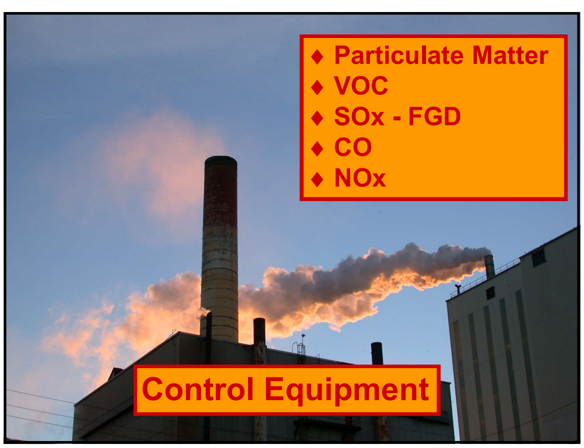

National Training Program
NACT 299
Introduction to Control Devices


House Keeping
• Bathrooms
• Emergency Evacuation
• Cell Phones
• Refreshments
• Questions
• Agenda


♦ Particulate Matter
♦ VOC
♦ SOx - FGD
♦ CO
♦ NOx
Control Equipment

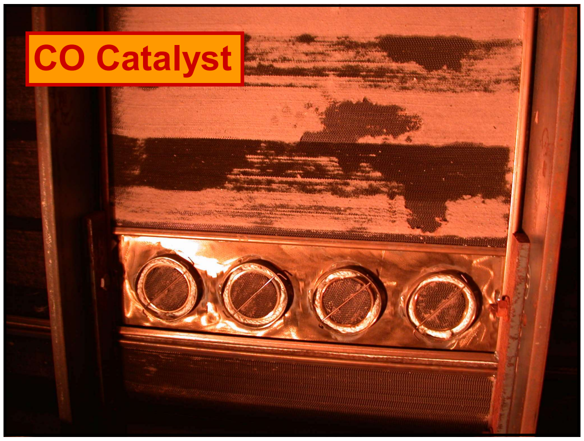
Combustion Considerations

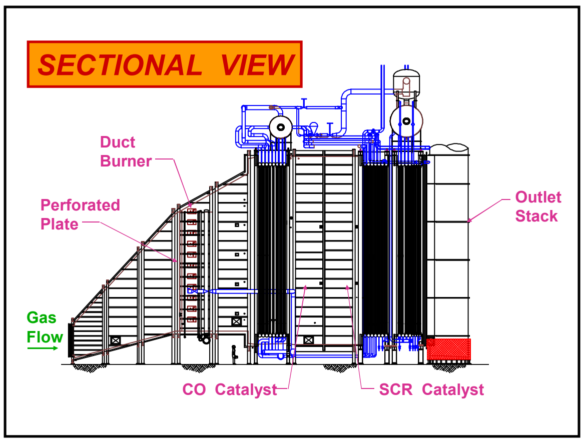
3 T's of Combustion

- Time (residence time)
- Temperature
- Turbulence (mixing)
- Increase 3T's > more NOx
- Decrease 3T's > more CO & PICs

CO Catalyst

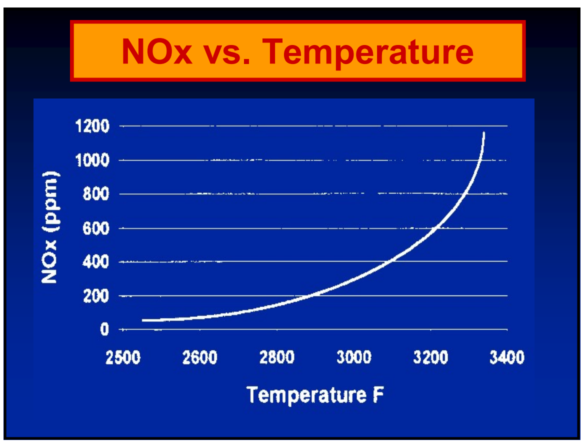
- **$2CO + O_2 \Rightarrow 2CO_2$**
- **700 to 1000 ^{o}F operating temp**
- **90% plus efficiency**
- **Pressure drop 1-2 in. H_2O**
- **Problems**
  - **Expensive**
  - **High maintenance**
  - **Catalyst replacement**


CO Catalyst

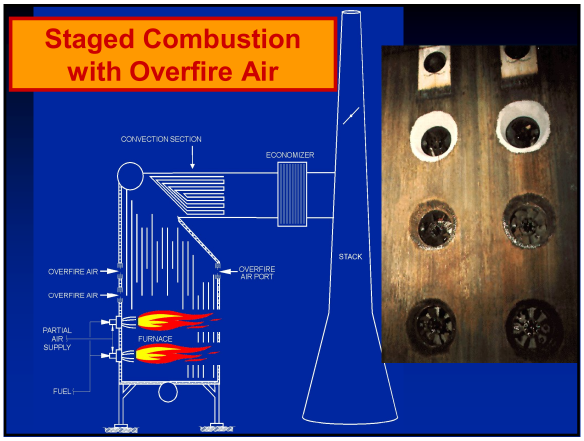

SECTIONAL VIEW
Duct Burner
Perforated Plate
Outlet Stack
Gas Flow
CO Catalyst
SCR Catalyst


Let's Discuss NOx Control
Formation of NOx
Low-NOx combustion techniques
Ammonia injection (SCR & SNCR)
Catalytic controls


Thermal NOx
Fuel-bound NOx
Prompt NOx
NOx Creation

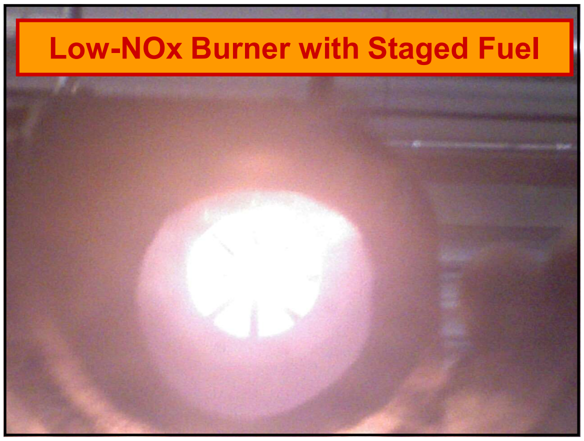

NOx vs. Temperature
1200
1000
800
600
400
200
0
NOx (ppm)
2500
2600
2800
3000
3200
3400
Temperature F


Babcock & Wilcox Utility Boiler

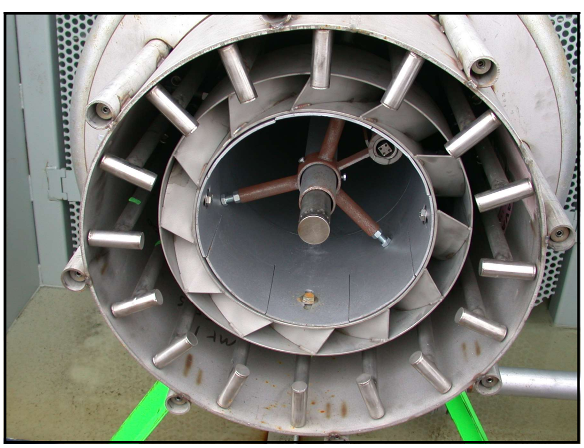

Staged Combustion
with Overfire Air
CONVECTION SECTION
ECONOMIZER
STACK
OVERFIRE AIR
OVERFIRE AIR
OVERFIRE
AIR PORT
PARTIAL
AIR
SUPPLY
FURNACE
FUEL


Fire-Tube Boiler

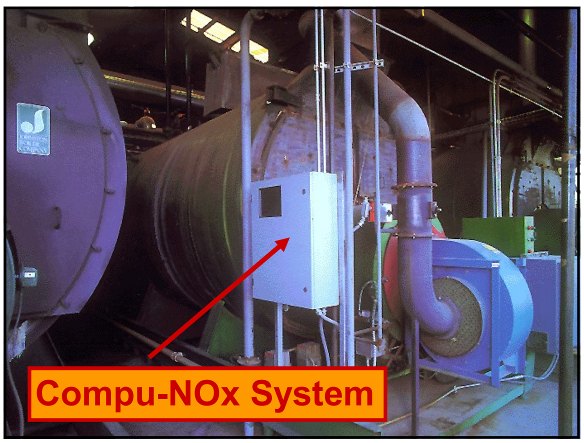

Low-NOx Burner with Staged Fuel

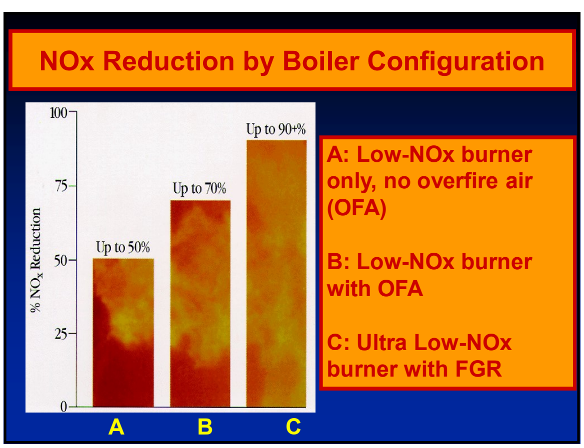

Low-NOx Burner with Staged Fuel


NATCOM
Ultra Low-NOx Burner (9 ppm)



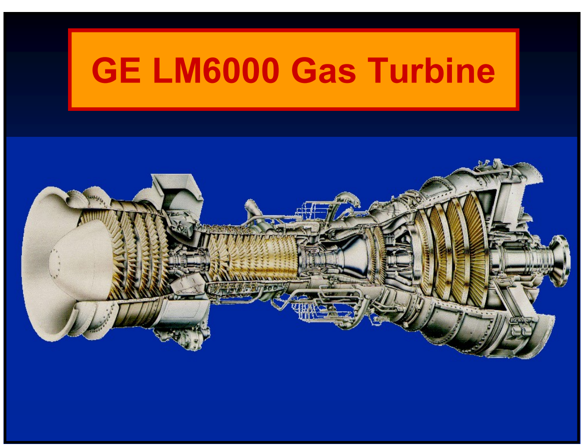

Flue Gas
Recirculation

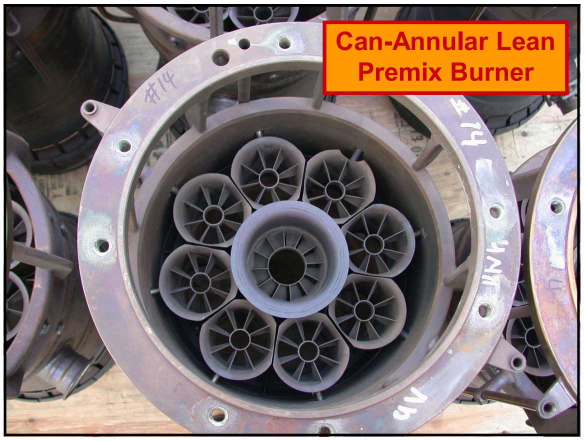

Compu-NOx System

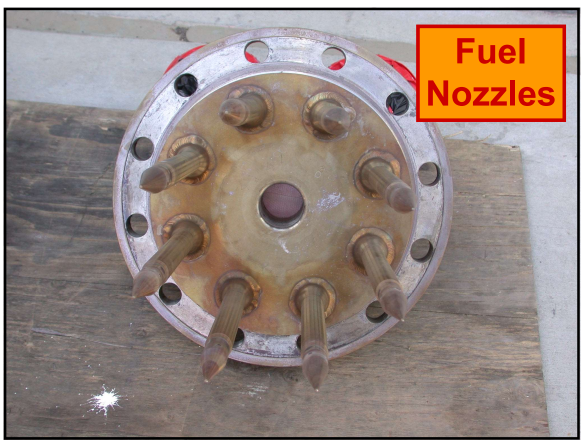

NOx Reduction by Boiler Configuration
100
75
50
25
0
% NOx Reduction
Up to 50%
Up to 70%
Up to 90+%
A
B
C
A: Low-NOx burner only, no overfire air (OFA)
B: Low-NOx burner with OFA
C: Ultra Low-NOx burner with FGR

