Course Overview

- Air Pollution
- Boiler Uses
- Boiler Theory and Operation
- Air Pollution Formation
- Air Pollution Control Devices
- Boiler Regulations
- Typical Permit Conditions
- Inspection Procedures
Boilers

Uses of Boilers

- Electrical generation
- Space heating
- Food preparation
- Commercial laundries
- Pulp & paper industry
- Petroleum industry
- Chemical industry

High Pressure (1,800 – 3,800 psi)

Low Pressure (150 – 1,600 psi)

Small Firetube Boiler

Industrial Boiler
**Boilers**

**Phase Changes of Water**

- Boiling Point
- Saturated Steam
- Liquid Water
- Liquid Water and Steam (Quality 0 – 1)
- Superheated Steam
- Melting Point
- Ice
- Liquid Water and Ice

**Hot Numbers**

- **British Thermal Unit (BTU)**
  - 1 BTU the amount of energy needed to heat one pound of water one degree Fahrenheit or energy given off by burning one wooden match.

- **Lower Heating Value (LHV)**
  - Heating value of a fuel not counting heat needed to vaporize water.

- **Higher Heating Value (HHV)**
  - Heating value of a fuel including heat needed to vaporize water.
Boilers

Heat Transfer Methods

Boilers & Opacity

What Opacity is This?
Boilers

Millions of BTU/hr
Boiler HP
Pounds of Steam/hr
Megawatts
Tons per day

Boiler Ratings

COMBUSTION ENGINEERING, INC.

C-E STEAM GENERATOR

Typical Boiler Rating

Let's Discuss Firetube & Watertube Boilers
Boilers

Boiler Tubes with Fins

Boiler Circulation

Water to Steam Circulation Loop
Let's Discuss Boiler Air Requirements

Boiler Air Requirements

- Draft
  - Natural
  - Forced
  - Induced
- Combustion air
  - Primary
  - Secondary
  - Excess

Forced Draft Fans
Let's Discuss Economizers, Feedwater Heaters & Air-Preheaters
Let’s Discuss Fluidized Bed Boilers
Boilers

Fluidized Bed Modes

- Start: No Air Flow
- Fixed Bed
- Minimum Fluidization
- Bubbling Bed
- Circulating Bed

Bubbling Fluidized Bed (BFB)

Circulating Fluidized Bed (CFB) Boilers
Boilers

Circulating Fluidized Bed Boiler

Let’s Discuss Stoker Boilers

I'm a STOKER jack and I'm Ok

I sleep all night and I work all day

Superheater
Economizer
Furnace
Air Preheater
Combustion Using a Stoker Boiler

- “Stoker” involves combustion on a grate
- Fuel Distribution Onto the Grate
- Undergrate or Underfire Air
- Overfire Air
- Three Steps of Biomass Combustion
  - Step 1 - Drying
  - Step 2 - Gasification and Volatile burnout
  - Step 3 - Char Burnout (Step #3) on the grate
Boilers

Pneumatic Distribution

Classified by Grate Designs

- Fixed Grate (Pinhole)
- Vibrating Grate
- Watercooled Hydrograte
- Reciprocating Grate
- Kablitz Grate
- Traveling Grate
Boilers

Fixed Grate

Vibrating Grate

Watercooled Hydrograte
Boilers

Traveling Grate

Let's Discuss Power Generation

Typical Electric Utility Plant
Boilers

Typical Control Room

Moss Landing

2,600 MW
2 = 750 MW boilers
4 – Gas turbines and
2 steam turbines in a
2 to 1 arrangement

Let’s Discuss Biomass
Wood As A Fuel

- Wood is man’s oldest fuel
- Until very recently, wood was considered industrially as a waste material to be disposed of
- Escalating fuel costs and environmental concerns have changed things
- Wood use has opened up other “biofuels”

History

- 200,000 to 300,000 years - Controlled Use of Fire
- 10,000 to 20,000 years - Domesticated (living area)
- 800 years ago - First wood fuel shortages
- 400 years ago - Coal use in Europe
- 250 years ago - Industrial Revolution
- 150 years ago - Oil use
- 130 years ago - Natural gas use and electrification
- 70 years ago - Industrial wood-firing
- 50 years ago - Air pollutant investigations
- 20 years - Biofuels and “space age” investigations
Wood differs from conventional fossil fuels
- Physical structure
- Chemical structure
- Moisture content
- "It's alive" when harvested
- Therefore it burns and must be burnt differently
- Commercially viable for other uses
- Relatively scarce resource
- Development of "urban wood wastes"

Wood Fuel Physical Characteristics
- Xylem interior “white wood”
  - Board lumber
  - Chips
- Cambium layer
  - new growth
  - source of nutrients
- Bark

Wood Fuel Physical Characteristics
- Debarking removes the Cambium layer and bark
- Yard wastes
- Processed through a hammermill (“hog”) for size reduction
- White wood
  - Sawdust
  - Sanderdust
  - Chip fines
- Other - plywood trim
Random reclaim operations will result in significant variations in fuel quality.

