Building Operator Certification – Level I

A Partnership of the CUNY Institute for Urban Systems Building Performance Lab, the CUNY School of Professional Studies, and the New York State Energy Research & Development Authority
Boilers and Heating Distribution:
Lesson 7
Topics

Boilers & Efficiency
Boiler Types & Construction
Energy Conversion and Boiler Efficiency
Combustion, Burners and Combustion Efficiency
Boiler Control for Efficiency
Steam Distribution
Steam and condensate cycle
Distribution System
Traps
Distribution Maintenance
Hot Water Heating Systems
Hot Water Sources – hydronic boilers and steam converters
Circulating Pumps and Zoning
Hot Water Piping Configurations and Balance
Boiler Types & Construction

Boilers are designed to deliver either steam or hot water

Hot Water Boiler
  > Heats the water used in a “hot water heating system”
  > **Condensing boilers** can achieve very high efficiencies

Steam Boiler
  > Low Pressure—below 15 psi
  > High Pressure—above 15 psi, up to thousands of psi (for power generation)
Boiler Types & Construction

Boilers are most commonly constructed of steel (tubular) or cast iron (sectional). Steel tube boilers can be configured as either “fire tube” or “water tube”

Firetube
> Flame goes through tubes surrounded by water.
> The “scotch marine” fire-tube boiler is used commonly for commercial space heating.

Watertube
> Water is contained inside tubes and the hot gasses passes outside the tubes.
> Water tube boilers have less water content and therefore respond faster. They are used in high pressure industrial and power applications.
Key maintenance items on the fire-side are: combustion efficiency and the cleanliness of the heat exchange surfaces. Incomplete combustion can rapidly deposit soot on the fire-side of tubes, dramatically reducing heat exchange and resulting in heat wasted up the chimney.
Boiler Water-Side Elements

Feedwater system
Make-up water
Back-flow preventer
Water level controls
Low-water cut-off
Mechanical pressure relief
Blow-down

Chemical Treatment

Water boilers are simpler than steam, as they are maintained filled by continuous water pressure from the main. That the system is not cyclically exposed to air also means that water boilers have less accumulation of sediments so they require less blow-down and less chemical treatment.

DEFINITIONS IN NOTES (below)
Energy Conversion Process in a Boiler

Energy Conversion Steps in a Boiler

1. Combustion – The energy in the fuel is converted to heat energy. The first step to good efficiency in the boiler is good combustion.
2. Heat Exchange – The heat energy of the combustion gasses is transferred through the metal surfaces of the boiler to the water in the boiler.

Heat Transfer from Hot Combustion Gas
- If there is a soot on the tubes it acts like insulation, reducing heat transfer to the water, which reduces boiler efficiency.
- On the water side of the tubes, scale can build up: these mineral deposits also act like insulation on the tubes and decrease boiler efficiency.
- Both (soot and scale) cause poor heat transfer to the water, and cause more heat energy to go up the stack. Elevated stack temperature is a direct indicator of reduced efficiency.

The operator’s role is to ensure that both combustion and heat transfer are at good efficiency so that the highest amount of heat energy from the fuel is transferred to the water in the boiler.
The Combustion Process: A chemical process of combining fuel and oxygen

Fuels - coal, oil, natural gas, biomass - are “Hydro-Carbons” (CH). All biological materials are hydrocarbon molecules. Oxygen (O2) is in the air for combustion. Oxygen is normally 21% of air.

For efficient combustion the burner must mix fuel and air thoroughly and in the right proportions. 
*Good, “complete” combustion will produce: CO2 + H2O(vapor) + heat*
  Complete combustion: no residual Carbon (C) or Carbon Monoxide (CO).

**Insufficient air for Combustion** causes incomplete combustion.
Incomplete combustion of Fuel Oil will produce Carbon particulates, seen as soot and smoke
Incomplete combustion of Natural Gas will produce higher levels of Carbon Monoxide, but not particulates or smoke.

