Worldwide Pollution Control Association

ESKOM Scrubber Seminar

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Overview of Basic Types and Configuration of Wet Scrubber Technologies

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Marsulex Environmental Technologies

1. Overview of WFGD Processes

2. Comparison of Processes

3. Typical FGD Processes

4. Major Components

5. Factors Affecting Performance

6. Summary

1. Overview of WFGD Processes

Reagents

- All require use of an alkaline chemical “reagent”
  - Limestone
  - Lime
  - Ammonia

Byproducts

- All convert gaseous SO_2 to either liquid or solid waste byproduct
  - Throwaway process
  - Gypsum process
  - Regenerative process
  - Fertilizer product process

2. Comparison of Processes

Limestone Systems

Reactions taking place in absorber & recycle tank:

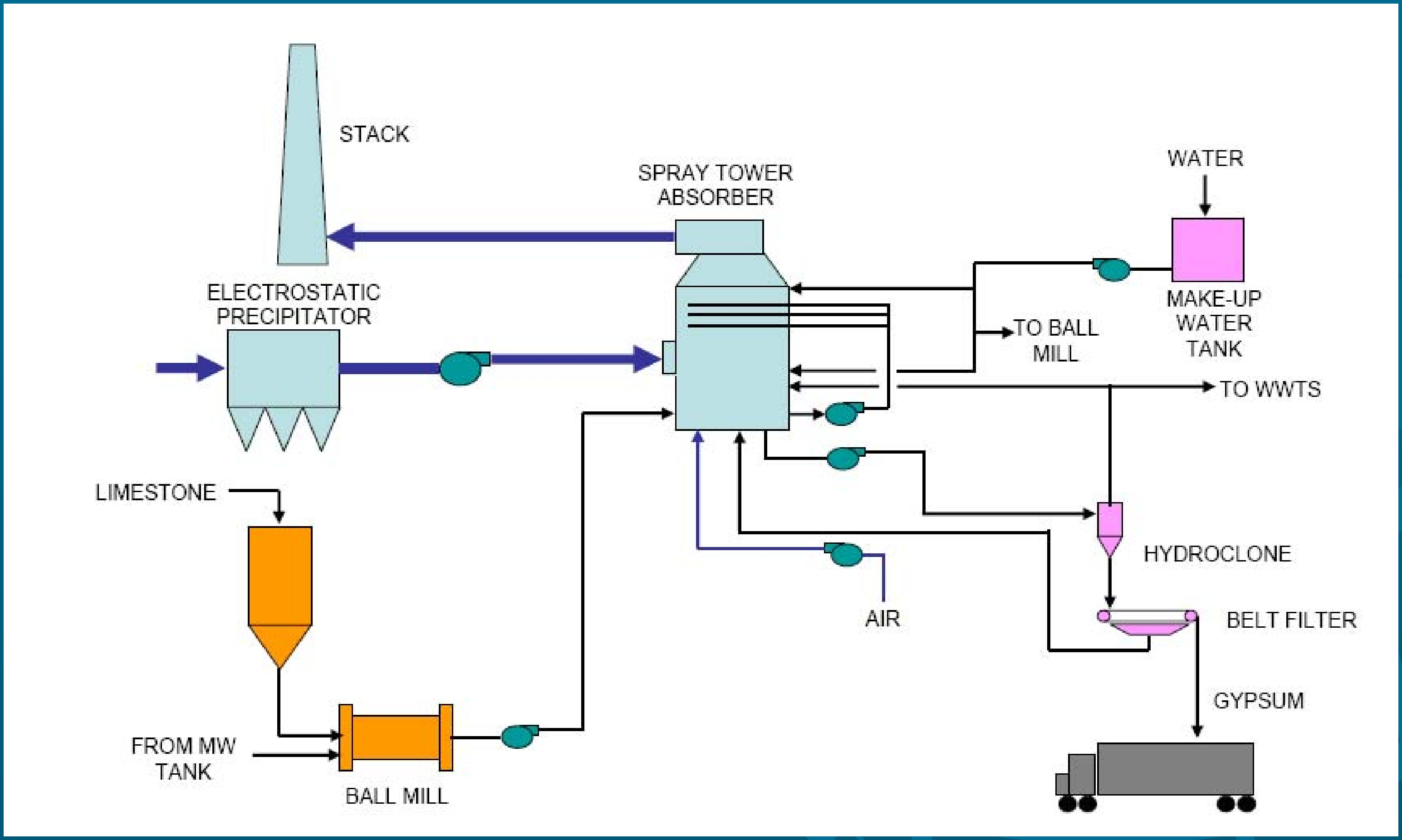
1. $SO_2 + H_2O$	$\longleftrightarrow$	H_2SO_3	*Absorption*
2. $CaCO_3 + H_2SO_3$	$\longrightarrow$	$CaSO_3 + CO_2 + H_2O$	*Neutralization*
3. $CaSO_3 + \frac{1}{2}\ O_2$	$\longrightarrow$	$CaSO_4$	*Oxidation*
4. $CaSO_3 + \frac{1}{2}\ H_2O$	$\longrightarrow$	$CaSO_3 \ + \frac{1}{2} H_2O$	*Crystallization*
5. $CaSO_4 + 2H_2O$	$\longrightarrow$	$CaSO_4 \cdot 2H_2O$	*Crystallization*

Lime Systems

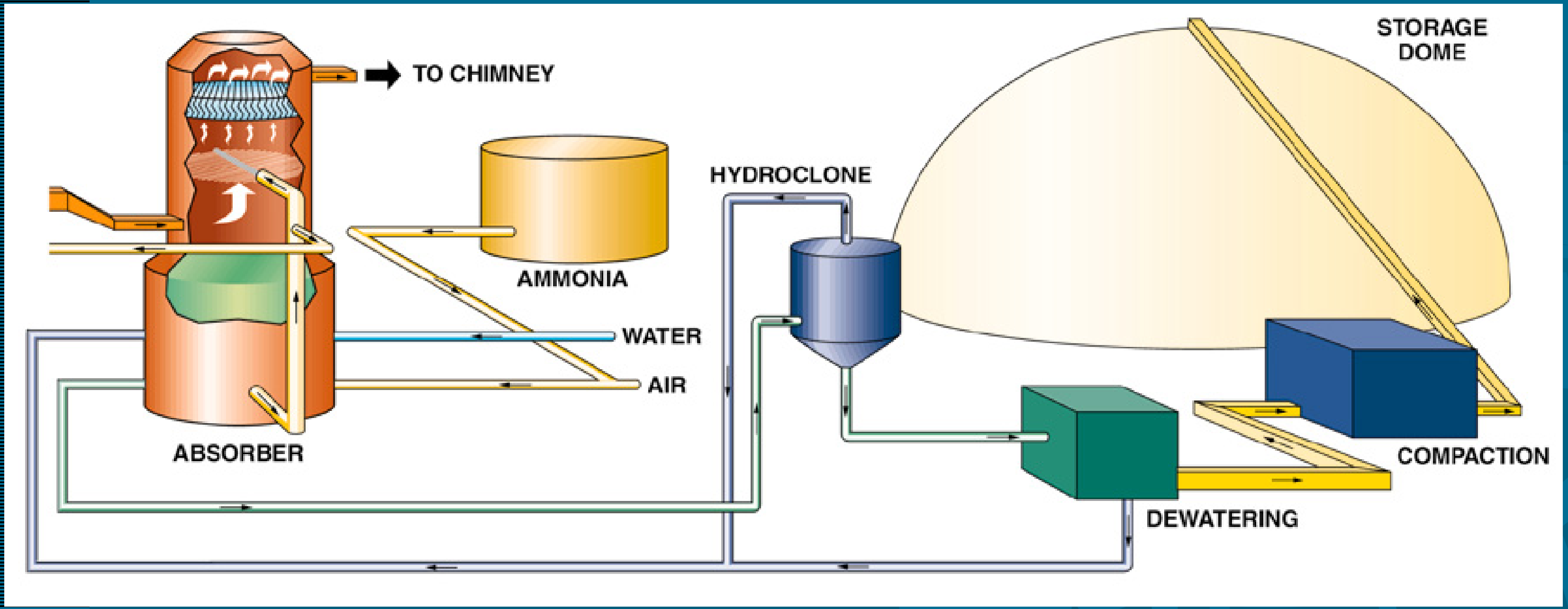
Reactions taking place in absorber & recycle tank are very similar to those in the limestone system. The main chemical differences are:

(2) $CaO + H_2O$	$\longrightarrow$	**$Ca(OH)_2$**	**Slaking**
(3) $H_2SO_3 + Ca(OH)_2$	$\longrightarrow$	**$CaSO_3 + 2H_2O$**	**Neutralization**

Typical Limestone FGD



Ammonia-Based WFGD System



Ammonia WFGD Process

$$SO_2 + 2NH_3 + H_2O \longrightarrow (NH_4)_2SO_3 \quad (1)$$

$$(NH_4)_2SO_3 + 1/2\ O_2 \longrightarrow (NH_4)_2SO_4 \quad (2)$$

- For every pound of SO_2 removed:
  - Need one-half pound Ammonia
  - Produces two pounds of Ammonium Sulfate
- One pound of Ammonia generates four pounds Ammonium Sulfate

4:1 product / feed ratio generates favorable economic leverage

Advantages of Ammonia Systems

1. Reduced Fuel Cost
2. Increased Load Factor
3. Production of high value byproduct

3. Typical FGD Processes

Typical WFGD Processes

1. SO_2 Outlet Emissions
2. pH and Stoichiometry
3. Liquid-to-Gas Ratio
4. SO_2 Inlet Concentration
5. Residence Time
6. Mist Elimination

SO_2 Outlet Emissions

- Allowable SO_2 outlet emissions are based on either maximum outlet level or on overall system SO_2 removal efficiency
- Requirements dictated by environmental regulations
- Depending on requirements, absorbers may be designed to treat all or only a portion of flue gas

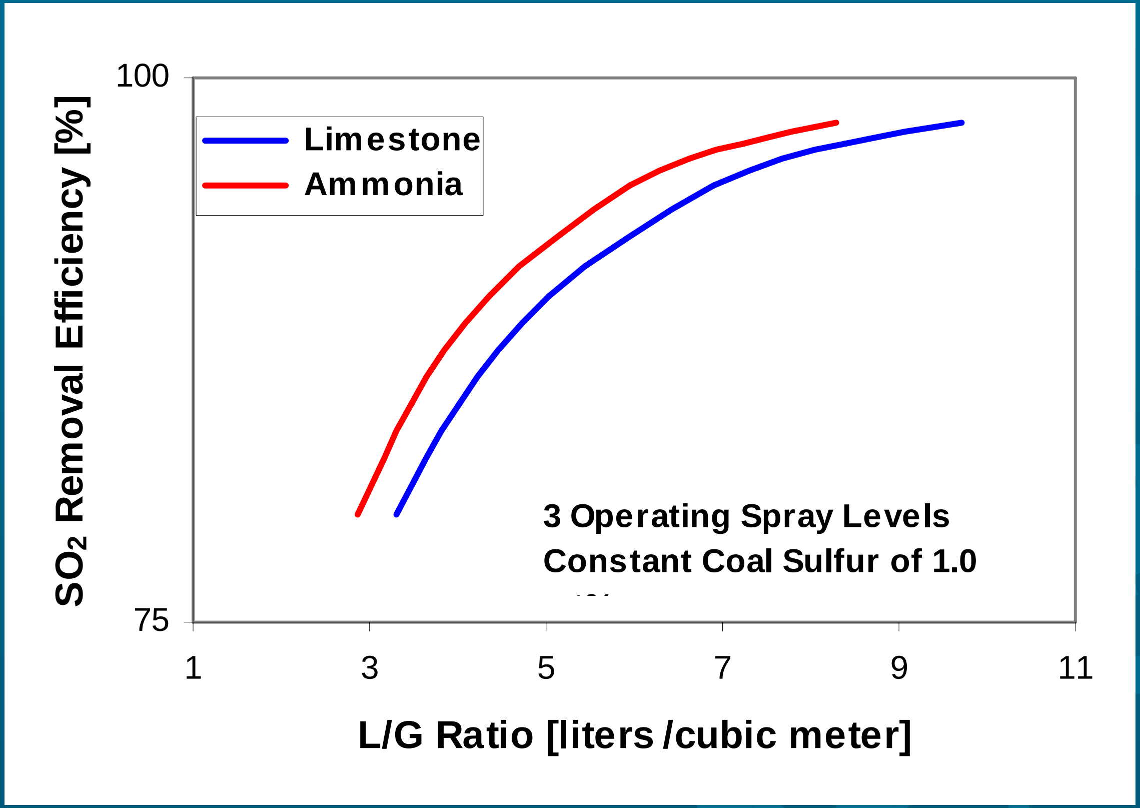
pH and Stoichiometry

- Slurry pH is likely the most important control variable for absorber operation
- pH determines amount of reagent used
- pH is related to reagent stoichiometry – the number of mols of reagent added per mol of SO_2 removed.

