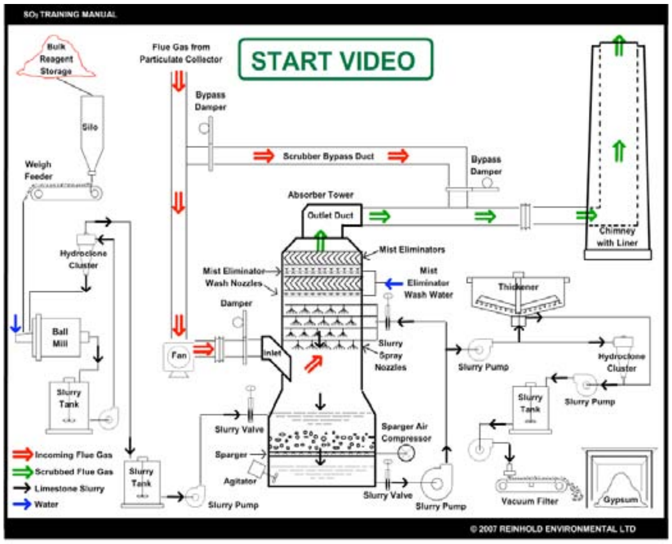
It should be noted that the dry scrubbing process increases the pressure drop in the combustion system, so fan capacity must be increased, usually requiring a booster fan or fan replacement. This increased pressure drop may require a complete structural review of the combustion system, and possibly structural reinforcement.

The installation of a dry scrubber will require additional plant personnel. As a minimum for a small plant site, one operator per shift would be needed.

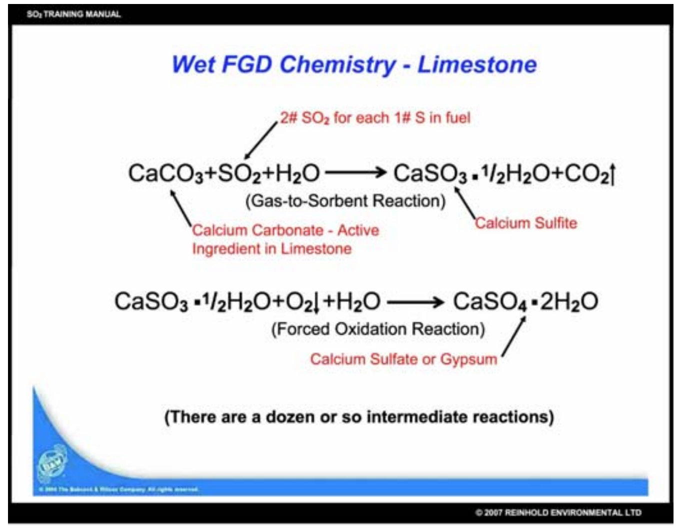
Generally, dry scrubbers are used on smaller units. The spray dryer size typically reaches a maximum at 300 MW, however it is possible to install multiple spray dryers to accommodate larger units.

There are usually some recycle pump liner problems, which can reoccur frequently.

CHAPTER 1 - WET SCRUBBER CHEMISTRY



Chapter 1 Summary
(Narrated by Ron Richard, RE Consulting)



Wet FGD Limestone Chemistry
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Calcium based processes have become more popular than sodium or ammonia based processes. There are important chemical and physical parameters that control the calcium based SO_2 removal process. Moreover, there are typical operating ranges for each parameter.

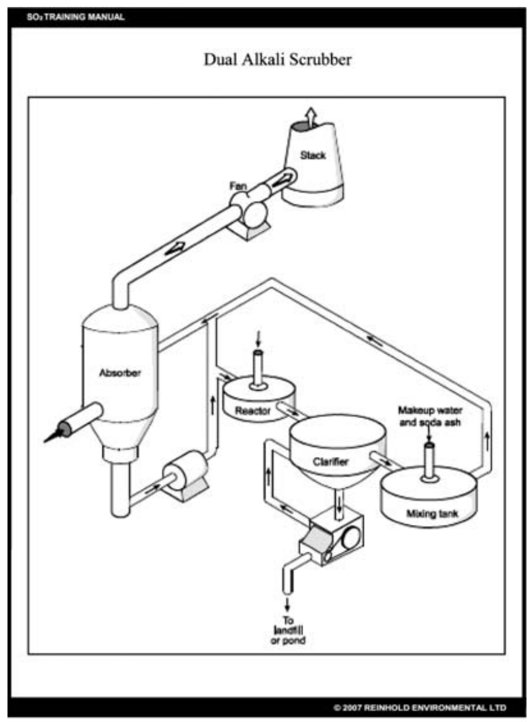
This chapter briefly discusses sodium and ammonia reagents, describes the sources and properties of the two main sources of calcium (lime and limestone) and highlights the physical and chemical differences between them. This chapter also identifies each parameter and the reasons why certain ranges have proven to be more effective.

1.1 Sodium and Ammonia Scrubber Reagents

The majority of scrubbers in service operate using calcium chemistry. This is not the only chemistry that can be used however.

Sodium

Sodium chemistry was one of the first chemistries to be used. Most sodium scrubbers use Soda Ash, Trona, or Nacolite as the source of the sodium. The sodium chemistry is very reactive and one of its advantages is high SO_2 removal. The other major advantage is that sodium compounds are soluble in water. This results in clear fluids circulating within the scrubber system. In comparison, the fluids in calcium based systems are slurries of solid particles that are abrasive and can settle out of solution causing plugging of equipment. The clear sodium solutions lead to long pump life and very little maintenance or cleaning of the absorber tower.Unfortunately, the clear sodium solutions are also the sodium scrubber's biggest downfall. The sodium sulfite, sodium bisulfite, and sodium sulfate reaction products are impossible to separate from the sodium hydroxide and sodium carbonate reagents. If a stream of liquid is bled off of the system to remove the reaction products, fresh reagent chemicals are lost also. At the cost of sodium hydroxide or soda ash, the addition of fresh chemical to replace that which is lost leads to high operating costs.



Dual Alkali Scrubber
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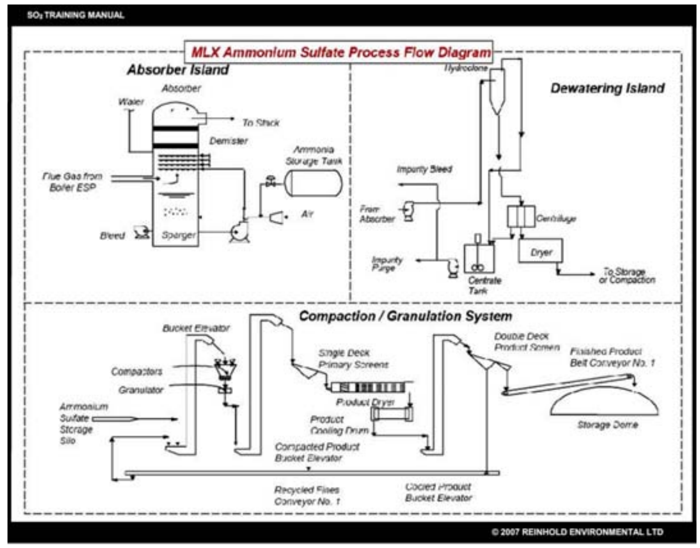
Dual Alkali scrubbing was developed in an effort to solve this problem with the sodium based process. The bleed stream of sodium chemistry is removed from the absorber tower. It is vigorously mixed with lime and then sent to a clarifier. Since the clarifier has a long retention time, the calcium can react with the sodium byproducts and convert them to calcium sulfite and calcium sulfate. The calcium byproducts are insoluble and settle to the bottom of the clarifier. The sodium liquid stream is drawn off the top of the clarifier and returned to the absorber tower. The calcium byproducts are drawn off the bottom of the clarifier and sent to a filter where the solids are filtered out and washed. The solids are then disposed of and the liquids from the filter return to the clarifier. This process was able to keep most of the sodium reagents in the scrubber process. But in real life, there was still enough sodium loss to make this process more expensive than the calcium based scrubber processes.

Today most sodium based processes are found in dry scrubbing in the western United States where the sulfur content of the coal is low and they are close to the natural deposits of trona and nacolite.

Ammonia

Ammonia can also be used as a scrubber reagent. There are always additional safety concerns when ammonia is stored and used in a process. The process is the same as sodium or calcium based systems.

The ammonia reacts with the SO_2 forming ammonium sulfite and ammonium sulfate. This part of the system is simple unless large amounts of ammonia are added to increase removal efficiency. At higher feed rates, some ammonia may escape the absorber tower and exit the chimney with the flue gas. This might be a problem depending on emission regulations.



Ammonia Scrubbing System Diagram
Used with permission from Marsulex

The major problem with this system occurs in separating the ammonium sulfite and ammonium sulfate crystals from the byproduct stream. The bleed stream typically passes through hydroclones and then centrifuges to concentrate the crystal slurry as much as possible. Then the slurry goes to a dryer to remove the water. The remaining dry material has value as a fertilizer product. But in order to be sold as a commercial fertilizer product, it must be granulated into a specific size range that is compatible with the custom fertilizer blending operations in today's farming market. The operating costs of the drying and granulating operations can be significant.

The economics of most ammonia scrubbing projects hinge on the revenue generated by the sale of the ammonium sulfate fertilizer byproduct. As a source of nitrogen, ammonium sulfate cannot compete with anhydrous ammonia or urea. Thus the sale of ammonium sulfate is in the niche market where the farmer needs both nitrogen and sulfur on the field and is willing to pay the additional cost for the ammonium sulfate product. Many ammonia scrubbing projects have not proceeded based on the uncertainty of price and demand for this product and thus the revenue stream to offset the higher operating costs.

There has been a new interest in ammonia scrubbing in some new processes that are designed to remove SO_2 and NOx in the same process. To date these processes are only in the pilot scale or demonstration size. Time will tell whether this is a future alternative. The economics of these processes also relies heavily on the sale of the ammonium sulfate fertilizer byproduct.

1.2 Lime - Scrubber Reagent

Lime scrubber chemistry

To use lime in the FGD process, the quicklime is fed into a lime slaker where it is reacted with water. The specifics of the lime slaking process are covered in the Chapter 2 - Lime Slakers. The reaction produces heat and a solution of calcium hydroxide ($Ca(OH)_2$). The calcium hydroxide is very reactive and readily reacts with the SO_2 in the flue gas.

Because lime is so reactive, the absorber towers and slurry recirculation pumps can be smaller in a lime process. This can save initial capital cost and lower pump power requirements and operating costs. However, since lime is manufactured from limestone, the delivered cost of lime to a site may be on the order of five times more expensive than limestone delivered to the same site. Thus the choice whether to use a lime or limestone FGD process usually hinges on the balance between lower capital and pump operating costs balanced against the lower cost of limestone consumed over the life of the unit. This decision is always very utility company and site specific.

Lime - source

Lime is a manufactured product. It starts with limestone ($CaCO_3$) being quarried and crushed. This limestone is then passed through a rotary kiln. The heat of the kiln drives the carbon dioxide (CO_2) from the limestone in a process known as calcination and leaves what is referred to in the industry as quicklime (CaO). Limestone deposits occur throughout the United States. Since there is a high demand for lime in various industrial processes, lime kilns also occur throughout the United States.

There will be sand and clay impurities in the limestone that will remain in the lime. If the kiln does not heat the limestone particles all the way through, there will remain a small kernel of limestone in the middle of the lime particles. These impurities and unreacted limestone will not be dissolved in the lime slakers and will be rejected as grit. This material must then be disposed of. If the temperature in the kiln gets too high, the lime can be "dead-burned" to some degree. Completely and purposely "dead-burned" lime products are sold as refractory materials. So it should come as no surprise that "dead-burned" lime isn’t very reactive, will not dissolve in the slaker, and will also be rejected as grit. Since lime is a manufactured product, it is important that samples be collected of incoming shipments for quality control and to identify the source of material that does not slake well.

Quicklime is very hygroscopic (it wants to absorb moisture from the air) so it must be stored in enclosed silos. It is shipped in bulk in covered dump trailers, pneumatic hopper trucks and railcars, and covered barges. When it attracts water, heat will be generated from the chemical reaction, and the material may also clump and become difficult to transfer out of the storage silos. Thus it is important to keep the quicklime as dry as possible during storage and handling.

High calcium pebble quicklime is normally used in FGD systems. This means the lime was manufactured from a high calcium limestone (one containing little magnesium carbonates) that was crushed to a ¼ to 2 inch size. This size material conveys and transfers pneumatically so there is no need to spend extra money to reduce its size in the manufacturing process.

There are a group of scrubbers that use the thiosorbic lime FGD process. All of the properties of the lime are the same as above except this lime is manufactured from a limestone that contains magnesium which produces 3% - 6% by weight of magnesium oxide (MgO) in the lime product. This magnesium oxide reportedly improves the SO_2 removal rate and improves other process parameters. Almost all of these scrubbers are located on the Ohio River were they can receive barge shipments directly from the lime plants that produce this product.

1.3 Limestone - Scrubber Reagent

Limestone scrubber chemistry

With lime scrubbing the carbon dioxide was driven from the limestone by calcination in the kiln. Then the calcium oxide was reacted with water in the slaker to form calcium hydroxide which reacts readily with the SO_2. With limestone scrubbing, calcium carbonate is entering the absorber tower. Calcium carbonate cannot react directly with the SO_2. For the limestone to react well it must be ground very finely to expose a lot of surface area and the pH in the tower must not be too high. Both of these items will be discussed in more detail in Chapter 3 - Ball Mills and Chapter 5 - Absorber Tower Fundamentals.

Weather Protected Limestone Storage
(Narrated by Tony Licata, Babcock Power)

First the limestone must dissolve in the weak acid formed by the reaction of SO_2 and water. The resulting reaction will release the carbon dioxide (CO_2) from the limestone. (You can demonstrate this reaction by taking a piece of limestone from a driveway and placing it in vinegar.) Once the limestone has dissolved and the carbon dioxide has been released, the calcium can react with the SO_2 to form calcium sulfite ($CaSO_3$) and calcium sulfate ($CaSO_4$).

These reactions occur slowly, so limestone absorber towers must be large to give the required residence time and the slurry recirculation flows must be high to give the required contact between the limestone slurry and the flue gas. To obtain the needed residence time, the absorber towers must be larger than those in a lime system which adds to the capital cost. To obtain the higher slurry recirculation flows, the recirculation pumps must be larger and more of them may be required. This adds to the capital cost and installation space required as well as to the operating cost since more pumping horsepower is connected to the electrical feed. These higher costs can be offset by the lower delivered cost of the limestone versus the delivered cost of lime. Most of the recent wet scrubbers have been designed using limestone. Limestone is found naturally throughout the United States. In some areas it is near the surface and is quarried in open pits. In other locations it is located more deeply and is quarried in underground mines. In most locations it is readily available at a reasonable cost.

Limestone was formed when sections of the continent were covered with water. Because of this the limestone formations occur in layers. The layers have different thickness and composition depending on the prevailing environment at the time that particular ledge was formed. Because of this it is not unusual to find a three foot ledge of limestone with a 95% calcium carbonate ($CaCO_3$) content sitting on top of a seven foot ledge of limestone with a 65% calcium carbonate content. When the limestone is being crushed for use as a fill material or a road base, this variation in composition is not a problem. Often in an open pit quarry, the thickness of the limestone ledges that are removed in one blasting operation is a function of the length of the drill available to bore the holes that are filled with explosives.

FGD limestone preparation is a "once-through" process. If the limestone is to be used as an FGD reagent, this wide range of calcium carbonate content variation (quality) is unacceptable.

Limestone - Source

One must think of the limestone as a source of calcium. The more limestone one must transport and grind to get one ton of calcium into the absorber tower, the more costly per ton of calcium that limestone will be. Because of that fact, an FGD operator would prefer to buy a limestone that has 95% or greater calcium carbonate composition.

But in the real world, it can be difficult to consistently obtain such a high quality stone from a near by quarry. The scrubber owner and the quarry operator must work together for the most cost effective solution. The quarry operator will need to map and analyze all the ledges in his quarry. Then a quarry plan must be developed to obtain the highest quality stone at a reasonable cost. This may completely change the operation of the quarry. A quarry may be used to drilling 20 foot deep holes and blasting. They may find that they will have to drill 7 foot deep holes and blast a high calcium ledge for FGD use. Then they may have to drill 4 foot deep holes and blast a lower calcium ledge that must either go to waste or be sold as fill rock for a construction project. Then they may be able to drill 12 foot deep holes and blast another ledge of high calcium stone for FGD use. When first approached, many quarry operators are reluctant to make such major changes to their quarry operation. Once they determine the steady limestone consumption of a large utility sized FGD system, they become more willing to selectively separate their products and work with the FGD owner.

Once one has determined the reasonably sustainable calcium carbonate percentage from each quarry and the transportation cost from each quarry, one can calculate the delivered cost per ton of calcium to see which supplier offers the best value at your particular site. In doing this, one must be careful about the magnesium content of the limestone. A few percent of magnesium carbonate in the stone isn't a big concern unless it occurs in the mineral form dolomite. The composition of dolomite is $CaMg(CO_3)_2$ which means that for each percent magnesium in the dolomite there is an equal percent of calcium in the dolomite. Dolomite is not very reactive and will not grind easily. So for evaluation purposes it is best to consider the calcium in the dolomite as unavailable for the FGD reactions. Thus if one has a limestone that has 96% calcium carbonate but also contains 3% magnesium in the form of dolomite, then there is only 93% calcium carbonate available for use. So the 93% calcium carbonate value should be used in calculating the delivered cost of each ton of calcium.

It is very important that the limestone quality that will actually be used in long term operation be known before the grinding system is designed. A discussion of limestone hardness, particle size, and Bond Work Index is covered in Chapter 3 - Ball Mills. Suffice it to say at this point that the grinding system is designed for specific limestone properties and FGD performance requirements. If a limestone of differing properties is added to that same grinding system, a radically different result may be obtained.

The limestone can be delivered in open trucks, railcars, or barges. It does not have to be protected from the weather. However, wet stone that is cold can freeze into large chunks in limestone feed silos and block material flow into the ball mills. So locations that have severe winter weather may want to store limestone in a building or other protected location to minimize the freezing problems.

Another consideration is the size of the stone. A more coarsely ground stone will not freeze into large chunks as quickly as a stone that is a smaller size and contains more fine particles. But switching to a larger feed size can affect ball mill performance.

1.4 pH

The most critical parameter to monitor in real time when operating a scrubber system is pH. The pH scale was developed as a measure of the acidity or alkalinity of a solution. Since it is a logarithmic scale, each whole number is ten times different than the whole number on either side of it. Absorber towers usually operate in the 5 - 6 range of the pH scale. So a tower operating at a pH of 6 has ten times more alkalinity than a tower operating at a pH of 5. This can fool an operator. A pH change from 5.3 to 5.6 seems to be a small change looking at the numbers, but represents doubling the alkalinity in the tower. Doubling the alkalinity can have a large effect on both the SO_2 removal and the amount of lime or limestone being fed into the tower.

Since pH is such a critical parameter, it is typically measured and recorded continuously with redundant instruments. Typically a bleed stream from a slurry recirculation pump discharge line is routed to a sample sink area. The streams discharge into the sink and the sink drain returns to the absorber tower. The pH electrodes are usually mounted in the sample pipe so the slurry stream flows over the end of the electrode. Most pH electrodes have a very fragile special porous glass bulb that takes the measurement. If the slurry flow is too slow past the bulb, calcium sulfite and calcium sulfate can precipitate on the bulb. This will foul the surface of the porous glass and give an incorrect measurement. If the slurry flow is too fast past the bulb, the solid particles in the slurry will erode the glass and the bulb will disappear causing the pH electrode to cease functioning. As the pH electrode ages, its reading may become inaccurate. There is one style of pH electrode that uses a porous wooden plug at the tip instead of the porous glass bulb. Some people have found the wooden tipped electrodes to be more rugged and have a longer life in scrubber conditions.

SO$_2$ TRAINING MANUAL

Substance	pH
Acid mine runoff	3.6 – 1.0
Battery acid	< 1.0
Gastric acid	2.0
Lemon juice	2.4
Cola	2.5
Vinegar	2.9
Orange or apple juice	3.5
Beer	4.5
Coffee	5.0
Tea	5.5
Acid rain	< 5.6
Milk	6.5
Pure water	7.0
Healthy human saliva	6.5 – 7.4
Blood	7.34 – 7.45
Sea water	8.0
Hand soap	9.0 – 10.0
Household ammonia	11.5
Bleach	12.5
Household lye	13.5

Some Common pH Values
Used with permission

If the pH reading is falsely high, you will be feeding less lime or limestone than is needed and the SO_2 removal will be less than required which could lead to an air emissions permit violation. If the pH reading is falsely low, the SO_2 removal may be higher than required and you will be over feeding lime or limestone which will increase operating expense and if it is bad enough, could lead to sulfite and sulfate scale formation on the tower internals.

With so much at stake, there are several prudent strategies to follow. It is a good idea to have two separate pH monitors on each tower. If both monitors are reading approximately the same value, it is more likely that the value is correct. If the values are different, then a reading can be taken using a portable pH meter or collecting a sample for a laboratory analysis. It is also a good idea to run at least one daily set of readings using the portable meter or collecting a laboratory sample to calibrate the pH electrodes. If you are having scaling issues with the pH electrodes, it is possible for both electrodes to become fouled at the same rate and the pH reading may drift erroneously but still agree with each other. The pH monitoring equipment requires constant and frequent maintenance.

The pH value is usually used in some manner to control the lime or limestone addition. The large reaction tank in the lower part of the absorber tower can act like a fly wheel. With such a large volume of slurry in the tank, a change in the inlet SO_2 may not cause a change in the tank pH for a significant period of time. Then once the pH starts to change, it may take a large change in the chemical feed rate to return the pH to its set point. It usually works better to use the inlet SO_2 monitor and the boiler load as the "feed forward" signals to the chemical feed valve. The valve should be immediately opened or closed in proportion to the amount of change in the inlet SO_2 value and/or the volume of flue gas being produced by the boiler. The pH value is then used as the "trim" signal to slowly adjust the valve position to obtain the desired tower pH value. This type of control scheme will minimize the swings that can occur in tower chemistry.

SO_2 removal changes with pH value. The slope of the curve is in the general direction of higher pH (more alkalinity) resulting in a higher percentage of SO_2 removal. The curve is not linear.

Lime Chemistry

Since the lime enters the absorber tower as the very reactive calcium hydroxide ($Ca(OH)_2$), it is simple to get high SO_2 removal by operating at higher pH values. Again real life intrudes with some practical limitations. At a pH above 6.3 the chemical equilibriums will shift to where calcium sulfite ($CaSO_3$) begins to precipitate out in the tower causing scaling problems and pluggage of the tower internals. Also since the pH scale is logarithmic, each 0.1 increase in the tower pH requires significantly more lime feed. The increased lime cost may not justify higher SO_2 removal. In light of these practical matters, most lime scrubbers operate in the pH range of 5.8 - 6.0.

Limestone Chemistry

Since the limestone enters the absorber tower as calcium carbonate ($CaCO_3$), it must first be dissolved before it can react with the SO_2. The slope of the dissolution curve is in the general direction of lower pH (more acidity) will dissolve the limestone more quickly. We now enter into the conflict between the two curves. A lower pH will cause the limestone to dissolve more quickly but will result in lower SO_2 removal. A higher pH will result in greater SO_2 removal but will make it difficult to dissolve the limestone which will increase limestone consumption. If you plot both curves on the same graph, the "valley" where the two curves cross is in the pH range of 5.2 - 5.4 for a natural or inhibited oxidation scrubber and in the pH range of 5.4 - 5.7 for forced oxidation scrubbers. So the most economical pH to operate a limestone scrubber is in the valley where the two curves cross.

Operating FGD systems tend to operate in the 5.2 – 5.7 range with the inhibited oxidation units operating in the lower end of this range and the forced oxidized units operating in the higher end of this range. However, if higher SO_2 removal is needed for short time periods, the pH can be increased with the only penalty being the higher limestone cost due to increased consumption.

Another interesting phenomenon with limestone is a "blinding" event that can take place during sudden large increases in inlet SO_2 or boiler load. This is most likely to happen to units that cycle up and down following load. It is most likely to happen on a Monday morning. The unit may have been set at 50% load all day Saturday and Sunday. Then on Monday morning the load increases rapidly to 100%. The symptoms of a "blinding" event are:

- The limestone feed valve is completely open
- The pH is staying the same
- The SO_2 removal efficiency is decreasing

The only way to stop this phenomenon is to close the limestone feed valve. The pH will remain the same even though no more limestone is being fed. After some period of time the pH will start to fall. When this happens, place the limestone feed control back on automatic and the system should return to normal operation. It is theorized that the sudden increase in calcium sulfite production due to the increased gas flow overwhelms the precipitation sites on the seed crystals of calcium sulfite in the tower. This causes the calcium sulfite to begin precipitation on the limestone particles. This may coat the limestone particles with calcium sulfite (like the outer sugar shell on a popular chocolate candy) preventing the limestone from dissolving. Once the limestone feed is discontinued, the increasing acidity in the tower dissolves this coating off the limestone particles and the reactions return to normal.

Pulp Density Scale
Used with permission from Motive Traction Pty Ltd.

1.5 Solids

Besides the dissolved materials in the scrubber liquid there are also solid particles. They consist of calcium sulfite crystals ($CaSO_3$), calcium sulfate crystals ($CaSO_4$), and in a limestone scrubber undissolved particles of calcium carbonate ($CaCO_3$). These particles serve specific purposes.

In a limestone scrubber, the limestone dissolves slowly as it reacts with the weak acid formed by the SO_2 combining with water. The lower portion of the absorber tower is designed to contain a large volume of slurry to give the liquid between six to ten hours of residence time before it moves out of the absorber tower into the primary dewatering process. A large volume of finely ground limestone particles presents the acid with a lot of calcium carbonate surface area to react with.

As the calcium sulfite and calcium sulfate concentrations reach their solubility limits in the absorber liquid, they begin to precipitate out of solution. They prefer to join an existing crystal making it grow in size. Having an abundance of small "seed" crystals in the tower helps this process and large calcium sulfite crystals and calcium sulfate crystals are grown. If there aren't sufficient "seed" crystals, some of the calcium sulfite and calcium sulfate will precipitate out on the tower internals forming a layer of scale which can aggravate corrosion issues and/or cause pluggage issues. Large chunks of scale have been know to break off causing damage to pump linings as they pass through the pumps and to lodge in the small openings of slurry spray nozzles plugging the nozzles and affecting tower performance.

In the early days, some of the absorber towers were designed to operate at 5% - 10% density. Experience has shown that it is better to operate the towers at 15% - 20% density. This gives a larger inventory of limestone particles and "seed" crystals. Less scaling problems occur at this higher density and larger crystals can be grown. There are two main drawbacks to higher density operation. The higher amount of solids in the slurry cause more erosion damage to pump liners, piping and spray nozzles. It also requires more pump horsepower to lift the more dense slurry to the spray elevations.

There are many different processes occurring simultaneously that affect tower density:

- The lime or limestone feed is introducing solid particles
- Crystals of calcium sulfite and calcium sulfate are growing as the lime or limestone is reacting with the SO_2
- The mist eliminator wash water (which contains few solids) enters the tower during mist eliminator wash cycles
- Flush water from mechanical seals and packing glands on pumps and mixers enters the tower
- A blow down stream of tower slurry is bled off to the primary dewatering process
- Low solids recycle water from the dewatering process is added to the tower.

Gypsum Particles
Used with permission from Babcock and Wilcox

The solids content in the tower is usually controlled via a simple control loop. A density meter measures the density of the slurry in the tower. This is usually a flow through device located on a sample stream that is coming from a slurry recirculation pump discharge pipe to a sample sink location. There are several styles of flow through density meters available in the market.

When the measured density exceeds the set point, a control valve is opened adding low solids recycle water from the dewatering process into the tower. As water is added to the absorber tower, the slurry level raises in the tower. A level control monitors the level and opens another control valve when the level exceeds the set point. This valve is usually located on a slurry recirculation pump discharge pipe. The slurry is routed to the primary dewatering process.

There have been occurrences of density monitor failures, water addition control valves sticking open, or mist eliminator wash valves sticking open. These occurrences can change the density in the tower. Due to the large slurry volume in the tower, the density doesn't change that quickly, but can move into an undesirable range during a single operating shift. Because of this, it is recommended that the operators take a manual density measurement on each tower at least once during their shift.

A manual density measurement is quick and easy to take using a pulp density meter. The sample bucket from the pulp density meter is filled with slurry from a sample sink stream or some other convenient sampling point. The bucket is then hung from the scale and the density value is read directly from the appropriate specific gravity band on the scale face. (Using this device will require that the laboratory measures the specific gravity of the tower slurry one time. This number will not change with time that much. So once you have a specific gravity value, you will know which band to use on the scale face.)

1.6 Oxidation

There are many definitions for the terms oxidation and reduction. A very simple definition will suffice when referring to scrubber operation. Oxidation is when oxygen is added to a material to chemically transform it into a different material. Reduction is when oxygen is removed from a material to chemically transform it into a different material.

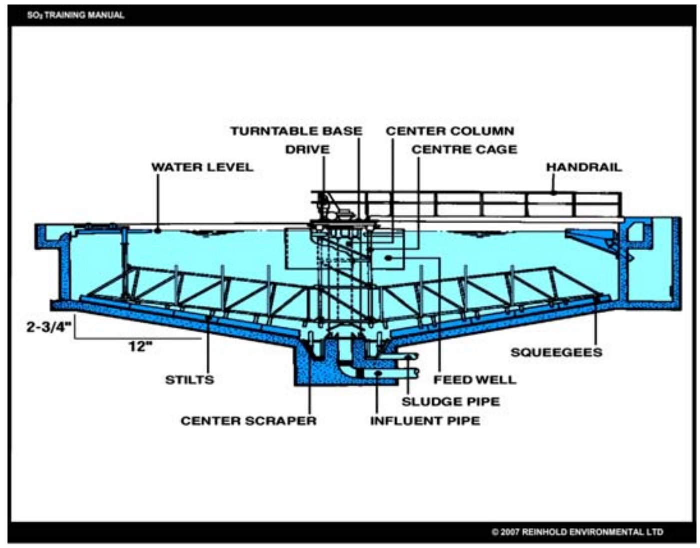
Natural Oxidation

In the scrubber reactions, calcium from the lime or the dissolved limestone reacts with the SO_2 to form calcium sulfite ($CaSO_3$). Once this has been completed, all the oxygen that was in the lime (CaO) or the limestone ($CaCO_3$) has been involved in the reactions and is accounted for. There is still extra oxygen in the flue gas. There is usually 3.5% - 4.5% excess air leaving the boiler as part of the normal combustion control practices. There is also leakage around air heater seals and through leaks in expansion joints. It would not be unreasonable to find 5%-6% oxygen in the flue gas entering the absorber tower. This oxygen can react with some of the calcium sulfite converting it to calcium sulfate ($CaSO_4$). When this occurs with just the oxygen normally found in the flue gas, the process is referred to as natural oxidation.

In early scrubbers it was not unusual to find 20%-40% of the calcium sulfite converted to calcium sulfate through this process. It was soon discovered that there were problems due to the crystal structure of the co-precipitated solid mixture. Pure calcium sulfite crystals are dense flat thin plates that under a microscope look a lot like pieces of broken window glass. Pure calcium sulfate crystals are dense hexagonal rods that under a microscope look a lot like pieces of a broken pencil. However the crystal that was formed by both shapes trying to grow at the same time in the same place has been described as a spiny ball or a porcupine ball.

This open and fragile structure led to several problems. The spiny balls were very fragile. As they continually passed through the slurry recirculation pumps, the mechanical stresses from the pump impellers and slurry spray nozzles broke the crystals into small fragments. The crystals that were not broken contained a lot of liquid due to all the voids in the crystals and the liquid captured by surface tension between the spines.

The primary dewatering process at the time involved thickeners. A thickener is a large diameter tank with a conical bottom and some sort of rotating rake that moves the settled material along the sloped bottom and out a center drain pipe. Its operation depends on the density of the crystalline material to cause it to settle to the bottom in the quiet volume of liquid. The remaining clear liquid overflows around the top edges of the vessel while the settled solids are removed through the bottom drain pipe. Chemicals called flocculants may be added to help attract the solid particles and form larger particles that settle more quickly.



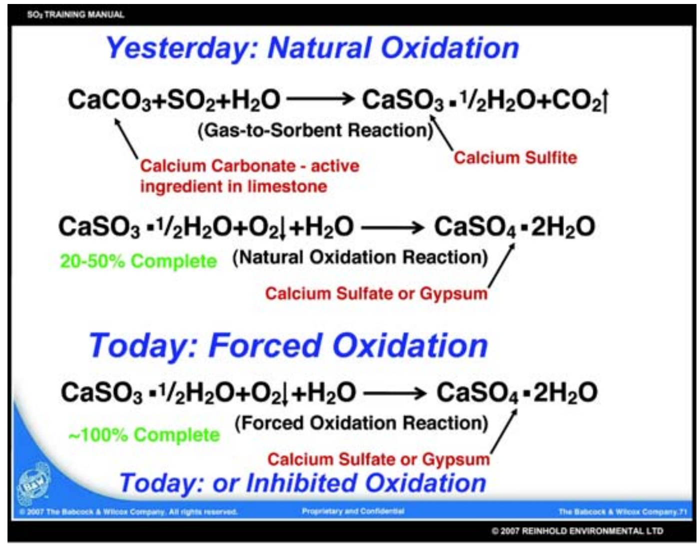
Thickener - Mechanical Diagram
Used with permission from Dorr-Oliver (GL&V)

The large amount of liquid trapped in the spiny balls caused them to have almost the same density as the bulk liquid. The small broken fragments of crystals were also very light weight. This caused the thickener to not operate very well. Large amounts of flocculants had to be added to make the materials settle. The liquid overflowing the top of the thickener was very turbid. The material exiting the bottom of the thickener still contained a lot of liquid.

Another problem in the absorber tower occurred because the precipitating calcium sulfite and calcium sulfate had a difficult time attaching themselves to the abnormal crystal matrix. This caused much of the material to end up precipitating on the tower internals forming a layer of scale which can aggravate corrosion issues and/or cause pluggage issues. Large chunks of scale have been known to break off causing damage to pump linings as they pass through the pumps and to lodge in the small openings of slurry spray nozzles plugging the nozzles and affecting tower performance. Mist eliminator scale formation that restricted flue gas flow through the absorber was also a common problem with early FGD installations.

The Electric Power Research Institute funded a study that determined that if the amount of oxidation could be kept below 18% (Inhibited Oxidation) pure calcium sulfite crystals would form, or if the amount of oxidation could be kept above 95% (Forced Oxidation) pure calcium sulfate crystals would form.

Inhibited Oxidation



Oxidation - Natural vs. Forced
Used with permission from Babcock and Wilcox

A way was needed to inhibit the extra oxygen that was entering the absorber towers with the flue gas from oxidizing the calcium sulfite. It was known that sodium thiosulfate (Na2S2O$_3$) was a reducing agent that could inhibit the oxidation of calcium sulfite to calcium sulfate. It was fed into absorber towers in concentrations of several hundred parts per million (ppm) but the results were not that effective. Due to the cost of sodium thiosulfate, it was too expensive to feed it in higher concentrations. So the idea was dropped.

Then Dr. Gary Rochelle at The University of Texas theorized that if elemental sulfur was ground into a colloidal suspension and added into an FGD system, the natural reactions with the scrubber chemistry would produce thiosulfate. This was tried at a full sized scrubber operation and found to be true.

Due to the low cost of colloidal sulfur, the concentration of thiosulfate could be raised. It was found that at concentrations of several thousand ppm, the calcium sulfite oxidation was inhibited. The co-precipitate crystals were replaced by the dense flat calcium sulfite crystals. This caused the scaling problems in the absorber towers to become minimal. It also allowed the solids to settle easily in the thickeners and the entire dewatering process was greatly improved.

The calcium sulfite took the form of the hydrated crystal $CaSO_3 \cdot ½ H_2O$. A substantial number of FGD system operators converted their systems to inhibited oxidation operation.

Forced Oxidation

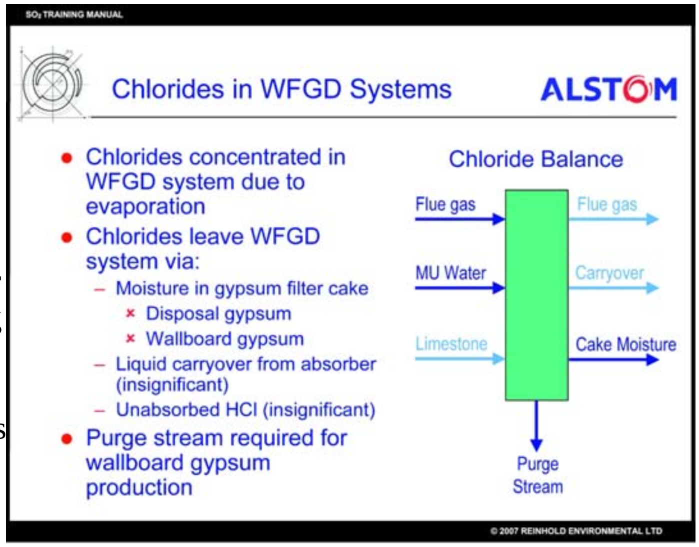
The other option that was available was to add enough oxygen to the absorber towers to oxidize most of the calcium sulfite to calcium sulfate. This was accomplished by blowing air through the scrubber slurry. Usually two to three times the theoretically required air was used. The details of this process are covered in the later "Oxidation Air" section.

Once the slurry was sufficiently oxidized, the co-precipitate crystals were replaced by the dense hexagonal columnar calcium sulfate crystals. This caused the scaling problems in the absorber towers to become minimal. It also allowed the solids to settle easily in the thickeners and the entire dewatering process was greatly improved.

The calcium sulfate took the form of the hydrated crystal $CaSO_4 \cdot 2H_2O$ which is more commonly known as gypsum. Gypsum is used extensively in the construction industry. One of the more common products is the wall board (sheet rock, dry wall) that is used in most buildings today. It was demonstrated that the FGD generated gypsum could be used in the wall board manufacturing process in place of the naturally occurring gypsum that was being mined. Because of this, most of the newest FGD systems are being designed using the forced oxidation process. If the generating station is in a favorable geographic location, it can sell the gypsum produced and receive an additional revenue stream that helps offset the operating costs of the FGD system. This is discussed in more detail in the later "Byproduct Handling" section.

1.7 Chlorides/Fluorides

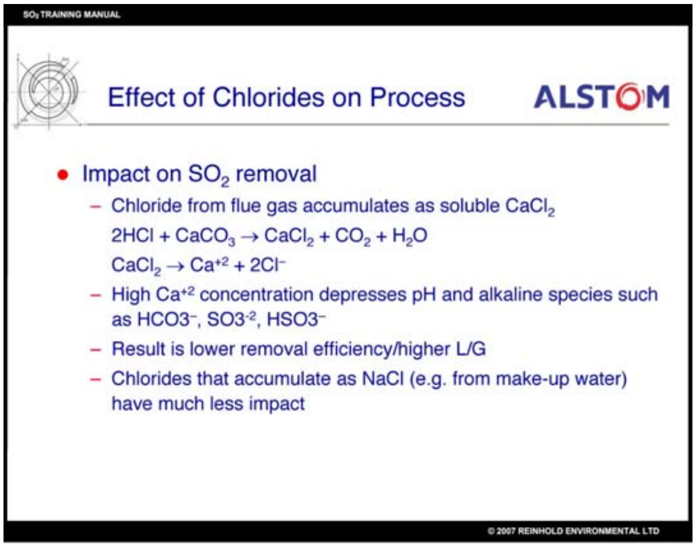
There is nothing beneficial about having chlorides or fluorides in a scrubber system. There are however no means to not have them in a system. All coal contains some chlorine and fluorine. The amount varies in different parts of the country and in different coal seams in the same part of the country. Coal purchases are typically based on delivered price, heating value, and sulfur content. The scrubber operator just has to adjust according to the coal being supplied.



Chlorides in Wet FGD Systems
Used with permission from Alstom

In the combustion process the chlorine and fluorine is converted into hydrogen chloride (HCl) and hydrogen fluoride (HF). These gases are part of the flue gas that enters the scrubber. A wet scrubber will very efficiently remove these gases. The total amount of chlorides and fluorides is small compared to all the SO_2 being removed.

The problem occurs because the chloride and fluoride compounds are water soluble. The sulfites and sulfates precipitate and are removed from the system. As dewatering processes have improved, less liquid is lost from the system. Due to gypsum quality specifications, gypsum is washed on the filter belt to remove most of the chlorides it contains. Since all of this liquid is recycled into the scrubber process, the levels of chlorides and fluoride continues to concentrate to very high levels.



Effect of Chlorides on Process
Used with permission from Alstom

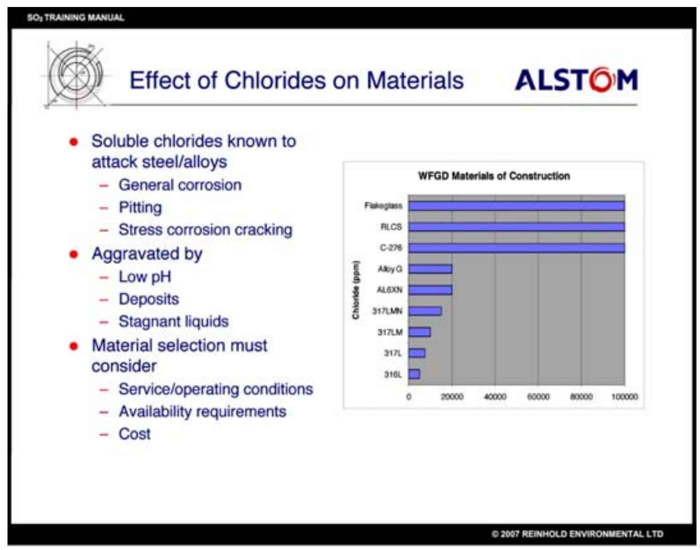
Fluorides

The fluoride concentrations are typically in the range of 10% of the chloride concentrations. This has to do with the ratio of fluorine and chlorine in most coals. Fluoride can cause corrosion issues with various metals. Since the fluoride concentration is much lower than the chloride, the chloride levels are used in selecting the materials of construction. It is not necessary to analyze the scrubber liquids for fluoride concentration on a routine basis.

The biggest problem with fluorides occurs if they react with fly ash in the scrubber tower. Fly ash contains aluminum. The aluminum fluoride (AlFx) compounds that form can cause limestone blinding. There is no way to prevent this blinding or reverse the blinding if these aluminum fluoride compounds are present. The best means of prevention is to keep the amount of fly ash entering the scrubber tower to a minimum through proper precipitator operation and maintenance.

Chlorides

The biggest problem with chlorides is the corrosion issue with most metals. The materials of construction in the entire FGD process must be chosen with the typical and maximum chloride values expected in the process constantly in mind. This means the typical coals that will be burned must be known during the design process. If other coals are purchased later, care must be taken to determine what effect they will have on chloride levels in the scrubber system. A more detailed discussion on chloride values and materials of construction selections based on these values will occur in Chapter 7 - Materials of Construction.



Effect of Chlorides on Materials
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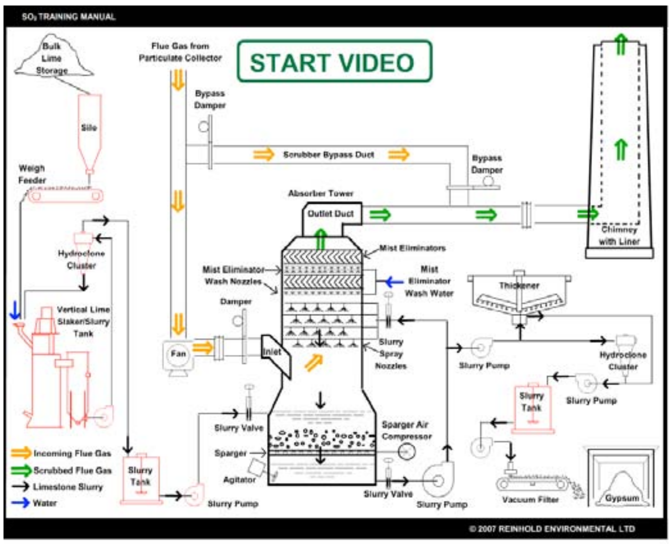
Chloride levels build up over a period of time. It is sufficient to collect weekly samples of FGD liquids to determine the chloride concentrations. The chloride concentrations should then be compared against the allowable concentrations based on the materials of construction used in the system. The only way to lower chloride concentrations is to remove liquid from the FGD process and replace it with fresh water. This is best done with a small continuous bleed stream that will not upset the chemistry cycle in the system.

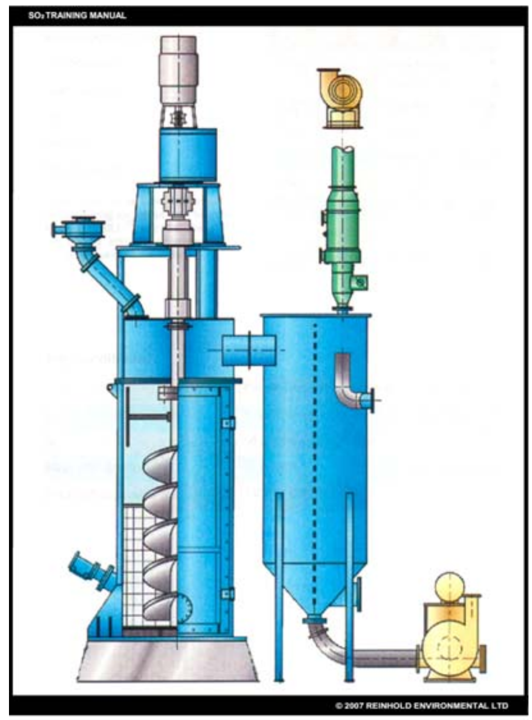
The treatment of this bleed stream will depend upon site conditions and environmental permits. At some locations this stream can be routed into an ash pond without detrimental affects on the NPDES properties of the ash pond discharge. At other locations, the liquid may need to be evaporated and the remaining solids disposed of properly.

Another impact of chlorides can occur in the area of SO_2 removal. The removal relies on soluble alkali materials reacting with the SO_2. This is predominantly calcium but can also be magnesium that was in the lime or limestone. At lower levels of chlorides, the chloride reacts with the magnesium to form magnesium chloride ($MgCl_2$). At higher chloride levels, the calcium begins to react to form calcium chloride ($CaCl_2$). Once the chloride has reacted with the alkali material, it is no longer available for use in SO_2 removal. This results in more lime or limestone being fed to maintain pH and removal efficiency. More chemical being fed results in a higher operating expense.

CHAPTER 2 - LIME SLAKERS



Chapter 2 Summary
(Narrated by Ron Richard, RE Consulting)



Ball Mill - Vertical Lime Slaker
Used with permission from Metso Minerals

Lime slakers are used to convert dry quicklime powder into a liquid reagent capable of removing SO_2 in the absorber tower. Lime is typically delivered to generating stations as pebble quicklime. This is calcium oxide (CaO) in the size range from powder to pieces larger than one inch in diameter. This dry material must be chemically reacted with water to form a fine slurry of calcium hydroxide ($Ca(OH)_2$). This is done in a lime slaker.

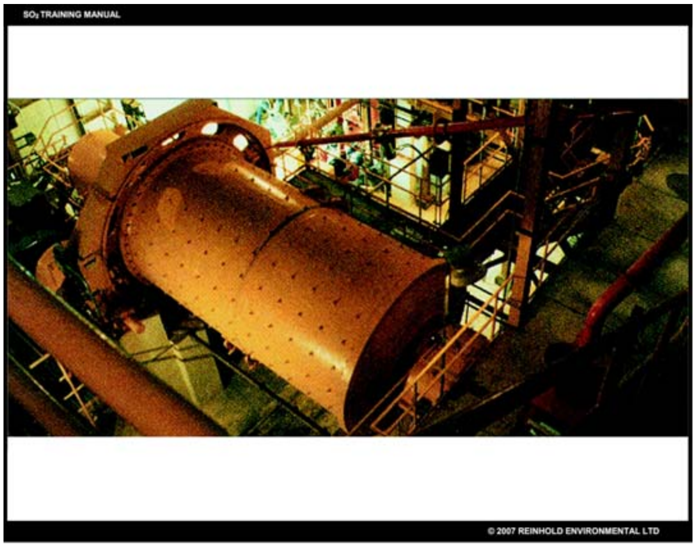
There are three major types of lime slakers:

- Slurry detention slakers
- Paste slakers
- Ball mill slakers

Most utility installations use ball mill slakers, so that is the only type of slaker that will be discussed.

This chapter discusses how to operate a ball mill slaker to optimize this chemical conversion which in turn maximizes the amount of SO_2 removed for each ton of lime consumed.

2.1 Lime Slaker Ball Mills



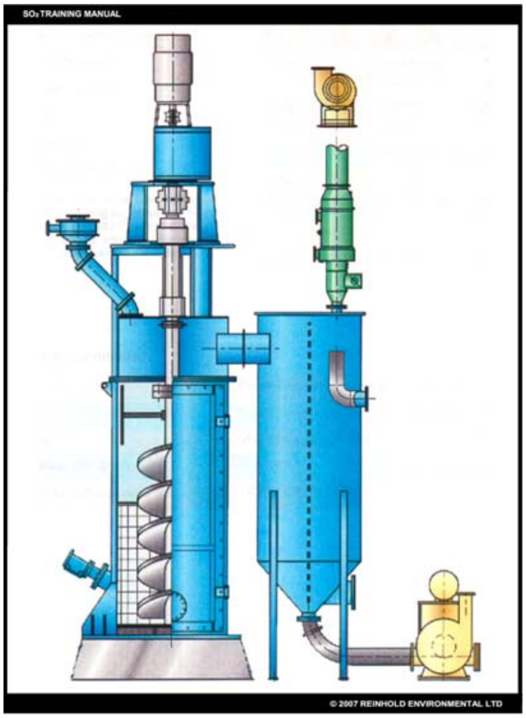
Ball Mill - Horizontal
Used with permission from Metso Minerals

Lime Slaker ball mills have several advantages for utility operations. Many utilities have experience with ball mills for grinding coal. Ball mill slakers can handle the larger tonnage per hour requirements of a large utility unit. Lime contains a large amount of inert material (silicates, unburned limestone, clays) which are called grit, which are rejected by the slurry and paste slakers and must be disposed of. The ball mill slaker can grind the grit until it is fine enough to pass through the scrubber process. Therefore the ground grit leaves in the final scrubber byproduct and no removal and separate disposal is required. The tumbling balls also supply the agitation needed to thoroughly mix the quicklime and water.

The slaking process works best if the final temperature of the product slurry is near 210°F. This can be controlled by varying:

- the quicklime feed rate,
- the water to lime ratio, or
- the inlet water temperature.

It works best if the quicklime feed rate and the inlet water temperatures are held constant and the lime to water ratio is adjusted to control temperature. The inlet water temperature should be at least 150ºF. Fresh water is typically used since the slaking reaction can be adversely affected by sulfites and sulfates in the water. The lime to water ratio can vary from a 1 to 3 ratio to a 1 to 5 ratio. The slaking reaction is exothermic which means it gives off heat. Excess water will absorb some of the heat. That is why varying the ratio will control the final slurry temperature. In real life, the slaker operating temperature is controlled to about 185ºF.



Ball Mill - Vertical Lime Slaker
Used with permission from Metso Minerals

2.2 Lime Slaker Hydroclones

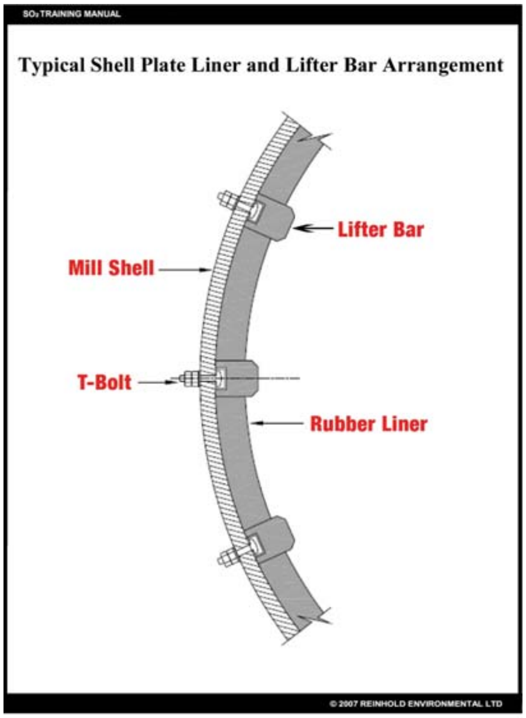
The oversized grit and unreacted quicklime will be separated by the hydroclones and returned to the ball mill for further grinding and slaking. It is important that the correct number of hydroclones are in service. Most hydroclone installations have several installed spares. The separation of particles by size is based on velocity in the vortex and the size of the apex opening. If all the installed hydroclones are placed in service, the velocity in each will be lower and the size separation will change. Also, if an apex of a hydroclone becomes plugged, all the slurry will be forced out of the top which will introduce oversize material to the final product stream. So the hydroclones should be checked several times per shift to assure that proper flow is coming from the bottom apex of each.

Hydroclone
Used with permission from Cavex (Weir Slurry Group Inc.)

2.3 Lime Slaker Ball Mill Performance

It is best to run a ball mill at a specific capacity and cycle it on and off as needed to maintain product tank level. If you lower the quicklime feed and water addition, you still have the same motor horsepower being supplied to the mill. This horsepower must be converted into work. If the mill does not have as much quicklime to grind, it will start grinding the rubber linings, lifter bars and mill balls. This will increase the operating and maintenance costs on the mill.

There are two critical items in maintaining proper ball mill performance. When the ball mill is operating with a full charge of mill balls, the motor amperage should be read and recorded. This is the target amp reading. As this amp reading drops over time, additional mill balls should be added to return the amp reading to the target and to maintain full grinding capacity. Ball addition could happen as frequently as weekly. Typically, one or two 55 gallon drums (1 ton of balls per drum) of mill balls are added at a time. If the amp readings are low, a coarser product is being produced by the mill.



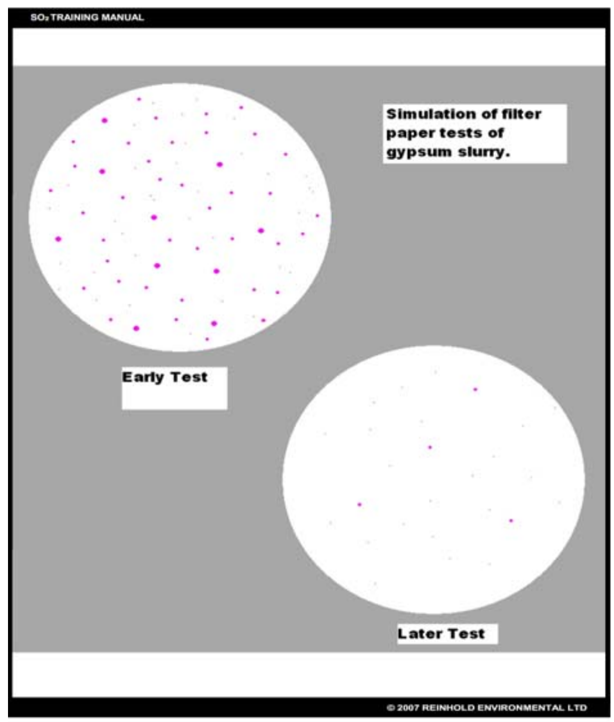
Typical Shell Plate
Used with permission

The other item is lifter bars. The lifter bars protrude out into the mill past the rest of the rubber lining. Their job is to raise the mill balls to a higher elevation and then drop them back into the grinding area. This impact helps to break up the larger particles in the mill. In a year or so, the square profile of the lifter bars can become rounded from wear. This allows the mill balls to roll off at a lower elevation which reduces the impact. Lifter bars may need replacement every year or two depending on the hours of mill operation. Often the lifter bars can be removed one time, rotated 180º and then be reinstalled. This puts a new square profile in the lifting position. There are also some lifter bars with embedded hardened metal corners which will provide a longer life before needing to be replaced.

2.4 Real Life Example of Why Lime Slaker Temperature is Important

Real Life Example

One lime FGD system had been operating for several years. It always had a low slaker operating temperature. This was because the source of fresh water to the slaker came from a location in the station where the water temperature varied with the river temperature. The slaker temperature was marginal in the summer and terrible in the winter. This problem had been brought to the attention of the station several times, but to change the source of the water or to heat the water would require a large expenditure. Since there were no other issues based on the current operation, no one saw a problem.



Filter Paper Diagram
Used with permission

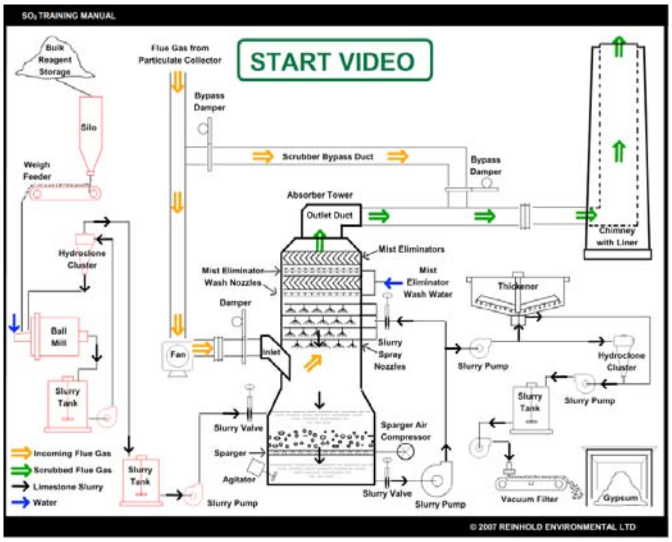
The FGD system was converted to produce the sale of wallboard quality gypsum. After the normal period of start-up and checkout, a problem became apparent. The purchaser of the gypsum started complaining of high pH in the gypsum. If the gypsum was sampled coming off the belt filter, the pH was within specification. After the gypsum had been loaded on a barge, delivered to the purchaser, and sampled during the unloading, the pH was higher than the specified maximum. Sources of contamination from the barge and other issues were investigated. Nothing was found and the problem persisted. Acid was added to the belt filter wash water in an attempt to lower the pH, but to no avail. One of the lab personnel had an idea. Some of the gypsum slurry was filtered using a laboratory filter disk. The filter paper was then sprayed with a solution of phenolphthalein which is a pH indicator that is colorless below a pH of 8.2 and turns bright pink at a pH above 10. After several minutes there were numerous small bright pink dots of various sizes on the filter paper. Each time the test was repeated with different samples over several days, the results were very similar.

The only logical explanation for these small areas of pH above 10 was that small particles of unreacted quicklime had survived the several day journey through the entire scrubber process. They were then slowly reacting with the moisture in the gypsum on the barge and raising the pH of the entire gypsum shipment.

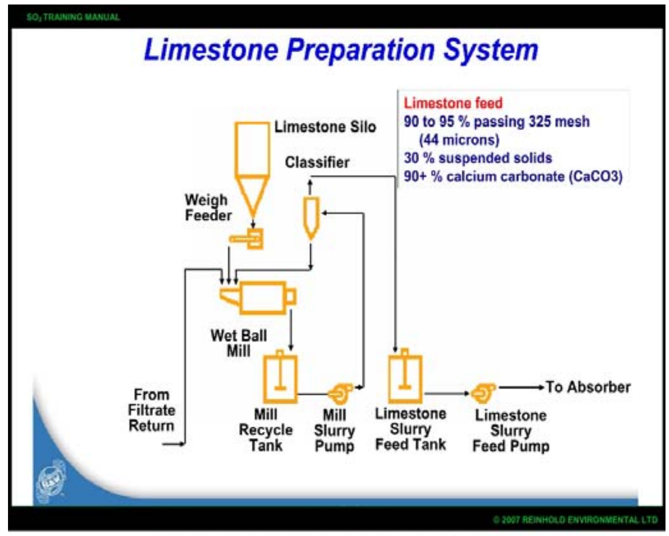
Attention focused back to the slaker and the low operating temperature which would be the obvious cause of incomplete slaking. A small package boiler was obtained to heat the slaking water for a test. The water was heated and the slaker controls were adjusted to obtain a slaker operating temperature in the 185ºF – 195ºF range. After several days of proper operation, the laboratory tests were run again on the gypsum slurry samples. The numbers of bright pink dots were significantly less and the size of the dots were significantly smaller.

Permanent arrangements to heat the slaking water were made and the gypsum pH problem did not return.

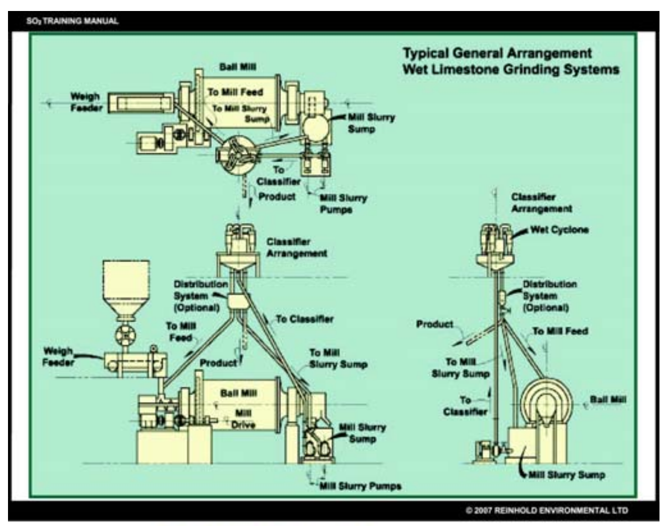
CHAPTER 3 - LIMESTONE BALL MILLS



Chapter 3 Summary
(Narrated by Ron Richard, RE Consulting)



Limestone Preparation System
(Narrated by Greg Bielawski, The Babcock & Wilcox Co.)



Ball Mill - Typical Arrangement
Used with permission from Metso Minerals

Limestone does not react quickly with SO_2. In order to use limestone efficiently in a scrubber, it must be ground to extremely small particles that have an enormous surface area. Ball mills are used to wet grind limestone to the desired particle size. There are horizontal and vertical models. Most systems use the horizontal model.

This chapter discusses the design and operating factors that determine how well a ball mill will reduce the limestone to the desired particle size. It also discusses the normal operating and maintenance practices that must be followed to consistently produce the desired particle size on a continual basis.