- Emphasizes the importance of good fuel management and blending.
- Selective fuel purchasing is also very important.
- But ... generally, you burn what you got.
**Fuel Quality**
- Poor combustion performance and high CO
- Small wood particles
  - Not handled well in the feed and distribution systems
  - Rapidly entrained with insufficient time to complete the 3-Step combustion process within the furnace
- High moisture content
  - Tends to pile on the grate
  - Causes “thick-bed” grate conditions
  - Disrupts undergrate airflow

**Fuel Preparation**
- Screening
- Metal Removal
- Drying
- Deicing
- Sizing
- Blending

**Wood Fuel Sizing**
- “Overs” (> 3 inches) => Plug fuel chutes
  - Screen out
  - Mill to a smaller size
- “Fines” (<1/4 in) => Not completely burned
  - Segregate
  - Blend up to 20% with larger materials
Boilers

Wood Fuel Screening

Tub Grinder for Gross Size Reduction

Hammermill for Fine Size Reduction
**Wood Fuel Drying**

- Part of another wood processing operation
  - Kiln dried trim
  - Dried planer shavings
  - Sanderdust
- MC > 65% requires some type of drying or blending with drier fuel
- MC < 15% is potentially explosive

**Fuel Blending**

**Importance of Blending**

- Control moisture content
- Improve fines burnout
- Implement by:
  - Gross mixing using a front-end loader
  - Separate fuel bins feeding a common feed system
### Wood Fuel Characteristics - Moisture Content
- Water needed for life
- Present in the cell structure and on surface
- Moisture content varies with:
  - Species
  - Location
  - Season
  - Handling practices
- Nature levels of 30% to 65%+
- Kiln dried to less than 10%

### Effect of Moisture
- Decreases combustion temperatures
- Leads to incomplete combustion and the generation of higher levels of CO and ash C
- Decreases boiler efficiency
- Leads to more fuel use, higher energy costs and increased air pollutants

### Wood Fuel Characteristics - Volatility
- 70% to 80% of dry wood is “volatile” hydrocarbons
- Released from the wood structure at relatively low temperatures (500 F)
- Volatiles burn “in suspension” away from the wood particles
- Balance is “fixed carbon” or “char”
Wood Chemistry

Hydrocarbons
- Methane \( \text{CH}_4 \)
- Ethane \( \text{C}_2\text{H}_6 \)
- Propane \( \text{C}_3\text{H}_8 \)
- Complex Fuels \( \text{C}_x\text{H}_y \)
- More Complex Fuels \( \text{C}_x\text{H}_y\text{S}_z\text{N}_a \)

Wood Species

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pine</th>
<th>Redwood</th>
<th>Hemlock</th>
<th>Fir</th>
</tr>
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<tbody>
<tr>
<td>C (%wt,dry)</td>
<td>50.3</td>
<td>53.5</td>
<td>50.4</td>
<td>52.3</td>
</tr>
<tr>
<td>H (%wt,dry)</td>
<td>6.2</td>
<td>5.9</td>
<td>5.8</td>
<td>6.3</td>
</tr>
<tr>
<td>O (%wt,dry)</td>
<td>43.1</td>
<td>40.3</td>
<td>41.4</td>
<td>40.5</td>
</tr>
<tr>
<td>N (%wt,dry)</td>
<td>0.04</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>S (%wt,dry)</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Ash (%wt,dry)</td>
<td>0.3</td>
<td>0.2</td>
<td>2.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Moisture (%)</td>
<td>30 - 60</td>
<td>30 - 60</td>
<td>30 - 60</td>
<td>30 - 60</td>
</tr>
<tr>
<td>Btu/lb</td>
<td>9,153</td>
<td>9,220</td>
<td>8,620</td>
<td>9,058</td>
</tr>
</tbody>
</table>

3-Step Combustion Process

Step #1 - Drying

- Fresh wood particles absorb heat by convection and radiation from the ongoing combustion processes
- Initially, the heat energy evaporates the water in the cells and on the surface
- The evaporated water vapor diffuses away and mixes with the combustion products
3-Step Combustion Process
Step #2 – Devolatilization