**Excess Air for Combustion**
All boilers use some “excess air” above the exact amount of air required for the chemical process of combustion. Excess air is needed due to the incomplete mixing of the air and fuel, to make sure that enough oxygen is supplied to burn all of the fuel.

**Recommended is usually 10 - 15% excess air**
> Too much excess air will lower the efficiency of the boiler.
> When more air is supplied to the combustion process than needed, it absorbs the heat and carries extra heat up the stack, as stack losses. Getting the right amount of air is a key element of good combustion, and it is achieved by the proper adjustments to the burner.
When fuel is burned in a boiler, the heat energy released is either used in the building (shown by the large lower arrow to the right) or the heat energy is wasted (shown by the three arrows moving up the diagram). These three upper arrows describe the types of losses that determine a boiler’s overall efficiency.

There is a big difference in how efficient your plant can be, based on how well it performs in each of the areas of loss.

Efficiency = Energy Output / Energy Input
Assessing Overall Heating Plant Efficiency

**Steady-State Tests**

- Carbon Dioxide (or Oxygen) & Stack Temperature
- Smoke/CO (incomplete combustion)

**CE** (combustion efficiency)

- Air Leakage ("tramp air")
- Blow-down, Make-up water (system leakage)
- Insulation
- Cycling & Stand-by

**BE** (boiler efficiency, afue)

- Insulation (piping, fittings, valves)
- Leakage
- Thermostatic Control & Balance

**HE** (overall heating efficiency)
Heat Recovery

Boiler efficiency can be improved by recovering heat wasted to the chimney. A heat exchanger installed in the boiler breeching recovers heat to pre-heat combustion air or feedwater -this is called an economizer and is very common on shipboard boiler applications.

**Condensing** hot water boilers recover both the sensible and latent heat from the exhaust gas to achieve efficiencies of 90%
Burner Types

The main job of a burner is to properly mix fuel and air for good combustion. This is accomplished in different ways by these three burner types.

**Pressure Atomizing Burner:** Oil is atomized by pressure (100 psi) across a nozzle. Residential and small commercial applications. Burns light (#2 oil) only.

**Air-atomizing Burner:** Oil atomized by primary air injected from a compressor. Burns any grade of oil and also natural gas. Good combustion efficiency and firing rate modulation. Most common commercial unit.

**Rotary Cup Burner:** Oil is atomized by centrifugal force as it flows through a spinning cup. Burns heavy oil but often not cleanly, producing smoke and soot. Cup needs daily cleaning. The combustion air-flow usually needs assist from negative draft at breeching to induce adequate secondary air. Limited firing rate modulation.
Flame Conditions

A good boiler operator can visually inspect the flame and get a feeling if good combustion conditions exist. This should be done on a daily basis. This only comes with experience. HOWEVER, EVEN AN EXPERIENCED OPERATOR CANNOT SEE THE AMOUNT OF EXCESS AIR. TO GET EXCESS AIR RIGHT, MUST TEST FOR CO2 OR O2.

Flame position and stability should be monitored. A roaring flame or weak, pulsing flame indicate problems. Flame should be centered in the combustion zone without contacting wall surfaces. Flame should not have “sparks” which are incompletely atomized bits of burning fuel.

Smoke (oil only, not gas) - Dark smoke in the stack indicates insufficient air or air poorly mixed with fuel.

Flame Color - Bright, lemon yellow is desirable for oil. Whiter generally indicates too much excess air. Darker indicates insufficient or poorly mixed air. Gas should burn with a bluish flame.

Flame condition is determined by the following:
- Burner settings: Air to Fuel Ratio and Air Flow
- Fuel pressure and temperature
- Combustion chamber temperature
- Draft conditions in boiler and stack
Combustion Efficiency Test

The Combustion Efficiency Test is also called the Boiler Efficiency test or Combustion Gas Analysis.

The test instrument draws a sample of stack gas. Sample must be taken between the boiler and barometric damper or draft hood.

Sample is analyzed to determine the percentage of CO2 (Carbon Dioxide) or O2 (Oxygen) in the stack gas, indicating excess air.