3.1 Limestone Ball Mill Design

Originally FGD process designs specified that the limestone was ground so that 80% passed through a 200 mesh (74 micron opening) sieve. Then it was decided that scrubbers worked better if the limestone was ground so that 80% passed through a 325 mesh (44 micron opening) sieve. Today, most specifications call for a product where 90% - 95% passes through 325 mesh sieve. The holes are so small in a 325 mesh sieve that it looks more like a sheet of wax paper across the bottom of the sieve. As was discussed in the previous Limestone Section 2.1, the limestone must react with the weak acids in the absorber tower to release the CO_2 from the calcium carbonate ($CaCO_3$) thus enabling the calcium to react with the SO_2. The smaller the ground limestone particles are sized, the more total surface area of calcium carbonate is exposed to the weak acids. Also there will be a greater possibility that most of the limestone particles will dissolve completely before leaving the absorber tower to enter the primary dewatering area.

Size of mesh opening

Mesh	Micron	Inches
4	4760	0.185
6	3360	0.131
8	2380	0.093
12	1680	0.065
16	1190	0.046
20	840	0.0328
30	590	0.0232
40	420	0.0164
50	297	0.0116
60	250	0.0097
70	210	0.0082
80	177	0.0069
100	149	0.0058
140	105	0.0041
200	74	0.0029
230	62	0.0023
270	53	0.0021
325	44	0.0017
400	37	0.0015
625	20	0.0008
1250	10	0.0004
2500	5	0.0002

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Mesh Size
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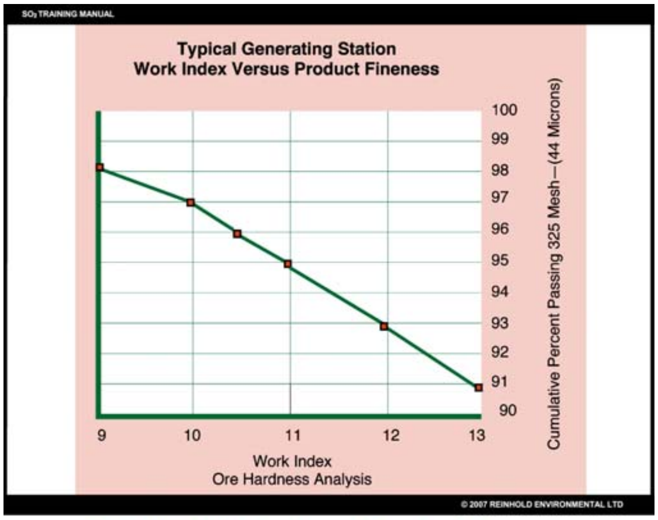
When designing a ball mill, several parameters must be known

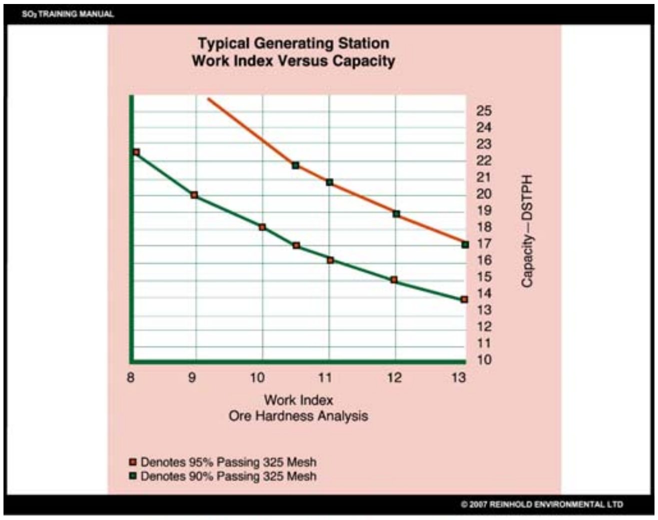
- The hardness of the limestone to be ground (Bond Work Index)
- The size range of the limestone particles that will be entering the ball mill
- The size range of the desired product leaving the ball mill circuit
- The feed rate (tons/hour) of limestone entering the ball mill

Testing Sieves
Used with permission

The Bond Work Index testing determines how much energy per ton is required to grind the limestone to the desired size. The limestone with the highest Bond Work Index should be used for the design. The tons per hour feed rate multiplied by the energy required per ton determines the horsepower of the ball mill motor.



Ball Mill - Work Index vs. Product Fineness
Used with permission from Metso Minerals

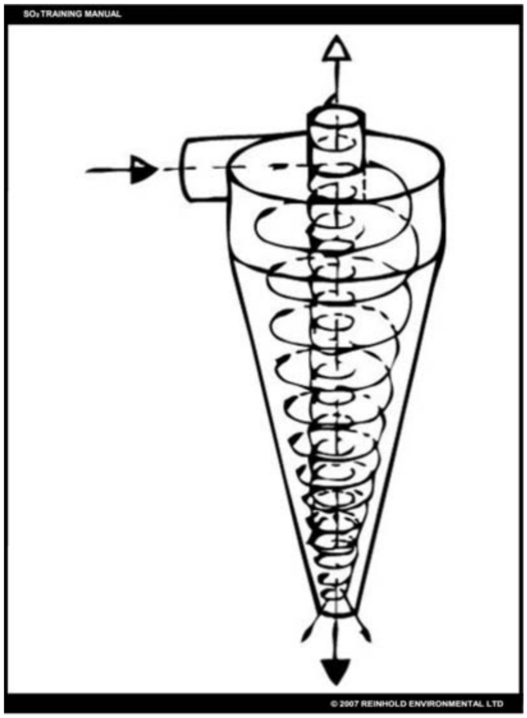


Ball Mill - Work Index vs. Capacity
Used with permission from Metso Minerals

3.2 Limestone Slurry Hydroclones

Hydroclone
Used with permission from Cavex (Weir Slurry Group Inc.)

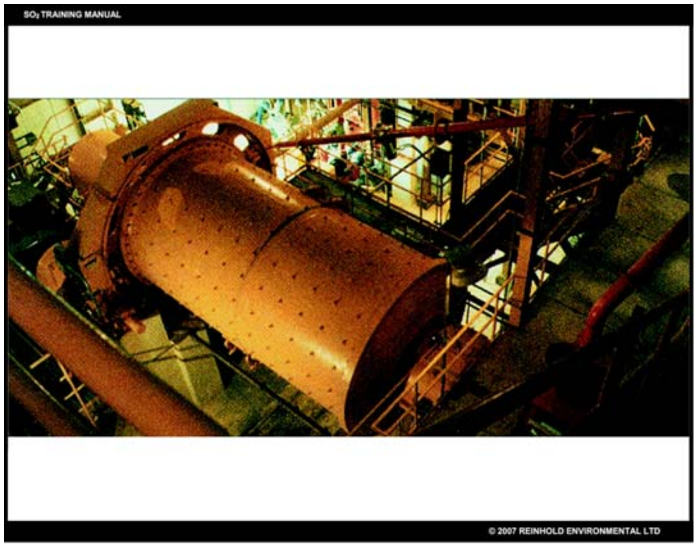
In the ball mill cycle, the oversized limestone particles that are in the slurry leaving the grinding compartment are separated by the hydroclones and returned to the ball mill for further grinding. It is important that the correct number of hydroclones are in service. Most hydroclone installations have several installed spares. Hydroclone operation relies on constant inlet pressure to provide consistent product separation through fixed opening sizes. The separation of particles by size is based on velocity in the vortex and the size of the apex opening. If all the installed hydroclones are placed in service, the velocity in each will be lower than designed and the size separation will change. Also, if an apex of a hydroclone becomes plugged, all the slurry will be forced out of the top which in turn will introduce oversize material to the final product stream. So the hydroclones should be checked several times per shift to assure that proper flow is coming from the bottom apex of each.



Hydroclone Flow Path
Used with permission

A plugged hydroclone should be the first thing one suspects if there is indication of increasing particle size in the ball mill product. Each hydroclone should be disassembled at least once a year to check on the condition of the rubber lining inside the hydroclone. The apex is usually fabricated from a ceramic material because of the high erosion potential. The hole in the apex should be checked to see that it is still the correct diameter. If not, the apex should be replaced. The size of the hole in the apex influences the size split between the underflow (reject stream) and the overflow (product stream) in the hydroclone. If a permanent change needs to be made to adjust the particle size of the final limestone slurry, some adjustment can be made by replacing the apex pieces with new ones with larger or smaller holes. It might be best in this case to work with the hydroclone vendor since a balance must be maintained between total apex opening and total flow through the hydroclones.

One system design feature being utilized to compensate for grinding circuit wear is the installation of variable speed drives on the slurry feed pumps to provide consistent pressure and flow at the hydroclone inlet.



Ball Mill - Horizontal
Used with permission from Metso Minerals

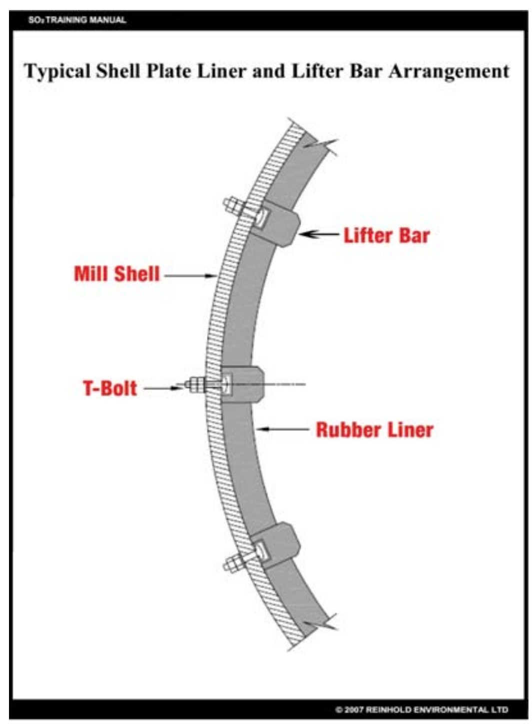
3.3 Limestone Ball Mill Maintenance

Once the ball mill is designed and built, there are only so many things the operator can do to keep it grinding at maximum efficiency, especially if there are changes in the limestone supply. The first order of business is to maintain the mill's maximum grinding efficiency. There are two critical items in maintaining proper ball mill performance, grinding media charge (mill balls) and the condition of the mill internals.

- When the ball mill is operating with a full charge of mill balls, the motor amperage should be read and recorded. This is the target amp reading. One can determine if there is a full ball charge by entering the mill and measuring the ball level and size variation compared to the design drawings. As this amp reading drops over time, additional mill balls should be added to return the amp reading to the target and to maintain full grinding capacity. The balls are ground (along with the limestone) and disappear from the mill over time. Ball addition typically (top size only) happens on a weekly basis. Typically, one or two 55 gallon drums (1 ton of balls per drum) of mill balls are added at a time. If the amp readings are low, a coarser product is being produced by the mill. It is important to periodically add the larger balls to maintain the proper mix of grinding media sizes for optimum ball mill performance.
- The second item is lifter bars. The lifter bars protrude out into the mill past the rest of the rubber lining. Their job is to raise the mill balls to a higher elevation and then drop them back into the grinding area. This impact helps to break up the larger particles in the mill. In time the square profile of the lifter bars can become rounded from wear. This allows the mill balls to roll off at a lower elevation which reduces the impact. Lifter bars may need to be replaced every year or two depending on the hours of mill operation. Often the lifter bars can be removed one time, rotated 180º and then be reinstalled. This puts a new square profile in the lifting position.

There are also some lifter bars with embedded hardened metal corners which have a longer life expectancy before replacement. The other rubber linings in the mill body will typically have a life two to three times longer than the lifter bars. It is best to run a ball mill at a specific limestone feed rate and cycle it on and off as needed to maintain product tank level. If the limestone feed rate is lowered, the same motor horsepower is still being supplied to the mill. This horsepower must be converted into work. If the mill doesn't have as much limestone to grind, it will start grinding the rubber linings, lifter bars

Ball Mill - Vertical
Used with permission from Metso Minerals



Typical Shell Plate
Used with permission

and mill balls. This will increase the operating and maintenance costs on the mill.

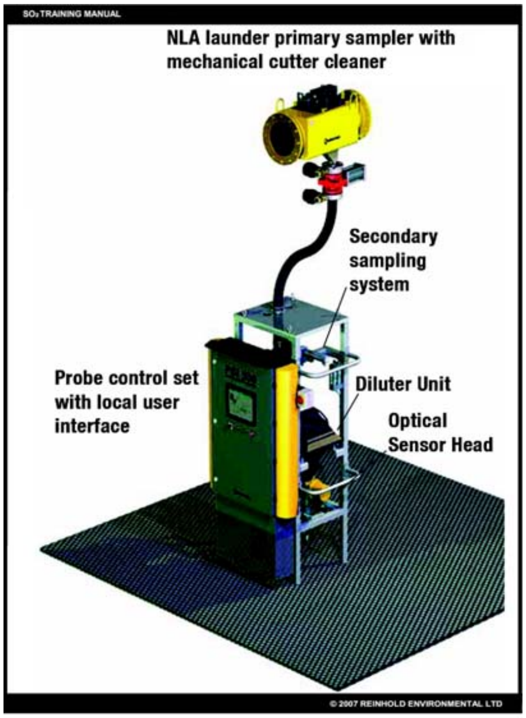
An area of high maintenance is the mill inlet throat area.

- All of the limestone passes through this area.
- All of the grinding water is added in this area
- All of the oversize slurry is returned to the mill through this area.
- All of the mill balls that are added pass through this area.

Since the grinding water is typically liquid recycled from the dewatering area, it is very corrosive to bare metal. So this area typically has some sort of lining applied to protect it. All the sliding, impact, and turbulent liquid that occur in the inlet throat are very hard on any type of lining. This area should be inspected several times per year and lining repair done as needed. Once the lining fails, the metal underneath it will corrode and erode rapidly. Voids in the ball mill internal lining can allow slurry to accumulate between the rubber liner and the shell and quickly damage the rotating drum. Periodic internal inspections are recommended.

3.4 Limestone Slurry Particle Size

If the mill is being maintained properly, the operator only has a couple of options left to change final slurry particle size.



Slurry Particle Size Analyzer
Used with permission from Outokumpu Technology Minerals Oy

- A mill can produce a finer product if the particle size of the limestone being fed is smaller. There can be some material handling issues with this approach. A limestone with more fines that becomes damp will tend to clump and not slide out of chutes and silos as easily as a larger stone. It becomes even worse in the winter when a larger amount of fine material will increase the chances of large frozen chunks which can block the discharge openings of limestone feed silos.
- The other option relates to the Bond Work Index formula. If something about the mill or the limestone has changed that is causing the mill to produce oversize particles, the formula indicates one needs more horsepower per ton of limestone. It would be impractical to replace the ball mill motor. So since the horsepower is constant and one needs more horsepower per ton of limestone, the only possible action is to reduce the limestone feed rate to the mill. It would appear that this could lead to a shortfall in limestone slurry, but this is not always the case as will be shown in the "real life example" that follows in the next section.

Many operators choose to monitor slurry particle size by collecting periodic grab samples and having them analyzed in a laboratory. This will show long term trends in mill performance. But, a plugged hydroclone can change the slurry fineness instantly.

It can prove cost effective to install an on-line particle size analyzer. Such an instrument can immediately trigger an alarm when the slurry particle size changes so the hydroclones can be checked before a large amount of oversized product is sent to the limestone slurry product tank.

3.5 Real Life Example of Limestone Slurry Fineness Importance

A station had a 40 ton per hour (TPH) ball mill installed on an FGD unit. Over the years, some changes had been made to the ball mill design due to maintenance issues. The limestone properties had remained relatively consistent.

Slurry Particle Analyzer
Used with permission from Thermo Fisher Scientific

The FGD system was installed on a unit that generally ran at full capacity during the day and ran at reduced capacity during the evenings and weekends. The level in the limestone slurry product tank would normally drop during the day and then recover over the evening hours. Often the ball mill could be removed from service for short periods during the evening or weekends whenever the limestone slurry product tank became full.

During a period of extremely hot weather, the unit remained at full load 24 hours per day for several weeks. During this time the unit operators were forced to curtail unit load on several occasions due to low levels in the limestone slurry product tank. The unit couldn't remain at full load without the FGD system in operation without violating emission permits. During these load curtailments, the utility had to purchase replacement power at high prices.

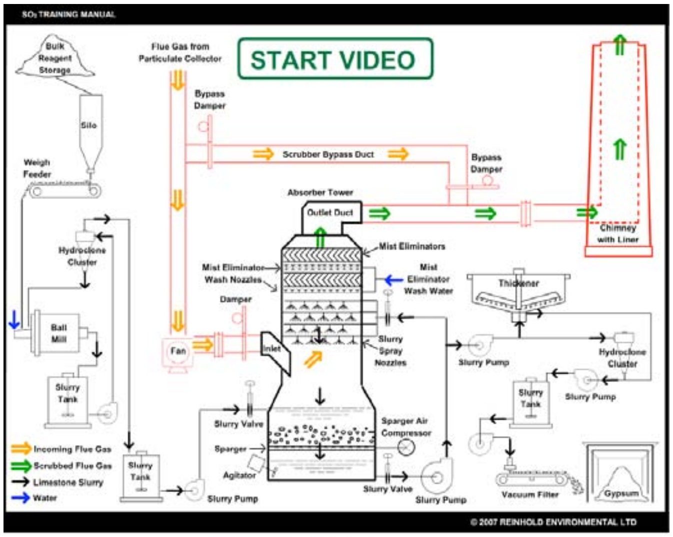
A new on-line particle size analyzer had been installed in the ball mill circuit about this same time. It indicated that when the ball mill was grinding 40 TPH of limestone, the slurry particle size was near 80% passing through a 325 mesh sieve. The particle size was supposed to be 90% passing through a 325 mesh sieve.

It was decided to decrease the limestone feed rate to see if the fineness would improve. As the feed rate was reduced, the particle size analyzer indicated improvement in slurry fineness. Once the feed rate was in the 33 – 34 TPH range, the particle size analyzer indicated the slurry fineness was back in the range of 90% passing through a 325 mesh sieve.

What happened next surprised the operators. As the mill was operated at the 33 – 34 TPH limestone feed rate, the level in the limestone slurry product tank began to increase. After several days they were able to keep an adequate level in the tank even as the unit continued to operate at full load 24 hours per day. This resulted in substantial savings by eliminating the requirement to purchase replacement power.

This also indicated that when the slurry had a fineness near 80% passing through a 325 mesh sieve and the unit was operating at full load, 6 – 7 tons per hour of undissolved limestone was passing through the absorber tower without reacting with the SO_2. This ball mill continues to operate with a limestone feed rate of 33 – 34 TPH, and many tons of limestone have been saved over the years with a resulting savings in operating expenses.

CHAPTER 4 - FANS, DUCTS, EXPANSION JOINTS, DAMPERS & CHIMNEYS



Chapter 4 Summary
(Narrated by Ron Richard, RE Consulting)

Absorber Inlet-Outlet Ducts
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Because of the FGD system, the fans, ducts, dampers, expansion joints, and chimneys are operating in conditions not normally experienced in traditional utility plants.

This chapter discusses the materials of construction and design details that allow this equipment to operate and survive in this extremely hostile environment with the least amount of maintenance possible.

4.1 Fans

Some FGD systems rely on the unit's induced draft fans to move gas through the absorber towers while others have separate booster fans for each tower. Most FGD systems have the fans upstream of the absorber towers while some have them downstream. Some FGD systems use axial fans while most use centrifugal fans.

The fans that are located downstream of the absorber towers have proven troublesome. The scrubbed flue gas downstream of the absorber tower is cool and completely saturated. The liquid droplets contained chlorides and fluorides and typically have a very acidic pH (1 or less). This means the fan has to be constructed of expensive corrosion resistant alloys. In service the fan wheel heats up due to friction of the gas across its surface. When the cool slurry droplets come in contact with the hot fan metal, the liquid can evaporate leaving salt deposits on the fan wheel. These deposits can throw the wheel out of balance.

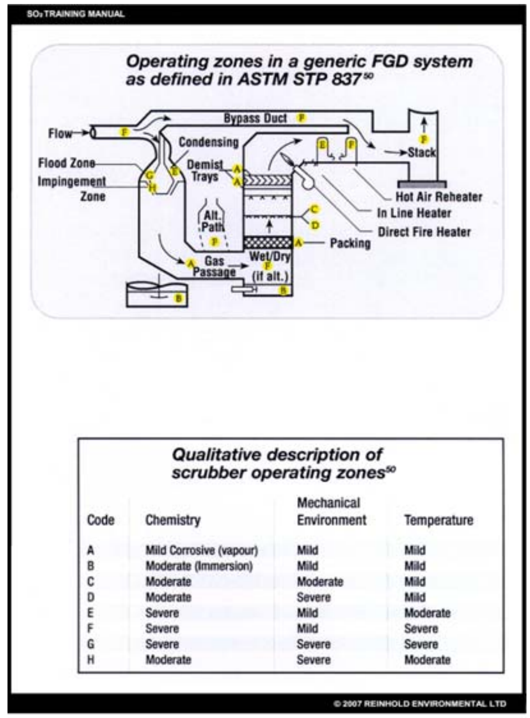
The fan would then have to be taken out of service to wash the deposits from the fan wheel. These deposits contained arsenic, so protective equipment is required for the wash crew.

Fans located upstream of the absorber tower are in contact with hot, unsaturated flue gas. They can be constructed from the metals typically used in large fans. The operating and maintenance issues aren't any different than with typical induced draft fans. The fan outlet to absorber inlet ductwork detail is a critical FGD design parameter.

It may seem far fetched, but upstream FGD fans have been known to fill with slurry while sitting idle. It depends on the location of the fan in relation to the absorber tower and the slope of the duct between. There is the potential for absorber high liquid level or foaming to cause slurry to flow back into the scrubber fans. As the scrubber is removed from service, the dissolution of limestone continues. Since there is less gas flow to brake the surface tension as CO_2 bubbles are released, the level of slurry rises as a foam and backs into the ductwork, often filling the fan with slurry. There have been incidents where this foaming has allowed enough slurry to back flow into the fans to trip fans at low loads. The addition of oxidation air into the recycle tank as well as operation of recycle pumps will effect absorber liquid level.

Foreign material can partially plug a slurry spray nozzle. When this happens, the spray pattern can change. Occasionally this will spray slurry into the inlet duct. If the fan is in service, this liquid will be blown back into the tower. If the fan is out of service and the slope of the duct is towards the fan, the slurry will run into the fan. There have been instances of operators noticing slurry running down fan bearing pedestals because the fan housings were full of slurry all the way to the fan rotors. It is a prudent practice to open the fan housing drains to check for liquid before starting an FGD fan. This could prevent fan wheel and motor damage.

4.2 Ducts



FGD Operating Zones
Used with permission from Nickel Institute

From the figure to the right one can see that the duct areas have the potential to be one of the most severely corrosive areas in the FGD system or only mildly corrosive. It all depends upon the physical location of the duct and as well as the gas composition and temperature of the flue gas.

The duct coming from the FGD booster fan or precipitator to the FGD tower contains normal high-sulfur flue gas at a temperature around 300ºF. This section of duct will experience normal corrosion similar to that found in ducts coming from the boiler. Corrosion will occur wherever there are cold spots which lead to condensation of acids on the duct wall or floor. This can occur due to insulation problems on the duct exterior. It can also occur due to air leaks through expansion joint tears, uncapped test ports or guillotine damper seals.

The entrance to the absorber tower is one of the most severely corrosive duct areas. It is referred to as the “wet/dry interface”. Ahead of this zone, the gas is hot and unsaturated. After this zone, the gas has been cooled to about 125ºF and is completely saturated with water. Within the zone, hot duct walls are being splashed with droplets of cool slurry from the tower. This evaporates the water and leaves a layer of slurry solids deposited on the duct wall. The slurry itself is not that corrosive, but the deposit contains high levels of chlorides. It is not unusual to find under a deposit on a duct wall chloride levels many times higher than those in the tower slurry. Deposits tend to concentrate salts against the duct wall. The deposit (usually referred to as scale) also insulates the duct wall. The heat from the incoming flue gas keeps the surface of the scale hot, but the duct wall under the scale begins to cool. The water that condenses against the duct wall under the scale along with the concentrated levels of chlorides under the scale will quickly cause pitting of the duct wall. Most new designs will take the 10 - 15 foot section of duct immediately preceding the tower inlet and construct it out of a highly corrosion resistant alloy or lining (See Reference 7.1.a - FGD Materials of Construction Presentation by Ron Richard). Thus, the “wet/dry interface” is constructed of a material that can withstand the severely corrosive nature of this area. It is also prudent to remove the scale layer from this “wet/dry interface” whenever maintenance work is being performed in the tower.

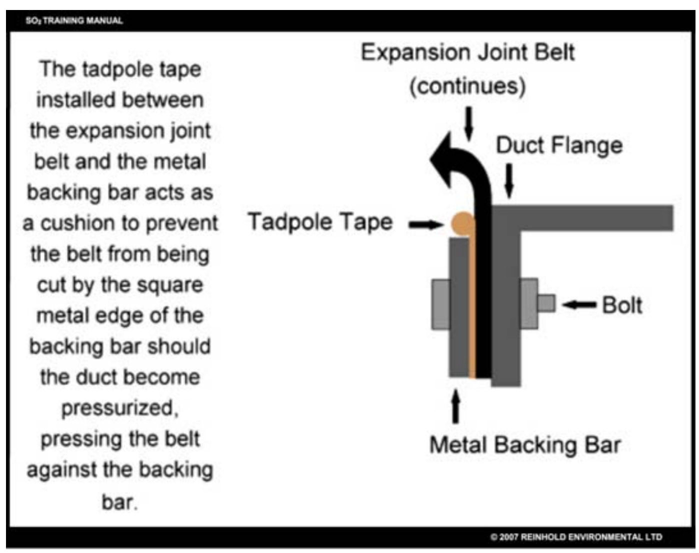
It is also possible during times of low load gas flow or no gas flow, for slurry droplets to get back into the inlet duct. It is best if a section of the inlet duct slopes towards the absorber tower. Then this liquid will run back to the tower. If the duct floor is level or slopes towards the fans, the liquid will pool in the duct or run back into the fan housing. At first, this liquid is not corrosive since it contains lime or limestone particles. As it comes in contact with flue gas, the alkalinity reacts with the SO_2 and the pool becomes acidic. This liquid can then attack the duct floor. Some operators have had to place linings or alloy materials over the floors and several feet up the side walls to protect the inlet ducts from this type of acidic attack.

The zone from the tower inlet to the mist eliminator inlet is mildly corrosive. The pH in this zone is above 5 due to the recirculating slurry. The chloride level in the recirculating slurry will determine which materials will corrode in this zone. Erosion damage is a greater danger in this zone than corrosion. Erosion can occur from locating slurry spray nozzles too close to the tower wall. It can also occur when a properly located slurry spray nozzle becomes plugged. The pluggage can cause all of the slurry to exit the nozzle as a narrow jet that impinges directly on the tower wall. The solids in the slurry cause it to act as an abrasive blaster cutting through the metal or tower lining/coating.

Once the gas passes through the mist eliminator, the corrosion potential rapidly increases. This is because most of the slurry droplets are have been removed by the mist eliminator. This means that there is little excess alkalinity remaining in the damp flue gas. Any remaining SO_2 can react with and deplete this alkalinity. This will cause the acidity of the wet gas to increase. It is many times worse if there is any bypass of hot unscrubbed flue gas with high SO_2 available to mix with this wet gas. (This was done in some older designs to add some heat back into the flue gas due to “plume rise” or “chimney rain-out” concerns. Where this hot gas enters the outlet duct, another “wet/dry interface” will occur.) Condensation of liquid on cool duct walls or scale deposits on duct walls can set up severely corrosive regions. This condensed liquid can have a pH less than 1. For these reasons, most utilities choose to use the most corrosion resistant materials available when building these outlet ducts.

Expansion Joint Section
Used with permission from Effox, Inc.

Duct drains should be designed from corrosion resistant materials. Often the liquid draining from ducts can have a pH less than 1 and contain high levels of chlorides. It is also desirable to route duct drains where they will be accessible. Elbows should be a long radius, or a better design in place of elbows is cross tees. Piping diameters should not be too small. Duct drains will likely plug from the solids in the slurry or scale deposits falling off the duct walls. It is helpful to have drain piping designed for the use of poke rods or water blasting equipment.



Tadpole Tape Installation Detail
Used with permission

4.3 Expansion Joints

All duct systems needs expansion joints to allow for the expansion and movement of the duct sections with temperature changes. There are various styles of joints, but for FGD service the fluoroelastomeric belt type joint gives the best service. Metallic bellows type joints do not survive any length of time because of the severely corrosive environment in the ducts and the residual stresses in the shaped metal.

The fluoroelastomers such as Viton or Ryton provide the chemical resistance and flexibility needed for the expansion joint belt. Care must be taken to have a wide enough belt for the joint so that there is slack in the belt for the entire range of duct movement. There have been cases of torn belts due to the required gap becoming greater than the width of the belt. For rectangular ducts, the sharp change in direction at the corners can be a problem. The belt can become bunched and difficult to bolt between the duct flange and the backing bar. There are adapters that can be used to “round off” the square corners. It is more successful to have the belt made to the exact dimensions of the duct with molded square corners installed in the belt at the appropriate locations.

Another cause of premature expansion joint failure occurs when the duct is pressurized. This can flex the belt outward against the square edge of the backing bar. Over time, this edge will act as a knife and cut the belt along this line. The use of tadpole tape during the joint installation can prevent this problem.

The floor section of the expansion joint can fill with liquid or solids which can stretch and stress the belt material. It is best to have a duct drain near the expansion joint and on the side of the incoming liquid. A small bar can be welded to the floor between the joint and the drain to act as a dam to keep the liquid from

Expansion Joint Installed in Duct
Used with permission

Large Expansion Joint
Used with permission from Effox, Inc.

flowing into the joint. Any time work is being done in a duct, it is prudent to inspect the expansion joints and remove any liquid or solid material that has collected in the joints.

4.4 Dampers

Most FGD designers have chosen to use guillotine dampers to isolate absorber towers. This is probably because when the damper is open, there are no blades or shafts left in the duct to be exposed to the corrosive environment and duct pressure drop is minimized. Some are single bladed while others are double bladed. The double bladed design typically has seal air between the blades when the blades are closed to provide "man safe" entry into the absorber towers while the unit remains in service. Some FGD owners require redundant damper seal air supply fans.

Guillotine Damper
Used with permission from Effox, Inc.

Where the blades penetrate the duct walls, some sort of sealing arrangement will be used. The typical designs are interleaving seal strips and bellows type seals. The interleaving strips are stacks of very thin metal strips bolted on each side of the penetration. The strips are long enough to overlap with the strips from the opposite side of the opening. The damper blade flexes the two stacks of strips out of its way as it penetrates the seal. In theory, these overlapping strips will interlock with each other (much like your fingers if you spread them slightly and clasp your two hands together) as the damper blade is withdrawn from the duct and the flexed seal strips return to their straight positions. In real life, the thin strips can catch on irregularities on the blade and subsequently curl or break. The thin strips should be made from highly corrosion resistant alloy or they will shortly look like swiss cheese. Typically, interleaving seals should be replaced every few years.

The bellows type seal consists of two metallic bellows, each attached to the opposite sides of the opening. The bellows expand until the two bellows touch, sealing the opening. There are guide bars attached which guide the damper blade as it wedges between the two bellow pieces, pressing them apart as the blade penetrates the seal. The bellows type seals typically seal well for a longer period of time. But the blade can catch the edge of a bellows as it penetrates it, causing it to be damaged and preventing it from sealing properly after the blade is retracted. The bellows are fabricated from thicker pieces of corrosion resistant alloys which give them a longer life than the interleaving seal strips.

The important question to ask about damper seals is not whether they are going to leak; they are. The two important questions are:

- How soon will they begin leaking and
- How large will the leaks be.

The design in the damper area must take this leakage into consideration.

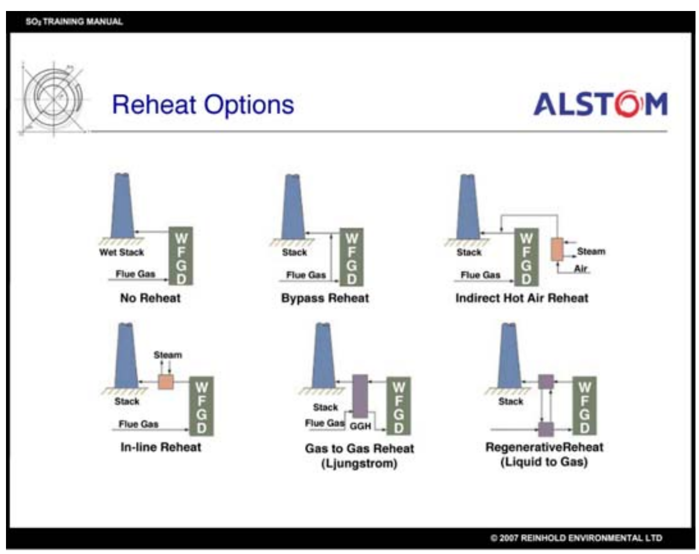
The best design has the blade entering through the top of the duct. An acceptable design is to have the blade entering through the side of the duct. The worst design is to have the blade entering through the bottom of the duct. An opening in the floor of the duct will allow corrosive liquid to drain out through the damper seals and corrode the retracted blade, guide rails and drive mechanisms.

Some damper designs place an enclosed bonnet over the retracted blade and the driving mechanism. This is to protect these components from the weather and minimize temperature variations for large blades. The most severe weather is mild compared to the flue gas and condensing liquid environment that will occur inside the bonnet from seal leakage. It is better to insulate the bonnet so the leaking flue gas can warm and minimize corrosion of the components in the top half of the guillotine damper.

Most of the guillotine dampers use a chain drive system, although some use a rack and pinion drive or a screw drive. The screw drives require more maintenance and lubrication to prevent corrosion issues from causing drive issues. There are two types of chain drives. The one that uses a roller type chain requires more maintenance. If the hinge pin area of the chain isn't kept lubricated, the chain will bind, jump and "pop" as the damper moves. This may cause the chain to eventually break. The traditional link style "log chain" doesn't require any lubrication. Both types of chain can stretch, so tightening of adjustment bolts may be required from time to time.

The area where the drive mechanism attaches to the blade should be inspected occasionally. Seal leakage can cause corrosion in this area. If the damper blade should become detached from the drive mechanism, the blade can fall into the duct. In some cases, it has fallen through the duct, penetrating the bottom of the damper frame.

Gas leakage through the seals can also cause corrosion damage to the exterior portions of the damper frame. It is prudent to fabricate the damper frames from a corrosion resistant alloy. Some damper designs use a small seal air fan to fill a seal chamber (or the cavity between a two bladed damper) with air. This is designed to keep flue gas from leaking around the closed guillotine damper blade into the area being isolated by the damper. When the damper is open, these seal air fans are typically taken out of service. Leakage through damper seals has been known to fill the seal chambers with wet flue gas which then exits through the idle seal air fan inlet. Operators have been surprised to find seal air systems incapable of being used when needed because they were destroyed by corrosion during these idle times when the damper was open. Some operators have chosen to run the seal air fans at all times. This pressurizes the seal air chambers with air, prevents flue gas from entering even when the damper is open, and prevents corrosion of the seal air system and fan. However, ambient air capable of cooling the seal chamber could promote corrosion of inadequate materials. Heating damper seal air has been cost prohibitive.



Reheat Options
Used with permission from Alstom

4.5 Chimneys

A typical utility chimney handles dry flue gas at a temperature around 300ºF. The chimney on a scrubbed unit handles wet saturated flue gas at a temperature around 125ºF. This creates some challenges for the chimney designer. The hot gas has natural buoyancy as it leaves the chimney that causes it to continue to rise. The cool gas is more dense and may tend to settle back towards the ground.

Attempts have been made over the years to remedy this problem by adding heat to the flue gas once it has exited the absorber tower. Heat exchangers were placed in the absorber outlet ducts. The interaction of liquid droplets on the hot gas side surfaces of the heat exchanger tubes formed corrosive environments that rapidly caused the tubes to fail. Hot, unscrubbed flue gas was bypassed around the absorber tower and then mixed with the scrubbed gas. This reduced overall SO_2 removal and created one of the most corrosive environments ever seen in scrubber systems. Even corrosion resistant duct and chimney materials were attacked by this mixture.

European FGD installations often use an enameled plate rotary air heater to remove heat from the flue gas entering the scrubber and return it to the flue gas leaving the scrubber. The corrosion and maintenance problems on these air heaters are manageable.

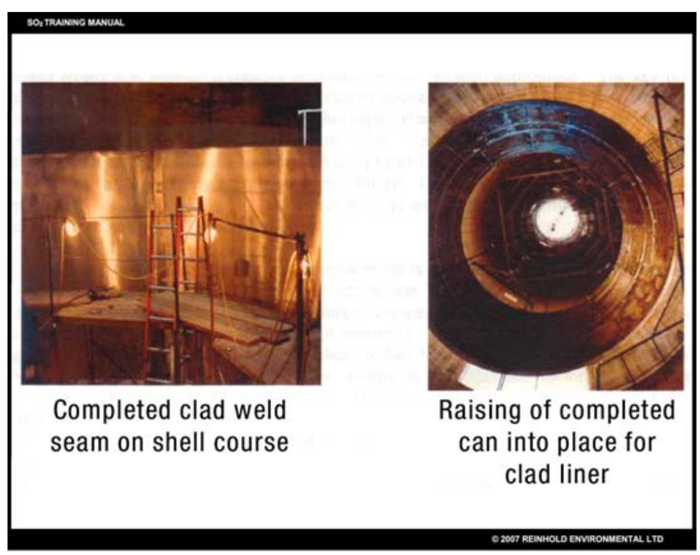
Most current chimney designs have abandoned the idea of any type of gas reheating and rely instead on a mechanical "choke" (restrictive nozzle) at the chimney exit to impart a greater velocity to the exiting gas. This increased velocity propels the plume to a higher elevation before it begins to settle.

Due to the wet gas, low pH and high chlorides, traditional carbon steel and brick liners cannot be used. Materials used for chimney liners on scrubbed units include:

- Acid resistant brick and mortar,
- Stainless steel,
- C-276 and other high nickel alloys both solid and clad,
- Titanium,
- Fiberglass reinforced plastic (FRP),
- Gunite coating,
- Refractory coating,
- Vinylester coating.

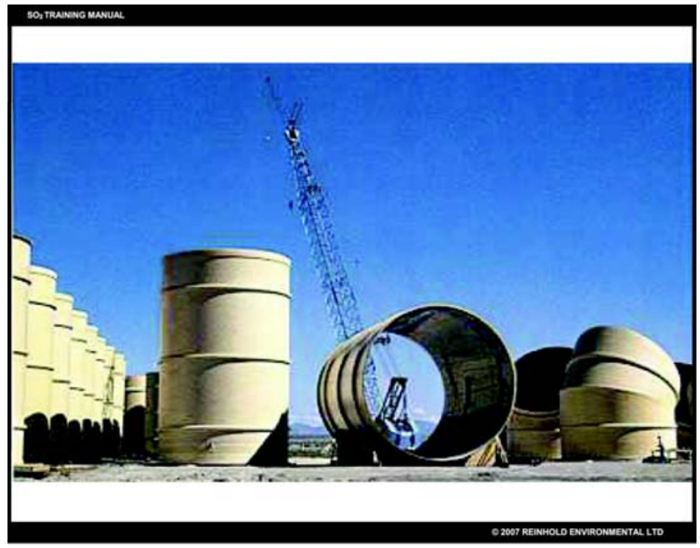
The high nickel alloy and FRP liners are used in most systems today.

The FRP liners are usually constructed on site. A large mandrel is erected and the stack liner rings are spun on the mandrel. The rings are then stacked on top of one another and joined together inside the concrete chimney shell. Sometimes helicopters are used to lower the rings into the chimney shell. Sometimes the liner column is hoisted from the top and new rings are added to the bottom of the growing liner.



Chimney Liner - Roll-Bonded Clad
Used with permission from ISG Plate

The acid resistant brick and mortar design has experienced some problems that have made it less popular. The mortar is porous. Liquid can leach through the mortar and evaporate on the outside of the liner bricks. This leaves corrosive salt deposits on the exterior of the liner. Brick liners are strengthened by compression bands placed at regular intervals along the height of the chimney. These bands are typically fabricated from carbon steel. The corrosive salts attack these bands, and they corrode and fall from the liner. They must then be replaced. Designers now utilize coated compression bands and ambient air fans to pressurize the annulus between the concrete shell and the brick liner. This elevated pressure is supposed to minimize the wicking of the liquid through the mortar. In practice it is hard to continuously maintain this annulus pressure. Any openings in the shell or the chimney cap will allow this air to escape and the pressure will be lost.



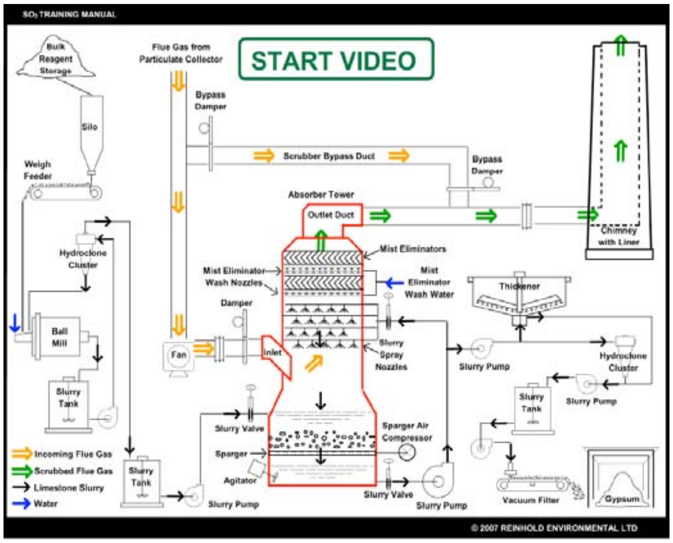
Chimney Liners FRP
Used with permission from Ershigs, Inc.

There was another problem with "leaning brick liners". This occurred when cooler scrubbed gas and hot unscrubbed gas entered a brick liner from separate breeching openings. Due to certain reaction phenomenon in the mortar, the mortar joints on one side of the liner would grow slightly while those on the other side didn't. This caused the top of the liner to move in a direction away from the growing mortar joints. In some cases the liner actually came in contact with the chimney shell. These liners had to be partially torn down and rebuilt.

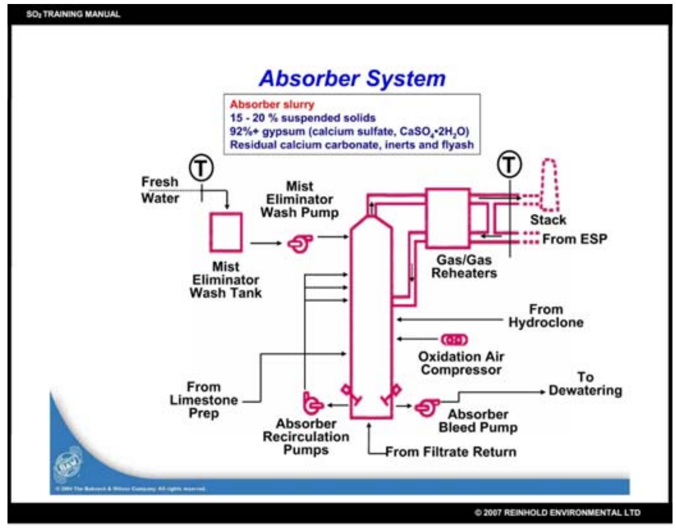
Chimney drains are another important item. The best way to remove liquid from the chimney is to first minimize the quantity getting into the chimney. This means keeping the scrubber mist eliminators clean and functioning well. This means keeping duct drains from becoming plugged. This may mean putting liquid collecting/diverting devices on duct walls after changes in direction to collect and drain away liquid that impinges and runs along duct walls. This means placing bars across the duct floor near the breechings to act as dams to keep water from running along the floor into the chimney. But even with all these items, there will be some condensation on chimney walls that will run back into the bottom of the chimney. A pool of liquid in the bottom of the chimney can be detrimental to liner life. Chimney drain piping should be as straight and short as possible. It should be designed so that it can be cleaned by rodding or water blasting from the outside of the chimney with the chimney in service.

Re-entraining liquid droplets into the chimney plume should also be avoided. Liquid will collect on and run down the chimney liner wall. Some utilities have placed an awning/diverter above each breeching. It should be designed to divert any liquid running down the wall above the breeching to either side of the breeching. This prevents a "water fall" at the top of the breeching where the liquid falls into the moving flue gas stream and droplets are carried out of the top of the chimney. This minimizes the chances of "chimney rain-out" events in the area surrounding the chimney. Minimizing stack plume and liquid re-entrainment begins with stack liner design (flow, velocity, liquid separation, exit detail, etc.) as well as quality control during liner construction and installation.

CHAPTER 5 - ABSORBER TOWER FUNDAMENTALS



Chapter 5 Summary
(Narrated by Ron Richard, RE Consulting)



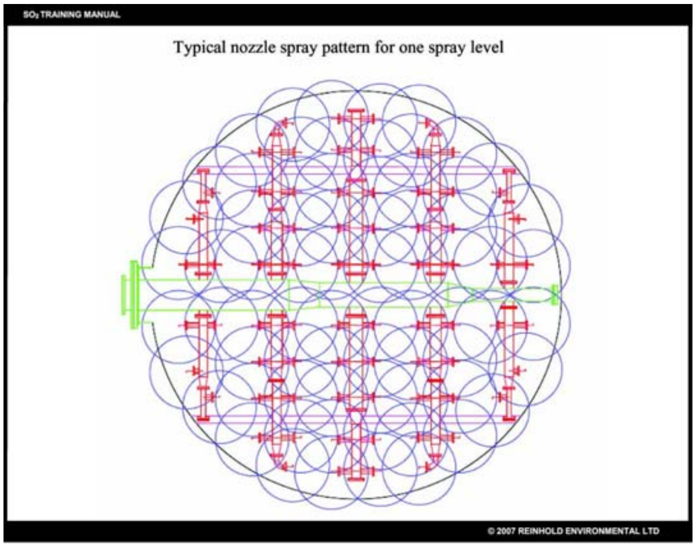
Wet FGD Absorber System Diagram
Used with permission from Babcock & Wilcox

Although it appears to be a simple process to spray slurry through flue gas, there are many factors that control how quickly and completely the SO$_2$ is removed from the flue gas. This chapter gives an understanding of what these factors are in the spray zone.

It also covers the slower reactions that occur in the liquid sump portion of the absorber that complete the conversion of the SO$_2$ into the final byproduct, as well as the chemical and physical factors that can accelerate or slow down these reactions in both sections of the absorber tower.

5.1 Gas Phase Limited

The scrubbing reactions are gas phase limited when the SO_2 in the gas can't move through the gas to the liquid as fast as the liquid can react with the SO_2. Diffusion of molecules in a gas happens very quickly. So when an area in a gas cloud becomes depleted of SO_2, additional SO_2 will rapidly move to fill the void. The measured variations of a certain gaseous substance in a small gas area are typically very uniform. Thus scrubbing reactions are not typically gas phase limited.



Typical Nozzle Spray Pattern Diagram
Used with Permission

There can be small areas in a large absorber tower where the reactions are gas phase limited. These typically happen along the tower wall. If one looks at a typical spray pattern for a spray level in a tower, there are areas along the tower wall where only one spray nozzle or no spray nozzles are covering an area. As the gas passes through the spray level, it will experience less resistance to flow along the wall. This will cause more of the gas to flow through this zone which will increase the gas velocity near the wall.

This combination of higher gas velocity and few or no liquid droplets will allow some of the SO_2 to pass through the spray level without having the time to move towards a liquid surface to react.

5.2 Liquid Phase Limited

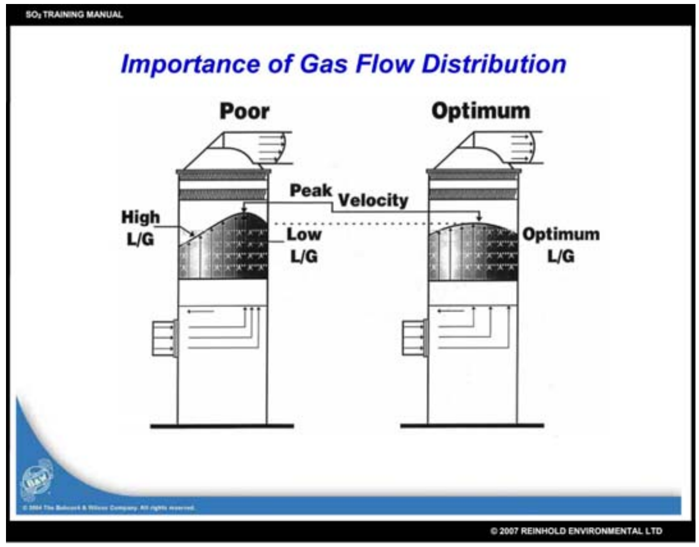
The scrubbing reactions are liquid phase limited when there are more SO_2 molecules present at the gas interface with the liquid than the liquid can react with. This is the typical rate limiting mode in absorber towers. It occurs for several reasons.

Depending on the size and shape of the gas/liquid interface, much of the liquid is not at the surface of the interface. The larger the droplet size, the larger the percentage of the volume that is not at the interface. A pool of liquid has most of its volume not at the interface. However, the surface of a froth bubble (like the head on a glass of beer) has most of its volume at the interface. The alkalinity at the interface may become exhausted. As the alkalinity reacts with the SO_2, the reaction products need to move away from the interface and be replaced with fresh reactants. This can be dependant on the turbulence in the liquid. The volume of liquid can also make a difference. In a froth bubble surface, all of the alkalinity may become consumed and there are no fresh reactants to take its place.

There can also be insufficient alkalinity to react with the SO_2. This could occur due to a control problem with the lime or limestone feed. This could occur due to an error in the pH measuring cells. In a limestone system it can occur due to limestone particle size or slurry pH which is preventing the limestone from dissolving as quickly as the reactions are consuming it.

5.3 Liquid/Gas Contact

An absorber tower designer has to keep both principles of Gas Phase Limited and Liquid Phase Limited in mind when deciding how to bring the flue gas into contact with the alkaline slurry. One wants all the flue gas to arrive at a gas/liquid interface at least one time and hopefully more times as it travels through the tower. One wants the slurry to be turbulent and present a large surface area to the flue gas. Many different design concepts have been developed to make this happen.



Importance of Gas Flow Distribution
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Getting a uniform gas distribution across the entire diameter of the tower is a prime concern. In a vertical absorber tower, the gas typically enters the tower in one quadrant. The velocity momentum of the gas causes more of it to flow up the tower directly opposite from the inlet and less of it to flow up the tower directly above the inlet. Flow model studies and turning vane devices can be used to minimize this improper distribution of gas flow. Some designs add a device which causes a back pressure to the gas to even out the distribution. This may be in the form of a tray or some sort of packing that the gas must pass through while contacting the slurry.

Absorber Internals - 2
Used with permission from Babcock Power

In the Chiyoda design, the gas passes down through a large number of smaller pipes which bubble it up through the pooled slurry.

In a venturi design, all of the gas must pass through the narrow throat of a venturi nozzle where it comes in contact with the liquid. The slurry must be pumped into the tower. It typically passes through a spiral nozzle or a tangential whirl nozzle which breaks it up into a circular pattern of droplets. The smaller the droplet size, the more total surface area per volume of liquid will be obtained. Of course the smaller the droplet size, the more pressure drop across the nozzle which equates to increased pumping horsepower. So the designer has to compromise between droplet size and installed pump horsepower.

Some studies have indicated that the actual droplet size in a tower relates to liquid surface tension and gas velocity. In an absorber tower, the multiple spray nozzles produce patterns that impinge on each other. Droplets that collide may combine to create larger droplets. When a droplet becomes too large for the surface tension to hold together against the gas flow, it will break into smaller droplets. So the theory may indicate that adding additional pump horsepower and nozzle pressure drop may not actually create smaller droplets under actual tower conditions. The "fountain nozzles" used in one current design rely on this principal of pumping a large volume of slurry vertically to an elevation, spreading it out into a thin sheet, and letting it break up and fall through the flue gas stream on its own into smaller droplets.

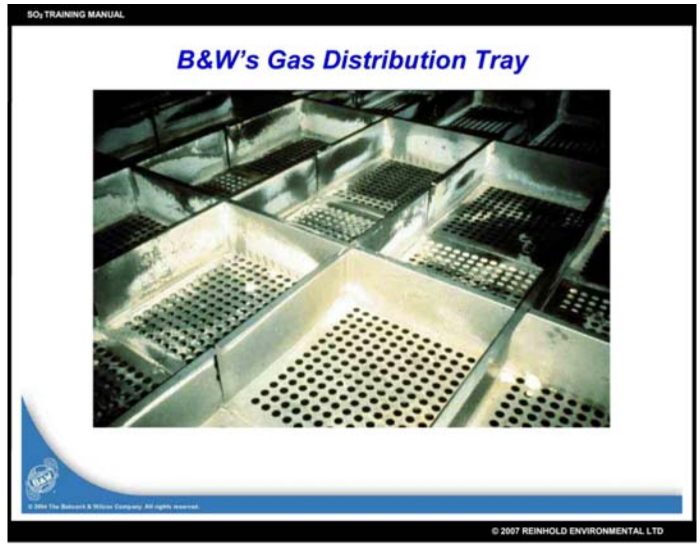
Early tower designs had multiple levels of spray nozzles. The nozzles in each level were directly above the nozzles in the level below it. It was soon discovered that this led to lanes of low liquid density along the walls and other areas where few nozzle patterns overlapped. The flue gas would find these lanes of low back pressure and pass through at increased velocity and minimal slurry contact. This lowered SO_2 removal efficiency.

Current designers have rotated each level of slurry spray nozzles. This puts the nozzles in a higher row directly over a space between nozzles in the row below it. This provides a more uniform slurry density across the entire tower diameter and eliminates the lanes for the gas to "sneak" through the spray zone. Also more attention has been paid to the spray patterns along the wall. Too much spray on a wall can erode holes through the wall due to the abrasive nature of the slurry. Also slurry running down the tower wall does not provide as much surface area for the gas to react with as droplets. But too little slurry along the wall can allow the flue gas to "sneak" past.

Wall Rings
Used with permission from Alstom

One new design uses liquid distribution rings attached to the wall below each spray level. The ring does two things. It forces the gas away from the wall and into the spray pattern of the nozzles above it. It also takes the slurry running down the wall and puts it back into the gas stream as a "water fall" running over the lip of the ring from above as the flue gas passes over the lip of the ring from below.

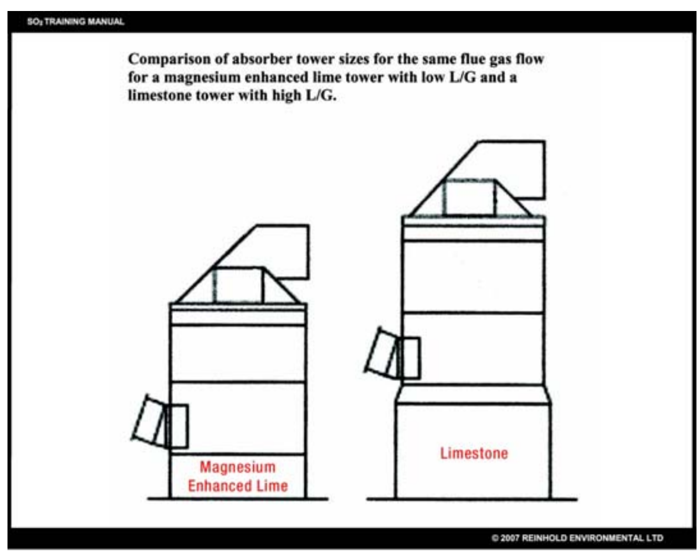
Packing can break the slurry into thin films running over the packing devices. This provides a large surface area of liquid to the gas while providing a more uniform gas flow distribution across the tower. Many times the packing layer can be several feet thick. The biggest problem with packing over the years has been the build up of scale (calcium sulfite and calcium sulfate) in the packing which will eventually plug the gas passages and increase pressure drop across the packing. When this happens, the existing packing must be removed and replaced with new packing. Most current tower designs have chosen not to use packing.



Gas Distribution Tray
Used with permission from Babcock & Wilcox

A tray is a plate of metal with large holes spaced across it. The slurry falls onto the tray from the spray zone above it. The slurry must pass down through the holes in the tray to get back to the slurry recirculation pumps. The flue gas must pass up through the holes to pass through the tower. The gas passing through the slurry in the holes tends to produce a froth-like layer on the tray. The tray is also creating a more uniform gas distribution across the tower diameter. If the area of the holes is too small for the gas flow or holes become plugged, slurry can flood the tray and not be able to return to the slurry recirculation pumps.

In the Chiyoda design, the slurry resides in the lower portion of the tower and there are no slurry recirculation pumps or spray nozzles. Larger fans have to produce enough pressure to bubble the flue gas through the slurry through a large number of small diameter pipes that protrude to near the bottom of the slurry pool. (This is exactly like blowing through a soda straw into one's glass of beverage.) The turbulence of the gas bubbles in the slurry, as well as the froth layer on top of the slurry pool, provides the gas/liquid interface needed for the reactions to occur.



Comparison of Absorber Tower Size
Used with permission

5.4 Liquid/Gas Ratio

Liquid/Gas ratio is a number that can quickly allow someone to compare one scrubber's design against another just like SCA is used in precipitator designs. The liquid portion is the gallons per minute of slurry being recirculated through the absorber tower. The gas portion is the actual cubic feet per minute of wet cool flue gas exiting the absorber tower expressed in units of 1000 ACFM. So the liquid/gas ratio is in units of gallons/1000 cubic foot.

An absorber tower that has a slurry recirculation flow of 10,000 GPM and a gas flow of 100,000 ACFM would have a liquid/gas ratio (10,000/100) of 100 gallons/1000 cubic foot. Or in more common terms, one would say the tower has an L/G of 100.

A scrubber using very reactive sodium chemistry might be designed with an L/G of 10. Scrubbers using lime chemistry are typically designed with an L/G in the 30 – 40 range. Early limestone scrubbers were designed with an L/G in the 80 – 100 range. With the desired increase in SO_2 removal to meet current environmental regulations, limestone scrubbers are being designed with an L/G as high as 150.

The L/G ratio sets the size of the slurry recirculation pumps on the tower based on the flue gas flow that will be passing through the tower. The higher the L/G, the bigger the pumps and the higher the capital costs. The operating costs will also be higher because of the higher horsepower requirements. The size of the absorber tower will also be larger to accommodate more slurry spray nozzles and spray levels. Again this adds to the capital cost.

A design with a higher L/G will have more slurry in contact with the flue gas at any given instant. This is necessary for limestone since it has a much slower dissolution and reaction rate than the other chemicals, so there are less reactive sites in each droplet. It takes more droplets, in contact with the gas, to have the same number of reactive sites in contact with the gas. Some designers design the absorber tower with a smaller L/G based on feeding performance enhancing chemicals with the limestone. This can save some capital and operating costs. A utility has to decide whether to choose this design or insist on a design with the higher L/G and without the performance enhancing chemicals. This saves the option of adding the chemicals at a later time in case the original design falls a little short or in case a higher removal percentage is required by future regulations or fuel supply change.

An absorber tower will have a better removal efficiency as boiler load is reduced. This is because with the same number of pumps operating and lower flue gas flow, the L/G will be higher. That is why it is possible to take slurry recirculation pumps out of service during sustained low boiler load operation and still maintain the required SO_2 removal.

5.5 Reaction Time

There are two separate reactions occurring in the absorber tower. The first is the reaction with the SO_2 in the upper section of the tower. The second is the limestone dissolution and crystal formation in the lower section of the tower which is typically referred to as the reaction tank. The SO_2 removal happens relatively quickly. The time can vary based on the "gas phase limited" and "liquid phase limited" principles discussed previously as well as the levels of bisulfite ions (HSO_3-), bicarbonate ions (HCO_3-) and any performance enhancing chemicals in the slurry. The flue gas is typically traveling through the absorber tower at a velocity of about 10 feet per second. So the gas is only in the removal section of the tower for several seconds. If the SO_2 doesn't cross the gas/liquid interface in those few seconds, it will not be removed and will exit the absorber tower.

Once the L/G ratio has been selected, the designers typically size the lower reaction tank portion of the tower so that its entire contents will be recirculated through the upper section of the tower every 6 – 8 minutes. This gives the chemical reactions that start as the SO_2 crosses the gas/liquid interface time to complete before that liquid is exposed to more flue gas. Based on the feed rate of fresh slurry into the tower to control pH, mist eliminator wash water entering the tower, and any water added to control slurry density, the slurry typically resides in the reaction tank for 8 – 10 hours before leaving the absorber tower towards the primary dewatering process.

This time is required to completely dissolve the limestone particles. The outer surface of the particles continually dissolves.

The completeness of this dissolution is dependent on the particle size coming from the ball mill, the pH in the absorber tower, and whether any limestone blinding is occurring in the tower. Any limestone that does not dissolve completely in the tower is wasted and adds to operating cost.

The longer retention time is also required to grow large crystals of calcium sulfite in an inhibited oxidation process or calcium sulfate (gypsum) in a forced oxidation process. The crystals grow slowly adding one atom at a time to the crystal matrix. A higher slurry density aids crystal formation due to the presence of a larger number of "seed" crystals. These present more active crystal matrix sites to which the chemical atoms can attach. Proper agitation of the slurry also aids in crystal formation. Once the sizes of the slurry recirculation pumps and absorber tower are designed, the amount of time available for the reactions to take place is set. If the reactions are not complete at the end of this time, changes will have to be made to the gas/liquid contact or the slurry chemistry to speed up the reactions. These changes are discussed in the various separate sections of this manual.

5.6 Stoichiometry

Stoichiometry is another ratio for measuring and comparing scrubber performance similar to the liquid/gas ratio. Stoichiometry is a measurement of the chemical efficiency of the scrubber operation.

The theoretical amount of lime or limestone required to remove some quantity of SO_2 can be calculated by determining how much calcium is required to react with that much SO_2 based upon the chemical reactions that are taking place. The theoretical quantity of lime or limestone required to supply that much calcium is then calculated.

The actual amount of lime or limestone consumed can be measured by the slurry fed to the absorber towers for some period of time along with the physical and chemical properties of the slurry. For that same time period, the amount of SO_2 removed can be measured using the flue gas flow through the towers and the difference between the inlet and the outlet SO_2 concentration monitors.

The stoichiometry is the ratio of how much lime or limestone was added to the scrubber to remove a quantity of SO_2 divided by the theoretical amount of lime or limestone that should have been used to remove that same quantity of SO_2. This ratio would be 1.00 if everything was perfect. Since nothing is perfect in the real world, the stoichiometry will always be larger than 1.00. This ratio is a convenient way to compare performance of different scrubbers. A scrubber with a stoichiometry of 1.05 is running more efficiently than a scrubber with a stoichiometry of 1.10.