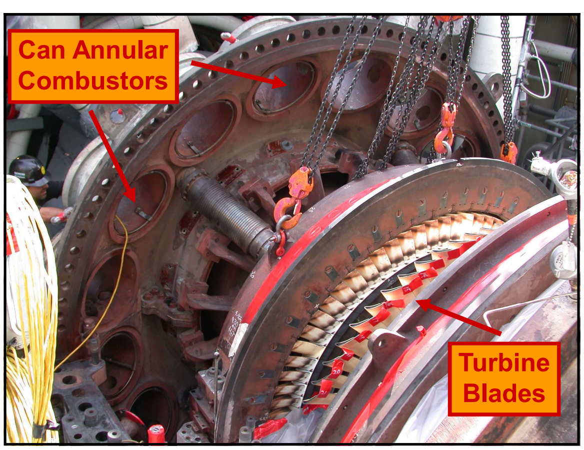

Let's Discuss Gas Turbine
Power Plant Controls

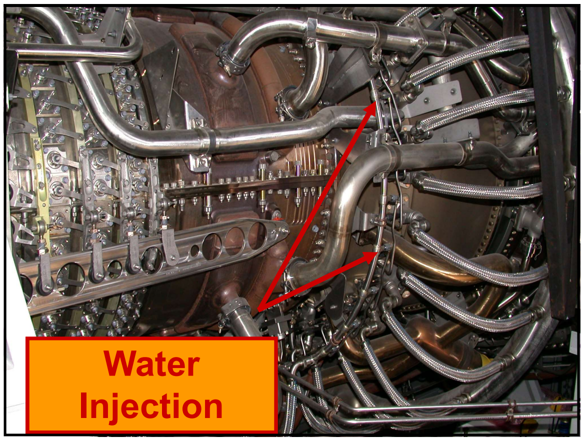

Gas Turbine
Power Plant

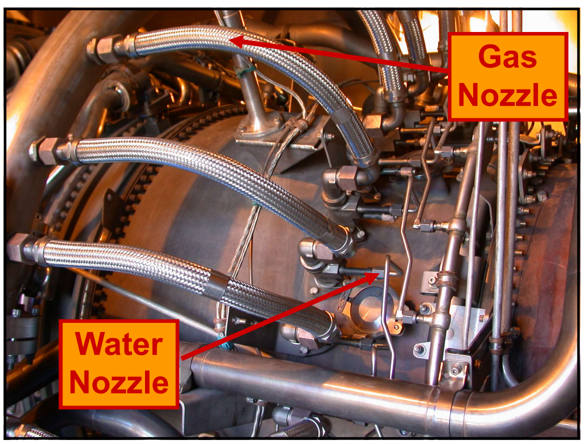

GE LM6000 Gas Turbine

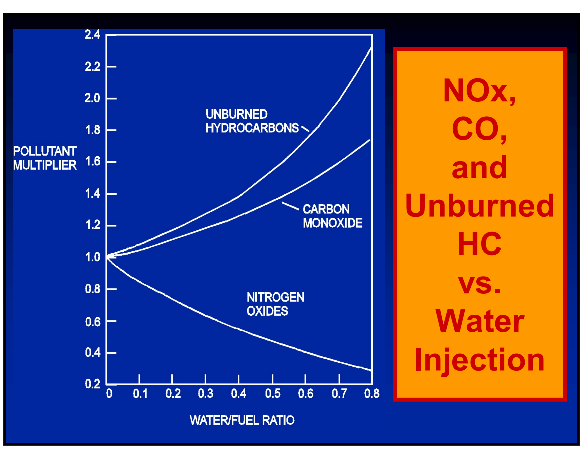

Can-Annular Lean
Premix Burner

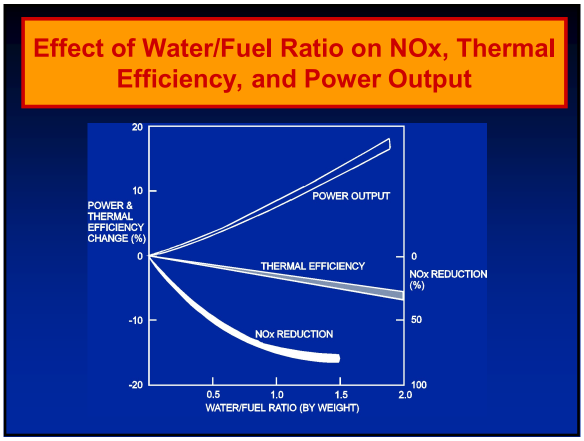

Fuel
Nozzles

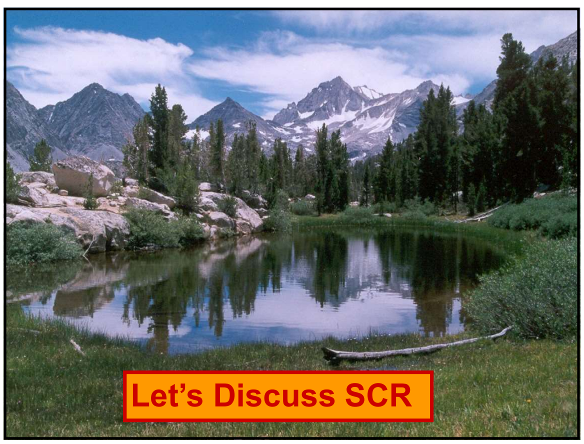

Can Annular
Combustors
Turbine
Blades

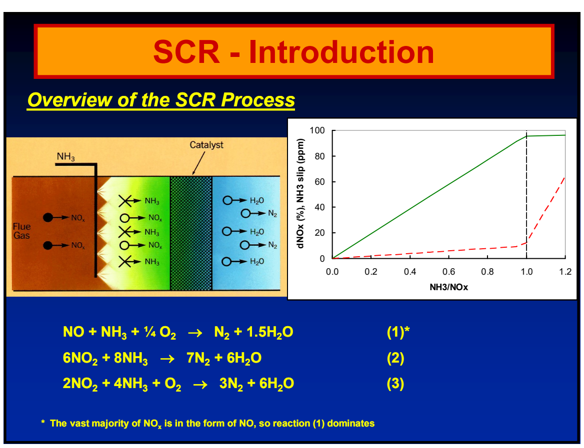

Water
Injection


Gas
Nozzle
Water
Nozzle

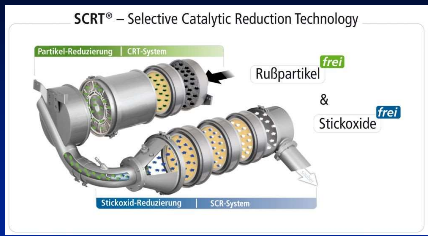

POLLUTANT
MULTIPLIER
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
UNBURNED
HYDROCARBONS
CARBON
MONOXIDE
NITROGEN
OXIDES
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
WATER/FUEL RATIO
NOx,
CO,
and
Unburned
HC
vs.
Water
Injection


Effect of Water/Fuel Ratio on NOx, Thermal Efficiency, and Power Output
POWER & THERMAL EFFICIENCY CHANGE (%)
20
10
0
-10
-20
POWER OUTPUT
THERMAL EFFICIENCY
NOx REDUCTION
NOx REDUCTION (%)
0
50
100
0.5
1.0
1.5
2.0
WATER/FUEL RATIO (BY WEIGHT)


Let's Discuss SCR


SCR - Introduction
Overview of the SCR Process
NH3
Catalyst
Flue Gas
dNOx (%), NH3 slip (ppm)
NH3/NOx
NO + NH3 + ¼ O2 → N2 + 1.5H2O (1)*
6NO2 + 8NH3 → 7N2 + 6H2O (2)
2NO2 + 4NH3 + O2 → 3N2 + 6H2O (3)
* The vast majority of NOx is in the form of NO, so reaction (1) dominates

SCRT®
Johnson Matthey



$2\,NH_3 + NO + NO_2 \rightarrow 2\,N_2 + 3\,H_2O$

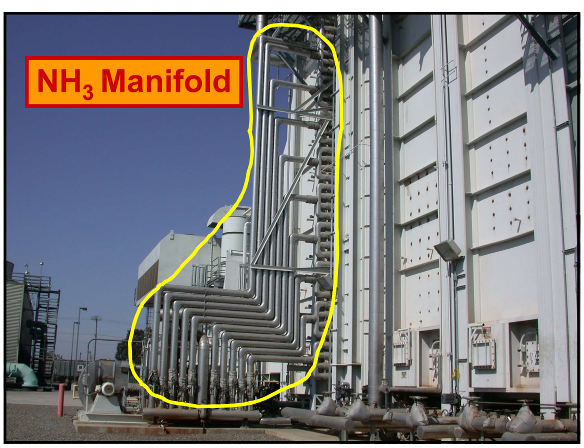
Selective Catalytic Reduction (SCR)

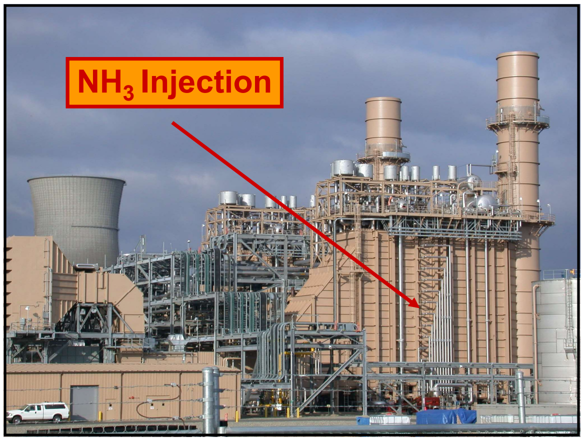
- **65-90% control**
- **Problems**
  - **Expensive**
  - **High maintenance**
  - **Ammonia "slip"**
  - **Catalyst replacement & disposal**

SCR – Where is it Used?

- Widespread Use
  - Coal and Gas Fired Utility Boilers
  - Gas Turbine Electric Generators (Simple and Combined Cycle)
- More Recently
  - Refinery Combustion Systems
  - Smaller Industrial Boilers (Gas, Biomass Fired)
  - Mobile Diesel Engines

Introduction to Control Devices

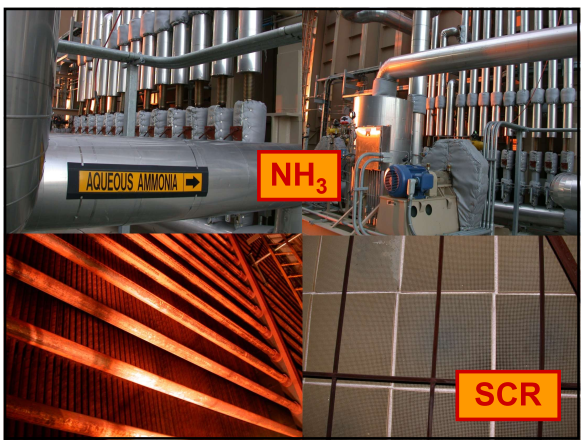



NH_3 Injection


SCR &
NH_3 Tubes


ANHYDROUS
AMMONIA

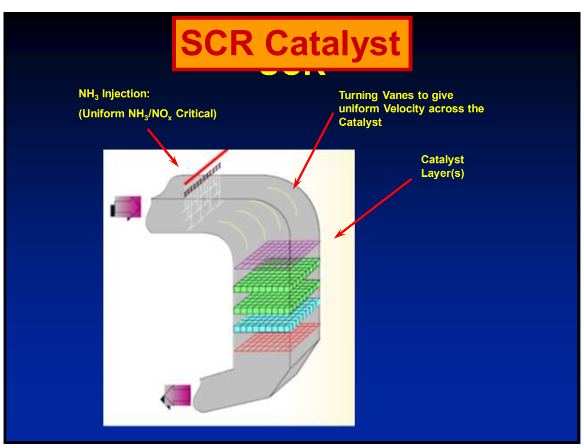

Ammonia Storage Tank
AQUEOUS
AMMONIA

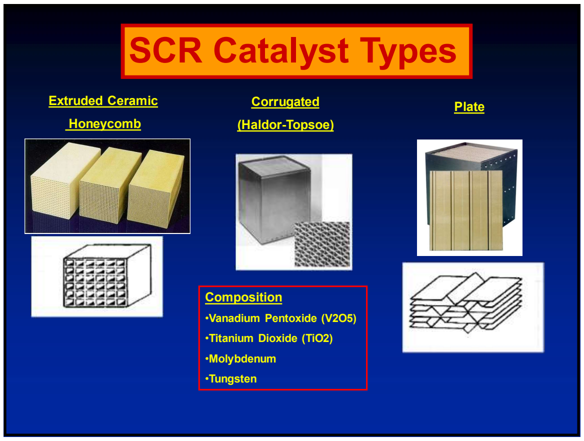

AQUEOUS AMMONIA
NH3
SCR


SCR Catalyst &
NH3 Tubes


SCR Catalyst


Utility Boiler with SCR

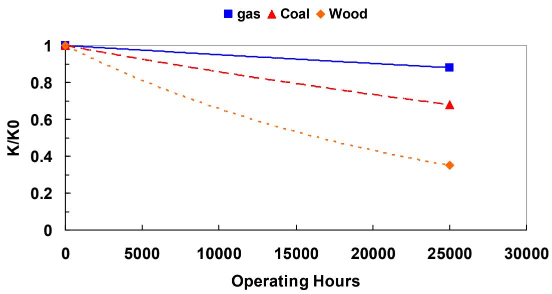

SCR Catalyst
NH_3 Injection:
(Uniform NH_3/NO_x Critical)
Turning Vanes to give uniform Velocity across the Catalyst
Catalyst Layer(s)


SCR Catalyst Types
Extruded Ceramic Honeycomb
Corrugated (Haldor-Topsoe)
Plate
Composition
•Vanadium Pentoxide (V2O5)
•Titanium Dioxide (TiO2)
•Molybdenum
•Tungsten


Utility Boiler: ID Fans for SCR


Catalyst Degrade with Time
Reason for Degradation Fuel Dependent
▪ Bituminous Coal-Arsenic Poisoning
▪ Other Coal- Calcium sulfate blinding
▪ Potassium & Chlorine Poisoning

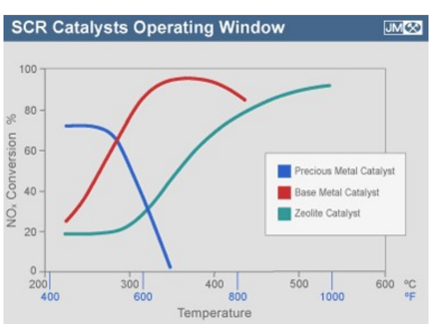
Typical Catalyst Deactivation Rates



NO_x Control Techniques – Selective Catalytic Reduction

- Factors affecting efficiency
  - Catalyst activity
  - Masking or poisoning
  - Space velocity (gas flow rate divided by bed volume)
  - Excess ammonia or urea slip

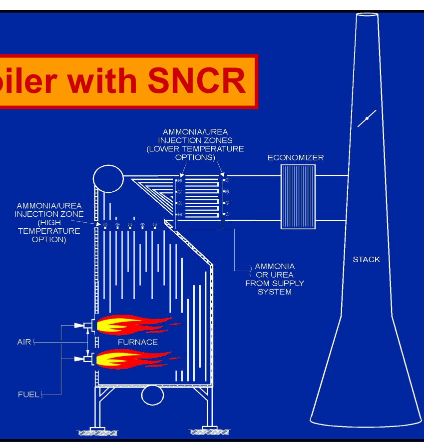
Typical SCR Catalysts Operating Windows



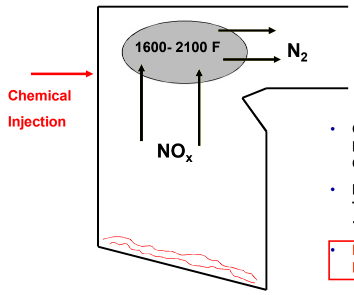
NOx Control Techniques – Selective Catalytic Reduction

- Performance indicators
  - Inlet and Outlet NOx concentration
  - Ammonia / urea injection rate
  - Catalyst bed inlet temperature
  - Catalyst activity (coupon)
  - Outlet ammonia concentration
  - Inlet gas flow rate
  - Fuel sulfur content
  - Pressure differential across catalyst bed

Boiler with SNCR



SNCR Process

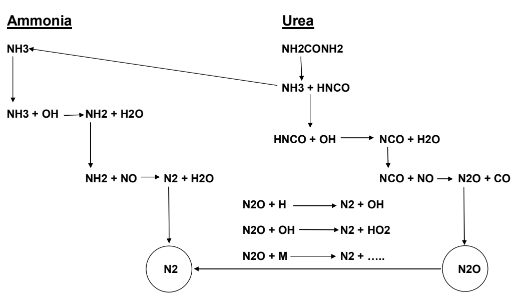


- Gas Phase Reaction Between the Injected Chemical and NOx
- Reactions Occur in the Temperature Region of 1600-2100 F
- Furnace is the Chemical Reactor

Selective Non-Catalytic Reduction

- NOx control through ammonia injection
- No catalyst necessary
- Temperature range 1600 °F – 2100 °F
- Injected upstream of convection section
- 20% - 50% control under normal conditions
- Problems:
  - Changing flue temperatures with changing load
  - Formation of ammonium salts
  - Ammonia slip

