Introduction to Control Devices

National Training Program

NACT 299
Introduction to Control Devices

House Keeping

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

Control Equipment

♦ Particulate Matter
♦ VOC
♦ SOx - FGD
♦ CO
♦ NOx
Combustion Considerations

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

Let's Discuss CO Catalyst

CO Catalyst
- \(2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2\)
- 700 to 1000 °F operating temp
- 90% plus efficiency
- Pressure drop 1-2 in. H₂O
- Problems
  - Expensive
  - High maintenance
  - Catalyst replacement
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Let’s Discuss NOx Control

- Formation of NOx
- Low-NOx combustion techniques
- Ammonia injection (SCR & SNCR)
- Catalytic controls
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Thermal NOx
Fuel-bound NOx
Prompt NOx

NOx vs. Temperature

NOx Creation

Babcock & Wilcox Utility Boiler
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Staged Combustion with Overfire Air

Fire-Tube Boiler

Low-NOx Burner with Staged Fuel
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Low-NOx Burner with Staged Fuel

Ultra Low-NOx Burner (9 ppm)
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Flue Gas Recirculation

Compu-NOx System

NOx Reduction by Boiler Configuration

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
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Water Injection

Gas Nozzle

Water Nozzle

NOx, CO, and Unburned HC vs. Water Injection
Effect of Water/Fuel Ratio on NOx, Thermal Efficiency, and Power Output

Let’s Discuss SCR

SCR - Introduction

Overview of the SCR Process

\[ \text{NO} + \text{NH}_3 + \frac{3}{4} \text{O}_2 \rightarrow \text{N}_2 + 1.5\text{H}_2\text{O} \quad (1)* \]
\[ 6\text{NO} + 8\text{NH}_3 \rightarrow 7\text{N}_2 + 6\text{H}_2\text{O} \quad (2) \]
\[ 2\text{NO} + 4\text{NH}_3 + \text{O}_2 \rightarrow 3\text{N}_2 + 6\text{H}_2\text{O} \quad (3) \]

* The vast majority of NO\(_x\) is in the form of NO, so reaction (1) dominates.
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**SCRT®**
Johnson Matthey

\[2 \text{NH}_3 + \text{NO} + \text{NO}_2 \rightarrow 2 \text{N}_2 + 3 \text{H}_2\text{O}\]

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**Selective Catalytic Reduction (SCR)**

- 65-90% control
- Problems
  - Expensive
  - High maintenance
  - Ammonia “slip”
  - Catalyst replacement & disposal

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**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
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Combined Cycle Power Plant w/SCR

Small Boiler with SCR

NH₃ Manifold
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SCR Catalyst

Utility Boiler with SCR

SCR Catalyst

NH₃ Injection: (Uniform NH₃/NOₓ Critical)

Turning Vanes to give uniform velocity across the Catalyst

Catalyst Layer(s)
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**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
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Typical Catalyst Deactivation Rates

NOx 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

Let's Discuss SNCR

Boiler with SNCR
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**SNCR Process**
- Chemical Injection
- Gas Phase Reaction Between the Injected Chemical and NOx
- Reactions Occur in the Temperature Region of 1600-2100 F
- Furnace is the Chemical Reactor

**SNCR Process**
- 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**
- Ammonia
  - NH₃
  - NO₂ + OH → N₂O₂ + H₂O
  - N₂O₂ + NO → N₂ + H₂O
  - N₂O + OH → N₂ + HO₂
  - N₂O + M → N₂ + …..
- Urea
  - NH₂CONH₂
  - NO₂ + OH → N₂O₂ + H₂O
  - N₂O₂ + NO → N₂ + H₂O
  - N₂O + OH → N₂ + HO₂
  - N₂O + M → N₂ + …..
  - N₂O + H₂ → N₂ + OH
  - N₂O + CO → N₂ + CO₂

Catalyst
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Detailed SNCR Mechanism