Many of the early scrubber towers operated with a stoichiometry in the 1.10 – 1.15 range.

As a result of advances made in gas/liquid contact, ball mill and slaker operation, as well as scrubber chemistry, most of today's scrubbers can operate in the 1.03 – 1.06 range. These lower numbers mean less lime and limestone is being wasted which lowers operating costs.

5.7 Limestone Blinding

Limestone blinding is the term used to describe a condition that prevents the limestone from dissolving and reacting in an absorber tower. It occurs when a thin layer coats the surface of a limestone particle preventing the surrounding liquid from coming into contact with the limestone surface. An analogy would be the thin coating surrounding the medicine in a coated aspirin. There are conditions which cause temporary blinding and others which cause permanent blinding.

Temporary Blinding

Limestone blinding has been observed in forced-oxidation systems when insufficient oxidation air is provided. The increasing amount of dissolved sulfite results in blinding as sulfite begins to precipitate on the limestone particles. This phenomenon disappears quickly when sufficient oxidation air is provided and sulfites are converted to sulfates, which lowers the saturation of dissolved sulfites. This causes the precipitated sulfite to dissolve from the surface of the limestone particles.

Another interesting phenomenon with limestone is a "blinding" event that can take place during sudden large increases in inlet SO_2 or boiler load. This is most likely to happen to units that cycle up and down following load. It is most likely to happen on a Monday morning. The unit may have been set at less than 50% load all day Saturday and Sunday. Then on Monday morning, the load increases rapidly to 100%. The sudden influx of SO_2 causes a sudden increase of dissolved sulfites in the slurry. The increasing amount of dissolved sulfite results in blinding as sulfite begins to precipitate on the limestone particles. The symptoms of a "blinding" event are:

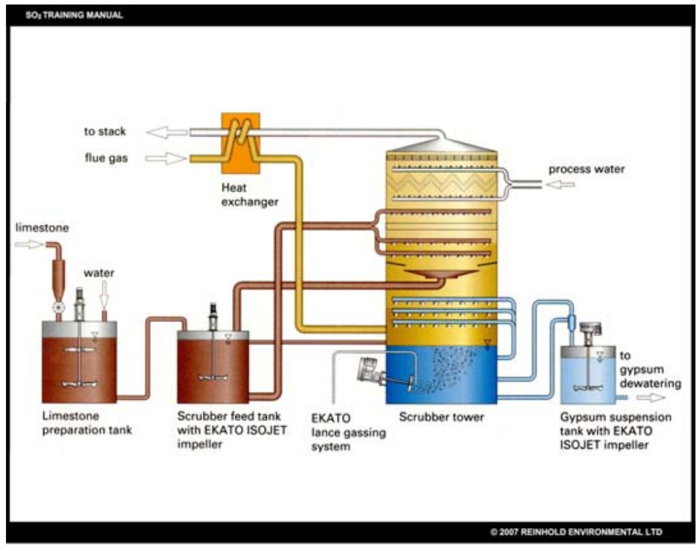
- The limestone feed valve is completely open
- The pH is staying the same
- The SO_2 removal efficiency is decreasing

The only way to stop this phenomenon is to close the limestone feed valve. The pH will remain the same even though no more limestone is being fed. Once the limestone feed is discontinued, the increasing acidity in the tower dissolves this coating off the limestone particles and the reactions return to normal. After some period of time the pH will start to fall. When this happens, place the limestone feed control back on automatic and the system should return to normal operation.

Permanent Blinding

Fluorides in the slurry can react with fly ash in the scrubber tower. Fly ash contains aluminum. The aluminum fluoride (AlFx) compounds that form can cause limestone blinding by precipitating on the surface of limestone particles. There is no way to prevent this blinding or reverse the blinding if these aluminum fluoride compounds are present. There will always be some amount of fluorides in the scrubber slurry since the fluorides are in the coal and are part of the flue gas entering the scrubber.

The best means of prevention is to keep the amount of fly ash entering the scrubber tower to a minimum through proper precipitator operation and maintenance. The result of permanent limestone blinding is increased limestone consumption and higher operating costs because purging the slurry and replacing with fresh limestone reagent is the only way to regain tower performance.



Agitators in Wet Limestone FGD
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5.8 Mixing

Mixers are some of the most important components in an FGD system since many of the liquid streams are slurries of limestone particles as well as calcium sulfite and calcium sulfate crystals. In a non agitated tank, the solid particles in these slurries will quickly settle to the bottom of the tank. If there is a power outage in an FGD area (yes, this has happened more frequently than you would think), one of the first priorities when the power returns should be to get all mixers back in service as quickly as possible. The longer a mixer is out of service, the more solids will settle. If enough solids settle, the impeller of a mixer could become buried in solids which could cause problems when trying to restart the mixer. Many of the specifications for newer FGD systems require that the mixers must be able to restart and resuspend the solids in a tank after a 24 hour power outage.

Agitator - Side Entry
Used with permission from EKATO Corp.

Due to the height and configuration of absorber towers, many FGD designs use side entry mixers. One main issue with this arrangement is that a mechanical seal must be installed where each mixer shaft penetrates the tower wall. Since the mixers are mounted below the liquid level in the tower, seal maintenance is critical to keep slurry from leaking out of the tower along the mixer shaft. Due to the corrosive and abrasive nature of the slurry, all the mechanical seal components (including the metal springs and components inside the seal) must be fabricated out of materials that can withstand the pH, chloride levels, and abrasive particles in the slurry.

There are some absorber tower designs that allow for top mounted mixers. Most of the other tanks and sumps in an FGD system can also use top mounted mixers. A top mounted mixer has the advantage of not needing a mechanical seal where the shaft penetrates the tank roof. The shaft is also vertical, so longer shafts and larger impellers can be used since the weight will not be deflecting the shaft as it does with a horizontal shaft. The main disadvantage of a top mounted mixer is its large size and weight. Often some type of structural steel frame must bridge the top of the tank with legs extending to the ground to support the mixer since it is too heavy to be supported by the tank walls.

Agitator - Top Entry
Used with permission from EKATO Corp.

Mixer impellers come in a variety of designs. For FGD purposes, most are axial flow (meaning the liquid leaves the impeller parallel to the mixer shaft). Typically the liquid flow is in the direction away from the mixer motor. The liquid is then directed by the geometry of the tank floor and walls into a flow path that circulates it back towards the mixer.

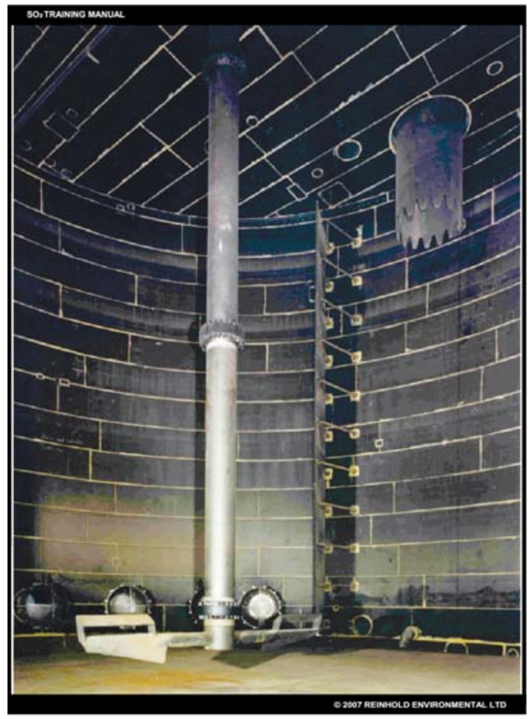
In single top mounted mixer installations the flow is typically down to the floor in the center of the tank, across the floor, up the side walls, and then back towards the mixer along the upper surface of the liquid. Often baffles are mounted vertically to the side walls around the inner circumference of the tank to prevent a rotational swirl from forming which would disrupt the desired flow pattern. When multiple side entry mixers are mounted in a circular tank, they are usually angled to cause an overall swirl in the tank. The liquid leaves one mixer and travels towards the next mixer. This continues from mixer to mixer as the liquid

Agitator - Side Entry Impeller
Used with permission from EKATO Corp.

circulates around the circumference of the tank. This swirling flow pattern can lead to several problems.

In the center of the swirl (at the center of the tank) there is a zone of low liquid velocity. In this zone, solid particles will settle into a conically shaped pile which may be many feet wide and tall. The pile will never grow any larger than the size of the low flow zone. During scrubber maintenance, when the tower has been drained, some operators have spent large sums of time and money removing this pile from the tower and disposing of it. They were severely disappointed to find a new pile of exactly the same size had formed within the first week of scrubber operation. Unless the pile is causing some problem with inspection or maintenance outage work, it may be left in place.

Another problem can occur with the mixers themselves. If one is having a lot of maintenance problems with mixer mechanical seals and bearings, one needs to be suspicious of this problem. The forces from the swirl can generate lateral forces on the mixer impeller and shaft in combination with the axial forces the mixer is trying to generate. To test for this problem, do the following:



Agitator - Top Entry Impeller
Used with permission from EKATO Corp.

- Run each mixer individually with the others out of service
- Monitor each mixer for vibration and movement of the motor and gear box on the mounting bracket (typically each mixer individually runs smoothly and quietly)
- Place all the mixers back into normal service
- Allow some time for a normal flow pattern to be reestablished
- Again monitor each mixer for vibration and movement of the motor and gear box on the mounting bracket
- If the mixer shafts are now experiencing fluctuating vibration patterns or the motors and gear boxes are trying to twist or jump on the mounting brackets, the mixers are experiencing swirl induced forces

Some utilities have been forced to remount their mixers at different angles to change the swirl and eliminate the problem.

The earliest impeller designs were 3 – 4 flat pieces of metal attached to a hub at some angle that would create the desired axial flow. They performed adequately. The newer impellers have more aerodynamic shapes. They can create the same flow using about half the horsepower. Due to the corrosive and erosive nature of the slurries, early mixers had shafts and impellers covered with rubber linings. Rubber linings still work well for low RPM mixers such as most of the top mounted mixers. The side entry mixers typically run at high RPM values. Rubber lining may work on the shaft but the rubber won't stay on the impellers. Impellers must be fabricated from corrosion and erosion resistant metal alloys.

Besides keeping the solids suspended in the slurry in the absorber tower reaction tank, the mixers are providing turbulence so that the limestone particles are constantly coming in contact with fresh liquid to dissolve the limestone surface. The mixing also aids crystal growth as the "seed crystals" are also constantly coming in contact with fresh supplies of calcium sulfite and calcium sulfate atoms. However, mixing that is too vigorous can break up newly forming crystals. In a forced oxidation system, mixers used in conjunction with air lances can provide very small air bubbles with large surface area to react with the calcium sulfite atoms and convert them to calcium sulfate. This will be discussed in more detail in Chapter 12 - Oxidation Air.

5.9 Performance Enhancing Chemicals

For a new system still in the design phase, the debate is whether to decrease L/G and tower size to save capital costs based on the affects of feeding performance enhancing chemicals or to base the design on operating without these chemicals. Many utilities have decided to base their designs on not using the chemicals. The logic is based on the fact that there is always some uncertainty in design performance versus actual achieved performance.

If the design doesn't include the chemicals and fails to perform to expectations, chemicals can quickly and cost effectively be added to bring the design to the required performance level. If the design is based on using the full potential of these chemicals and fails to perform to expectations, there are not any options that don't include major hardware revisions and cost to provide the required performance level.

Also uncertainty about future regulations or fuel supplies can influence this decision. If the FGD design is based on meeting current regulations without the use of performance enhancing chemicals, then future increases in required removal efficiency may be achieved in full or part by adding the chemicals when the new regulations take effect.

Magnesium

The first performance enhancing chemical used in FGD systems was magnesium. There are typically small amounts of magnesium in limestone deposits. Some of this magnesium may dissolve in an FGD system. If limestone is converted to lime, the magnesium is converted to magnesium oxide (MgO) which is very soluble in FGD systems. Besides this naturally occurring magnesium in the system, some operators add high magnesium lime to their systems to obtain the desired magnesium levels.

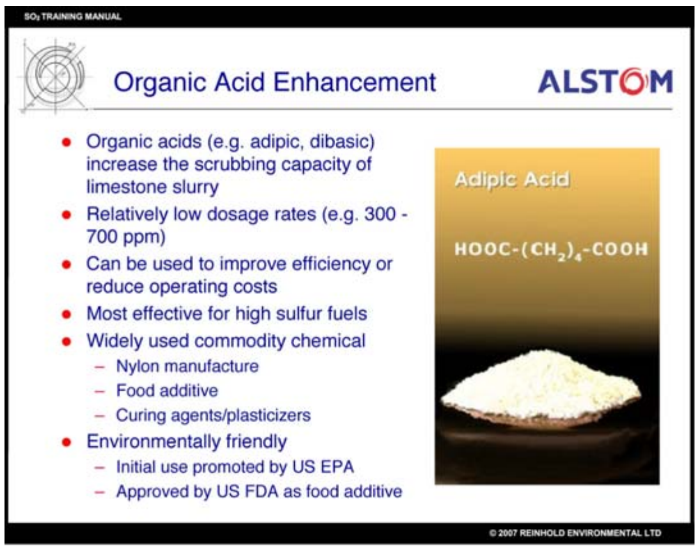
In the absorber tower, the magnesium compounds tend to stay in solution while the calcium compounds form calcium sulfite or calcium sulfate crystals which precipitate and are removed in the dewatering process. The magnesium compounds will stay in the liquid stream thru the dewatering process and return to the absorber tower as the liquid stream is recycled. So a small amount of magnesium added to the FGD system will tend to remain at high residual values in the system.

At the gas/liquid interface, SO_2 reacts with water to form a weak acid (HSO_3-) which then reacts with the calcium ions to form calcium sulfite ($CaSO_3$). As the calcium is depleted at the interface, the remaining weak acid ions drive the pH down which slows the SO_2 removal reactions. Due to the slow dissolution of the limestone, the calcium concentration can be depleted rapidly at the gas/liquid interface in a limestone scrubber. The magnesium can also react with the weak acid. The reaction of the magnesium and the weak acid neutralizes more of the acid which allows the pH to remain at a higher value. A buffer is a substance in solution that has the ability to react with and neutralize large amounts of acid, thus preventing the pH from changing substantially with small additions of acid. The buffering action of the magnesium keeps the SO_2 removal rate at a higher level at the gas/liquid interface.

The magnesium is not consumed in this process. It can be in the form of magnesium sulfite ($MgSO_3$) or magnesium bisulfite ($Mg(HSO_3)_2$). The magnesium sulfite can react with the weak acid and be converted into magnesium bisulfite while removing SO_2 from the flue gas. During the longer residence time in the reaction tank, dissolving calcium can react with and remove one of the sulfite groups from the magnesium bisulfite converting it back into magnesium sulfite. This mechanism allows the faster magnesium reactions to capture SO_2 at the gas/liquid interface and transfer it to the slower calcium in the reaction tank without removing the magnesium from the system.

Chlorides have a negative affect on SO_2 removal. One cause of this is that chlorides will react with magnesium to form magnesium chloride ($MgCl_2$). This will permanently remove that magnesium from the previously discussed buffering reactions. A magnesium enhanced absorber tower can remove the same amount of SO_2 at a lower L/G ratio or it can remove more SO_2 at the same L/G ratio.

Organic Acids



Organic Acid Enhancement
Used with permission from Alstom

The first organic acid that was used in FGD systems was pure adipic acid. It was primarily used in the manufacture of nylon, so large quantities were readily available. After it proved successful, alternatives were investigated that might lower cost. It was discovered that the waste liquid stream left from the nylon manufacturing process also worked well. It contained unreacted adipic acid as well as shorter chain succinic and glutaric acids. This was a waste product that the nylon manufacturers had to pay to have disposed. Once utility stations began to consume the waste, nylon manufacturers were glad to sell it to them as the price was still lower than the pure adipic acid.

The molecular chains of these acids have a hydroxyl group (OH) on each end. Because of this, these acids are referred to as dibasic acids. The mixture of these various acids is more typically referred to as DBA. The proportions of the various acids in the mixture may vary but this doesn't seem to affect the performance in scrubbers. Because of its lower cost, DBA is the most used organic acid for performance enhancement.

The organic acids function much like magnesium at the gas/liquid interface. They act as buffers which keep the pH from dropping as quickly. They also help move some of the SO_2 away from the interface so more can move from the gas into the liquid. One difference is that the organic acids allow the absorber towers to operate at a lower pH. This lower pH allows the limestone to dissolve more quickly and completely.

Organic acids can minimize the negative effect chlorides have on scrubber performance. They also seem to minimize the limestone blinding effect that fluorides and fly ash can produce. An organic acid enhanced absorber tower can remove the same amount of SO_2 at a lower L/G ratio or it can remove more SO_2 at the same L/G ratio.

The cost of organic acid addition is dependent on system conditions and how fast the organic acid concentration is lost. The acid can be lost in liquid leaving the scrubber system. The acid can be lost through co-precipitation into the calcium sulfite and calcium sulfate crystals. The acid can degrade and break down into other compounds. One of these degradation products is valeric acid. Valeric acid can produce a noticeable unpleasant odor. To fully realize the benefits from performance enhancing additives, the overall scrubber water balance must be controlled and optimized to minimize chemical usage (relative to the FGD performance required).

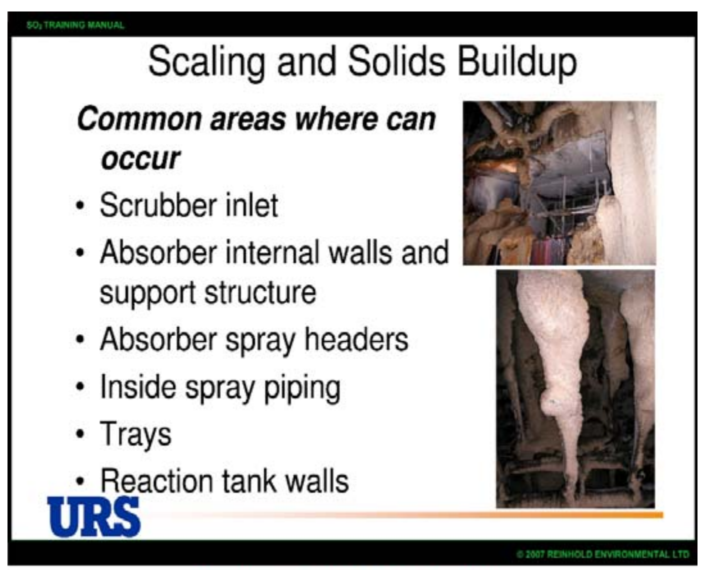
Economics

The economics of performance enhancing chemicals are fairly straightforward. On the one hand is the total cost of purchasing, storing, and feeding the chemical. On the other hand are the benefits of higher SO_2 removal, possible lower L/G, change of tower size in the design phase, savings in lime or limestone consumption, or any other identified benefit. If the benefits outweigh the cost, then performance enhancing chemicals should definitely be considered.

5.10 Scale Formation

Deposits on the walls and other parts of the FGD system are typically referred to as scale. It can be formed when water evaporates from slurry and leaves the solids behind. It can also form when the saturation limit of calcium sulfite is reached in the slurry and calcium sulfite deposits begin to form.

There are several areas in the FGD system where it is normal to find scale formation due to the evaporation of water from the slurry. The first is the wet/dry interface where the inlet duct enters the absorber tower. Slurry droplets from the tower tend to splash back onto the hot duct wall in this area. The heat from the duct wall evaporates the water and leaves the solids behind on the duct wall. There isn't anything that can be done to prevent this. It is prudent to clean as much of this deposit as possible off this area whenever tower



Scaling and Solids Buildup
(Narrated by Gordon Maller, URS Corp.)

maintenance is being performed.

Another area is the tower wall directly above the inlet duct. Slurry running down the tower wall falls into the incoming hot flue gas stream. Deposits start to grow at the wall and continue to grow down into the gas stream. Many operators refer to these large flat hanging deposits as “elephant ears”. These deposits can cause more of the flue gas to flow towards the opposite tower wall and prevent gas from flowing properly up the tower near the inlet duct. When large segments of the deposit break off and fall into the reaction tank below, they can cause damage to mixers and slurry recirculation pumps. These deposits can be minimized by building an awning above the inlet duct that directs the slurry running down the tower wall to either side of the inlet duct without letting the slurry fall into the inlet gas stream.

Once the saturated gas is down stream of the mist eliminator, there is little excess moisture and solids left in the gas. If an area of duct wall dries out, some solids may be left on the wall. This is more prevalent with some of the older designs where hot, unscrubbed gas bypasses the absorber tower and is then mixed back into the flue gas stream in the FGD outlet duct for outlet gas reheating. This heated gas can evaporate the few remaining slurry droplets leaving any solids to build up as a deposit. It is prudent to remove any scale deposits in outlet ducts during FGD system maintenance.

In the absorber tower area, scale formations typically grow because the calcium sulfite concentrations in the slurry have exceeded the limits of solubility. This was more prevalent when towers were being operated in the natural oxidation mode. The disrupted crystal matrixes of the co-precipitate crystals slowed crystal growth. As the uncrystallized calcium sulfite concentrations rose, the calcium sulfite started forming crystal deposits on tower walls and other internal parts. The introduction of inhibited oxidation and forced oxidation has minimized this problem since the regular crystal matrixes grow more quickly taking the calcium sulfite or calcium sulfate out of solution more rapidly.

Another practice that has helped reduce scale formation is running with higher slurry density. This puts more “seed crystals” in the slurry which provides more sites for crystal growth in the slurry, so less growth occurs on walls. The use of performance enhancing chemicals can also reduce the amount of scale formation.

The final area of scale formation is in the mist eliminator blades. The shape of the blades causes liquid droplets to impact the blade walls, removing them from the flowing gas stream. This liquid must drain down the wall of the blade and then drip off into the tower below. If the liquid resides on the blade for very long, the calcium sulfite concentrations can build up and deposits will begin to form on the blade walls.

Most mist eliminators are designed with wash systems to wash each blade several times per hour. It works best if this wash water is fresh water. Fresh water will lower the calcium sulfite concentration on the blade wall and help dissolve any deposits that have formed. Even with wash systems, most mist eliminators will eventually plug with scale deposits. Then the tower must be taken out of service and the deposits removed either mechanically or more typically with a high pressure water stream. Care must be taken during this operation so as not to damage the thin mist eliminator blades. Scale deposits and/or damage from aggressive cleaning in mist eliminators seriously degrade their ability to remove liquid droplets from the gas stream.

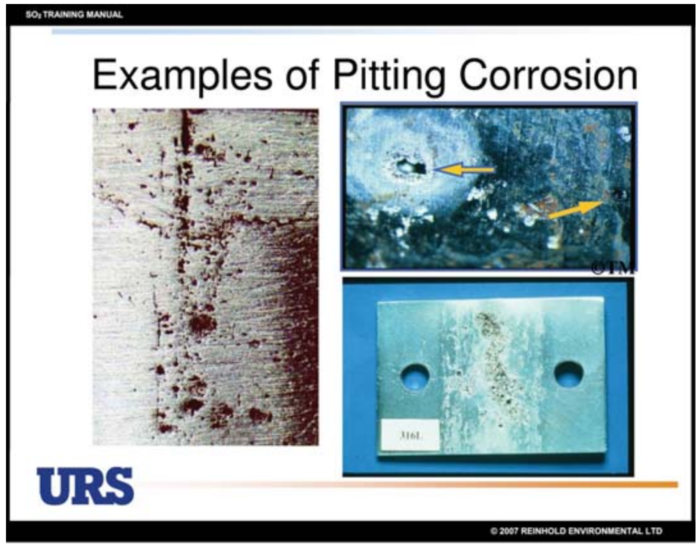
5.11 Corrosion

General Corrosion

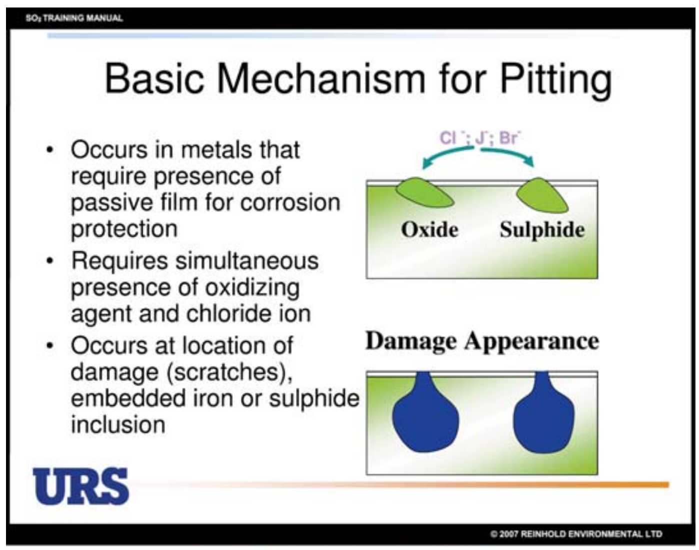
With general corrosion, the entire metal surface corrodes at about the same rate so that the entire area disappears at about the same rate while maintaining roughly its normal shape. Sometimes one must measure the thickness of the metal to determine how much corrosion has actually occurred.

If corrosion resistant alloys are being used in an FGD system, general corrosion is typically only seen in the outlet duct and chimney areas where the pH is at its lowest values. In systems where unscrubbed bypass gas is mixed with scrubbed gas in the outlet duct, everything downstream of the mixing area is very susceptible to general corrosion due to the strong acids formed in this mixture.

Carbon steel is susceptible to general corrosion anywhere in an FGD system. If slurry gets back into an unlined carbon steel inlet duct, corrosion can be rapid, especially on the floor if there is pooling of the liquid. The outside surfaces of equipment can suffer severe corrosion if there is gas or slurry leakage. This is very prevalent around dampers since damper seals will leak sooner or later. Structural steel can be corroded away. Electrical conduit, cable trays, junction boxes, etc. will be subject to attack and can simply disappear. Plastic conduit and boxes or PVC coated conduit and boxes should be used in these areas.



Examples of Pitting Corrosion
Used with permission from URS

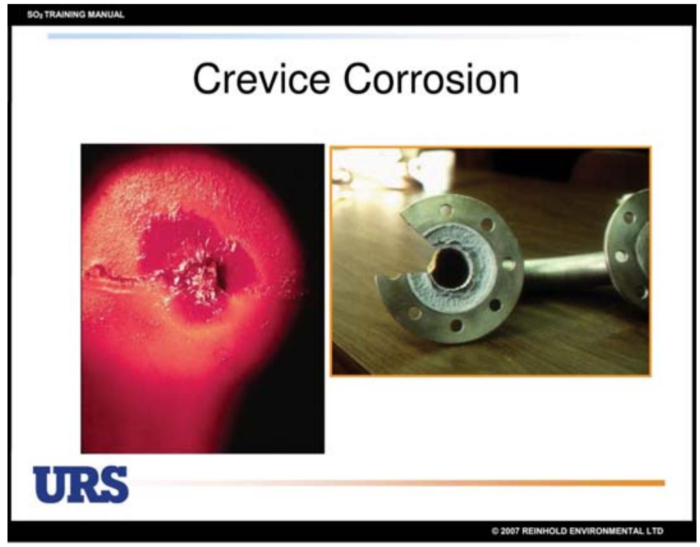


Basic Mechanism for Pitting
Used with permission from URS

Flake glass, epoxy, or rubber lined carbon steel tanks, pipes, pumps, and valves will corrode rapidly if the lining fails. All linings are permeable, so after some period of years, the corrosive liquid will penetrate through the lining. Corrosion will then occur behind the lining and the lining will delaminate from the steel. Linings should be inspected during maintenance outages by looking for blisters or soft spots. Also look for erosion damage on pump liners and impellers, in piping elbows, and at restrictions or changes in flow such as around the edges of the slurry recirculation pump suction pipes where they exit the reaction tank. Linings are more easily repaired if action is taken before corrosion occurs to the steel substrate.

Utilities have found that if slurry pump liners are replaced before the erosion completely penetrates the rubber, new pump liners can be quickly bolted in. If the erosion has penetrated the pump liner, then severe corrosion of the pump housing occurs rather quickly. Then extensive repair or replacement of the pump housing must be done before the liner can be reinstalled. Rubber covered pump impellers are similar. If replaced soon enough, the old rubber can be removed and new rubber molded onto the old impeller. But if the rubber has been penetrated, the impeller will have experienced enough corrosion that a new impeller will need to be purchased.

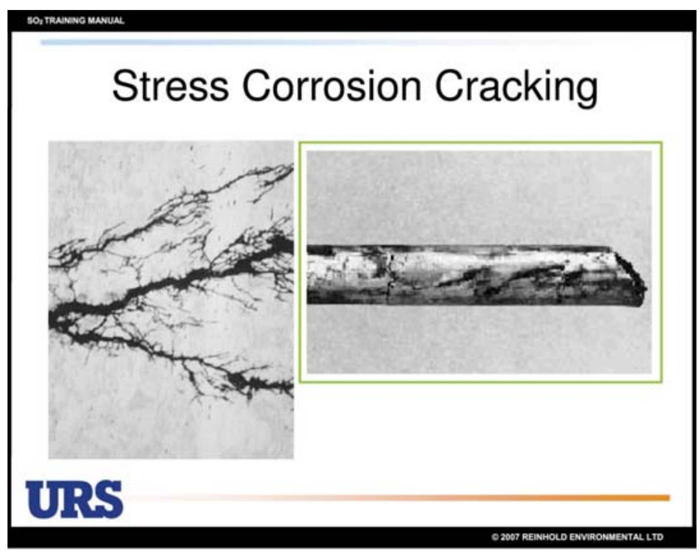
Real Life Example



Crevice Corrosion
Used with permission from URS

At one utility, a large slurry recirculation pump suction knife gate valve was replaced under warranty. The vendor decided to substitute a rubber lined carbon steel valve body for the original alloy valve body. After one month of service it was noticed that the rubber lining had failed on the valve body. Further inspection showed that 1" of the 1.5" thick valve body was no longer present under the lining failure. Needless to say, the vendor again replaced the valve but used an alloy valve body this second time.

Pitting Corrosion

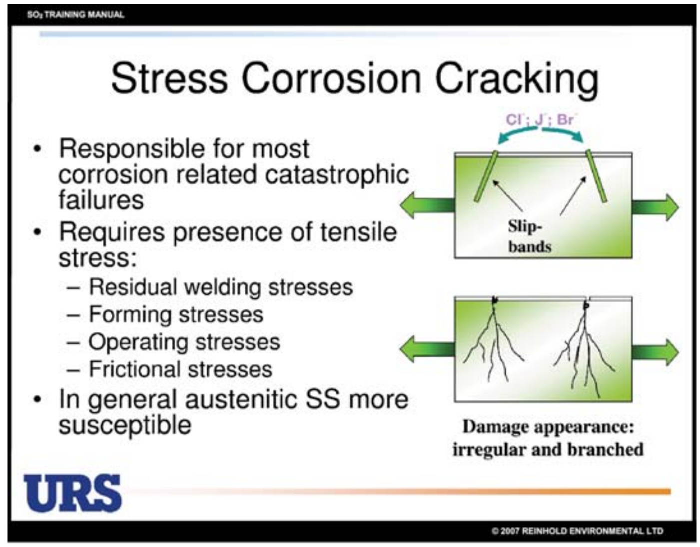


Stress Corrosion Cracking
Used with permission from URS

Pitting can occur anywhere in the system if chloride levels rise to levels above the tolerance of the metal alloys in an area. Chloride samples should be tested weekly to determine the chloride levels in the system. Whenever these levels approach the threshold tolerance of the lowest metal alloy in contact with the liquid, blow down of liquid and the addition of fresh water to the system should occur to lower the chloride levels.

Even at tolerable chloride levels, pitting can occur under scale formation. This happens because chloride and fluoride levels can become concentrated under deposits. The deposits also block contact with oxygen which can cause a condition that will accelerate pitting attack. This is why scale formations should be removed and the areas under them inspected for attack during maintenance outages.

Metals containing residual stress are also more susceptible to chloride attack. This is true for thin formed shapes such as damper seals and mist eliminator blades. The stresses are in the pieces of metal due to the process of bending them into their shapes. There are cases where these types of parts fabricated from metal alloys that should have been pitting resistant at the levels of chlorides in a system have looked like Swiss cheese after a short time in service.



Stress Corrosion Cracking Diagram
Used with permission from URS

Sulfate Reducing Bacteria (SRB)

SRB is prevalent and can be found in almost any ground water sample or river in the world. Since they are anaerobic (hate oxygen) they usually don't multiply and cause problems in fresh water. If the water is stagnant and loses its oxygen content, the SRB can begin to multiply. They can feed on iron or sulfur as their source of energy. So an FGD system can be an ideal place for them to multiply.

Under scale formations or in piles of stagnant solids (such as the pile in the center of a thickener or absorber reaction tank,) it is not unusual to find a black slimy layer and smell a "rotten egg" odor (this is the hydrogen sulfide (H_2S) gas they produce). These occurrences are more of a nuisance than a problem.

CAUTION! A large release of hydrogen sulfide gas when the material is disturbed can be a personnel safety hazard since it is highly toxic. But there usually aren't any corrosion issues if the deposits are on alloys or linings.

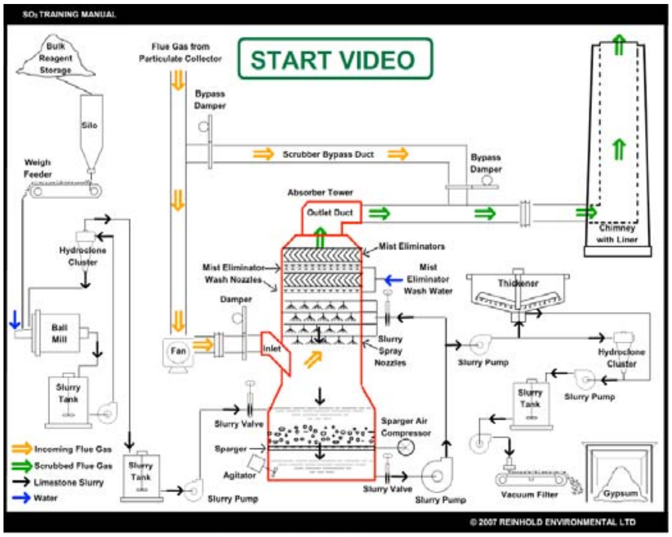
Carbon steel tanks or piping is a different story. SRB attack will look similar to pitting attack. The bacterial colonies will eat narrow deep pits through the steel. Once a colony forms, it builds a slime deposit over itself to protect it from the environment and maintain anaerobic conditions. This makes it harder to stop the corrosion.

Often conditions aren't right for the bacteria to grow during normal operating conditions but if the bacteria form a colony during construction and testing, they can continue to grow once the system is put in service.

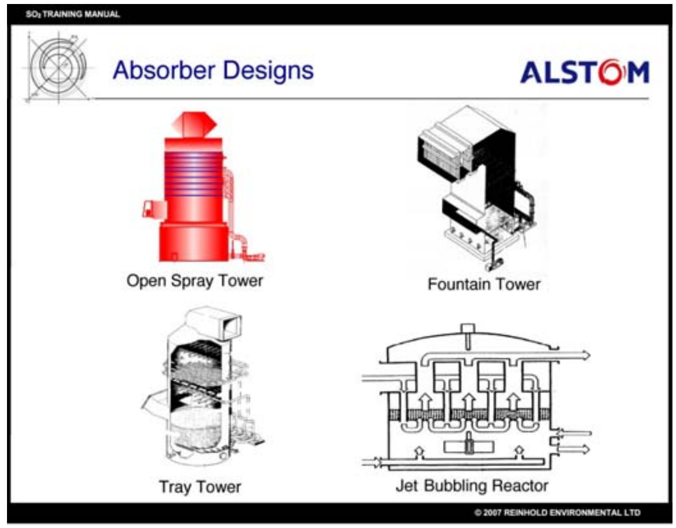
Real Life Example: At one utility, the slurry feed tank was constructed of unlined carbon steel. Because the pH of the slurry wasn't that low, corrosion wasn't expected. During construction, the tank was filled with well water for hydro testing and after the test, the water was allowed to sit in the tank for many weeks waiting for testing of the pumps and piping. After about a year of normal operation, the tank started to weep slurry from numerous small holes in the tank wall. The tank was drained and inspected. SRB colonies were found at random locations covering the entire tank wall. When each colony was removed, a small diameter hole was found partially or fully penetrating the tank wall.

The pH and agitated conditions in the tank were not conducive for SRB growth. But each colony had built a slime roof over itself to protect itself from these tank conditions. It was decided to high pressure water blast the tank wall, removing the slime deposits and the bacteria beneath. Immediately after the water blasting, the tank was refilled with agitated slurry. The corrosion problem never returned. Apparently the SRB colonies were established during the time that the stagnant hydro test water sat in the tank. It would have been better to drain the water immediately after the hydro test or add chemicals to the water to prevent the bacterial growth.

CHAPTER 6 - TOWER TYPES



Chapter 6 Summary
(Narrated by Ron Richard, RE Consulting)



Absorber Designs
Used with permission from Alstom

There are several absorber tower arrangements that have been widely used in the world and some newer arrangements that are just beginning to find wider acceptance. This chapter discusses the predominate features of the most popular designs currently in use.

The chapter also describes the strengths and weaknesses inherent in each design that ultimately determined why some were preferred over others.

6.1 Co-current/Counter Current

Co-current

In co-current flow, the liquid and the gas are moving in the same direction. The major advantage of this design is pressure drop. The moving liquid tends to pull the gas along with it. This results in a low pressure drop, no pressure drop, or even a slight pressure increase through the spray zone. This reduces required fan horsepower, capital coats, and operating costs.

The disadvantage is that there is less turbulence between the gas and liquid to provide mixing and intimate contact between the bulk liquid and the gas. Because of this, many of the co-current designs use some sort of packing layer. This packing divides and spreads out the liquid into thin films to expose more liquid surface area to the gas.

Counter Current

In counter current flow, the liquid and the gas are moving in opposite directions. The moving liquid tends to stop the gas and cause it to move in the opposite direction. The major disadvantage of this design is that the fans must create enough pressure to keep this from happening as well as keeping the gas flowing through the tower. The higher the back pressure is, the larger the fan horsepower requirement, capital costs, and operating costs.

The advantage is this forcing of the gas flow against the liquid flow is the creation of a lot of turbulence and mixing which brings more of the bulk liquid and gas together. This is why high SO_2 removal rates can be achieved in an open spray tower design.

If there are areas of lower liquid density, the back pressure will tend to find the lower resistance to flow in these areas and more of the gas will flow through these areas, thus decreasing the efficiency of the spray zone. This is why so much work has been done in recent years looking at spray patterns, droplet size, nozzle overlap, and tower wall effects.

6.2 External/In-situ Oxidation

Forced oxidation is the process where additional air is bubbled through the slurry to oxidize all the calcium sulfite to calcium sulfate. If this is done in the lower part of the absorber tower in the reaction tank, it is referred to as in-situ oxidation. If it is done in a separate oxidation tank, it is referred to as external oxidation.

External Oxidation

A constant bleed stream of slurry leaves the absorber tower and enters a separate oxidation tank. There needs to be a specific depth of slurry above the air inlets to provide enough reaction time between the air bubbles and the slurry. There needs to be enough residence time in the tank for the complete oxidation of the calcium sulfite. For these reasons the external oxidation tanks are quite tall and large in diameter. The oxidation reaction gives off heat, so the tanks operate at an elevated temperature.

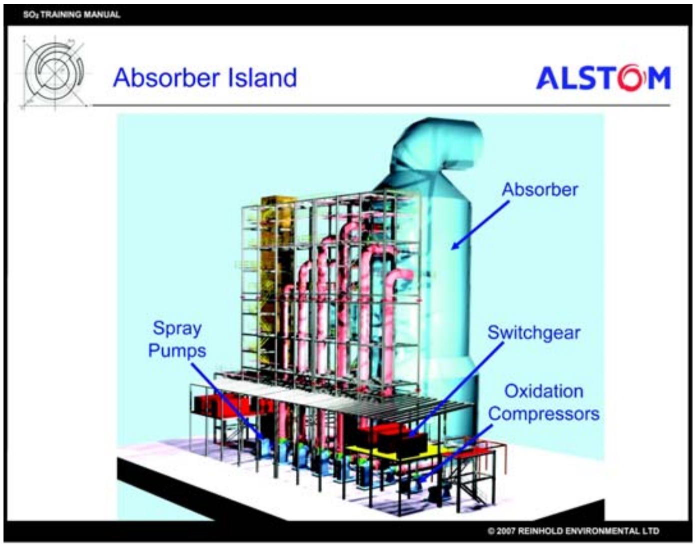
The oxidation reactions proceed more quickly at lower pH values. It is preferable to operate somewhere in the 4.5 – 5.0 pH range. This may be why most of the lime based FGD systems have chosen to use external oxidizers. It is more difficult to oxidize the calcium sulfite in a tower with a pH around 6. Acid can be added to the external oxidizer to adjust the pH to the desired value. This cannot be done in an absorber tower. A larger more uniform gypsum crystal may be grown in an external oxidizer.

The major disadvantages of external oxidizers are:

- The space required for another large tank
- The cost of another large tank
- The additional pumps, piping, and mixers required for another large tank
- The potential need to add acid for pH adjustment.

In-situ Oxidation

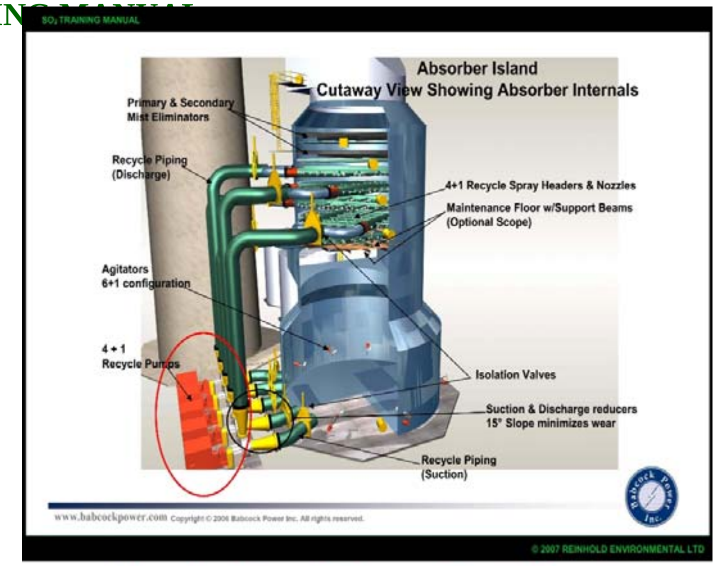
The biggest advantage of in-situ oxidation is that it is done in the absorber towers, so there is no need for additional tanks, pumps, piping, or mixers. However, the oxidation conditions are not as ideal as in the external oxidizer. The slurry temperature is lower and the pH is higher. This slows the oxidation process and may not produce gypsum crystals that are as uniform. But in limestone based towers, the results are still acceptable.



Absorber Island
Used with permission from Alstom

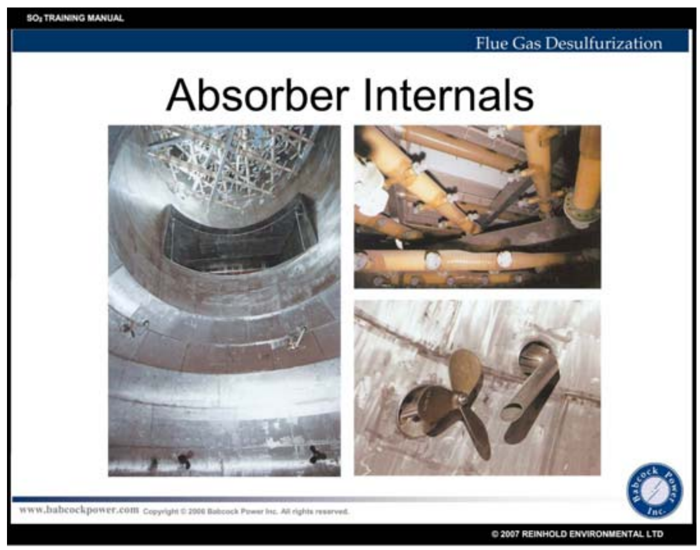
6.3 Spray Tower

The spray tower is one of the oldest and most widely used absorber tower designs. It is a very open design with few tower internal parts. It is typically a counter current design with the flue gas entering about a third to a half way up the tower and exiting the top of the tower. The gas enters the side of the tower in one quadrant with a slight downward angle to keep liquid from running back into the duct. So the gas must turn slightly more than 90º before traveling up the tower. It is important to do some flow modeling and install some turning devices to help the gas make this turn or the momentum can cause more of the gas to flow up the side of the tower across from the inlet rather than the side above the inlet.



Absorber Island Cutaway-Slurry Pumps
(Narrated by Tony Licata, Babcock Power)

Most spray towers have been designed with a gas velocity through the tower of around 10 feet per second. This was based predominately on the performance characteristics of the mist eliminators. With improvements to mist eliminator design, some of the newer spray towers are being designed with gas velocities in the 13-15 feet per second range.



Absorber Internals
Used with permission from Babcock Power

The spray patterns and droplet size have a large influence on SO_2 removal efficiency. There are typically 2 – 5 levels of spray headers depending upon the removal required and the sulfur content of the coal. It is best if one discharge header from a single slurry recycle pump goes to each spray level. It does not work well to feed spray levels at different elevations from the same header. The pressure differences make it impossible to balance the flows between levels. If two pumps are pumping into the same discharge header, the stronger pump will prevent the other pump from pumping at full capacity.

If spare pumps are desired, it is best to arrange valves so that the spare pump can be attached to a discharge header while the normal pump is isolated from the discharge header.

Recycle Slurry Spray Headers
Used with permission from Alstom

If the spray patterns don't overlap properly in a spray level, there will be areas of low liquid droplet concentrations. The gas will find these areas of lower back pressure and more gas will flow through these areas making contact with fewer liquid droplets. It was found that if the nozzles in each spray level were directly above and below those in other levels, lanes of low back pressure were formed that penetrated completely through the spray zone. Much of the gas would bypass liquid droplet contact and removal efficiency was lower. Today's designs minimize this problem by using identically designed spray levels where each level is installed at a 10-15º rotation from the one below it. This causes gas passing through a low droplet concentration area in one spray level to be directed into a higher droplet concentration area in the next higher spray level.

The area near the walls can be another area of gas bypass. If spray nozzles are too close to the wall the abrasion from the slurry particles can erode holes in the tower wall. If the nozzles are too far away, more gas will travel along the wall. Some designs have started adding wall rings between the spray levels to force the gas and the liquid running down the wall back out into the spray patterns.

Once the gas passes through the spray levels, it typically passes through two stages of mist eliminator vanes and then exits the top of the tower.

The lower part of the absorber tower is the reaction tank where the slurry resides between trips through the slurry recycle pumps and the slurry spray nozzles. There are mixers to keep the solids in suspension. If it is a forced oxidation unit, there may also be oxidation lances or sparger headers in the reaction tank.

The open nature of the tower and the reaction tank full of slurry cause issues for certain maintenance work. A decision has to be made whether to drain the reaction tank or work above the slurry pool. If it is drained, ladders or man lifts can be used for access to the spray levels.

To use a man lift, a large removable hatch may need to be installed in the reaction tank wall. If it is not drained, scaffolding suspended from the spray headers or supported from a grid installed just for that purpose must be used.

Also, there is the concern that sulfites in the slurry may consume oxygen creating an unsafe work environment. Therefore, confined space work procedures should be used.

Wall Rings
Used with permission from Alstom

Once the pressure drop across the mist eliminator reaches its maximum allowable value, the mist eliminator will need to be cleaned. Most mist eliminators will support the weight of people walking on them. It is prudent to walk on pieces of plywood laid on top of plastic or FRP mist eliminators to minimize cracking or breaking the edges of the vanes. Cleaning the underside of the first stage mist eliminator will require some sort of scaffolding, usually supported from the spray levels below, or some support grid installed for just that purpose.

Most cleaning is done with high pressure water lances. The pressure, the nozzle pattern, and the distance and angle the nozzle is held from the mist eliminator are critical. One needs enough force to dislodge the scale deposit. But with plastic or FRP mist eliminator vanes, one does not want to cut, crack, or break the vanes. This type of structural damage can lead to failure of mist eliminator sections in the future.

It is important to collect and remove the dislodged scale from the tower. If one doesn't do this, the next major maintenance task will be to clean or replace plugged slurry spray nozzles.

Tarps can be used below the work area to collect the material and a vacuum truck can be used to remove it from the tower. If the tower is drained, the vacuum truck can clean the reaction tank floor at the end of the cleaning. The vacuum truck should also clean any debris left laying on the mist eliminators. If you are going to clean both stages of mist eliminators, it is best to clean the upper stage first since the debris will fall onto the lower stage.

Mist eliminator wash nozzles should also be checked for pluggage, flow and spray pattern when the mist eliminators are being cleaned.

Since the slurry spray pattern is critical to spray tower efficiency, the slurry spray nozzles should be inspected periodically for pluggage. The amount of pluggage is a direct function of how clean the system is maintained. As discussed above, if mist eliminator wash debris is not removed from the tower, it can result in slurry spray nozzle pluggage. If scale forms above the flue gas inlet area and then breaks off, these pieces of scale can plug nozzles. If a slurry nozzle adjacent to the wall becomes partially plugged, there have been instances where the resulting concentrated stream of slurry has eroded a hole through the tower wall. If left in the absorber, pump impeller pieces, flange and door gaskets, nuts, bolts, tools, rags, ear plugs, rope, safety glasses, etc. are usually not conducive to FGD performance.

One often overlooked source of nozzle pluggage can be absorber area floor sumps. In many designs these floor sumps discharge back into the absorber tower. If this is the case, then any trash and debris that is washed from the floor into the drains which go into the sump can end up causing slurry nozzle pluggage. Any oil or spill entering the FGD process could become an issue.

The size and design of the slurry spray nozzles can also have a bearing on the frequency of nozzle pluggage. If there is no way to prevent certain debris from entering the tower, then one needs to look for nozzles with a large throat opening that will let the debris pass through. Of course this must be balanced with the fact that such a nozzle will produce a larger droplet size which may degrade SO_2 removal efficiency. Tower internals and spray headers should be inspected periodically for both erosion and corrosion damage. Mixer impellers and shafts should be inspected regularly. If there are oxidation sparger headers in the reaction tank, the holes should be inspected to assure that they are not restricted or plugged.

If large deposits of accumulated solids are going to be removed, care should be taken. Sulfate reducing bacteria may be living inside the deposit and forming hydrogen sulfide. This trapped gas can be extremely dangerous if enough is present. The area should be ventilated and monitored as the work progresses.

6.4 Tray Tower

The tray tower is another widely used design. A tray tower is a spray tower with a tray installed. So, one should read the Spray Tower section first. This section will point out the differences that occur due to the tray being installed.

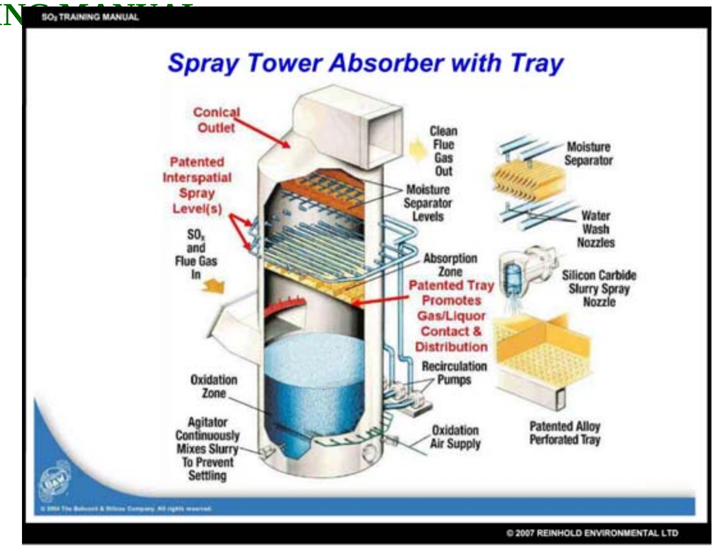
The tray percent open area is designed to a specified L/G to create a back pressure on the flue gas since the gas must pass through the holes in the tray. This back pressure causes the flue gas flow distribution across the tower to be more uniform. This minimizes the need for gas turning devices in the inlet duct area.

One tray is typically installed below the slurry spray levels. There have been a few instances where one slurry spray level is below the tray. Some installations utilize multiple trays.

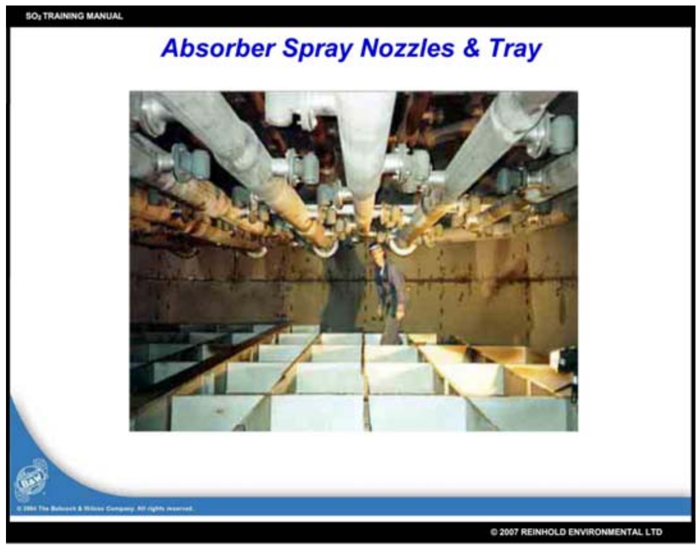
The droplets from the spray zone fall onto the tray and form a pool of slurry. The slurry in this pool must drain down through the holes in the tray to return to the slurry recycle pumps. At the same time, the flue gas is traveling up through these same holes. Like the spray tower, uniform slurry flow distribution is required

The tray should be inspected periodically to assure that the holes remain clean and open. Blockage of too many holes could result in a situation where the gas velocity through the remaining holes could be so great that the slurry would have difficulty draining back to the slurry recycle pumps. Or, blockage of holes in one section could disrupt the gas pattern going through the slurry spray levels above.

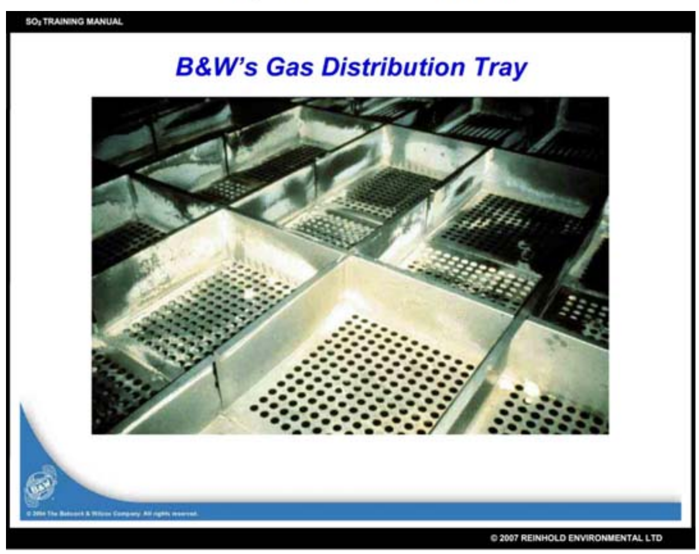
The interaction of the slurry and the gas forms a froth layer on the tray. The turbulence and large liquid surface area in the froth results in efficient SO_2 removal. Because of the SO_2 removal on the tray, less slurry spray levels are typically required than would be installed in an open spray tower. However, the design of these slurry spray levels is just as critical since they must remove the remainder of the SO_2.



Tray Tower Design
Used with permission from Babcock & Wilcox



Absorber Spray Nozzles and Tray
Used with permission from Babcock & Wilcox

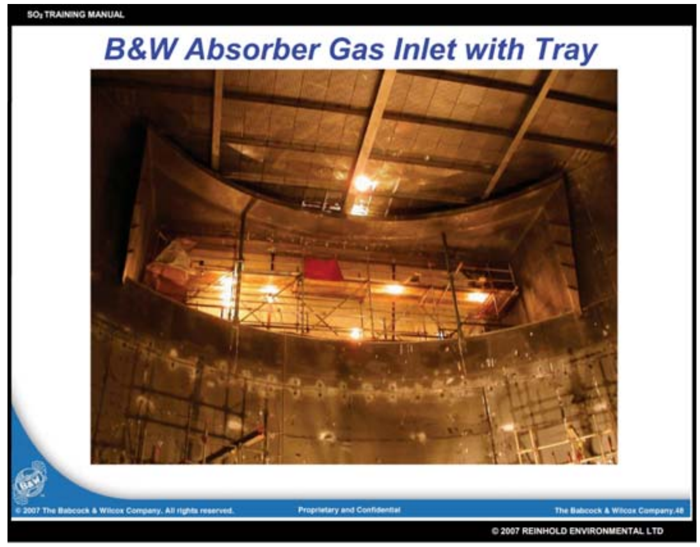


Gas Distribution Tray
Used with permission from Babcock & Wilcox

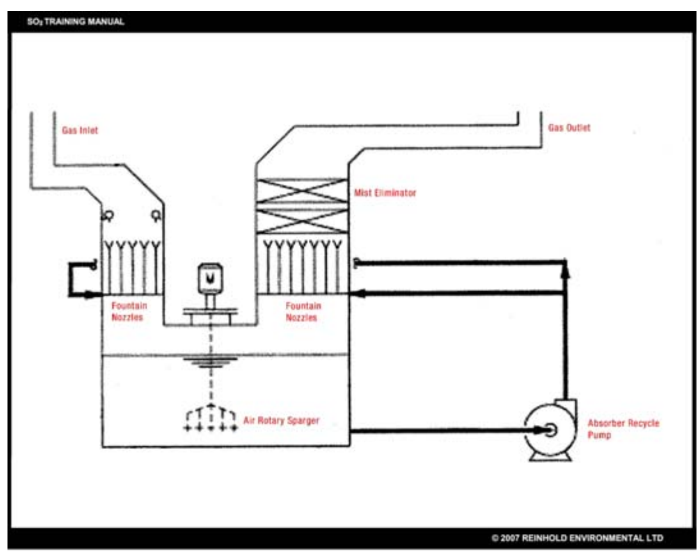
The presence of the tray allows for some additional maintenance options. The tray can act as a platform for staging maintenance work above the tray. That makes it less necessary to drain the slurry from the reaction tank.

Caution must still be exercised because of the large pool of oxygen absorbing calcium sulfite slurry below the work area. Ladders and scaffolding can be placed on the tray for access to the spray headers and distribution nozzles above. Care needs to be taken to use plywood or other suitable material to properly support the ladders and scaffolding on the tray and not damage the tray.

Tarps can be placed on the tray to collect the debris from cleaning work above on slurry headers or mist eliminators.



Absorber Gas Inlet with Tray
Used with permission from Babcock & Wilcox



Advatech Tower Design
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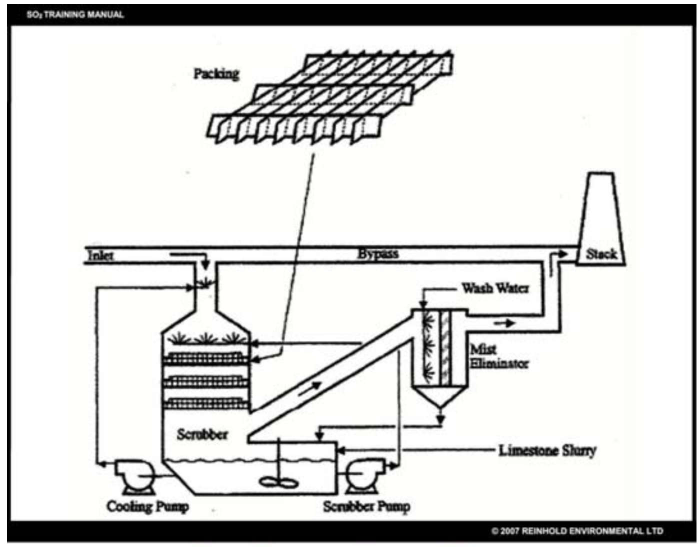
6.5 Fountain Nozzle Tower

Fountain nozzle towers have been around for years. Even the single towers operate as both co-current and counter current flow towers at the same time.

Some variations include two towers in a "U"-shaped configuration. Their distinguishing characteristic is the fountain style nozzle array positioned low in the spray zone. A fountain nozzle is a small diameter pipe open in a vertically upward orientation. Multiple solid cylindrical "fire hose" streams of slurry leave the nozzles flowing vertically upwards and contact the flue gas. Under the influence of gravity, the velocity of the stream slows. When the velocity reaches zero, the slurry spreads out in an umbrella shaped pattern and then starts to fall. Depending upon the surface tension of the slurry and the velocity of the flue gas through the tower, the falling sheet of liquid will break up into certain sized droplets. At this point the interaction between the flue gas and the droplets is the same as in a spray tower. Current designs utilize a recycle slurry density near 30% solids.

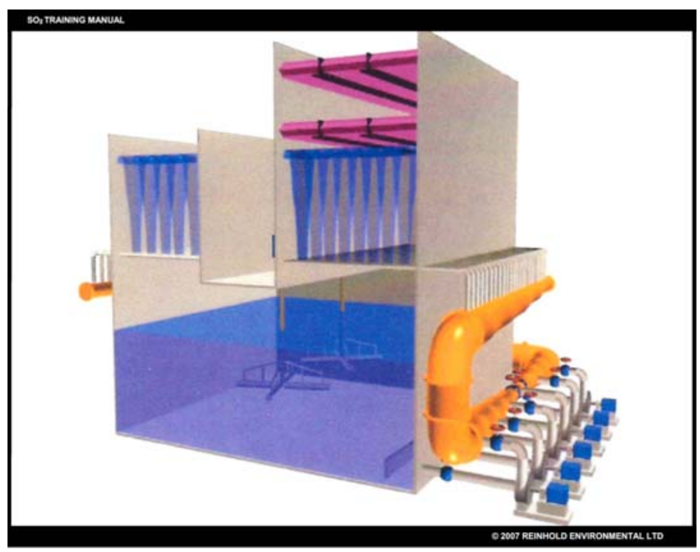


Early Fountain Nozzle Tower
Used with permission

The gas adjacent to the rising column of slurry is acting as though it is in a co-current tower. The gas is moving in the same direction as the slurry and is being pulled along with the slurry. The gas in the falling stream of droplets is impacting the gas and acting as though it is in a counter current tower. It is flowing in the opposite direction as the droplets and mist push its way through the droplet zone.

The early fountain nozzle towers used low pressure, low height fountains mostly for uniform slurry distribution. They relied on layers of packing to give them the liquid/gas interface area that was need for SO_2 removal.