Selective Non-Catalytic Reduction

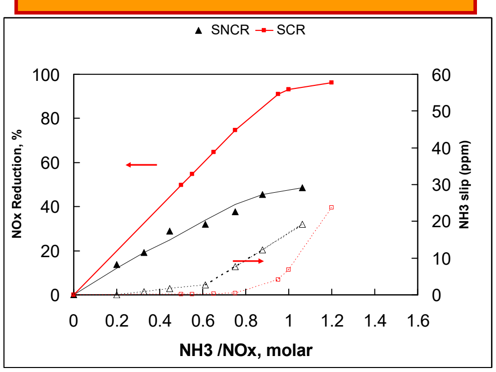


Detailed SNCR Mechanism

Ammonia vs. Urea

Parameter	Ammonia	Urea
Form	High Vapor Pressure Liquid Ammonia/Water Solution	Liquid Solution
Safety	Anhydous/29.4% Aqueous – Safety Issue 19% Aqueous – Fewer Safety Issues	No Safety Issues
Storage	Anhydrous – Pressure Vessel Aqueous – Atmospheric Pressure	Atmospheric Pressure Crystallization at Low Temps.
Injectors	Needs Carrier Gas	Atomizer (Pressure or Twin Fluid)
Temperature	Peak Removal @ 1750° F	Peak Removal @ 1850° F Large Dilute Drops Shield Urea
System Complexity	Relatively Simple	Relatively Simple

SCR vs. SNCR



SCR vs. SNCR

	SNCR	SCR
NOx Reductiuon	20-50%	50-95%
Hardware	Simple	More Complex
Capital Cost	Low (1)	High (5-10)
Reagent Utilization	Typ. 30%	Almost 100%
O&M	Reagent	Reagent/Catalyst
Designability	Poor	Good
NH3 slip	5-20 ppm	<10 ppm

NH_3 Emissions Limits

- Regulatory Limit
- NH_3/SO_3 Reactions
  - Ammonium Bisulfate: $NH_3 + SO_3 \rightarrow NH_4HSO_4$
  - Ammonium Sulfate: $2NH_3 + SO_3 \rightarrow (NH_4)_2SO_4$
- NH_3/Ash Absorption (issue for coal-fired utility units that sell their ash for making cement)
- NH_3/HCl Reactions (detached plume)
  - NH_3/HCl $NH_4Cl(s)$

Comparison of NOx Control Technologies – Gas-Fired Boilers

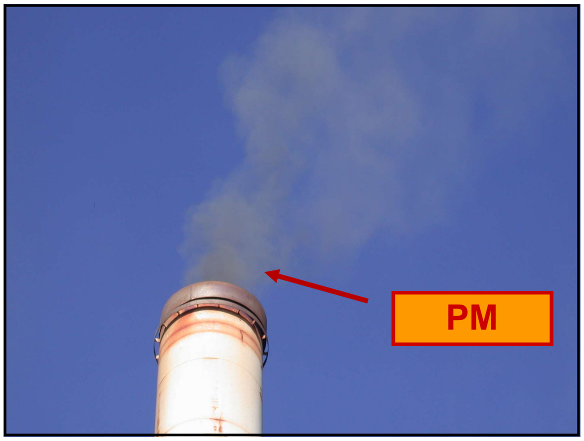
Technology	Approx. Reduction	Approx. lbs/MMBTU	Approx. ppmv @ 3% O2
Standard burners	Base case	0.14	120
Low NOx burners	60%	0.06	45
Ultra Low NOx Burners – Ist gen.	80%	0.03	25
Ultra Low NOx Burners – 2nd gen.	95%	0.007	6
FGR	55%	0.025	20
Compu- NOx w/ FGR	90%	0.015	12
SNCR	40%	0.033 - 0.085	27 - 70
Catalytic Scrubbing	70%	0.017 - 0.044	14 - 36
SCR	90 – 95%	0.006 - 0.015	5 - 12

Objectives

- Define "particulate matter or PM"
- Identify sources of particulates
- Analyze opacity issues
  - Potassium plumes
  - Ammonium-chloride plumes

What is Particulate Matter??

- It is what the test measurement says it is
- Meaning:
  - Solid particles that are captured on a filter
  - Condensable matter collected in a set of impingers
- What eventually condenses in the atmosphere is also considered as particulate matter along with "solid" particulate in the gas stream



Sources of "Particulate Matter"

- Ash in the fuel
  - Silica and Alumina - generally large particles that are retained or collected in the boiler/precipitator
  - Intrinsic ash - generates the small particles that are more troublesome to control
  - Alkalis - potassium, sodium and calcium
- Condensables (HCl, SO_3, NH_4Cl) which are also considered as "particulates"

Ammonia Slip

- NH_3 + OH => NH_2 + H_2O
- NH_2 + NO => N_2 + H_2O
- $2NH_3$ + OH + NO => $2H_2O$ + N_2 + NH_3
- 10 to 25 ppm NH_3 Slip
- Could be higher
- Always have Some NH_3 slip

NH_3 (g) + HCl (g) => NH_4Cl(s)

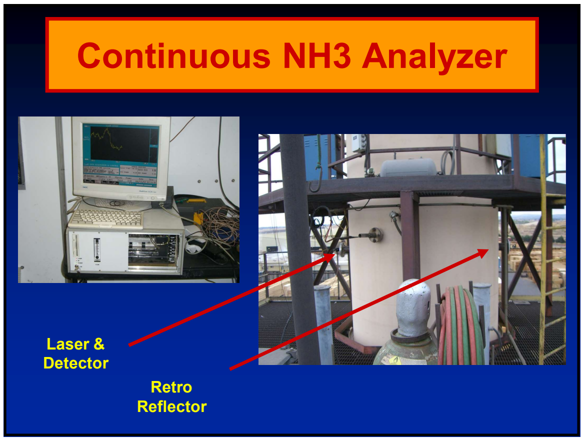
- NH_3 and HCl released as gases
- Combine and condense into aerosol particles
- Two parallel processes taking place
  - Rate of formation reaction controlled by concentrations
  - Rate of condensation control by temperature
- Both affected by air dilution in the plume

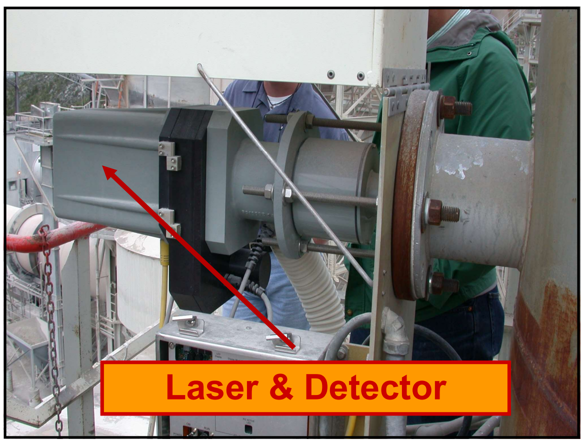
NH_4Cl Formation

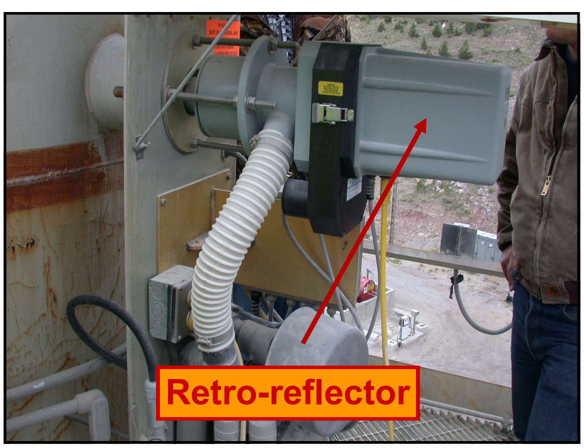
- Function of the concentrations of NH_3 an HCl
- Concentrations decrease as air is mixed into the plume
- Lower concentrations => less NH_4Cl formed
- Therefore: air dilution is good

What Can Be Done??

- Minimize (eliminate Cl) in fuel
- Install acid gas controls
- Minimize NH_3 slip <= monitor
- High stack gas temperatures
- High ambient air temperatures (winter time a problem??)
- Promote rapid gas/air mixing ??
- Install high gas temperature concentric stack annulus ??


Continuous NH3 Analyzer
Laser & Detector
Retro Reflector


Laser & Detector

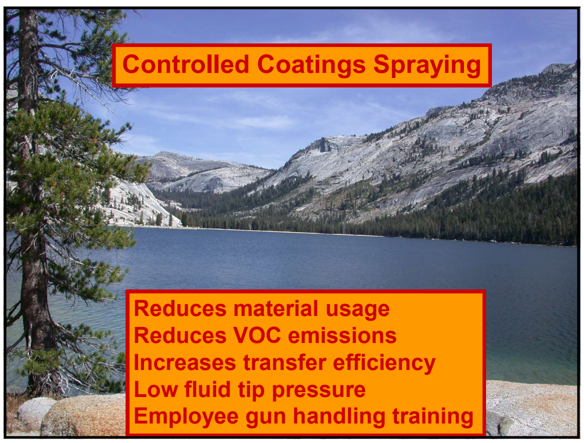

Retro-reflector


Let’s Discuss VOC Control
♦ Material Usage Minimization
♦ Containment
♦ Absorption
♦ Adsorption
♦ Oxidation

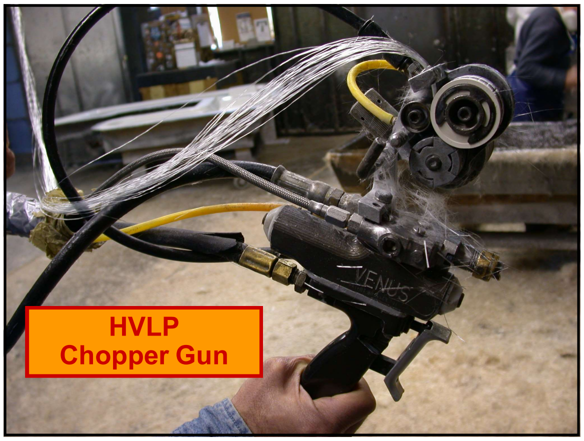

Material Usage Minimization
Basic Strategy:
If we optimize the efficiency of the amount of VOC-containing material we use, we also limit VOC emissions


sikkens
Materials Minimization


We must consider real-world demands
e.g. Spray painted cars look better


Controlled Coatings Spraying
Reduces material usage
Reduces VOC emissions
Increases transfer efficiency
Low fluid tip pressure
Employee gun handling training

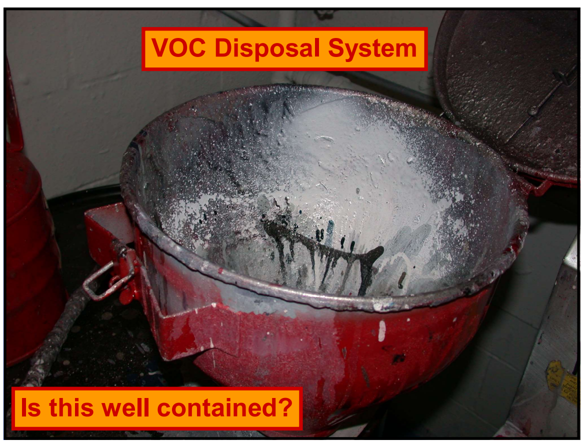

Motor Vehicle Coating –
High Volume Low Pressure (HVLP)
Spray Gun

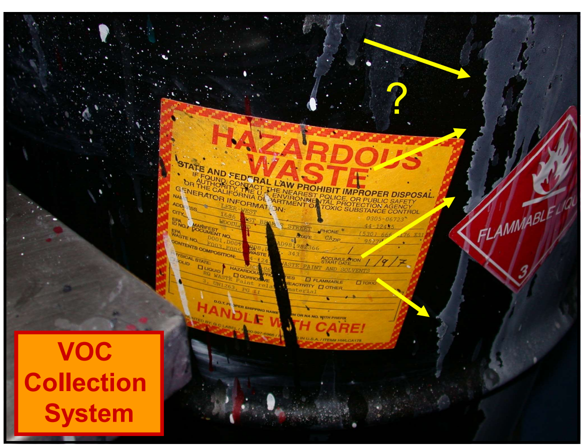

HVLP
Chopper Gun


Chopper Gun
Gel Coat Application in a Spray Booth


Hand Layup of Fiberglass
Materials Minimization


Containment Strategy
Solvent Reclaim System


VOC Disposal System
Is this well contained?


?
HAZARDOUS WASTE
HANDLE WITH CARE!
VOC Collection System


ACETONE
ACETONE
Look for housekeeping habits


Look for housekeeping habits


Look for housekeeping habits

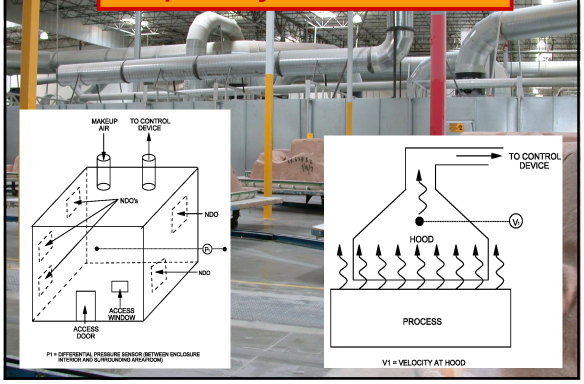
VOC Control Techniques – Capture System

- General description
  - Total efficiency is product of capture and control device efficiencies
  - Two types of systems
    - Enclosures and local exhausts (hoods)

VOC Control Techniques – Capture System

- General description
  - Two types of enclosures
    - Permanent total (M204) – 100% capture efficiency
    - Nontotal or partial – must measure capture efficiency

Capture System Schematic



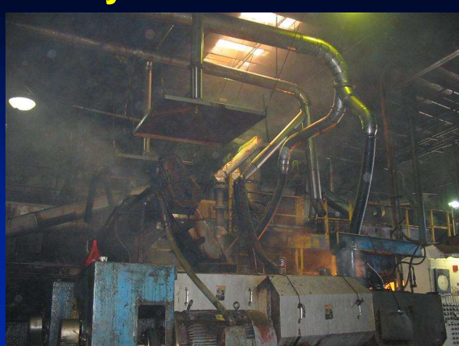
VOC Control Techniques – Capture System

- Performance indicators
  - Enclosures
    - Face velocity
    - Differential pressure
    - Average face velocity and daily inspections

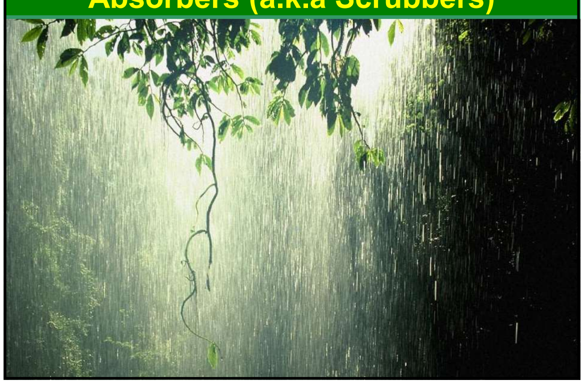
VOC Control Techniques – Capture System

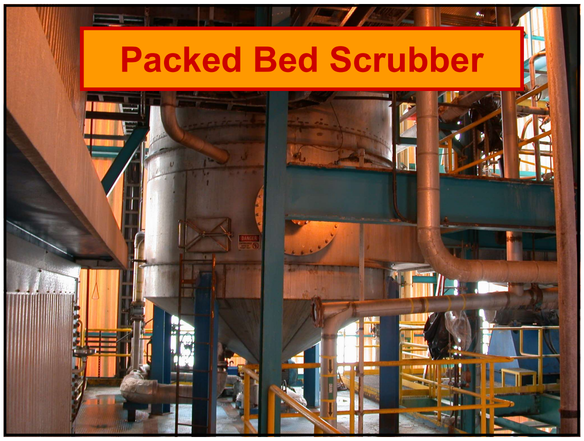
- Performance indicators (cont.)
  Exhaust Ventilation
  - Face velocity
  - Exhaust flow rate in duct near hood
  - Hood static pressure

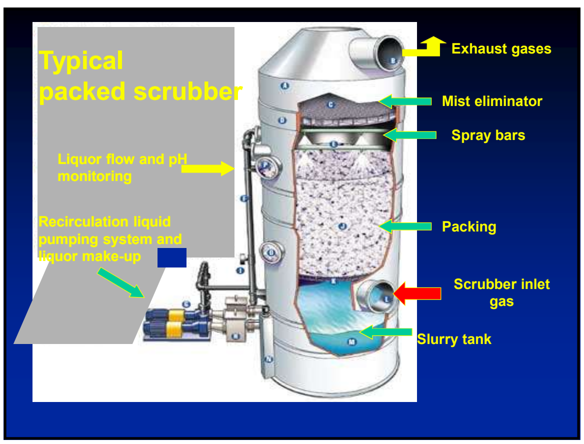
Any Concerns Here?