- The wood fuel particles continue to absorb heat
- The energy absorbed releases the volatile combustibles
- The volatiles diffuse away, mix with air (oxygen), and burn
- The energy released radiates back and helps to sustain combustion

3-Step Combustion Process
Step #3 - Char Burnout

- The char remains after the volatiles have been released
- Char is primarily pure carbon and requires:
  - An extended time period to burn
  - Air (oxygen) transported to it
- Inert ash remains after the char burnout

Boilers
Ash

- Intrinsic ash (potassium) can combine with alumina and silica to form a relatively low melting point temperature ash (1600 to 1800 F)
- Potassium also volatilizes at low temperatures (1500 F) and reacts with ash in the boiler flue gas stream contributing to fouling problems
- Ash accumulation causes
  - Airflow problems
  - High draft levels and fan horsepower
  - Reduced superheat temperatures
  - Boiler shutdowns
Let’s Discuss Emissions & Controls

Emissions From Boilers

Fuel + Air (N₂, O₂)

- H₂O
- CO₂
- CO
- NOₓ
- HC
- SOₓ
- PM
- Cl⁻

Emissions Control Methods

- Boiler design
- Proper maintenance
- Operating conditions
- Fuel types
- Combustion modifications
- Exhaust treatment
Boilers

Control of Gaseous Emissions
- Low-NOx burners
- OFA
- Ammonia injection (SNCR)
- Catalysts (SCR)
- RSCR
- FGR

Combustion Considerations
- Time
- Temperature
- Turbulence
- Oxygen
- Nitrogen

NOx Creation
- Thermal NOx
- Fuel-bound NOx
- Prompt NOx
Boilers

Flue Gas Recirculation (FGR)

Flame Temperature vs. FGR

Let's Discuss Staged Combustion
Let's Discuss SCR, SNCR and RSCR

**What is SCR?**

Selective Catalytic Reduction

( This means that NO\textsubscript{x} will selectively react with NH\textsubscript{3} in the presence of Oxygen, similar to SNCR but a catalyst is needed to help the reaction which takes place at a lower temperature than SNCR)
Where is SCR 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)
Boilers

SCR @ Typical Utility Boiler

SCR

NH, Injection:
(Uniform NH₃/NOₓ, Critical)

Turning Vanes to give
uniform Velocity across the
Catalyst

Catalyst
Layer(s)

SCR Catalyst Types

Extruded Ceramic
Honeycomb

Composition
- Vanadium Pentoxide (V₂O₅)
- Titanium Dioxide (TiO₂)
- Molybdenum
- Tungsten

Corrugated
(Hidden Topics)

Plate
Catalyst Degrades With Time

Reason for Degradation Fuel Dependent

- Bituminous Coal- Arsenic Poisoning
- Other Coal- Calcium sulfate blinding
- Potassium & Chlorite Poisoning
Boilers

Typical Catalyst Deactivation Rates

Ammonia Injection Grid

SCR & NH₃ Tubes
Let's Discuss Particulate & NH₃ Controls

What is SNCR?

SNCR - Selective Non-Catalytic Reduction

(Means that a chemical will selectively react with NOₓ in the presence of Oxygen)

Ammonia (NH₃)  Urea (NH₂CONH₂)

SNCR vs SCR

<table>
<thead>
<tr>
<th></th>
<th>SNCR</th>
<th>SCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx Reduction</td>
<td>20-50%</td>
<td>50-95%</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 (5-10)</td>
</tr>
<tr>
<td>Reagent Utilization</td>
<td>Typ. 30%</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;10 ppm</td>
</tr>
</tbody>
</table>
## Boilers

### Ammonia Storage Tank

### Anhydrous Ammonia Storage Tank

### 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 issues</td>
<td>No Safety Issues</td>
</tr>
<tr>
<td></td>
<td>19% Aqueous - fewer Safety Issues</td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>Anhydrous-Pressure Vessel</td>
<td>Atmospheric Pressure</td>
</tr>
<tr>
<td></td>
<td>Aqueous-Atmospheric Pressure</td>
<td>Crystallization at Low Temperature</td>
</tr>
<tr>
<td>Injectors</td>
<td>Needle Carrier Gas</td>
<td>Atomizers (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>Large Dilute Drops Shield Urea</td>
<td></td>
</tr>
<tr>
<td>System Complexity</td>
<td>Relatively Simple</td>
<td>Relatively Simple</td>
</tr>
</tbody>
</table>
Boilers

