Better Plants
U.S. DEPARTMENT OF ENERGY

Industrial Steam Systems
Virtual INPLT Training & Assessment

Session 2
Thursday – October 3, 2024
10 am – 12:30 pm

Welcome

- Welcome to the second Steam Virtual INPLT training series
- Eight, 2-1/2 hour webinars, focused on Industrial Steam Systems Energy Assessment and Optimization
- These webinars will help you gain a significant understanding of your industrial steam system, undertake an energy assessment using a systems approach, evaluate and quantify energy and cost-saving opportunities using US DOE tools and resources
- Thank you for your interest!

Acknowledgments

- Greg Harrell, PhD, PE
- US Department of Energy
- United Nations Industrial Development Organization
- Several industrial clients – both in the US and internationally

Steam Virtual INPLT Facilitator

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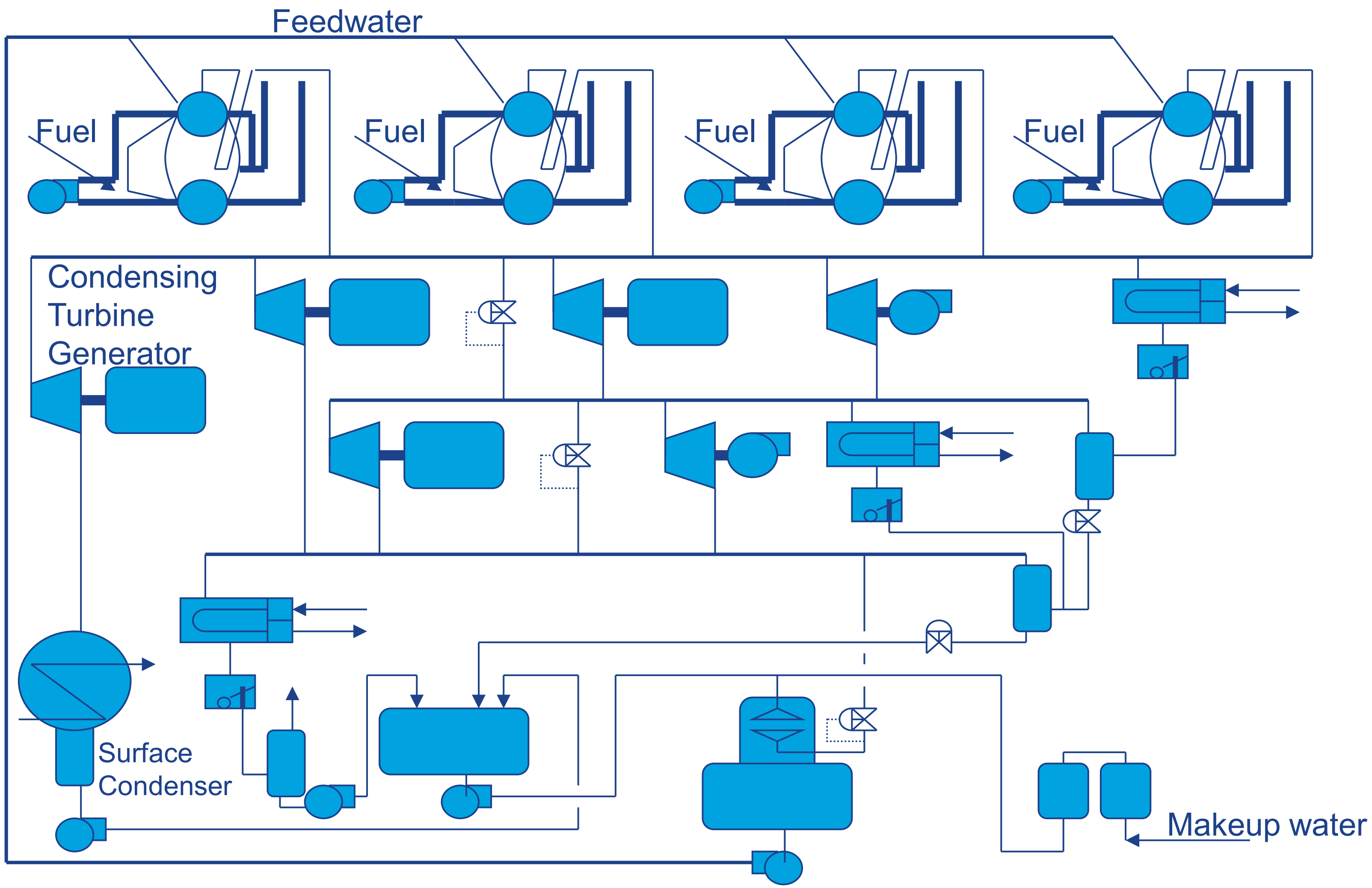
Steam System Line Diagram