The newer design forces the slurry from a single recycle header supplied by multiple slurry pumps to multiple nozzles at a higher pressure which causes the fountain stream to rise to a higher elevation. They have eliminated the packing and are relying on this thicker droplet zone to provide the needed liquid/gas interface area for desired SO_2 removal.

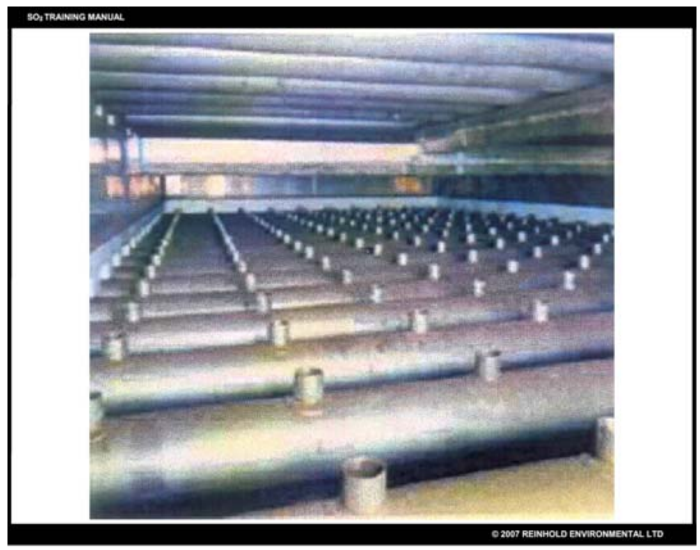


Fountain Nozzle Twin Tower
Used with permission from Advatech

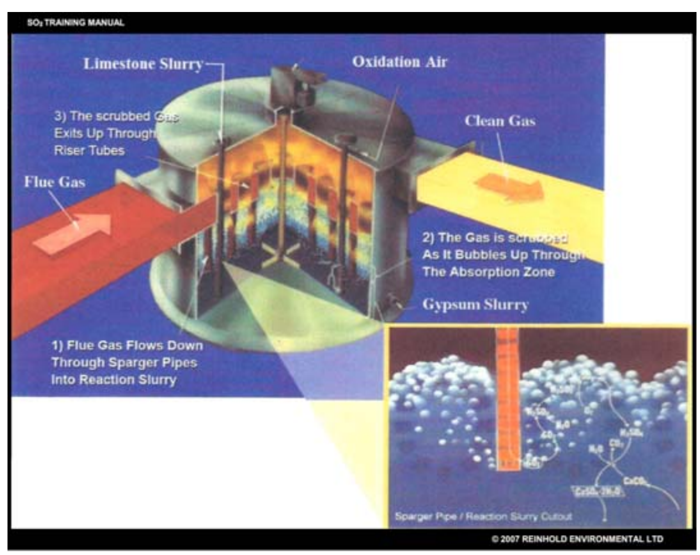
The Advatech design being offered for high-sulfur applications in the United States uses two sections of fountain nozzles in a "U"-shaped tower configuration. In the first section, the flue gas is traveling downward through the droplet zone. In the second section, the flue gas is traveling upward through the droplet zone.

The current designs have a rectangular tower shape. They tend to be not as tall as the vertical spray or tray towers.

There are minimal nozzle pluggage concerns or maintenance since the nozzles are open pipes with constant diameter from one end to the other. The materials of construction, process issues, mist eliminator pluggage concerns and maintenance requirements are similar to the spray and tray towers.



Slurry Spray Nozzles - Fountain
Used with permission



Jet Bubbling Reactor
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6.6 Jet Bubbling Reactor

The jet bubbling reactor (JBR) is completely different from the other types of absorber towers. In this design, the slurry remains in a large pool in the reaction tank. There are no large slurry recirculation pumps moving the slurry through spray nozzles. Instead, the required energy is provided by the flue gas fans forcing the flue gas out of numerous sparger pipes that are submerged below the surface of the slurry. Everyone has demonstrated this principle f they have ever blown through a soda straw that was submerged in a glass of their favorite beverage.

This design requires larger fans using more horsepower. The cost of this is offset by the fact that there are no slurry recycle pumps, valves and piping and the horsepower they require.

The flue gas distribution across the tower remains uniform at all loads due to the submerged sparger pipes. It takes the same pressure and flow through each pipe to create the bubbles in the slurry. No one individual sparger pipe can be operating at a different pressure. (This is true if all the pipes are submerged to the same depth in the slurry. This is one adjustment that must be made during the construction of the JBR.)

The rising bubbles of flue gas create a layer of froth on the top of the slurry pool. The surface of these bubbles creates a large liquid/gas interface area. A large, slow mixer continually circulates new slurry in the reaction tank into the upper sparger zone. Oxidation air sparger pipes also extend below the surface of the slurry to provide oxygen to oxidize the calcium sulfite to gypsum. Fresh lime or limestone is added to the reaction tank to maintain the desired pH.

The claim is made that due to the lower operating pH and less mechanical forces to break apart growing gypsum crystals, the gypsum crystals are larger than those from the other absorber tower types.

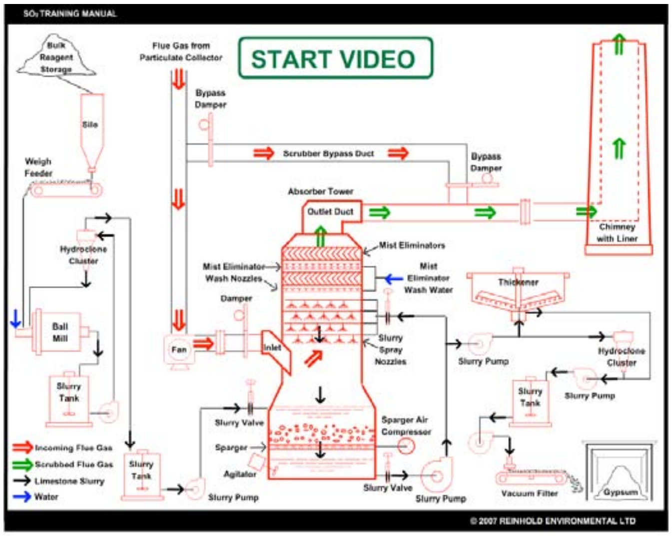
This design has gas cooling sprays in the flue gas inlet duct. Care must be taken when quenching the gas. If one reaches the saturation point, the resulting liquids can be very corrosive due to the amounts of acids formed. Newer designs incorporate a significant amount of FRP materials.

This design has mist eliminators orientated for horizontal gas flow. The claim is made that the mist eliminators do not have to remove that much liquid. This is due to the lack of slurry spray droplets suspended in the flue gas stream as well as the large volume of the gas plenums situated before the mist eliminator which allow moisture to settle out. This results in less pluggage and mist eliminator washing.

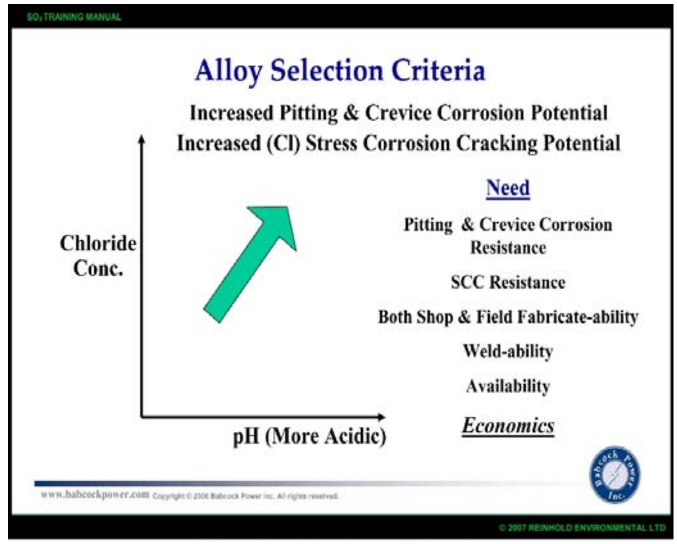
There are few moving parts to maintain and no nozzles to plug in this design. The biggest issues are scale formation and corrosion if the proper materials haven't been selected.

The JBR towers are not as tall as the vertical spray or tray towers.

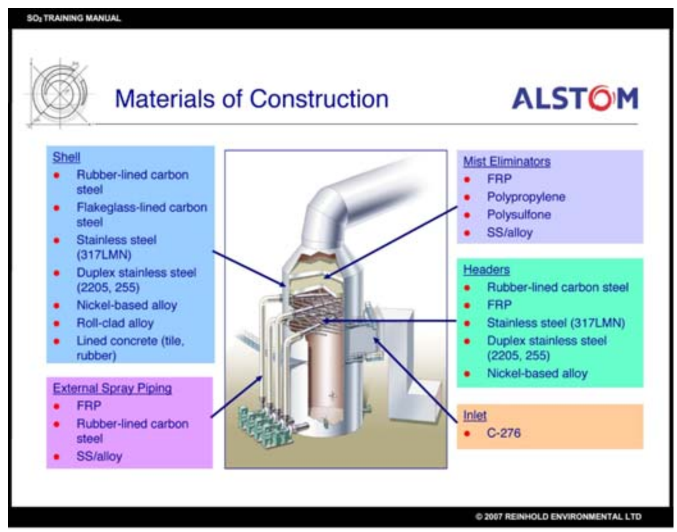
CHAPTER 7 - MATERIALS OF CONSTRUCTION



Chapter 7 Summary
(Narrated by Ron Richard, RE Consulting)



Alloy Selection Criteria
(Narrated by Tony Licata, Babcock Power)



Materials of Construction
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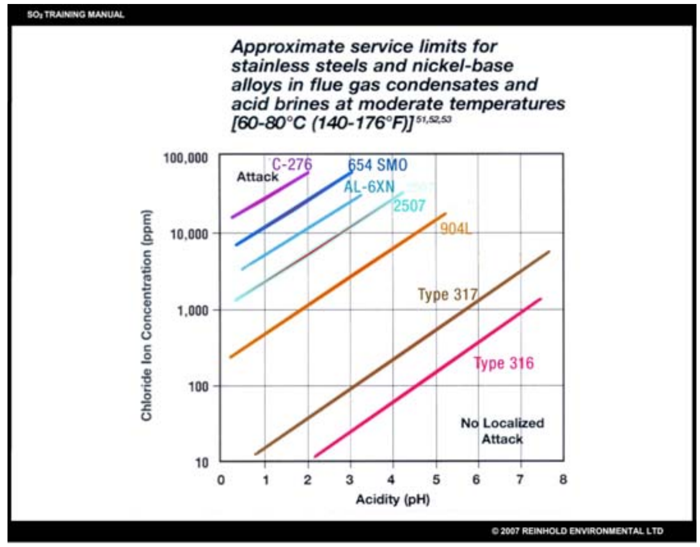
The erosive and corrosive nature of the slurry that circulates in FGD systems has proven challenging to the traditional materials of construction. Over the years there have been numerous costly failures of materials and important lessons learned.

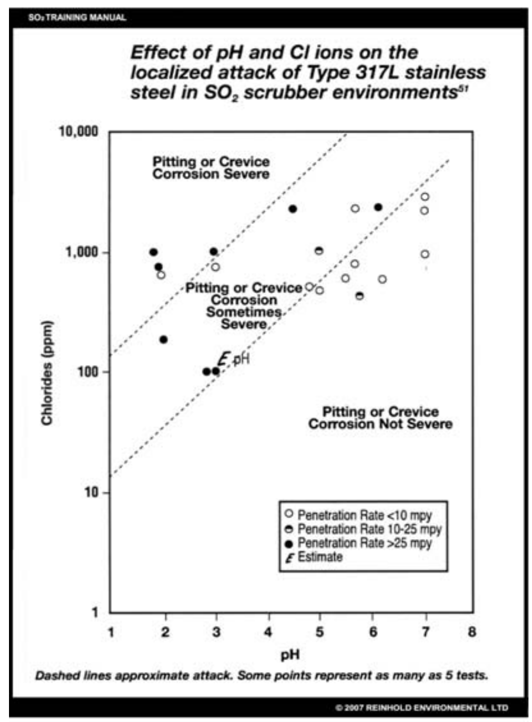
This chapter discusses the materials of construction that have a proven track record of surviving the FGD conditions, as well as the properties and limitations of each material. Included are examples of typical applications where each material has been used successfully



Approximate Service Limits for Alloys
Used with permission from Nickel Institute

7.1 Metals

Metals are typically used in the fabrication of process equipment. In the early days of FGD equipment, it was quickly learned that the life of bare carbon steel could be measured in months, weeks, or in some cases days. This was highly dependant on where the metal was located in the system (See Reference - PacifiCorp's 32 Years of Experience). The first response was to replace the carbon steel with 304 stainless steel. This lasted longer, but still suffered severe corrosion attack. So the next step was taken to use the more costly 316 stainless steel. Again, this material performed better but still succumbed to corrosion damage after a period of time.



Effect of pH and Cl Ions
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During this time, research was being done to determine the cause of the corrosion. It was determined that the pH and the chlorides were the main factors that led to failure. Fluorides also influenced corrosion, but were usually in low enough concentrations to not be a determining factor. The chlorides led to pitting and crevice attack which occurred much more rapidly than general corrosion of the entire area.

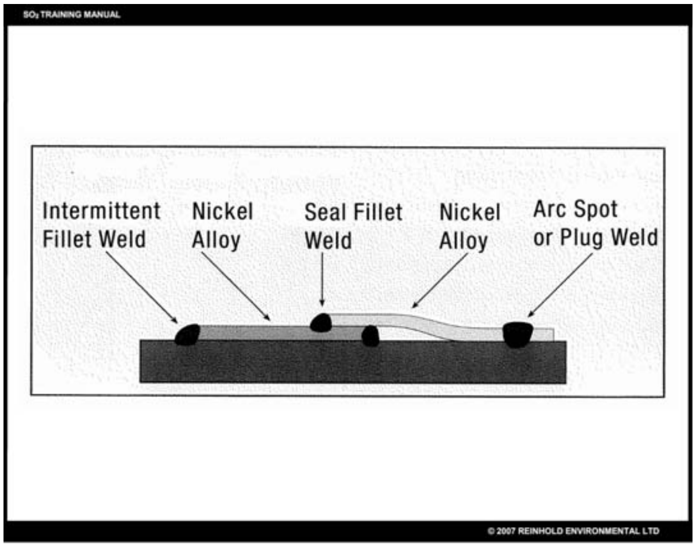
Scrubber operators had to rely on rubber or vinyl ester linings to protect the metal surfaces (these are covered in separate sections) or find metals that could withstand the chloride attack.

The alloy suppliers developed and tested many materials and have come up with a wide range of alloy choices that can be used depending upon the ph and chloride levels present. After years of experience, they have developed a chart of recommended materials depending upon the pH and chloride values.

It was discovered that nickel, chrome, and molybdenum were the key factors in developing corrosion resistant alloys for FGD systems. As the total content of these three elements increases, so does the corrosion resistance and also the cost. Some of the other elements added to the alloys improve the welding properties or the ability to work the metal. Titanium linings attached to carbon steel have also been used in FGD systems. Titanium's use has been limited so there is not as much performance history as there is with the other alloy materials.

Due to the high cost of the most corrosion resistant metal alloys, a method was needed to make their use more competitive with rubber lined and vinyl ester lined carbon steel. For new construction, this was accomplished by using explosives to bond a thin layer of alloy onto a carbon steel plate. This method was expensive and has been replaced by the roll bonding method of attaching the alloy to the carbon steel. For existing installations, a method to weld thin sheets of alloy to the existing steel duct walls was developed. This has been referred to in the industry as "wallpapering". The success of either method depends upon proper welding and fabrication procedures so that the carbon steel backing material does not contaminate the thin alloy sheet welds. Any carbon steel contamination will result in the loss of the alloy's corrosion resistant properties. NACE International has developed recommended practices for the proper installation of both types of materials (See Reference - Wallpapering Sheet Lining with Nickel Alloys)

Selecting the right alloy for a location in the system is not completely straight forward. The pH and chlorides can be sampled. This works well in areas



Wallpapering Lining Technique
Used with permission from Nickel Institute

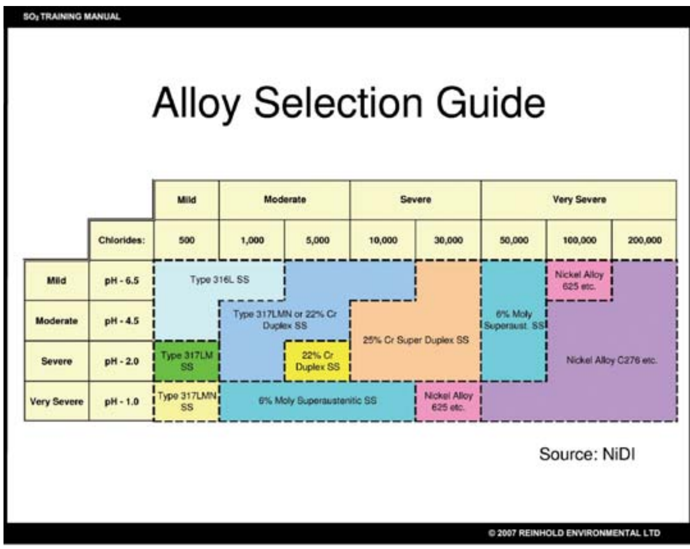
Composition of Representative FGD Alloy Materials

Alloy Common Name	Alloy UNS Number	Fe	Cr	Ni	Mo	Cu	N	Others
		Nominal Composition, weight %						
316L SS	S31603	Bal.	17	12	2.5	-	-	-
317L SS	S31703	Bal.	19	13	3.5	-	-	-
317LM SS	S31725	Bal.	19	16	4.5	-	-	-
317LMN SS	S31726	Bal.	19	16	4.5	-	0.15	-
317LN SS	S31753	Bal.	19	13	3.5	-	0.16	-
254 SMO	S31254	Bal.	20	18	6.3	0.8	0.2	-
2205 Duplex	S31803	Bal.	22	5.5	3.0	-	0.14	-
255 Duplex	S32550	Bal.	26	5.5	3.4	2.0	0.18	-
Zeron 100	S32760	Bal.	25	7	3.5	1.0	0.25	-
904L	N08904	Bal.	21	26	4.5	1.5	-	-
904hMo	N08925	Bal.	20	25	6.5	1.2	0.15	-
1925hMo	N08926	Bal.	21	25	6.4	0.9	0.22	-
AL-6X	N08366	Bal.	21	25	6.5	-	-	-
AL-6XN	N08367	Bal.	21	25	6.5	0.8	0.22	-
JS-700	N08700	Bal.	21	25	4.7	0.5	-	-
20	N08020	Bal.	20	35	2.5	3.5	-	0.5Cb + Ta
20 Mo-6	N08026	Bal.	24	35	5.9	3.0	-	-
825	N08825	Bal.	22	42	3.0	2.3	-	0.9Ti
G	N06007	20	22	Bal.	6.5	2.0	-	2.2Cb + Ta, 1.0W, 2.5Co
G-3	N06985	20	22	Bal.	7.0	2.0	-	0.5Cb + Ta, 1.5W, 5.0Co
H-9M	N06920	19	22	Bal.	9.0	-	-	2.0W, 5.0Co
Allcorr	N06110	-	31	Bal.	10.0	-	-	2.0W
625	N06625	5.0	22	Bal.	9.0	-	-	3.7Cb + Ta
C-276	N10276	5.5	15	Bal.	16.0	-	-	3.8W, 2.5Co
C-4	N06455	3.0	16	Bal.	16.0	-	-	0.7Ti, 2.0Co
C-22	N06022	3.0	22	Bal.	13.0	-	-	3.0W, 2.5Co
59	N06059	1.5	23	Bal.	16	-	-	-

Composition of FGD Alloy Materials
Used with permission

such as the absorber tower where there is either a lot of liquid in a pool in the reaction tank or a constant spray from the slurry nozzles. The value measured is typical of what the alloy is exposed to. It gets more difficult in duct locations. Under a deposit, such as the wet/dry interface area of the inlet duct, the chloride/fluoride values can be many times higher than what is measured in the duct itself. In the outlet duct and chimney, there is not much SO_2 left in the gas but there is also not much unreacted alkalinity in the liquid. Thus, any condensation on duct or chimney walls can result in a low pH condition on the wall. Experience has shown that the outlet duct and chimney have a severe corrosive environment that requires the most corrosion resistant materials. Fortunately, the alloy suppliers and utilities have published a large volume of experience that can be referred to when the time comes to select an alloy for a specific location.

The duplex stainless steels are a very cost effective material in today's steel market. They contain less high



Guidelines: Stainless Steel and Nickel Alloy
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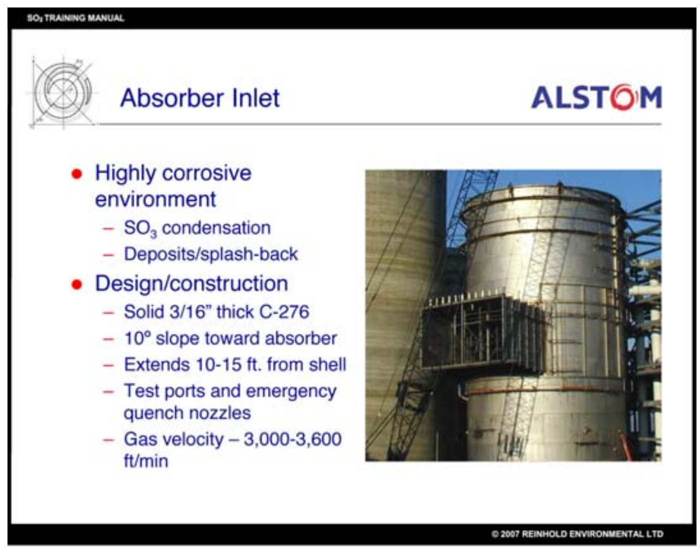
Spray Headers - Alloy
Used with permission from Babcock and Wilcox

cost nickel and chrome than many of the alloys.
But they have higher resistance to chlorides than might be indicated by these values. They depend on their unique structure of having both austenitic grain structure (resists general corrosion) and ferritic grain structure (resists pitting corrosion) in the same metal. This is why they were given their duplex designation. Not only do they have high chloride corrosion resistance, but they are more erosion resistant and have higher tensile strength. They have been used in the fabrication of several absorber towers.

Once the material has been selected, then proper welding procedures must be developed. It is often best to use a higher alloy weld filler material to prevent chromium depletion in the weld area. The effect of chromium depletion will be seen as pitting in the heat affected zone (HAZ) of the weld (the metal immediately adjacent to but not in the weld). The molten metal pool when welding high nickel alloys is more viscous and will not flow like a welder may be used to. It takes some practice to produce a proper weld bead profile. When welding the duplex alloy, care must be taken with the heat input of the weld so as not to change the grain structure and lose the corrosion resistant properties of the duplex materials. The alloy suppliers have experience in these areas and will make recommendations as to proper filler materials and welding procedures.

The high nickel alloys have the property of "work hardening" very quickly. This can make it very difficult to bend even thin material around a 90º bend. It also makes it virtually impossible to drill a hole through the material with a twist drill. It works best to cut a hole in the material with a plasma torch.

Beware of "hidden" metal in an FGD system. If one buys an off-the-shelf mechanical seal, it probably contains carbon steel or 304 stainless steel components in the interior of the seal assembly. If any slurry penetrates into the seal assembly, it can fail fairly rapidly. Make sure you ask or specify which metals are used in the seal design. Also beware of bolts and nuts. If the original erection contractor or the utility maintenance personnel need additional nuts and bolts, they often go to a tool crib and select stainless steel nuts and bolts of the required size. These will look similar or identical to what is installed in the area. But if they are not the required alloy, the difference will become apparent after a period of time in service. Alloy nuts have a tendency to gall on alloy bolts making them difficult or impossible to remove. A thread lubricant can help minimize this problem.



Absorber - Alloy
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Beware of metal that is not designed for corrosion resistance coming in contact with a corrosive environment. This can happen if sprayed slurry makes it back into the absorber inlet duct and comes in contact with the carbon steel. It is more likely to happen around test ports, guillotine gates or expansion joints. Leaks around damper seals or in expansion joints can subject external support steel to corrosive gas or liquid. There will always be leaks in these areas so use corrosion resistant alloys for damper and expansion joint frames. Use corrosion resistant coatings or linings on carbon steel in these areas.

Electrical conduit, junction boxes, hand switches, and cable trays can also be destroyed by flue gas or slurry leakage. PVC, PVC coated steel, or FRP electrical components will have a significantly longer life than standard electrical components in the FGD area. Remote hand switches should have rubber covers over push buttons and switches.

7.2 Rubber

Rubber has been used extensively in FGD systems. It is abrasion resistant which allows it to survive the pounding of erosive slurry particles. It is also resistant to extremely high levels of chlorides. It can withstand pH and chloride values that would attack most of the metal alloys. But is also has problems that have led to dramatic failures in some cases. So, one must understand its properties and limitations.

Different types of rubber have different flexibilities. This flexibility is measured with a Durometer using the Shore A scale. The lower the Durometer reading, the softer and more flexible a rubber is. A softer rubber will flex when impacted by a jagged slurry particle. This will absorb some of the impact energy and the slurry particle is less likely to erode the surface of the rubber. A more firm rubber with a higher Durometer reading will not absorb as much of the impact energy and will be more susceptible to erosion.

All rubber is also permeable to gases and liquids. This permeability varies with the type of rubber. This is important in the FGD application because it means that liquid will eventually pass through the rubber and come in contact with the metal behind it. Once the liquid penetrates, it will build pressure at the interface which will break the bond between the rubber and the metal. A blister full of liquid will form. If the liquid contains chlorides, corrosion of the metal will occur. The greater the permeability of the rubber, the shorter its useful life will be.

Unfortunately for FGD operators, the softer rubber is the most permeable. Thus rubber selection is a compromise between Durometer reading for erosion and permeability to give the desired longevity of service in a particular application.

All rubber must be vulcanized before it achieves it final physical properties. For smaller parts, such as rubber lined pipe, pump impellers and housings, and mixer shafts and impellers, this is done by placing the rubber covered or lined part in an autoclave. Steam is then introduced and the autoclave is held at a specified temperature and pressure for a specified time. This produces a very uniform and complete vulcanization of the rubber.

Of course, one cannot put an absorber tower or duct into an autoclave. Once the rubber sheet is field applied to the vessel, steam must be introduced to heat the vessel and the rubber to the proper temperature for the proper time to vulcanize it. Or else one must use a self vulcanizing rubber sheet. Some of the rubber failures that have occurred in FGD systems can be attributed to improper vulcanization of the rubber lining. It is difficult to hold every part of a large vessel at the same temperature for a period of time.

Other failures have been attributed to improper surface preparation and application. All sharp metal edges and welds must be ground smooth. All corners must be rounded to a specific radius. Then the metal surface must be solvent cleaned and sandblasted to a specific cleanliness and surface roughness. The adhesive must be applied and the rubber attached to it within a certain window of time before the adhesive sets up. All seams must be properly overlapped and glued. There are many opportunities for errors and they have all been experienced on some of the less successful rubber applications.

It is very important to have the proper installation procedures and an experienced application contractor who follows the procedures if one expects a long life from a rubber lining.

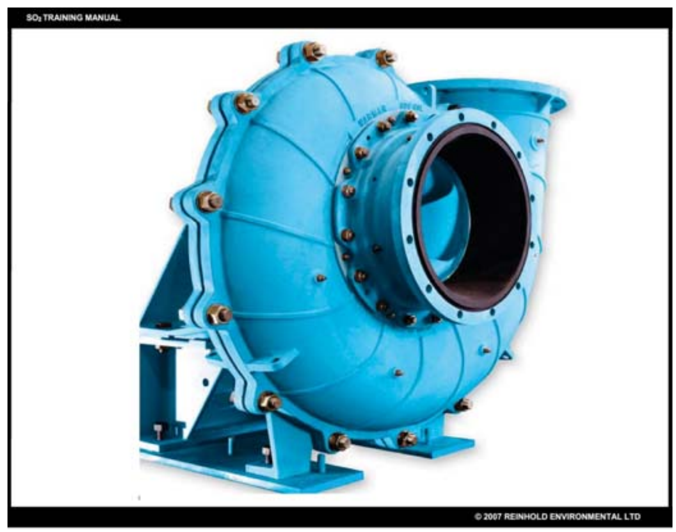
Even with everything going according to procedures, there have been cases where some rubber sheets in a tower were in perfect condition when other adjacent sheets failed completely.

These cases have been attributed to manufacturing problems of the rubber itself or to improper storage of the rubber before it was applied. Rubber can age and change its properties if not stored correctly. Outside storage with rubber exposed to sunlight must be avoided.

The interface between rubber linings and other linings or materials must be designed properly. It usually works best for the rubber to overlap the other lining or material. Proper surface preparation of the other lining or material and proper adhesives must be used to assure that the rubber will adhere to the other lining or material.

Rubber linings should be inspected for erosion damage, blisters, or other signs of delamination during maintenance outages. Small areas can be repaired by cutting out the damaged area and gluing in a new piece of rubber. Proper repair procedures and materials must be used for this operation to be successful. Large areas of blisters and delaminations are an indication that the rubber lining is reaching the end of its useful life and will need to be replaced.

Erosion damage is the other main cause of rubber failure. This can happen in piping elbows if the velocity is too high. Using a longer radius elbow or changing the velocity can fix this problem. This can happen if a slurry nozzle is too close and impinging on a rubber lining. Moving the nozzle or placing a metal shield over the rubber can fix this problem. Erosion damage can also happen to pump and mixer impellers. If the tip speed of an impeller is too high, the velocity can erode the rubber and expose the metal below. To fix this problem, the part covered in rubber must usually be replaced with a corrosion resistant metal alloy or ceramic part.



Slurry Pump (Cast Iron with Rubber Lining)
Used with permission from Weir Slurry Group Inc.

One of the biggest problems in large slurry recirculation pumps is damage to rubber pump liners from large pieces of debris in the system. For example, this may be pieces of scale that have fallen off a wall or the area above the inlet duct entrance into the tower. Or this may be material that was washed from a plugged mist eliminator during a cleaning operation and allowed to remain in the absorber tower. This may be nuts, bolts, clamps, tools and other metal pieces that have fallen off in service or were dropped during maintenance work in the tower. Or, lastly, this may be trash from absorber area floor sumps that pump back into the absorber tower. It cannot be stressed enough how important it is to minimize this type of debris in the towers if one wants to get the normal life from rubber pump liners. Large slurry pump liners and ball mill liners should be inspected on a regular basis. If the rubber liner is replaced before there is a hole through it, the new liner can be bolted back in place relatively quickly. If liquid penetrates the liner, then the housing will experience severe corrosion. That means the housing will need to be repaired or replaced before the new liner can be installed. Such repairs or replacements can be expensive and time consuming.

Rubber is being used successfully in FGD systems around the world. To be successful, one needs to select the proper rubber for the application, store and install it properly, and inspect it regularly.

7.3 FRP

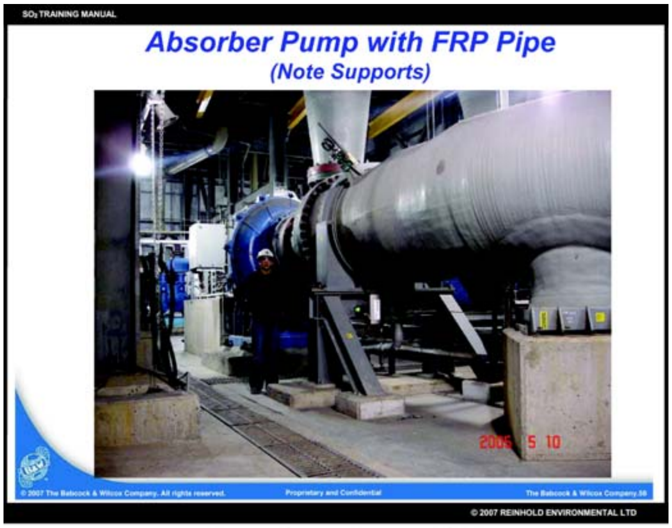
Fiberglass Reinforced Plastic (FRP) is a generic term. It describes a whole host of products and materials. FRP is an engineered material that is designed for each specific application. The fiberglass can be in the form of continuous filaments for winding, woven fiber mat, or chopped fiber mat. The resins used can be thermoplastics (melt with heat) or thermosets (harden with heat) with a wide range of chemical and physical properties.

Spray Headers - FRP
Used with permission from Babcock and Wilcox

The shapes are usually built up in layers. The outer layers contain more resin and can be chemical resistant or wear resistant. The inner layers contain more glass fiber which gives the shape its strength. The type of fiber and the orientation of the fiber determine the tensile strength and stiffness of the material. The exterior layer of resin is typically resistant to ultraviolet light which tends to attack the plastic resins if they are exposed to sunlight.

Grating

FRP grating can be a good choice around equipment and over floor drains and sumps where slurry or gas contact is likely to occur. The FRP grating is chemical resistant and will not be attacked like painted or galvanized steel grating. The only caution about using this material is in a traffic area. It takes a much thicker piece of FRP grating to support the weight of a forklift.



Pipe - Slurry Pump - FRP
Used with permission from Babcock and Wilcox

Piping

Piping can be fabricated in all shapes and sizes. It can be continuous or have flanged connections. FRP piping is lighter weight than an equivalent sized steel pipe. This can be an important consideration for a four foot diameter slurry recycle header hung on the outside of an absorber tower if it ever has to be removed and replaced. A complex header shape with multiple branches can be fabricated in one piece, but thought should be given whether to design it with flanged sections for ease of maintenance once it is in service.

The piping can be designed for the fluid it will be handling. A clear liquid pipe would only need an internal corrosion resistant resin layer. A slurry pipe would need both internal corrosion and abrasion resistant resin layers. A slurry header inside the spray tower would need both internal and external corrosion and abrasion resistant layers. A pipe that will be installed outside needs an external ultraviolet light barrier resin layer to protect it from attack by sunlight.

One of the big mistakes people make with FRP pipe is to support it just like they would an equivalent sized steel pipe. FRP pipe typically does not have the strength to support itself across the same spans as steel pipe. So they end up with a sway backed run of piping. Piping supports for FRP pipe should be engineered based upon the recommendations of the FRP pipe supplier.

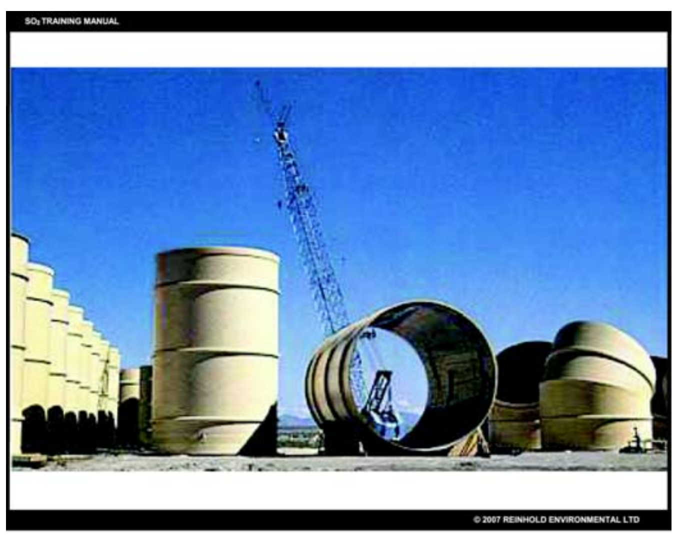
FRP pipe can be repaired by cutting and gluing in a new piece or wrapping the failed area with mat and resin and letting it cure. If a slurry spray header is showing erosion damage on its exterior, that area can be reinforced by placing more layers of mat and wear resistant resin over the worn area. Proper cure time and control of ambient conditions during FRP joint repairs must be considered as a part of normal maintenance.

Valves and Nozzles

It is possible to buy FRP bodied valves and spray nozzles. The have the same chemical resistance as the FRP piping.

Tanks, Towers, Ducts, and Chimneys

It is possible to fabricate rectangular tanks from FRP. This is not always the most efficient design. The tank walls need a lot of stiffeners to keep them from flexing. The most efficient design for FRP tanks, towers, ducts, and chimneys is cylindrical. This design takes advantage of the hoop strength of the wound glass filaments.



Chimney Liners FRP
Used with permission from Ershigs, Inc.

These shapes are usually spun in sections on a large rotating mandrel. The mandrel is built to the diameter of the tank and 10-15 feet tall. The entire mandrel slowly rotates as glass filaments are wound about it. At the same time, resin and glass mat are also added layer upon layer. The wound glass filament gives the cylindrical shape a lot of hoop strength. When finished, they have an FRP hoop the diameter of the tank, tower, duct, or chimney.

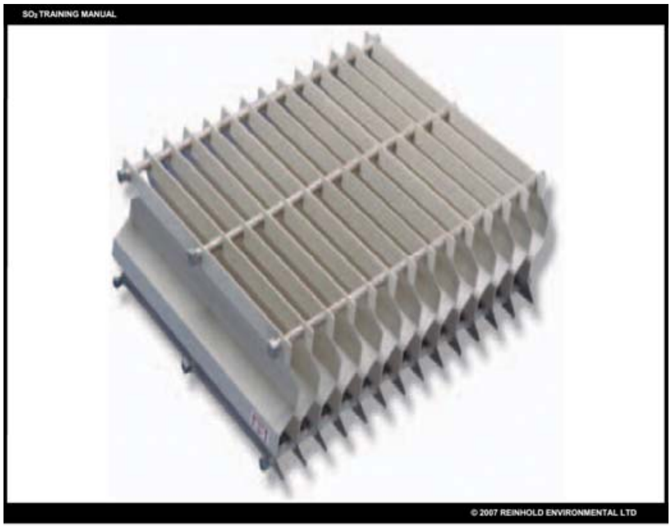
The hoops are then stacked for a tank, tower, or chimney or laid end to end for a duct. The hoop sections are joined together with additional glass reinforcement and resin. The hoops are relatively light, so they are lowered down chimney shells by helicopter to construct a liner. Or they are raised up a chimney shell with winches, joining new sections to the bottom of the liner as the completed liner was raised.

Service temperature limitations and supporting combustion in event of fire are FRP issues. A majority of the entire Chiyoda scrubber at Georgia Power's Plant Yates was fabricated from FRP. This included the ducts, absorber tower, piping, and chimney.

Mist Eliminator

Mist eliminator blades and components have been fabricated from FRP. Care must be taken that blades are stiff enough not to flutter in the gas flow. This vibration can cause cracking and breaking of the blades and supports. There has been at least one case where the FRP blades delaminated and the blades swelled. This narrowed the gas passages causing high gas velocity and liquid carry over.

Care must be taken when cleaning FRP mist eliminators. Pieces of plywood should be placed on the mist eliminators where equipment and workers will be in contact with the blades to prevent damage. Care should be taken with high pressure water lances to prevent cutting the surfaces of the blades.



Mist Eliminator FRP
Used with permission from Koch-Glitsch L.P.

Structural Shapes

One can buy FRP "I" and "H" beams, channels, and box beams. Once again, these components are engineered and built for a specific job.

FRP Linings

FRP can be applied as a lining to protect steel and concrete. As with any lining application, proper preparation of the substrate surface must be done if the lining is to adhere properly. Proper procedures must be followed in applying the FRP lining. The selection of resins and glass mat and the sequence of layers will depend upon the desired performance of the lining.

7.4 Resin Based Linings

Resin based lining systems are very similar to FRP. Most are based on the thermosetting (hardens with heat) polyester and vinyl ester resins. Recently some urethane based linings are being used. The resin used determines the basic physical and chemical resistance characteristics of the lining. There would be problems if only the resin were used for the lining. The resins have a much higher expansion coefficient than steel. It could be difficult to maintain a bond between the resin and the steel as the temperature changed and blistering of the lining could occur. Most of the resins are permeable to liquid. Most of the resins aren't very abrasion resistant.

Flakeglass Lining Application
Used with permission from Babcock and Wilcox

Because of this, fillers are added to the resin to modify the expansion coefficient, reduce the permeability, and resist abrasion. Many different materials can be used as fillers. For FGD service one of the most widely used filler materials is glass flakes.

The presence of the glass flakes retards the expansion and contraction of the resin/glass mixture during temperature swings. This causes the lining expansion coefficient to more closely match that of the carbon steel. The thermal expansion coefficient of a lining is an important property to consider when selecting a lining. In areas such as tanks and absorber towers, the temperature swings are moderate. In ducts and stack applications the temperature swings can vary more widely. The maximum sustained temperature and short term temperature limits of a lining material must also be considered depending upon where in the FGD system the lining will be installed. This is mostly a concern in the inlet and bypass ducts where gas temperature can be over 300º F.

SYSTEM	Permeability (Perm-inch)
Vinyl Ester Flake Glass Trowel Applied	0.0002
Vinyl Ester Flake Glass Spray Applied	0.0005
Vinyl Ester Mica Flake Filler	0.0009
Vinyl Ester Aluminum Oxide Filler	0.0006
Flake Glass Polyester Spray Applied	0.0016
Fiberglas Mat Laminate Hand lay-up epoxy or polyester	0.0078
Flake Filled Epoxy Coating: Spray – 2 coats	0.00157

Resin Based Lining Permeability Table
Used with permission from Blome International

All resin based linings are permeable. As the water vapor penetrates the lining, it will be trapped at the lining/steel interface. Eventually the pressure will break the bond between the lining and the steel. When this happens, a liquid filled blister will form. If this liquid is corrosive, it will attack the steel under the lining. The glass flakes act as a moisture barrier. As the water vapor is penetrating the resin, it must travel around the glass flakes. If there are several layers of glass flakes whose positions overlap each other, the water vapor has to travel a tortuous path to completely penetrate the lining. This can add several years to the useful life of a lining. As these linings are being applied, they are often worked with a trowel. The trowel flattens and aligns the glass flakes so they are parallel with the steel substrate. This gives the lining maximum water vapor penetration resistance.

The glass flakes also make the lining more abrasion resistant. Aluminum oxide can also be added to the outer layer to increase abrasion resistance.

These linings are typically applied in multiple layers. The thinner linings may be applied by spray, brush, or roller. In more abrasive areas such as absorber towers and thickeners, the linings are applied in thicker layers using trowels. The layers are typically given different colors to aid in proper application. This can also aid the scrubber operator.

Let's say an absorber was given a 40 mil thick pink first layer, a 40 mil thick blue second layer, and a 20 mil thick tan abrasion resistant final layer. If the operator sees only tan lining during an inspection, he knows there are over 80 mils of good lining still in service. If the operator sees any areas of blue lining he knows that between 40 – 80 mils are remaining in service and a repair of the abrasion resistant layer needs to be made. If the operator sees any pink lining, he knows this is serious since over half the lining thickness is gone and lining failure could be imminent. Both the corrosion barrier and the abrasion barrier must be replaced. It is important for the scrubber operators to know the thickness and color of each layer installed in their equipment.

During inspections, careful attention should be paid to the areas of highest abrasion. This would be near spray nozzles, around mixers, and where piping leaves the absorber tower. The areas where the slurry leaves the reaction tank and enters the slurry recirculation pump suction headers are areas that may need lining repair every maintenance outage.

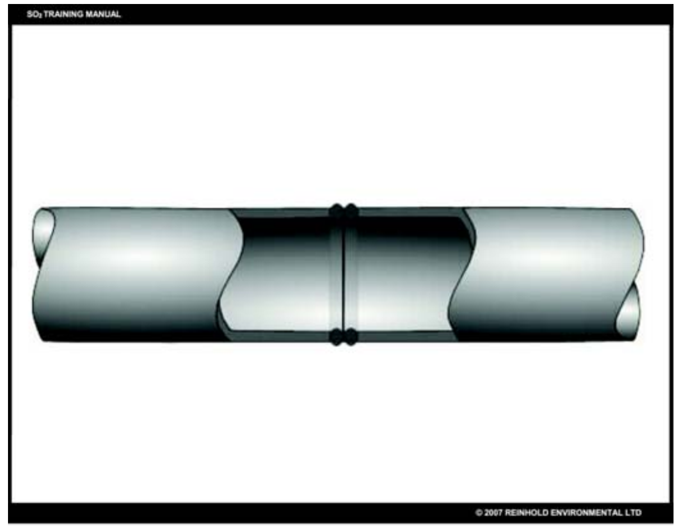
Areas around personnel and equipment entry points may suffer mechanical damage during outages when there is a lot of activity through these areas. Some utilities place a permanent layer of concrete or a temporary layer of plywood over the floor lining in high traffic areas where scaffolding and other equipment may damage the linings on the floor.

As the water vapor penetrates the lining, it will break some of the chemical bonds and the lining will soften. During the inspections, a metal pointed object can be used to test the lining.

If it is lightly pressed against the lining, it should not penetrate the lining. As the lining ages, the point will begin to penetrate the lining to an increasing depth. Once it is penetrating into the lowest layer, plans should begin to replace the lining. Also any areas of blistering or delaminated lining should be removed and replaced.

Proper surface preparation must be done when installing resin based linings. All sharp metal edges and weld profiles must be ground smooth. All corners must be rounded to a specific radius. All metal or concrete surfaces must be grit blasted to a specific cleanliness and surface profile. All of this information will be specified by the lining supplier. All lining application must be done within specific windows of surface and surrounding temperature and humidity. There is usually a minimum and maximum time between subsequent layer applications. Most utilities have found it advisable to hire an independent certified lining inspector to watch all phases of the lining application.

There are also lining supplier specifications for cleaning and surface preparation for making lining repairs. Lining repairs can have the same life as the original lining if applied properly. If not done properly, the repair patches can detach from the lining.



Pipe - Plastic - Butt Fusion Joint
Used with permission from Plastic Pipe Institute

7.5 Plastics

Plastics have been used successfully in many areas of FGD systems. PVC pipe will withstand the corrosive nature of FGD liquids. It will not withstand the abrasion of fast moving slurry streams. PVC pipe has been used for vent and drain piping. It has also been used frequently for small bore pipe systems carrying clear liquid streams at moderate pressures. PVC or PVC coated electrical conduit and junction boxes have survived where regular conduit and junction boxes have failed. PVC liners are used in FGD waste water ponds to prevent groundwater contamination.

High Density Polyethylene (HDPE) pipe is finding more use in FGD systems. Besides being chemical resistant, HDPE pipe is very abrasion resistant and is being used to transport bottom ash at many utilities. HDPE is a thermoplastic (melts with heat) that is joined by melting the surfaces of the two pieces and then holding them together until they cool. The HDPE pipe is flexible which means it can snake around objects and corners without needing elbows. It also means it needs a different support system than traditional lined steel pipe. It can be used to make a quick temporary connection in a system as well as a permanent connection. Some utilities have actually fabricated large diameter slurry recycle pipe elbows from wedge shaped sections of HDPE pipe fused together. The abrasion resistance of the HDPE can provide an elbow with a longer life than traditional lined steel pipe. HDPE liners are also used in FGD waste water ponds to prevent groundwater contamination. As with any plastic or FRP installation, thermal expansion relative to adjacent materials should be considered.

Pipe - Plastic - Butt Fusion Machine
Used with permission from Plastic Pipe Institute

A large number of mist eliminators in FGD systems are fabricated from plastics. Some of the common materials are polypropylene, Noryl, PVC, and Ryton. The biggest issues with plastic mist eliminators are mechanical issues. The individual blades must be stiff enough not to flutter in the gas flow. Fluttering can cause fatigue cracks and blade breakage. Plywood walk boards should cover mist eliminators during maintenance activities to keep feet and equipment from bending and breaking mist eliminator blades. Care must be taken when using high pressure water blasting equipment to remove deposits so as not to cut or gouge plastic blade material. This can lead to blade breakage under gas flow conditions.

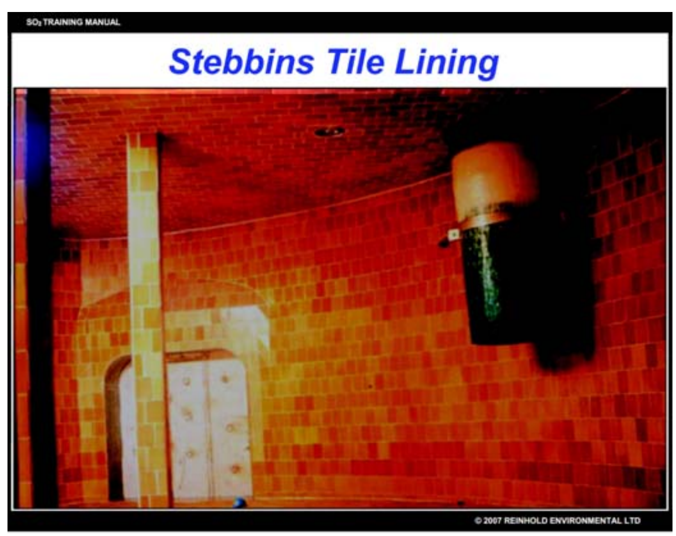
7.6 Masonry

Reinforced concrete has been used in the construction of thickeners. Sometimes the entire thickener vessel is formed and poured. Sometimes metal side walls are attached to a poured conical floor. The liquid in an FGD system contains high levels of chlorides and sulfates. Both can cause damage to reinforced concrete.

Concrete is a porous material that can readily be penetrated by the soluble chloride ions. This does not damage the concrete itself. The problem occurs when the chloride ions come in contact with the steel reinforcing bars. Corrosion of the steel occurs and the corrosion products take up more space than the steel bar. The pressure this creates can crack the concrete and pieces of the concrete can break off. This is a common occurrence on bridge decks in northern states where they use salt for road deicing or on support columns of structures in contact with sea water. A resin based lining properly installed in the thickener can prevent this attack.

Sulfate attacks the concrete itself. There are apparently two chemical reactions involved in sulfate attack on concrete. First, the sulfate reacts with free calcium hydroxide in the cement to form calcium sulfate (gypsum). Next, the gypsum combines with hydrated calcium aluminate to form calcium sulfoaluminate (ettringite). Both of these reactions result in an increase in volume. The second reaction is mainly responsible for most of the disruption caused by volume increase of the concrete. In addition to the two chemical reactions, there may also be a purely physical phenomenon in which the growth of crystals of sulfate salts disrupts the concrete. Visual examination will show map and pattern cracking as well as a general disintegration of the concrete. Laboratory analysis can verify the occurrence of the reactions described. A resin based lining properly installed in the thickener can prevent this attack.

Stebbins Engineering offers a ceramic tile product that has been used extensively in the pulp and paper industry. It is finding use in the FGD market due to its chemical and abrasion resistance. Some of the newer FGD systems are using this system because they are anticipating chloride levels in the 40,000 – 100,000 ppm range. Most of the metals will not withstand such high levels of chlorides. The ceramic tile can be a cost effective material of construction compared to the high nickel/chrome content alloys. In some areas there are also some labor advantages to building absorber towers and tanks using masons instead of boilermakers. There are two methods of construction that have been used.



Stebbins Tile Lining
Used with permission from Babcock and Wilcox

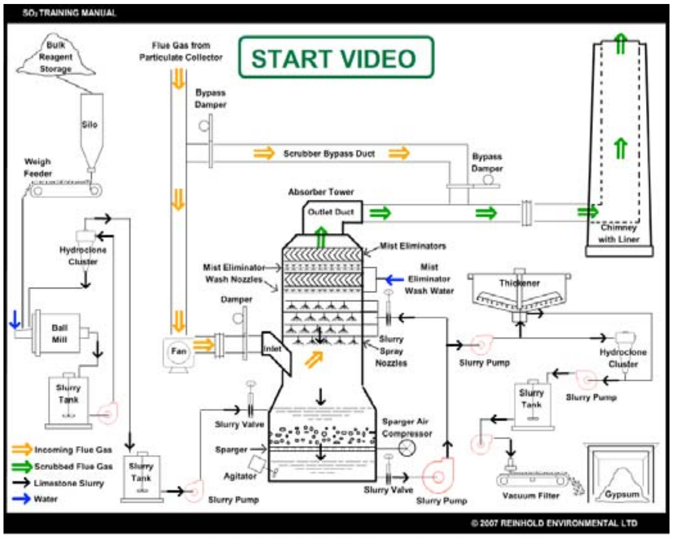
The ceramic tile can be used as a lining in a vessel. The tiles are laid in the vessel using epoxy based mortars. The tile structure is self supporting much like a brick liner in a chimney. High alloy metal sleeves penetrate the tile wall wherever pipe penetrations or vessel access are required.

The other method uses the ceramic tiles as part of the erection of the vessel. The ceramic tile is laid with the epoxy based mortar such that it will form the inner wall of the vessel.

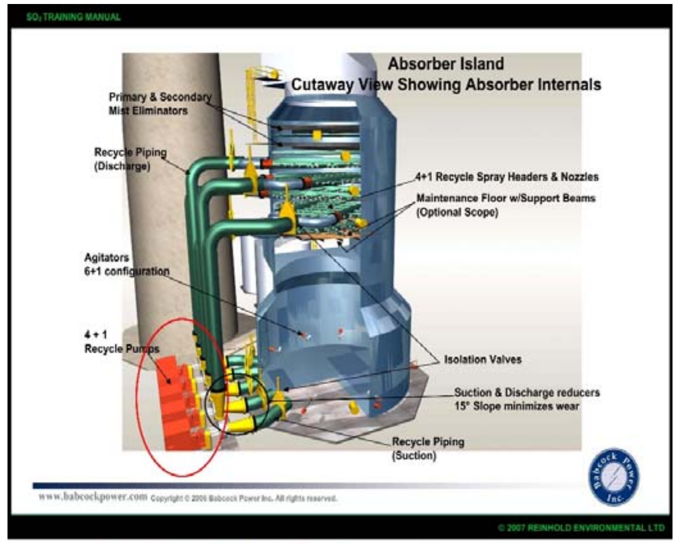
Another wall of thin solid concrete blocks is laid such that it will form the outer wall of the vessel. In the space between these two walls, the necessary reinforcing bars are placed and then the space is filled with poured concrete. This process proceeds in a step wise process just as “slip forming” would proceed. The difference is that there is no “slip form”. The ceramic tile wall and the block wall act as permanent forms with the reinforcing bars and the concrete sandwiched between giving the vessel its structural strength. These have been built in both rectangular and cylindrical configurations. High alloy metal sleeves penetrate the wall wherever pipe penetrations or vessel access are required.

The ceramic tile wall is the barrier protecting the material behind it from chloride and sulfate attack. The tile and epoxy grout joints should be inspected on a regular basis. Cracks can be repaired using epoxy mortar. Damaged tile can be chipped out and replaced.

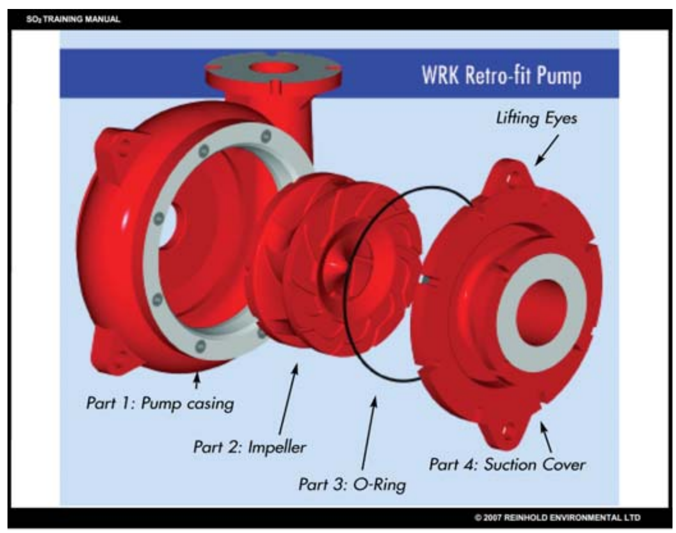
CHAPTER 8 - SLURRY PUMPS



Chapter 8 Summary
(Narrated by Ron Richard, RE Consulting)



Absorber Island Cutaway-Slurry Pumps
(Narrated by Tony Licata, Babcock Power)



Slurry Pump - Exploded View
Used with permission from Townley Engineering & Manufacturing Co.

Pumping large volumes of erosive, corrosive slurry has proven to be challenging over the years. As the size of the pumps has increased, some pump parameters have exceeded the design range of certain materials. Slurry pumps are not necessarily the exception.

Pumping large volumes of erosive, corrosive slurry has proven to be challenging over the years. As the size of the pumps has increased, some pump parameters have exceeded the design range of certain materials. Slurry pumps are not necessarily the exception.

The original slurry pumps had rubber lined casings, rubber lined impellers, packing glands with fresh water flush, and multiple belt drives. An evolution in design has occurred over the years. The typical large slurry pump today has a rubber or urethane lined casing, a high chrome iron impeller, dry mechanical seal, and gear box drive.

This chapter discusses the current designs and materials of construction that have allowed these increasingly larger pumps to provide the maintenance free life between major overhauls that utilities are currently expecting. It also discusses some of the operating practices that can prevent damage to these pumps.

8.1 Pump Casings

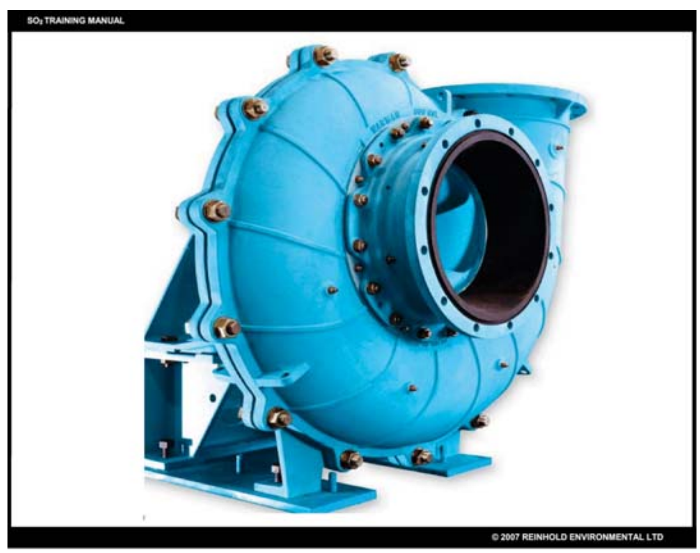
Rubber works well as a liner for the iron pump casing with the small particle size of the limestone and gypsum slurry particles. It has enough resilience to withstand the pounding of such small particles. The pump liner can be damaged by debris passing through the pump. This may be large pieces of scale that have broken off of the absorber tower walls. This may be nuts, bolts, and other chunks of metal that fall off in service or are dropped and not retrieved during maintenance work, or it may be trash that gets into floor sumps.

Slurry Pump Casing (FRP with Rubber Lining)
Used with permission from Weir Slurry Group Inc.

Urethane rubber was found to give longer service than some of the other types of rubber used as pump liners. A urethane liner is typically more expensive than a normal rubber liner.

When one considers the cost to overhaul the pump and the longer life of the urethane liner, many utilities have chosen to go with urethane liners.

A high chrome iron liner can be fabricated or a complete alloy casting can be used for a pump casing. The cost of the materials and the cost of casting such a liner make it very expensive. Unless one is having severe life issues with rubber and urethane liners, the economics of converting to a metal liner will probably not be favorable.



Slurry Pump (Cast Iron with Rubber Lining)
Used with permission from Weir Slurry Group Inc.

Most of the original rubber casing linings came in three or more pieces split along with the pump casing. Some of the lining suppliers have developed a one piece casing liner with a separate suction cover. This speeds pump reassembly and eliminates the joint in the high wear area of the liner.

It is important to discover pump casing liner wear before it penetrates the liner. If the liner has not been penetrated, the old liner can be removed and the new liner reinstalled fairly quickly.

If the liner has been penetrated, the corrosive nature of the slurry can attack the pump casing in a short amount of time. If the corrosion is severe, the pump casing will have to be repaired or replaced before the new liner can be installed. This adds to the time required and the cost.

8.2 Pump Impellers

The pump impeller sees the highest particle velocities and so has a shorter lining life than the pump casing. The urethane rubber does last longer on an impeller than the normal rubber. The impeller lining is also damaged by debris passing through the pump.

As impellers grew to larger diameters, a problem arose with the impeller tip speeds. At higher tip speeds, the rubber linings could not withstand the forces and would not stay on the impellers. This forced the pump manufacturers to convert to the high chrome iron impellers. They held up well and lasted through several replacements of pump casing liners.

This longer life has caused many utilities to reconsider the impeller material for existing pumps.

Many are finding it economical to pay the higher first cost for the high chrome iron impellers but avoid the frequent impeller replacements due to lining failure. Most new pumps are being installed with high chrome iron impellers.

Slurry Pump Impellers
Used with permission from Goulds Pumps (ITT)

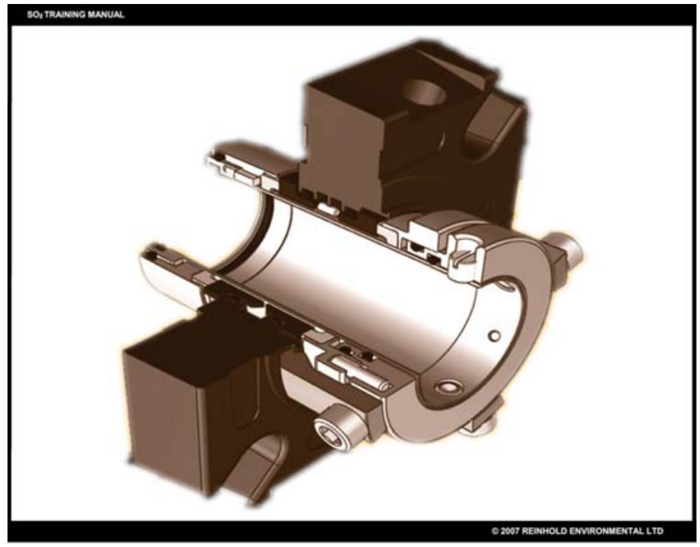
With a rubber lined impeller, it is important to find lining problems before they penetrate the lining. If you do, the old impeller can be sent to the lining shop where they will salvage the hub, remove the old lining, install a new lining, and return the impeller for only the cost of the lining.

If the slurry penetrates the lining, the flow and corrosive nature of the slurry will quickly attack the vanes of the impeller. Since this attack may only occur on one vane or will not be uniform on all the vanes, the impeller will get out of balance and take the pump out of service. The impeller is now scrap and the replacement cost will be for a new impeller plus lining.

8.3 Pump Seals

The packing type seals required a lot of maintenance. The seal water piping was small bore piping that had to be insulated and heat traced to prevent freezing in colder climates. The constant flow of fresh water through the seal into the pump diluted the slurry in the tower. As utilities worked to tighten their FGD system water balances, this extra water was undesirable.