Liquid-to-Gas Ratio

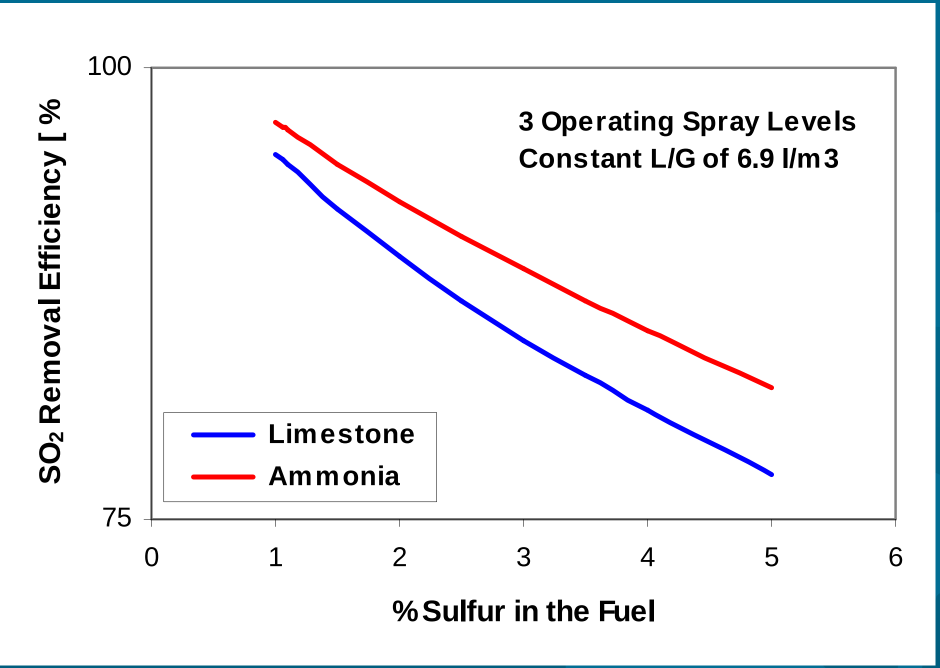
- L/G is the ratio of recycle slurry (in l/hr) to absorber outlet gas flow (m^3/hr, actual)
- The amount of surface system available for reaction with SO_2 is determined by L/G
- L/G ratio can be changed by altering either recycle flow rate or flue gas flow rate
- Liquid flow is typically varied by changing the number of operating recycle pumps

Liquid-to-Gas Ratio



The maximum flue gas velocity sets the absorber vessel diameters and impacts the ability of the mist eliminators to prevent droplet carryover.

SO_2 Inlet Concentration



- At constant operating conditions, increasing the concentration of SO_2 (increasing the sulfur content of the fuel) will decrease SO_2 removal
- Increased SO_2 concentration causes an increased depletion of liquid phase alkalinity

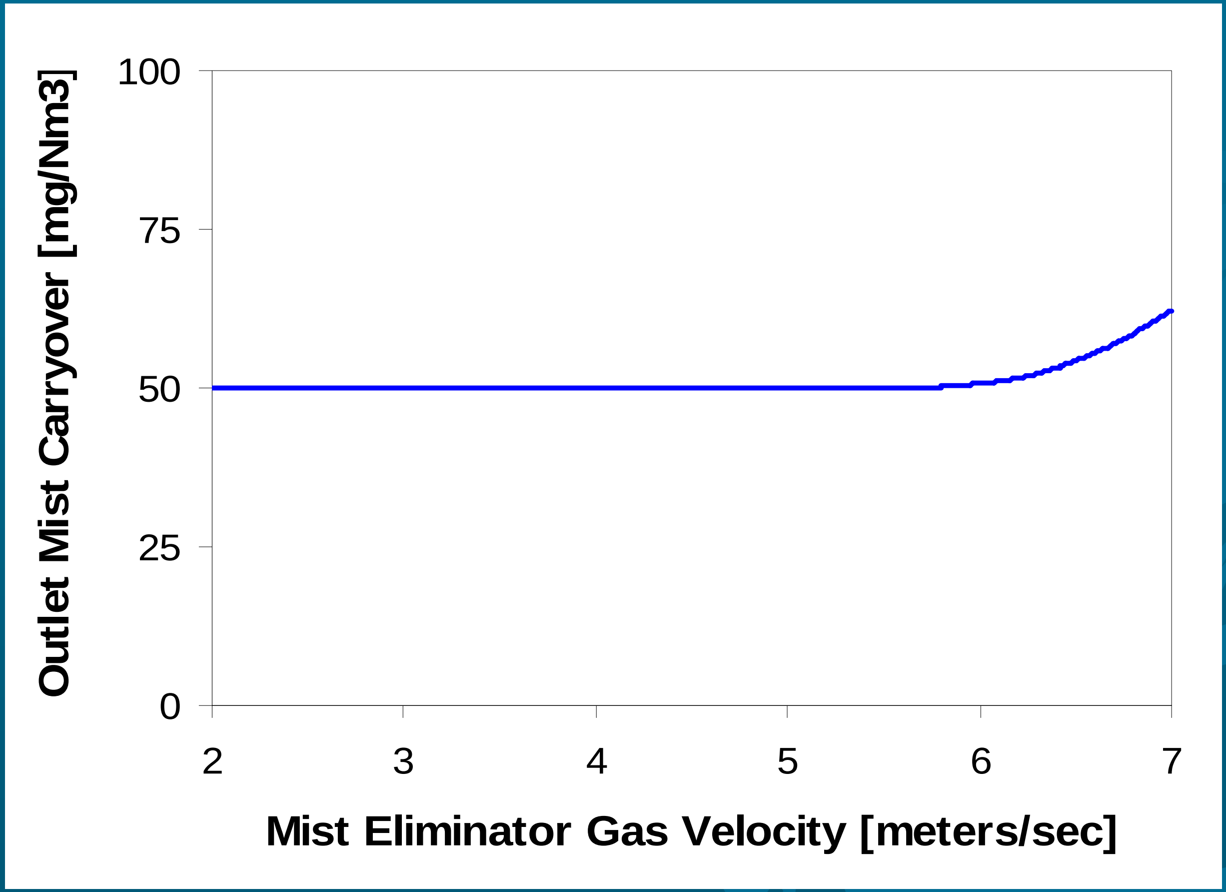
Residence Time

- Residence time – the time that slurry spends in the reaction tank before being recycled for further SO_2 absorption
- Residence time allows the liquid to desupersaturate and avoid scaling in lime/limestone systems
- Typically, for limestone systems, a residence time of 3-5 minutes is provided

Mist Elimination

- Important to remove entrained liquid droplets in order to avoid carryover of the liquid into downstream ducts and stack.
- Good performance of mist eliminators depends on:
  - Operation of absorber at flue gas velocities below critical velocity at which re-entrainment of mist occurs
  - Proper washing techniques

Mist Elimination



Mist Elimination

- Major parameters to be considered for proper mist eliminator washing include:
  - – Wash water rate
  - – Water quality
  - – Timing sequence
  - – Washing area coverage
  - – Nozzle pressure
  - – Nozzle spray angle

Other Areas of Importance

1. Water Balance
2. Forced Oxidation
3. Stack Gas Reheat
4. Primary Dewatering
5. Secondary Dewatering

Water Balance

- Due to water management restraints, utility plant operation will benefit if the WFGD system is designed to:
  - Minimize the consumption of fresh water
  - Maximize the consumption of plant waste water
- WFGD systems consume (lose) water by
  - Evaporation
  - Disposal of Byproduct

Forced Oxidation

- Both gypsum and ammonia processes require that most of the sulfite salt crystals be converted to sulfate salt crystals by means of oxidation.
- This is accomplished by injecting compressed air into the reaction tank.
- The degree of oxidation is based on:
  - Air stoichiometry (rate of oxidation air to SO_2 removed)
  - Depth of the air sparger below liquid level
  - pH in the reaction tank

Stack Gas Reheat Systems

- Two approaches are used to address the corrosive nature of wet scrubber carryover, stack gas reheat and stack lining
- Reasons for using reheat
  - Prevention of condensation and subsequent corrosion in downstream equipment such as ducts, dampers, fans and stack
  - Prevention of the formation of a visible plume
  - Enhancement of plume rise and therefore pollutant dispersion

Primary Dewatering

- First stage of dewatering of slurry byproduct
- Limestone systems – increases solids concentration from 15-20% to 40-60% solids by weight
- Ammonia systems – increases suspended solids from 4-6% to 15%
- Hydroclones are typically supplied for modern units rather than thickeners

Primary Dewatering

- Advantages of Hydroclones
  - Lower capital costs
  - Better dewatering (higher underflow percent solids)
  - Higher reliability
- Disadvantages of Hydroclones
  - The overflow is not as clear as thickener overflow
  - Without the use of an underflow tank, there is no surge capacity between the hydroclone and the secondary dewatering system.

Secondary Dewatering Systems

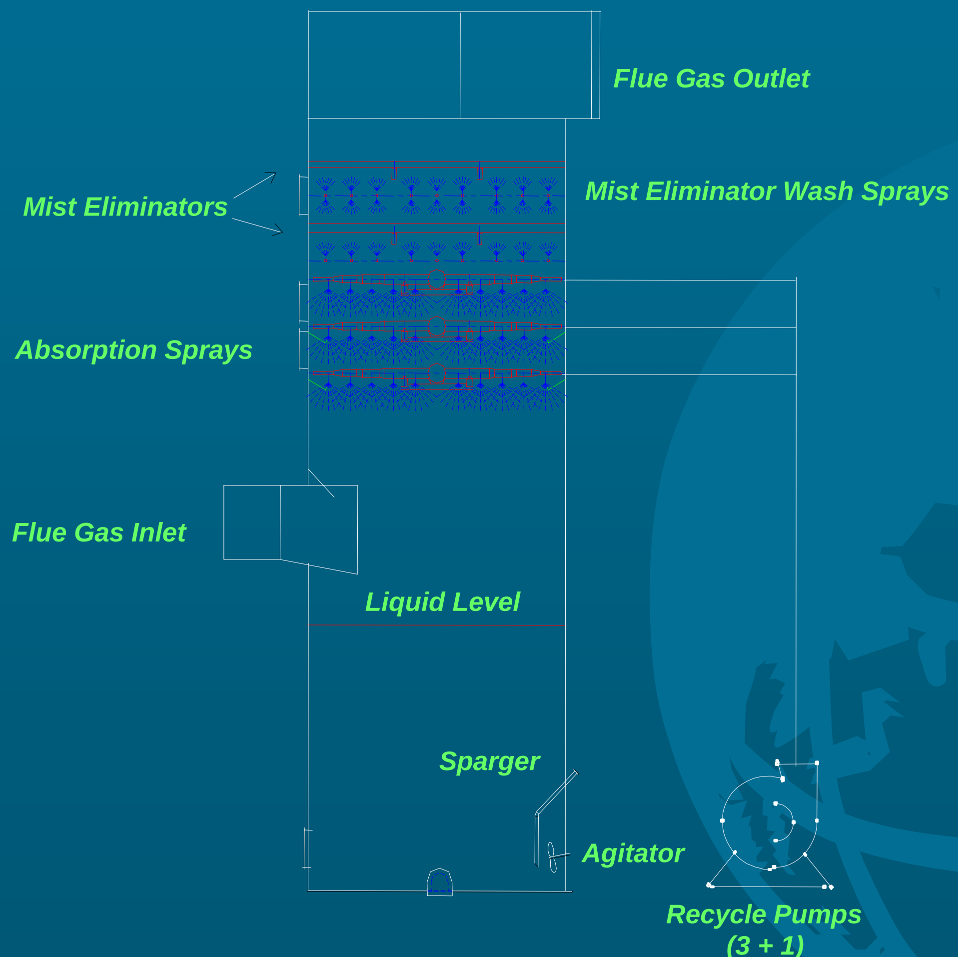
- Final stage of solids-liquid separation
- Limestone systems – either vacuum filters or centrifuges used
- Ammonia systems:
  - Second set of hydroclones along with a centrifuge for raw product
  - Additional dryer
  - Compactor for granular product