Let's Discuss Packed Column Absorbers (a.k.a Scrubbers)




Packed Bed Scrubber


Typical
packed scrubber
Liquor flow and pH monitoring
Recirculation liquid pumping system and liquor make-up
Exhaust gases
Mist eliminator
Spray bars
Packing
Scrubber inlet gas
Slurry tank


Typical Packing Material

Scrubbers

- Used for a variety of pollutants
  - Both particulates and VOCs
  - Acid gases
  - Odors (e.g. rendering operations)
- Primary indicators
  - Water (liquor) flow rate
  - pH
  - Outlet temperature
- Secondary (longer term) indicators
  - Inlet & water temperatures
  - Gas pressure drop

Monitoring Approach – SO_2

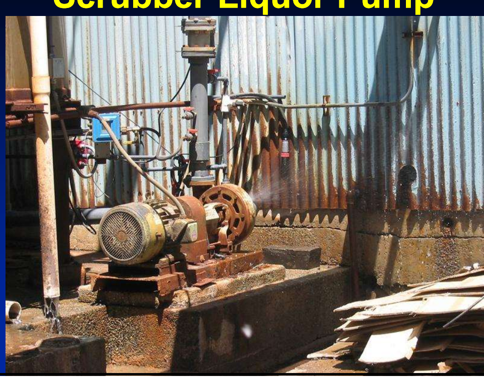
Indicator	Slurry pH	Slurry flow rate
Indicator range	<9.0 - corrective action, reporting	<175 – corrective action, reporting
Measurement location	Recirculation line	Recirculation line
QA/QC	Annual cal.	Annual cal.
Frequency	1/15 minutes	1/15 minutes
Averaging time	hourly	hourly

Compliance Concerns?

Scrubber Leaking Liquor

Compliance Concerns?

Scrubber Liquor Pump

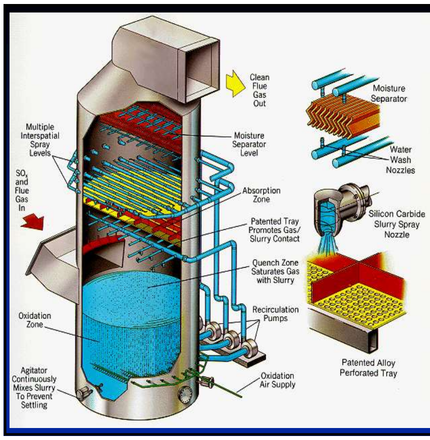


Let's Discuss FGD : Flue Gas Desulphurization

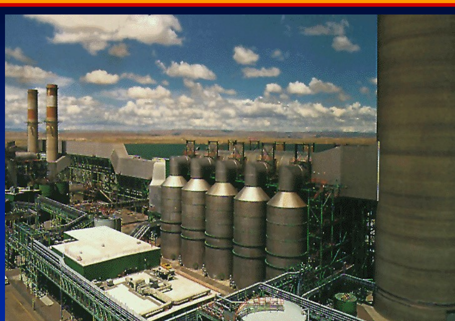
SO_2 Scrubbers
- Wet
- Spray Dry (Semi-Dry)
- Dry (DSI : Dry Sorbent Injection)

SOx Control

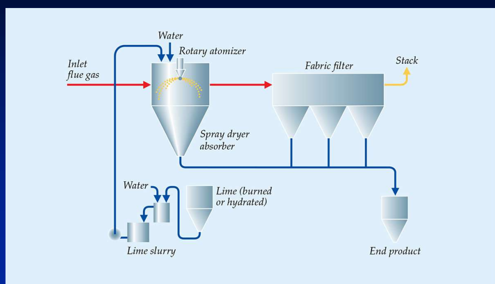
Wet FGD



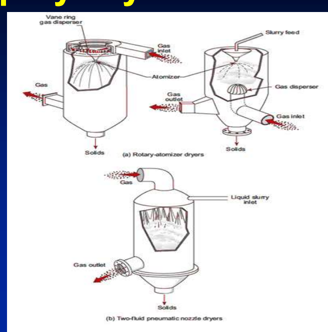
Five FGD Scrubber Modules on Utility Boiler



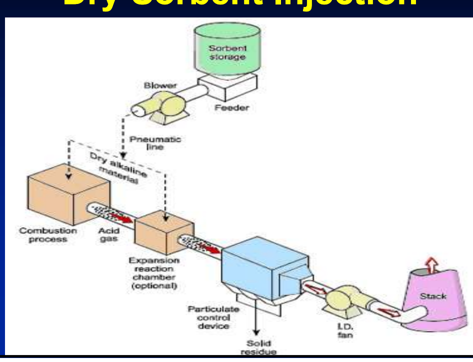
Spray Dryer Absorber



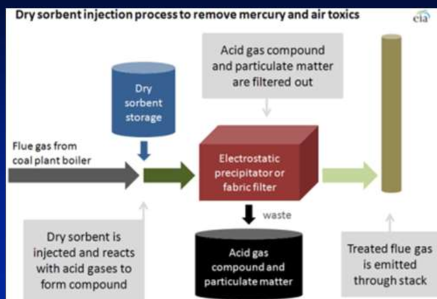
Spray Dryer Absorbers



Dry Sorbent Injection

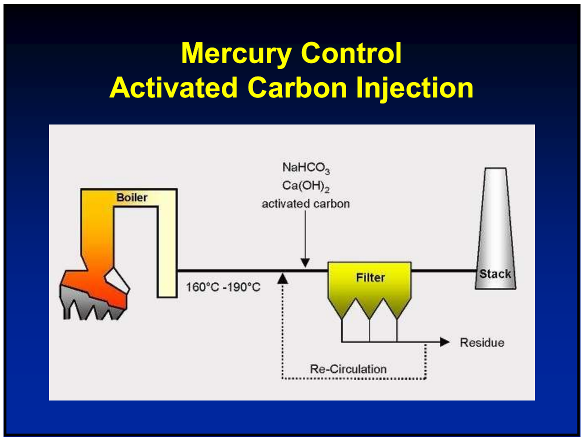


Dry Sorbent Injection



Pensacola's Gulf Power Scrubber

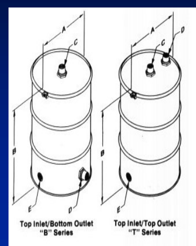
Dry Fork (Wyoming) Station

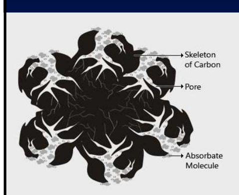

Mercury Control
Activated Carbon Injection
$NaHCO_3$
$Ca(OH)_2$
activated carbon
Boiler
160°C -190°C
Filter
Stack
Residue
Re-Circulation

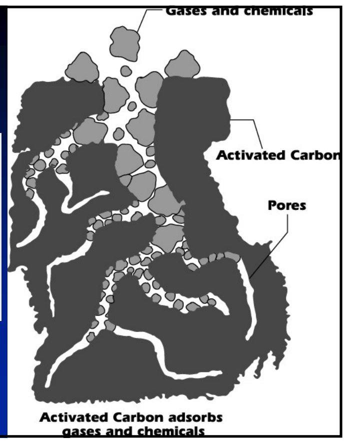

Let's Discuss Carbon Adsorption Systems


Carbon Adsorber

Carbon Adsorber – Fixed Bed Example







Carbon Adsorber

- General description
  - Gas molecules stick to the surface of a solid
  - Activated carbon often used as it
    - Has a strong attraction for organics
    - Has a large capacity for adsorption (many pores)
    - Relatively inexpensive

Carbon Adsorber

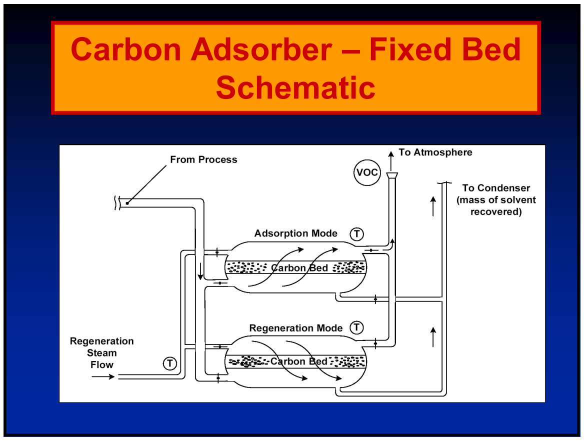
- Activated Carbon is typically made of charcoal
  - Wood
  - Coal
  - Nutshells
  - Coconut shells
- Other Common Types of Adsorbers
  - Silica gel
  - Activated alumina
  - Zeolites

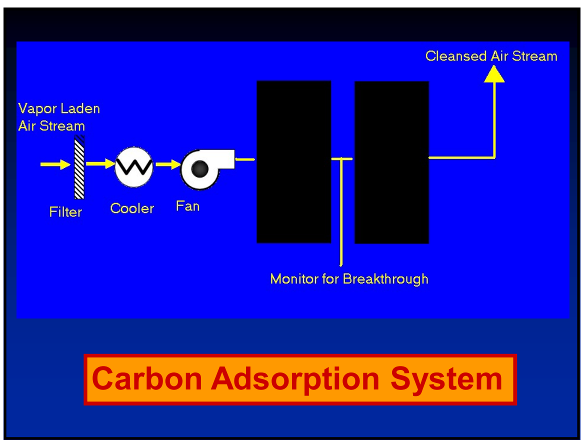
Carbon Adsorber

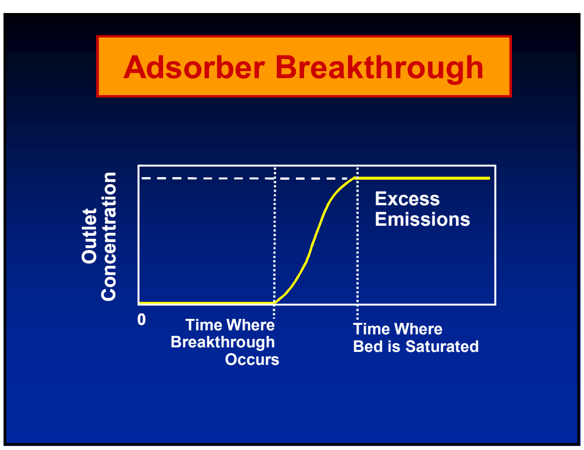
- 3 types – fixed bed (most common), moving bed, and fluidized bed
  - Typically appear in pairs – prevent carbon breakthrough
  - Used for control as well as recovery

Carbon Adsorber

- General description (continued)
  - Regeneration process
    - Steam
    - Hot gas
    - Vacuum
  - Work best if molecular weight of compound between 50 & 200 (depends on source of carbon raw material)


Carbon Adsorber – Fixed Bed Schematic
From Process
VOC
To Atmosphere
To Condenser (mass of solvent recovered)
Adsorption Mode
T
Carbon Bed
Regeneration Mode
T
Carbon Bed
Regeneration Steam Flow
T


Cleansed Air Stream
Vapor Laden Air Stream
Filter
Cooler
Fan
Monitor for Breakthrough
Carbon Adsorption System


Adsorber Breakthrough
Outlet Concentration
Excess Emissions
0
Time Where Breakthrough Occurs
Time Where Bed is Saturated

Carbon Adsorber

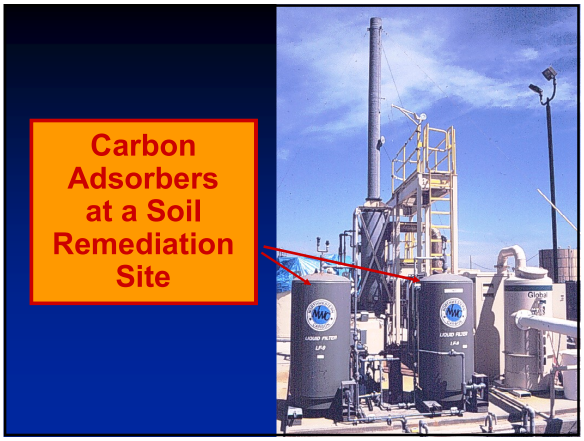
- Factors affecting efficiency
  - Presence, polarity, and concentration of specific compounds
  - Flow rate & channeling
  - Temperature & fouling
  - Relative humidity

Carbon Adsorber

- Performance indicators
  - Outlet VOC concentration
  - Regeneration cycle timing or bed replacement frequency
  - Total regeneration stream flow or vacuum profile during regeneration cycle
  - Bed operating and regeneration temperature

Carbon Adsorber

- Performance indicators
  - Inlet gas temperature
  - Gas flow rate
  - Inlet VOC concentration
  - Pressure differential
  - Inlet gas moisture content
  - Leaks

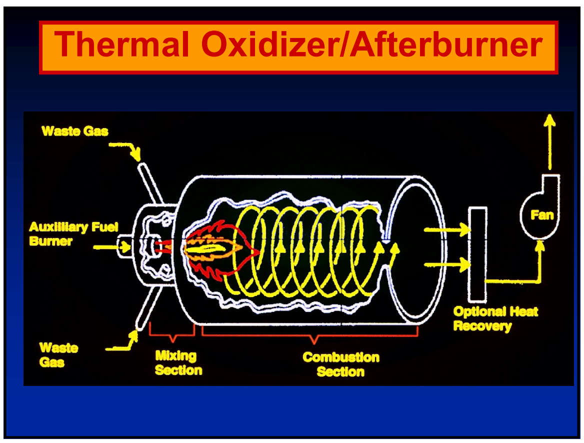


Monitoring Approach – VOC

Indicator	Vacuum	Carbon bed I/M	LDAR
Approach	Pressure transducer	Daily insp. And annual sample	Monthly leak check w. portable analyzer
Indicator range	<2.5 min @ -27.5" Hg, shutdown	Failure to conduct, corrective action and reporting	> 10K ppm, corrective action and reporting