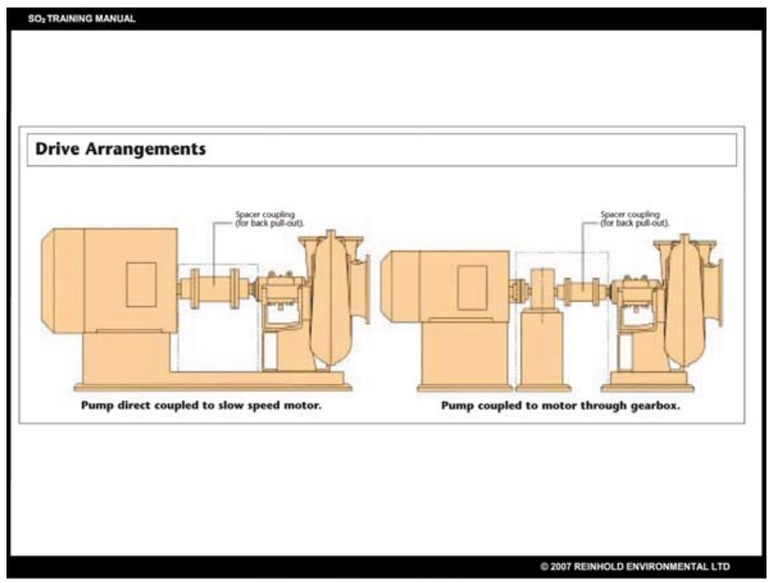
Improvements to mechanical seals have allowed them to be used in place of the packing type seals. After some problems with the first generations of mechanical seals used in this service, the lessons have been learned and the mechanical seals are experiencing long lives with little maintenance. Care must be taken to purchase mechanical seals designed for FGD service. Some of the materials used in “off the shelf” mechanical seals will not withstand the corrosive and abrasive nature of FGD slurry. They will last until the first time slurry gets into them and then they will fail rapidly.



Slurry Pump Seal - Cutaway
Used with permission from Goulds Pumps (ITT)

8.4 Pump Drives

Belts were used on slurry pumps to absorb some of the starting shock of the larger pumps and absorb the shock of debris passing through the pumps. Belts could also tolerate some misalignment between the pump and the motor. As the pumps grew larger, multiple belts were needed on the sheave to provide the power to the pump without excessive belt slippage.



Slurry Pump Drives
Used with permission from Warman (Weir Slurry Group Inc.)

As pump horsepower requirements increased due to pump size and tower height, the transition had to be made to gear boxes. The gear boxes have served well with minimal maintenance requirements but require some a method to cool the oil. Smaller slurry pumps are still belt driven in most cases.

It works best to have slurry pump motors bolted to a frame and grouted similar to the pump mounting. Some manufacturers mount the motors on smaller pumps on plates mounted above the pump to save floor space. This arrangement is not as rigid and leads to more problems maintaining belt torque, belt alignment, and motor vibration.

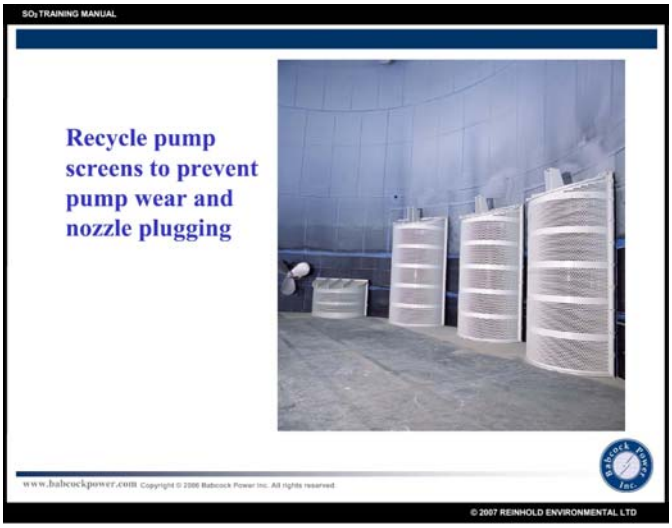
8.5 Maintaining Pump Output

The larger slurry pumps can gradually lose pumping capacity over time for several reasons.

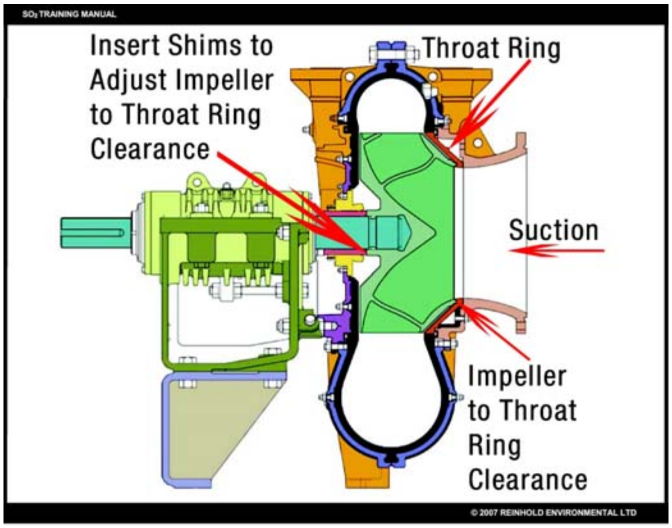
In some absorber vessel designs, slurry pump inlets may be covered by screens to prevent large chunks of debris from entering the pump and causing damage to the impeller or lining, or plugging the spray nozzles. If so, you should inspect and clean these screens whenever the absorber is taken out of service. Partially plugged screens can reduce pumping capacity

Another reason why this can occur is because the gap between the impeller suction opening and the casing liner throat ring has widened due to erosion of the impeller or the throat ring. This allows more flow to short circuit the pump flowing from the impeller discharge past the throat ring and back to the impeller suction. This can be reduced by adjusting this gap back to the proper setting.

Fortunately with the large slurry recirculation pumps, the suction pipe diameter is large enough for a person to crawl into the pump suction. They can then easily measure this gap without having to disassemble the pump. The gap can normally be adjusted by adding or removing shims to the pump bearing assemblies to move the impeller closer to the throat ring. This will recover the lost flow rate.



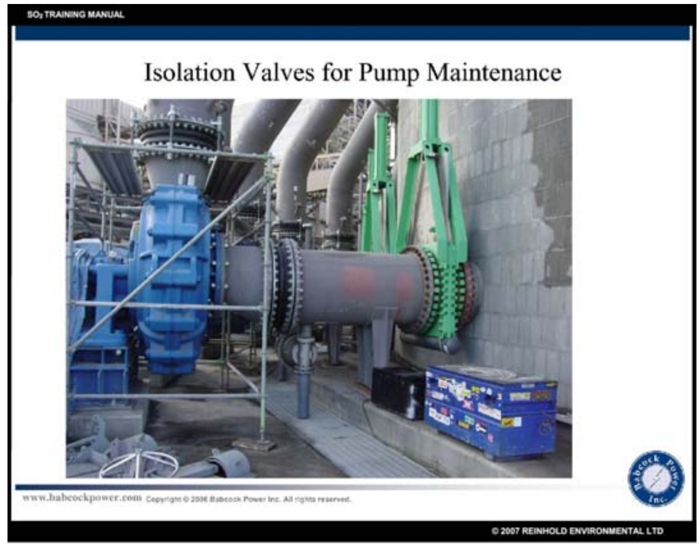
Slurry Pump Screens
(Narrated by Tony Licata, Babcock Power)



Slurry Pump - Impeller Clearance Adjustment
Used with permission

8.6 Taking a Slurry Pump Out of Service

A slurry pump should not set idle full of slurry. The solids can settle in the pump casing. If there are enough solids and they set long enough, the pump impeller can become locked in place by the solids. This can damage the pump drive or the impeller when the pump is placed back in service. Pump operation sequence is FGD system and site specific. Depending on the particular pump and piping orientation, many FGD slurry pump casings cannot be drained below the suction line. Dilution of the material remaining in the pump is recommended as practical.



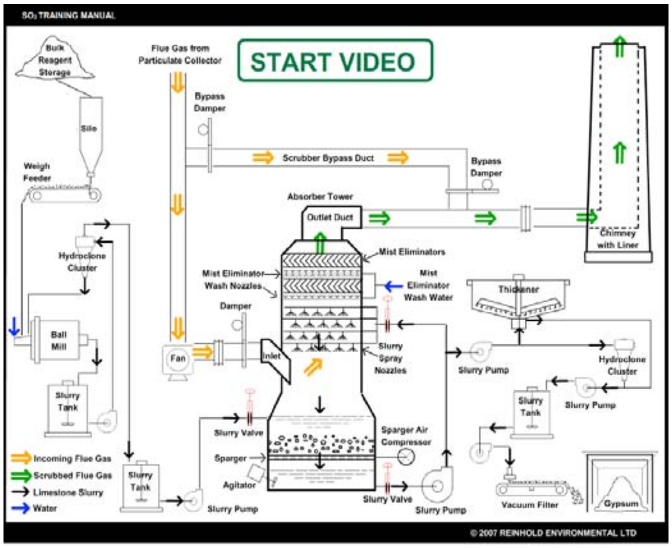
Isolation Valves For Pump Maintenance
Used with permission from Babcock Power

For smaller bore piping systems, the pump shut down sequence often includes an automatic flush cycle of the pump and piping. A normal pump shutdown signal will cause a flush water valve to open and the slurry suction valve to close. A timer will allow the pump to run pumping flush water down the pipe. Once enough time has elapsed to fill the pump and piping with clear flush water, the pump motor will be taken out of service and the flush water valve will close.

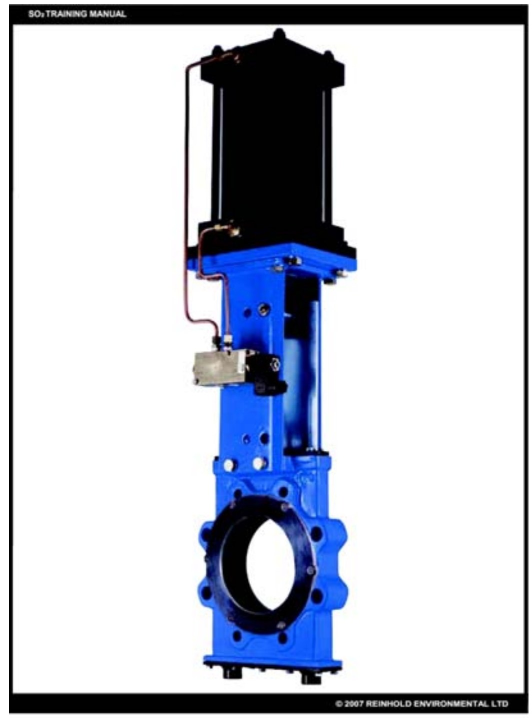
For large systems such as the slurry recirculation pumps, other start, stop, drain/flush, flush/drain, etc. systems may be used. A typical single pump per spray level system recycle pump shutdown signal may cause the pump motor to be taken out of service and the slurry suction valve will close. A pump casing drain will open draining the slurry from the pump discharge piping and the pump casing. After the predetermined drain time, a flush water valve will open, flushing clear water through the pump and out the pump casing drain. The flush water valve and the casing drain valve will then close. The slurry pump will then be sitting empty and idle.

Multiple pump recycle systems with "headered" schemes would require an isolation sequence different than the single-pump-per-header arrangement noted above and may leave the pump idle with the drain open. It should be noted that the pressure rating of large pump system's components (casing, seals, valves, expansion joints, gaskets, etc.) must address the potential deadhead pressure of the flush water supply.

CHAPTER 9 - SLURRY VALVES



Chapter 9 Summary
(Narrated by Ron Richard, RE Consulting)



Knife Gate Valve (Air Operated)
Used with permission from Weir Slurry Group Inc.

It takes specially designed valves to control the flow of the erosive, corrosive slurry circulating in FGD systems. Certain style valves work only in on/off service, other styles can be used for throttling flow, and other styles must be used for precise control of slurry flow rates.

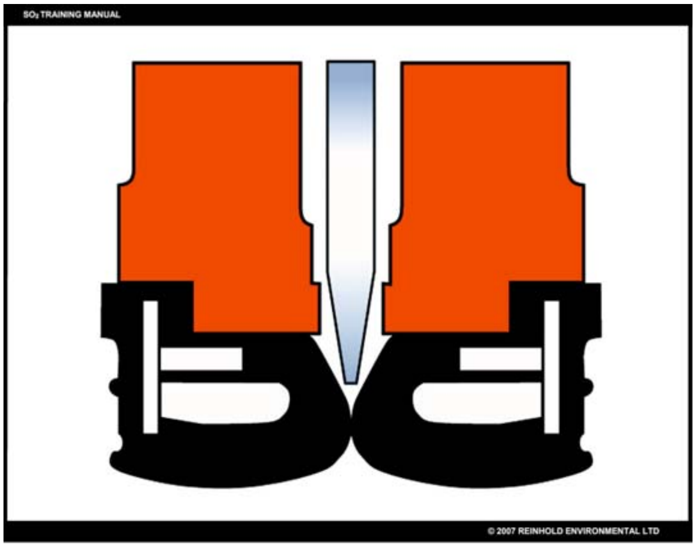
Many types of valves have been tried over the years for slurry applications with mixed results. The best valves seem to be those that have no obstructions in the flow path when completely open. Butterfly valves often do not work well because the disk is exposed to the erosive slurry during the entire time they are open. Butterfly valves do work well for zero solids streams such as mist eliminator wash system valves.

It is also best if as much of the valve as possible does not come in contact with the corrosive slurry. The designs of the valves described below are very simple with a minimum number of parts wetted by the slurry.

This chapter discusses the various styles of valves that have successfully operated in FGD systems. The strengths and limitations of each style are discussed. The materials of construction that will survive in this service are also discussed.

9.1 Knife Gate Valves

A simple knife gate valve is the best type of valve for applications where the valve is normally completely open or completely closed. These are the valves used to isolate pumps and other equipment. These valves are particularly suited for the large slurry recirculation pump piping systems that must be isolated and made man-safe during "on-line" maintenance activities.



Knife Gate Valve-Two-piece Rubber Sleeve System
Used with permission from Weir Slurry Group Inc.

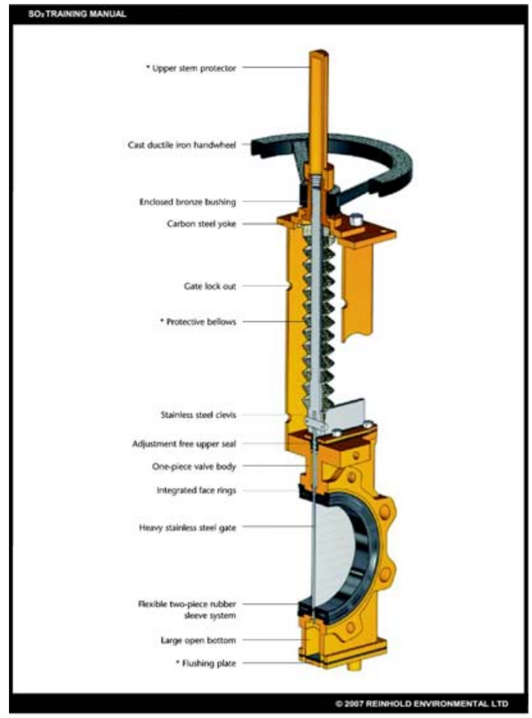
There are different styles of knife gate valves, but one particular design is the one that has been most reliable while requiring the least amount of maintenance. It is available from several manufacturers.

When the valve is open the only thing in contact with the slurry are two rubber sealing rings. The rings are compressed against the pipe faces on either side of the valve. The rings are compressed against each other in the center of the valve preventing any leakage of slurry between the rings. The knife gate is completely withdrawn from the pipe and from between the rings. With the valve in this position the entire upper portion of the valve (knife gate, screw, actuator, etc.) can be removed for maintenance. These parts are only needed to cycle the valve.

Knife Gate Valve-Handwheel Operated
Used with permission from Townley Engineering & Manufacturing Co., Inc.

When the valve is being closed, the tapered edge of the thin alloy knife gate enters from one side spreading the two rubber sealing rings apart, penetrates completely through the sealing rings, and exits to the opposite side. The two sealing rings are compressed against the pipe faces on either side of the valve. The rings are also compressed against each side of the knife gate so no slurry can leak out of the valve. The solid knife gate prevents any slurry from passing through the valve. The only parts in contact with the slurry are the two rubber sealing rings and the alloy knife gate. The alloy material of the knife gate needs to be selected to withstand the chloride concentrations and pH of the slurry.

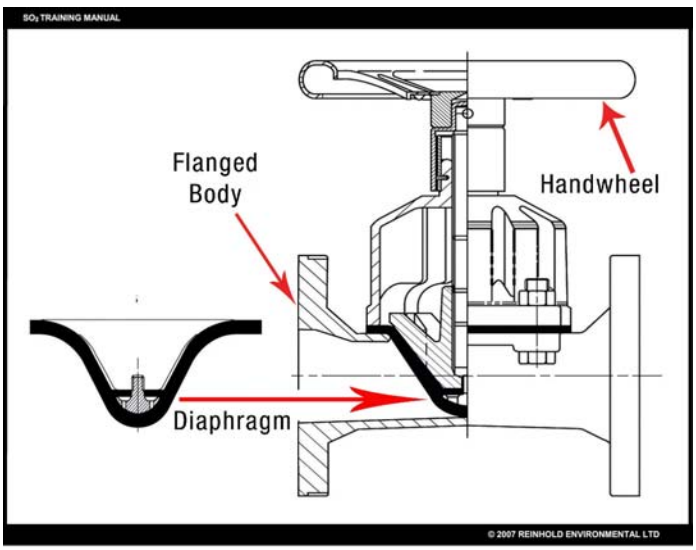
One issue with this type of valve occurs when the knife gate is changing position. As the knife gate enters or exits the space between the sealing rings, there is a wedge shaped opening between the sealing rings on both sides where slurry runs out of the valve and onto the floor. Depending on how fast the valve actuator moves, this only occurs for a brief period. A drain can be placed under the valve to catch this slurry or the floor can be simply washed down after the valve is in position. For all the good features of this valve, this one issue doesn't occur that often and is not a real problem if dealt with correctly.



Knife Gate Valve Cutaway
Used with permission from Weir Slurry Group Inc.

9.2 Diaphragm Valves

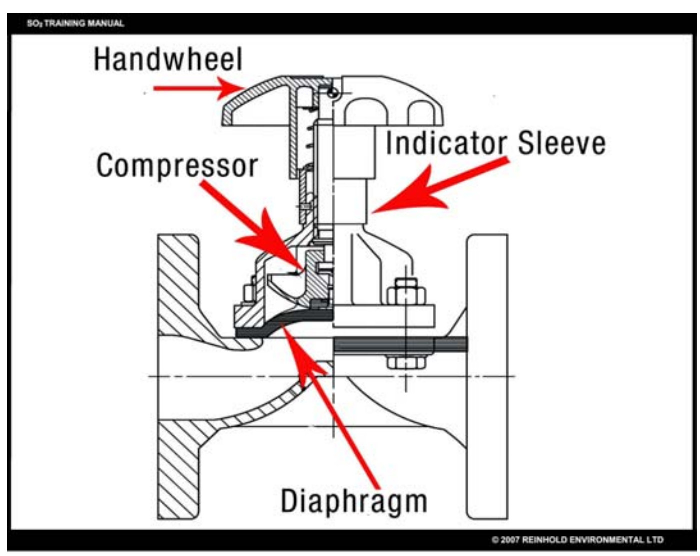
The diaphragm valve also has only rubber in contact with the slurry. The valve body is a rubber lined flanged pipe with a larger square rubber lined tapered chamber in the center of the valve body. An upper chamber section bolts to the top of this lower



Diaphragm valve (straight through) Cutaway
Used with permission from Crane Process Flow Technologies

chamber. A rubber diaphragm sits below this upper chamber with the screw mechanism attached to the top side of this diaphragm. The diaphragm is bolted between the upper and lower chamber.

When the valve is open, the screw mechanism pulls the diaphragm into the upper chamber leaving an open unobstructed path through the valve body. This allows one to run a rod though this valve to clear pipe obstructions ahead of the valve (as one might find in a drain valve situation where solids have settled in the closed drain line). When the valve is closed, the tapered plug in the screw mechanism presses the diaphragm against the



Diaphragm Valve (weir) Cutaway
Used with permission from Crane Process Flow Technologies

rubber lining in the tapered lower chamber blocking the flow path.

A diaphragm valve can be used to throttle the flow by placing the diaphragm in some intermediate position which will let some flow pass. As long as the valve is open most of the way, the rubber valve lining and diaphragm will last a long time. If the valve spends most of its time nearly closed, the high velocity of the slurry past the nearly closed diaphragm will erode the rubber valve lining and diaphragm.

There is another type of diaphragm valve typically referred to as a weir type valve. This design has a weir across the lower chamber. The diaphragm closes the valve by making contact with the top of this weir. This valve is not recommended for FGD system slurry piping.

Even when the valve is fully open, the slurry must turn at the weir, flow over the weir, and turn again to flow past the weir. The impact of the slurry on the weir and the diaphragm as it makes these turns will erode the lining and diaphragm away fairly quickly in a fast moving stream. Also, a rod will not pass through this valve when it is open because of the obstruction caused by the weir.

9.3 Pinch Valves

The main component of a pinch valve is a rubber tube that extends from pipe flange to pipe flange. This rubber tube is the only part in contact with the slurry. The rest of the valve consists of a clamping mechanism which squeezes the tube together.

When the valve is open, the clamp is not in contact with the tube leaving the tube completely open and unobstructed. This allows one to run a rod though this valve to clear pipe obstructions ahead of the valve (as one might find in a drain valve situation where solids have settled in the closed drain line). When the valve is closed, the two rounded clamping jaws have squeezed two opposing sides of the tube together blocking all flow.

A pinch valve can be used to throttle the flow by placing the clamping mechanism in some intermediate position which will let some flow pass. As long as the valve is open most of the way, the rubber tube will last a long time. If the valve spends most of its time nearly closed, the high velocity of the slurry through the narrow opening will erode the rubber tube.

Ceramic Ball Valve
Used with permission from Nilcor

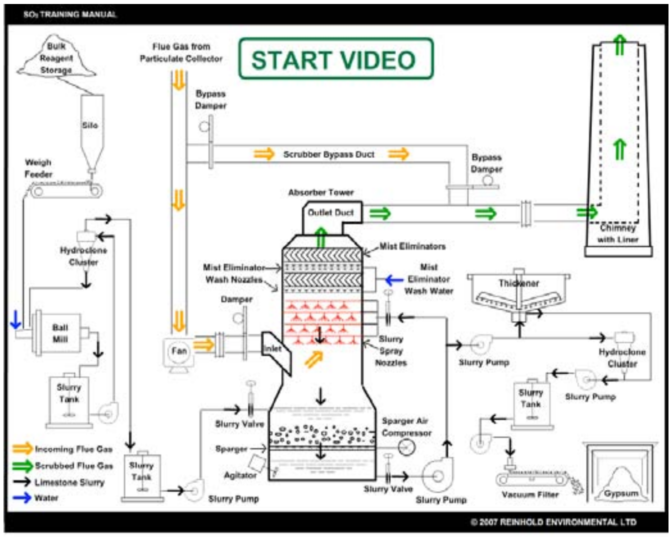
9.4 Ceramic Ball Valves

If one has to throttle a slurry flow significantly and often (such as the lime/limestone feed into an absorber tower), a ceramic ball valve will have the longest life. The valve body lining and the ball are both fabricated from a ceramic material. Not only are ceramics chemical resistant, they are extremely abrasion resistant. Thus, a small, higher velocity stream through the throttled valve will not erode the valve body or ball like it does in a diaphragm or pinch valve.

There are two styles of ball valves. One has the traditional round hole through the ball. This type of ball will give a large increase in flow with a small movement of the ball. The other style has a wedge shaped hole through the ball. The type of ball gives a fairly constant increase in flow as the ball is moved.

The ball with a round hole would be advantageous if one needs a completely unobstructed opening when the valve is fully open. The ball with a wedge shaped hole would be advantageous if one needs to precisely control the flow. When this ball is fully open, the flow path is partially obstructed on one side by the wedge shape.

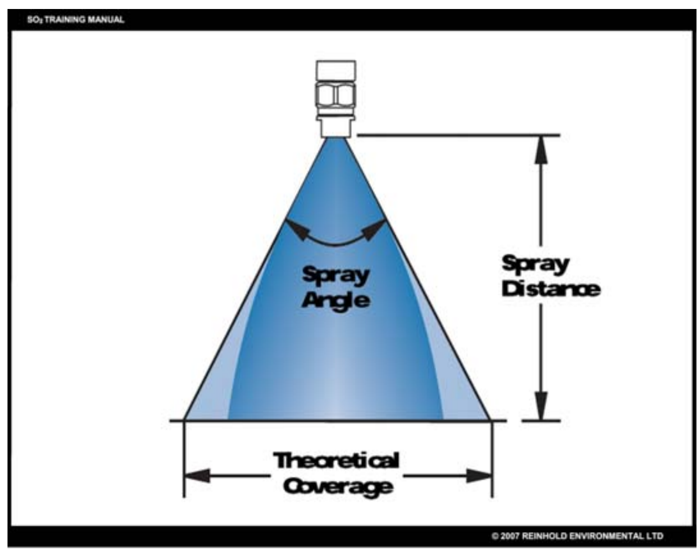
CHAPTER 10 - SLURRY SPRAY NOZZLES



Chapter 10 Summary
(Narrated by Ron Richard, RE Consulting)

Slurry Spray Nozzles
Used with permission from Alstom

The challenge of spraying slurry through the flue gas lies in designing a spray nozzle that will 1) not plug with the solids in the slurry or 2) be eaten away by the erosion of the solids passing through the nozzle while providing the correct spray pattern for proper gas/liquid contact.



Slurry Spray Nozzle - Pattern
Used with permission from Spraying Systems Co.

In the early FGD systems, large, low pressure, high flow slurry spray nozzles were used to evenly distribute the slurry on top of a layer of fill material. This fill material could be ping pong balls, egg crate packing, or other shapes of packing material. The packing material provided a large thin film liquid surface for the liquid/gas interface. Due to the pluggage problems experienced with the fill materials, the more open tower designs were developed.

In the open style towers, the slurry spray nozzles have to do more than just distribute the slurry evenly across the tower. They must break the slurry into small droplets that will provide the needed liquid surface area for the liquid/gas interface. They must also distribute these droplets to create a zone of fairly even density so the gas will pass through evenly and not bypass the droplets through areas of low droplet density.

The nozzles generate circular spray patterns. By overlapping these circular patterns, the designers can generate a solid wall of droplets that the flue gas must pass through. The designer uses multiple levels of spray nozzles to achieve the liquid/gas contact time that is needed to obtain the desired level of SO_2 removal.

The orientation of these layers is rotated so the nozzle patterns overlap each other from level to level.

This chapter discusses the various types of spray nozzles currently in use, their spray patterns and limitations, and the limited number of materials that have proven successful in spray nozzle construction.

Slurry Spray Nozzle - Full Cone
Used with permission from BETE Fog Nozzle Inc.

10.1 Full Cone Spray Nozzles

The nozzle most used in the early FGD systems was the full cone spray nozzle. It provides a pattern with fairly uniform droplet density across the entire circular pattern. The issue with this type of nozzle is that it requires internal swirling vanes to create this droplet pattern. The openings between these vanes are typically small and at an angle. Any debris in the slurry can get caught in these openings and distort the spray pattern. Nozzle pluggage is a frequent problem. It is very difficult to clean the pluggage out of the swirl vanes without breaking the vanes. The use of this type of nozzle has declined in favor of the more open styles of nozzles.

Slurry Spray Nozzle - Tangential Whirl
Used with permission from BETE Fog Nozzle Inc.

10.2 Tangential Inlet Whirl Nozzles

A similar nozzle without this problem is the tangential inlet whirl nozzle. This nozzle relies on the tangential inlet flow to create the swirl in the nozzle that creates the droplet pattern.

Thus, there are no internal parts. The outlet opening in the nozzle is essentially the same size as the inlet, so any debris can pass through the nozzle without becoming lodged. The other difference in this nozzle is that it produces a hollow cone pattern. This means that the droplets form a circular ring with an inner circle that is devoid of droplets. Since the droplets are more concentrated in a narrow ring, the designer must take this into account when laying out the spray patterns with their overlaps to produce a droplet zone of even density.

10.3 Spiral Nozzles

Another slurry spray nozzle being used today is the spiral nozzle which is also commonly referred to as the "cork screw" nozzle. This nozzle does not swirl the slurry. The shape of the nozzle actually shaves off slices of the slurry stream and directs them out at an angle which creates a spiraling circular pattern of droplets. The droplets fill the circle completely more like a full cone nozzle, but are not as uniform as the full cone pattern. The pattern has areas of higher and lower droplet concentrations.

Slurry Spray Nozzle - Spiral
Used with permission from Spraying Systems Co.

The openings in the spiral are fairly large but not as large as the inlet. So the nozzle is not as prone to pluggage, but will plug if the debris is about as large as the nozzle inlet opening. The pluggage is easy to see and remove.

If a nozzle does plug, it tends to shoot a concentrated stream of slurry in a mostly horizontal direction. There have been cases of a plugged spiral nozzle close to the tower wall actually eating a hole through the wall or through adjacent slurry headers due to slurry impingement erosion.

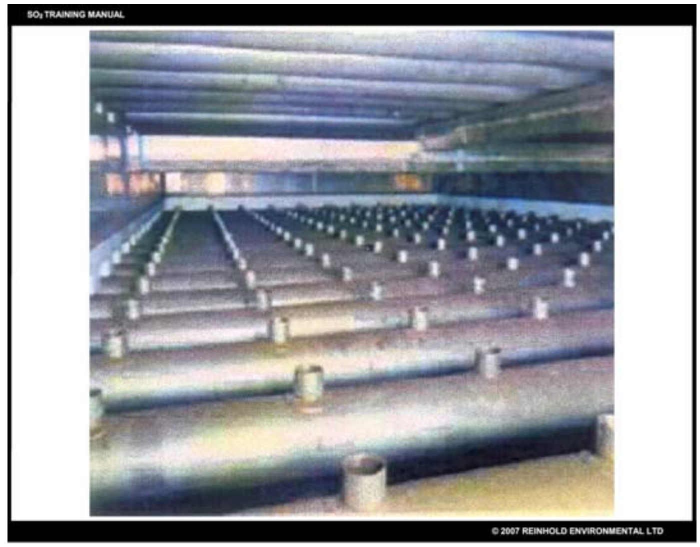
One word of caution about the spiral nozzles, the wear pattern will be a series of grooves cut into the angled face of the spiral. The grooves will gradually become deeper and deeper.

This doesn't affect the spray pattern that much. The problem occurs near the narrow tip of the nozzle. When the grooves become deep enough, the flow force of the slurry plus possibly some flow induced vibration will cause the entire tip to suddenly break off. This will have some impact on the flow pattern. The real danger is that this chunk of metal or ceramic can do damage to slurry recirculation pump linings and impellers. If one tip breaks off, it is time to change out all the nozzles that have similar wear patterns.

10.4 Fountain Nozzles

The last type of nozzle being used today is the fountain nozzle. It actually barely considered a nozzle. It is an open pipe pointed in the vertically up position. Gravity supplies the force to stop the slurry flow. As it stops and begins to falls, the slurry forms an umbrella shaped sheet that then breaks into droplets as it interacts with the flue gas flow.

Since it is an open pipe, there is no pluggage issue unless the debris is too large to pass through the pipe opening.



Slurry Spray Nozzles - Fountain
Used with permission

10.5 Nozzle Materials

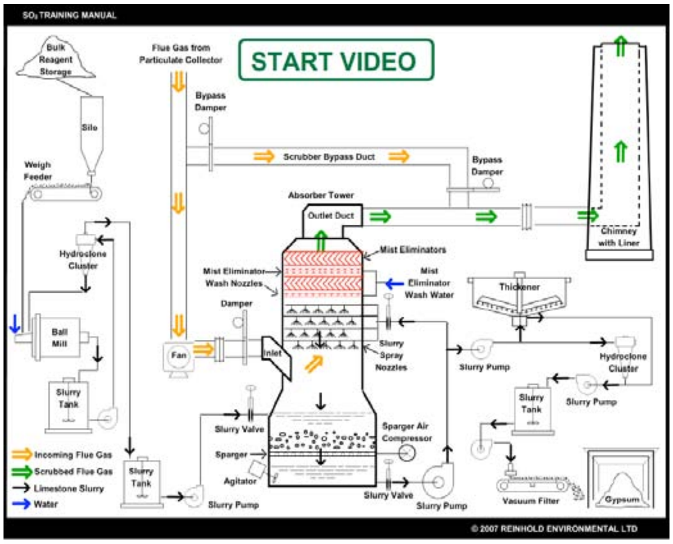
Due to the extremely abrasive nature of the slurry, the typical materials used for slurry spray nozzles in FGD systems are ceramics, abrasion resistant metals, and polyurethane. The nozzles are typically supplied with a four bolt flange mounting connection.

Ceramic nozzles are very erosion resistant, but they are brittle and subject to breakage due to impact. This is not usually a problem when they are in service, but they can be damaged during maintenance outages if care isn't used in working near them. If someone uses a ceramic nozzle for a "step", they will usually find their weight will break it off at the mounting flange. Some mechanics have found that the easiest way to remove a worn ceramic nozzle is to hit the mounting flange with a hammer. This will break the nozzle off. It is then easier to remove the old bolts.

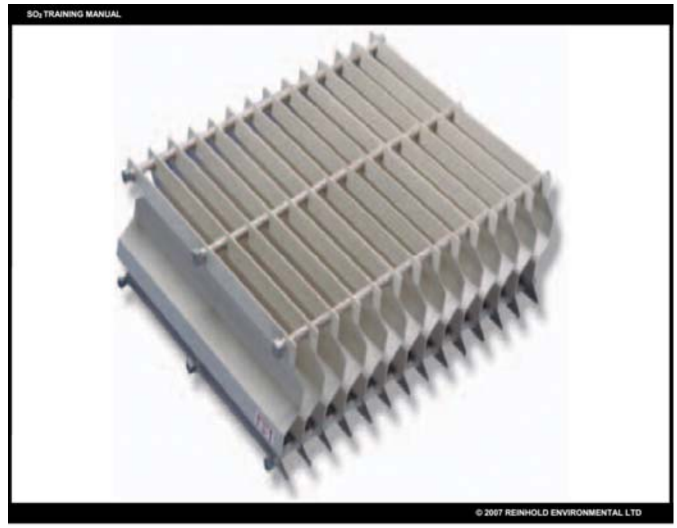
Slurry Spray Nozzle - Ceramic
Used with permission from Spraying Systems Co.

The metal nozzles are usually a cast metal with high cobalt content that is very erosion resistant. They are not subject to breakage under normal conditions. The polyurethane nozzles are also cast and are abrasion and breakage resistant.

CHAPTER 11 - MIST ELIMINATORS



Chapter 11 Summary
(Narrated by Ron Richard, RE Consulting)



Mist Eliminator FRP
Used with permission from Koch-Glitsch L.P.

A properly functioning mist eliminator is necessary to prevent the slurry droplets in the absorber tower from entering the chimney and raining down on the surrounding countryside. Mist eliminators can be placed in various orientations and have different blade configurations. Moreover, more than one level of mist eliminators may be used. Maintenance costs at some mist eliminator installations have been high due to pluggage of the mist eliminator gas passages or failure of the materials of construction.

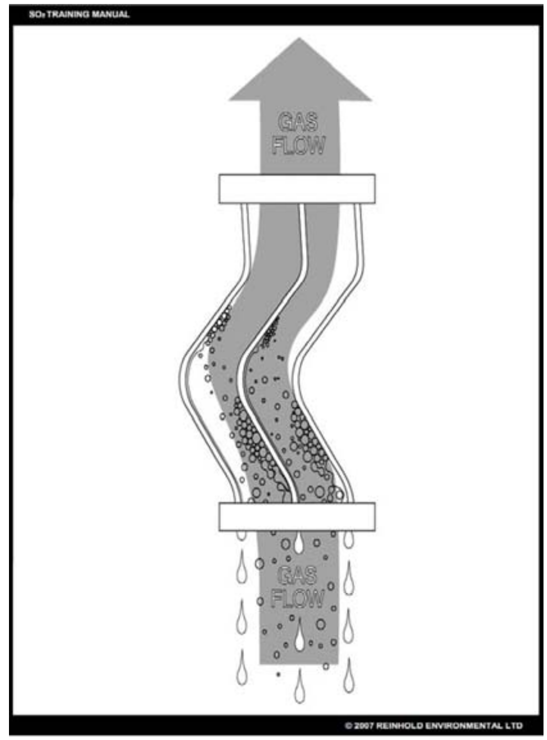
This chapter discusses what is necessary to have a proper mist eliminator design that will operate with low maintenance cost.

11.1 Horizontal vs. Vertical Flow

There can be confusion in referring to the orientation of a mist eliminator. The mist eliminator in a vertical spray tower is installed in the horizontal orientation with the gas flowing through it in a vertical flow. Does that make this a horizontal or a vertical mist eliminator? To avoid confusion, most people refer to a mist eliminator in reference to the direction of the gas flow. So, this would be a vertical flow mist eliminator.

The vertical flow mist eliminator is the most prevalent design in existing FGD systems. The job of the mist eliminator is to eliminate the droplets of slurry from the moving gas stream.

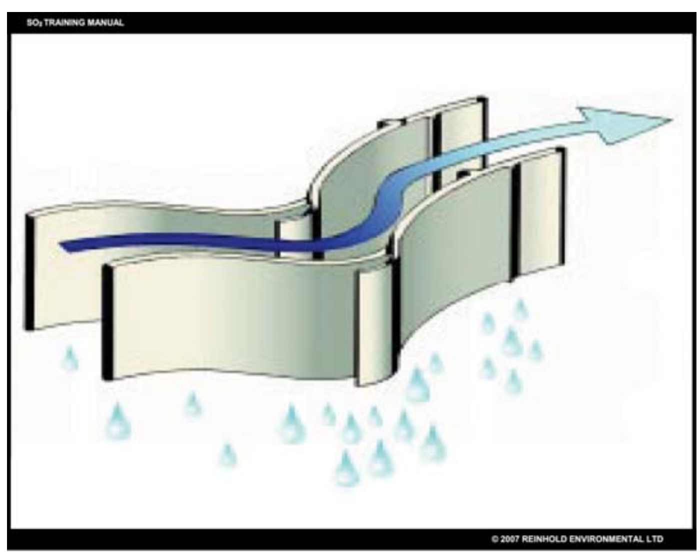
This happens by forcing the gas to make a sharp bend. The inertia of the liquid droplets causes them to continue in a straighter path and they collide with the blades of the mist eliminator. Once the liquid is on the blade, gravity causes it to flow down the blade and collect at the bottom edge of the blade. Large droplets then form and fall from the mist eliminator into the oncoming gas flow.



Mist Eliminator - Vertical Flow Diagram
Used with permission from Munters Corp.

The gas velocity operating limit for vertical flow mist eliminators was in the range of 10 – 12 feet per second (FPS). This limit existed because at higher velocities, the liquid could not flow down the blade against the oncoming gas flow, or if it did, the falling liquid droplets would be carried by the oncoming gas flow back into the mist eliminator. A build up of liquid on the mist eliminator blades will eventually cause liquid to pass through the mist eliminator and enter the down stream duct. Because of this limitation, vertical FGD towers had to be designed with a diameter that resulted in approximately a 10 FPS velocity at the maximum design gas flow.

The tower designers would like to design for a higher velocity to reduce tower diameter and thus capital cost. Work is being done to design mist eliminator blades that will work effectively in the 13 – 15 FPS range. Some testing has been done and some towers are already in operation at 13 FPS.



Mist Eliminator Horizontal Flow Diagram
Used with permission from Munters Corp.

The horizontal flow mist eliminator can operate in the 20 – 25 FPS range. This is because the blades are installed in a vertical up/down orientation. This means the liquid is draining down the blade perpendicular to the gas flow instead of directly into the gas flow. The liquid can also drain down the blade all the way to the end of the blade which is in a drain box out of the gas flow. This means the liquid will not be carried back onto the blades by the moving gas stream.

There have only been a few FGD towers designed in the horizontal orientation. They were smaller because of the higher velocity of the gas. A horizontal flow mist eliminator can also be installed in the outlet duct from a vertical tower since it can handle the higher gas velocity of the duct.

Some of the horizontal flow blade designs have hooks to help capture the liquid on the blade. The hooks provide a channel for the liquid to flow down the blade and not be pushed along the blade surface by the gas flow. The problem with the hooks occurs when the mist eliminator gets dirty. If scale forms in the hooks, it acts as a dam to the liquid flowing down the channel. As the liquid encounters this dam, it is forced out of the channel and back into the moving gas stream as large droplets. The liquid is then carried back through the mist eliminator and may pass on through. So a dirty hook is a large detriment to proper mist eliminator performance. When cleaning a mist eliminator with hooks, it is very important that the hooks are completely cleaned of any scale deposits.

The vertical flow mist eliminator is usually installed in a flat horizontal layer. There are some designs when the mist eliminator panels are installed in a series of inverted V shapes (looks like rows of tents) across the tower. This gives the vertical flow blades some of the draining characteristics of the horizontal flow blades. The water drains somewhat across the gas flow and the large droplets form and drop off just in the valleys formed by the inverted Vs. This improves the performance of the vertical flow mist eliminator.

11.2 Two Pass vs. Three Pass

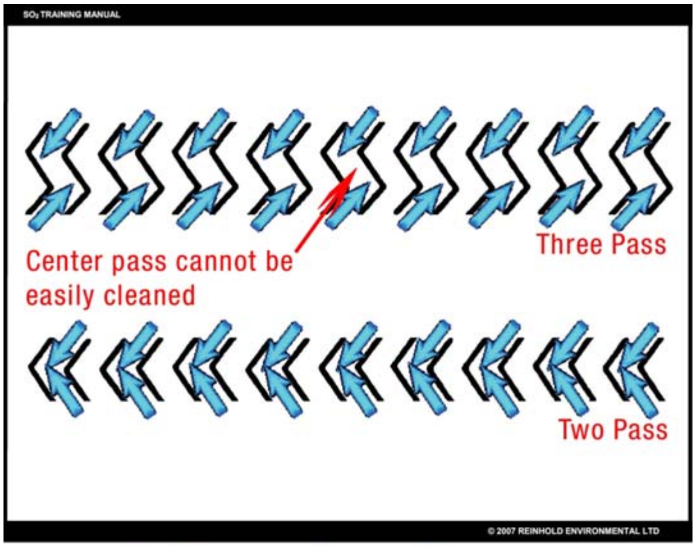
Most mist eliminators being used in FGD systems are either two pass or three pass designs. The difference is the number of bends the gas must negotiate in passing through the mist eliminator blades. In the two pass design, the gas passes one direction, makes the turn, and passes the second direction. In the three pass design, the gas passes one direction, makes a turn, passes a second direction, makes a turn, and passes the third direction. Some manufacturers use a fairly square corner. Other manufactures use more of a sinusoidal shaped turn.

Mist Eliminators - Two Pass vs. Three Pass
Used with permission from Koch-Glitsch L.P.

It would seem logical that the addition of the second turn would cause more of the droplets to be removed resulting in a more dry gas stream at the mist eliminator exit. This logic is correct if the mist eliminator remains clean at all times.

However in an FGD system, the real world intrudes with its own reality. The question in an FGD system is not if the mist eliminator will become dirty, but when it will become dirty. The calcium sulfite and calcium sulfate in the slurry has a tendency to form scale on the mist eliminator blades. There are wash nozzles to slow this scale formation, but it will eventually form.

The scale build up between the blades reduces the open area which causes the gas velocity through the mist eliminator to increase. Increased gas velocity causes more liquid to be carried through the mist eliminator. The decreased open area also increases the back pressure on the gas and increases the pressure drop across the mist eliminator. The increased pressure drop indicates it is time to clean the mist eliminator.



Mist Eliminator - Cleaning Effectiveness
Used with permission

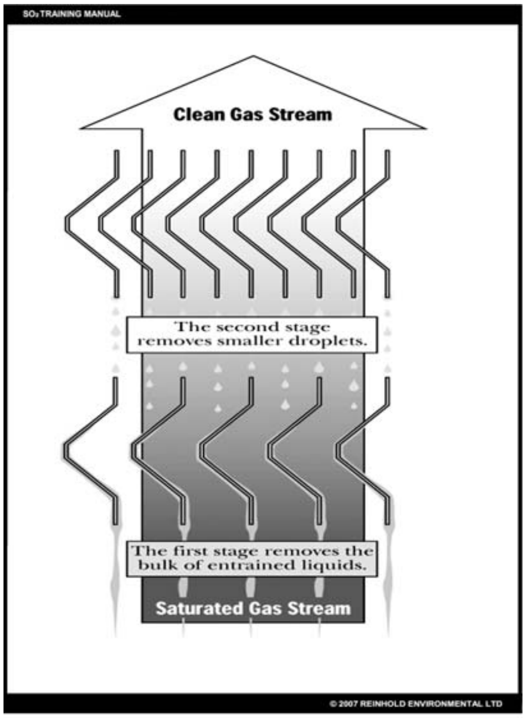
Cleaning is usually done using high pressure water lances. The water lance shoots a narrow straight stream of high pressure water. If one looks at the lower portion of the two pass vs. three pass diagram, one can see that lancing a two pass mist eliminator from the top side and the bottom side will clean both passes of the mist eliminator. Doing the same thing to a three pass mist eliminator will clean the first and third passes, but the water stream cannot be directed into the center pass. Thus some of the scale deposit will remain in the mist eliminator after cleaning.

When the mist eliminator is placed back in service, the gas will be given a higher velocity through the center pass due to the restriction caused by the remaining scale deposit. Any liquid trying to drain from the third pass back to the first pass to drop off the mist eliminator will be swept up by the high gas velocity through the center pass and carried back to the third pass. So the liquid from the second and third passes will tend to build up in the third pass and be swept through the mist eliminator.

So the moral of the story is that a clean two pass mist eliminator is always more efficient than a dirty three pass mist eliminator. And, a three pass mist eliminator is usually dirty because there is no effective way to clean the center pass.

11.3 Multiple Stages

Instead of having a single mist eliminator with multiple passes, it is better to have multiple layers of two pass mist eliminators. This design has mist eliminator layers that can be cleaned as well as multiple stages for maximum droplet removal. Most FGD



Mist Eliminator - Two Stage Diagram
Used with permission from Munters Corp.

systems have two stages of mist eliminators. A few may have more than two stages.

The first stage will remove most of the larger slurry droplets. It is sometimes referred to as the “roughing demister”. Often the blades have a slightly wider spacing. This allows the liquid to drain from the blades more easily against the oncoming gas flow. It also makes it easier to clean between the blades when they become plugged with scale deposits.

The second stage will remove most of the remaining small slurry droplets. It is sometimes referred to as the “finishing demister or polishing demister”. The blades are typically spaced closer together than they are in the first stage mist eliminator. This gives the smaller droplets more blade surface area to impact against. There isn’t as much liquid left in the gas stream to collect and drain back off of these blades. This closer spacing does make it harder to clean the scale deposits from between the blades.

It is best to place the first stage mist eliminator as far as economically possible from the last slurry spray nozzle layer. This gives more space for the droplets to collide with each other and grow larger before they make contact with the mist eliminator. It also allows some of these large droplets to fall back into the tower under the influence of gravity so they never make contact with the mist eliminator.

The second stage mist eliminator must be placed far enough above the first to allow workers access to clean the top side of the first stage and the bottom side of the second stage.

Some designs have a first stage arranged in the inverted V configuration to increase blade liquid handling capacities and a second stage of the more typical flat horizontal layer since there isn’t that much liquid impacting on these blades.

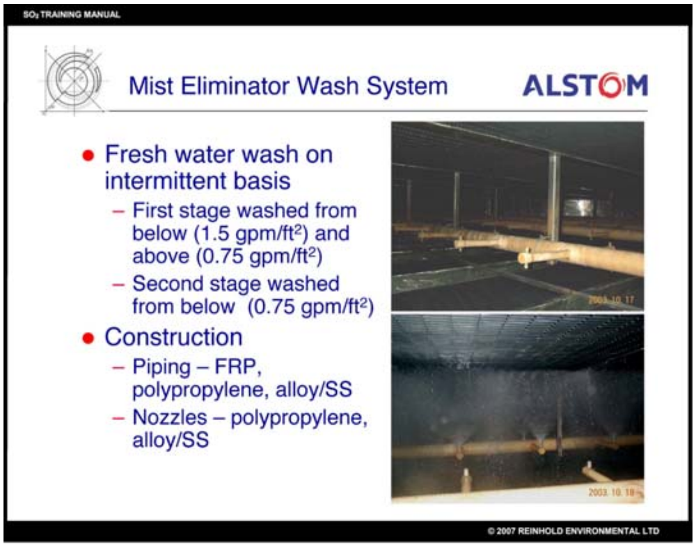
Real Life Example

One utility chose to have a single stage vertical flow mist eliminator in the top of the tower and then a second stage horizontal flow mist eliminator in the tower outlet duct. This allowed many of the droplets exiting the first stage to impact on the tower transition hood walls and the duct walls in an elbow and drain to the floor before the gas stream entered the second stage. The only problem encountered was the gas was so dry entering the second stage that the mist eliminator blades would dry out. Then any liquid droplets impacting the blades would evaporate, leaving the solids behind on the blades which caused scale deposits that were not washed off by the normal mist eliminator wash system.

11.4 Keeping Them Clean

Mist Eliminator Wash System

There can be a misconception about the normal mist eliminator wash system. It is not designed to wash off scale deposits that grow on the mist eliminator blades. It is designed to dilute and flush deposit forming liquids and crystals off the mist eliminator blades before deposits are formed. As slurry remains on the blades, it still has the capacity to remove SO_2 from the passing flue gas. The calcium sulfite or calcium sulfate concentrations can increase to the levels where crystals start to grow in the slurry. If left in contact with the mist eliminator blades for enough time, the crystals can attach to and continue growing on the blades forming a scale deposit.



Mist Eliminator Wash System
Used with permission from Alstom

The nozzles used in mist eliminator wash systems don't operate at a high enough pressure or a narrow enough spray pattern to dislodge scale deposits that have attached themselves to the blades. Over time, if it is using mostly fresh water, a mist eliminator wash system may be able to dissolve some scale deposits that have formed, but not very effectively. The mist eliminator wash system must be designed and operated in a manner to keep the scale deposits from forming. The important factors in accomplishing this are described below.

If at all possible, the mist eliminator wash water should be fresh water instead of recycled FGD process water. The goal is to dilute the saturation of calcium sulfite or calcium sulfate in the liquid on the blade surface. Spraying fresh water on the blade will have more of a diluting effect than using recycled FGD process water which contains calcium sulfite and calcium sulfate.

Most modern scrubbers have a tight water balance. They try to have minimal waste liquid streams to dispose of. About the only liquid leaving the process is in the byproduct material and in the water that passes through the mist eliminator in the cool saturated flue gas. This means there is a finite amount of fresh water that can enter the system without causing a liquid overflow waste stream that is not desired. If at all possible, all fresh water entering the FGD process should enter as mist eliminator wash water. (This is not possible in a lime based FGD system since lime slaking also requires fresh water.) If more mist eliminator wash water is needed than can be supplied using fresh water, then fresh water should be mixed with recycled FGD process water in a mist eliminator wash water tank The easiest way to do this is to manually set the fresh water flow into the tank at the maximum allowed and then let a level control valve add recycled FGD process water to maintain the desired tank level.

Since to total amount of mist eliminator wash water that can be added to a tower without diluting the tower solids is limited, it works best to use small amounts of water frequently. A small volume of wash water sprayed on the blades one or more times per hour will keep the slurry on the blades more diluted on average for the entire time period than a large volume of water sprayed on the blades once every several hours.

To effectively dilute the slurry, all of the blades must receive an equal amount of water. To do this, designers use a large number of small wide angle full cone spray nozzles spaced so there is adequate spray pattern overlap. They must have the full cone spray pattern so there is even water distribution across the entire spray pattern. Since the mist eliminator wash water contains minimal solids, small nozzles can be used without a lot of pluggage problems. The spray patterns should be tested and inspected during maintenance inspections so that any damaged or plugged nozzles can be replaced. Spray nozzles may be metal (if a proper corrosion resistant alloy), plastic, or FRP.

If one were to spray the entire mist eliminator surface at the same time, the additional volume of water could flood the blades and the flue gas flow would carry a lot of liquid into the outlet duct. Because of this, the mist eliminator spray headers are designed so that smaller sections of the mist eliminator are sprayed sequentially. Usually no more than one quarter of the mist eliminator is sprayed at one time. Some designs spray even smaller sections at a time. A controller is programmed to open solenoid operated spray header valves in a predetermined sequence. One valve is opened for a short time and then it closes and the next valve opens. This continues until all the spray header valves have been opened and closed. Then there may be a wait period before the sequence begins again, or it may immediately start again. FGD systems with multiple towers may sequence all the wash valves in one tower and then do the same for each additional tower before restarting the sequence in the first tower. Or, one valve in each tower may be open simultaneously as the sequence occurs. It all depends upon the system design.

Most FGD systems are designed with separate banks of mist eliminator wash nozzles for the front of the first stage, the back of the first stage, the front of the second stage, and some even have a bank for the back of the second stage. The nozzles for the fronts of the first and second stages are very important and should be sprayed as often as possible. If one thinks about the wide angle full cone spray pattern directed at the back of the first stage, one realizes that most of these droplets will never reach the mist eliminator blades against the oncoming flue gas flow. All is not lost since the droplets will impact the second stage mist eliminator and dilute the slurry on those blades. Most would be lost with the nozzles on the back of the second stage if operated at full gas flow. Most of the droplets will never reach the mist eliminator blades and most will end up in the outlet duct where the water can lead to corrosion of the duct walls. If the FGD system does have nozzles for the backs of the stages, it is best not to use them with the tower at full capacity, which will allow for more spray cycles of the nozzles for the fronts of the stages.

It is best to have the mist eliminator wash water flow recorded on a graph or in a data acquisition system. The output will be a series of peaks as each valve opens and closes. Looking at the output can show the operator several things. If a peak is less than adjacent peaks, that header valve may not be opening completely or there may be plugged nozzles on that header. If a peak is missing, that header valve is not opening. If all the peaks are reduced, there is a problem with the mist eliminator wash pump.

If a mist eliminator is in service for an extended time without the mist eliminator wash system functioning properly, the differential pressure drop across it will increase as scale deposits form on the blades. If the mist eliminator wash system is repaired, it may reduce the differential pressure drop by a small amount, but will not be able to remove all the scale deposits that formed. A maintenance outage will be required to mechanically clean the mist eliminator blades.

Mechanical Cleaning

A mechanical cleaning of the mist eliminator blades is typically done using high pressure water lances. This method is very effective, but can cause damage to mist eliminator blades and mist eliminator frames and supports if not done correctly. Other methods are more time consuming and not as effective. Using fire hoses and nozzles doesn’t work very well and can cause a lot of damage.

The lance nozzle should produce a narrow fan pattern. A wide fan pattern will dissipate too much of the spray energy and will not remove the deposit. A narrow solid stream will have too much energy and will cut or score plastic and FRP blades. The nozzle should not be held too closely to the blades or it will still cut or score plastic or FRP blades. Some testing and close inspection should be done at the start of the job to determine the proper nozzle pattern and distance.

The pressure should not be any higher than that required to remove the deposit. The angle of the lance should be mostly parallel with the direction of the blades. Having too much pressure or hitting the blade at a more perpendicular angle can bend, crack, or break the blades. The task of the cleaning crew is to remove as much of the deposit as possible while doing the least damage possible to the blades and frames. If the blades have hooks, it is important that the channels formed by the hooks be cleaned of all scale deposits.

There are various designs of spacers to stiffen the blades and to keep the blades separated at the proper spacing. Care must be taken not to cut or break these spacers. Broken spacers will allow the blades to flutter in the flue gas flow or to fold over blocking the flue gas flow. Fluttering blades will eventually crack and then break.

The mist eliminators will need to be water lanced from both the front and back sides to remove all the scale deposits. If it is a three pass mist eliminator, it is virtually impossible to remove all the scale deposits it the center pass. Various methods have been tried, but they usually result in significant damage to the blades with only limited scale removal effectiveness.

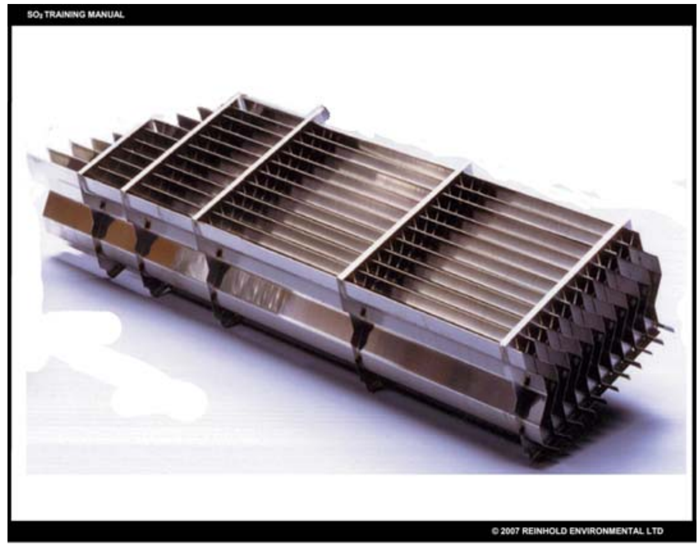
Most vertical flow mist eliminators are designed to support a person walking directly on the blades. It is prudent, however, to use “walk boards” when doing a lot of work on the mist eliminators. Narrow sheets of plywood that will fit through the access door work well. Walking or placing ladders and equipment on the plywood distributes the weight over more blades which minimize the chance of cracking or breaking any single blade.

It is also prudent to prevent the scale debris from circulating in the tower where it will damage slurry recirculation piping, pump liners, and pump impellers. The tower can be drained before the mist eliminator cleaning and the debris vacuumed off the tower floor at the end of the cleaning. If the tower is not going to be drained, tarps or nets should be hung in a way to catch the debris so it won’t fall into the slurry. This is easier to do in a tray type tower where the tarp or net can lay on the tray.

11.5 Materials of Construction

Mist eliminators for FGD systems have been fabricated from metal alloys, FRP, and plastics. Each material has success stories and each material has failure stories. These differences occur because of tower conditions, material limitations, design parameters, and improper fabrication.

Metal Alloys



Mist Eliminator Metal
Used with permission from Koch-Glitsch L.P.

Metal blades are stronger and more rigid than blades fabricated from the other materials. Metal blades are fire/heat resistant and not as prone to damage from mechanical cleaning of scale deposits. The cost of metal blades fabricated from corrosion resistant alloys is significantly higher than the blades fabricated from FRP and plastic.

There have been surprises with metal blades that were fabricated from corrosion resistant alloys. Some looked like Swiss cheese after several years of service. One factor that can cause this is residual stress in the thin metal that remains from when the metal was formed into the blade shape. This residual stress can make a metal more susceptible to chloride attack. The values shown in corrosion resistance charts are for unstressed metal plate. Also, the scale deposits on the blades can lead to concentrated values of chlorides and fluorides under the deposits. These values can be many times higher than they are in the bulk slurry.

Care must be taken in selecting the metal alloy used to fabricate a mist eliminator. Allowance needs to be made to select an alloy with enough safety margin to withstand the chemical environment on the actual mist eliminator blade. Of course the higher performance alloys have a higher price and may be more difficult to form into a shape.

FRP

Mist Eliminator FRP
Used with permission from Koch-Glitsch L.P.

FRP blades are not as strong or rigid as metal blades but are stronger and more rigid than plastic blades. FRP blades are resistant to the FGD chemical environment. FRP blades are more brittle than plastic blades. Vibration from a fluttering blade is more likely to result in a cracked or broken blade. High pressure or improper lancing angle during mechanical cleaning can easily break the edge of an FRP blade. See the Mechanical Design Considerations section below for other cautions.

Real Life Example

At least one utility experienced delamination of FRP mist eliminator blades. The layers of resin and glass reinforcement separated. This caused the individual blades to swell and take up more space. This left less space between the blades. This caused a higher gas velocity through the mist eliminator which resulted in more carry over of liquid out the top of the chimney.

Plastics

Various plastics have been used to fabricate mist eliminator blades. These include polypropylene, Noryl, Ultem, Polysulfone, and Ryton. Plastic blades are not as strong or rigid as the other blade materials. These properties must be taken into account in the mist eliminator design. Plastic blades are resistant to the FGD chemical environment. Plastic blades are not as brittle as FRP blades. During mechanical cleaning, plastic blades are less likely to be broken. They can be cut or scored by the water jet which further weakens their mechanical properties.

Most failures in plastic bladed mist eliminators relate to structural deficiencies in the design of the mist eliminator sections or the method of securing them into the absorber tower. There have only been a few problems related to failures of the blade material itself.

Mechanical Design Considerations

Especially when using plastic or FRP blades, the design of the entire mist eliminator assembly has a major bearing on the serviceable life of the mist eliminator. Since the blades don't have that much strength and aren't that rigid, it is very important that the frame holding the mist eliminator panel is strong enough to support the entire assembly on the mounting system in the absorber tower. This includes the forces exerted by the flowing flue gas on a partially plugged mist eliminator. There have been cases where sections of mist eliminators have "blown out" in service because the frame buckled under the stress of the flue gas flow through partially plugged blades.

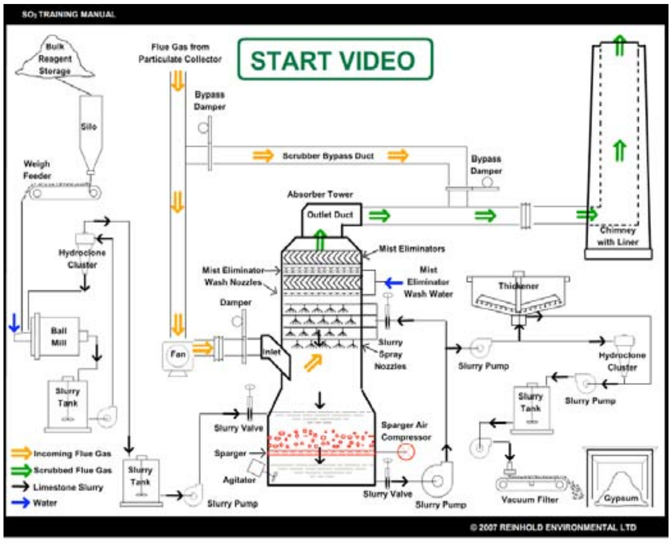
The next challenge is to support the blades in this strong frame. The blades typically have spacers at several points along their length. The spacers have two purposes. The first is to maintain the correct spacing between the blades. The second is to make the blades more rigid. This means rigid so the blades will not twist about their mounting axis. If a blade twists, the pressure from the flowing gas can push it on around until the edge touches the blade beside it closing off the gas passage between the two blades. This also means rigid so the blades will not flutter along their length. If a blade flutters as the flue gas flows past it at high velocity, the movement will eventually cause fatigue in the plastic material and it will crack or break.