Ammonia vs. Urea

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ammonia</th>
<th>Urea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form</td>
<td>High Vapor Pressure Liquid Ammonia/Water Solution</td>
<td>Liquid Solution</td>
</tr>
<tr>
<td>Safety</td>
<td>Anhydrous/29.4%- Aqueous – Safety Issue</td>
<td>19% Aqueous – Fewer Safety Issues</td>
</tr>
<tr>
<td></td>
<td>Anhydrous – Aqueous – Atmospheric Pressure</td>
<td>Atmospheric Pressure Crystallization at Low Temps.</td>
</tr>
<tr>
<td>Injectors</td>
<td>Needs Carrier Gas</td>
<td>Atomizer (Pressure or Twin Fluid)</td>
</tr>
<tr>
<td>Temperature</td>
<td>Peak Removal @ 1750°F</td>
<td>Peak Removal @ 1850°F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large Dilute Drops Should Urea</td>
</tr>
<tr>
<td>System Complexity</td>
<td>Relatively Simple</td>
<td>Relatively Simple</td>
</tr>
</tbody>
</table>

SCR vs. SNCR

SNCR vs. SCR

NH₃/NOₓ, molar

NOₓ Reduction, %

0 20 40 60 80 100

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
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### SCR vs. SNCR

<table>
<thead>
<tr>
<th>Feature</th>
<th>SNCR</th>
<th>SCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx Reduction</td>
<td>20-50%</td>
<td>60-95%</td>
</tr>
<tr>
<td>Hardware</td>
<td>Simple</td>
<td>More Complex</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>Low (1)</td>
<td>High (6-10)</td>
</tr>
<tr>
<td>Reagent Utilization</td>
<td>35%</td>
<td>Almost 100%</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Reagent</td>
<td>Reagent/Catalyst</td>
</tr>
<tr>
<td>Designability</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>NH3 slip</td>
<td>5-20 ppm</td>
<td>&lt;1 ppm</td>
</tr>
</tbody>
</table>

### NH₃ Emissions Limits

- **Regulatory Limit**
- **NH₃/SO₃ Reactions**
  - Ammonium Bisulfate: \( \text{NH}_3 + \text{SO}_3 \rightarrow \text{NH}_4\text{HSO}_4 \)
  - Ammonium Sulfate: \( 2\text{NH}_3 + \text{SO}_3 \rightarrow (\text{NH}_4)\text{SO}_4 \)
- **NH₃/Ash Absorption** (issue for coal-fired utility units that sell their ash for making cement)
- **NH₃/HCl Reactions** (detached plume)
  - \( \text{NH}_3/\text{HCl} \rightarrow \text{NH}_4\text{Cl(g)} \)

### Comparison of NOx Control Technologies – Gas-Fired Boilers

<table>
<thead>
<tr>
<th>Technology</th>
<th>Approx. Reduction</th>
<th>Approx. lbs/MMBTU</th>
<th>Approx. ppbv @ 3% O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard burners</td>
<td>Base case</td>
<td>0.14</td>
<td>120</td>
</tr>
<tr>
<td>Low NOx burners</td>
<td>50%</td>
<td>0.05</td>
<td>45</td>
</tr>
<tr>
<td>Ultra Low NOx Burners - 1st gen.</td>
<td>85%</td>
<td>0.03</td>
<td>25</td>
</tr>
<tr>
<td>Ultra Low NOx Burners - 2nd gen.</td>
<td>95%</td>
<td>0.007</td>
<td>6</td>
</tr>
<tr>
<td>FGR</td>
<td>55%</td>
<td>0.025</td>
<td>10</td>
</tr>
<tr>
<td>Compr NOx w/ FGR</td>
<td>90%</td>
<td>0.014</td>
<td>10</td>
</tr>
<tr>
<td>SNCR</td>
<td>40%</td>
<td>0.033 - 0.055</td>
<td>27 - 70</td>
</tr>
<tr>
<td>Catalytic Scrubbing</td>
<td>70%</td>
<td>0.017 - 0.044</td>
<td>14 - 36</td>
</tr>
<tr>
<td>SCR</td>
<td>90 - 95%</td>
<td>0.006 - 0.015</td>
<td>5 - 12</td>
</tr>
</tbody>
</table>
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Let's Discuss Particulate & NH₃ Controls

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
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**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$_4$Cl) which are also considered as “particulates”

**Ammonia Slip**

- $\text{NH}_3 + \text{OH} \rightarrow \text{NH}_2 + \text{H}_2\text{O}$
- $\text{NH}_2 + \text{NO} \rightarrow \text{N}_2 + \text{H}_2\text{O}$
- $2\text{NH}_3 + \text{OH} + \text{NO} \rightarrow 2\text{H}_2\text{O} + \text{N}_2 + \text{NH}_3$
- 10 to 25 ppm NH$_3$ Slip
- Could be higher
- Always have Some NH$_3$ slip
**NH₃ (g) + HCl (g) => NH₄Cl(s)**

- NH₃ 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

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**NH₄Cl Formation**

- Function of the concentrations of NH₃ and HCl
- Concentrations decrease as air is mixed into the plume
- Lower concentrations => less NH₄Cl formed
- Therefore: air dilution is good

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**What Can Be Done??**

- Minimize (eliminate Cl) in fuel
- Install acid gas controls
- Minimize NH₃ 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 ??
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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

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
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Containment Strategy

Solvent Reclaim System

Is this well contained?