Instrument also measures the temperature of the stack gas. Higher stack gas temp shows lower efficiency.

The results will tell you the quality of combustion. To make an improvement, a “Tune-up” of the boiler is done by a Boiler Tech, who will adjust the Air-Fuel Ratio of the burner.

The boiler must be brought up to temperature and running in a “steady state” Results will also differ at different firing rates, so a burner must be tested and adjusted (tuned) across its full firing range.

**Picture on Right** - Drawing a sample of stack gas for a smoke spot test. Stack gas is drawn through a piece of filter paper and compared to a standard chart.

Flame must be free of smoke (oil) or CO (gas) before the other tests are conducted.
Combustion Efficiency Test Targets

- This chart shows the recommended targets for the Boiler Efficiency Test.
- Oil burns somewhat hotter and produces more CO2.

- Lower stack gas temperature indicates higher efficiency, but you can’t go too much lower on stack temperature because it will cause condensation in the chimney. Very low stack temperature indicates under-firing (firing rate too low) or very high excess air, either from burner adjustment or excess air drawn in.

<table>
<thead>
<tr>
<th></th>
<th>OIL</th>
<th>GAS</th>
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<tr>
<td><strong>Net Stack Temperature</strong></td>
<td>350-450 dF</td>
<td>300-400 dF</td>
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<tr>
<td><strong>Carbon Dioxide</strong></td>
<td>12-14%</td>
<td>8-10%</td>
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<tr>
<td><strong>Oxygen</strong></td>
<td>5-7%</td>
<td>2-5%</td>
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### Savings Calculation from Improved Combustion Efficiency

<table>
<thead>
<tr>
<th>Excess</th>
<th>Excess</th>
<th>Excess</th>
<th>Combustion Efficiency at Net Temperature Difference</th>
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<tr>
<td>Air %</td>
<td>O2 %</td>
<td>CO2 %</td>
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<tr>
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Source: Table extracted from: Boiler Efficiency Institute, "Boiler Efficiency Improvement" by David F. Dr. Glennon Maples, Copyright 1991.
Good Boiler Operating Practice: Minimize Short-cycling

Short-cycling at light heating loads wastes energy, as both pre- and post-purge cold air is being blown through the boiler.

Avoid by proper pressure control settings
  > Operating pressure control
  > Modulating pressure control

Avoid by proper lead-lag control of multiple boilers.

The same principles apply for hot water boilers, except that water temperature rather than steam pressure is the controlled variable.
Boiler Pressure Controls

We will discuss 3 types of Boiler Pressure Controls:
• Operating Pressuretrol
• Manual Reset High-limit
• Modulating Pressuretrol

• **Operating Pressuretrol** – An “on-off” control that starts and stops the burner to keep the boiler within a set steam pressure range. When boiler steam pressure goes up to the high pressure set point (Cut Out Pressure), switch opens and turns off the burner. Switch will close automatically when pressure falls to the low pressure set point (Cut In Pressure), turning the burner back on.

• **Manual Reset High-limit** – switch opens when cut-out set-point is reached but will not automatically close; operator must push button to manually re-set.
Modulating Pressure Control

Modulating Pressuretrol
Acts to maintain a steady boiler pressure by increasing or decreasing the firing rate of the burner (like raising or lowering the flame on a pot of boiling water to maintain a steady rate of boiling). As boiler steam pressure increases, the modulating pressuretrol will decrease the firing rate of the burner, to control the steam pressure.

Main parts of the Modulating Pressuretrol:
• **Bellows Housing** - pressure sensing diaphragm.
• **Controller Potentiometer** – Converts the pressure signal into a voltage signal, by moving the wiper arm.
• **Terminal Block** – The electrical output signal, a variable voltage signal, is sent from the wires on the terminal block to the ModuTrol Motor on the burner.

- Goal of modulating boiler pressure?
- Are the modulating pressuretrols properly set and working on your boilers?
Modulating Boiler Pressure Control:

Modulating PressureTrol – Uses a potentiometer to send a variable voltage signal to the modulating motor on the burner.