The early blade spacers were slotted bars that slid over the edges of the blades and bolted to the frames. These worked well for metal blades. However with the plastic and FRP blades, the blade edges soon fatigued and broke off where they fit in the slots and the blades were then free to move. A different design was needed for these blades.

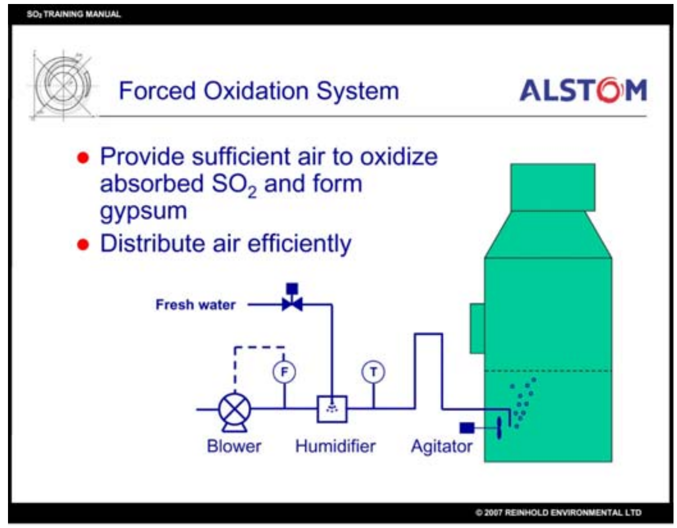
The best spacer for plastic and FRP blades consists of plastic rings the thickness of the desired blade spacing and plastic rods. Holes have to be drilled or punched through the centerline of the blades where each support rod will be located. The blades and rings are then alternately stacked onto the rods. The rods are attached into the frames. The blades are sandwiched between the rings and locked in by the rods. This provides a long lasting support of the blades. If the rods are adequately attached to the frame, the entire assembly is very rigid.

When considering material, one overall FGD design issue is the risk of overheating and fire. There is less risk of damage to a tower with "all alloy" internals than one containing FRP, rubber, resin and plastics. Mist eliminators are one component for the FGD owner's risk evaluation.

CHAPTER 12 - OXIDATION AIR



Chapter 12 Summary
(Narrated by Ron Richard, RE Consulting)



Forced Oxidation System
Used with permission from Alstom

It has proven beneficial to oxidize the reaction products of the scrubbing reactions to produce gypsum. This solves some of the operating and maintenance problems experienced by FGD systems in the past and it also produces a more structurally stable material that can be sold.

This chapter discusses the design and operation of the hardware that is used in the oxidation process.

12.1 Compressors

Compressor - 2000 HP
Used with permission from Turblex

Compressors are usually referred to as oxidation air blowers, but in reality they can be large single stage air compressors. They don't need to produce a lot of pressure, just a large volume of air. The gear boxes and other components are similar to other centrifugal compressors that might be at the station. One major difference is that there may be only one impeller wheel operating at high speed or multi-stage units can be utilized.

One word of caution regarding the location of the air intakes for the compressors. It would be best to locate them where they will not pick up any SO_2 from leaks in expansion joints or guillotine gate seals. One should also avoid areas where dense damp vent plumes from various FGD process equipment or fly ash from ESP operations are present. Either item could cause corrosion of the compressor components.

The discharge piping from the compressor should be routed so that at least one portion of it is significantly higher than the liquid level in the oxidation tank. If the compressor should trip off line, one doesn't want slurry coming back into the oxidation air header to come all the way back to the compressor. It is best to always have the compressor running if there is a slurry level above the sparger or lances. But Murphy's Law says a compressor will sometimes trip off and the sparger or lances will fill with slurry. Warm compressed air temperature requires pipe materials capable of the service and may require spot insulation for personnel protection.

There is usually some sort of water addition nozzle and control system in the oxidation air header. This is to humidify the oxidation air. If the oxidation air is dry, it may evaporate water from the slurry leaving the solids to build up around the sparger holes or the ends of the lances. The quality of the water should be considered so it doesn't leave deposits in the oxidation air piping.

12.2 Spargers

The oxidation process brings one back to liquid/gas interface issues. In the absorber tower, one was dealing with slurry droplets surrounded by gas. In the oxidizer, one is dealing with gas bubbles surrounded by slurry. The goal in both cases is the same, to provide the maximum amount of liquid/gas interface surface area for the longest time possible.

Other factors affect the performance of the oxidizer. These include:

- slurry pH,

- temperature,
- suspended solids concentration,
- dissolved solids,
- sulfur content of the coal,
- mixing,
- vessel geometry,
- slurry depth,
- slurry viscosity,
- and percent of natural oxidation in the slurry.

But from the sparger perspective, one is concentrating on bubble size and bubble rise time.

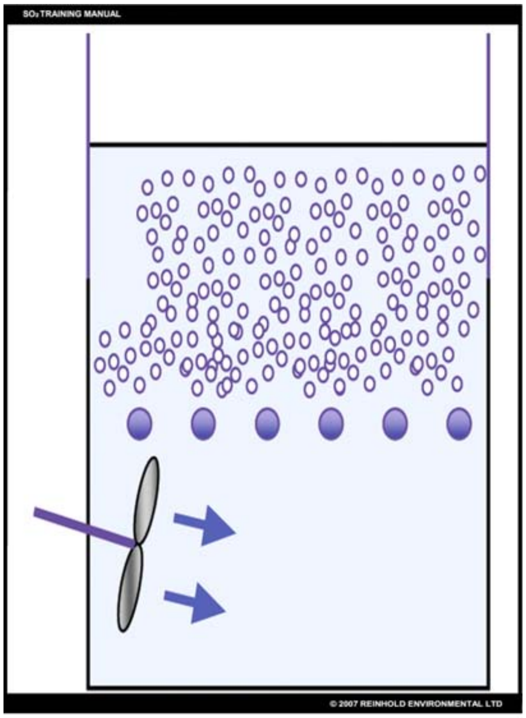
Large air bubbles have less total surface area and rise rapidly to the liquid surface. Small bubbles have more total surface area and rise less rapidly to the liquid surface. Swirling of the liquid by mixers can cause large bubbles to break up into smaller bubbles. Swirling of the liquid can also give the bubbles a longer trajectory to travel in their rise to the surface, thus extending contact time.

The choice of which type of sparger system to use must be made by a designer that has had experience in determining how all the factors listed above will interact in the particular FGD system into which the sparger will be installed.

Fixed Grid Sparger

The fixed grid sparger is the oldest sparger design. It can be as simple as a length of pipe with holes or slots drilled along its length. This type of sparger tends to make larger bubbles. If the sparger holes are too small, they tend to close over time. The dry air can absorb some of the water from the slurry making the slurry more concentrated at the edge of the hole. The oxidation will convert the slurry solids to calcium sulfate. The concentrated calcium sulfate crystals will grow around the edge of the hole and eventually grow into the hole blocking the air flow.

One of the other problems with this sparger is that the air must be flowing any time the sparger is submerged in slurry. If the air flow stops, the slurry will flow into the holes and fill the sparger pipe. When the air flow returns, some of the slurry can remain in the pipe. The water will be evaporated by the dry air passing over the slurry and the solids will be oxidized to calcium sulfate and form a deposit in the sparger pipe. This deposit can restrict air flow and can also dislodge and plug the sparger holes from the inside.



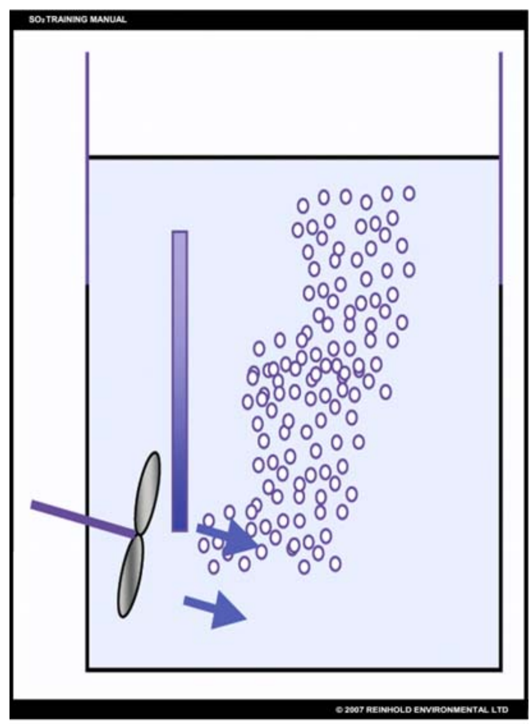
Fixed Grid Sparger
Used with permission

Most fixed sparger grids are a network of pipes connected together in a pattern that covers a slice of the tank over its entire diameter. The sparger pipes and holes must be sized to produce an even amount of bubbles across the entire sparger grid area. The holes or slots are typically on the underside of the pipes. It is prudent to install removable end caps on the sparger pipes. This makes it much easier to gain access to the inside of the pipes to remove calcium sulfate deposits that may form if slurry enters the pipes when air flow is lost.

The sparger grid is typically mounted above the mixers. In an external oxidation tank, this may be one large vertical shaft mixer mounted on the top of the tank with the shaft in the center of the tank and the impeller below the sparger grid. In an in-situ oxidizer, this may be a series of horizontal shaft mixers located around the tank circumference. The mixers prime purpose is to keep the slurry solids in suspension.

The flow of the mixers will also help break the larger bubbles into smaller bubbles. The challenge of the designer is to optimize the interaction between the sparger grid and the mixers.

The swirling motion imparted on the slurry by the mixers also helps to keep the bubbles in contact with the slurry for a longer time since they must travel a longer path to the surface. To obtain proper oxidation time, the slurry level above the sparger grid must always remain over the minimum level specified by the designer. The higher the slurry level, the more pressure the compressor must develop to push the air through the sparger holes.



Lance Sparger
Used with permission

The “turn down ratio” of the fixed grid sparger is determined by the compressor characteristics and the number and size of the sparger holes. Some compressor models have the capability to operate efficiently over a wider range of flow and pressure. But one must assure that there is always enough air pressure and flow to keep bubbles coming out of every hole in the sparger at the maximum tank liquid level. If not, slurry will enter the idle holes and cause deposit problems inside the sparger pipes.

There is typically a “stand by” compressor that will automatically start if the compressor in service should trip out of service for some reason. But Murphy’s Law indicates there will be instrumentation problems, mechanical problems, or a power failure that will occur from time to time that will cause no compressors to be in service with an oxidizer tank full of slurry.

As the sparger holes plug, the compressor will be required to work harder to force the air through the smaller open surface area. The compressor pressure, flow and horsepower should be measured and charted over time. This can give the operator some warning that the sparger grid is plugging. The amount of plugged holes that can be tolerated will be dependent on the compressor’s performance capabilities. The other indication will be lower oxidizer efficiency as the volume of air entering the oxidizer is diminished.

Lance Sparger

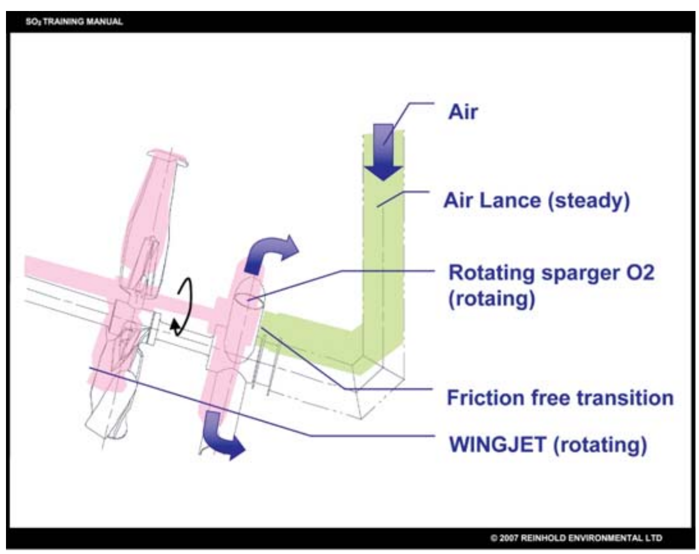
As in-situ oxidation became more prevalent, designers were looking for ways to more effectively couple the mixer and sparger performance. It was found that if a large open air pipe was centered in the discharge flow from a mixer impeller, the turbulence of this flow would break the large column of air coming from the pipe into the desired small bubbles. These bubbles were being formed lower in the oxidizer and were traveling in the slurry flow which maximized their rise time to the surface.

Rotating Sparger
Used with permission from EKATO Corp.

Besides forming smaller bubbles, this design has another advantage. The larger open pipe is not as prone to pluggage as are the small sparger grid holes. It also doesn't matter if the compressors remain in service at all times, when there is a slurry level in the tank. If the compressor is out of service, the slurry will enter the pipe, but it will all be discharged when the compressor returns to service.

The "turn down ratio" of the lance sparger is only limited by the performance characteristics of the compressor. One doesn't have to worry about slurry getting back into the sparger pipes.

The weakness of the lance sparger is that it is extremely dependant on the mixer. If a mixer goes out of service, that sparger lance will be much less efficient. If recycle pump suction is a concern, the lance must also be removed from service. Without a mixer, all the air coming from that lance will form very large bubbles that will have minimal surface area and will rise to the surface rapidly due to their buoyancy.



Rotating Sparger - Air Flow Diagram
Used with permission from EKATO Corp.

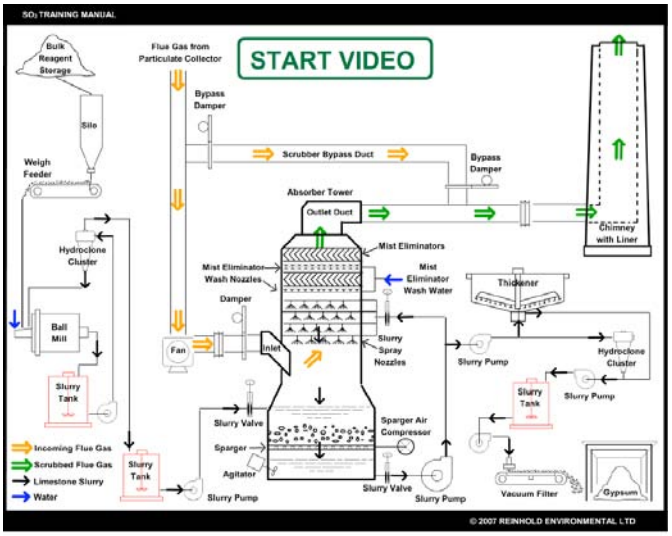
Other Types of Spargers

Mitsubishi Heavy Industries (MHI) has developed several versions of what they have named an air rotary sparger (ARS). It is designed much like a vertical shaft mixer. The motor and gearbox are mounted on top of the tank. There is a hollow shaft that hangs down into the tank. Air is fed into this hollow shaft through a rotary coupling. There have been various designs of impellers or sparger pipes mounted at the end of the shaft. There are holes in the impellers or sparger pipes where the air is discharged into the slurry. The entire assembly rotates in the slurry which provides agitation of solids while dispersing small bubbles throughout the slurry.

Ekato has developed a rotating variation of the lance sparger. The main difference is that instead of an open pipe mounted in the centerline of the mixer impeller, this design has a rotating hub with multiple smaller open pipes that place the air directly in front of each mixer impeller blade.

MHI has also developed an inductor type jet nozzle. Slurry from the slurry recirculation pump passes through a ceramic nozzle. Air is introduced downstream from an orifice plate mounted in the nozzle. The turbulence after the orifice mixes the air with the slurry forming small bubbles.

CHAPTER 13 - SLURRY STORAGE & TRANSFER



Chapter 13 Summary
(Narrated by Ron Richard, RE Consulting)

Bulk Slurry Storage Tanks
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The solid particles in the FGD slurry are heavy and have a tendency to settle to the bottom of tanks and pipes if they are not moving at a high enough velocity.

During slurry storage and transfer, the slurry must be in one of two states. The first state is flowing and the second state is agitated. If it is not in either of these states, the solids will enter another state called settling.

This chapter discusses the issues and the operating practices needed to keep slurry solids from settling in tanks and pipes during slurry storage and transfer operations.

13.1 Slurry Storage

When the slurry is in a FGD process or is awaiting the next FGD process, it usually resides in tanks. These tanks must be agitated at all times. The type of agitator used will depend on the size and shape of the tank. A large single vertical shaft agitator is usually preferred if there is sufficient space to mount and maintain the motor and gear box above the tank. Multiple horizontal shaft side entry agitators are used if a vertical shaft agitator can't be used.

Bulk Slurry Storage Tanks
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Some recent agitator specifications require that the agitator must be capable of restarting in a tank full of slurry after being out of service for 24 hours. This is to protect the owner in case of a power outage in the FGD area. After 24 hours, most of the solids in the slurry will have settled to the bottom of the tank. If the agitator impeller becomes buried in these solids and the agitator motor cannot turn the shaft, the tank will have to be drained and the solids manually removed. Two design methods have been used to meet this specification requirement:

- Significantly over design all agitator system components at significant cost, or
- Install the mixers above the tank floor relative to the stored percent solids.

Tanks that suffer from the "out of sight out of mind" syndrome are called sumps. If a sump is going to receive slurry from time to time, it needs to have some type of agitation system installed. This may be a mechanical agitator or it may be an air or liquid sparger grid. Something needs to keep the solids from accumulating on the bottom of the sump and clogging the sump pump suction.

13.2 Slurry Transfer

Slurry transfer in a pipe needs to be done at a high enough velocity to maintain turbulent flow in the pipe at all times. This can become impossible if there is a regulating valve in the pipe that is controlling a level in a tank or the feed rate to a process. If the regulating valve is limited to operate in a range where even at its most closed position there is adequate flow to maintain the solids in suspension, then this is permissible. Otherwise, other alternatives must be found.

The lime/limestone feed valves must close completely from time to time to maintain absorber tower pH control. What is typically done in this type of situation is to establish a recirculation loop from the feed tank, past the absorber towers, and back into the feed tank. The lime/limestone feed valves branch off of this loop. (The branch piping runs must be as short as possible to keep them from plugging when the valves are closed for short periods of time.) The flow rate in the loop is designed so that even with all of the lime/limestone feed valves completely open, there is still sufficient flow in the loop to keep the solids in suspension all the way back into the feed tank. The cost of this type of system is a larger pump and the wasted horsepower pumping the additional slurry around the loop back into the feed tank.

The savings are a reliable pH control in the towers which provides efficient reagent utilization and the avoidance of continual header pluggage and its associated maintenance cost.

For the tank level control situation, a simple on/off scheme with a level “dead band” is typically used. When the level reaches the first set point, the pump will start and the slurry will flow. When the level reaches the second set point the pump will stop. When the level reaches the first set point again, the pump will restart. During the time the pump is idle, some type of action must be taken to prevent solids from settling in the pump and piping.

For smaller bore piping systems, the pump shut down sequence often includes an automatic flush cycle of the pump and piping. A normal pump shutdown signal will cause a flush water valve to open and the slurry suction valve to close. A timer will allow the pump to run pumping flush water down the pipe. Once enough time has elapsed to fill the pump and piping with clear flush water, the pump motor will be taken out of service and the flush water valve will close.

For large bore piping systems such as the slurry recirculation piping, another system may be used. A normal shutdown signal will cause the pump motor to be taken out of service and the slurry suction valve will close. A pump casing drain will open draining the slurry from the pump discharge piping and the pump casing. After the predetermined drain time, a flush water valve will open flushing clear water through the pump and out the pump casing drain. The flush water valve and the casing drain valve will then close. The slurry pump will then be sitting empty and idle.

Slurry transfer piping between FGD processes can often be routed outdoors between buildings. It is often not insulated since the slurry is warm. Because of freezing concerns in the winter, such systems may have a vent and drain feature. During freezing temperatures, when the pumps are stopped and the flush of the system has occurred, the control system opens low point drains and high point vents. This empties the flush water from the piping. That is, of course, as long as the pipe spools to the drain valves are not full of solids that have settled into them during the normal flow of slurry in the pipe or that the immediate area receiving the flushed drainage is not plugged or frozen.

One utility learned this the hard way. They experienced a forced boiler outage during severe winter weather. The FGD system was taken out of service. After about a week, when the FGD system was being put back into service it was discovered that the 6 inch and 8 inch slurry transfer lines that ran for half a mile between the absorber area and the primary dewatering area were frozen solid. The drain valves and the vent valves were open, but the drain valve pipe spools were full of slurry solids. The flush water had never drained from the pipe. Since this was rubber lined flanged pipe, the only way to thaw it was to unbolt all the flanges and move the piping into a warm building.

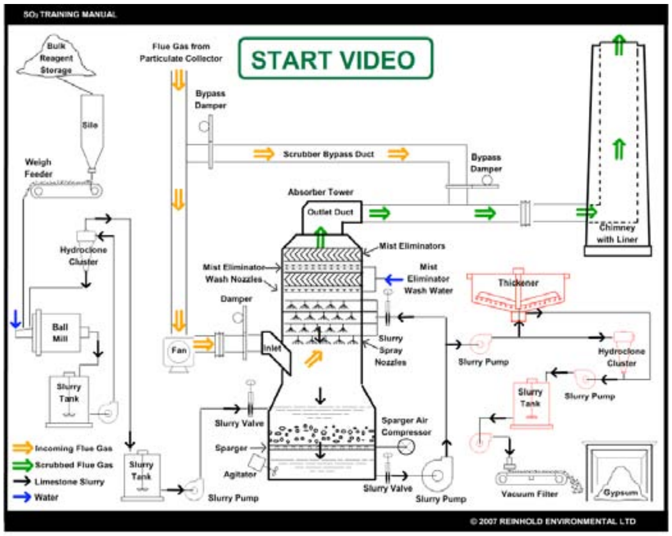
Another utility experienced the same problem with frozen slurry transfer lines after a forced outage. But the cause was different. The drain lines emptied into a pipe trench that was full of snow and ice. The FGD line liquid level equalized with the liquid level outside in the trench, and as a result the pipe and could not drain.

13.3 Drain Pipes or Trenches

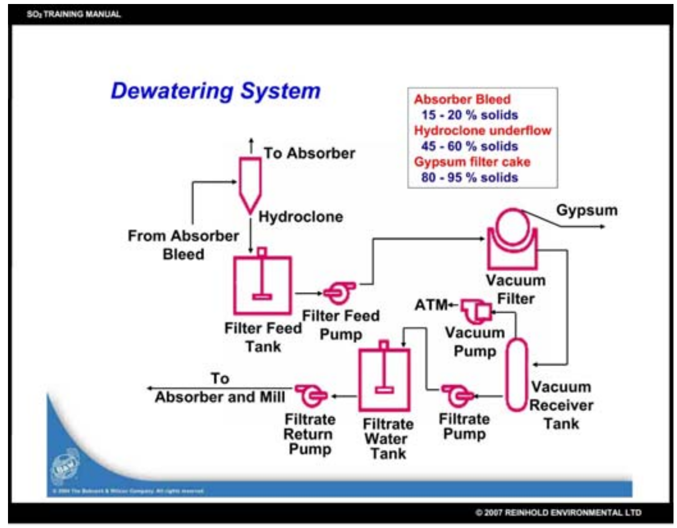
The problem with drain pipes and trenches is that they don't typically have enough flow velocity to keep the solids from settling out of the slurry. Because of this they need some sort of intermittent flush system to keep them clean. The drain pipes can have a water supply with a timer that opens occasionally to flush away collecting solids before they accumulate to the point where they block the line. Trenches are usually pretty flat so they don't drain well. One may need a series of high pressure nozzles spaced along the floor of the trench to occasionally flush the solids in the direction they need to flow.

Drain pipes need sufficient clean out ports along their length for easy manual cleaning access. Drain trenches should have covers that can be removed along the entire length of the trench to allow for manual cleaning.

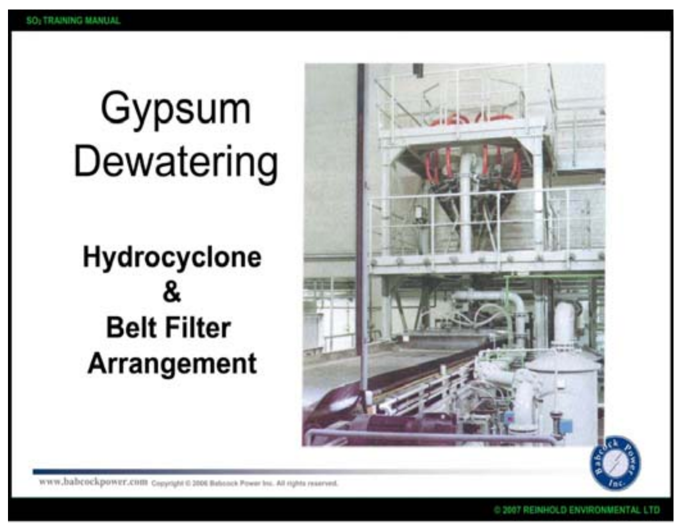
CHAPTER 14 - PRIMARY SOLIDS SEPARATION



Chapter 14 Summary
(Narrated by Ron Richard, RE Consulting)



Wet FGD Dewatering System Diagram
Used with permission from Babcock & Wilcox



Gypsum Dewatering
(Narrated by Tony Licata, Babcock Power)

After the completion of the scrubbing process, most of the liquid is separated from the slurry and recycled to the scrubbing process while the solids are concentrated for subsequent treatment. This is known as primary dewatering.

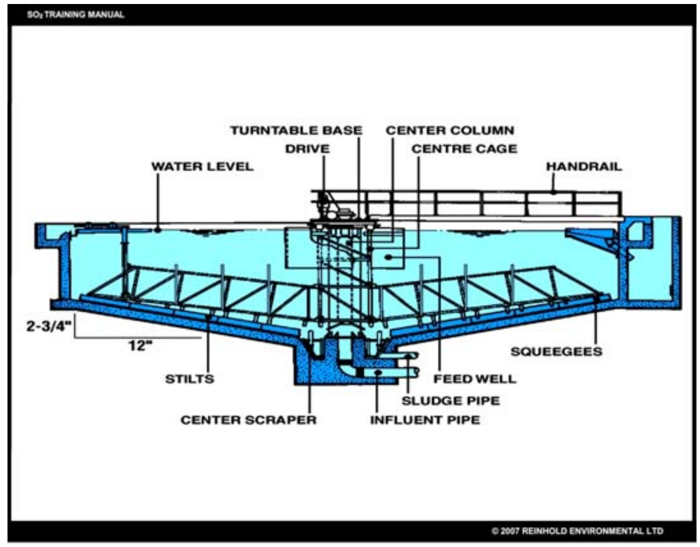
This chapter discusses the design and operation of the equipment that is used to perform this primary dewatering process.

FGD operators will quickly realized that "everything" ends up in the dewatering area. Recall the "Keep it Clean" message from prior sections on cleaning scale from tower walls and mist eliminators to proper slurry fineness and limestone grind to returning floor sump solids to the absorber, eventually the solids must pass through the final thickener or hydroclone. Several utilities have removed FGD systems from service to clean concentrated debris from dewatering equipment.

14.1 Thickeners

Gravity thickeners are used to separate solids from slurry streams producing a low solids content overflow stream and a high solids content underflow stream. The basic parts of a thickener include:

- A large diameter circular tank of low height with a conically shaped floor.
- A stilling well which is a ring in the center of the tank with an open bottom. The slurry feed into the tank flows into the stilling well. The ripples at the liquid surface are contained by the ring and the slurry flows into the tank below the liquid surface. It is very important that the rest of the tank surface be as calm and quiet as possible.
- An overflow weir and collection trough around the entire circumference of the upper tank wall lip. The low solids overflow liquid runs over this weir and is collected in the trough and routed to the overflow collection tank. It is important that the weir is perfectly level so there is an even flow from all parts of the tank.
- A rotating rake mechanism with plows attached to the rake arms. The plows move the solids collecting on the tank floor towards an opening at the apex of the conical floor as the rake mechanism rotates. The solids leaving this opening are the underflow stream that typically passes through a pump and is routed to the underflow collection tank.



Thickener - Mechanical Diagram
Used with permission from Dorr-Oliver (GL&V)

The diameter of the thickener is determined by the size of the solids particles and the flow rate of slurry to the thickener. Small particle size or high flow rates require larger thickeners. Large particle size or low flow rates result in smaller thickeners. Many large FGD systems have thickeners that are over 100 feet in diameter. Gravity acting on the particles in the still liquid in the thickener tank causes the particles to settle to the bottom of the tank. Polymers, known as flocculants, are typically used to accelerate this settling process. There are cationic, anionic, and nonionic polymers. The type of polymer required and the proper feed rate depends upon the properties of the particles. This is typically determined by performing “jar testing” using the actual slurry.

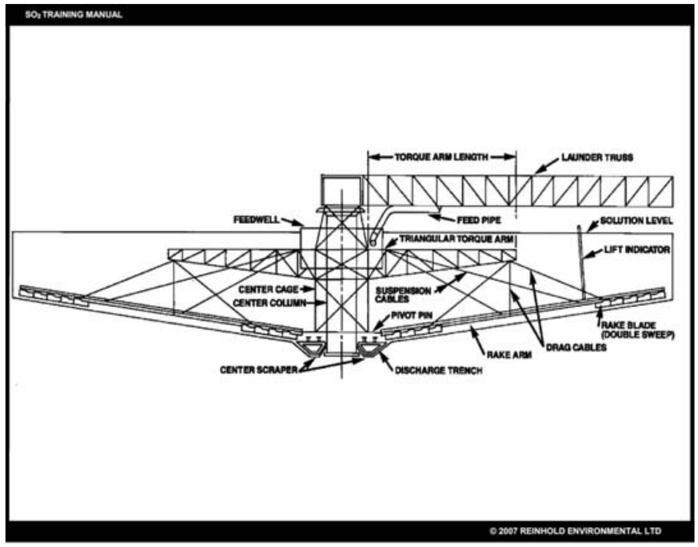
Thickener - Mechanical
Used with permission from Dorr-Oliver (GL&V)

A flocculant feed system is used to meter the polymer into the incoming slurry. Systems such as the PolyBlend system provide the proper feed and mixing of the polymer. This type of system uses less polymer and produces a better flocculant than the old feed tank and metering pump option. These new systems have led to cost savings for the utilities that have replaced their older systems.

The weight of the solids settling on themselves squeezes more of the water out of the solids. This produces a higher density underflow. One would like to obtain the highest density underflow that the pumps will handle to minimize the water that will have to be removed in the secondary dewatering step.

The rake is used to move the solids out of the thickener tank. There are two types of rakes that are typically used.

- The cable-driven rake is mounted to the rake drive mechanism with a swivel joint and is supported and driven by cables attached to the rake drive mechanism. The advantage of this rake design is that the rake will automatically rise up over areas of high density solids. This will prevent the rake from becoming trapped in a deposit of dense solids. One disadvantage of this is that the operator has no control over the density of the underflow. The weight of the rake arm determines how much pressure is applied to the plows which determines the maximum density of the solids that will be moved by the plows. One other disadvantage to the cable-driven rake design is that it is much more fragile and difficult to restart if an incident would bury the rake.
- The mechanically driven rake is part of the rake drive structure. The rake arms are rigidly attached to the rake drive mechanism. The advantage of this rake design is that the operator can raise and lower the rake arms as desired. The rake arms can be lowered which forces the plows into the solids. The more force that is placed on the plows, the denser the underflow stream will become. The disadvantage of this is that if care isn't taken, the force exerted by the plows can stall the rake or bend the rake arms, or overload the underflow pump. Typically, torque controls are installed on this type of rake in order to raise the rake or trip the rake drive motors if the forces on the rake arms approach the critical values that could cause damage.



Thickener - Cable Driven Diagram
Used with permission from Dorr-Oliver (GL&V)

Thickener - Cable Driven
Used with permission from Dorr-Oliver (GL&V)

If the solids become too dense for the rake to move, one will have to drain the thickener and use high pressure water hoses to break up the deposit and flush it out through the underflow pumps.

Some utilities have used a skid steer loader to clean out the solids. The problem with this is the sloping floor and the damage the loader can do to the floor linings. The water hoses are a safer alternative. If the rake is buried in the deposit, it is best to start cleaning half way between the rake arms on both sides and work towards the rake arms. The rake arms will stabilize the deposit.

One utility cleaned both rake arms out of the deposit first. As the cleaning progressed, the weight of the deposit suddenly caused one side of it to slide down the sloped floor. The deposit hit one rake arm and bent it back like a pretzel. Another utility maintenance crew partially uncovered the rake arms of a cable-driven thickener and attempted to raise the outer portion out of the sludge bed. The result was a bent and broken rake arm.

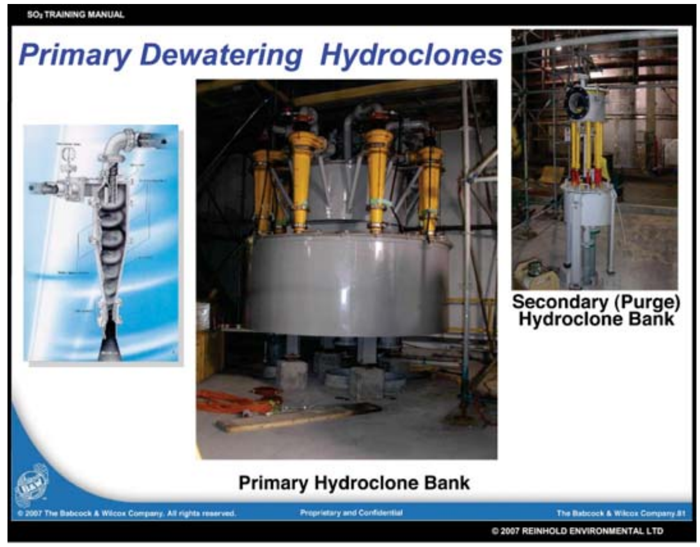
Sulfate reducing bacteria will live in the environment of the thickener sludge. If one sees black, slimy looking areas in the solids deposit during the cleaning, this is probably sulfate reducing bacteria colonies. The danger here is that such colonies produce hydrogen sulfide gas (H_2S) in their normal life cycle. This toxic gas is heavier than air and will remain in the thickener tank. Care must be taken to prevent worker exposure to this gas. The good news is that the strong "rotten-egg" odor is evident at relatively low concentrations.

The underflow pumps can be installed at grade (at the top of the conical slope) with the suction pipe running up the slope. They can also be installed in a tunnel under the thickener. The installation in the tunnel provides maximum suction head for the underflow pump and is the best choice. Trying to suck the underflow up the slope will limit the density of the underflow so as not to exceed the suction head that the pump can develop. Underflow solids in excess of 50% solids can be handled by pumps located beneath the thickener. Some form of back flushing the underflow pump suction lines and the center cone outlet port of the thickener is recommended.

One caution about tunnels under thickeners, There should be more than one direction of exit from the pump area under the thickener. There have been piping and valve failures that have led to flooded thickener tunnels. One wouldn't want to be trapped by such a failure with no way past it to exit the flooding tunnel.

Thickener tanks can be metal or concrete. Both will need to be lined with a rubber or resin based lining. The metal tank is susceptible to pH and chloride attack. The concrete tank is susceptible to chloride and sulfate attack. The solids in the tank are also abrasive. The overflow weir can be plastic, FRP, or corrosion resistant alloy. The rake mechanism is typically fabricated from metal tubes for strength that are covered with a rubber or resin based lining. All linings should be inspected whenever the thickener is empty for maintenance work. It is best to keep liquid in the thickener, even if it is out of service, to protect the linings from ultraviolet radiation from the sun and extreme temperature changes as well as help equalize ground pressures under the floor.

One utility was lining a new thickener during autumn. At the end of each shift, the lining applied passed the test for pin holes. If the same lining was tested a day or two later, it failed the test. Testing determined that the temperature change from warm sunny day to cool evening was causing the concrete shell to expand and contract more than the resin based lining could withstand. A change was made to a resin based lining that was more flexible, and the problem was solved. The lesson learned was that an empty thickener tank is more susceptible to lining damage due to temperature fluctuations than a tank full of liquid. Another utility posted a notice at the outer edge of the thickener rake drive access platform to remind personnel that leaving hard hats and loose tools before walking out over the slurry tank could avoid an unscheduled outage to retrieve material from the center cone of the thickener.



Hydroclone Clusters
Used with permission Babcock & Wilcox

14.2 Hydroclones

The forced oxidation process produces a large gypsum crystal. Most of the gypsum crystals are similar in size. This makes them ideal for separation using hydroclones. The hydroclone works best separating a solid that settles quickly under the influence of gravity. The solids from the other processes don't settle very quickly, that is why thickeners have been used. The gypsum solids settle rapidly. The hydroclones are also more efficient when the solid particles are large and uniform in size range and the rest of the liquid stream contains very small particles. This makes it easy for the hydroclones to produce a high density gypsum underflow stream and a low solids concentration overflow stream.

Hydroclone
Used with permission from Cavex (Weir Slurry Group Inc.)

The advantages of the hydroclones are that they require a minimal space that can be in the higher elevations of a building and they are a low capital cost item. The disadvantage of hydroclones is that there is no slurry storage capacity in the hydroclones. A slurry storage tank is typically installed ahead of the hydroclones to store slurry when the hydroclones are out of service. There is another storage tank that stores the overflow stream from the hydroclones until it is reused in the FGD process. But the capacity of both of these tanks is still many times smaller than the storage capacity of a thickener. This means that the FGD process cannot tolerate having the hydroclones and the vacuum filters out of service for an extended period of time without running into slurry inventory problems.

The good news is that the hydroclone cluster typically has at least two spare hydroclones installed. That means individual hydroclones can be taken out of service for maintenance without affecting the performance of the hydroclone cluster. There is typically also a spare vacuum filter. So with proper planning and maintenance, it is not that difficult to keep the hydroclones and vacuum filters in service at all times during FGD operation.

The main factors that determine a hydroclone's performance are:

- Slurry flow rate (which determines spin velocity in the hydroclone)
- Vortex finder diameter
- Apex nozzle diameter
- Length of hydroclone

Since the slurry flow rate is a critical factor, the correct number of hydroclones must be in service. If the hydroclone cluster is designed to have 10 hydroclones in service, then it will not perform correctly if 9 or 11 hydroclones are in service. The flow rate through each hydroclone will be different than the designed flow rate. This will cause the separation of the particles to be different than design.

This also means that the hydroclone cluster should either be in service at full flow or out of service. It will not perform properly if the flow is reduced when the FGD system is operating at lower loads. At low loads, the hydroclones should be placed in service when the slurry tank feeding them is at a higher level. Once the tank level becomes low, the hydroclones should be removed from service while the tank level recovers.

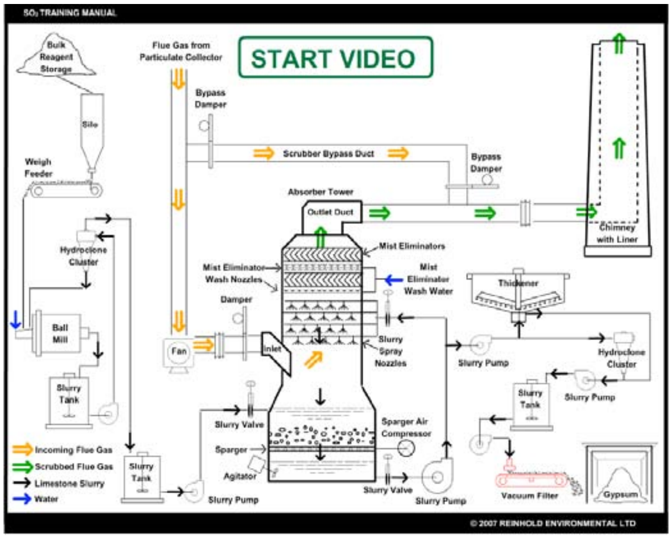
For a gypsum system, there are usually two clusters of hydroclones. The primary hydroclones separate the final gypsum particles into the underflow which goes directly to the vacuum filters or to the byproduct storage operation (depending on system's byproduct handling). The overflow is the feed to the secondary hydroclones. These are smaller diameter hydroclones that separate smaller particles from the stream. The underflow contains small gypsum particles which are routed back to the oxidizer to act as "seed crystals". The overflow is relatively solids free and goes to the waste water treatment process.

The hydroclone has no moving parts. The only items to be maintained are the liners, the vortex finder, and the apex nozzle. The damage will be erosion caused by the velocity of the abrasive slurry solids. Liners need to be replaced before the slurry wears completely through and begins attacking the hydroclone body. The liners are typically rubber, but more expensive urethane and ceramic liners are available if longer life is needed. The apex nozzle can be rubber or ceramic. Since the size of this hole is critical for proper size separation, the ceramic nozzle will provide more consistent results. An apex nozzle needs to be replaced when the diameter of the hole in the nozzle has changed. Once liner life has been determined, the hydroclones can be maintained in a rotating cycle so there are always enough available for service.

The hydroclone clusters should be inspected several times per shift. The same amount of underflow should be coming from the apex of each hydroclone. If an apex nozzle plugs, all or most of the slurry flowing into that hydroclone leaves as overflow. This can amount to a large volume of solids in a relatively short period of time. If it is a primary hydroclone, product gypsum will be routed back to the oxidizer. If it is a secondary hydroclone, fine gypsum solids will be entering the waste water treatment process. These solids may have detrimental effects on the process.

Often a pressure indication is available at the inlet to the hydroclone cluster for reference. If a plugged hydroclone is found, a spare hydroclone should be placed in service and the plugged hydroclone removed from service. The hydroclone may need to be disassembled to remove the blockage.

CHAPTER 15 - VACUUM FILTERS



Chapter 15 Summary
(Narrated by Ron Richard, RE Consulting)

Horizontal Belt Filter
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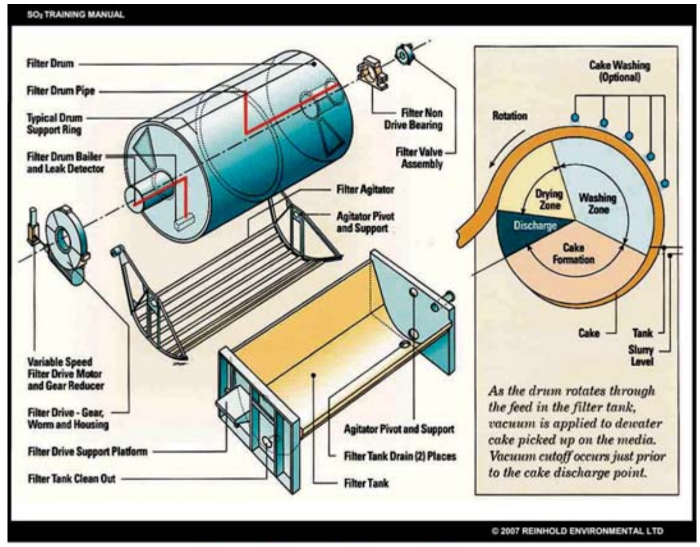
The solids from the primary dewatering process must be further dried before the solids are sold or disposed of. This is traditionally done using rotary drum or horizontal belt vacuum filters.

This chapter addresses the design and operation of both types of filters.

15.1 Rotary Drum Filter

Rotary drum filters have been the most used filters in existing FGD systems. One of the reasons may have been because they were fairly compact. Three or four drum filters would fit in the space required by one belt filter. Also, many of the older systems were placing the byproduct material in a landfill after mixing it with fly ash and lime. So it didn't matter if the filter cake was washed or still contained 25% moisture.



Filter - Rotary Drum Diagram
Used with permission from Dorr Oliver (GL&V)

Rotary drum filters can be used to filter gypsum. The disadvantage is that the total length of usable filter cloth is approximately 75% of the drum's circumference. This doesn't leave much space to wash and dry the cake. The drum has to rotate at a slow speed to give much wash and dry time.

The slurry enters a vat in which the lower portion of the drum is submerged. There is typically some sort of oscillating bar mechanism that agitates the slurry in the vat. Without agitation, the heavier solids will settle in the vat and fill the lowest portion. The agitator should remain in service any time slurry is in the vat, even if the drum is out of service. If the agitator is going to be taken out of service, the vat should be drained and flushed with clear water from a hose until all solids are washed away. If the agitator is removed from service while there is slurry in the vat, the solids can settle around the agitator and it may not restart or worse, shear off the drive mechanism.

Filter - Rotary Drum
Used with permission from Dorr Oliver (GL&V)

In service, the drum rotates through the vat and the vacuum pulls solids onto the filter cloth forming the filter cake. There are two things that control the thickness of the cake. One is the drum speed and the other is vat level. Often the drum speed is controlled to give the desired drying time for the cake, so the vat level must be used to control cake thickness. Besides affecting the dryness of the cake, it is possible to damage the drum drive or support structure if the cake becomes too thick.

If one looks at the end of the drum that is rotating clockwise, one will find that the cake forms and leaves the vat at the 7:00 position. It then rotates around the drum until it is removed from the filter at the 3:00 position. The drum is then clean until it enters the slurry in the vat at the 5:00 position. The weight of the cake from the 9:00 position to the 3:00 position balances itself. But the weight of the cake from the 7:00 position to the 9:00 position must be raised by the drive gears. If the cake becomes too thick, this weight can exceed the design and damage can occur to the drive gears. Some designs have a shear device that will shear and stop the rotation of the drum before gear damage occurs.

More than one utility have activated shear devices or damaged drive gears due to allowing the cake to become too thick on their drum filters.

The vacuum actually occurs in shallow pans that are mounted inside the circumference of the drum. The pan forms a three sided compartment with a support grid across the top. The filter cloth lies on the support grid. If one is inside the drum, it looks a lot like a bicycle wheel. The series of vacuum pans form the outer ring. A hub is attached to the center of each end of the drum to allow it to rotate. A series of vacuum pipes come from the individual pans towards the center looking like the spokes in the wheel. The vacuum pipes have an elbow at the end so that the pipes form a circle of openings through one side of the drum around the hub. The filter valve assembly covers the ends of the pipes.

The filter valve assembly has adjustable compartments that allow a pan to experience different conditions as its pipe rotates past these compartments. Typically the pan would experience vacuum from the 5:00 position to the 2:00 position. It can then experience ambient pressure from the 2:00 position until the 5:00 position. Or sometimes the pan may be given a slight positive pressure from the 2:00 position to the 4:00 position to flex the cloth and help the cake release from the filter cloth.

The filter cloth can lie on the drum as individual strips over each vacuum pan, or one large cloth that wraps completely around the drum. In either case, the cloth is wedged into a groove that is located between each vacuum pan. This secures the cloth to the pan making each vacuum pan and cloth an individual filtering compartment. Various materials have been used to wedge the cloth into the groove. These have included rope, bungee cord, rubber strips, and stainless steel wire threaded through a plastic tube and secured on each end of the drum. The wedge must remain secure or the edges of the cloth can come loose and catch and tear as the filter drum rotates.

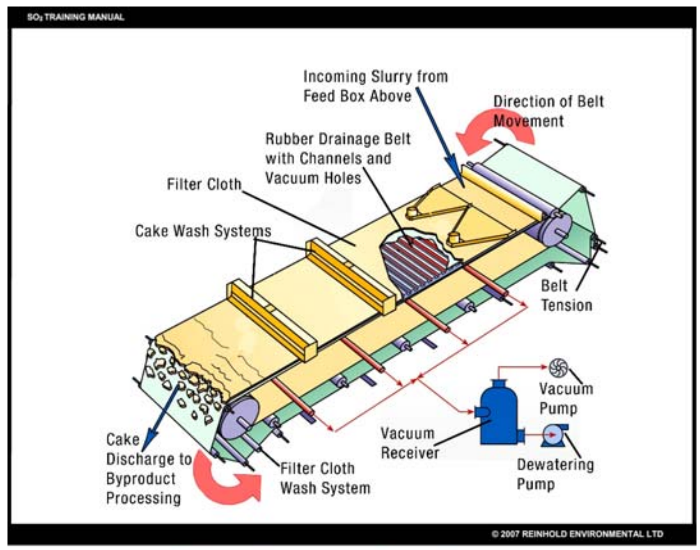
The weave and the thread material and size are important parameters for the filter cloth. The cloth must be able to filter out the fine particles in the slurry. But the cloth cannot be washed from the back side since it is attached to the compartments. So it is important that the filter cake releases from the cloth completely at the end of the cycle. If not, solids will build up in the holes in the cloth and the cloth will blind. Once this happens, the cloth must be removed and replaced with a new cloth. It often takes some experimentation with different cloth materials and different weaves to find the cloth that will give the longest life in a particular FGD system.

Most installed drum filters use a plastic knife at the cake discharge. The knife doesn't always have to touch the filter cloth. If the cake releases well, most will fall off the cloth and the knife acts as a deflector to keep the cake from falling back into the vat. The discharge from the knife falls onto a conveyor belt. If the knife is too close to the cloth, it can abrade or tear the cloth. If it is too far away, a lot of the cake will fall into the vat and come around on the filter again as chunks of material in the cake.

A cake wash system is typically one or more spray headers with nozzles that spray a uniform pattern of wash water onto the drum. There isn't much space to install wash headers if one wants sufficient drying time for the cake.

The outer surfaces of the vat, agitator, drum, vacuum pans, and vacuum pipes must have a corrosion resistant lining or be fabricated with a corrosion resistant material. Often for the lined systems, the inside of the drum and vacuum pans are not protected. This is all right as long as it stays dry inside the drum. The problem can occur if corrosion eats a hole in a vacuum pan or pipe. If corrosive liquid passes through the hole and gets into the drum internals, severe corrosion damage can occur quickly. The inside of the drum should be inspected during every maintenance outage. If there are holes in the vacuum pipes, the entire inside of the drum can be placed under vacuum. The drum is not designed for this and the vacuum can bow the ends of the drum inward.

The cake conveyor operates in a corrosive environment. The cake falls some distance from the drum onto the conveyor. This impact can shorten the life of the conveyor rollers. Some utilities have replaced the rollers in the impact zone with an impact slide bed. This supports the conveyor belt more and is not damaged by the impact. The corrosive liquids in this area can cause the bearings on conveyor rollers to freeze up. If the roller doesn't turn, the friction of the conveyor belt will cause a flat spot to form on the roller. If the roller then turns slightly, the sharp edge of the flat spot will slice the conveyor belt. Some utilities have used ceramic conveyor rollers. If a ceramic conveyor roller fails to turn, the belt will slide over it without forming a flat spot that could slice the belt.



Filter - Horizontal Belt Diagram
Used with permission

15.2 Horizontal Belt Filter

A horizontal belt filter has the disadvantages of additional cost and taking up the space in which several rotary drum filters could fit. A single horizontal belt filter could be 12 ft. wide and over 100 ft. long for FGD gypsum applications requiring a final product with 10% moisture. The advantage of the belt filter is that it is much more efficient when it comes to washing and drying the filter cake. For gypsum that is to be sold commercially, this is very important since there are stringent moisture and chloride content specifications. That is why most commercial gypsum producing FGD systems use horizontal belt filters.

Horizontal Belt Filter
Used with permission

The key moving parts in a belt filter are the rubber drainage belt and the filter cloth. The filter cloth is longer than the drainage belt and travels a different path from the end of the filtering section back to the beginning. This allows water sprays to wash the filter cloth from the back side as it leaves the filtering section. This is important since small particles of gypsum or other solids can build up in the small openings of the filter cloth and “blind” it. This “blinding” of the filter cloth will prevent the vacuum from efficiently drawing the moisture out of the filter cake. The operator needs to check that all the cloth wash sprays are working and applying a uniform spray of clean water on the back side of the filter cloth. There is also another set of sprays that wash the drainage belt that should be checked regularly.

At the beginning of the filtering section, the filter cloth lies on the drainage belt. There are tracking adjustments for both the filter cloth and the drainage belt. These must be adjusted so the drainage belt runs down the filter in a straight line and the filter cloth lies centered on the drainage belt. There must be enough tension on the drainage belt to keep it from slipping but not so much that it is stretched. On the underside of the filter, the return rollers must be clean and rotating freely so they support but don’t stretch or tear the drainage belt or the filter cloth.

A vacuum is pulled through holes in the drainage belt as it travels over the vacuum pan beneath it. The belt/cloth pass under the slurry feed area. The rubber “side boards” on the drainage belt contain the slurry on the filter cloth. The vacuum pulls the liquid through the cloth and out the holes in the drainage belt to a receiver which separates the liquid from the air stream entering the vacuum pump. It is important that the slurry feed system be adjusted so there is a uniform depth of filter cake across the entire width of the belt/cloth.

The speed of the belt can be adjusted to provide the required filtering rate (TPH capacity) and product quality. A fast speed will result in a thin cake which is easier to pull air through but will have less time to wash and dry on the belt. A slow speed will result in a thick cake which is harder to pull air through but will have more time to wash and dry on the belt. The key is to operate at the speed that is the best combination between cake thickness, cake purity, and cake moisture content. This can be found by trying different speeds and running laboratory tests for chlorides and moisture. Once the best speed and cake thickness is determined, it typically won’t change unless there is a major chemistry upset or mechanical problem in the absorber tower/oxidizer.

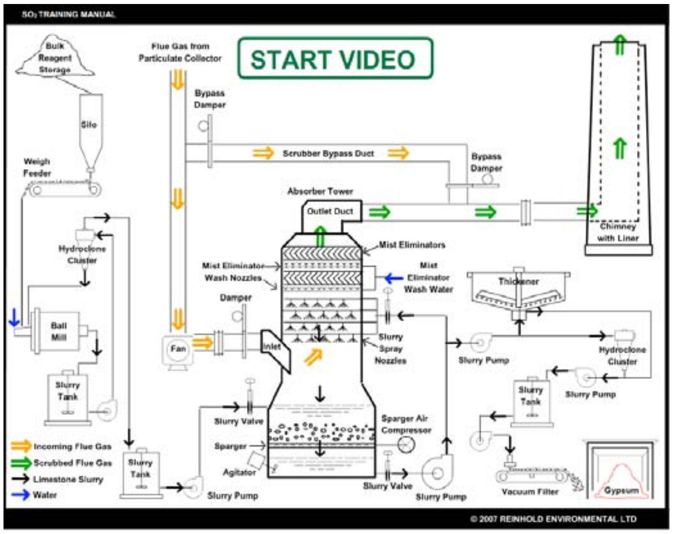
The cake then passes under one or two wash stations. The final wash stage is typically with warm fresh water to remove the chlorides and other soluble impurities. If the wash water is not at the proper temperature, the wash will not be as effective. The rest of the filtering section is drying time for the cake. At the end of the filtering section, the belt/cloth make a sharp bend over a roller which causes the gypsum filter cake to fall into a hopper that leads to a conveyor belt. Depending on the properties of the cake, there is sometimes a plastic knife blade that scrapes any residual gypsum off the cloth. The drainage belt and filter cloth then separate, are washed, and return back to the beginning of the cycle.

Horizontal Belt Filter - Cake Discharge
Used with permission

There are some sort of moving or stationary seals where the rubber drainage belt travels over the vacuum pan. And typically there is some water added along the seal to lubricate it and help stop air leakage. This water must be flowing when the filter is in service. The vacuum pan should be lowered on a regular basis to check for wear on these seals and for replacement of these seals as needed.

If the filter cloth becomes worn, torn, or permanently "blinded", it will need to be replaced. The easiest way to do this is to connect the new cloth onto one end of the old cloth. The filter can be run at a low speed as it pulls the new cloth around the entire loop and through all the support rollers. The old cloth can then be detached and the two ends of the new cloth connected. The tensioning rollers are then adjusted to place the proper tension on the new cloth. The alignment of the new cloth should be watched and adjusted frequently until the new cloth has stretched to its permanent dimensions.

CHAPTER 16 - BYPRODUCT HANDLING



Chapter 16 Summary
(Narrated by Ron Richard, RE Consulting)

Gypsum Storage/Handling
Used with permission from Alstom

The remaining solids from the FGD process must be either sold or disposed of.

This chapter discusses the options that have been traditionally used in dealing with these solids in the most environmentally acceptable manner.

16.1 Fixated Materials

Most of the early scrubbers were designed as "throw away" systems. This meant that the FGD byproduct material was handled as a waste material rather than a saleable commodity. Some installations had large ponds where the calcium sulfite/calcium sulfate material was pumped and allowed to settle. Most of the installations disposed of the material in a landfill operation.

The problem with calcium sulfite/calcium sulfate dewatered sludge is that it has thixiotropic properties. This means that as more force is applied to it, it begins to behave more like a liquid. So as it travels down a conveyor, the jostling over the rollers turns it into a sloppy mess that looks a lot like wet concrete and sticks to the belt instead of dropping off at the end. And if it is hauled in a truck, the vibrations can cause it to ooze out of any cracks around the tail gate seal. Furthermore, if one tries to drive a truck over previously placed materials, the truck can become mired down to the axles. Worse, as a pile of this material grows, the bottom of the pile starts to flow like an ultra slow motion tidal wave that could envelop anything in its path.

To solve these mechanical handling problems as well as minimize the potential for leaching from the landfill site, the fixation process was developed. The FGD filter cake is mixed with fly ash and an alkaline material such as lime. Under the proper conditions, chemical reactions take place over several days (similar to concrete curing) which cause the material to become hard and non-flowing.

Often the filter cake has more than 20% moisture. The fly ash helps in forming a drier material that can be transported more easily. It is important to have enough moisture for the curing reactions. It is possible to get the mixture too dry. The final mixture should look and feel like damp (not completely wet) soil. The fly ash is also the source of some of the chemicals needed in the curing process. Most or all of the fly ash produced from the utility generating unit can be added to the filter cake. In this way the landfill becomes the disposal site for both the FGD byproduct and the fly ash.

The lime provides the alkalinity needed in the curing process to form the bridging matrix that forms between the calcium compounds in the filter cake and some of the trace elements present in the fly ash. These links that form give the material its strength. The more lime that is added, the stronger the material becomes. But, the lime is the major costly ingredient in the mix. So utilities try to balance the cost of the lime against the strength the mixture needs to achieve in deciding how much lime to add to the mixture.

The ingredients are typically blended in a pug mill. After a thorough mixing, they drop onto a conveyor and go to a stack out pile. It is important when the pug mill is taken out of service for an extended time that the top covers are opened and the pug mill is rinsed out with a high pressure hose. If the fixated material is allowed to remain in the pug mill, it can cure and harden. Then when the pug mill returns to service, the hardened material can interfere with the flow of fresh material. In extreme cases, the hardened material has led to the shearing off of paddles in the pug mill as well as gearbox damage.

The fixated material may sit in the stack out pile for several days before it is placed in the landfill. The higher the outside temperature, the faster the curing process will proceed. The curing process generates heat that also accelerates the curing process. If the material sits in the pile too long, the center of the pile can cure and harden making it difficult to break up the material and load it into a truck.

The material is placed in the landfill in layers. Landfills are often regulated by local environmental agencies

Until it is fully cured, the material still has thixiotropic properties. This means that haul trucks cannot travel over fresh material. It works best for the trucks to travel on the existing cured layer, backing up to the new layer and dumping their load at the edge of it. Bulldozers with "low ground pressure tracks" installed can then travel over the material leveling it out. Bulldozers with standard tracks will sink into the material. A layer is typically less than three feet thick.

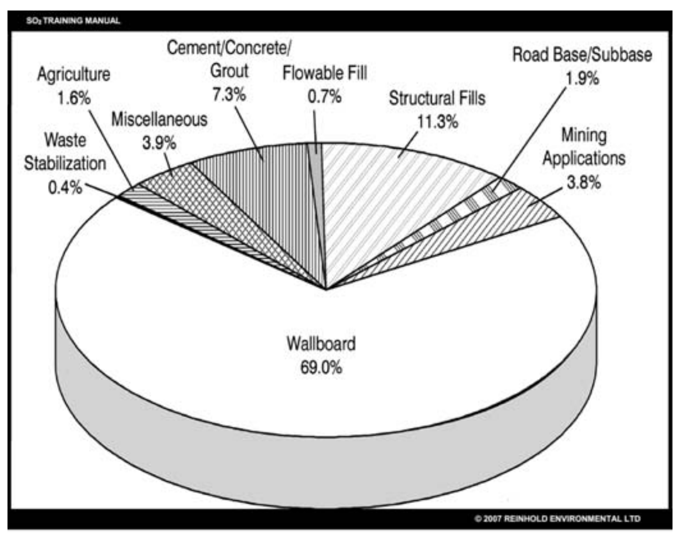
After several days of curing, a roller compactor can be driven over the material. The job of the roller compactor is to pack the layer to its maximum density. This not only saves space in the landfill, it produces a stronger, denser final product.

When the outside temperature is below about 50º F, the curing slows or stops completely. This means that during winter months, the material in the landfill will not cure. This means that trucks will not be able to travel over areas where fresh material has been placed without getting stuck. This also means that the roller compactor can't be used on the material. It works best if there is sufficient space in the landfill so that the material only needs to be placed in one layer during the winter months. Otherwise, the logistics of placing the material can become a real nightmare. Once the weather warms back up in the spring, the placed material will cure normally and operations can return to normal.

Landfill operation and management is a significant portion of the activity and budget involved with this type of FGD process. Byproduct handling schemes are evaluated given site-specific situations.

16.2 Gypsum

The forced oxidation systems produce gypsum as their final byproduct. The value of this gypsum depends upon its moisture content, the levels of other specified impurities and the proximity of a potential byproduct customer. The wallboard grade gypsum is worth the most money. Gypsum is used in the manufacture of cement. Gypsum is also used as a soil additive to loosen clay type soils. Gypsum can also be disposed of in a landfill operation.



Gypsum Uses
Used with permission from U.S. Dept. of Energy

One unique form of landfill operation is the gypsum stack. The gypsum stack is located in an area with a low impervious berm surrounding it. The area within the berm may have a synthetic liner to prevent any liquids from penetrating into the ground water. Any drainage within the berm is collected and sent back to the FGD system or treated for disposal. The gypsum slurry is pumped into the area through a hose that can be moved about the area. No vacuum filter is needed for this type of operation. The liquid quickly drains out of the gypsum and runs into the collection area. As the stack begins to gain height, some of the gypsum is moved to the edges of the stack forming a gypsum berm. More slurry is pumped into this gypsum berm enclosed area. The liquid quickly drains out of the bottom of the stack leaving the gypsum behind. The berming and filling operation continues as the stack continues to rise in elevation.

The gypsum in the stack is available for sale later as opportunities arise. Some wallboard companies have bought gypsum from utilities with gypsum stacks and treated it to convert it into wall board grade gypsum. The chlorides may slowly wash out of the gypsum in a gypsum stack as rain water drains down through the stack.