4. Major Components

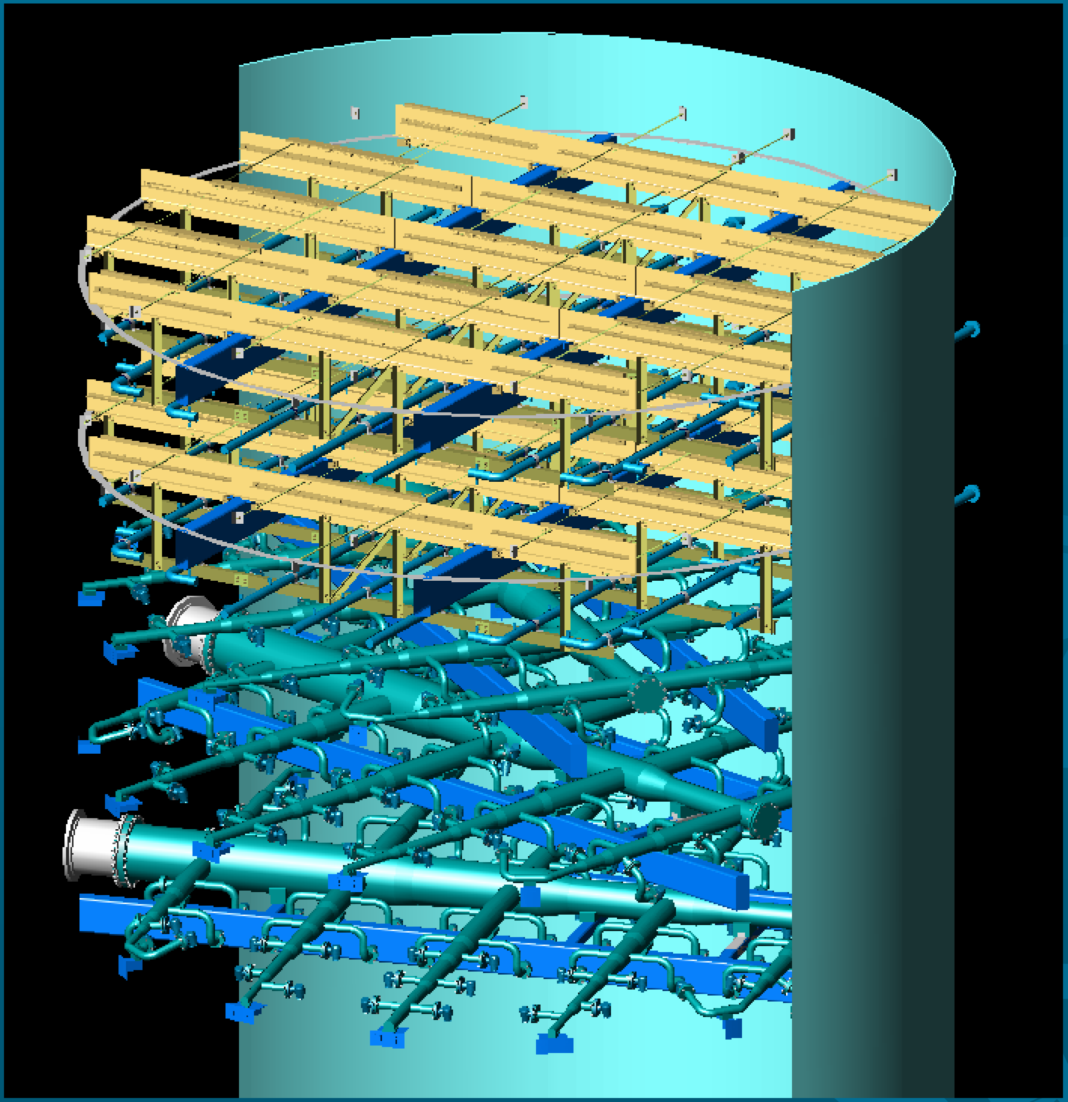
Absorbers – Traditional Reagents

1. Spray Absorbers – Open Tower
2. Tray Towers
3. Packed Towers
4. Jet Bubbling Reactors
5. Wulff Process

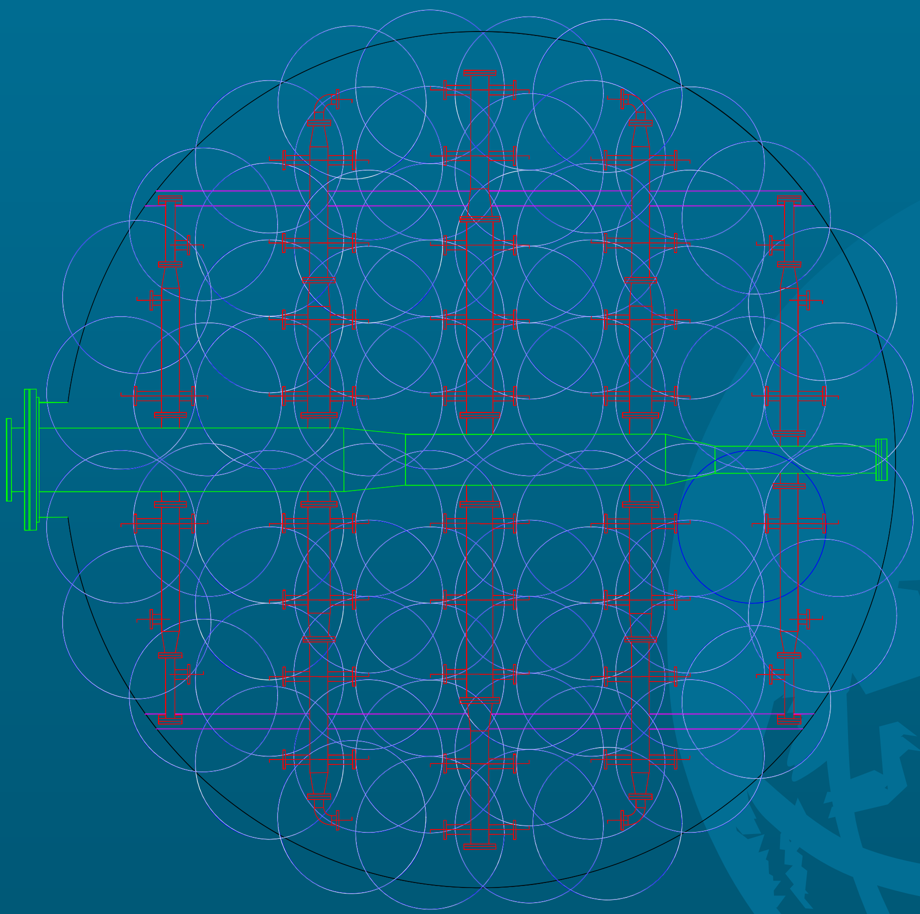
Spray Absorbers



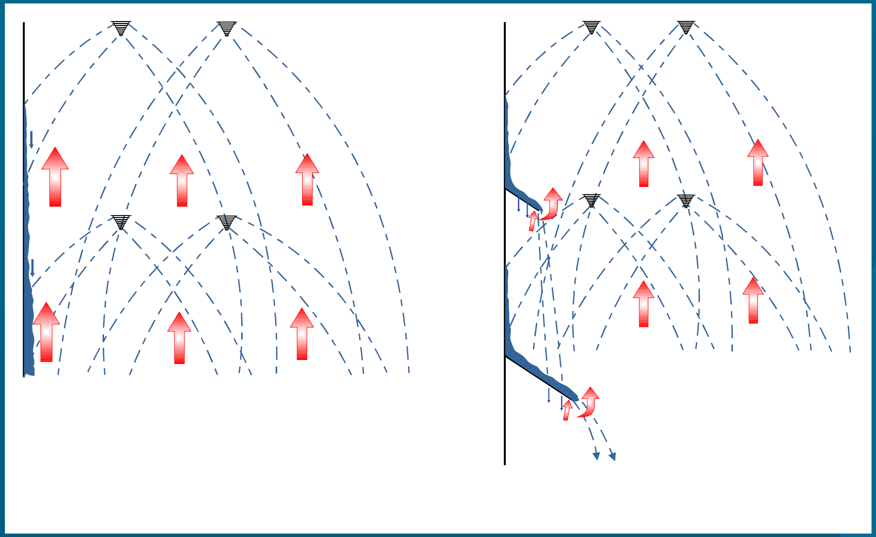
Isometric of “Open” Spray Tower

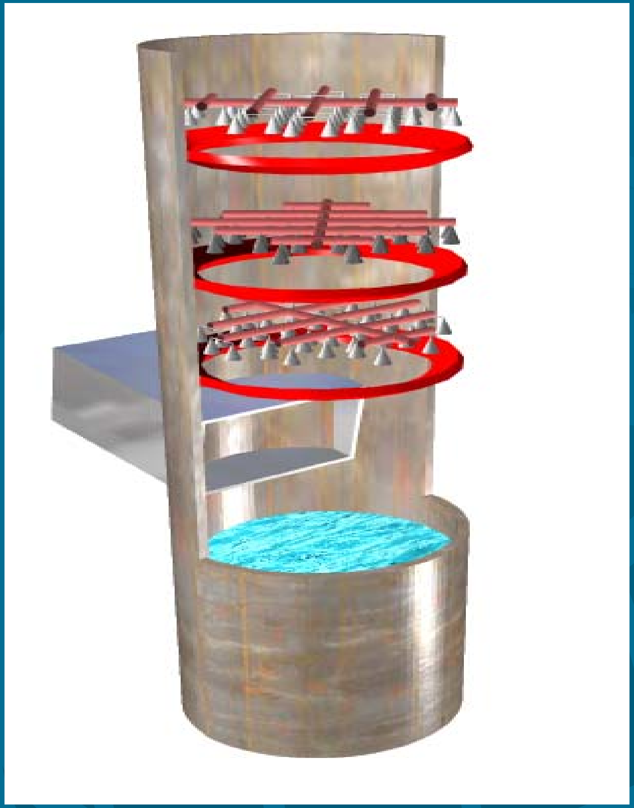


Typical Spray Pattern

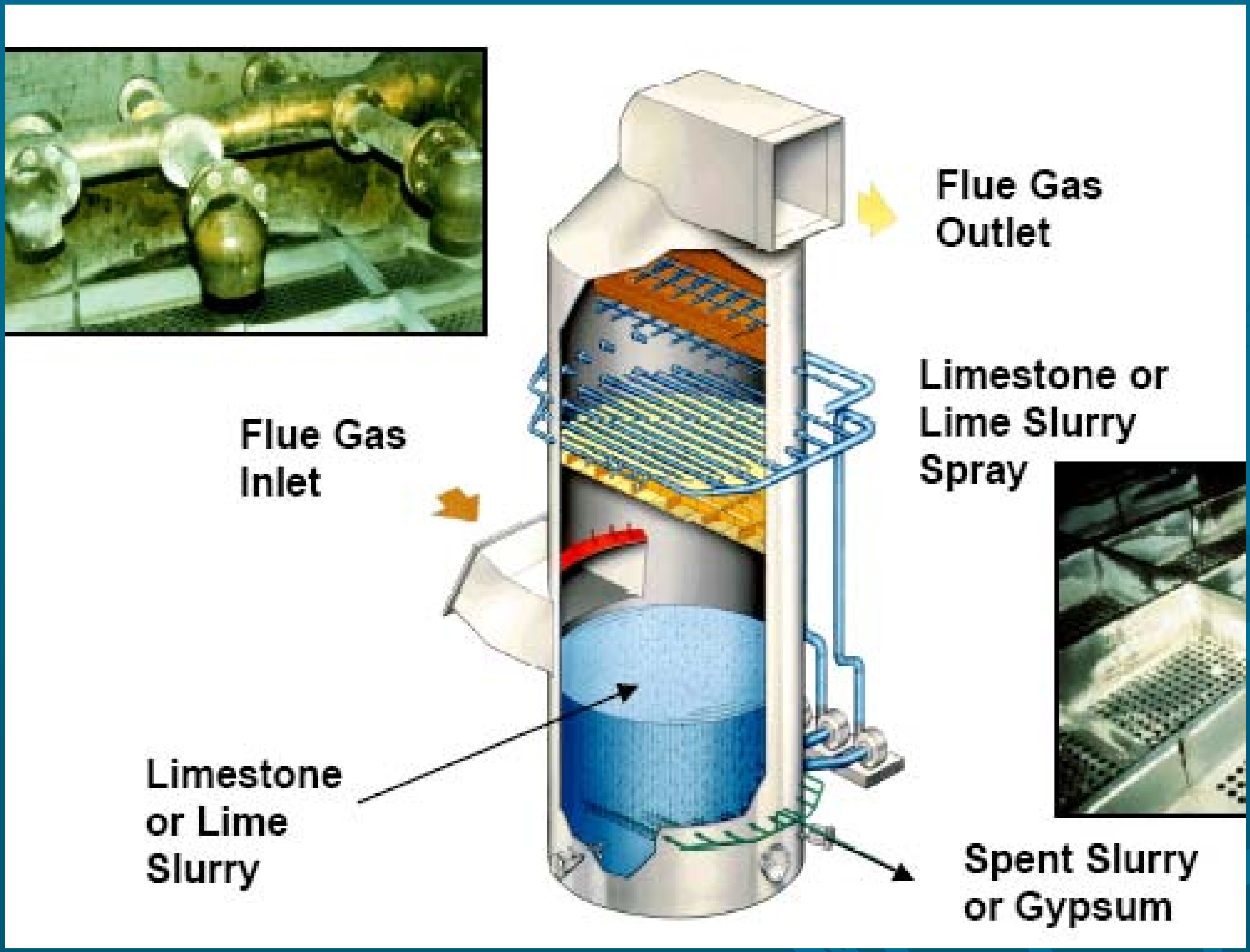


Wall Slip Phenomenon

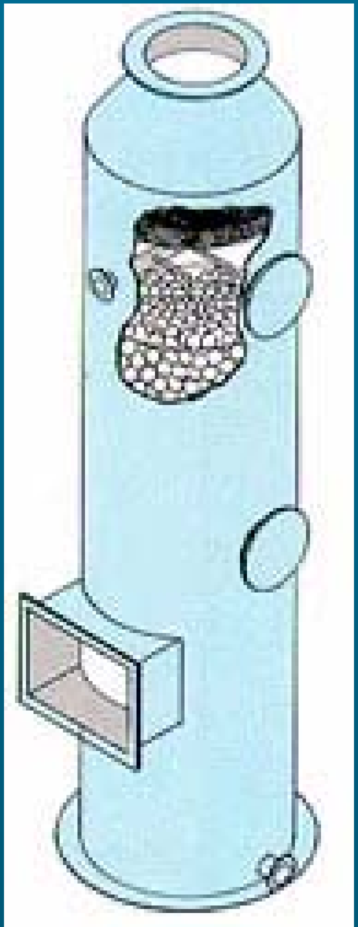




Tray Towers

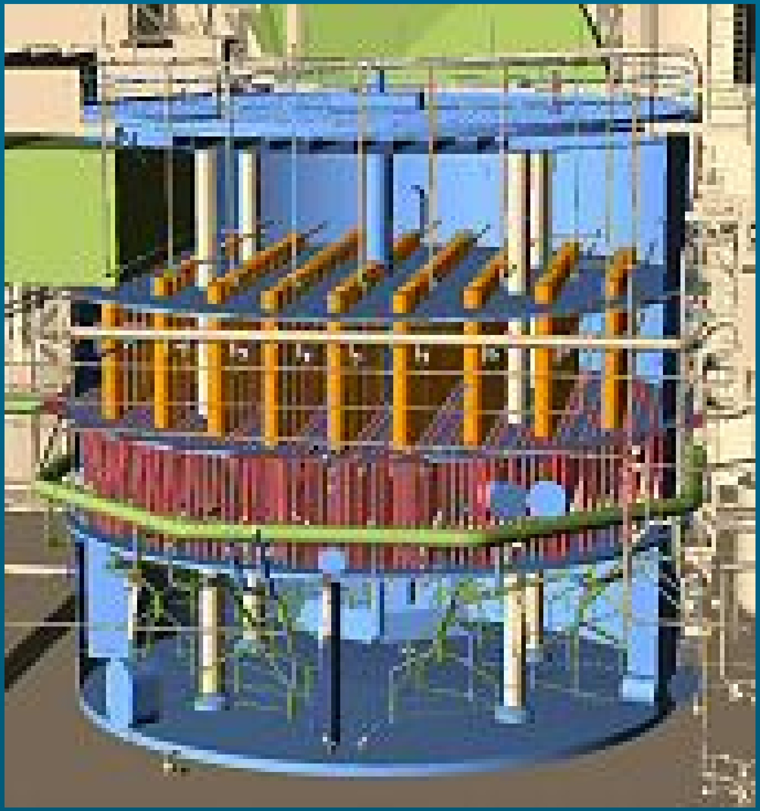

Flue Gas
Outlet
Limestone or
Lime Slurry
Spray
Flue Gas
Inlet
Limestone
or Lime
Slurry
Spent Slurry