VOC Disposal System

VOC Collection System
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Look for housekeeping habits

Capture and Control

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)
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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

• Performance indicators
  – Enclosures
    • Face velocity
    • Differential pressure
    • Average face velocity and daily inspections
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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)
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Packed Bed Scrubber

Typical packed scrubber

- Exhaust gases
- Mist eliminator
- Spray bars
- Packing
- Scrubber inlet
gas
- Slurry tank

Recirculation liquid pumping system and liquor make-up

Typical Packing Material

- Liquor flow and pH monitoring

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Atomizing Spray Nozzles

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 – SO₂

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Slurry pH</th>
<th>Slurry flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indicator range</td>
<td>&lt;9.0 - corrective action, reporting</td>
<td>&lt;175 – corrective action, reporting</td>
</tr>
<tr>
<td>Measurement location</td>
<td>Recirculation line</td>
<td>Recirculation line</td>
</tr>
<tr>
<td>QA/QC</td>
<td>Annual cal.</td>
<td>Annual cal.</td>
</tr>
<tr>
<td>Frequency</td>
<td>1/15 minutes</td>
<td>1/15 minutes</td>
</tr>
<tr>
<td>Averaging time</td>
<td>hourly</td>
<td>hourly</td>
</tr>
</tbody>
</table>
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Compliance Concerns?

Scrubber Leaking Liquor

Compliance Concerns?

Scrubber Liquor Pump

Scrubber Liquor Pump
Let's Discuss FGD: Flue Gas Desulphurization

SO₂ Scrubbers
- Wet
- Spray Dry (Semi-Dry)
- Dry (DSI: Dry Sorbent Injection)

Five FGD Scrubber Modules on Utility Boiler
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Mercury Control
Activated Carbon Injection

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
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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

Carbon Adsorption System

Adsorber Breakthrough

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Carbon Adsorber

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

• 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

• Performance indicators
  – Inlet gas temperature
  – Gas flow rate
  – Inlet VOC concentration
  – Pressure differential
  – Inlet gas moisture content
  – Leaks
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Carbon Adsorbers at a Soil Remediation Site

Absorber/Condenser/Adsorber Unit at Marketing Terminal

Monitoring Approach – VOC

<table>
<thead>
<tr>
<th>Indicator Approach</th>
<th>Vacuum</th>
<th>Carbon bed I/M</th>
<th>LDAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure transducer</td>
<td>Daily insp. And annual sample</td>
<td>Monthly leak check w. portable analyzer</td>
<td></td>
</tr>
<tr>
<td>&lt;2.5 min @ 27.5” Hg, shutdown</td>
<td>Failure to conduct, corrective action and reporting</td>
<td>&gt; 10K ppm, corrective action and reporting</td>
<td></td>
</tr>
</tbody>
</table>
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Monitoring Approach – VOC

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Vacuum</th>
<th>Carbon bed IM</th>
<th>LDAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring location</td>
<td>Pump suction line</td>
<td>Visual, bed sample</td>
<td>Handheld monitor</td>
</tr>
<tr>
<td>QA/QC</td>
<td>Annual cal.</td>
<td>Training</td>
<td>Method 21</td>
</tr>
<tr>
<td>Frequency</td>
<td>Continuous during cycle</td>
<td>Daily and annual</td>
<td>Monthly</td>
</tr>
</tbody>
</table>

VOC Control via Incineration in Oxidizers

Combustion Considerations

Remember the 3 T’s of Combustion

- Residence Time
- Temperature
- Turbulence (mixing)
- Increase 3T’s = more NOx
- Decrease 3T’s = more CO and uncontrolled pollutant
Thermal Oxidizer