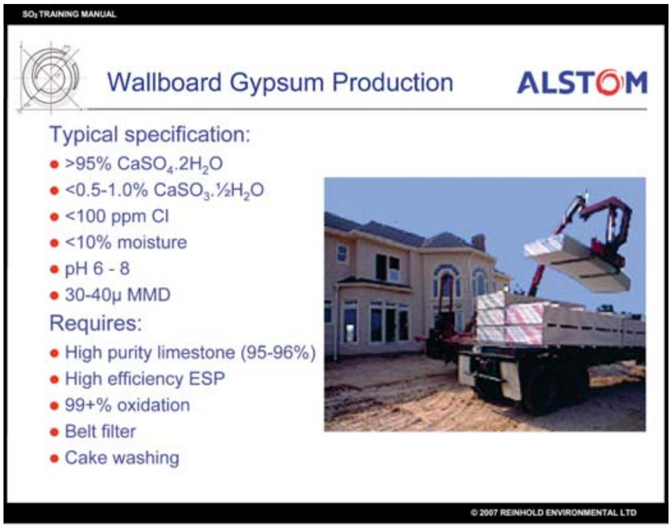
To be wallboard quality, the gypsum must typically contain:

- 95% minimum gypsum dihydrate crystals
- 100 ppm chlorides maximum
- 10% moisture maximum
- pH of 6 – 8

The wallboard plants prefer gypsum that is white instead of tan in color.

For use in cement manufacturing, the gypsum must typically contain:

- 90 – 92% minimum gypsum dihydrate crystals
- 1000 ppm chlorides maximum



Wallboard Gypsum Specifications
Used with permission from Alstom

The gypsum is added to the cement clinker in the finish mills to control the setting time of the cement.

The wallboard plants are finding that synthetic gypsum (how they refer to FGD produced gypsum) is often a higher purity and a more consistent product than natural gypsum. Wallboard plants can deal with different qualities of gypsum, but they don't like supplies that change. Changing properties can wreak havoc upon their manufacturing line. In the early days it was difficult to get them to try synthetic gypsum since they had so much experience and control with natural gypsum. Now many wallboard plants prefer to use synthetic gypsum whenever it is available at a competitive price. But, it is important that the utility produces as consistent a product as possible. This isn't that difficult if the chemistry is controlled properly in the absorber towers and oxidizers.

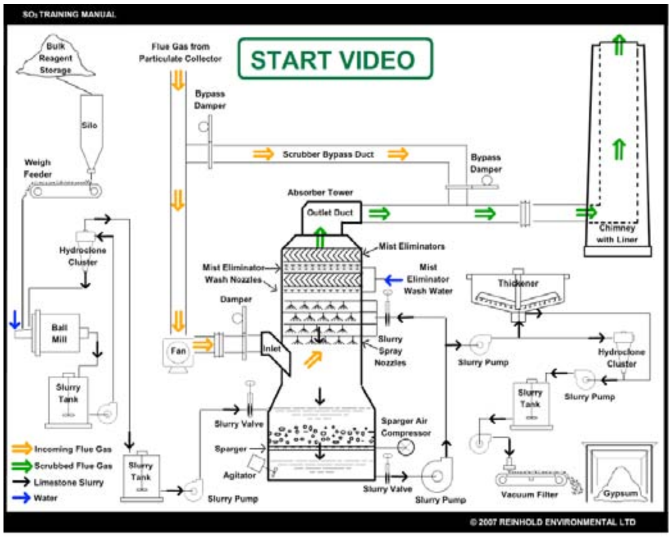
The biggest problem experienced in selling synthetic gypsum is the transportation cost. FGD units located on navigable rivers usually have an advantage selling their gypsum. FGD units located where they must use rail or trucks to move their gypsum to the wallboard plant can't always compete against established, or on-site natural gypsum supplies. This is why some utilities must landfill gypsum until the economics change. Sometimes a source of natural gypsum is depleted and the synthetic gypsum may be more economic than a new source of natural gypsum for that wallboard plant.

The wallboard plants take the raw supply of either rock or FGD gypsum and completely dry it and grind it.

This initial drying to "bone dry" condition is the reason FGD gypsum moisture content is an important quality parameter to the wallboard customer. They then add a controlled amount of water and other additives so that it will set properly as the wallboard moves down the production line. The energy, usually natural gas, needed to dry the gypsum is a significant cost. That is why there are premiums paid if the gypsum is drier than the specification and penalties if the gypsum is wetter. There is always a debate whether the gypsum should be stored under roof while it is waiting to be shipped from the FGD unit. One has to weigh the potential bonus/penalty amounts over time against the cost of a roof or a total building. The time that it is exposed to the weather before loading, the annual average rainfall amounts, and the change in gypsum moisture caused by rain are all factors in this decision.

Even though the other uses for gypsum don't offer the same revenue potential as wallboard manufacturing, they can still be very attractive when one considers the avoided cost of not having to landfill it. Or in the case of gypsum that has already been land filled, selling the gypsum makes room for future material and may prevent expanding the landfill site. Some utilities have chosen to give away the gypsum as long as the user paid the loading and transportation costs. Again, utility options are very site-specific.

CHAPTER 17 - INITIAL START-UP AND SHUT-DOWN



Chapter 17 Summary
(Narrated by Ron Richard, RE Consulting)

Absorber Erection
Used with permission from Korea Cottrell Co., Ltd.

The erection and commissioning of an FGD system is a highly complex operation that only occurs once in the life of the unit. Testing of equipment must be done to assure that it meets its specified performance. Tanks and piping must be filled with liquid. Chemicals must be introduced to the system and chemical reactions must be brought under control in circumstances that will usually never occur again. Documenting system performance parameters during the initial test period also provides a reference for comparisons back to "as new" conditions, if questions arise at a later date.

This chapter provides a flow path of activities that has proven successful at other utilities in accomplishing these activities in an orderly and efficient manner. Each FGD installation has its own set of site-specific issues which are not addressed.

17.1 Testing

Most FGD system flow paths are highly integrated. The slurries and liquids flow in a complete loop around the entire system. They pass from tank to tank through specific pumps and piping. People who have tried to test various tanks, piping, or pumps in a random pattern are soon frustrated that they have no liquid supply or else have no place to pump it to. They must also use a multitude of jumper wires to bypass control system permissives in order to start equipment in this abnormal configuration.

Testing progresses more efficiently if the test plan is developed to follow the normal flow path of the liquids and system interlocks around the entire loop. It doesn't make much difference where in the loop one starts, as long as one follows the loop from that point around until one returns to the starting point.

Using some of the normal operating personnel to develop and carry out the test plan can be very beneficial. This serves as training for them in becoming familiar with the equipment and gaining experience in operating the equipment and controls. They must research and learn all the various permissives in the control circuit to allow the various equipment to start and to operate. If all of the permissives are met, the equipment can be started normally from the control panel.

Note: Having a sump system available to handle potential liquid leaks and spills is recommended.

A good starting point is the slurry feed tank located in the lime/limestone preparation area. This tank should be filled with water to its normal operating level. The slurry agitators and feed pumps can be started, pumping water around the slurry feed loop back into the slurry feed tank. CAUTION: Filling tanks with well or surface water and leaving it in the tanks for extended time periods has been the cause of sulfate reducing bacteria corrosion attacks in new FGD systems. Sodium hydroxide or sodium carbonate should be added to the water to maintain the pH value at the level it will typically be in the system. A residual of bleach or other biocide can also be maintained as a control measure.

Once the absorber towers are ready, instrumentation lines can be flushed, the slurry feed valves can be opened and the absorbers filled from the slurry feed tank. Once the absorber liquid is at its normal level, the agitators and slurry recycle pumps can be started and the slurry spray headers tested. If it is an in-situ oxidation system, the oxidation blower system can be tested and the liquid level rise due to oxidation air noted. The mist eliminator wash system can also be tested now or at a later time since it is typically an independent loop.

With the slurry recycle pumps in service, the slurry bleed lines can be tested and the slurry bleed tank (or the external oxidizer tank) filled. If there is an external oxidizer, its agitator and blower can be tested after the tank fills. Then the primary dewatering system can be tested. This may entail filling thickeners or testing hydroclones.

If thickeners are involved, additional sources of water will probably be needed to fill them in a reasonable time. One may not want to fill a thickener completely, but it should be filled to cover the rake to protect the rake lining from ultraviolet light damage. The thickener overflow and underflow systems can be tested. A hose can be used to fill the thickener overflow tank if the thickener isn't filled completely.

If hydroclones are involved, flow can be routed through them filling the tank that feeds the vacuum filters (if there is one) and also the tank that recycles the overflow liquid back to the FGD system. If the primary hydroclone underflow feeds directly onto the vacuum filter belt, the water can pass through the belt to test the vacuum system liquid handling or else provisions need to be made to route that water to the recycle tank along with the overflow stream.

The liquid piping and pumps can now be tested in the vacuum filter system.

The thickener or hydroclone overflow recycle tanks can now be used to test the liquid recycle systems to the various parts of the FGD system. With recycled water available, the limestone ball mill system can be tested. The slaker is typically tested with the fresh water supply it will typically use.

With the ball mill or slaker testing, liquid is now entering the slurry feed tank and the complete FGD loop is in service and tested.

At some construction sites, the contractors test all gauges and pressure switches and then mount them. Before acceptance, the utility has its people remove all the gauges and pressure switches to verify their calibration. To avoid re-testing, it is more efficient to have a utility person present when the contractor does the initial testing.

The same is true with motor alignment and initial fills with proper lubricant. It is more efficient to have a utility person witness and collect data for all motor and gearbox alignment and lube activities as they are being performed by the millwrights.

The test plan should include methods to test the various permissives in the control logic by actually causing the situation (such as high or low level in a tank) or simulating the situation (such as isolating a pressure switch and using an external pressure source to cause the desired pressure).

17.2 Initial Start-up

The reagent slurry feed tank should be drained and then the ball mill or slaker should be placed in service to fill the tank with the normal alkaline slurry. The recycled water system will have to be placed in service with “system test” or fresh water in the recycled water tank to supply grinding water for the ball mill. This slurry feed loop is then placed in normal service.

The absorber towers should start full of water to about a normal level. The pH controls on the absorber towers are set at their normal set points which will allow the slurry feed valves to open routing lime/limestone slurry into the towers. The agitators and slurry recycle pumps are now placed in service. Once the pH has reached its set point, the fans can be started and the dampers opened to allow flue gas to flow through the absorber towers.

As soon as flue gas is flowing through the towers, the mist eliminator wash systems should be placed in service. If it is an in-situ oxidation system, the oxidation blower should be placed in service.

It will take several hours for the density of the slurry in a tower to reach its normal range of values. Because of the continued addition of lime/limestone slurry into the tower, the slurry bleed valve may operate occasionally to maintain a normal slurry level in the tower. This will route slurry to the external oxidizer or slurry bleed tank.

If it is an external oxidation system, the oxidizer should start filled with water to the minimum level with the agitator and oxidation air blower in service. The oxidizer will gradually fill with slurry. The acid addition system should be in service to maintain the desired oxidizer pH. Once the oxidizer fills, the slurry will be pumped to the slurry bleed tank or the primary dewatering system depending on system design.

The slurry bleed tank should start with water in it at the minimum operating level and the agitator in service. This tank will gradually fill with less than normal density slurry.

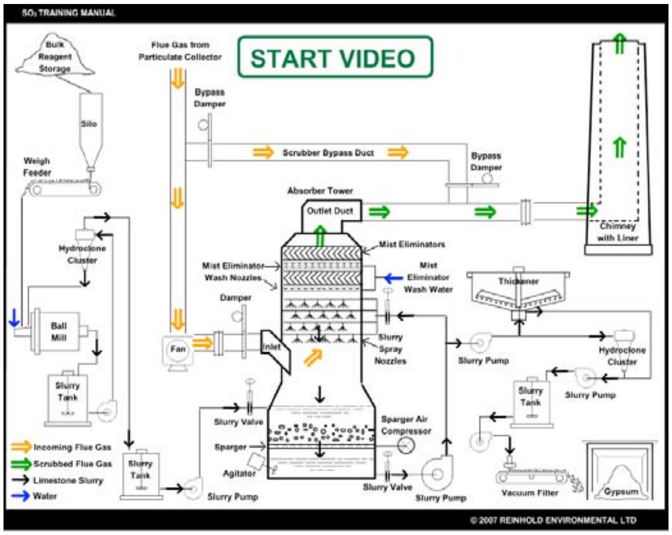
If a thickener is the primary dewatering device, some FGD procedures suggest it should start filled with water to a level that just covers the rake. The rake should be in service. As the slurry bleed tank fills, the slurry will be pumped into the thickener. It may take several days for the thickener to fill to the overflow weir. It may also take several days for a bed to form. Once the bed is at the desired density, the underflow pumps can be placed in service. The underflow tank should start filled with water to the minimum level with the agitator in service. The slurry going into the underflow tank will be near its normal density. This means the vacuum filters will be starting at near normal conditions. Note: Some FGD system control logic may require a full thickener and return water tank to establish a water balance prior to flue gas.

If hydroclones are involved, they will have to be placed in service when the slurry bleed tank (or external oxidizer) level gets high. Since there will be less solids in the slurry, the underflow from the hydroclones will not contain the normal amount of solids. Depending on system design, the vacuum filters may have to be placed in service if the hydroclones are in service.

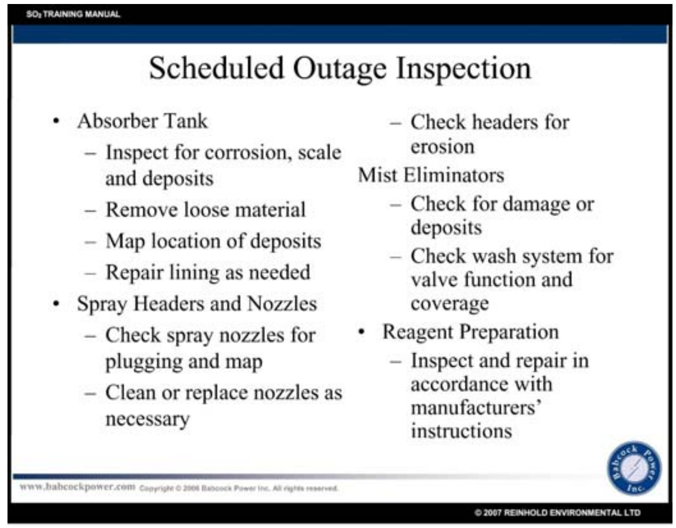
This means that the filter cake will be thin and the gypsum will not meet the normal specifications. This condition may continue for several days until the tower solids and oxidizer performance achieve normal conditions.

The overflow from the primary dewatering system will flow into the recycled water tank and the loop is now complete. It will take a day or two for the recycled water to reach equilibrium values and the chemistry in the entire FGD system to stabilize. When this happens, the FGD system is finally operating in what could be considered its normal mode.

CHAPTER 18 - NORMAL START-UP AND SHUT-DOWN



Chapter 18 Summary
(Narrated by Ron Richard, RE Consulting)



Scheduled Outage Inspection
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An FGD system will normally be placed in and out of service numerous times due to planned and unplanned outages of the unit to which it is attached. With the current environmental regulations, it is important that the emissions of the unit are within permit values as quickly as possible after the restart.

This chapter discusses how to properly shut down the FGD system in such a manner that will allow it to return to operation and full SO_2 removal capability as quickly as possible.

18.1 Normal Shut-down

The first step is closing the absorber tower flue gas inlet and outlet dampers and taking the fan out of service. If it will be a longer outage and one wants to reduce the solids concentration in the tower, manually open the slurry bleed valves and test the solids concentration regularly with a pulp density scale. Once the solids are at the desired value (or if it is a short outage and the solids concentration is not going to be reduced), the slurry recycle pumps can be taken out of service, flushed and drained. The lime/limestone slurry feed pumps can be taken out of service and the feed loop drained back to the slurry feed tank.

The mist eliminator wash system should remain in service for several cycles through all the wash headers to clean any slurry off the mist eliminator blades. The reaction tank agitators should remain in service anytime there is slurry in the towers. For an in-situ oxidation system, the oxidation air blowers should remain in service whenever there is slurry in the tower. If one has air lances instead of air spargers, the consequences of not keeping the blowers in service aren't as great.

For an external oxidation system, the agitator and oxidation air blowers should remain in service any time there is slurry in the tank. The oxidized gypsum can continue to be fed to the primary dewatering system until the oxidizer slurry level reaches the minimum level recommended for proper oxidation.

If there is a slurry bleed tank, the agitator should remain in service any time there is slurry in the tank. The slurry can continue to be fed to the primary dewatering system until the slurry level reaches the minimum level for proper agitator operation.

If there are hydroclones, they will be shut down when the external oxidizer or the slurry bleed tank reach their minimum levels. If there is a thickener, the rake will remain in service anytime there is liquid in the thickener. After the towers shut down, the rake should continue moving solids to the underflow pumps until the solids concentration falls to a lower value. At this point the underflow pumps can be taken out of service or placed on recirculation. If the rake has a raise/lower mechanism, the rake can be raised out of the bed.

Once all of the solids have been processed through the vacuum filters, the filter cloths can be washed and the filters taken out of service. If it is a rotary drum filter, the vat should be drained and flushed. If there is a pug mill, the covers should be removed and it should be washed out.

Everything should be cleaned up around the various areas and most FGD equipment can remain in this configuration until the next start-up.

18.2 Shut-down/Drain Absorber

Depending on the specific FGD system configuration, the absorber could be at a positive pressure (from oxidation air and damper seal air fans) or at a negative pressure (as from stack draft).

The first step is closing the absorber tower flue gas inlet and outlet dampers and taking the fan out of service. The lime/limestone slurry feed pumps can be taken out of service and the feed loop drained back to the reagent slurry feed tank. The slurry bleed valves should be opened manually and the tower slurry level will be lowered through the bleed valves.

During this drain time, the mist eliminator wash system should remain in service for several cycles through all the wash headers to clean any slurry off the mist eliminator blades. When the slurry level reaches the minimum for running the slurry recycle pumps, they will be removed from service. The rest of the slurry in the tower will have to be drained through the tower drain into the tower sump. For an in-situ oxidation system, when the slurry level is below the oxidation sparger or lances, the oxidation air blower can be removed from service. Once the slurry level reaches the minimum for agitator operation, they should be removed from service.

If the tower sump has storage capacity, saving the slurry to use in refilling the tower will place solids back into the tower. This will cause the SO_2 removal capacity of the tower to recover more quickly on start-up. If not, the sump will pump the slurry to the external oxidizer or bleed tank for processing with the rest of the slurry. When the tower is refilled with just water, it will take a day or two for tower performance to return to normal after the start-up.

For an external oxidation system, the agitator and oxidation air blowers should remain in service any time there is slurry in the tank. The oxidized gypsum can continue to be fed to the primary dewatering system until the oxidizer slurry level reaches the minimum level recommended for proper oxidation.

If there is a slurry bleed tank, the agitator should remain in service any time there is slurry in the tank. The slurry can continue to be fed to the primary dewatering system until the slurry level reaches the minimum level for proper agitator operation.

If there are hydroclones, they will be shut down when the external oxidizer or the slurry bleed tank reach their minimum levels. If there is a thickener, the rake will remain in service anytime there is liquid in the thickener. After the towers shut down, the rake should continue moving solids to the underflow pumps until the solids concentration falls to a lower value. At this point, the underflow pumps can be taken out of service or placed on recirculation. If the rake has a raise/lower mechanism, the rake can be raised out of the bed.

Once all of the solids have been processed through the vacuum filters, the filter cloths can be washed and the filters taken out of service. If it is a rotary drum filter, the vat should be drained and flushed. If there is a pug mill, the covers should be removed and it should be washed out.

Everything should remain in this configuration until the next start-up.

18.3 Normal Start-up

Assuming the flue gas flow is isolated from the FGD system, the absorber liquid is at normal level with oxidation air and agitators in service, and all auxiliary equipment is available, place the lime/limestone feed pump and the feed loop in service. Place the slurry recycle pumps in service. Place the mist eliminator wash system in service. Place the fan in service and open the absorber tower flue gas inlet and outlet dampers.

The pH control should start feeding lime/limestone as needed to maintain the pH set point. As the slurry density increases, the density control will open the slurry bleed valves to the external oxidizer or the slurry bleed tank.

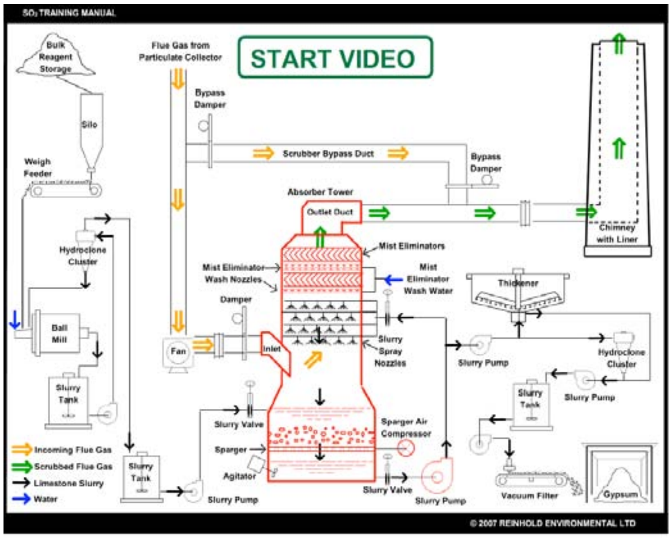
If an external oxidizer is involved, check that the acid feed system is in service and controlling oxidizer pH. Once the oxidizer slurry reaches the normal level, start pumping slurry to the primary dewatering system.

If there is a slurry bleed tank, once the slurry level reaches the normal level, start pumping slurry to the primary dewatering system.

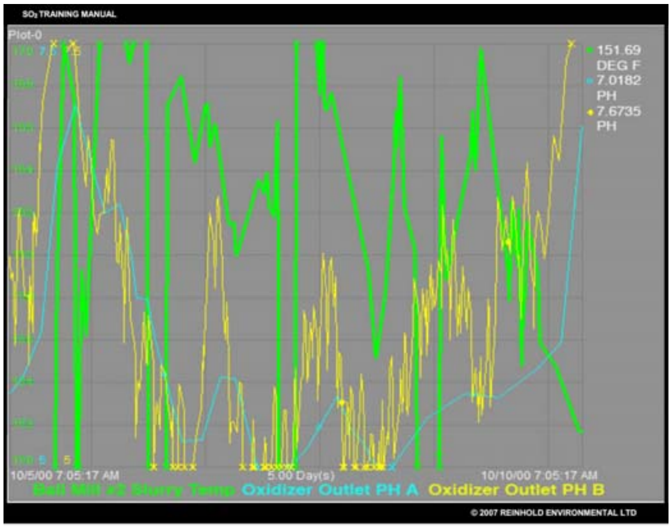
If there is a thickener, lower the rake and let a bed begin to build. Once the rake torque and bed density reach the desired levels, place the underflow pumps in service and start pumping slurry to the vacuum filters. Place the vacuum filters in service.

If hydroclones are involved, place the vacuum filters and hydroclones in service.

CHAPTER 19 - USING DATA ACQUISITION SYSTEMS



Chapter 19 Summary
(Narrated by Ron Richard, RE Consulting)



Gypsum Purity Graph
Used with permission

The new DCS control and data acquisition systems give the FGD operator tools the monitor and troubleshoot the FGD system that were impossible to imagine just a few years ago.

This chapter does not try to mandate the use of these tools in any given system. It does, however, show actual examples from operating systems of how such tools were used to recognize and solve problems. It is hoped that this will spark consideration of how these tools can be utilized.

The modern DCS control systems look at thousands of data points every several seconds. All the data is stored in the system or archived off line. The nice thing is that all these data points are available electronically. There are software vendors that have systems to access these points and present the data in graphical format.

One can use this data for both performance monitoring and problem troubleshooting. The problem with the control board screens is that they show an instantaneous "snapshot" of what is happening at that instant. However, with the graphical programs, one can look back into time to see what happened over any time range desired. This allows one to see trends over long time periods or to "zoom" in on a specific time when many things were happening so quickly that one couldn't see it all at once. One can determine what happened first, second, etc. that led to the final outcome.

Most software allows one to build screens and then save them. Each time the screen is opened, it repopulates the graphs with the latest specified values in the specified time period.

This can be extremely helpful to a scrubber operator. Screens such as these can be developed for a 24 hour or any desirable time period:

- Absorber tower pH, absorber slurry density, lime/limestone feed rate, slurry bleed flow rate, inlet SO_2 ppm, outlet SO_2 ppm
- Absorber slurry recycle pump amps
- Mist eliminator differential pressures, mist eliminator wash water flows
- Ball mill motor amps, limestone feed rate, grinding water flow, particle size (if one has an on line particle size monitor), slurry feed tank level
- Lime feed rate, slaker inlet water flow, lime to water ratio, slaker inlet water temperature, lime slurry outlet temperature, slurry feed tank level
- Vacuum filter speed, cake thickness, slurry flow to filter

If an operator looks at this type of data at the beginning of the shift, he/she has a better idea of how the process has been running for the last 24 hours and what can be expected on his/her shift.

Such information can also be helpful if things start changing on the control board screens. A quick check of the graphical screens can help identify what is changing in the process that is causing the controls to respond.

If a problem occurs, these systems greatly aid the problem solving process. On the long range basis, one can look back days, weeks, or months to see what was happening that led up to the problem. Different data points can be placed on the same graph to see if there was any interaction or correlation that led to the problem. Different theories can be explored by plotting different data on the same graph.

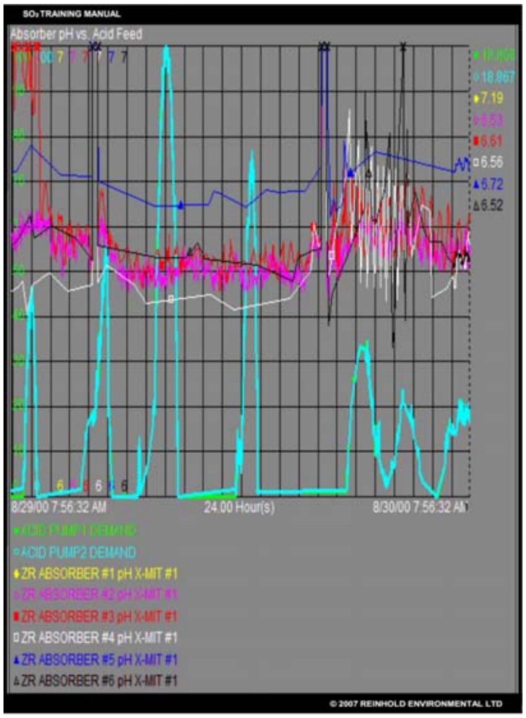
Once the probable solution is determined, graphs can be developed that let one track the progress of the solution as it occurs (or doesn't occur if the right solution wasn't chosen). These graphs may be plotted on a one hour or a 15 minute time scale so any changes will be apparent more quickly.

Another helpful tool is to "zoom" in on a problem. If several things happened at about the same time, one can plot the data on a 10 minute or one minute time scale. By placing all the data points in question on the same graph, it is easier to resolve which event happened first and follow the chain of events as it unfolds.

All the links in this section bring up actual screens that were used to solve a variety of FGD operational problems in actual FGD systems. They are intended to illustrate what can be done using the software packages. The actual use of such systems will be dependant on the software package and the control system data points available in each particular FGD system. The usefulness of these systems is limited mostly by the imagination and the understanding of the person selecting which points to display over which time scale to determine what is actually happening that is causing the problem. There can be a lot of trial and error to find the right combination of data points that shows what is really happening.

19.1 Absorber pH vs. Oxidizer Acid Feed

More sulfuric acid feed than normal was being required to maintain the external oxidizer pH at the desired value. In this graph, one pH reading from each of the six absorber towers was plotted against the two oxidizer acid feed pumps stroke control values. The pH range is from 6.0 to 7.0. The acid feed pump stroke control range is from 0 to 100 percent. The time period is a 24 hour window. The numbers to the right of the graph are the last instantaneous values for each data point.

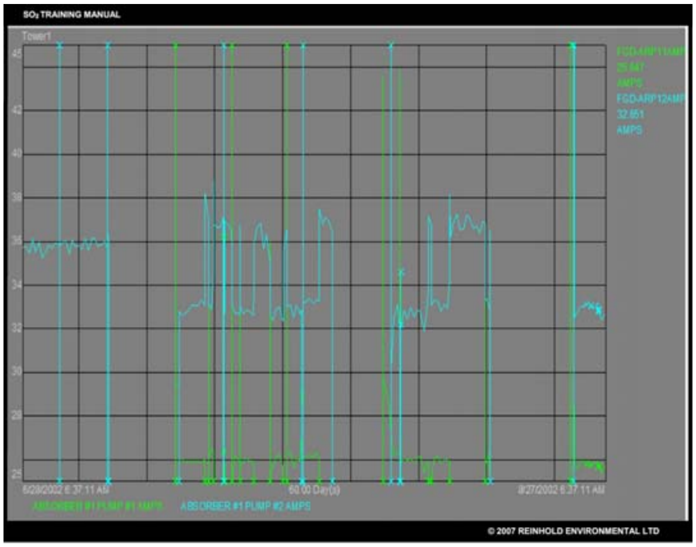


Absorber pH vs. Acid Feed Graph
Used with permission

The graph shows the correlation between absorber pH and oxidizer acid feed. You can see that when the absorber pH's were around 6.5 (middle of graph) that the oxidizer acid feed was minimal (periodic spikes). As evening load decreased and the pH was raised to around 6.6 to maintain SO2 removal, the acid feed picked up and was fairly continuous.

If it would be possible to target the tower pH to 6.5 or below and put more absorber recycle pumps in service if more SO2 removal is needed, the acid feed rate would be minimized. The pH would be raised above 6.5 only if the additional recycle pumps didn't get the needed removal.

19.2 Slurry Recycle Pumps



Absorber Slurry Recycle Pumps Graph 1
Used with permission

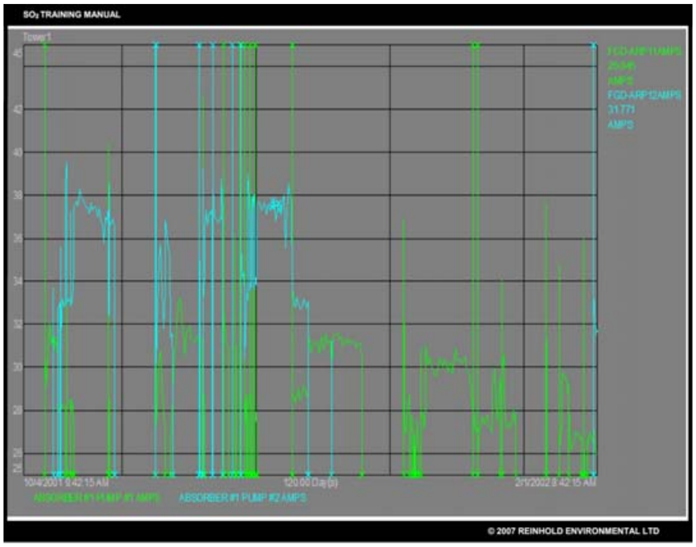
Graph 1

The #1 absorber tower has two slurry recycle pumps that pump into a common spray header. Not much difference in SO_2 removal was seen with both pumps in service. Graph 1 is a plot of both pumps' amps. The range of amps is 25 to 45. The time range is a 60 day period. The numbers on the right of the graph are the last instantaneous values of the data points.

The more amps a pump is drawing, the more fluid it is pumping. One can see that the #2 pump draws about 36 amps when pumping by itself. When both pumps are pumping to the header, this drops to about 33 amps. The #1 pump only draws about 26 amps sharing the header. If both pumps were pumping equally, their amps would be about the same when sharing the header. From the small decrease in the #2 pump amps when the #1 pump is running also, it would appear that there is no benefit to run the #1 pump until it has been overhauled.

Graph 2

A look back to an earlier time period shows that this had been occurring for quite a while (See Graph 2). Look at the difference when the #2 pump is pumping by itself and drawing about 38 amps versus when the #1 pump is pumping by itself and drawing about 28 – 30 amps. It also appears that the #1 pump performance was deteriorating over this 120 day period since the single pump amp draw fell from about 31 amps at the beginning of the period to 27 amps by the end of the period.



Absorber Slurry Recycle Pumps Graph 2
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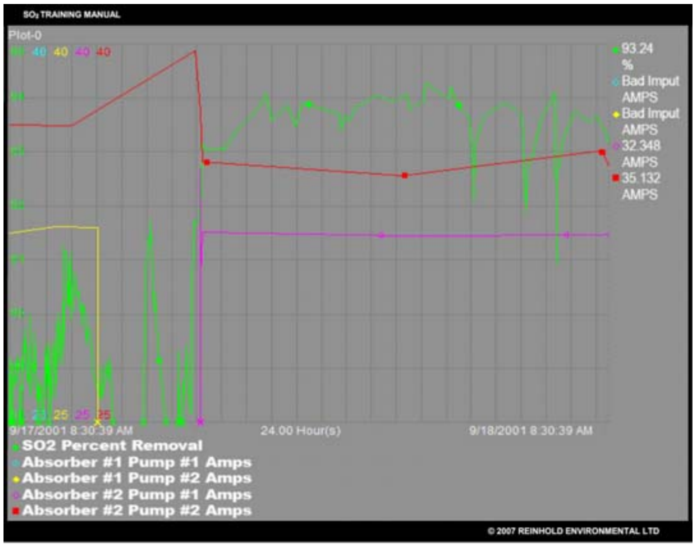
If one is looking at pumps that are pumping to different elevations, there will be differences in amp draw due to more pump head being required for the higher elevations. One must compare pumps pumping to the same elevation or allow for the difference due to head.

Graph 3

This problem shown in Graph 3 occurred during the same time period where the #1 absorber tower #1 slurry recycle pump was in need of an overhaul. The #2 absorber tower was out of service. The SO_2 removal was lower than needed with the #1 tower in service. The amp scale range is 25 – 40. The SO_2 removal range is 88 – 95. The time period is 24 hours. The numbers to the right of the graph are the last instantaneous values of the data points.



Absorber Slurry Recycle Pumps Graph 3
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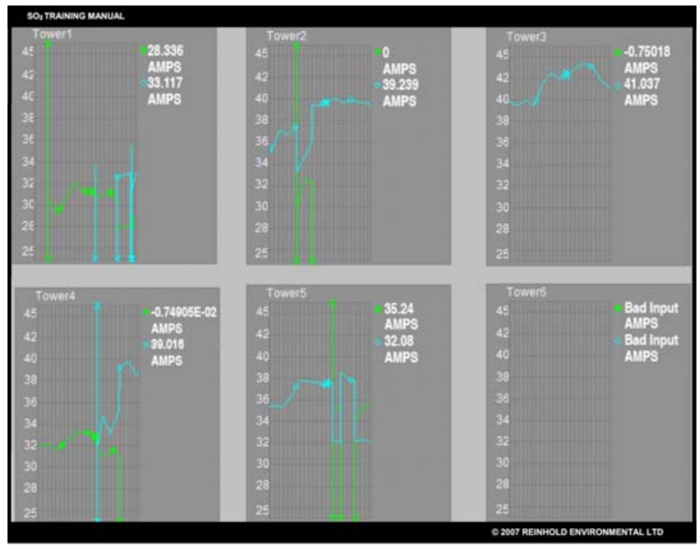
The SO_2 removal was about 89%. The #2 pump was in service on the #1 tower drawing about 32 amps. The #1 tower was taken out of service and the #2 tower was put in service with both pumps in service. The pumps draw about 32 and 35 amps so they were pumping more slurry through the spray header than was occurring in the #1 tower. This higher L/G ratio caused the SO_2 removal to immediately jump to 93 – 94%.

Graph 4

All the slurry spray nozzles and headers were cleaned during the outage so the pumps should have minimal restrictions. It was desired to take a look at pump performance (See Graph 4). The range of amps is 25 – 45. The numbers to the right of each graph are the last instantaneous values of the data points. Tower #6 is out of service.

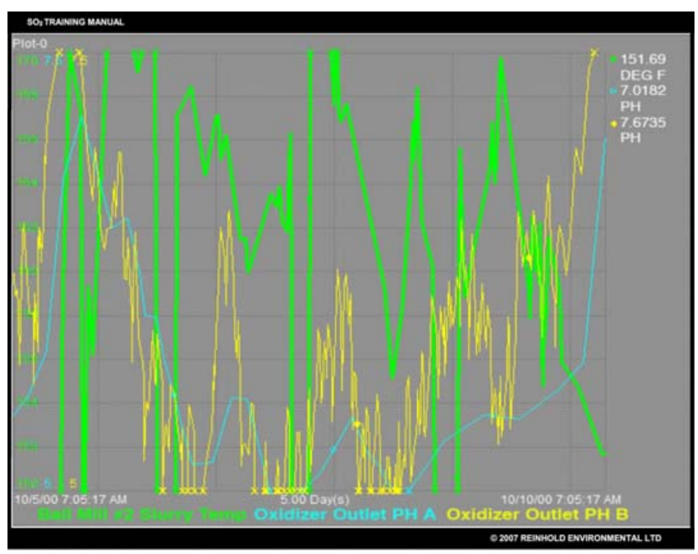


Absorber Slurry Recycle Pumps Graph 4
Used with permission

For tower #1, the #1 pump has significantly less amp draw in single pump operation than the other pumps and significantly less amp draw than the #2 pump in dual pump operation. The #1 pump needs to be looked at. For tower #2, the #2 pump looks normal in single pump operation and both pumps draw about the same amps in dual pump operation. Both pumps look O.K. For tower #3, the #2 pump looks normal and the #1 pump hasn't run. For tower #4, the #1 pump draws significantly less amps in single pump operation while the #2 pump draws normal amps in single pump operation. The #1 pump needs to be looked at. For tower #5, the #2 pump draws normal amps in single pump operation and both pumps draw about the same amps in dual pump operation. Both pumps look O.K.

19.3 Gypsum Purity

There was a decline in gypsum purity (the percentage of calcium sulfate dropped). This caused a problem meeting the wallboard quality specification. The range of lime slaker outlet slurry temperature is 150 – 170ºF. The range of oxidizer pH is 5 – 7.5. The time period is 5 days.



Gypsum Purity Graph
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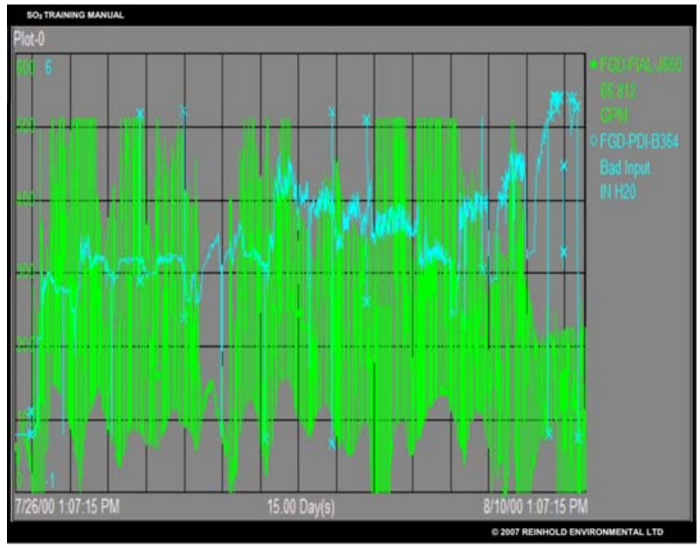
This graph illustrates what was happening since they were unable to feed acid into the external oxidizer due to leaks in the acid piping. As the slaker outlet slurry temperature (green line) went up, the oxidizer outlet pH (yellow and blue lines) soon followed by going down. As the slaker outlet slurry temperature went down, the oxidizer outlet pH soon followed by going up.

When the pH got above 5.5, the amount of sulfite left in the oxidizer discharge increased which decreased the gypsum purity and was detrimental to filter operation. At the time the graph was plotted, there was no way to control slaker outlet slurry temperature because there was no way to control the slaking water temperature. A system was installed to preheat the slaking water which allowed the slaker outlet slurry temperature to remain above 180ºF and gypsum purity was no longer a problem.

19.4 Mist Eliminator Pluggage

A mist eliminator had plugged and needed cleaned just 15 days after a previous cleaning. The question was why this had happened. On this graph the green line is mist eliminator wash water flow and the range is 0 – 600 GPM. The blue line is mist eliminator differential pressure and the range is -1 – 6 inches of water. The time period is 15 days. The numbers to the right of the graph are the last instantaneous values of the data points.

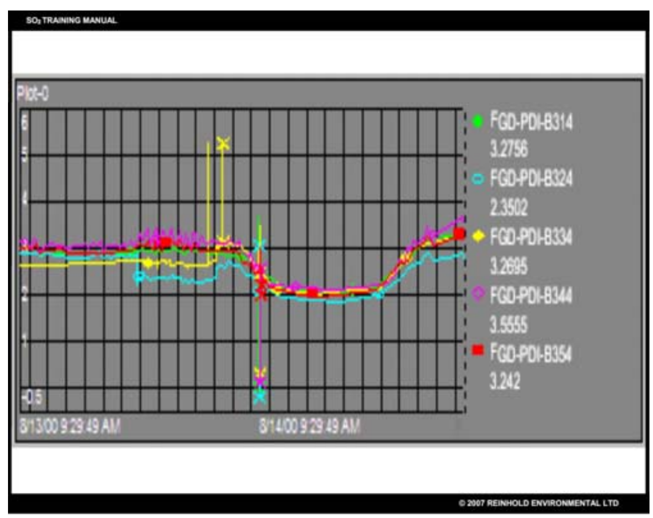


Mist Eliminator Pluggage Graph
Used with permission

The graph shows the entire run since the previous cleaning. It looks like there have been some wash water flow problems for some time. The differential went up after the period of almost no wash flow starting about day five. It came back down when good wash flow was reestablished. It then climbed back up when the wash flow went back down. So the pluggage problem was a direct result of wash water flow problems. An investigation of the wash water valve operation and wash water supply were then made to discover the root problem.

19.5 Mist Eliminator Strainer Pluggage

The following was noticed looking at FGD system graphs for the previous 24 hours. This was a routine daily scan of the data to see how the system was running. Graph 1a on the right is mist eliminator differential pressure for five different absorber towers and the scale is -0.5 – 6 inches of water. Graph 1b below is mist eliminator wash water flow for five different absorber towers and the scale is 0 – 600 GPM. The numbers to the right of the graphs are the last



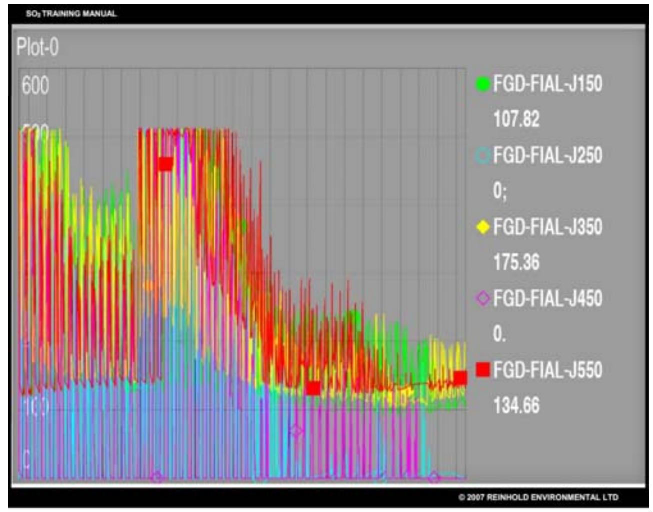
Mist Eliminator Strainer Pluggage Graph 1a
Used with permission

instantaneous values of the data points.

The investigation of the problem found the following. That night around 8:30 pm a large amount of Asiatic clam shells plugged the suction strainers of the mist eliminator wash pumps. This drop in mist eliminator wash flow can be seen on the graph on the right.

Looking at the graph on the right, one can see that the mist eliminator differential pressures were running pretty flat before this. The dip on the graph was from the large load drop that night. When the load came back in the morning, one can see that the mist eliminator differential pressures were starting to climb due to the lack of adequate mist eliminator wash.

The clam shells seemed to hit as a slug all at once. The station was chlorinating the service water system. One would expect more slugs of clam shells breaking loose from the piping as the chlorination continued. So it was very important to watch mist eliminator wash water flow and suction strainer differential pressure to catch any future events and correct them as soon as possible. (See the next example (Graph 2) for the outcome of this example.)



Mist Eliminator Strainer Pluggage Graph 1b
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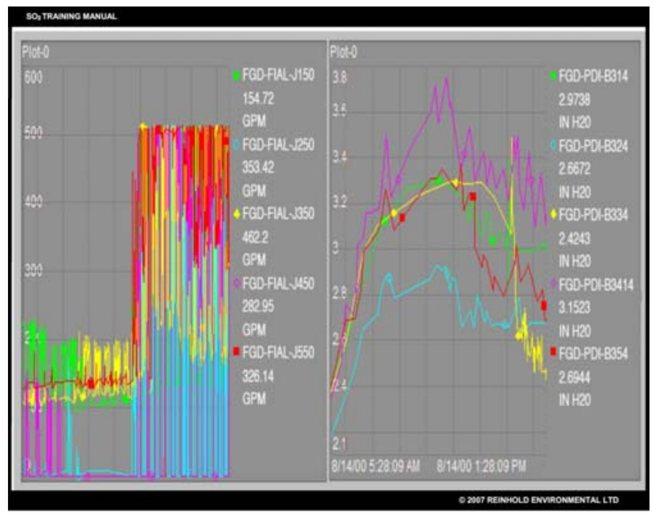
This is the outcome of the example shown in Graphs 1a and 1b. Graph 2 is mist eliminator wash water flow for five different absorber towers and the range is 0 – 600 GPM. Graph 2 is also mist eliminator differential pressure for five different absorber towers and the range is 2.1- 3.8 inches of water. The time range is 8 hours.



Mist Eliminator Strainer Pluggage Graph 2
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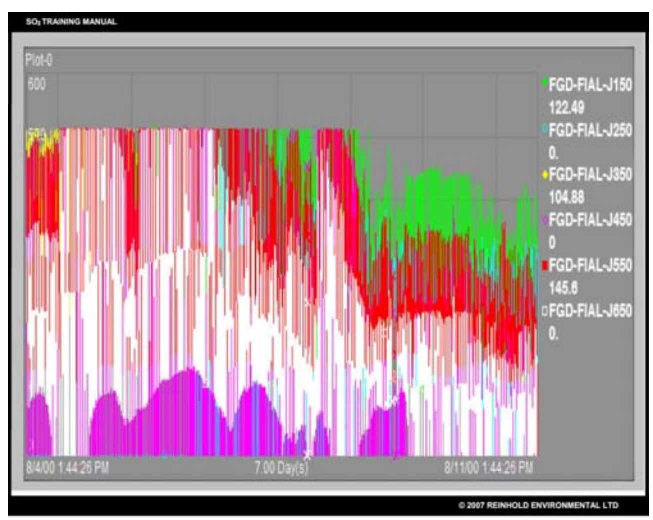
The suction strainers on the mist eliminator wash water pumps had plugged with Asiatic clam shells the



Mist Eliminator Strainer Pluggage Graph 3
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previous night. With low mist eliminator wash water flows, the differential pressures across the mist eliminators were quickly increasing. Once the suction strainers were cleaned and wash water flow returned to normal, the differential pressures quickly returned to normal.

The quick identification and resolution of the problem prevented the unit from having to be removed from service once all five mist eliminators plugged simultaneously and the FGD system had to be removed from service.

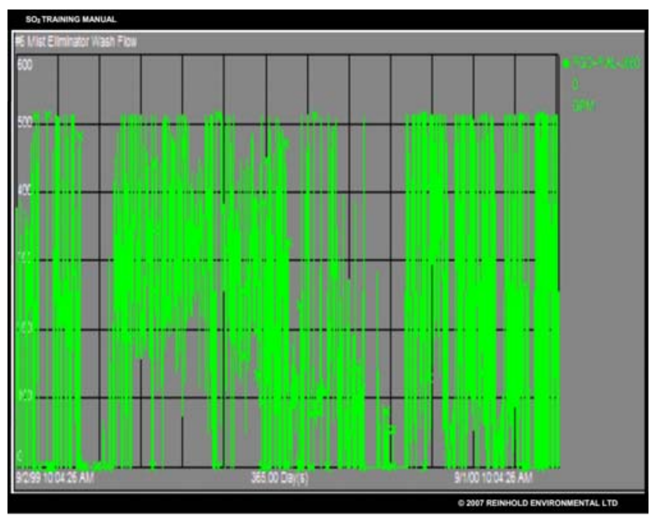
Graph 3 shows the mist eliminator wash water flows for six different absorber towers with the range being 0 – 600 GPM. The time period is 7 days. The numbers to the right of the graph are the last instantaneous values of the data points.

Graph 3 showed a sudden decrease in all flows at the same time. This means the problem had to occur in a part of the system that was shared by all six mist eliminator wash water systems. The logical place to look first was the mist eliminator wash water pumps. Since the pumps had suction strainers, the differential pressures across the strainers were checked. This indicated that the strainers were partially plugged.

The station had operated for a time period with no significant mist eliminator pluggage. Additional attention had been paid to the pluggage of the mist eliminator wash water pump suction strainers. Since the #6 absorber tower was at the end of the header, it was most sensitive to the pressure in the mist eliminator wash header.

Graph 4 shows the #6 mist eliminator wash water flow. The range is 0 – 600 GPM. The time period is 365 days. The number to the right of Graph 4 is the last instantaneous data value.

Notice the difference in the last quarter of the graph on the far right since more attention had been paid to strainer pluggage versus the earlier times of the year when the flow appeared to have dropped off significantly. It is the small things like this that can have a major impact in the system performance.



Mist Eliminator Strainer Pluggage Graph 4
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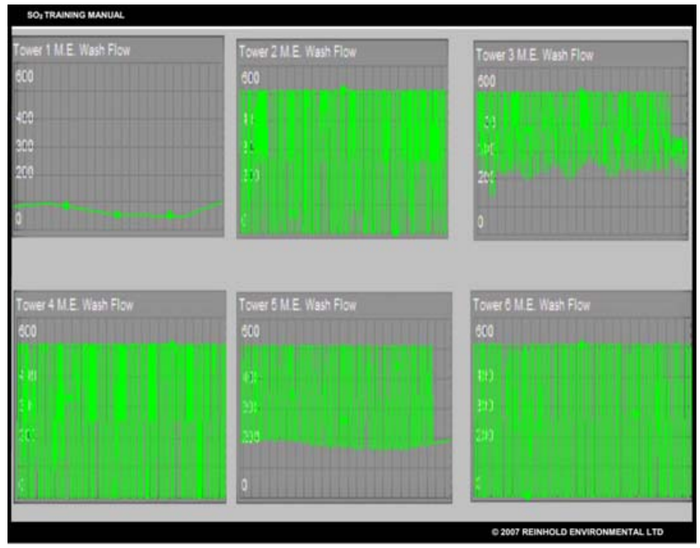
19.6 Mist Eliminator Valve Leakage

These graphs show the mist eliminator wash water flows to six different absorber towers. The range is 0 – 600 GPM. The time range is 24 hours.

The concern was with towers #3 and #5 since the flow didn't return to zero. As one can see from the graphs, there either were some faulty flow meters or some leaking quadrant valves on towers #3 and #5. If there were leaking valves, the additional fresh water addition would continually dilute tower chemistry.

An investigation was made of the flow meters and wash water valves.



Mist Eliminator Valve Leakage Graph
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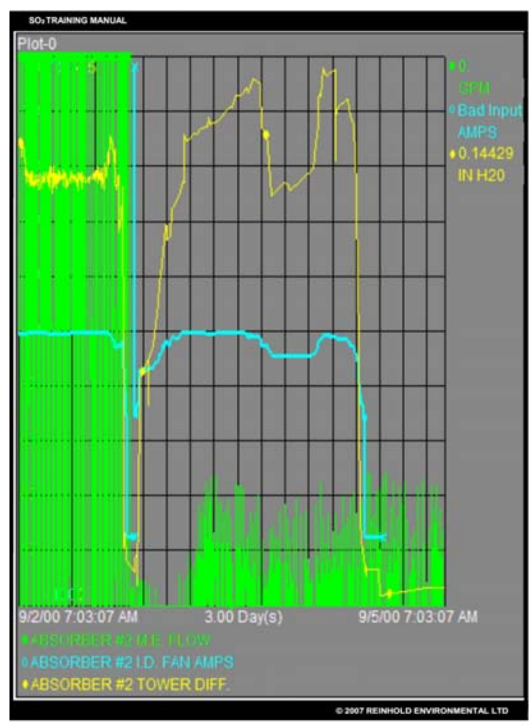
19.7 Mist Eliminator Wash Failure

The #2 absorber tower came off due to high mist eliminator differential pressure. It was inspected and a large amount of soft deposit was found in the mist eliminators. Some sections of the second stage mist eliminator were completely blocked in patterns that made one suspicious that some of the mist eliminator wash nozzles may have been plugged. The amount of deposit was much greater than had been seen lately. In plotting various data the following was found. The green line is mist eliminator wash water flow with the range being 0 – 500 GPM. The blue line is I.D. fan amps with the range being 100 – 700 amps. The yellow line is mist eliminator differential pressure with the range being 0 – 4.5 inches of water. The time range is 3 days. The numbers to the right of the graph are the last instantaneous values of the data points.

The I.D. fan (blue line) tripped off at 1:40 AM on September 3. The mist eliminator wash water flow (green line) looked normal before then and the tower differential pressure (yellow line) was running about 3.5 inches. For some reason after the fan came back on, the mist eliminator wash water flow did not return to normal. The tower ran for about 40 hours with no mist eliminator wash. The tower differential climbed to about 4.4 inches during this time. The large amount of deposit in the mist eliminators was a result of the 40 hours with no mist eliminator wash water flow.



Mist Eliminator Wash Failure Graph
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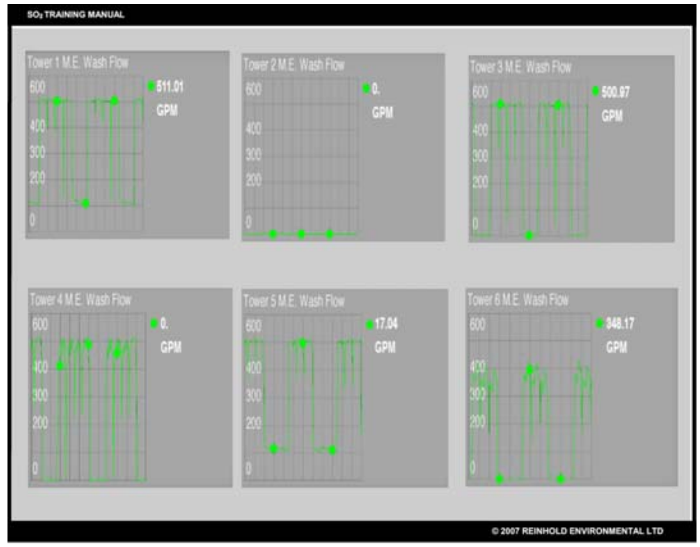
19.8 Mist Eliminator Wash

This was a close look at mist eliminator wash valve operation. Each mist eliminator was divided into four quadrants, each with its own mist eliminator wash header and valve. These graphs show mist eliminator wash flows with the range being 0 – 600 GPM. The time frame is 1 hour. The numbers to the right of the graphs are the last instantaneous values of the data points.

One can count 4 peaks for towers 1,3 & 4. One can only count 3 peaks for towers 5 & 6. One would conclude that one quadrant valve on each of these towers is not opening. Since there is no gap in the sequence, one would conclude that either the first or last valve in the sequence in not operating in both towers.



Mist Eliminator Wash Graph
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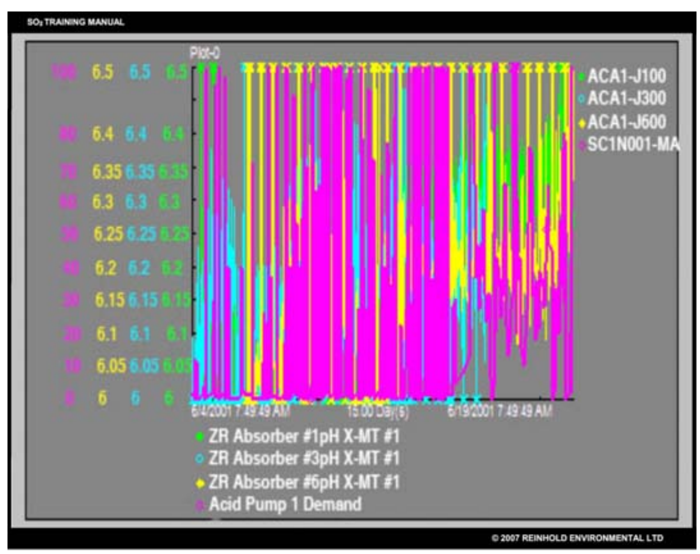
19.9 Absorber Oxidizer Acid Feed

The sulfuric acid feed to the external oxidizer had increased significantly. The question was why. The graph in Section 19.1 has the absorber tower pH values for three towers with the range being 6.0 – 6.5. The acid feed pump demand signal is shown with the range being 0 – 100. The time period is 15 days.

When the tower pH's were near 6.0 there were just a few short acid feed spikes. As the average pH rose to around 6.1, the spikes became more numerous. As the pH continued to rise to around 6.25, the spikes turned into peaks with significant area under each peak which increased oxidizer acid consumption significantly.

The increase in absorber tower pH caused the increased acid consumption in the external oxidizer as the control maintained the optimum oxidizer pH.



Oxidizer Acid Feed Graph
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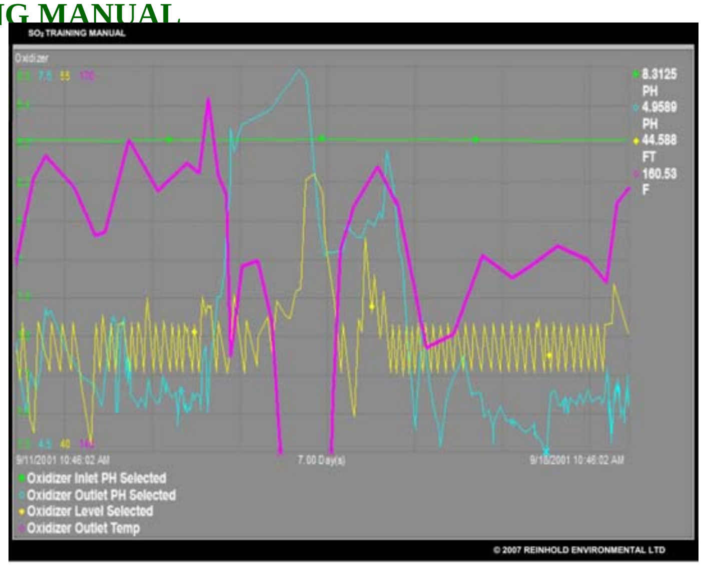
19.10 Oxidizer Performance

There had been an acid feed problem to the external oxidizer and the oxidizer pH had gone very high. The green line in this graph is oxidizer inlet pH with a range of 7.5 – 8.5. The blue line is oxidizer outlet pH with a range of 4.5 – 7.5. The yellow line is oxidizer slurry level with a range of 40 – 55 feet. The magenta line is oxidizer outlet temperature with a range of 140 – 170ºF. The time period is 7 days. The numbers to the right of the graph are the last instantaneous values of the data points.

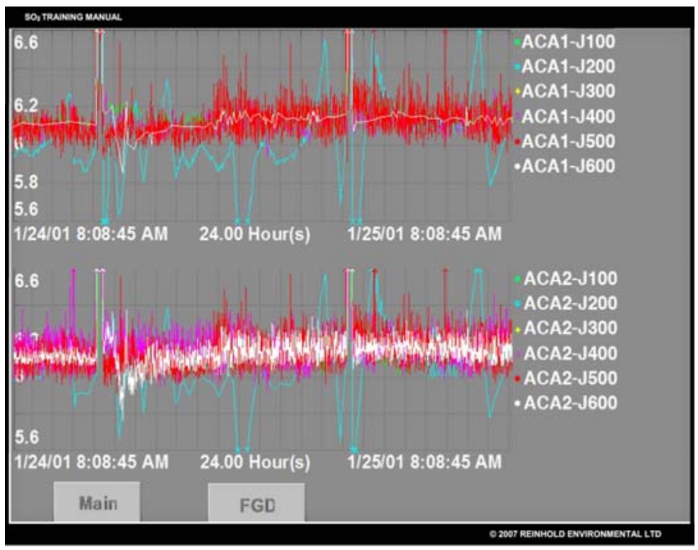
Ever since the pH problem 4 days previous, the oxidizer temperature had been running low. This would indicate incomplete oxidation which may have been why there had been so much off spec gypsum. The last morning the control system over shot on the 93% acid feed and the temperature began to rise and was near 160º. Maybe the oxidizer needed a bigger shot of acid to kick off the oxidation process and get the oxidizer temperature back above 165º.



Oxidizer Performance Graph
Used with permission

19.11 pH Control

This is a look at absorber tower pH. Each tower has two pH instruments. The top graph is one pH instrument for each of the six towers with the range being 5.6 – 6.6. The bottom graph is the other pH instrument for each tower with the same range. The time period is 24 hours. For five of the towers, the pH is being controlled in a very narrow band. For the #2 tower, the ph control is very erratic. It was recommended that the problem with the #2 tower pH control system be investigated and repaired.



pH Control Graph
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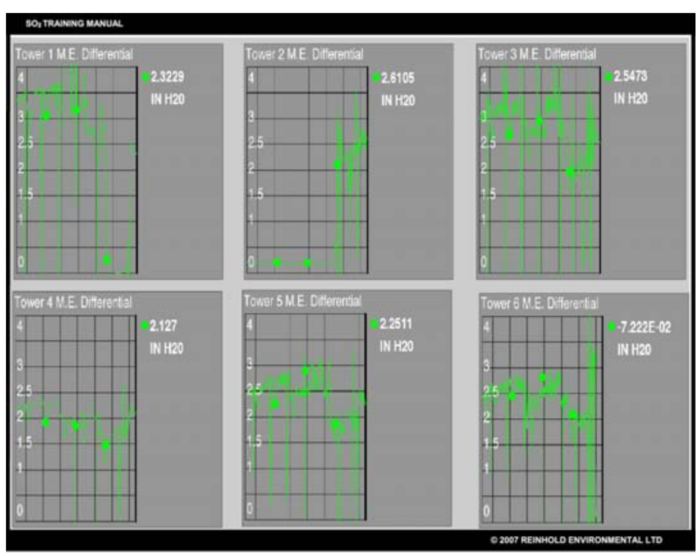
19.12 Poor Mist Eliminator Cleaning

The #2 tower mist eliminator had been cleaned. After it returned to service, the mist eliminator differential pressure values were looked at (See Graph). The range is 0 – 4 inches of water. The time period is 7 days. The numbers to the right of the graphs are the last instantaneous values of the data point.