or Gypsum

Packed Towers



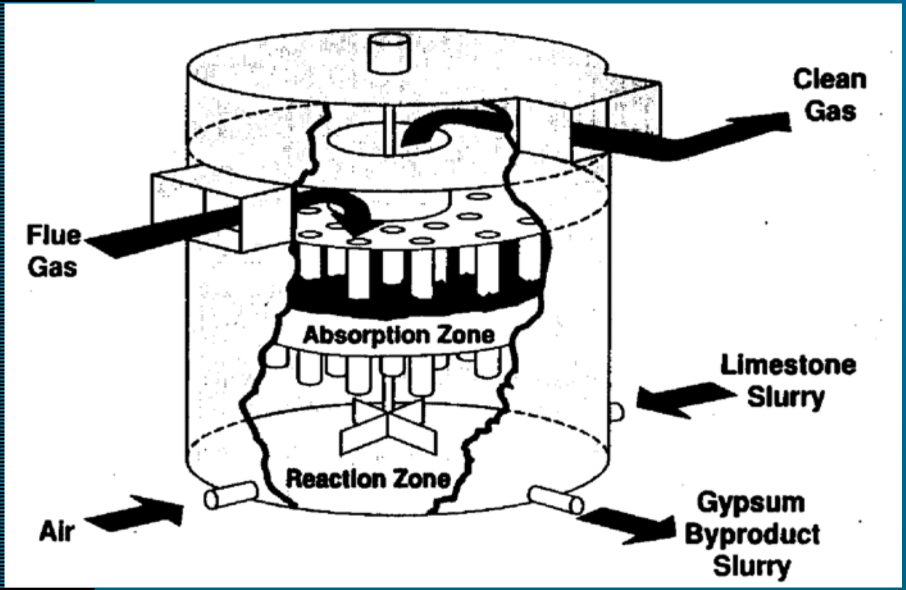
- Gas enters the base of the tower and passes up through the packing countercurrent to the scrubbing liquor which is introduced at the top of the tower.
- The liquid is dispersed by means of inert, stationary or molded packings of various shapes and configurations designed to add surface area and thus promote maximum vapor-liquid contact.

Jet Bubbling Reactor



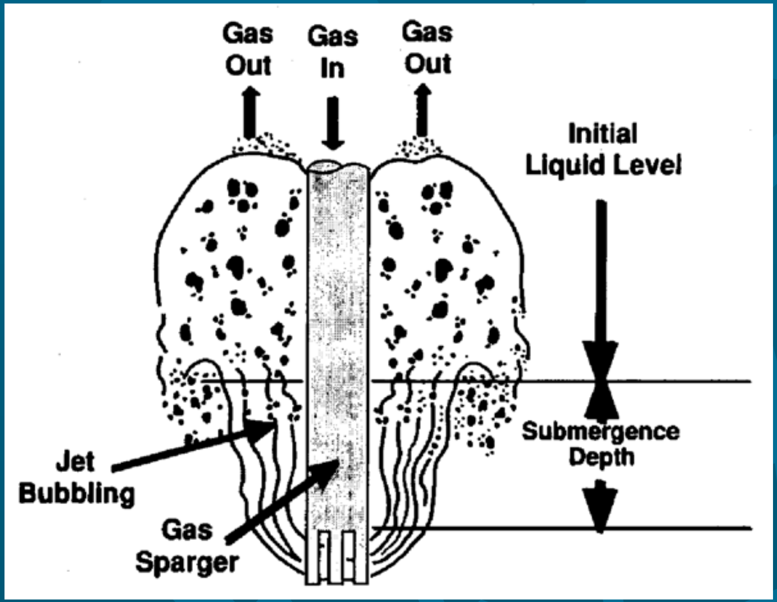
In one vessel combines concurrent chemical reactions of:
- limestone dissolution
- SO_2 absorption
- neutralization
- sulfite oxidation
- gypsum precipitation
- gypsum crystal growth