Monitoring Approach – VOC

Indicator	Vacuum	Carbon bed I/M	LDAR
Measuring location	Pump suction line	Visual, bed sample	Handheld monitor
QA/QC	Annual cal.	Training	Method 21
Frequency	Continuous during cycle	Daily and annual	Monthly



Thermal Oxidizer

- General description
  - VOC gas (& organic HAP) gets oxidized to H_2O and CO_2
  - Higher operating temperatures (~ 1400°F to 1800°F)
  - Typically requires auxiliary fuel (natural gas or propane)

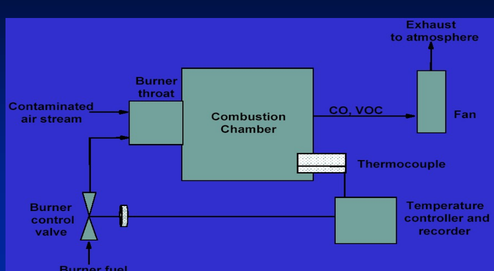
Thermal Oxidizer

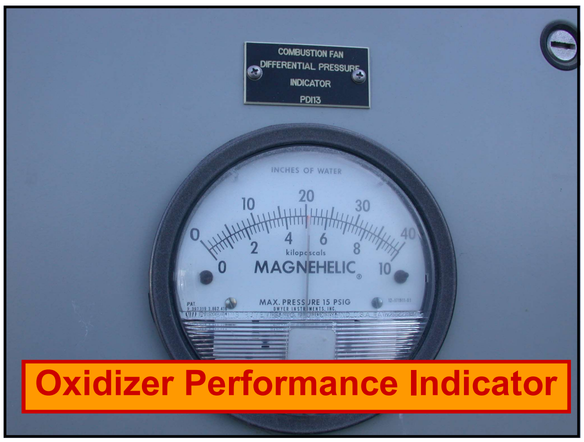
- Good combustion requires
  - Adequate temperature
  - Turbulent mixing of waste gas with oxygen
  - Sufficient time for reactions to occur
  - Enough O_2 to completely combust waste gas

Thermal Oxidizer

- Only temperature and O_2 can be controlled after construction
  - Waste gas has to be heated to autoignition temperature
  - Common design relies on 0.2 to 2 seconds residence time, 2 to 3 length to diameter ratio, and gas velocity of 10 to 50 feet per second

Thermal Oxidizer - Schematic

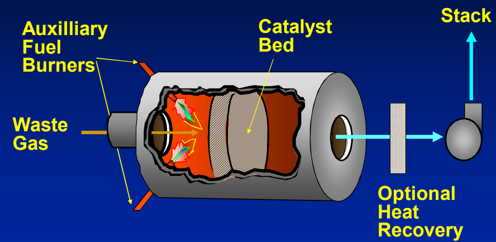




Thermal Oxidizer

- Performance indicators
  - Outlet VOC concentration
  - Outlet combustion temperature
  - Outlet CO concentration
  - Exhaust gas flow rate
  - Outlet O_2 concentration
  - Inspections

Catalytic Oxidizer/Incinerator



Catalytic Oxidizer/Incinerator

- General description
  - VOC gas (& organic HAP) gets oxidized to H_2O and CO_2
  - Catalyst causes reaction to occur faster and at lower temperatures
  - Saves auxiliary fuel

Catalytic Oxidizer/Incinerator

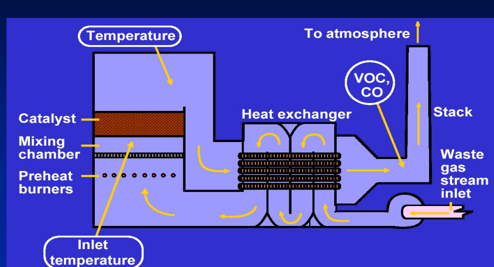
- General description (continued)
  - Catalysts allow lower operation temperatures (~ 600°F to 800°F)
  - Catalyst bed generally lasts from 2 to 5 years
    - Thermal aging, poisoning, and masking are concerns

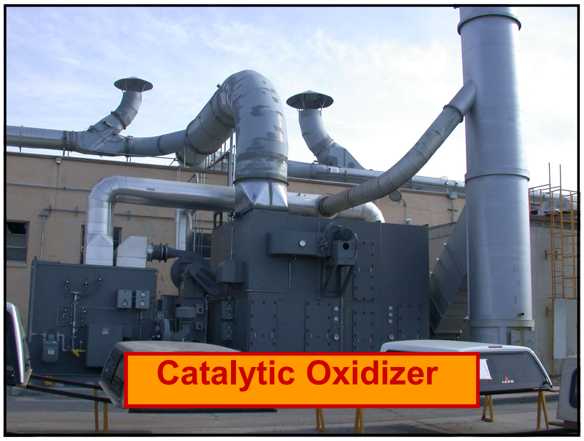
Catalytic Oxidizer/Incinerator

- General description (continued)
  - Excess air is added to assist combustion
    - Residence time and mixing are fixed during design
    - Only temperature and oxygen can be controlled after construction

Catalytic Oxidizer Incinerator Examples

Catalytic Oxidizer Incinerator Schematic





Catalytic Oxidizer/Incinerator

- Factors affecting efficiency
  - Pollutant concentration
  - Flow rate
  - Operating temperature
  - Excess air
  - Waste stream contaminants
    - Metals, sulfur, halogens, plastics

Catalytic Oxidizer/Incinerator

- Performance Indicators
  - Outlet VOC concentration
  - Catalyst bed inlet temperature
  - Catalyst activity
  - Outlet CO concentration
  - Temperature rise across catalyst bed
  - Exhaust gas flow rate

Catalytic Oxidizer/Incinerator

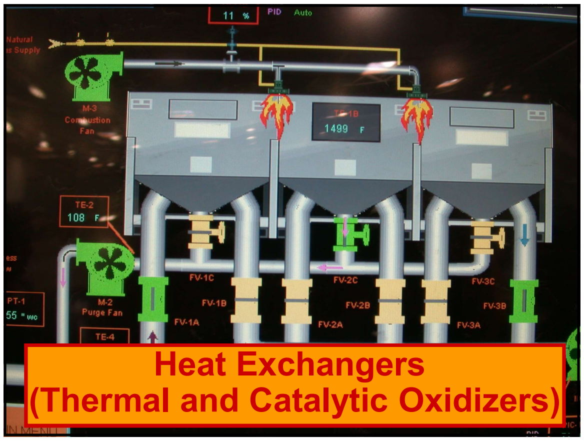
- Performance Indicators (continued)
  - Catalyst bed outlet temperature
  - Fan current
  - Outlet O_2 or CO_2 concentration
  - Pressure differential across catalyst bed

Catalytic Oxidizer – Monitoring Approach

- Key Factors to Consider When Monitoring a Catalytic Oxidizer:
  - Catalyst bed operating temperature (inlet & outlet)
  - Catalyst activity (life) (core sampling & testing)
  - Periodic Inspection
  - Annual performance testing

Catalytic vs. Thermal for VOC Control

Catalytic	Thermal
Lower Operating Temp. & Lower Fuel Usage	Higher Operating Temp. & Higher Fuel Usage
Higher Capital & Maintenance Costs	Lower Capital & Maintenance Costs
Catalyst Fouling & Poisoning	No Catalyst Involved Here

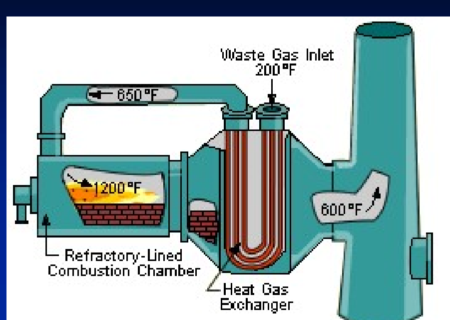


Thermal & Catalytic Oxidizer Heat Exchangers

There are two basic types of heat exchangers used for thermal or catalytic oxidizers

- Metal Heat Exchangers or "recuperative heat exchangers"
- Ceramic Bed Heat Exchangers or "regenerative heat exchangers"

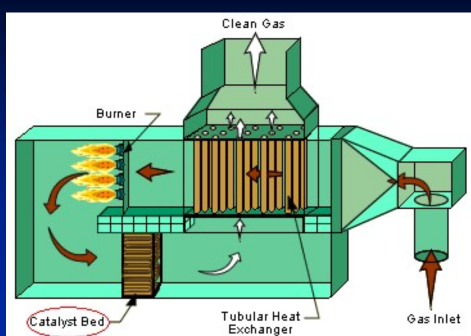
Recuperative TO



TO with Recuperative Heat Exchangers

- Thermal efficiency range of 30% to 70%
- Shell & tube or plate-type
- Usually constructed of alloy steel
- Welded systems have very low leakage rates when new
- Susceptible to cross-leakage as heat exchanger ages
- Not typically used with acid gases
- Susceptible to thermal shock on startup and shutdown

Catalytic Recuperative

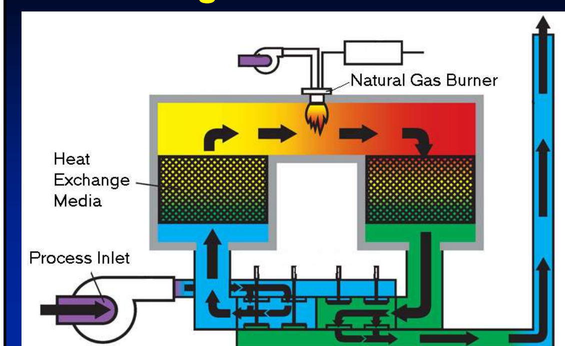


Recuperative TO – Monitoring Approach

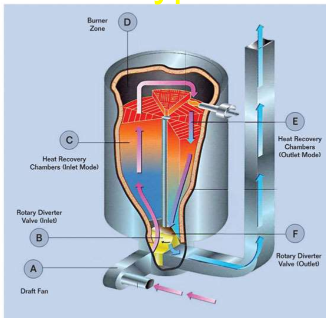
- Key Factors to Consider When Monitoring a Recuperative TO:
  - Annual inspection and/or testing of heat exchanger to assess leakage per manufacturer's recommendations.

Regenerative Thermal Oxidizers

Regenerative TO



Can Type RTO

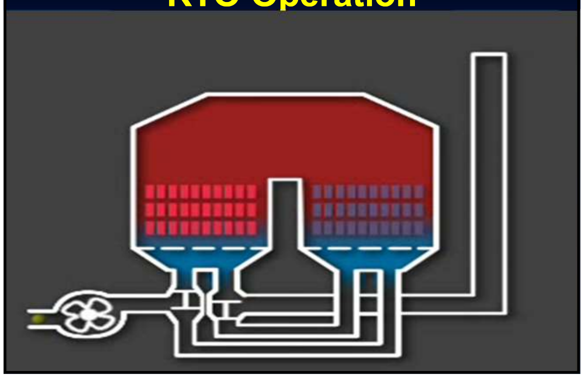


In the regenerative thermal oxidizer, the single rotary valve indexes across an open air path and methodically seals it off by reaching the next set position. A continuous air purge captures any scavenging dirty air in the switch and returns it for treatment in the oxidizer.

Regenerative Thermal Oxidizer (RTO)

- Thermal efficiency range of 80% to 95%
- Can be random packing or structured
- Extremely tolerant of very high temperatures
- Highly resistant to thermal shock
- Can resist corrosion by many acid gases
- May be susceptible to fouling or plugging
- Subject to cross-leakage because of geometry
- May be used with catalysts (RCOs)

RTO Operation



Regenerative Thermal Oxidizer Monitoring Approach

- Key Factors to Consider When Monitoring a Regenerative TO:
  - Assessment of proper closure of valves: Annual inspection/testing
  - Annual documentation of valve timing control system parameters

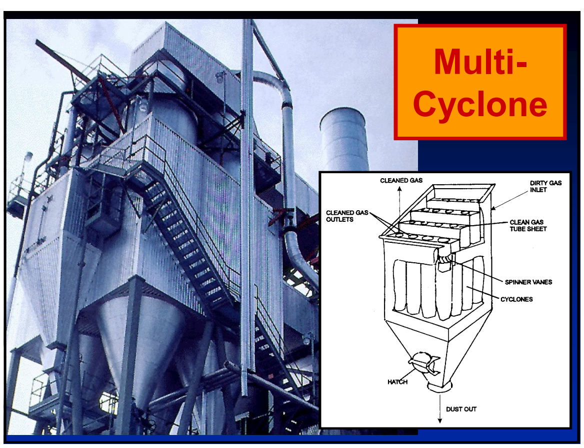
Heat Exchange Problems

- Any cracks or leaks in a recuperative HX will bleed emissions into the clean side
- Uncoordinated valves in a regenerative HX will transfer emissions into the clean air.
- A regenerative HX usually burps some emissions into the clean air each time the valves switch the flow.

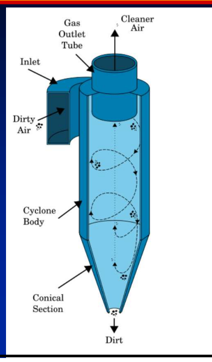
Compliance Issues?