The Modutrol Motor or “mod” motor, will position the air and fuel linkages to set the firing rate.
Multiple boilers or modular boilers must be controlled (“staged” or “sequenced”) to provide only the on-line capacity required to meet the heating load.

Too many boilers on-line causes short-cycling and other unnecessary losses, reducing plant efficiency.

A controller uses a sensor in the supply piping to determine the number of boilers to be on-line. It’s important to get this control set up correctly: individual boiler short-cycling means this control needs adjustment.
Optimize Start-up and Shut-down

Where heating or cooling equipment is shut off at night or temperatures are decreased (increased for cooling), the building will need to be brought back to temperature in the morning.

**Optimized Start-Up:** The optimum time to start the morning warm up depends on outside temp. When outside temp is lower, the morning warm-up should start earlier. When the outside temp is milder, morning warm-up should start later, saving energy. Reduced boiler and heating system operating time reduces fuel use.

→ To track the actual warm up time of your building, you can use data-loggers to see the warm up trend during time.
ALL PIPING AND EQUIPMENT

> Insulation is very important to plant energy efficiency. Keep insulation in good repair, with full, tight coverage of piping and equipment.

REMOVEABLE JACKETS

> Equipment, such as valves, are often left uninsulated for service access. These can be cost-effectively covered with removable insulation jackets – a very good improvement project.
Steam Distribution System

Major Components
- Steam Supply Main Header
- Steam Piping to radiators and heat exchangers
- Radiator Supply valve
- Thermostatic trap
- Air vents (not shown)
- Return riser
- F&T trap
- Dry & Wet Returns
- Condensate Receiver / Pump
- Feedwater Pump
- Equalizer and Hartford Loop piping

Condensate Receiver/Pump: The condensate receiver receives all the condensate from the system and pumps it back to the boiler or to the boiler feed pump (BFP). Note that the condensate receiver is vented (open to the atmosphere). A large system could have multiple condensate receivers in different parts of the building. Larger systems may have a Vacuum Pump to assist the condensate in returning more quickly.
Steam Distribution & the Steam Cycle

Most of the energy in the steam (970 btu out of 1,150 btu per pound) is in this “change of state” and expansion from liquid to vapor. This is why the radiator steam traps are so important – they make the steam give up all this heat energy by condensing where it is needed.

When steam is distributed in the system, and has filled the available space in the piping system it will increase in pressure. You can see this in your boiler operating pattern: it will fire for a long-time without making steam pressure -- this is when it is expanding to fill the system.
Steam Distribution & Steam Cycle

Steam Distribution Problems
• Do you have a problem in heating the entire building evenly?
• Do you have a problem with heating some parts of your building?
• A common solution is to increase the steam pressure the boiler. Is this the right approach?
• Let’s take a look at the sources of the problem.

Steam Distribution – Common Problems
• Condensate is not returning from the system
• Air is blocking the steam flow in the system
• Steam Traps are failed closed or failed open
• The vacuum system is not operating properly
• How much steam pressure do we need?
Steam Distribution – Loss of Water

- Closed System – should be minimal loss of water and make-up

- Where do systems leak?
  - Condensate Receiver Vents – flash steam or worse
  - Dripping and vaporizing at valves – you may not see it
  - Buried condensate returns – you may not see it

- Blow-down: Loss of water, chemicals and energy
  - Condensate is lost from the regular blow-down of the boiler, to remove sludge and accumulated dissolved solids. A “bottom” or “mud” blow-down is required periodically, but the frequency should be closely monitored to reduce water, chemical, and energy losses.