Balance-of-Plant Impacts

- NH$_3$ Slip
- SO$_3$/NH$_3$ Reactions (APH Deposition)
- HCl/NH$_3$ Reactions (Plume Visibility)
- Ash/NH$_3$ Absorption (Ash Sales, General Nuisance)
- N$_2$O Emissions
**What is RSCR?**

Regenerative Selective Catalytic Reduction

(This means that NOx will selectively react with NH3 in the presence of Oxygen, similar to SCR with a catalyst to help the reaction and two thermal transfer beds)

**Ammonia Slip**

- NH3 + OH => NH2 + H2O
- NH2 + NO => N2 + H2O
- 2NH3 + OH + NO => 2H2O + N2 + NH3
- 10 to 25 ppm NH3 Slip
- Could be higher
- Always have Some NH3 slip

**NH4Cl Formation**
**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

**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 ??

**Continuous NH₃ Analyzer**

- Laser & Detector
- Retro Reflector
### Comparison of NOx Reduction Technologies

<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>60%</td>
<td>0.06</td>
<td>45</td>
</tr>
<tr>
<td>Ultra Low NOx burners – 1st gen.</td>
<td>80%</td>
<td>0.03</td>
<td>25 - 30</td>
</tr>
<tr>
<td>Ultra Low NOx burners – 2nd gen.</td>
<td>95%</td>
<td>0.007</td>
<td>6 - 9</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>15 - 20</td>
</tr>
<tr>
<td>SNCR</td>
<td>80%</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 - 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 PM Control

### 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, SO₃, NH₄Cl) which are also considered as “particulates”
Control of Particulate Emissions

- Settling chambers
- Cyclones
- Baghouses
- ESPs
- Scrubbers

Water Spray

Soot Blowing
Regulatory Requirements

- Federal, state, and local requirements
- Boiler specific limits
- Permit requirements
- Monitoring requirements
- Visible emission limits
- Nuisance regulations
- Breakdowns & variances

Boiler Regulations

- NSPS 40 CFR Part 60 Subpart D, Da, Db, Dc, Ea
- Acid Rain Provisions (Parts 72,73,74,75, 76, 77, 78)
- RCRA 40 CFR Parts 264 & 266
- State Regulations including VE
- SIP Requirements
- Local Regulations
- MACT DDDDD & JJJJJJ

Boiler Emission Limits

- NOx, SO2, particulate, and opacity values for boilers are based on applicable subpart, heat input, date built or modified, and fuel used
- States and districts may have more stringent limits
**Boilers**

### BACT

<table>
<thead>
<tr>
<th>Type of Control</th>
<th>NOx Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas Fired with SCR &amp; Low NOx Burner</td>
<td>0.010 lb/MMBTU</td>
</tr>
<tr>
<td>Natural Gas Fired Units (&lt; 60 MMBTU/hr)</td>
<td>0.035 lb/MMBTU</td>
</tr>
<tr>
<td>Biomass Fuel Fired Boilers (Large), SNCR</td>
<td>0.10 lb/MMBTU</td>
</tr>
<tr>
<td>Municipal Solid Waste</td>
<td>110 ppmv @7% O2</td>
</tr>
</tbody>
</table>

### Permit Condition Categories

1. Emissions Limitations
2. Equipment Requirements
3. Operating Conditions
4. Monitoring and Recording Requirements
5. Compliance Testing
6. General Requirements

### Alternative Monitoring

- Portable analyzer monitoring of NOx, CO, O₂
- Determination of FGR rate
- Burner mechanical adjustments
- O₂ Trim concentration
- FGR valve(s) setting

Portable Combustion Analyzer
Boiler Inspections

Points of Inspection
- Capture
- Transport
- Air mover
- Control device
- Instrumentation
- Subsystem
- Records

Pre-Inspection
- Prepare inspection form
- File review
- Regulation review
- Equipment check
- Pre-entry & entry
- Pre-inspection meeting
- Permit check
**Reasons for Inspections**

- Compliance determination
- Complaint investigation
- Source plan approval
- Review or renewal of permits
- Special studies

**Inspection**

- Visible emission evaluation
- General upkeep & maintenance
- Monitoring instruments & records
- Fuel type and quality
- Maintenance records
- Operational records
- Source tests

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**Plant Safety**
Boilers

Inspector Safety
- Proper equipment
- Plant warnings
- Heat
- High pressure steam
- Electrical hazards
- Noise
- Moving parts
- Inhalation hazards
- Hazardous materials
- Machine disintegration
- Fires
- Other hazards & traps

Plant Safety

Plant Hazards