• General description
  - VOC gas (& organic HAP) gets oxidized to H₂O and CO₂
  - Higher operating temperatures (~1400°F to 1800°F)
  - Typically requires auxiliary fuel (natural gas or propane)
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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
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Factors affecting efficiency
- Waste gas flow rate
- Waste gas composition and concentration
- Waste gas temperature
- Amount of excess air

Oxidizer Performance Indicator

Performance indicators
- Outlet VOC concentration
- Outlet combustion temperature
- Outlet CO concentration
- Exhaust gas flow rate
- Outlet O₂ concentration
- Inspections
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Catalytic Oxidizer/Incinerator

• General description
  - VOC gas (& organic HAP) gets oxidized to H₂O and CO₂
  - Catalyst causes reaction to occur faster and at lower temperatures
  - Saves auxiliary fuel

• 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
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**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**
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Catalytic Oxidizer

• 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
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Catalytic Oxidizer/Incinerator

• Performance Indicators (continued)
  – Catalyst bed outlet temperature
  – Fan current
  – Outlet O₂ or CO₂ 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

<table>
<thead>
<tr>
<th></th>
<th>Catalytic</th>
<th>Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Operating</td>
<td>Higher Operating</td>
<td></td>
</tr>
<tr>
<td>Temp. &amp; Lower Fuel Usage</td>
<td>Temp. &amp; Higher Fuel Usage</td>
<td></td>
</tr>
<tr>
<td>Higher Capital &amp; Maintenance Costs</td>
<td>Lower Capital &amp; Maintenance Costs</td>
<td></td>
</tr>
<tr>
<td>Catalyst Fouling &amp; Poisoning</td>
<td>No Catalyst Involved Here</td>
<td></td>
</tr>
</tbody>
</table>
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"
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**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.
Can Type 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)

Regenerative Thermal Oxidizer (RTO)

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?

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Let’s Discuss PM Control

- Cyclones
- Baghouses
- ESPs
- Scrubbers
- Particulate Filters

Cyclones

Multi-Cyclone
**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 – Control Efficiency

- 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
Introduction to Control Devices

PM Control Techniques - Cyclone

- Performance indicators
  - Opacity (VEE)
  - Pressure differential

PM Control Techniques - Baghouses

Fabric Bag Baghouses
Introduction to Control Devices

Cartridge Type Baghouse

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

**Forced Draft vs. Induced Draft**

<table>
<thead>
<tr>
<th>Fan Type</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forced</td>
<td>Smaller motor</td>
<td>Fan Blade Erosion</td>
</tr>
<tr>
<td></td>
<td>Less expensive</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Easy to identify leaks</td>
<td></td>
</tr>
<tr>
<td>Induced</td>
<td>Fan on clean side</td>
<td>Larger motor</td>
</tr>
<tr>
<td></td>
<td>Particulate Contained</td>
<td>More expensive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Harder to identify leaks</td>
</tr>
</tbody>
</table>
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

Reverse Air
Introduction to Control Devices

Pulse Jet Bag

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

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Introducion to Control Devices

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
Introduction to Control Devices

Manometer

Measuring Pressure Drop

Magnehelic Gauge
Introduction to Control Devices

**Baghouse Pressure Drop**
- \( \Delta P \) shows air flow – it’s in operation
- \( \Delta P \) may fluctuate 10% as a function of the bag cleaning cycle.
- Continued rise in \( \Delta P \) will result from bags that become permanently plugged (blinded).
- High \( \Delta P \) will lead to premature bag failure.
- Daily/weekly record of \( \Delta P \) 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.
Introduction to Control Devices

Triboelectric Sensors

- Triboelectric 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.

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

Baghouse: Secondary Containment

Let’s Discuss Electrostatic Precipitators (ESP)
Introduction to Control Devices

Prometheus Tree – 4,844 years old

Bio Mass Power Plant

Electrostatic Precipitator

Electrostatic Precipitator
Introduction to Control Devices

Electrical Field Generation

Electrical Field

Collection Electrode

Discharge Electrode

Collection Electrode

Electrostatic Precipitator

Electrostatic Schematic

Corona
(voltage negative)
Introduction to Control Devices

Figure 301.3

Avalanche Multiplication

Figure 305.5

Particle Size & Collection Efficiency

Field Charging

Diffusion Charging

Particle Size & Collection Efficiency

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
  - 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