Let's Discuss PM Control
Cyclones
Baghouses
ESPs
Scrubbers
Particulate Filters


Cyclones


Multi-Cyclone
CLEANED GAS
DIRTY GAS INLET
CLEANED GAS OUTLETS
CLEAN GAS TUBE SHEET
SPINNER VANES
CYCLONES
HATCH
DUST OUT

PM Control Techniques - Cyclone

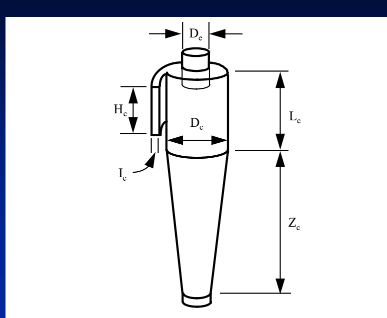


How a Cyclone Works

PM Control Techniques - Cyclone

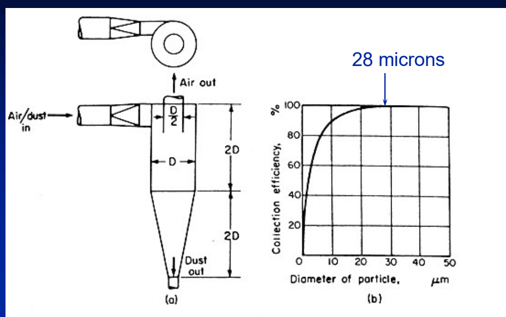
- General description
  - Particles hit wall sides and fall out
  - Often used as precleaners
    - Especially effective for particles larger than 20 microns
  - Inexpensive to build and operate
  - Can be combined in series or parallel

Cyclone - Classification



1D-2D vs. 1D-3D

Cyclone – Control Efficency

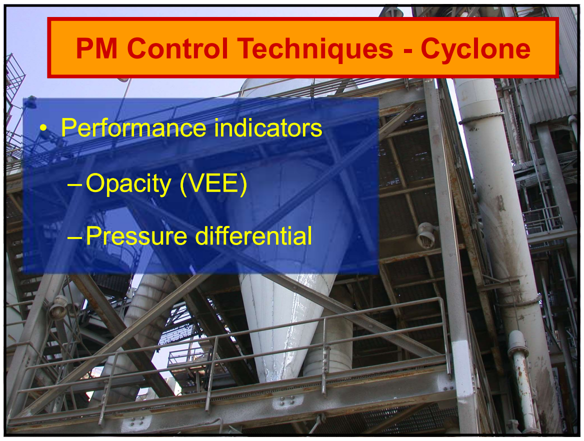


Cyclone – Control Efficency

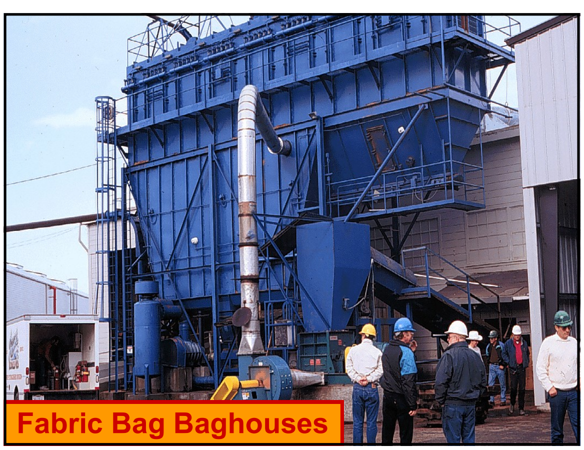
- Conventional Cyclones
  - 30-90% for PM_{10}
  - 0-40% for $PM_{2.5}$
- High Efficiency Single Cyclones
  - 60-95% for PM_{10}
  - 20-70% for $PM_{2.5}$
- Multi-Cyclones
  - 80-95% for PM_5

Cyclone – Failure Modes

- Failure Modes
  - Inlet and outlet plugging
  - Air leakage
    - Component erosion
    - Acid gas corrosion


PM Control Techniques - Cyclone
• Performance indicators
– Opacity (VEE)
– Pressure differential


PM Control Techniques - Baghouses


Fabric Bag Baghouses

PM Control Techniques – Baghouse

- General description
  - Generic name - dust collectors
  - Particles trapped on filter media, then removed
  - Either interior or exterior filtration systems
  - Forced Draft or Induced Draft fan
  - Require a cleaning mechanism

PM Control Techniques – Baghouse

Forced Draft vs. Induced Draft

Fan Type	Pros	Cons
Forced	• Smaller motor • Less expensive • Easy to identify leaks	• Fan Blade Erosion
Induced	• Fan on clean side • Particulate Contained	• Larger motor • More expensive • Harder to indentify leaks

PM Control Techniques – Baghouse

- **Cleaning Mechanisms**

  4 Types

  – Mechanical Shaker (off-line)

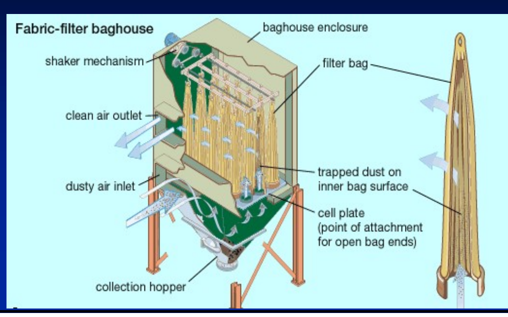
  – Reverse air (low pressure, long time, off line)

  – Pulse jet (60 to 120 psi air, on line)

  – Sonic horn (150 to 550 Hz @ 120 to 140 dB, on line) – rarely used alone

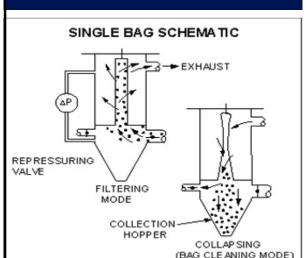
Baghouse Cleaning Methods

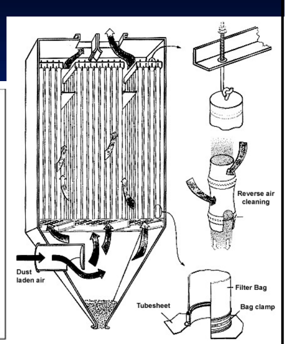
Mechanical Shaker



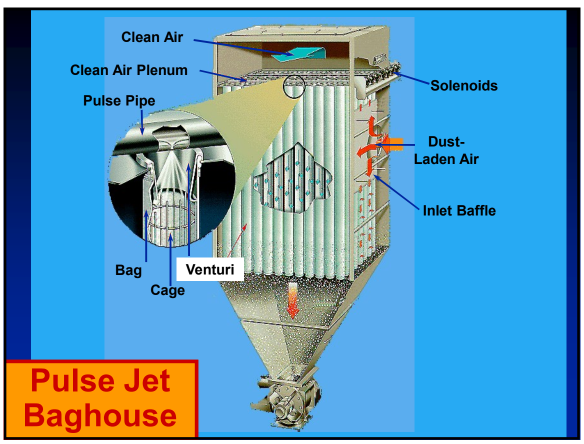
Baghouse Cleaning Methods

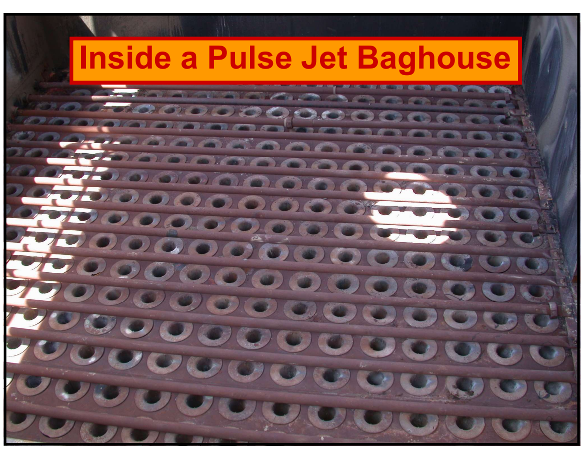
Reverse Air






Baghouse Cleaning Methods
Sonic Horns


Clean Air
Clean Air Plenum
Pulse Pipe
Solenoids
Dust-
Laden Air
Inlet Baffle
Bag
Venturi
Cage
Pulse Jet
Baghouse

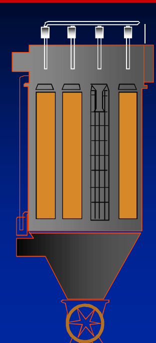

Inside a Pulse Jet Baghouse

Control Efficiency - Baghouse

- Conventional Baghouses
  - 95% - 99.9% for PM_{10}
  - 95% - 99% for $PM_{2.5}$
- High Efficiency Particle Air (HEPA)
  - 99.97% for $PM_{0.3}$
- Ultra Low Penetration Air (ULPA)
  - 99.9995% for $PM_{0.12}$

Baghouse Design Considerations

- Pressure Drop
- Air-To-Cloth Ratio
- Collection Efficiency
- Fabric Type
- Cleaning
- Temperature Control
- Space and Cost



Causes of Failure - Baghouse

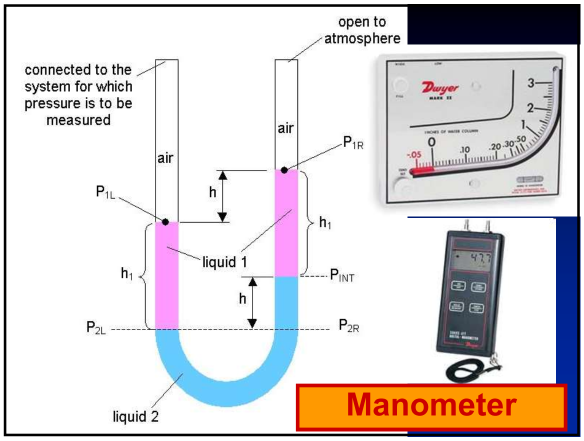
- Bag
  - Abrasion
  - High temperature
  - Chemical attack
  - Concretion of particulate
- Plenum
  - Abrasion
  - Chemical attack
  - Corrosion
- Outer Wall
  - Abrasion
  - Chemical attack
  - Corrosion
  - Physical Damage

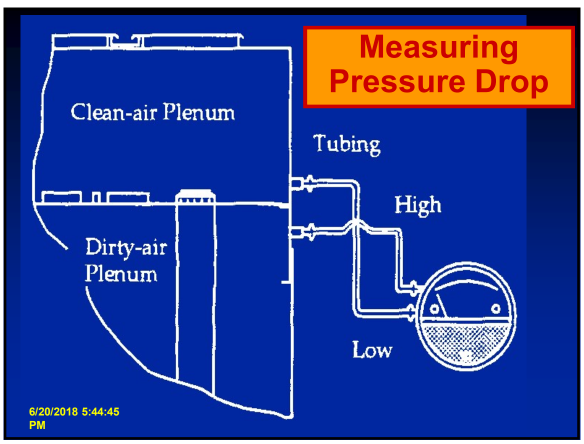
Baghouse – Performance Indicators

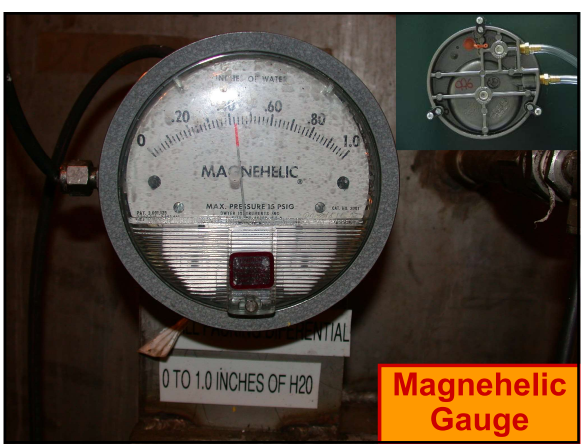
- Performance indicators
  - Outlet opacity (VEE)
  - Pressure differential
  - Outlet PM concentration (COMS)
  - Bag leak detectors
  - Exhaust gas flow rate
  - Cleaning mechanism operation
  - Inspections and maintenance

Monitoring Equipment

- Magnehelic or Manometer (ΔP)
- Continuous Opacity Monitoring Systems (COMS)
- Tribo Electric Sensors


open to atmosphere
connected to the system for which pressure is to be measured
air
air
P_{1R}
P_{1L}
h
h_1
liquid 1
h_1
P_{INT}
h
P_{2L}
P_{2R}
liquid 2
Manometer


Measuring Pressure Drop
Clean-air Plenum
Tubing
High
Dirty-air Plenum
Low
6/20/2018 5:44:45 PM


MAGNEHELIC
0 TO 1.0 INCHES OF H20
Magnehelic Gauge

Baghouse Pressure Drop

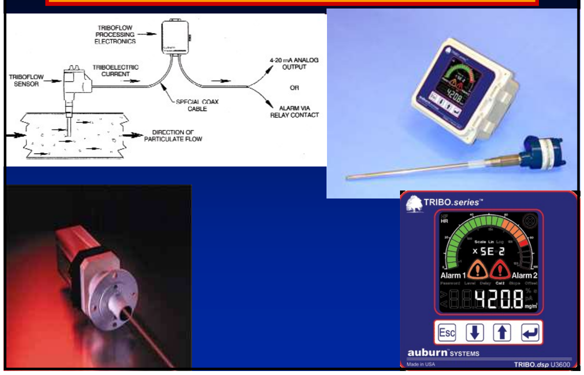
- ΔP shows air flow – it's in operation
- ΔP may fluctuate 10% as a function of the bag cleaning cycle.
- Continued rise in ΔP will result from bags that become permanently plugged (blinded).
- High ΔP will lead to premature bag failure.
- Daily/weekly record of ΔP can be a useful monitoring tool

PM COMS

Opacity

- Not very sensitive – shows a gross failure.
- Baseline (new) bag house opacity is probably << 1%
- Emissions must increase about 10x to be visible.
- Opacity useful where particulate emissions limit is high.

Triboelectric Sensors



Baghouse Monitoring

- Normal baghouse emissions are very low.
  - Opacity sensors (COM) aren't very good below 1-2%, so they don't detect initial problems.
  - Opacity will show a major particulate emissions increase.
  - COM or Method 9 may be OK for loose emission limits.

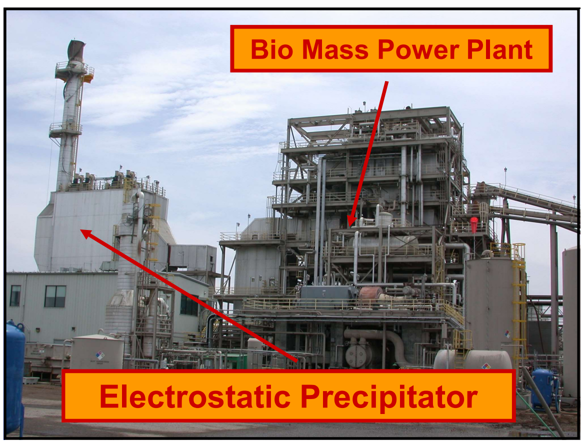
Tribo Electric Sensors

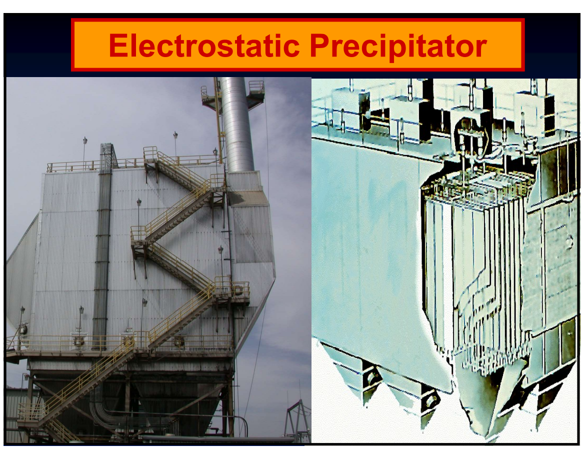
- Tribo electric sensors (TES) work well at very low particle concentrations (very sensitive).
- TES detects micro amp current from particles hitting a metal probe.
- TES is simple and inexpensive.
- TES is an effective monitor when a small to moderate increase in emissions is of concern.