Generation Area

- Boiler Efficiency (Direct Method)
- Specific Boiler Losses

Boiler Rating

- Two common methods of classifying boilers
  - Steam production
    - Mass flow rate of steam [lb/hr]
  - Boiler horsepower [BHp]
    - Boiler Horsepower is not Mechanical Horsepower but a description of the energy supplied to the steam (sometimes fuel input)
      - It is a measure of the evaporation or steaming rate of a boiler
    - 1 BHp = 33,475 Btu/hr
    - 1 BHp = 34.5 lb/hr of evaporation from and at 212°F
    - Generally, used for specifying smaller packaged (fire-tube) boilers

- Both methods are used in industry for specifying boilers

Operating Cost

- Boiler fired with natural gas
  - HHV is 1,000 Btu/scf
- Output: 100,000 lb/hr (steady)
- Fuel supply: 149,000 scf/hr (2,480 scf/min)
- Fuel cost: $5.00/MMBtu ($5/Mcf)
- **Determine the operating cost**
  - **Hourly**
  - **Annual – 8,760 hours**
- **Determine unit cost of steam ($/klb)**

<u>Units Syntax</u>
cf – cubic feet
scf – standard cubic feet

M – thousand
MM – million
k – thousand
c - hundred

Boiler Operating Cost

$$Fuel\ Cost = Fuel\ flow\ rate \times Fuel\ Cost \times Time$$

$$Fuel\ Cost = 149000 \times \frac{5}{1000} \times 1$$

$$\boldsymbol{Fuel\ Cost = 745\ \frac{\$}{hr}}$$

$$Fuel\ Cost = 149000 \times \frac{5}{1000} \times 8760$$

$$\boldsymbol{Fuel\ Cost = 6,526,200\ \frac{\$}{yr}}$$

Steam Cost Indicator

$$Steam\ Cost = \frac{Fuel\ Cost}{Steam\ Produced}$$

$$Steam\ Cost = \frac{745}{100}$$

$$\mathbf{Steam\ Cost = 7.45\ \frac{\$}{klb}}$$

$$Steam\ Cost = \frac{6{,}526{,}200}{100 \times 8760}$$

$$\mathbf{Steam\ Cost = 7.45\ \frac{\$}{klb}}$$

Classic Boiler Efficiency

- Steam generating unit efficiency is defined as the heat absorbed by the steam divided by the fuel input energy

$$\eta_{boiler} = \frac{\text{energy desired}}{\text{energy that costs}}(100)$$

$$\eta_{boiler} = \frac{\dot{m}_{steam}\left(h_{steam} - h_{feedwater}\right)}{\dot{m}_{fuel} HHV_{fuel}}(100)$$

Typical Boiler Efficiency

Polling Question

- A typical boiler will have an efficiency of ----?

What is your expectation for an operating boiler efficiency?

1. 0-50%
2. 50-75%
3. 75-85%
4. 85-100%
5. Need more information

Typical Boiler Efficiency

- A typical boiler will have an efficiency of ----?

75% to 82% to 90%

Wood | Natural Gas | Oil and Coal

Efficiency is dependent on the type of fuel and the installed equipment

Boiler Efficiency

- This is also called
  - Boiler efficiency
  - First law efficiency
  - Fuel to steam energy conversion efficiency

- Determine the steam generation efficiency for the example boiler

$$\eta_{boiler} = \frac{\dot{m}_{steam}\left(h_{steam} - h_{feedwater}\right)}{\dot{m}_{fuel} HHV_{fuel}}(100)$$

Example Boiler

- Boiler fired with natural gas
  - HHV is 1,000 Btu/scf
- Steam conditions: 400 psig, 700°F
- Output: 100,000 lb/hr (steady)
- Rating: 120,000 lb/hr (maximum continuous)
- Feedwater: 600 psig, 242°F
- Fuel supply: 149,000 scf/hr
- Fuel cost: $5.00 per MMBtu ($5/Mscf)
- Fuel related operating cost: ~$6,500,000/yr