Jet Bubbling Reactor

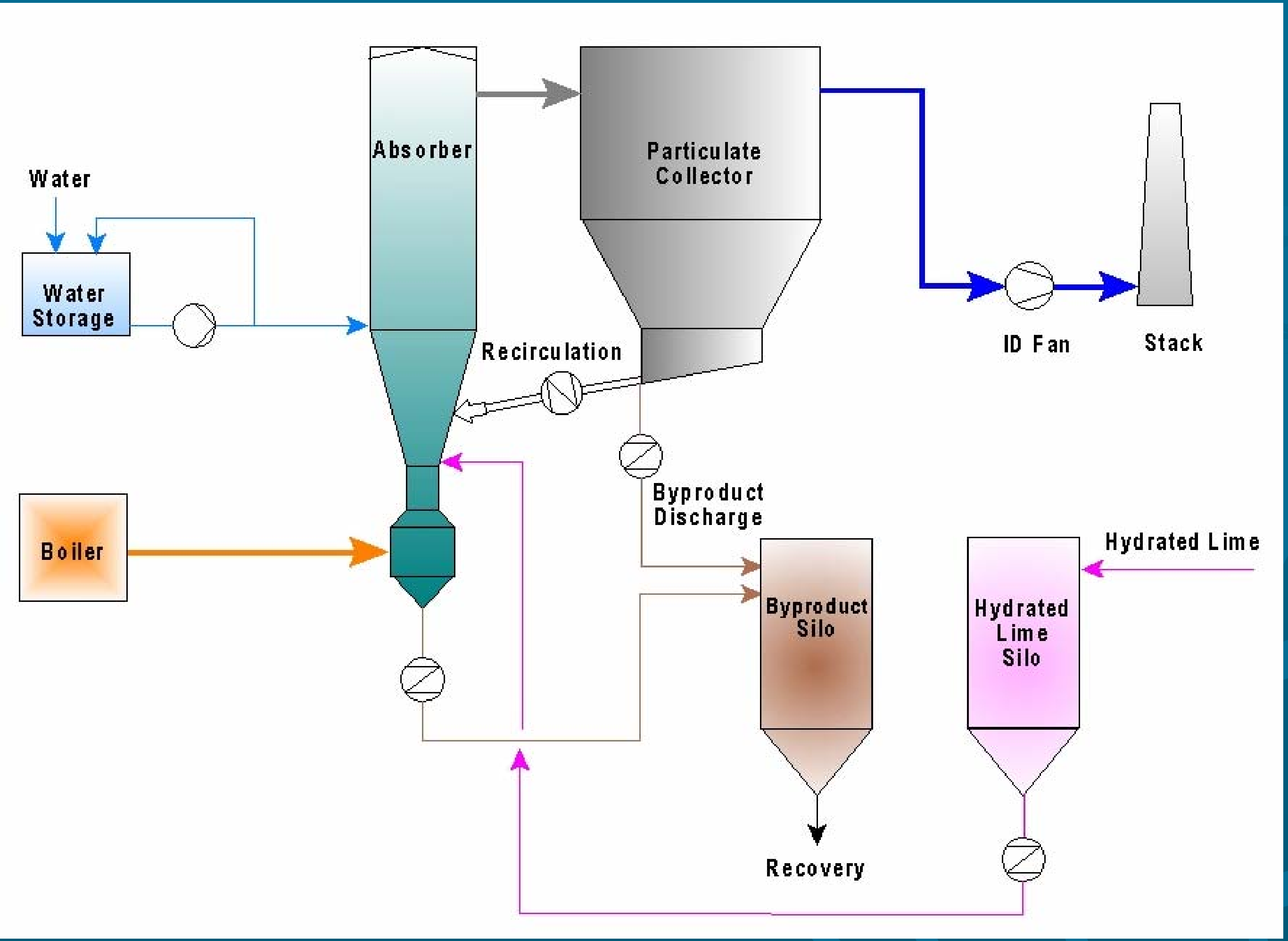


Cut-Away of JBR

Gas Sparger Action



Graf / Wulff Fluidized Bed



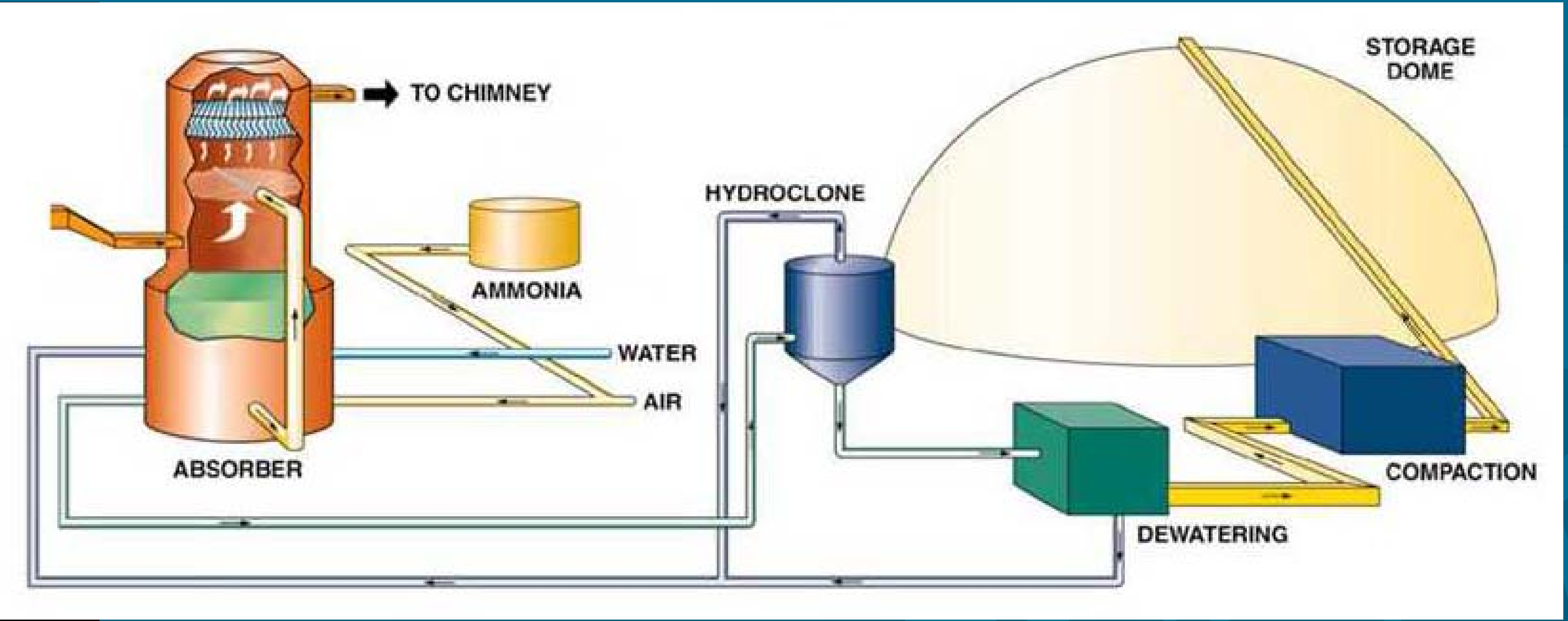
Reflux Circulating Fluid Bed Technology

Absorbers – Ammonia

1. Marsulex AS System
2. Powerspan ECO System
3. Benetech Clean & Green System
4. Lentjes-Lurgi Ammonia Water System

1. Marsulex AS System

MET Ammonium Sulfate Process



AS Process Chemistry

- For every pound of SO_2 removed:
  - Need one-half pound Ammonia
  - Produces two pounds of Ammonium Sulfate

- One pound of Ammonia generates four pounds Ammonium Sulfate

Advantages of the Marsulex

Ammonium Sulfate Process

MACT Environmental Compliance:

- *Meets and exceeds strictest environmental regulations*
- *>98% SO_2 removal efficiency burning highest available sulfur content fuels*
- *Gaseous emissions are converted into environmentally desirable high value byproduct which eliminates waste product disposal requirements*
- *Compliance with strictest opacity regulation requirements*
- *Reduction in CO_2 emissions*
- *Achieves > 99% system availability / reliability*

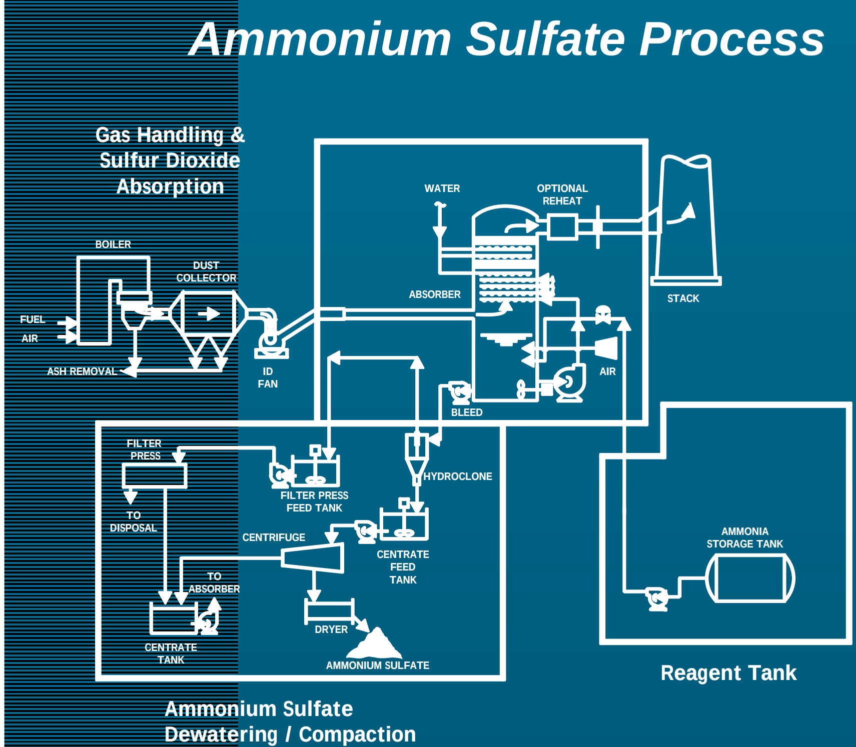
Lowest Cost Scrubbing Process:

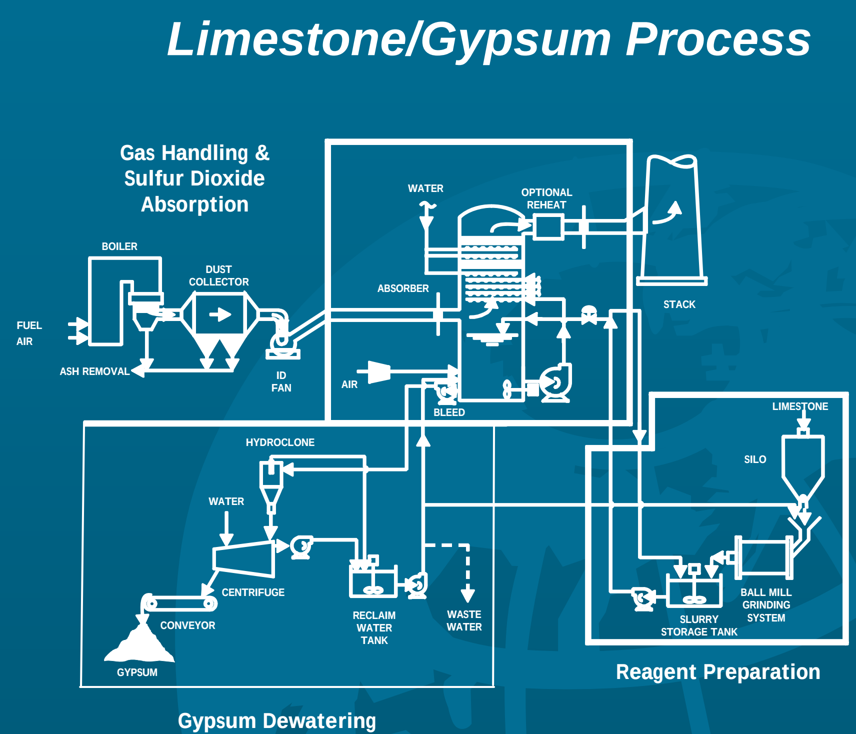
- *Flexibility to use higher sulfur content fuels*
- *Lower overall operating costs through elimination of waste product disposal & high value byproduct production*
- *High SO_2 removal efficiency without costly additives which minimizes costs and the need to purchase SO_2 credits*

Additional Benefits of the Technology:

- *Patented, proprietary technology*
- *Eliminates potential costs and liability from waste product disposal*