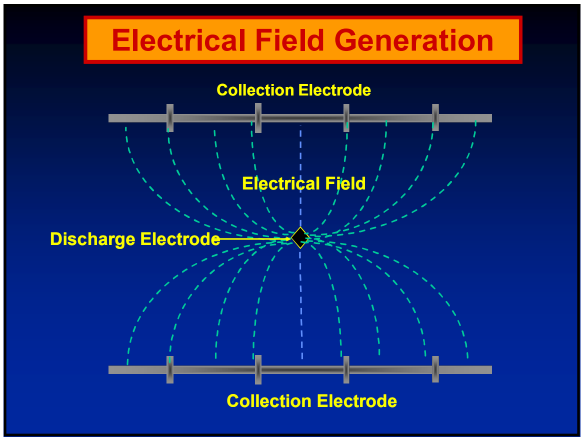
BH Monitoring Summary

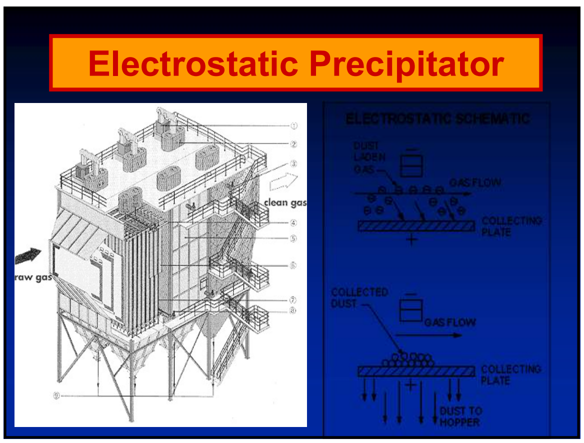
- Use TES for sensitive indication of changes in particulate emissions
- Opacity will indicate large increases in particulate emissions.
- An increasing pressure drop is indicative of long term problems

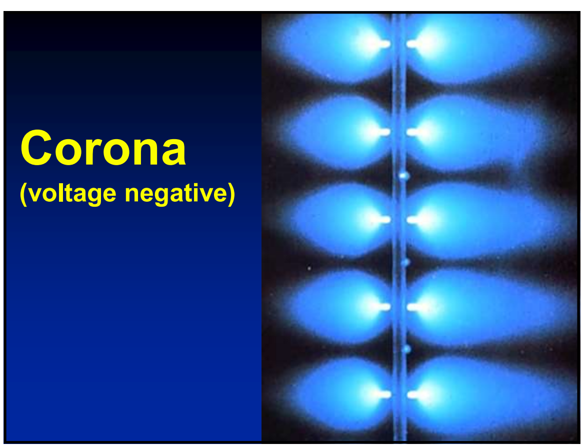

Prometheus Tree – 4,844 years old

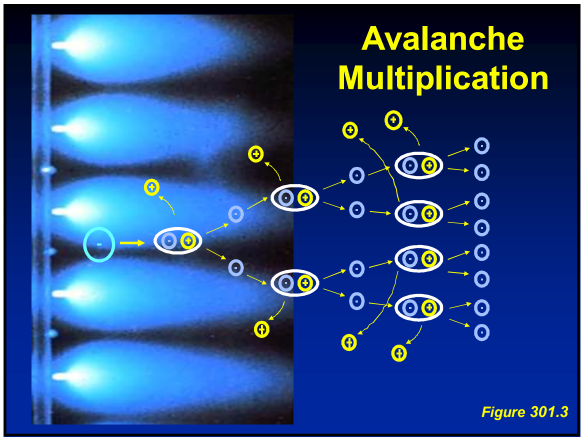

Bio Mass Power Plant
Electrostatic Precipitator

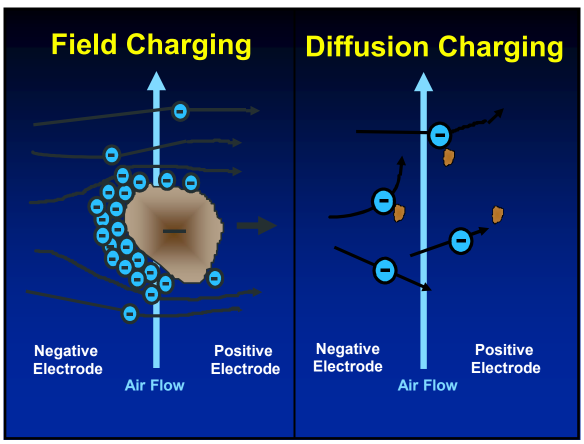

Electrostatic Precipitator

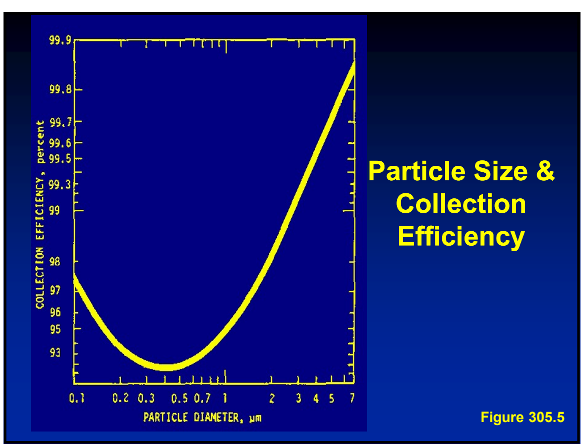

Electrical Field Generation
Collection Electrode
Electrical Field
Discharge Electrode
Collection Electrode


Electrostatic Precipitator
clean gas
raw gas
ELECTROSTATIC SCHEMATIC
DUST LADEN GAS
GAS FLOW
COLLECTING PLATE
COLLECTED DUST
GAS FLOW
COLLECTING PLATE
DUST TO HOPPER


Corona
(voltage negative)


Avalanche Multiplication
Figure 301.3


Field Charging
Negative Electrode
Positive Electrode
Air Flow
Diffusion Charging
Negative Electrode
Positive Electrode
Air Flow


Particle Size & Collection Efficiency
COLLECTION EFFICIENCY, percent
99.9
99.8
99.7
99.6
99.5
99.3
99
98
97
96
95
93
0.1
0.2
0.3
0.5
0.7
1
2
3
4
5
7
PARTICLE DIAMETER, µm
Figure 305.5

Electrostatic Precipitator

- General Description
  - Two types
    - Dry type use mechanical action to clean plates
    - Wet type use water to prequench and to rinse plates

Electrostatic Precipitator

- General Description
  - High voltages are required
    - 20,000 – 100,000 VDC
  - Multiple sections (fields) may be used
  - They usually can meet emission target with one field out of service or operating at reduced power

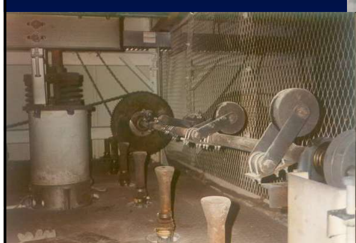
Electrostatic Precipitator

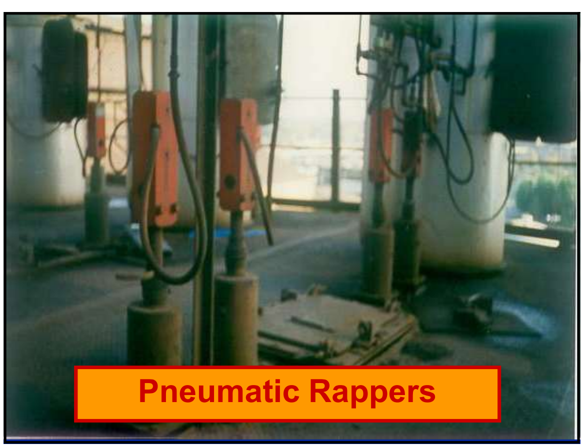
- General Description
  - High airflow rates
    - 200,000 – 1,000,000 scfm
  - High temperatures
    - Up to 1,300 °F
  - Pollutant Loading
    - 1 – 50 grains/scfm

Electrostatic Precipitator

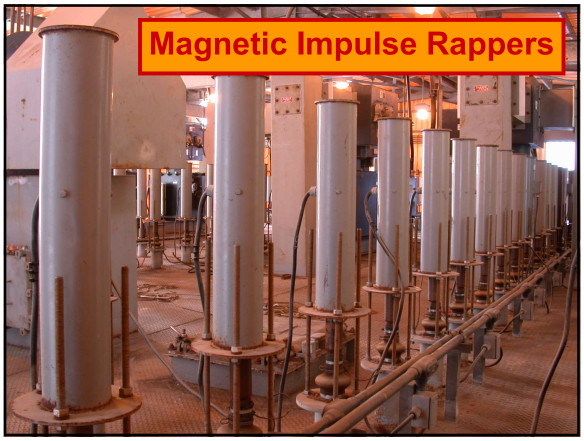
- A high voltage field creates a corona (current)
  - Particles are charged by electrons in the corona
  - The DC field draws charged particles to the plate
- Dust layers on the plates are cleared by mechanical rapping. Dust falls into the hoppers.
- Several fields in the direction of flow
  - Voltage/current to each is separately controlled
  - The first field collects most of the dust (75%)
  - Not much dust left in the last field

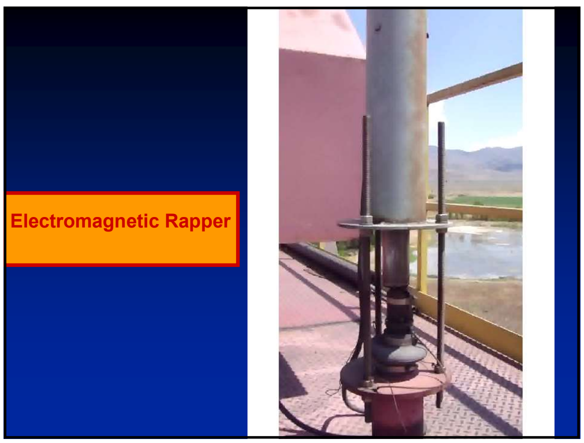
Mechanical Tumbling Hammer Rappers





Pneumatic Rappers


Magnetic Impulse Rappers


Electromagnetic Rapper


Control Efficiency - ESPs
• Older Existing ESPs
–90% - 99.9% for PM10
• Typical New ESPs
–99% - 99.9% for PM10

ESPs: Design Factors Affecting Performance

- Specific Collection Area
- Aspect Ratio
- Collection Plate Spacing
- Sectionalization
- Power Requirements/Spark Rate

Electrostatic Precipitator

- Factors affecting efficiency
  - Gas temperature, humidity, flow rate
  - Particle resistivity
  - Fly ash/Fuel composition
  - Plate length
  - Surface area

Electrostatic Precipitator

- Factors affecting efficiency
  - ESP is sensitive to gas flow rate
  - Flow monitoring may be appropriate
  - An ESP won't work well if the velocity distribution is not uniform.
- ESP internal factors
  - Dust layer thickness & electrical resistance.
  - Changes in geometry (damage)
  - Air leaks, condensation

Electrostatic Precipitator

Baseline operating and emission data is needed to establish:

- Emissions level and control capability at max gas flow.
  - Does it work as intended?
  - Typical secondary current and voltage levels
- Operating margin - number of fields and power required to meet emission requirements.
- Normal operating temperature.

Electrostatic Precipitator

- Performance indicators
  - Outlet opacity (VEE)
  - Pressure differential
  - Outlet PM concentration (COMS)
  - Secondary corona power (current & voltage)
  - Spark rate
  - Primary power (current & voltage)

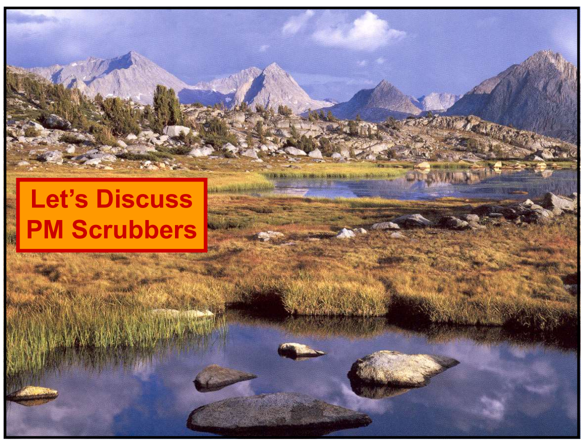
ESP: Performance Indicators

Electrostatic Precipitator

- Performance indicators (cont.)
  - Inlet gas temperature
  - Gas flow rate
  - Rapper operation
  - Fields in operation
  - Inlet water flow rate (wet type)
  - Flush water solids content (wet type)

Summary of ESP Monitoring

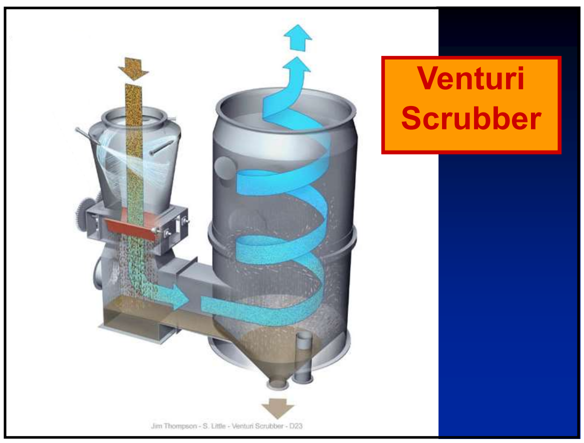
- Obtain convincing baseline emissions data
  - Linked to flow rate, power levels and type of fuel
- Key monitoring parameters
  - Opacity
  - Electrical power levels (Secondary I & V)
- Secondary parameters
  - Temperature
  - Fuel composition
  - Inspection & routine maintenance

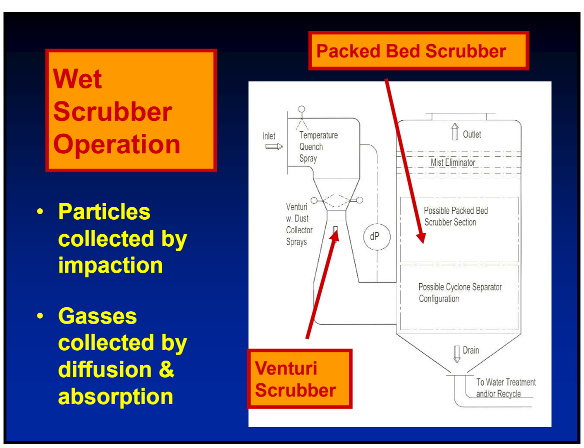


Control Techniques – Wet Scrubber

- General description
  - Particles (and gases) get trapped in liquids
    - Inertial impaction and diffusion
  - Liquids must contact pollutants and dirty liquids must be removed from exhaust gas
  - Four types
    - Spray; venturi or orifice; spray rotors; and moving bed or packed towers


Venturi Scrubber


Venturi Scrubber


Wet Scrubber Operation
• Particles collected by impaction
• Gasses collected by diffusion & absorption
Packed Bed Scrubber
Inlet
Temperature Quench Spray
Outlet
Mist Eliminator
Venturi w. Dust Collector Sprays
dP
Possible Packed Bed Scrubber Section
Possible Cyclone Separator Configuration
Drain
To Water Treatment and/or Recycle
Venturi Scrubber

Venturi Scrubbers

- Control Efficiency
  - 70 - 99% for PM_{10}
- Moderate airflow rates
  - 500 – 100,000 scfm
- Moderate temperatures
  - Up to 750 °F
- Pollutant Loading
  - 0.1 – 50 grains/scfm