Efficiency Example Steam Properties

Pressure (psig)	Temperature (°F)	Specific Enthalpy(Btu/lb)	Specific Entropy (Btu/lb-°F)	Quality	Known Variable	Specific Volume (ft³/lb)
400	700	1,362.018	1.6356	Gas	Temperature	1.5894
600	242	211.744	0.3554	Liquid	Temperature	0.0169
10	239.3567	207.8217	0.3525	Liquid	Saturated Quality	0.0169

Direct (Classic) Efficiency Calculation

This evaluation is also known as *direct* efficiency

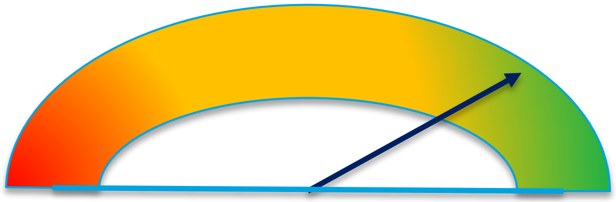
$$\eta_{boiler} = \frac{m_{steam} \times (h_{steam} - h_{feedwater})}{m_{fuel} \times HHV_{fuel}}$$

$$\eta_{boiler} = \frac{100{,}000 \times (1362.02 - 211.74)}{149{,}000 \times 1{,}000}$$

$$\eta_{boiler} = 0.772 \quad \text{or} \quad 77.2\%$$

Efficiency Calculation

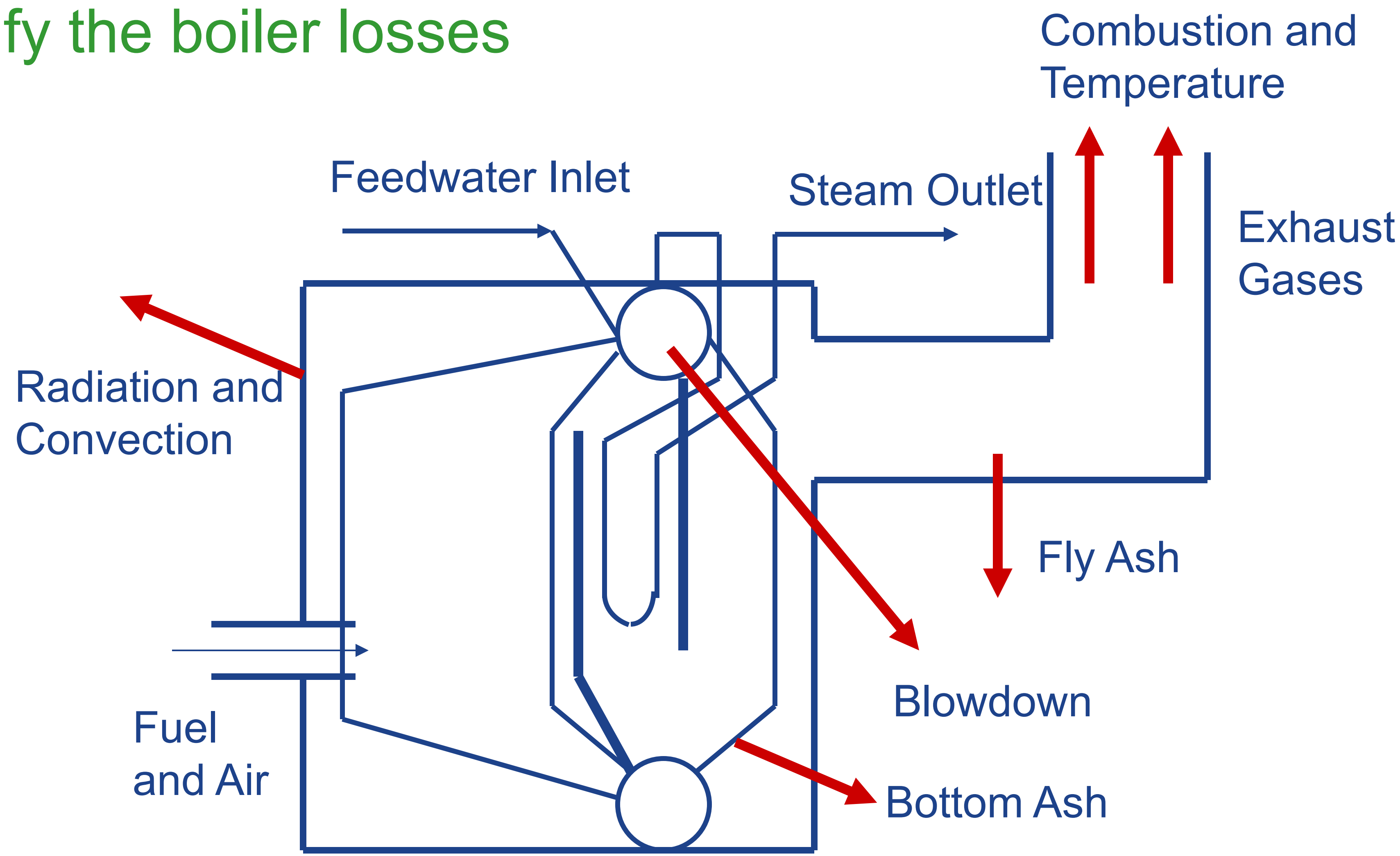
- This “Direct Efficiency” calculation can be done
  - On a real-time basis
  - Hourly, Daily, Monthly, Quarterly, Annual – basis
  - Seasonality and Production –related
  - Can be trended easily and should be used as a high-level bell-weather
  - Programmed on the Data Acquisition System and can provide a color-coded feedback to the operators