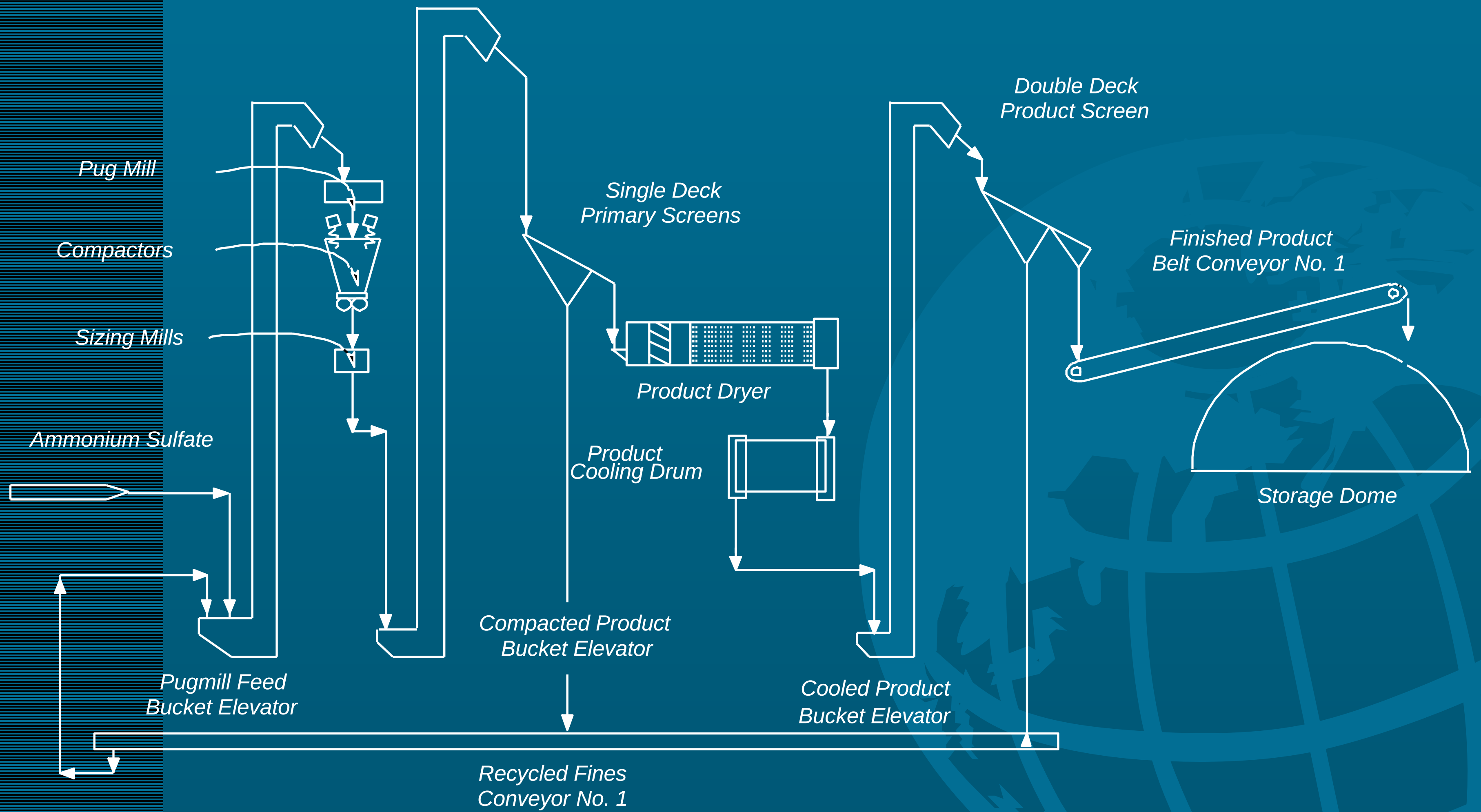
Process Comparison





Same Proven Equipment - Different Reagent

AS Compaction/Granulation System



Ammonium Sulfate Process Chemistry

$$SO_2 + 2NH_3 + H_2O \longrightarrow (NH_4)_2SO_3 \quad (1)$$

$$(NH_4)_2SO_3 + 1/2\ O_2 \longrightarrow (NH_4)_2SO_4 \quad (2)$$

- *For every pound of SO_2 removed:*
  - *Need one-half pound Ammonia*
  - *Produces two pounds of Ammonium Sulfate*
- *One pound of Ammonia generates four pounds Ammonium Sulfate ($175 - $200 / ton)*

Ammonium Sulfate Production
100 tpy per % Sulfur per MW

Proven Technology

MET Ammonium Sulfate History

Ammonium Sulfate Development History:

- *1985-87 Developed bench-scale ammonia scrubbing (AS) technology*
- *1987 GEESI awarded first AS patent*
- *1992-93 10 MW pilot demonstrated for two modes of operation*
- *1994 Awarded commercial contract with DGC*
- *1994 Second AS patent awarded*
- *1996-97 Startup and successful demonstration of 350 MW eq. AS with production of granular ammonium sulfate*
- *1997 Marsulex purchased substantially all the assets of GEESI*
- *1998 Applied for three (3) additional patents*
- *4/2001: Syncrude contracted with MET under long-term agreements for AS Technology Services*
- *1Q2006: Commercial operation of Syncrude AS operations*

Commercial NH_3 System Performance at DGC:

Design Parameter	Guarantee	Performance
SO_2 Removal Efficiency	93%	95-98+%
Ammonia Slip, ppm	< 10	3 – 7
Opacity	<4% from NH_3	0% from NH_3
Pressure Drop, "WC	< 11	7 – 8
Purity, %	99	99.5
Moisture, wt%	< 1.0	< 0.1
Hardness, %	< 5	1 – 2
Size Guide Number	240 – 290	240 - 260

Proven Technology

Ammonium Sulfate Basis of Design

First Generation Ammonia Systems

- *First Attempts At Ammonia Scrubbing Utilized High Ammonia Reactivity Resulting in Very Aggressive Absorber Designs - pH, L/G, Absorber Size*
- *As a Result, Early Generation Ammonia Scrubbers Resulted Very High Ammonia Slip and High Opacity Issues*
- *Higher pH's and Incomplete Oxidation Produce Free Ammonia in the Gas Phase*

MET Ammonium Sulfate Process

- *MET Demonstrated and Patented Optimum Operating Range to Minimize Ammonia Slip And Opacity*
- *Free Ammonia in the Gas Phase Determines Opacity Levels and is a function of Three Process Parameters; pH, Degree of Oxidation and Ammonia Injection Methods*
- *MET Demonstrated Minimal Gas Phase Ammonia and Zero Impact on Opacity From Ammonia and Ammonium Salts*

Essence of MET Patents Ensures Operation In Optimum pH Range, Complete Oxidation and Optimum Ammonia Injection Methods

Ammonium Sulfate

Product Quality Characteristics

Purity - 99+%
- Nitrogen - 21.0 - 21.1%
- Sulfur - 24.0 - 24.2%
- Water Insoluble Matter - < 0.1%
- Color - White to Beige
- Heavy Metals - < 10 ppm

Exceeds Fertilizer Standard

Residual Moisture
- Multiple Drying Steps
- Less Than 1.0 wt% Moisture
- Coated with Anti-caking Agent

Excellent Storage & Handling

Particle Size
- 1.0 mm - 3.5 mm
- 240 - 275 SGN
- Uniformity Index - 45 - 50

Ideal for Bulk Blending & Direct Application

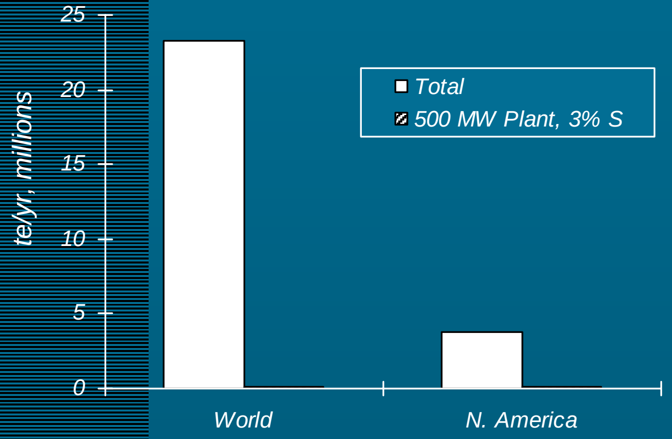
Hardness
- Demonstrated Compaction Technology
- Expertise in Product Hardening Technology
- 1 - 3% Attrition in Industry Test

Can be Handled and Transported Without Generating Dust

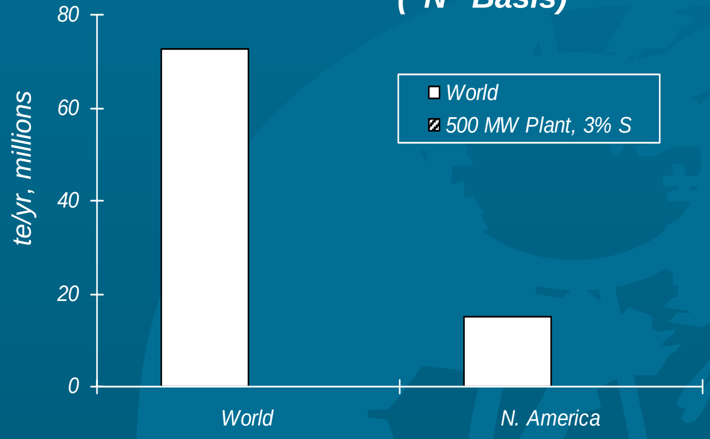
World Nitrogen Fertilizer Market

Ammonium Sulfate & Total Nitrogen ("N") Basis

Ammonium Sulfate Capacity



Total Nitrogen Based Fertilizer Capacity ("N" Basis)



Conclusions:

- *Each 500 MW ammonium sulfate plant (3% S) represents approximately 3% N. American capacity and 0.6% of world capacity*
- *Ammonium sulfate will compete with urea, ammonium nitrate and other nitrogen based fertilizers at its "floor" value ("N" content value only)*
- *Once competing at "N" value, each 500 MW plant represents only 0.2% of N. American capacity and 0.04% of world capacity*