The concern became that the mist eliminator that had just been cleaned had a higher differential pressure than the other towers in service. This led to questions about the effectiveness of the #2 mist eliminator cleaning and to whether the contractor had done the job properly.



Poor Mist Eliminator Cleaning Graph
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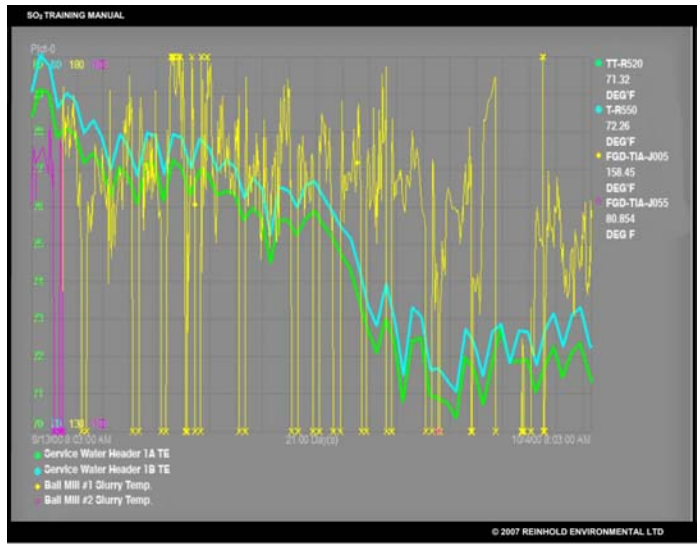
19.13 Slaker Slurry Temperature

It had been demonstrated that operating the ball mill slakers at a temperature between 160-170ºF had positive effects on oxidizer operation. The FGD operators had made adjustments to the lime/water ratio and total water to consistently operate the ball mills in this mode for several weeks. In the last week, even with more drastic adjustments, they had been operating more in the 150-160ºF range.



Slaker Slurry Temperature Graph
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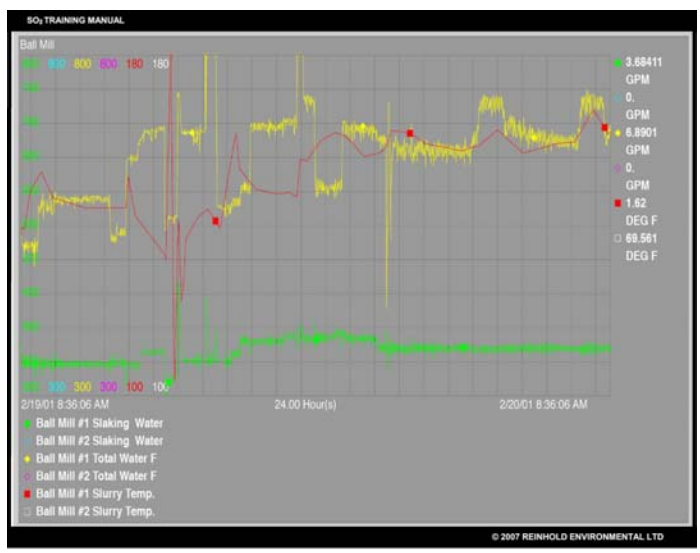
This graph showed the dependence of the slaking temperature to the incoming service water temperature. The service water was used as the slaking water. The green and blue lines are service water temperature with the range being 70 – 80ºF. The yellow and magenta lines are slaker slurry outlet temperature with the range being 130 – 180ºF. The time period is 21 days. The numbers to the right of the graph are the last instantaneous values of the data points.

The magenta and yellow lines showed operating in the 160-170º range for the first two weeks when the service water temperatures were in the high 70º range (green and blue lines). But cooler fall weather was causing the river temperature to decrease. Since the service water temperature had dropped into the lower 70º range during the last week, slaking temperature had been in the 150-160º range even with the operators making all the reasonable adjustments they could. This graph was used to illustrate the importance of installing a preheater for the slaking water. It also illustrated that the set point for the heated slaking water should be 80º.



Slaker Temperature vs. Oxidizer Performance Graph
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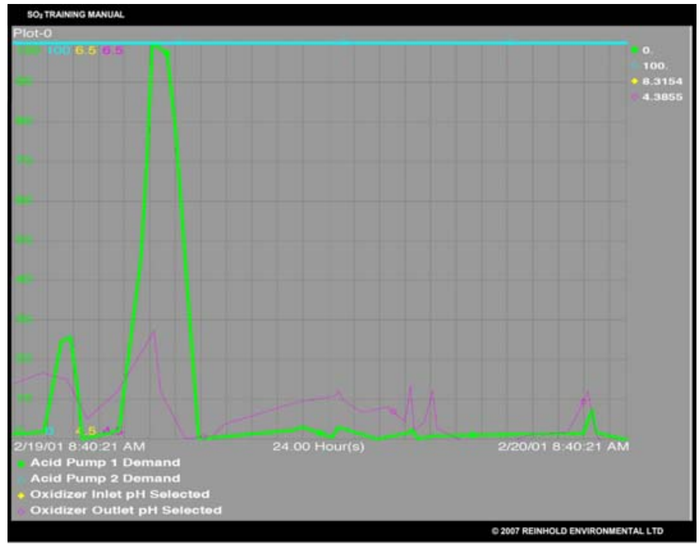
19.14 Slaker Temperature vs. Oxidizer Performance

Graph 1 in shows the #1 slaker performance. The green line is slaking water flow and the yellow line is total water flow to the slaker with the range being 300- 800 GPM. The red line shows the slaker slurry outlet temperature with the range being 100 – 180ºF.

Graph 2 shows the oxidizer performance. The #2 acid pump is actually out of service. The green line shows the acid pump demand signal with the range being 0 - 100%. The magenta line shows the oxidizer slurry outlet pH with the range being 4.5 – 6.5.

The time period is 24 hours. The numbers to the right of the graphs are the last instantaneous values of the data points.



Slaker Temperature vs. Oxidizer Performance Graph 2
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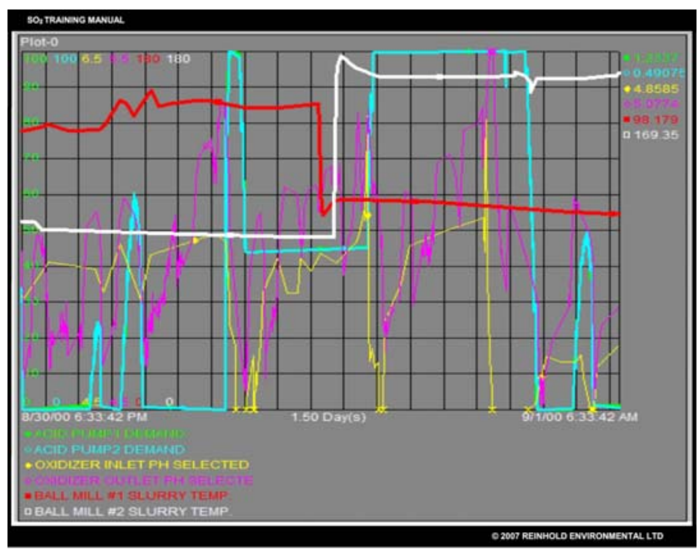
The slaker temperature started about 140ºF at the beginning of the time period and rose to about 165ºF by the end of the time period. One can see that the acid feed requirement to the oxidizer was reduced to about zero as the slaker temperature rose. This happened because there was less unslaked lime entering the oxidizer. Unslaked lime will not react with the SO_2 in the absorber tower but will dissolve and drive the pH up in the oxidizer.

Graph 3 is another illustration of the correlation between slaker operating temperature and external oxidizer performance. The green and blue lines are oxidizer acid pump demand with the range being 0 – 100 %. The yellow and magenta lines are oxidizer inlet and outlet pH with the range being 4.5 – 6.5. The red and white lines are slaker slurry outlet temperature with the range being 0 – 180ºF. The time period is 36 hours. The numbers to the right of the graph are the last instantaneous values of the data points.



Slaker Temperature vs. Oxidizer Performance Graph 3
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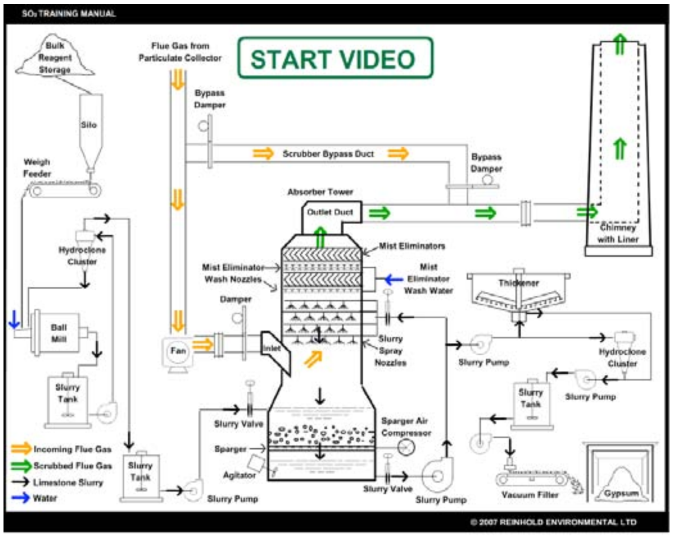
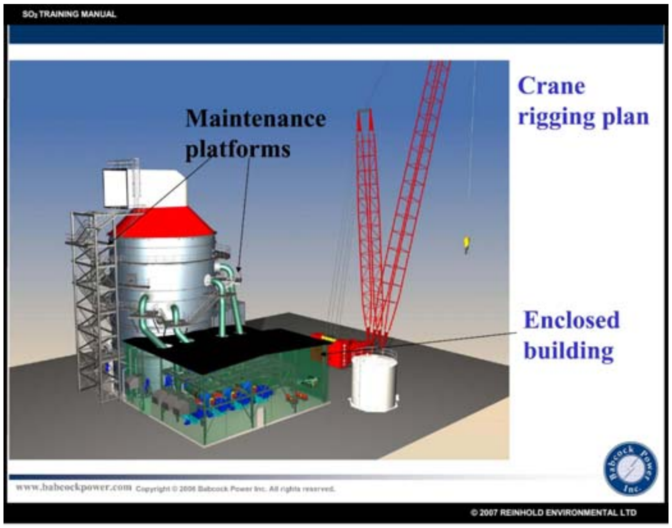
The first 18 hours showed the #1 slaker in service operating in the 140 – 150ºF range. When the red line came down and the white line went up is when they swapped slakers. The #2 slaker operated in the 160 – 170ºF range. One can see that with the #1 slaker in service, the oxidizer acid consumption went from almost nothing to 100% which represents 250 GPH with both pumps on. What wasn't shown on Graph 3 due to clutter was that the absorber towers pH remained fairly constant during this entire 36 hours. The thing that was most disturbing was that the oxidizer outlet pH (magenta line) was still climbing with the 100% acid feed. If the operators hadn't swapped slakers, it may not have come down like it did and the oxidizer would have stopped performing properly.

CHAPTER 20 - MAINTENANCE ISSUES



Chapter 20 Summary
(Narrated by Ron Richard, RE Consulting)



Maintenance Issues
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Much of the equipment in an FGD system is not similar to anything else typically used at a generating station. Therefore all of the maintenance personnel are not necessarily familiar with the issues and challenges of maintaining this equipment.

This chapter shares some of the lessons learned and maintenance tips developed at operating FGD systems across the country.

20.1 Linings

All linings are pervious to water vapor. This means over time, water vapor will eventually penetrate the lining and liquid will collect between the lining and the substrate. The pressure of this collecting water will tear the lining loose from the substrate. This time span may vary from as short as five years to much longer depending on the lining material and how well it was applied.

During every major maintenance outage, a complete inspection of all linings should be made, including linings in pipes where practical. One is looking for blisters or other signs that the lining is separating from the substrate. For resin based linings, one is also checking to see if the lining is becoming soft. As the water vapor penetrates the lining, it becomes much easier to press a pointed object into the lining. As signs of lining failure begin to appear, plans need to be started for lining repair or replacement. If the lining fails and the substrate is exposed, the corrosion will be rapid.

Linings should also be inspected for abrasion damage. If a resin based lining was applied in multiple layers of different colors, the color seen can be an indication of how much lining thickness remains. A thickness meter can also be used. Special attention should be given to areas of high flow or changes of shape. This can be where pipes leave tanks, where baffles are in an agitator flow pattern, or where there are elbows or concentric reducers in pipes.

Small areas of damage can be repaired. A section of rubber lining can be cut out and replaced with new rubber. Resin based linings can have the surface prepared and a new layer of lining placed on top of the existing lining.

If lined pipe is consistently damaged by erosion, some utilities have replaced the lined pipe with HDPE pipe. This has proven very successful in some difficult applications.

Welding should never be done on a surface that is lined on the opposite side. If welding must be done, then the lining on the opposite side should be inspected and repaired. Heating with torches or by connecting to a welding machine should never be done to thaw out frozen lined pipe.

20.2 FRP

The things one is looking for in FRP are cracks and abrasion damage. Cracks can be a sign that there is movement in the FRP part. Vibration or cyclic movement can lead to fatigue cracking. This is often found with smaller bore pipe or mist eliminator blades where flow can induce movement. Often extra support can prevent a reoccurrence of the problem. A layer of resin and reinforcing fiber mat can repair the cracked area. Cracks where FRP pipe are joined together can indicate the joint is weakening and may fail. Again the joint can be reinforced with resin and fiber mat.

Abrasion can be seen as an irregular appearing surface or bare fiber showing through the resin layer. These areas can be built up with resin and fiber mat. For areas of severe abrasion, a shield of another layer of FRP (such as a half pipe onto a pipe) can be glued to the surface followed by wrapping the entire area with fiber mat and resin.

20.3 Metal/Alloys

The things to look for in metals are cracks, pits or abrasion damage. There may be some discoloration of the metal surface (such as a thin brown, tan, or other color film that is somewhat transparent), but this is usually not a concern. If the metal is an austenitic stainless steel, this may be a concern if it is an indication of iron contamination due to welding, cutting, or grinding work that has taken place in the area. This is discussed in the NACE standards for installing metallic linings.

Cracking or abrasion indicates mechanical issues in the area that must be identified and corrected. General corrosion or pitting indicates a chemical environment that is more severe than was anticipated when that metal was selected. Either change can be made to the chemical environment or a higher grade of metal may need to be used.

Alloy nuts and bolts are notorious for galling and being difficult to remove. Some utilities have found it easier to cut bolts and replace them with new ones rather than trying to take them apart with wrenches. If one is replacing nuts and bolts, make sure they are the same alloy that was used originally. Having a mechanic go to the tool crib and bring back some “stainless steel” nuts and bolts is not always acceptable.

High nickel alloys have some unique properties. They “work harden” very quickly. This means that one cannot drill a hole through even the thinnest material with a twist drill. A plasma cutter is the best way to make a hole. The molten weld pool is very viscous. Welders describe it as flowing like molasses compared to the normal weld pool flowing like water. This means welders must be trained before sending them to weld high nickel alloys.

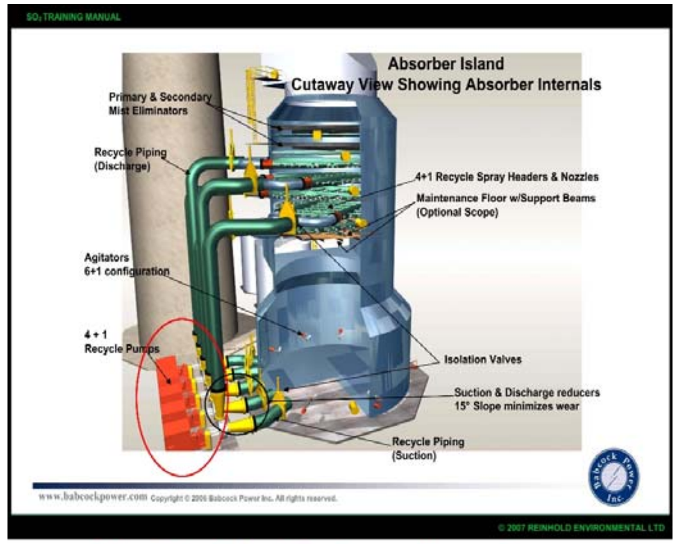
20.4 Masonry

Masonry is susceptible to damage from chlorides and sulfates in FGD slurries. This means one must inspect the ceramic tile or resin based lining that is in place to protect the masonry from the slurry. Any damage to the lining must be repaired immediately. Damage to the masonry will most likely appear as large areas of concrete that break loose from the surface (such as happens with bridge decks in the northern states). This happens because the chlorides cause the reinforcing rods to corrode and expand. The force from this expansion breaks the concrete loose from the reinforcing rod in one large chunk. If this happens, an area of concrete around the damaged area needs to be removed to remove any residual chlorides. The rebar reinforcing system is then repaired and a patch can be poured.

If a penetration is going to be made through a masonry wall or floor, it is typically sleeved with a corrosion resistant material. This is done to prevent slurry from coming in contact with the masonry surface and causing the damage described above.

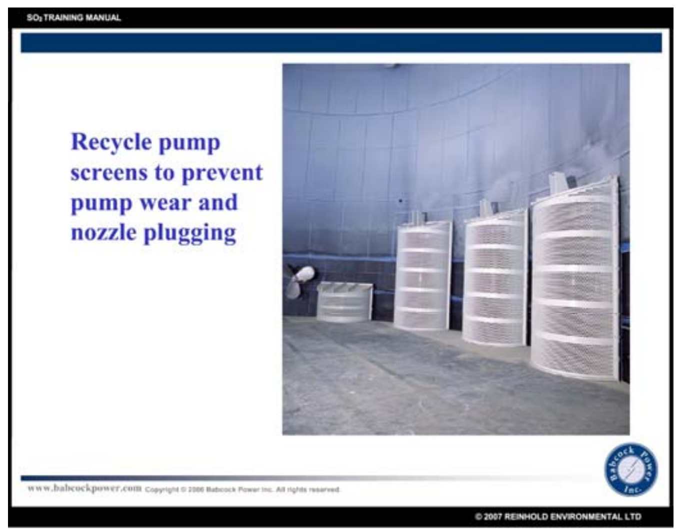
20.5 Slurry Pumps

Spare slurry pumps should rotated into service periodically (at least once a week). To do so, the next pump designated to be taken out of service should be stopped, its isolation valve closed, the isolation valve for the spare pump opened and the spare pump started. The slurry pump removed from service should not set idle full of slurry. The solids can settle in the pump casing. If there are enough solids and they set long enough, the pump impeller can become locked in place by the solids. This can damage the pump drive or the impeller when the pump is placed back in service. Pump operation sequence is FGD system and site specific. Depending on the particular pump and piping orientation, many FGD slurry pump casings cannot be drained below the suction line. Dilution of the material remaining in the pump is recommended as practical.



Absorber Island Cutaway-Slurry Pumps
(Narrated by Tony Licata, Babcock Power)

Some slurry pump inlets in the absorber vessel may be covered by screens to prevent large chunks of debris from entering the pump and causing damage to the impeller or lining, or plugging the spray nozzles. If so, you should inspect and clean these screenswhenever the absorber is taken out of service.



Slurry Pump Screens
(Narrated by Tony Licata, Babcock Power)

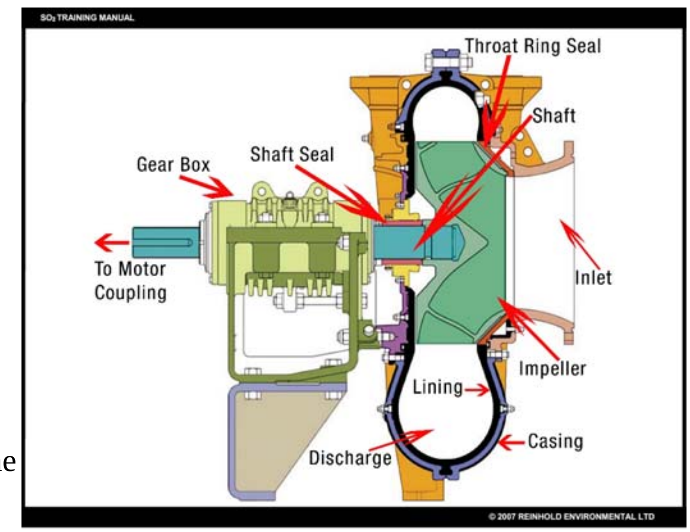
Slurry pumps typically have lined bodies and possibly lined impellers. The more debris that is allowed to get into the FGD slurry (chunks of scale, nuts and bolts, wood, rocks, tools, etc.) the shorter the life of these linings will be. Debris can enter during maintenance work when mechanics drop things and don't retrieve them. Debris can enter during cleanings if scale isn't removed from the system. Debris can enter if trash is washed into sumps which pump back to the system.

The pump liners often bolt in place. A liner change out can be done rather quickly as long as the liner is changed before it is penetrated. If one waits too long, the slurry penetrates the liner and erodes the pump casing. Then, before a new liner can be installed, the pump casing needs to be repaired. Some of the non-OEM liner suppliers have designed liners with fewer pieces that can be installed relatively easily.

A lined pump impeller can be reused if it is removed before the lining is penetrated. The old lining can be removed and a new one installed. Once a lining is penetrated, the slurry will quickly erode away the impeller vanes. At this point, the impeller hub is typically junk. Isolation valves, drain-vent flush sequence controls. pipe expansion joints, gear box and lube oil systems all require attention to keep these pumps operational.

Isolation Valves For Pump Maintenance
Used with permission from Babcock Power

The largest slurry pumps, such as the absorber slurry recycle pumps, typically have large diameter, short, straight suction piping. This means a person can actually crawl into the pump suction and inspect the impeller and casing linings without disassembling the pump. One can also measure the clearance between the impeller and the suction throat ring. As this clearance opens up, slurry can short circuit from the pump discharge back to the suction which reduces pump output flow.



Slurry Pump Cutaway
Used with permission from Weir Slurry Group Inc.

With most pump designs, one can shim the bearings to adjust this clearance and regain pump capacity.

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20.6 Absorber Spray Nozzles

Whenever maintenance work is being done in an absorber tower, it is a good practice to inspect the slurry spray nozzles. Safety and fall protection issues must be addressed while working overhead in large open tanks and towers. The first order of business is to make sure they are all still there. The second order of business is to inspect the nozzles to determine if any of them are plugged and the immediate spray area to note any irregular patterns. Any plugged nozzles should be unplugged or replaced. The newer styles of nozzles don't plug as often and are easier to unplug.

The spiral nozzles should be checked more closely occasionally to look for eroded grooves in the spiral. These grooves do not cause a problem until they get deep enough that the tip of the spiral falls off. Once a tip falls off one nozzle, consideration should be given to replacing all nozzles with similar wear patterns. Spiral nozzle tips can significantly shorten pump liner life.

20.7 Oxidation Air Spargers

Two things can happen to reduce the performance of oxidation air spargers. First, the holes can grow closed as deposits form around the outside edges of the holes. Sometimes this problem is aggravated by issues with the oxidation air humidification system.

Secondly, slurry can get inside the sparger whenever the oxidation air blower is out of service and there is a slurry level above the sparger. When the blower is put back in service, some of the slurry can stay in the sparger headers. The dry air will eventually evaporate the liquid leaving dry material inside the headers. This material may move around and plug sparger holes from the inside.

Whenever the sparger is exposed and accessible, it is prudent to check that all the holes are fully open. This can be done with a punch or twist drill of the proper size.

If there are signs of pluggage from the inside of the headers, the header internals should be checked. This is much easier if there are access caps on the ends of the headers. If deposits are present, they are most easily removed with water blasting lances run through the headers.

20.8 Ducts and Expansion Joints

Duct walls, support attachments and turning vanes should be inspected for cracks, corrosion and abrasion damage. The floor of the duct is even more susceptible to damage. Pools of low pH liquid can accelerate corrosion. Scale deposits should be removed if possible. The areas under deposits are more susceptible to pitting type corrosion and should be inspected closely.

From the inside of the duct, look for daylight and penetrations (usually not a good thing). Expansion joints and any moisture collection devices should be checked for deposits that may have built up, especially on the floor. Deposits in the folds of the joint can stretch and tear the joint material as the joint moves. All deposits should be removed. Sometimes shields are placed over the joint on the floor to minimize material falling into the joint. If liquid is a problem, sometimes metal angle is installed on the floor to act as a dam and a drain is installed to remove this liquid before it fills the joint. Special attention is warranted to potential "cool spots" or connections for access doors, test ports and stiffener supports.

From the outside of the duct, one should inspect the joint between the duct and the expansion joint. There should be no sign of leakage through this joint. There should be no corrosion of the bolts. Any leakage should be repaired if possible. If it is an elastomeric joint, one should look for any signs of the joint material being cut or scored from contact with the bolts or sharp edges of the duct. Tadpole tape can be installed to prevent this type of damage.

For square ducts, the corners of the expansion joint are more susceptible to damage. Some utilities have found that molded corners give longer life than just running the belt around the corner. There are methods and procedures for removing sections of expansion joint material and patching in a new piece.

20.9 Dampers

Damper seals and internal guides are the part that requires the most maintenance. The damper blades seal air fans, limit switches and drives should also be inspected but require attention less frequently than the seals. When the seals fail, flue gas will leak out causing corrosion damage to damper frames and surrounding structures. Stroking the dampers and internally inspecting their travel during outage opportunities is recommended.

Leaf type and bellows type seals are used. A leaf seal is a stack of thin metallic strips of different lengths. The longest strips overlap and supposedly interleaf with the strips from the other side of the opening. Every time the blade penetrates the seal, the strips flex about 90^{o}. Over time, they don't always return to their original position. Also, the strips sometime catch on irregularities or deposit buildup on the blade surface and curl back or are crunched. This prevents the strips from covering the opening when the blade is withdrawn. Even the most corrosion resistant alloys in such thin strips have been known to be attacked and develop holes. When these problems develop, the seal stack must be replaced with a new one.

The bellows type seals have given longer life. Each half of the seal is a corrugated metal bellows. A flat place on each half mates with the face on the other half. There are typically guides to direct the damper blade between the bellow halves. The two halves separate as the blade penetrates between them and compresses the bellows. The metal used for the bellows is thicker than that used for the leaf seals, so corrosion attack typically does not occur as soon. Also the metal bellows do not flex as much as the leaf seals. The most damage occurs if the blade does not follow the guides and catches one half of the bellows as it penetrates through them. When this happens, the bellows is stretched, deformed, or torn and the seal no longer functions properly. This used to mean that the entire bellow half needed to be replaced. Recently, some welding procedures have been developed which allow a section of a bellows to be cut out and a new piece welded in.

20.10 Mist Eliminators

The question is when and not if mist eliminators will have to be manually cleaned. Manual cleaning is typically done using high pressure water blasting equipment. Care must be taken. Using too high a pressure or too narrow a nozzle stream can cut and score mist eliminator blades. Holding the nozzle too close to the blades can have the same effect. Scored blades are weaker and flow vibrations will eventually cause them to break along the score mark. Broken mist eliminator blades are not as efficient in removing liquid droplets from the gas stream and any broken pieces or scale not contained can add debris to a process stream.

Most mist eliminator materials will tolerate someone walking on the surface of the blades. However, it is best to cover the blades with plywood strips (cut narrow enough to fit through the access door) if there is going to be a lot of foot traffic over an area. Plywood should always be placed under ladder feet and equipment to prevent damage to the blades.

The mist eliminator panels are typically made in sections that will fit through the access door. The sections are laid next to each other and secured to the support beams. The construction of these sections has a large bearing on the life of the mist eliminator. The frames of each section must be structurally strong. The support and blade spacer designs can vary. The designs that have proven most successful have rods that penetrate through holes in the frames and blades. Blade spacers are donuts threaded onto the rods between each blade. The rods are securely attached to the frames. This makes a very rigid structure with a long life. Safety concerns in this area must address fire potential for plastic and FRP materials. Welding restrictions are usually employed.

20.11 Ball Mill

The worst wear area of a ball mill is the inlet feed chute. All the limestone and water must slide down this area. Of course, the water is typically recycled water from the FGD system so it is very corrosive. Then there is the matter of dumping mill balls into the mill which means that ceramic isn't a good choice for this area. Many utilities look at this area every month or so. They have used various trowel on maintenance repair compounds to fill in holes with some success. This has allowed them to get up to several years life before this the chute is replaced.

One utility tried a feed chute fabricated from a special wear resistant alloy that was also corrosion resistant. It lasted significantly longer then the normal feed chute, but not long enough to justify its higher cost.

The liners and lifter bars are the other major maintenance area. Both bolt onto the ball mill barrel. Both can be replaced with the balls in the mill. One does half of the job and then rotates the barrel 180º to do the other half. Many mills have an "inching drive" to precisely rotate the barrel to the desired position for maintenance.

The shell liners and pie segments don't need replacement as often as the lifter bars. They do need to be replaced before they wear completely through to the barrel. If this happens, damage to the barrel can occur. Often the manufactured lining segments will need a little trimming to fit together snuggly. The shell liners will wear more quickly if the mill is often operated at a reduced limestone feed rate. If the motor horsepower transferred to the balls isn't grinding limestone, it begins to grind liner.

The lifter bars don't last until they wear down flush to the shell liners. Their job is to lift the balls to a certain elevation and then let them drop back down onto the limestone slurry. Once the square corner on the lifter bar begins to round off, the balls will begin to roll off at a lower elevation and the mill will lose grinding capacity. Periodic slurry fineness testing can help determine when the lifter bars need replacement. The nice thing is that a lifter bar has two square corners. When the first is worn off, the bar can be turned the other direction for another life cycle.

Some utilities have had to change lifter bars as often as yearly, depending on the operation of the mill. A new style lifter bar has been developed with a metal corner molded into the rubber. It has been reported that this style of lifter bar is giving a longer life.

Routine inspection and cleaning of the drive gear system is recommended. Turning the drive pinion and eventually the ring gear on horizontal mills is to be expected. Proper gear and bearing lubrication is critical.

20.12 Agitators

The obvious wear area for an agitator is the impeller. If it is a rubber covered impeller, the damage usually occurs near the tips of the impeller. If this is a regular occurrence, one should consider using a metal impeller. Rubber linings will typically have a long life on the agitator shaft.

If one begins having problems with mechanical seals or gear boxes, be suspicious of swirls and eddies in the tank putting forces on the agitator. Often it is bad enough that one can see the entire agitator move and twist on the mounting bracket. Instrumentation can also be used to monitor the movement. The answer is to mount the agitator at different angles to minimize the swirls and eddies. This usually requires the assistance of the agitator vendor.

If several side mounted agitators are mounted in a normal pattern in a circular tank full of slurry, one usually finds a mound of solids in the center of the tank. Some utilities would remove this material during an outage. But, they found that the mound returned after just a few days of normal operation. Many utilities now ignore this mound unless it is in the way of doing a specific job.

20.13 Hydroclones

There are no moving parts in a hydroclone. The only maintenance is lining and apex replacement or removing debris that has plugged an opening. Many utilities have found it most efficient to have a work area right at the hydroclone cluster. A table with a vise or jig to support the hydroclone during assembly/disassembly is all that is required. Some also have a cabinet with spare parts and the proper wrenches. Some hoisting/handling scheme designed for the weight of at least one fully-assembled hydroclone plugged solid with slurry is often provided.

Most hydroclone clusters have one or more spare installed hydroclones. This means a spare can be placed in service and the one needing service can be removed and brought to the table. The sections of the hydroclone bolt or clamp together. It is important to replace worn liners before the slurry penetrates the liner and erodes the housing.

The apex nozzle can be rubber or ceramic. The ceramic nozzles have a longer life. The size of the apex opening is critical for proper hydroclone performance. Care must be taken when removing foreign material from the apex nozzle not to enlarge the hole.

20.14 Belt Vacuum Filter

Properly training and tracking the carrier belt and washing the filter cloth is critical for vacuum belt filter operation. Several times a year, the vacuum pan should be lowered to check for wear on the vacuum seals. This can be done relatively quickly. How the pan is lowered is dependent on the filter design. The routine service required is dependent on the seal design. Refer to the vacuum filter manual.

It is not unusual for a belt filter cloth to last a year or more. Eventually it will need to be replaced. The easiest way to do this is to open the splice on the existing cloth and splice the new cloth to the end of the old cloth. The filter can be operated at low speed, letting the old cloth pull the new cloth through all the guides and rollers. Some installations provide an inch drive or jog button to aid cloth replacement. Once the new cloth is in place, the two ends can be spliced and the tension adjustments made. A close eye should be kept on cloth tracking for a few days as the new cloth stretches.

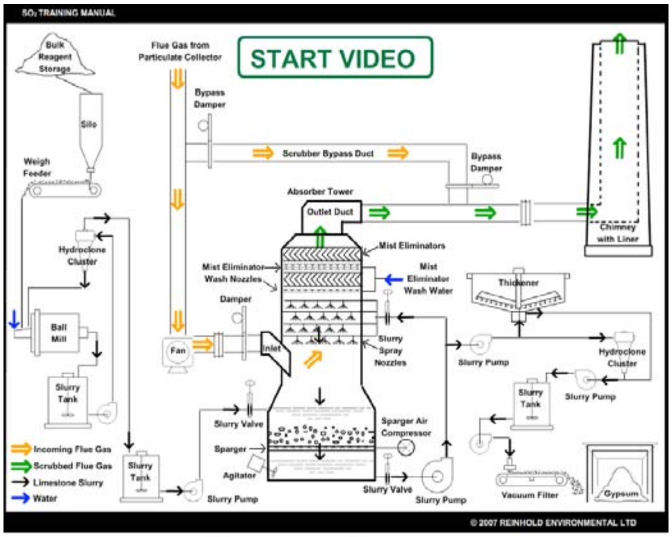
20.15 Drum Vacuum Filter

Filter cloth life is dependent on the type of slurry that is being filtered. Gypsum slurry filters easily and the cloth will have a long life. Calcium sulfite slurries can blind a cloth more rapidly. If a cloth gets a small hole in it, a dab of silicone sealant will often patch the hole. When the cloth is changed, care must be taken that all the edges are secured with the wedging material. If an edge comes loose, it can catch on the cake discharge knife and tear the cloth off the filter.

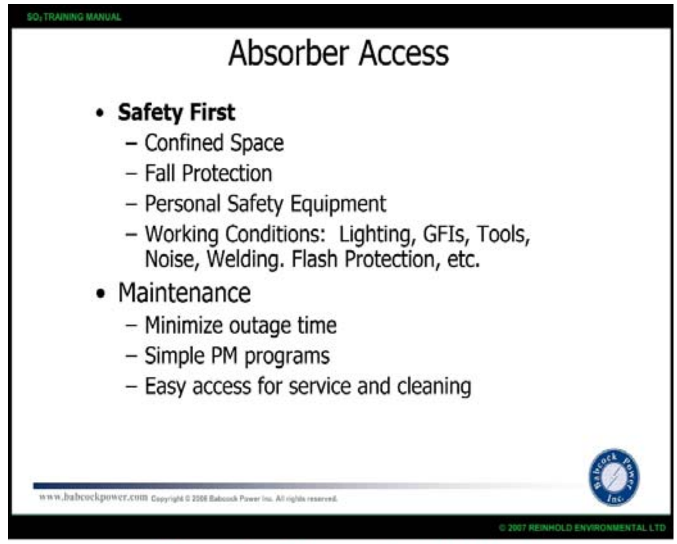
At least yearly an inspection should be made of the interior of the drum. One is looking for holes or cracks in the piping and the vacuum chambers. Any slurry inside the drum is a sign of problems. If there are leaks in the vacuum piping, a vacuum can be pulled on the drum interior. This can dish the ends of the drum inward.

The vat agitator can usually be rotated up out of the vat by removing the drive arm. This will allow room to inspect the vat lining for signs of wear. Once bare metal is exposed, the slurry will eat a hole through the vat relatively quickly. Rigging for shaft bearing replacement can include filling the vat and floating the drum up to gain access and clearance.

CHAPTER 21 - SAFETY CONSIDERATIONS



Chapter 21 Summary
(Narrated by Ron Richard, RE Consulting)



Absorber Access Safety First
(Narrated by Tony Licata, Babcock Power)

All of the typical generating station safety considerations apply to the FGD system. But due to the equipment and the chemicals present, the FGD system has some specific safety considerations of which all the station personnel may not be aware.

This chapter discusses these specific safety considerations and what must be done to address them.

21.1 Lime

Lime is very reactive with moist human tissue and can cause severe burns. Respiratory and eye protection should be worn when handling lime. Also, lime will cause burns if it comes in contact with sweaty, moist skin. Contact your lime supplier for an MSDS for quicklime to obtain more details.

The operating temperature of a lime slaker is typically over 180ºF, so thermal burns are a hazard when one is working near a lime slaker.

21.2 Absorbers/Slurry Tanks

Most of these vessels fall within the definition of a confined space, so proper procedures must be followed when entering them. Calcium sulfite in scrubber slurry has the capacity to react with oxygen as it converts to calcium sulfate. Care should be taken when entering a vessel that contains slurry. Monitoring for oxygen content before entering the vessel is prudent.

Sulfate reducing bacteria can live in stagnant sludge deposits in the bottom of vessels. They will appear as black slimy deposits within the sludge. A byproduct of their growth is poisonous hydrogen sulfide gas. As these deposits break up, this gas can be released and one may notice its “rotten egg” odor. This gas can cause paralysis of the lungs, so proper procedures and protective equipment should be used when this gas may be present.

Proper ladders, scaffolding, man lifts, and fall protection should be used when working on slurry spray headers and nozzles.

21.3 Ducts and Duct Drains

Liquid pools that collect on duct floors and fill duct drains can be very acidic in nature. This low pH liquid can burn skin and eyes.

21.4 Thickeners

Large amounts of torque are required to turn the thickener rake. Make sure that the rake is not bound up in the sludge bed and that all torque is released from the drive train before starting any work on the thickener rake arms or gearbox.

Sulfate reducing bacteria can live in stagnant sludge deposits in the bottom of vessels. They will appear as black slimy deposits within the sludge. A byproduct of their growth is poisonous hydrogen sulfide gas. As these deposits break up, this gas can be released and one may notice its “rotten egg” odor. This gas can cause paralysis of the lungs, so proper procedures and protective equipment should be used when this gas may be present.

Thickener tunnels should have sufficient ventilation. Thickener tunnels are subject to flooding should a thickener underflow pipe rupture. It is prudent to have more than one direction of exit from the area directly under the thickener, as well as emergency lighting in thickener tunnels in case of a power failure and the loss of normal lighting.

21.5 Conveyor Belts/Belt Vacuum Filters

Rope pull devices to stop the conveyor belt should be located within easy reach the entire length of each belt. Belt vacuum filters are considered conveyers and are designed for code compliance.

21.6 FGD Sludge Deposits

Dewatered slurry can leave sludge deposits in the bottom of tanks and thickeners, in drain trenches, or in pond areas. A gypsum deposit is usually more stable and not as dangerous.

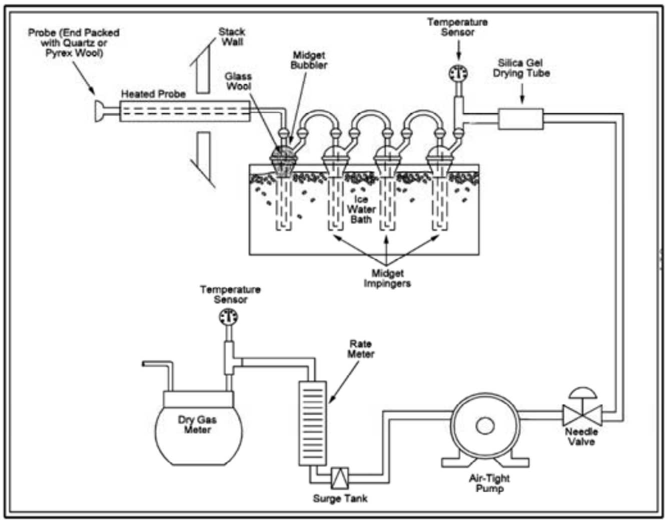
If the deposit contains significant calcium sulfite, the danger increases. Calcium sulfite solids are thixiotropic in nature. Another material that is thixiotropic in nature is commonly referred to as “quick sand”. One should not attempt to walk or drive across a sludge deposit, no matter how dry it may look, without extreme caution. A thixiotropic material will become more liquid as force is applied to it. The greater the force or the more often the force is applied, the more liquid it will become.

If one takes a handful of dry looking thixiotropic material and squeezes is rapidly and repeatedly in one’s fist, it will become very wet looking and some of it will tend to squeeze out of both sides of one’s fist.

21.7 Fire and Draft-Induced Smoke, Fumes or Ozone

- Materials of Construction that burn or emit toxic fumes.
- FGD maintenance activities carry downstream to stack inspection
- ESP maintenance activities carry downstream to FGD and stack.
- Duct isolation devices/procedures.
- Pump/piping isolations devices/procedures
- Fan Isolation

CHAPTER 22 - SAMPLING METHODS



22.0.1. SO2 Testing Sampling Train
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This chapter discussing SO_2 sampling methods will be added.

22.1 Sampling Methods

To be added

CHAPTER 23 - FUTURE CHAPTER TO BE ADDED

This is a future chapter is to be added

ABBREVIATIONS

AEGI - Amine Enhanced Gas Injection

AGR - Advanced Gas Reburning

AH-SCR - Air Heater Selective Catalytic Reduction

BACT - Best Available Control Technology

BOOS - Burners Out of Service

Btu - British thermal unit

CAAA90 - Clean Air Act Amendments of 1990

$CaCO_3$ - Calcium Carbonate (limestone)

CaO - Calcium Oxide (lime)

Cascade - SNCR/SCR Hybrid

$CaSO_3$ - Calcium Sulfite

$CaSO_4$ - Calcium Sulfate

$CaSO_4 \bullet 2H_2O$ - Gypsum

CCOFA - Closed-Coupled Overfire Air

CEM - Continuous Emissions Monitor

CFD - Computational Fluid Dynamics

CKM - Chemical Kinetic Model

CO - Carbon Monoxide

CO_2 - Carbon Dioxide

$CO(NH)_2$ - Urea

CR - Coal Reburning

CTR - Combustion Controls

DOE - Department of Energy

EPA - Environmental Protection Agency

EPRI - Electric Power Research Institute

ESP - Electrostatic Precipitator

FCC - Fixed Charge on Capital

FEGT - Furnace Exit Gas Temperature

FF - Fabric Filter

FGD - Flue gas Desulfurization

FLGR - Fuel Lean Gas Reburn

GR - Gas Reburn

H_2O - Water

H_2SO_3 - Sulfurous Acid

HSR - Hybrid Selective Reduction

IPPs - Independent Power Producers

kW - Kilowatt

kWh - Kilowatt hour

LAER - Lowest Achievable Emission Rate

L/G - Liquid to gas ratio

LNB - Low NOx Burners

LNCB - Low NOx Cell Burners

LNCFS - Low NOx Concentric Firing System

LOI - Loss of Ignition

MMBtu - Million Btu

MWe - Megawatt of Electrical Generation (generator gross output)

N_2 - Nitrogen

NGR - Natural Gas Reburn

NH_3 - Ammonia

NO - Nitric Oxide

NOx - Nitrogen Oxides (NO + NO_2)

NOxOUT® - SNCR Technology designed by Fuel-Tech N.V.

NSPS - New Source Performance Standards

NSR - New Source Review

NUG - Non-Utility Generator

O&M - Operation & Maintenance

OEM - Original Equipment Manufacturer

OFA - Over Fire Air

OLF - Operating Costs Levelization Factor

ppm - Parts per million

PRB - Powder River Basin Coal

RACT - Reasonably Available Control Technology

SCR - Selective Catalytic Reduction

SNCR - Selective Non-Catalytic Reduction

SOFA - Separated Overfire Air

SO_2 - Sulfur Dioxide

SO_3 - Sulfur Trioxide

SOx - Sulfur Oxides

TiO_2 - Titanium Dioxide

V_2O_3 - Vanadium Pentoxide

WO_3 - Tungsten Trioxide

GLOSSARY

Absorption - The operation in which one or more soluble components of a gas mixture are dissolved in a liquid.

Acid Rain - Precipitation containing harmful amounts of nitric and sulfuric acids formed primarily by nitrogen oxides and sulfur oxides released into the atmosphere when fossil fuels are burned. Acid rain has a pH below 5.6 which is slightly acidic.

Additive - Substance added to a liquid or gas stream to cause a chemical or physical reaction to enhance SO_2 sorption.

Adipic Acid – An organic acid used as a performance enhancing chemical in absorber towers.

Adsorption - The operation in which a solid substance retains on its surface a layer of gaseous or liquid substance by which gas molecules are selectively removed from a gas stream.

Allowance - One SO_2 allowance permits one ton of SO_2 emissions.

Anthracite - A hard, black lustrous coal, often referred to as hard coal, containing a high percentage of fixed carbon and a low percentage of fixed volatile matter. Anthracite contains approximately 22 million to 28 million Btu per ton.

Apex – The tip, point, vertex; the narrowest point at the bottom of a hydroclone or thickener.

Ash - Impurities consisting of silica, iron, alumina, and other noncombustible matter that are contained in coal. Ash content is measured as a percent by weight of coal on an "as received" or a "dry" (moisture-free, usually part of a laboratory analysis) basis.

Baghouse (Fabric Filter) - A fabric filter that collects the dry particulate matter as the cooled flue gas passes through the filter material

Ball Mill - Equipment used for pulverizing limestone as well as for slaking of lime. It consists of a rotating cylindrical or conical casing charged with metal balls or slugs along with water and the material to be pulverized or slaked.

Bituminous Coal - The most common coal. It is dense and black (often with well-defined bands of bright and dull material). Its moisture content usually is less than 20 percent. It is used for generating electricity, making coke, and space heating. The contents of bituminous coal range from 19 million to 30 million Btu per ton.

Blinding – Having no opening, closed at one end (such as covering the pores in a porous material).

Boiler - A device that generates steam for power. Heat from an external combustion source is transmitted to a fluid contained within the tubes in the boiler shell. This fluid is delivered at a desired pressure, temperature and quality.

Breeching – The rectangular opening in a chimney wall where a duct enters the chimney.

Btu (British Thermal Unit) - A standard unit for measuring the quantity of heat energy equal to the quantity of heat required to raise the temperature of 1 pound of water by 1 degree Fahrenheit.

Buffering – When a substance in solution has the ability to react with and neutralize large amounts of acid, thus preventing the pH from changing substantially with small additions of acid.

By-product - Saleable or usable product that has some economic value.

Cake – The layer of solids left on a filter cloth once the liquid has been drawn out of a slurry using vacuum.

Calcination – To change or burn to a powder using heat, such as changing limestone into lime in a kiln.

Centrifuge – A device which separates the phases in a composite fluid stream by applying centrifugal motion to the stream and forcing the higher density component to the outside wall of the device where it is collected.

Chimney Rain-out – A condition where moisture droplets leave a chimney plume and fall to the ground in the area around the chimney.

Clarifier – A large tank where slurries can be separated into a liquid stream and a solid stream. This is usually accomplished because the clarifier has a large volume that allows the dense solid particles to settle under the influence of gravity. The liquid steam exits the top of the clarifier and the more dense solid slurry is drawn from the bottom of the tank.

Coal - Low-sulfur - The EIA sulfur content category of coal with less than 0.60 pounds of sulfur per million Btu. Less than or equal to 1%.

Coal - Medium-sulfur - The EIA sulfur content category of coal with 0.60 to 1.67 pounds of sulfur per million Btu. Greater than 1% and less than or equal to 3%.

Coal - High-sulfur - The EIA sulfur content category of coal with greater than 1.67 pounds of sulfur per million Btu. Greater than 3%.

Colloidal – Having very small, insoluble, nondiffusible particles larger than molecules but small enough so that they remain suspended in a fluid medium without settling to the bottom.

Continuous Emission Monitor (CEM) - A device that approximates a continuous measurement of certain characteristics of a gas by making separate measurements frequently. For compliance with the CAAA90, the measurements must be taken at least every 15 minutes. Two common types are an Extractive Continuous Emission Monitor and an In Situ Continuous Emission Monitor.

Cyclone - A free vortex centrifugal separator that removes solids from liquids by combination of centrifugal force and liquid shear. Used in some systems to replace the liquid thickener/clarifier.

DBA (Dibasic Acid) – A mixture of organic acids (adipic acid, succinic acid, glutaric acid) used as a performance enhancing chemical in absorber towers.

Dead Band – In control circuits, the zone between the start of an action and when the action is reversed. This prevents the control action from cycling back and forth too quickly. In a home, the furnace starts when the temperature reaches a certain point. It continues to run until the temperature rises several degrees. This range of temperature is the dead band of the furnace control.

Density – The weight of a material divided by the volume of the material.

Dolomite – A mineral composed of calcium carbonate and magnesium carbonate found in limestone deposits. It has the chemical formula $CaMg(CO_3)_2$.

Dry FGD - An FGD process comprised of contacting a sulfur oxide containing flue gas with an alkaline material without saturating the flue gas and producing a dry waste product or dry by-product.

Durometer – A device for measuring the firmness of a material. A spring forces a small diameter foot into the material being tested. The amount of force required to push the foot down until the material is exerting the same force back is the Durometer reading measured on a scale specified by the size of the foot. Rubber is typically measured using the Shore A scale.

Electrostatic Precipitator (ESP) - A unit comprised of a series of parallel vertical plates through which the flue gas passes. It electrically charges the ash particles in the flue gas to collect and remove them.

Energy - Most of the world's convertible energy comes from fossil fuels that are burned to produce heat that is then used as a transfer medium to mechanical or other means in order to accomplish tasks. Electrical energy is usually measured in kilowatt-hours, while heat energy is usually measured in British thermal units.

Exothermic – A chemical change in which there is a liberation of heat, as in combustion.

Ex situ oxidation (wet FGD) - Forced oxidation that occurs outside of the scrubber and is used to produce FGD gypsum.

Extractive Continuous Emission Monitor - A CEM that draws exhaust gas away from the combustion system to the measurement equipment through special ducts.

Federal Energy Regulatory Commission (FERC) - A quasi-independent regulatory agency within the Department of Energy having jurisdiction over interstate electricity sales, wholesale electric rates, hydroelectric licensing, natural gas pricing, oil pipeline rates, and gas pipeline certification.

FGD Material - This wet thixiotropic sludge from limestone-based reagent wet scrubbing process is predominantly calcium sulfate dihydrate, which is gypsum. This material readily dewaters, and there are systems in use where the slurry is transported to a pond and construction equipment is used to excavate and stockpile the gypsum.

Filter Cake - The material produced by filtering equipment such as vacuum filters for dewatering wet FGD material.

Fixation - A process of stabilization of sludge involving the addition of reagents causing chemical reactions with the sludge, generally of a cementatious nature.

Flocculant - Charged polymers used in industry for clarifying suspensions. They cause suspended colloidal matter to aggregate, forming particles that are large enough to settle out under gravity.

Flue Gas Desulfurization Unit (Scrubber) - Equipment used to remove sulfur oxides from the combustion gases of a boiler plant before discharge to the atmosphere.

Fluoroelastomers - A class of synthetic rubber which provide extraordinary levels of resistance to chemicals, oil and heat, while providing useful service life above 200ºC. The outstanding heat stability and excellent oil resistance of these materials are due to the high ratio of fluorine to hydrogen, the strength of the carbon-fluorine bond, and the absence of unsaturation.

Fly Ash - Particulate matter from coal ash in which the particle diameter is less than .0001 meter. This is removed from the flue gas using flue gas particulate collectors such as baghouses and electrostatic precipitators.

Flywheel – A heavy wheel for regulating the speed and uniformity of motion of the machine to which it is attached.

Fossil Fuel - Any naturally occurring organic fuel, such as petroleum, coal, and natural gas.

Fouling - The formation of high temperature bonded deposits on convective heat absorbing surfaces.

Generating Unit - Any combination of physically connected generator(s), reactor(s), boiler(s), combustion turbine(s), or other prime mover(s) operated together to produce electric power.

Generation - Gross - The total amount of electric energy produced by the generating units at a generating station or stations, measured at the generator terminals.

Generation - Net - Gross generation less the electric energy consumed at the generating station for station to station use.

Generator Nameplate Capacity - The full-load continuous rating of a generator, prime mover, or other electric power production equipment under specific conditions as designated by the manufacturer.

Gigawatt (GW) - One billion watts of capacity.

Greenfield Unit - A newly constructed generating unit.

Grits – The hard, coarse particles that will not dissolve in a lime slaker and must be removed and disposed of.

Gypsum - Formed from forced oxidation in a calcium-based FGD process. Also, a precipitated gypsum formed through the neutralization of sulfurous acid (H_2SO_3) in FGD process at coal-fired power plants. This gypsum can vary in purity, which is defined as the percentage of $CaSO_4 \bullet 2H_2O$, and generally is over 94% for use in wallboard manufacturing.

Hardgrove Grindability Index (HGI) - A measure of the relative ease with which coal can be pulverized or ground. Higher grindability indicates coal which are easier to grind.

Hydrated Crystal – The natural form of many crystalline materials. Some water has been chemically combined in the crystal matrix.

Hydrated Lime – Calcium Hydroxide ($Ca(OH)_2$) that is formed by reacting quicklime and water in a lime slaker.

Hydroclone - A device for separating particles of varying densities in a liquid steam by spinning the liquid rapidly in a cyclonic manner and drawing off product steams at various locations in the cyclonic profile.

Hydrogen Sulfide – H_2S is a colorless highly toxic gas that is heavier than air and has a "rotten eggs" odor.

Hydroxyl Group - The term used to describe the functional group -OH when it is a substituent in an organic compound. Organic molecules containing a hydroxyl group are known as alcohols and have the formula $C_nH_{(2n+1)}$-OH, the simplest of which is methyl alcohol (CH_3-OH)

Hygroscopic – Attracting or absorbing moisture from the air.

In Situ Continuous Emission Monitor - A CEM that makes measurements directly in the flue or exhaust pipe.

In Situ Oxidation (wet FGD) - A process in which both SO_2 absorption and oxidation are carried out within the scrubber.

Kiln – A furnace or oven for drying, burning, or baking something.

Kilowatt (kW) - One thousand watts of capacity.

Kilowatt-hour (kWh) - One thousand watthours.

Landfill - A site for the disposal of all conducive wastes. Landfill configuration may be heaped, side hill or valley fill.

L/G - Liquid to gas ratio which is defined as the recirculated absorbent liquid flow rate (gpm) divided by the absorber outlet gas flow rate (acfm/1000).

Lignite - A brownish-black coal of low rank with high inherent moisture and volatile matter (used almost exclusively for electric power generation). It is also referred to as brown coal. Lignite contains approximately 9 million to 17 million Btu per ton.

Low-NO_x Burners - Burners that utilize special arrangements of fuel and air injection ports, which reduce the formation of NO_x during combustion.

Maintenance Costs - Maintenance costs are the portion of operating expenses consisting of labor, materials, and other direct and indirect expenses incurred for preserving the operating efficiency and/or physical condition of utility plants used for power production, transmission, and distribution of energy.

Mandrel – A large rotating circular form used as a core around which glass fiber covered with resin is wound creating a cylinder of fiberglass reinforced plastic (FRP)

Megawatt (MW) - One million watts of capacity.

Megawatt-hour (MWh) - One million watt-hours of electric energy.

Mist Eliminator - That part of an absorber designed to remove entrained liquid droplets from the exiting gas stream.

Nacolite – A natural mineral form of sodium carbonate used in sodium scrubbing or converted into Soda Ash.

Non-Regenerable FGD - Process that consumes the sorbent.

Opacity - The degree of imperviousness to the passage of light.

Operations Costs - Operations costs are the components of power production that incur cost for operations that are directly related to producing electricity. The major item is almost always fuel that has to be burned to generate electricity.

Oxidation - When oxygen is added to a material to chemically transform it into a different material.

Oxidation - Forced - An additional unit operation to a wet FGD process that intentionally oxidizes the sulfite specie to sulfate by the introduction of supplemental air or catalysts or both.

Oxidation - Natural - That which results from the reaction of absorbed sulfite specie with dissolved oxygen originating from flue gas and incidental contact with atmospheric oxygen.

Permeability – The property of being open to the passage or penetration of gas or liquid through a material.

pH - A measure of acidity or alkalinity that ranges from 0 to 14. A pH measurement of 7 is regarded as neutral. Measurements below 7 indicate increased acidity, while those above indicate increased alkalinity.

Pitting – An extremely localized form of corrosion that leads to the formation of small holes in metal.

Plant-Use Electricity - The electric energy used in the operation of a plant.

Plume Rise – As flue gas exits a chimney, it is desirable for it to be buoyant and continue to rise rather than fall back towards the chimney creating a mushroom shaped cloud. Heat is sometimes added to increase buoyancy or a restriction at the chimney exit is added to increase exit velocity and insure proper plume rise.

PPM – The concentration of one material mixed with another material expressed in parts per million. A 3 ppm solution of salt in water would be 3 pounds of salt added to one million pounds of water.

Precipitate – To cause a slightly soluble substance to become insoluble and separate out of a solution.

Pulverizers - Mills of various designs used to finely grind the coal which is swept from the mills by air for pneumatic transport directly to the burners.

Quarry – A place where stone is excavated.

Quicklime – Calcium Oxide (CaO) that has been produced by a calcination process where crushed limestone is fed through a kiln and the heat of the kiln drives the carbon dioxide (CO_2) from the limestone ($CaCO_3$).

Reagents – Pure forms of chemicals that are added to a process to react with other chemicals in the process to form reaction byproducts.

Reduction - When oxygen is removed from a material to chemically transform it into a different material.

Regenerable FGD - Process that regenerates and recycles the sorbent.

Reheat - A heat transfer process by which the absorber outlet flue gas temperature is increased for the purpose of increasing plume buoyancy, reducing a visible plume, or preventing downstream corrosion.

Residence Time - The time period for a given volume of liquid or gas throughput to pass through a vessel. When referred to an absorber, it is defined as the absorber's internal volume through which gas passes (cu. ft.) divided by the absorber outlet flue gas flow rate (acfs).

Retention Tank - Provides residence time for the absorbent recirculation flow for the purpose of allowing sufficient time to complete chemical reactions.

Scale – Any thin, flaky or plate like layer or coating which forms on the inside of metal containers.

SCFM - Gas flow rate in terms of cubic feet per minute measured at the standard conditions of 70ºF and one atmosphere pressure.

Scrubber - Any of several forms of chemical/physical devices that remove sulfur compounds formed during coal combustion and especially from coal-fired power plants.

Scrubber Sludge - Another name for wet FGD material

Set Point – In a control circuit, the value when an action by the control system will be initiated.

Sinusoidal - Moving in simple harmonic motion according to the function A sin (2 π f t) where A is the amplitude of the wave, f its frequency, and t is time.

Slagging - The formation of molten, partially fused resolidified deposits on furnace walls or other surface exposed to radiant heat.

Slaker – A device to mix quicklime and water in such a manner as to cause a chemical reaction producing calcium hydroxide.

Slurry - A mixture of liquid suspended solids (e.g. recycle slurry, lime slurry).

Soda Ash – The manufactured form of sodium carbonate used in sodium based scrubbing.

Soluble – Can be dissolved; capable of passing into solution.

Specific Gravity – The ratio obtained by taking the density of a volume of a material and dividing it by the density of the same volume of water.

Stabilization - The addition of fly ash, soil or other similar material to induce physical changes without chemical interaction between the additive and the sludge.

Stoichiometry - The ratio of how much lime or limestone was added to the scrubber to remove a quantity of SO_2 divided by the theoretical amount of lime or limestone that should have been used to remove that same quantity of SO_2.

Sub bituminous Coal - A dull black coal of rank intermediate between lignite and bituminous. The contents of sub bituminous coal ranges from 16 million to 24 million Btu per ton.

Sulfate Reducing Bacteria - A group of anaerobic bacteria (i.e. don't need oxygen) that obtain energy from iron or sulfur and generate hydrogen sulfide (H_2S).

Sulfate Saturation - The maximum concentration of the sulfate ion per unit volume of slurry or solution, above which the sulfate specie crystallizes as an alkali or earth alkali salt.

Sulfur - One of the elements present in varying quantities in coal which contributes to environmental degradation when coal is burned.

Tadpole Tape – A gasket material that has a flat cross section with a large bulbous section attached to one edge. It gets its name since this cross section looks like a tadpole.

Temperature - Adiabatic Saturation - The temperature, below which for a given mixture of gas and vapor, no additional vapor can be added at specified conditions (partial pressure of vapor is equal to vapor pressure of the liquid at the gas-vapor mixture temperature).

Temperature - Approach - The difference between the actual temperature of a given gas-vapor mixture and the adiabatic saturation temperature of that gas-vapor mixture.

Temperature - Spray Down - The difference between the inlet and outlet temperature of flue gas passing through an absorber.

Thickener – A large diameter vessel with a conical bottom used to separate solids from a liquid using the principal of gravity settling in a large still volume of liquid.

Thiosulfate – The ion S_2O_3 which is a strong reducing agent. In the photographic process, it dissolves the silver salts and is known as a fixer in developing films and prints.

Thixiotropic – A thixiotropic material is one that becomes more liquid as higher shear stresses are applied to it. When the stresses are removed, the material behaves more like a solid.

Trona – A natural mineral form of sodium carbonate used in sodium scrubbing or converted into Soda Ash.

Utilization - A measure of the extent to which the alkali added to the absorber reacts with SO_2.

Vacuum Filter - A mechanical continuous dewatering device, usually of a rotary drum design, which draws air and filtrate through a filter cloth coated with cake or sludge to be dewatered.

Valeric Acid – An organic acid produced by the degradation of dibasic acid in an absorber tower. Valeric acid can have a noticeably unpleasant odor.

Viscosity – The internal fluid resistance of a substance, caused by molecular attraction, which makes it resist a tendency to flow. Water has a low viscosity, tar has a high viscosity.

Vulcanization - A chemical process in which individual polymer molecules are linked to other polymer molecules by atomic bridges. The end result is that the springy rubber molecules become locked together to a greater or lesser extent. This makes the bulk material harder, much more durable and also more resistant to chemical attack. It also transforms the surface of the material from a sticky feel to a smooth soft surface which does not adhere to metal or plastic substrates.

Waste Product - Waste material that has little or no economic value and must be disposed.

Watt-hour (Wh) - An electrical energy unit of measure equal to 1 watt of power supplied to, or taken from, an electric circuit steadily for 1 hour.

Wet/Dry Interface – The zone at the absorber tower inlet where the hot flue gas first comes in contact with the slurry droplets.

Wet FGD - An FGD process comprised of contacting a sulfur oxide containing flue gas with a SO_2 sorbent liquid, saturating the flue gas, and producing a wet waste product or wet by-product.