- Why should I care about leakage?
  - Energy is wasted
  - Oxygen & minerals in fresh water and equipment life

- How can we tell how much leakage?
  - Meter the make-up water from City Water
Steam Traps

Function of Steam Traps

The two most common kinds of steam traps. Thermostatic steam trap, Float and Thermostatic Trap

Steam Trap Failure
Failed Open
Failed Closed
Steam Traps

More Problems of Failed Open Steam Traps
Boiler is not able to make steam pressure
Poor distribution of heat in the building

Steam Trap Testing

<table>
<thead>
<tr>
<th>Thermostatic Traps on Radiators</th>
<th>Operation of Trap</th>
<th>Entering Temp</th>
<th>Exit Temp</th>
<th>dT</th>
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<tr>
<td>Normal</td>
<td></td>
<td>212F</td>
<td>197F</td>
<td>15F</td>
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<tr>
<td>Failed Open</td>
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<td>212F</td>
<td>212F</td>
<td>0</td>
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<table>
<thead>
<tr>
<th>F&amp;T Traps on Main Line Drains</th>
<th>Operation of Trap</th>
<th>Entering Temp</th>
<th>Exit Temp</th>
<th>dT</th>
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</thead>
<tbody>
<tr>
<td>Normal - High Flow</td>
<td></td>
<td>212F</td>
<td>212F</td>
<td>0</td>
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</tbody>
</table>
Steam Distribution Maintenance

Steam traps: should be checked for a temperature difference across the trap, as previously discussed.

Y-Strainers: flush periodically (monthly) to remove accumulated sediment.

Air vents: check periodically that they open and close properly. Steam should not escape.

Pumps: lubricate according to the manufacturer’s recommended schedule.

Condensate Return: check for leakage in piping. If make-up water additions are high (as shown by meter readings) and no leakage is obvious, check buried piping and piping run in wall cavities.

Valves: should be checked to determine if leak-by is occurring when the valves are closed. Also tighten packing or re-pack if leakage is observed.

Developing a preventive maintenance checklist is a must.
Hot Water Heating Systems

Basic Operating Principle

Main Components
  > Hot Water Boiler(s)
  > Circulator pump(s)
  > Piping and Terminal Radiation
  > Controls

Balancing

Maintenance
Hot Water Boilers

Hot Water Boiler Trim
> Water-fill
> Air removal
> Expansion tank
> Pressure/Temp. Relief
> Water level control

Modular boilers (multi-unit installations)

Condensing boilers

Courtesy E-Instruments
Steam to Hot Water Converter

Motorized valve, controlled to open/closed based on circulating hot water temperature
Hot Water Heating Systems

Basic construction
  > Lubricated vs water-cooled
  > Multi-speed

Good piping practice
  > Valves and unions
  > Pressure gauges
  > Straight run

Pumps in parallel
Piping and Terminal Radiation

Fin-tube Convectors

Fan-coils

Air-handling units

Adjusting radiation design for condensing boilers

> Increase radiation to allow effective heating at lower operating temperatures so that condensing boiler efficiencies can be achieved.
Piping Layouts and System Balance

One-Pipe System

Direct Return Two-Pipe System

Reverse Return Two-Pipe System
Piping Layouts - Zoning

Why have multiple zones?
Common pump with zone valves
Zoning by multiple pumps
Piping Layouts – Primary-Secondary

BOILER

LOAD

PRIMARY/SECONDARY PUMPING
Controls

Control by water temperature
  > Aquastats
  > Temperature Reset

Control by Zoning
  > Electric zone valves, controlled by room thermostats
  > Self-acting Thermostatic Valves
  > Multiple loop and primary/secondary/tertiary pumping

Control by flow volume
  > Variable speed pump control
Summary of Good O&M Practice for Hot Water Heating Systems

Insulation

Combustion efficiency

Temperature reset (or variable volume)

Balancing

Capacity control

Condensing boilers and low temperature design/operation
Review and Reading Assignment

What were the main learning points in this class?
• Boilers and Efficiency
• Steam Distribution
• Hot Water Heating Systems

Reading Assignment for Lesson 8:
FEMP Sections 9.4 (CHILLERS) and 9.5 (COOLING TOWERS)

If time, view “Combustion Analysis of Oil Fired Boiler” at http://www.youtube.com/watch?v=nTrB_EG9qDg