Ammonium Sulfate Technology

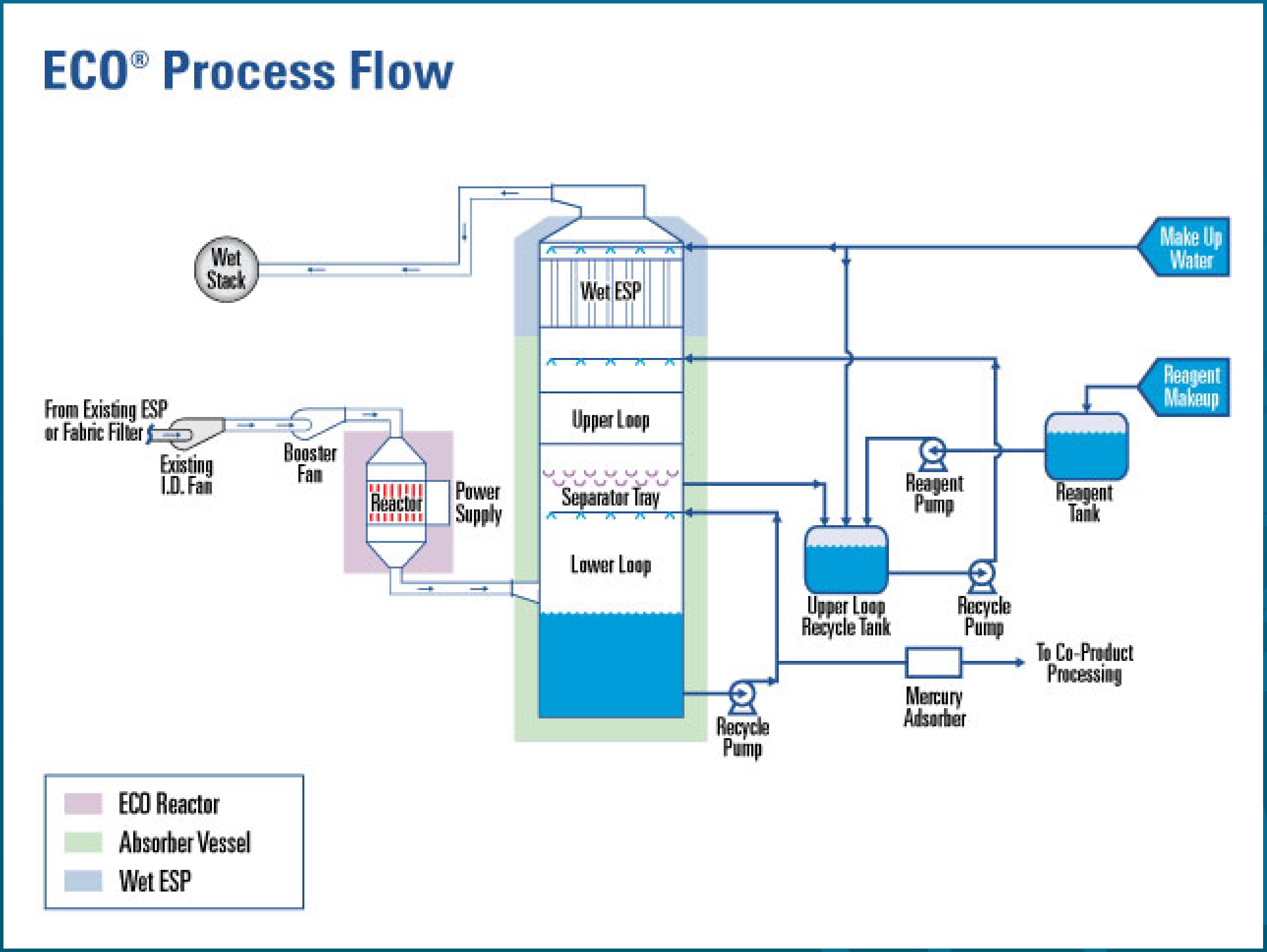
Opportunity Profile

The best opportunities to apply MET's AS technology will be found at power plants that match the following profile:

- *High fuel cost*
- *Proximity of navigable water, or good rail access for PetCoke, Ammonia and ammonium sulfate transportation*
- *Preferably in a location with high ammonium sulfate prices*

2. Powerspan ECO System

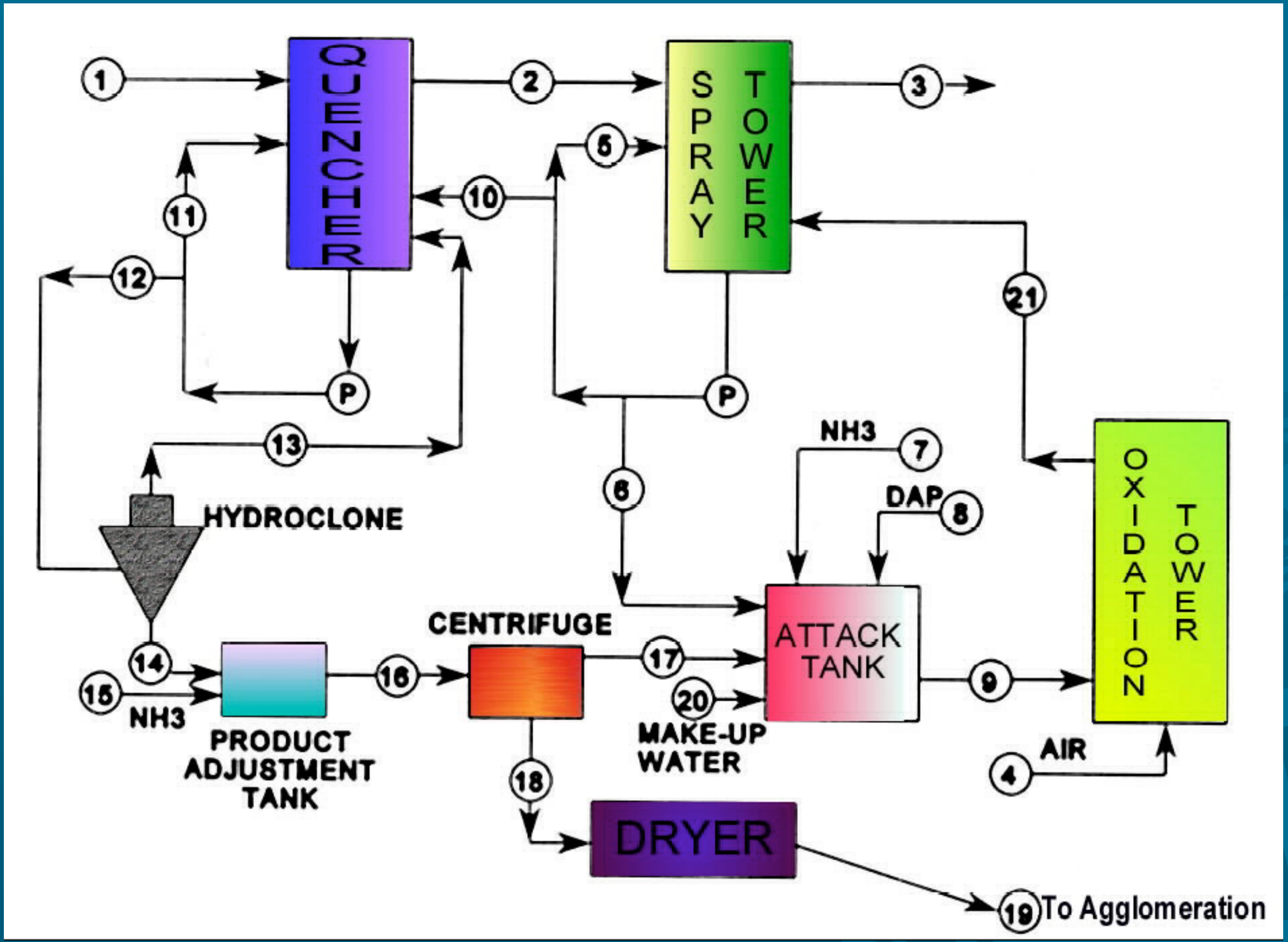
Powerspan ECO Process



(graphic courtesy Powerspan Corp.)

3. Benetech Clean & Green System

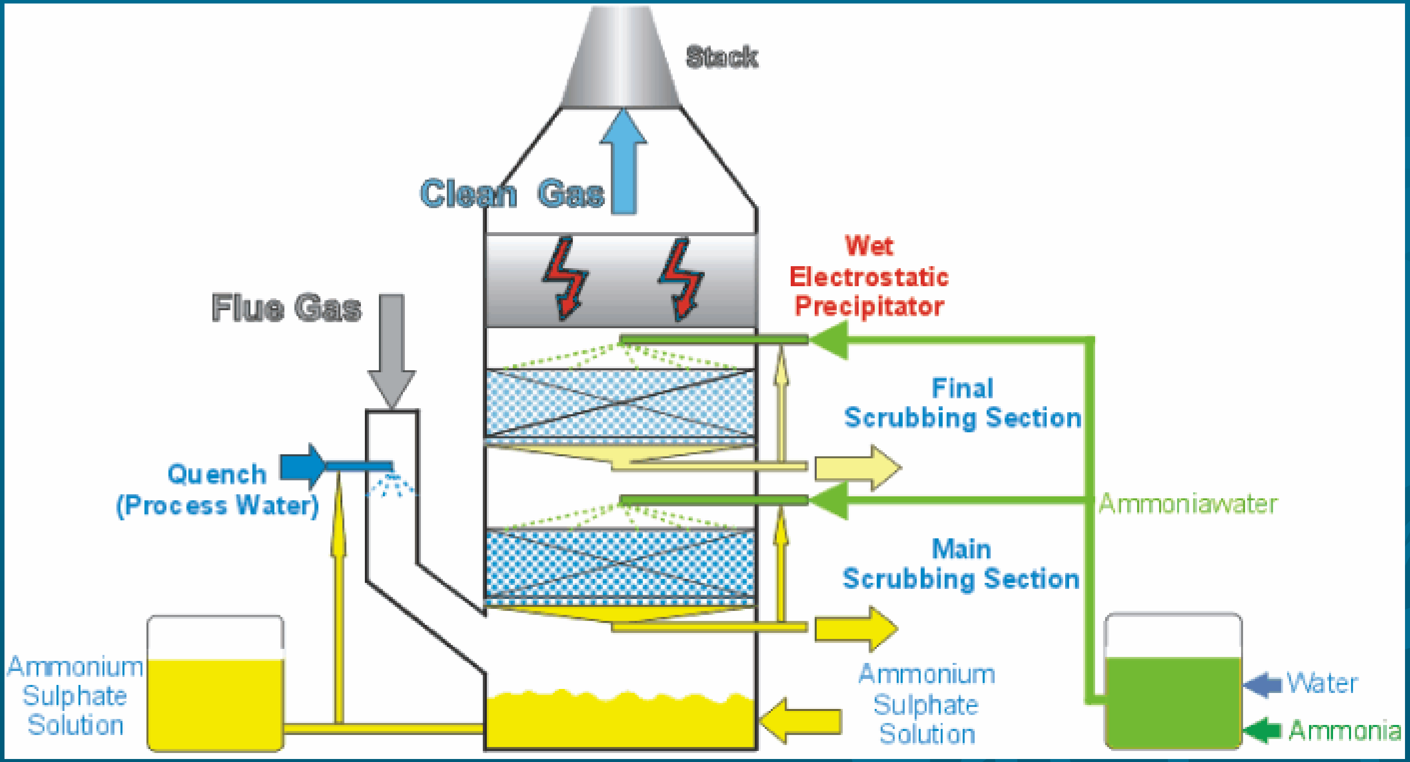
Clean & Green



(graphic courtesy Benetech, Inc.)

4. Lentjes-Lurgi Ammonia Water System

Lentjes-Lurgi System



Mechanical Equipment

1. Mist Eliminators
2. Spray Nozzles
3. Agitators
4. Slurry Pumps
5. Fans
6. Dampers
7. Instrumentation

Mist Eliminators

- Corrosion protection for downstream equipment
- Impingement-type most common in use today
  - Simplest method of mist elimination
  - Low pressure drop
  - High collection efficiency
  - Less likely to plug
- Two basic types – horizontal and vertical

Spray Nozzles

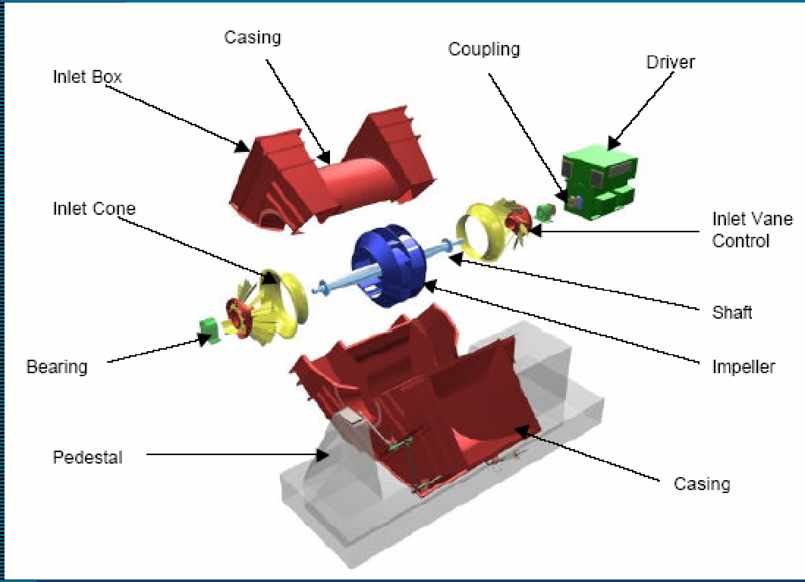
Hollow Cone Spray Nozzle
(courtesy Spraying Systems Co.)