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

**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**
Introduction to Control Devices

- Magnetic Impulse Rappers

- Electromagnetic Rapper

- Control Efficiency - ESPs

• Older Existing ESPs
  - 90% - 99.9% for PM_{10}

• Typical New ESPs
  - 99% - 99.9% for PM_{10}
Introduction to Control Devices

ESP: 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

• 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
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)
Introduction to Control Devices

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

ESP: Soot Blowing & Opacity
Let's Discuss PM Scrubbers

- 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

Control Techniques – Wet Scrubber
Introduction to Control Devices

- Venturi Scrubber
- Scrubber Operation
  - Particles collected by impaction
  - Gasses collected by diffusion & absorption

- Wet Scrubber Operation
  - Particles collected by impaction
  - Gasses collected by diffusion & absorption

- Packed Bed Scrubber
Introduction to Control Devices

### 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.
Introduction to Control Devices

**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)

**Venturi Scrubber Exhaust**
Introduction to Control Devices

Let's Discuss Diesel Particulate Filters

Diesel Particulate Filter (DPF)

Diesel Particulate Filter
Introduction to Control Devices

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

**Regeneration Strategies**
- Active
- Passive
Diesel Particulate Filter (DPF)

- High temperature regeneration (600-650 °C)
  \[ C + O_2 \rightarrow CO_2 \]
- Catalytic regeneration (~250 °C)
- Oxidize NO to NO\(_2\) \(\rightarrow\) adsorbs \(\rightarrow\) reduces regeneration temperature
- Fuel-borne catalyst
- Ceramic coatings
- Engine adjustments necessary
- Total PM efficiency > 90%

Active Regeneration

- Achieving 550°C
  - Electrical Heater
  - Dosing (flame front)

Electrical Heater

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

City Bus
Electrical Active Regeneration Cycle

Portable On-Board
Introduction to Control Devices

Fuel Dosing

- Auxilliary Fuel Injector
  - Taps into vehicle's fuel system
  - Utilizes a blower for fresh air
  - Fuel Penalty
Introduction to Control Devices

**Active Regeneration**

\( \text{\(O_2\) @ 550\(^\circ\) C} \)

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

**Passive Regeneration**

- NO2 oxidizes soot @ around 250\(^\circ\) 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

Typical PM Spray Booth
Introduction to Control Devices

Spray Booth
Filter Inspection

Spray Booth
Filter Inspection

Spray Booth
Filter Inspection

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3-way Catalyst: Non-Selective Catalytic Reduction

- Rich burn/NG fired engine
- \(2\text{CO} + 2\text{NO} \rightarrow 2\text{CO}_2 + \text{N}_2\)
- \(\text{NO} + \text{HC} + \text{O}_2 \rightarrow \text{N}_2 + \text{CO}_2 + \text{H}_2\text{O}\)
- 98% control for \(\text{NO}_x\) & CO
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
### Comparison of NOx Control Technologies – Gas-Fired Boilers

<table>
<thead>
<tr>
<th>Technology</th>
<th>Approx. Reduction</th>
<th>Approx. lbs/MMBTU</th>
<th>Approx. ppmv @ 3% O2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard burners</td>
<td>Base case</td>
<td>0.14</td>
<td>120</td>
</tr>
<tr>
<td>Low NOx burners</td>
<td>50%</td>
<td>0.06</td>
<td>45</td>
</tr>
<tr>
<td>Ultra Low NOx Burners – 1st gen.</td>
<td>90%</td>
<td>0.03</td>
<td>25</td>
</tr>
<tr>
<td>Ultra Low NOx Burners – 2nd gen.</td>
<td>90%</td>
<td>0.007</td>
<td>6</td>
</tr>
<tr>
<td>FGR</td>
<td>55%</td>
<td>0.025</td>
<td>20</td>
</tr>
<tr>
<td>Compu-NOx w/ FGR</td>
<td>90%</td>
<td>0.015</td>
<td>12</td>
</tr>
<tr>
<td>SNCR</td>
<td>40%</td>
<td>0.033 - 0.085</td>
<td>27 - 70</td>
</tr>
<tr>
<td>Catalytic Scrubbing</td>
<td>70%</td>
<td>0.017 - 0.044</td>
<td>14 - 38</td>
</tr>
<tr>
<td>SCR</td>
<td>90 – 95%</td>
<td>0.008 - 0.015</td>
<td>5 - 12</td>
</tr>
</tbody>
</table>

http://www.epa.gov/ttnchie1/ap42/

http://www.epa.gov/ttncategoria1/products.html