- The efficiency is not 100% since there are losses

Boiler Losses

- Identify the boiler losses



Indirect Efficiency

- Boiler efficiency can also be determined in an indirect manner by determining the magnitude of the losses
  - Primary losses are typically
    - Shell loss
    - Blowdown loss
    - Stack loss

$$\eta_{indirect} = 100\% - \sum_{losses} \lambda_i$$

$$\eta_{indirect} = 100\% - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \lambda_{misc}$$

ASME Boiler Efficiency

- American Society of Mechanical Engineers (ASME) has established a comprehensive testing standard for fired boilers
  - ASME Power Test Code 4 (ASME PTC-4)
    - Fuel efficiency (the same as the classic equation)
    - Gross efficiency (includes auxiliary input streams)
  - ASME PTC-4 describes two investigation methods
    - Input/output (direct method)
    - Energy balance (indirect method)

Generation Area

- Boiler Stack Loss

Stack Losses

- *Stack losses* are the largest of the boiler losses
- *Stack losses* are made up of two parts and defined as
  - Temperature losses
  - Combustion losses
- *Combustion analysis* is the method generally used to determine stack losses

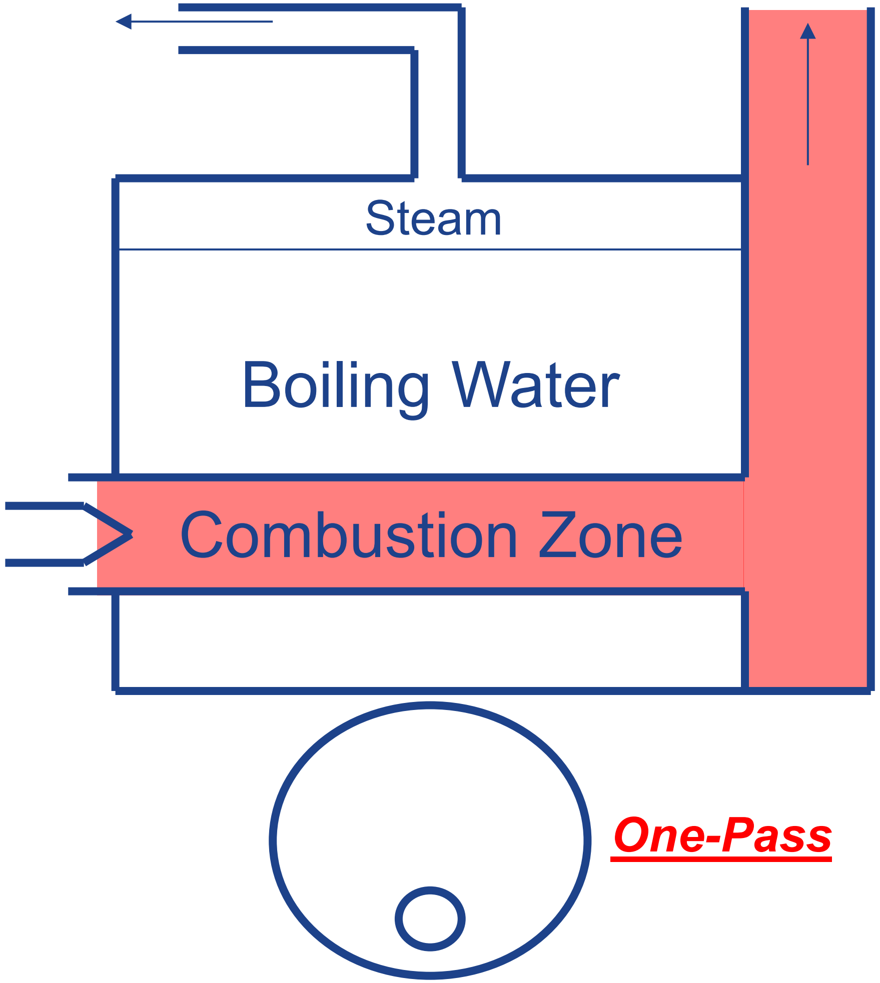
Stack Loss Evaluation

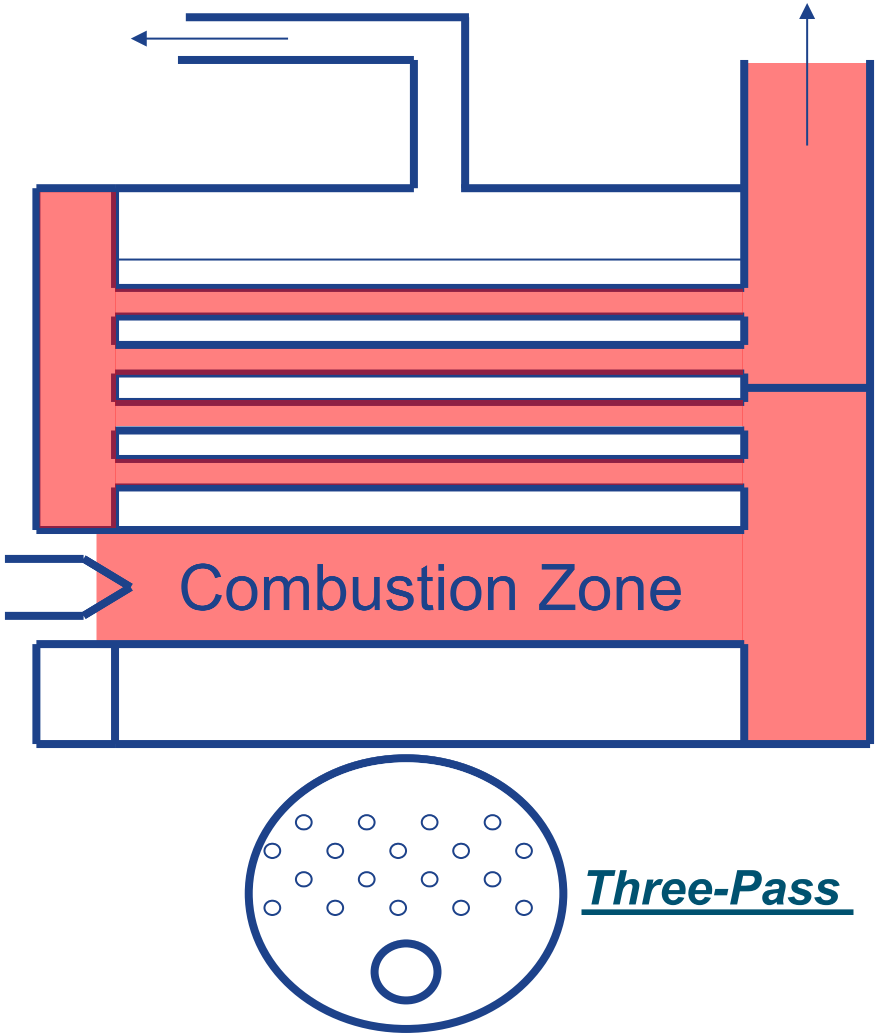
- Need a minimum number of measurements
- Can be via in-situ or portable instruments
- These measurements include:
  - Stack exhaust gas temperature
  - Flue gas oxygen content
  - Ambient temperature
  - Fuel composition
  - Flue gas combustibles concentration
- Stack loss tables
- Combustion models (software)