Agitators

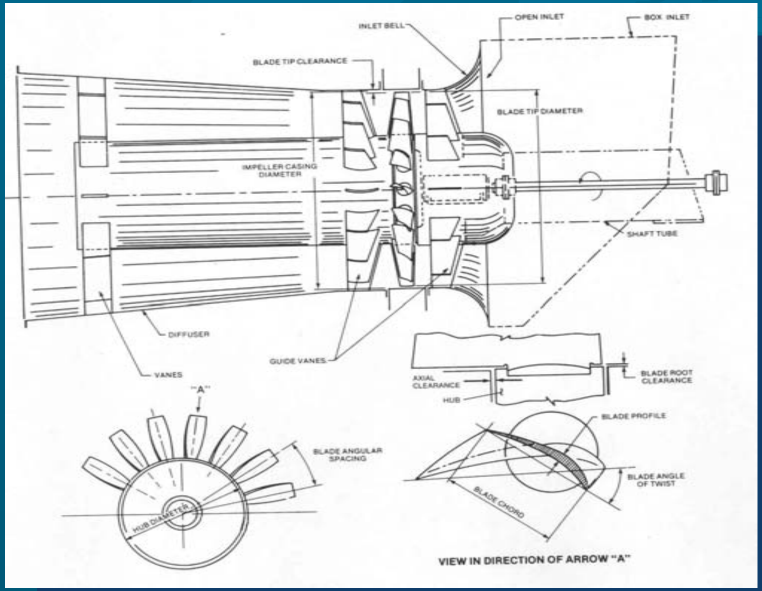
Recycle Tank Side-Mounted Agitator

Pumps - Slurry

Fans

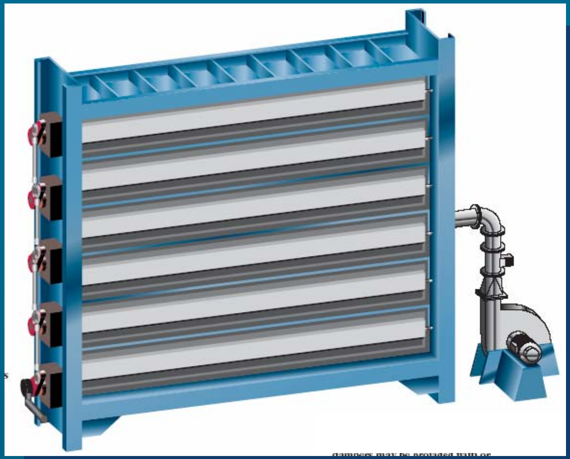


Typical Centrifugal Booster Fan (courtesy Howden Power)

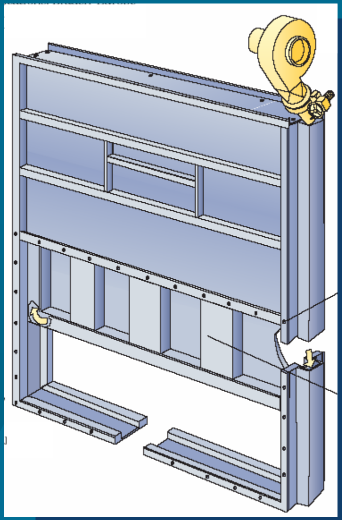


Typical Axial Booster Fan

Dampers



Double Louver Damper
(Courtesy Braden-Europe)



Guillotine Damper
(Courtesy Braden-Europe)

- Used for flow control and / or isolation of equipment for maintenance

Instrumentation

- pH Measurement
- Density Measurement
- SO_2 Measurement
- Liquid Level Liquid Flow

5. Factors Affecting Performance

Process Related Factors

- Low SO_2 Removal Efficiency
- Mist Eliminator Pluggage and Solids Carryover
- Poor Water Balance / Excessive Fresh Water Consumption

Equipment Related Problems

- Absorber Impact
  - Materials of Construction
  - Pluggage and Scaling
  - Mechanical failures of internal components

Materials of Construction

Absorber Reaction Tank
- Carbon steel with flakeglass linings
- Carbon steel with rubber lining
- Stainless steels
- High Nickel alloys
- Carbon steel with C-276 alloy cladding
- Carbon steel with C-276 alloy wallpapering
- Concrete with Stebbins acid brick tile lining
- Fiberglass reinforced plastic

Inlet Nozzle
- Carbon steel with PennGuard block linings
- Stainless steels
- Carbon steel with C-276 alloy wallpaper
- C-276 / C22 alloy steels

Spray Piping
- Carbon steel with rubber lining
- Fiberglass reinforced plastic
- Stainless steel
- High Nickel alloys

Spray Zones
- Carbon steel with abrasion resistant flakeglass lining
- Carbon steel with rubber lining
- Stainless steels
- High Nickel alloys
- Carbon steel with C-276 alloy wallpaper
- Concrete with Stebbins acid brick tile lining
- Fiberglass reinforced plastic

Outlet Duct
- Carbon steel with flakeglass lining
- Carbon steel with PennGuard block
- Carbon steel with C-276 alloy wallpaper
- Fiberglass reinforced plastic
- Solid Alloy

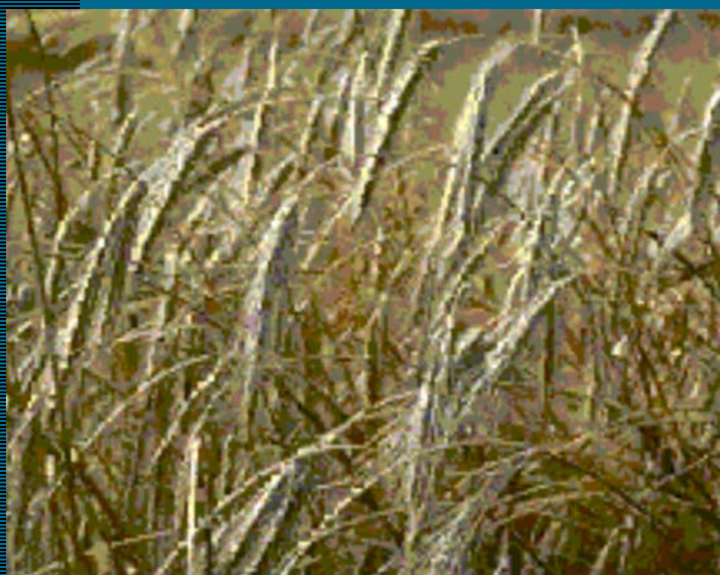
Mechanical Failures

- Heat excursions
- Defects in material
- Excessive plugging
- Abuse by maintenance personnel during cleanup and inspections
- Erosion from slurry sprays

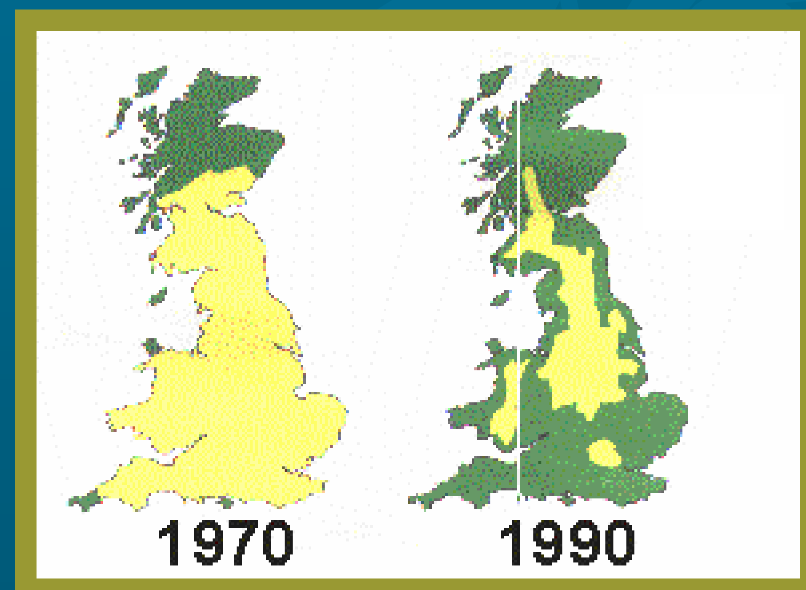
6. Summary

Soil Sulfur Deficiency

Removing SO_2 from industrial and utility stack gases has caused a depletion of sulfur in the soil.



Area receiving adequate sulfur for crop growth



Environmental controls also have detrimental effects on agriculture production

Byproduct Values

	($US/ton)
Gypsum	*-4 to +4*
*Sulfuric Acid (100% basis)**	*60 to 88*
*Elemental Sulfur**	*50 to 80*
*Ammonium Sulfate**	*110 to 196*

**Source: Green Markets*

Ammonium Sulfate is the Highest Value Byproduct

US Emissions from Energy Consumption at Conventional Power Plants and Combined Heat and Power Plants, 1994 through 2005

	Carbon Dioxide (CO_2)	Sulfur Dioxide (SO_2)	Nitrogen Oxides (NO_x)	FGD Installations	Capacity (MW)
2005	2,513,609	10,340	3,961	248	101,648
2004	2,456,934	10,309	4,143	248	101,492
2003	2,415,680	10,646	4,532	246	99,567
2002	2,395,048	10,881	5,194	243	98,673
2001	2,389,745	11,174	5,290	236	97,988
2000	2,429,394	11,297	5,380	192	89,675
1999	2,326,559	12,444	5,732	192	89,666
1998	2,313,008	12,509	6,237	186	87,783
1997	2,223,348	13,520	6,324	183	86,605
1996	2,155,452	12,906	6,282	182	85,842
1995	2,079,761	11,896	7,885	178	84,677
1994	2,063,788	14,472	7,801	168	80,617

Note: These data are for plants with a fossil-fueled steam-electric capacity of 100MW or more. Beginning in 2001, data for plants with combustible renewable steam-electric capacity of 10 MW or more were also included. Data for Independent Power Producers and Combined Heat and Power Plants are included beginning with 2001 data. Totals may not equal sum of components because of independent rounding.

Source: Energy Information Administration, Form EIA-767, “Steam-Electric Plant Operation and Design Report”

Average US FGD Costs 1994 through 2005

	Average Overhead & Maintenance Costs (mills per kilowatt hour)	Average Installed Capital Costs (US dollars per kW)
1994	1.14	127
1995	1.16	126
1996	1.07	128
1997	1.09	129
1998	1.12	126
1999	1.13	125
2000	0.96	124
2001	1.27	130.8
2002	1.11	124.18
2003	1.23	123.75
2004	1.38	133.64
2005	1.23	141.34

Note: These data are for plants with a fossil-fueled steam-electric capacity of 100MW or more. Beginning in 2001, data for plants with combustible renewable steam-electric capacity of 10 MW or more were also included. Data for Independent Power Producers and Combined Heat and Power Plants are included beginning with 2001 data. Totals may not equal sum of components because of independent rounding.

Source: Energy Information Administration, Form EIA-767, “Steam-Electric Plant Operation and Design Report”

Summary of FGD Cost Information

Summary of Cost Information in US$/MW (2001 Dollars)[a]

Scrubber Type	Unit Size (MW)	Capital Cost (US $/kW)	O&M Cost[b] (US$ / kW)	Annual Cost (US$ / kW)	Cost per Ton of Pollutant Removed (US$/ton)
Wet	➢400	100 – 250	2 – 8	20 – 50	200 – 500
Wet	< 400	250 – 1,500	8 – 20	50 – 200	500 – 5,000
Spray Dry	➢200	40 – 150	4 – 10	20 – 50	150 – 300
Spray Dry	< 200	150 – 1,500	10 – 300	50 – 500	500 – 4,000

[a] (EIA, 2002; EPA, 2000; Srivastava, 2001)

[b] Assumes capacity factor >80%

Comparison Wet vs Dry FGD

- % removal
- % sulfur in coal
- SO3 removal
- Landfill costs
- Water requirements