Scrubber Control Efficiency

- **Factors affecting efficiency**
  - **Gas and liquid flow rate**
  - **Condensation of aerosols**
  - **Poor liquid distribution**
  - **High dissolved solids content in liquid**
  - **Nozzle erosion or pluggage**
  - **Re-entrainment**
  - **Scaling**

Scrubber Monitoring

- **Venturi pressure drop (ΔP)**
  - **The higher the ΔP the smaller the collected particles**
  - **Some venturis have adjustable vanes**
- **Water flow rate (gallons/min)**
  - **Flow below a critical level will degrade performance.**
- **Water cleanliness – evaporated residue & mist carryover.**

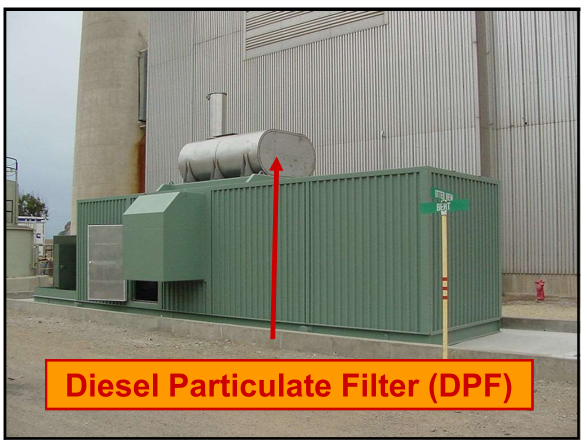
Scrubber Performance

- Performance indicators
  - Pressure differential
  - Liquid flow rate
  - Gas flow rate
  - Scrubber outlet gas temperature
  - Makeup / blowdown rates
  - Scrubber liquid solids content (PM)

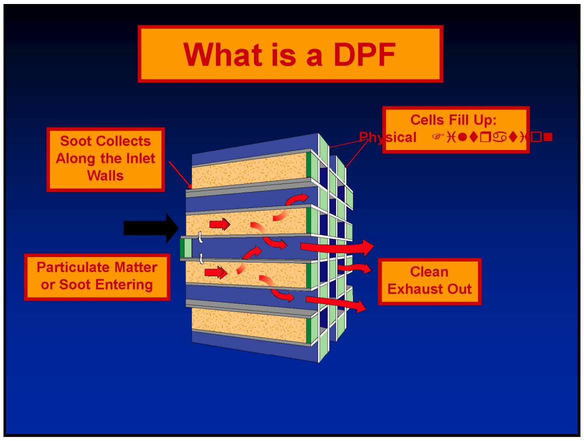
Scrubber Performance

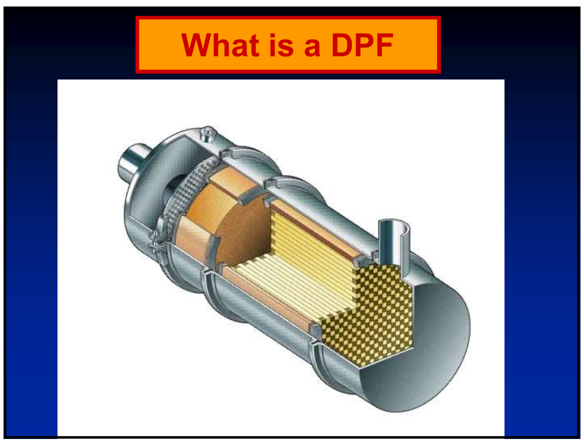
- Performance indicators (continued)
  - Scrubber inlet gas and process exhaust gas temperature (PM)
  - Scrubber liquid pH (Acid gas)
  - Neutralizing chemical feed rate (Acid gas)
  - Scrubber liquid specific gravity (Acid gas)

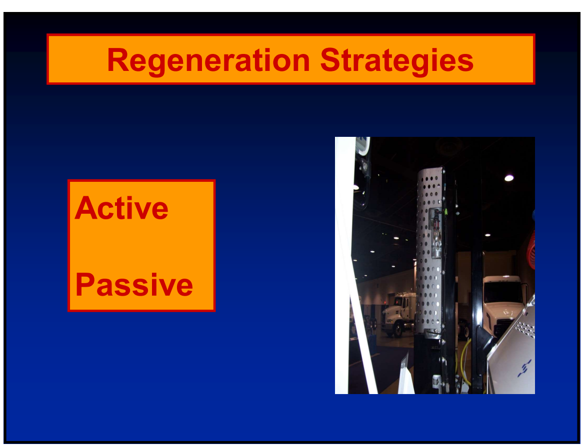

Let's Discuss Diesel
Particulate Filters


Diesel Particulate Filter (DPF)


Diesel Particulate Filter


What is a DPF
Soot Collects Along the Inlet Walls
Cells Fill Up:
Physical
Particulate Matter or Soot Entering
Clean Exhaust Out


What is a DPF


Regeneration Strategies
Active
Passive

Diesel Particulate Filter (DPF)

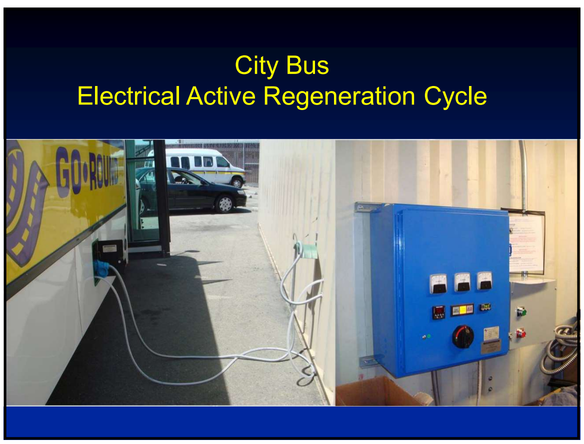
- High temperature regeneration (600-650 °C) C + O2 → CO2
- Catalytic regeneration (~250 °C)
- Oxidize NO to NO_2 → adsorbs → reduces regeneration temperature
- Fuel-borne catalyst
- Ceramic coatings
- Engine adjustments necessary
- Total PM efficiency > 90%

Active Regeneration

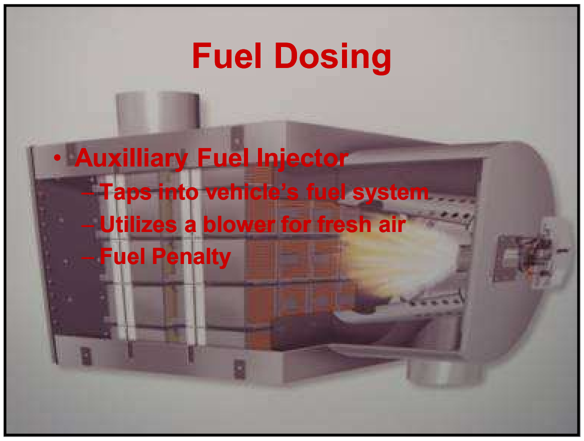
- Achieving 550ºC
  - Electrical Heater
  - Dosing (flame front)

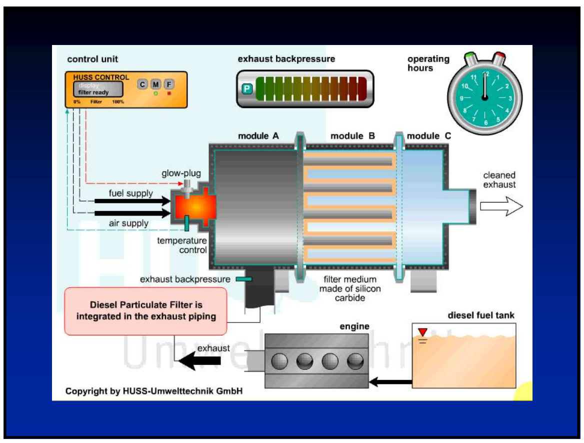
Electrical Heater

- Uses a heating element similar to an electric stove
- Performed while vehicle is offline


City Bus
Electrical Active Regeneration Cycle


Portable On-Board


Fuel Dosing
• Auxilliary Fuel Injector
– Taps into vehicle's fuel system
– Utilizes a blower for fresh air
– Fuel Penalty

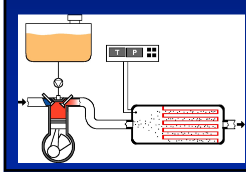

control unit
HUSS CONTROL
exhaust backpressure
operating hours
module A
module B
module C
glow-plug
fuel supply
air supply
temperature control
cleaned exhaust
exhaust backpressure
filter medium made of silicon carbide
Diesel Particulate Filter is integrated in the exhaust piping
engine
exhaust
diesel fuel tank
Copyright by HUSS-Umwelttechnik GmbH

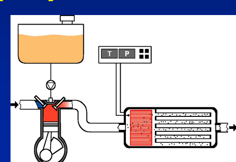
Active Regeneration (O_2 @ 550º C)

- Electrical
  - Online Electrical (Rypos)
  - Offline/Off-board
  - Offline/On-board
- Fuel Dosing
  - Flame front using auxiliary injection and vehicle's fuel supply
  - Air intake

Passive Regeneration

- NO2 oxidizes soot @ around 250º C
- NO2 generation
  - Diesel Oxidation Catalysts
  - Catalyzed Filters
  - Fuel Born Catalysts (FBC)?





Soot & Ash

Definition of Soot

Soot is a byproduct of incomplete combustion

Soot Cleaning

- DPF Collects the soot
- Elevated exhaust temperatures convert the soot to vapor

Definition of Ash

Ash is Noncombustible residue of a lubricating oil or fuel

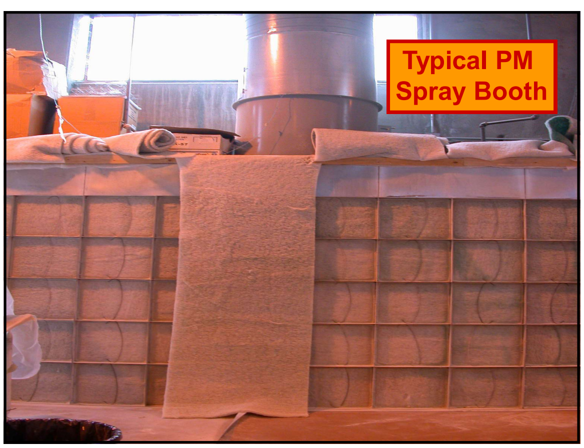
Ash Cleaning

- DPF Collects the ash
- Ash is removed using a special service tool

Aftertreatment Regeneration Device (ARD)

- What is ARD?
  - ARD is the device that increases exhaust gas temperature to enable regenerate the DPF
- What are the benefits of the CRS System?
  - Regenerates under all conditions

Comical Relief




Spray Booth
Filter Inspection

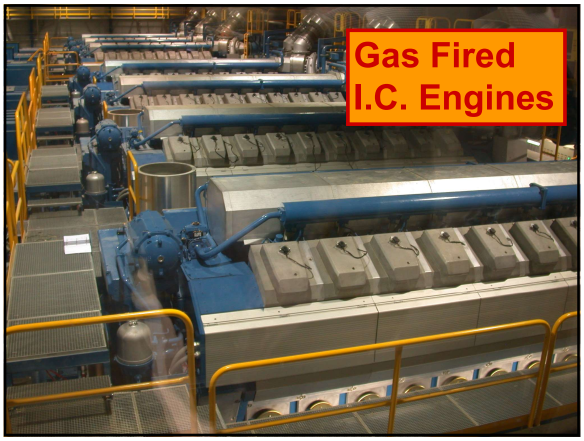

Spray Booth
Filter Inspection


Spray Booth
Filter Inspection


PM Control: Wet Suppression

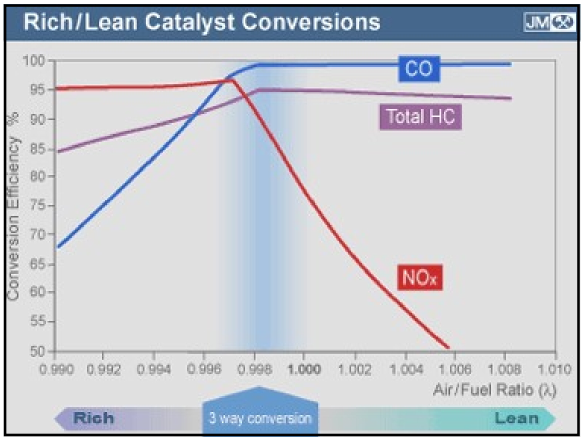

PM Control: Wet Suppression

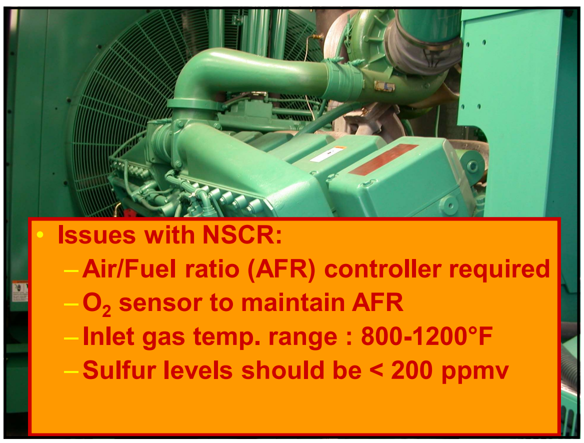

Gas Fired
I.C. Engine
Controls



3-way Catalyst:
Non-Selective Catalytic Reduction

- Rich burn/NG fired engine
- $2CO + 2NO \rightarrow 2CO_2 + N_2$
- $NO + HC + O_2 \rightarrow N_2 + CO_2 + H_2O$
- 98% control for NO_X & CO


Rich/Lean Catalyst Conversions
CO
Total HC
NOx
Conversion Efficiency %
100
95
90
85
80
75
70
65
60
55
50
0.990 0.992 0.994 0.996 0.998 1.000 1.002 1.004 1.006 1.008 1.010
Air/Fuel Ratio (λ)
Rich
3 way conversion
Lean


Issues with NSCR:
– Air/Fuel ratio (AFR) controller required
– O2 sensor to maintain AFR
– Inlet gas temp. range : 800-1200°F
– Sulfur levels should be < 200 ppmv


SCR Catalyst for IC Engines

Comparison of NOx Control Technologies – Gas-Fired Boilers

Technology	Approx. Reduction	Approx. lbs/MMBTU	Approx. ppmv @ 3% O2
Standard burners	Base case	0.14	120
Low NOx burners	60%	0.06	45
Ultra Low NOx Burners – 1st gen.	80%	0.03	25
Ultra Low NOx Burners – 2nd gen.	95%	0.007	6
FGR	55%	0.025	20
Compu- NOx w/ FGR	90%	0.015	12
SNCR	40%	0.033 - 0.085	27 - 70
Catalytic Scrubbing	70%	0.017 - 0.044	14 - 36
SCR	90 – 95%	0.006 - 0.015	5 - 12