Flue Gas Temperature Loss

- The most common factors influencing flue gas temperature are:
  - Boiler design
  - Boiler load
  - Fire-side fouling
  - Water-side fouling
  - Failed flue gas path component
  - Excess air (possibly)

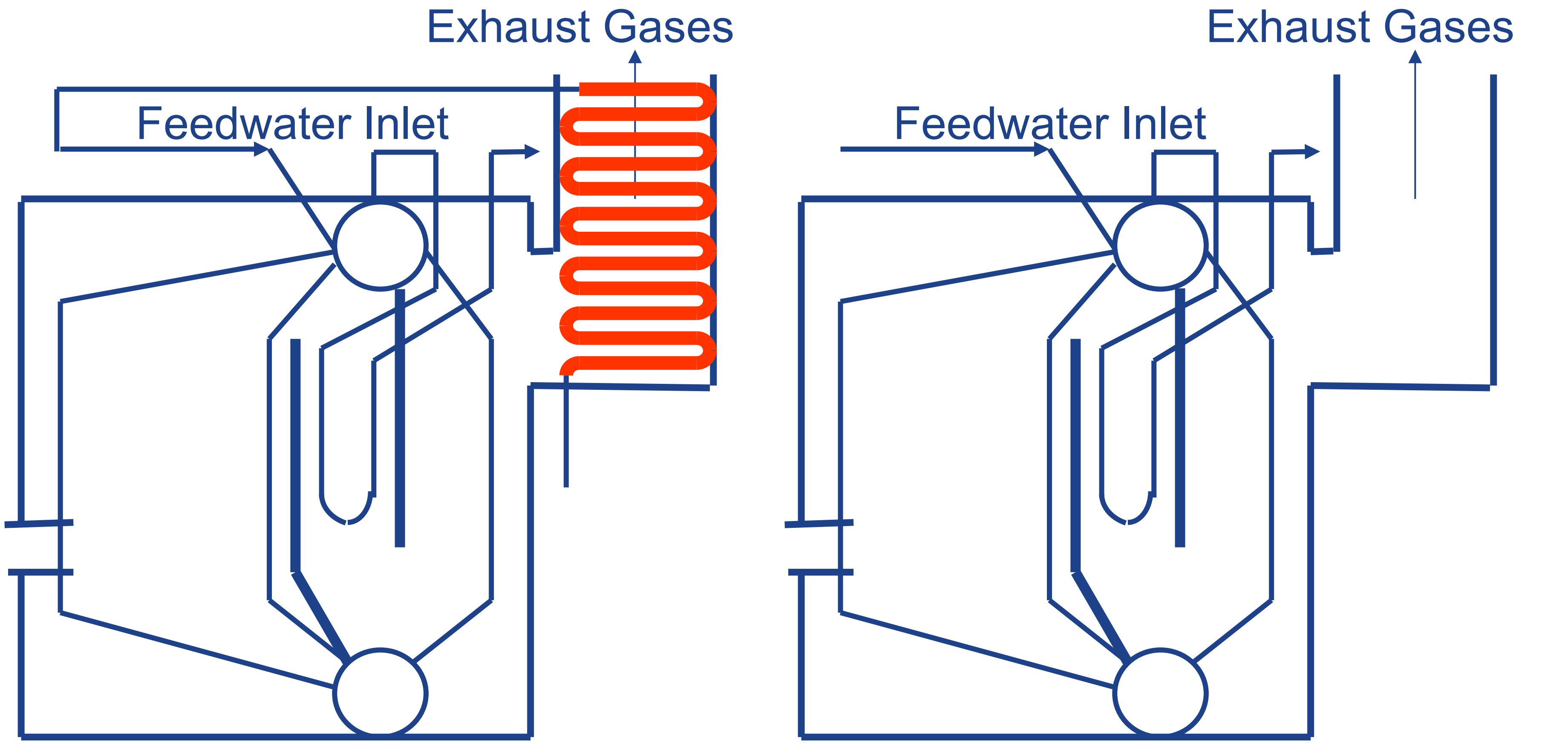
Boiler Design





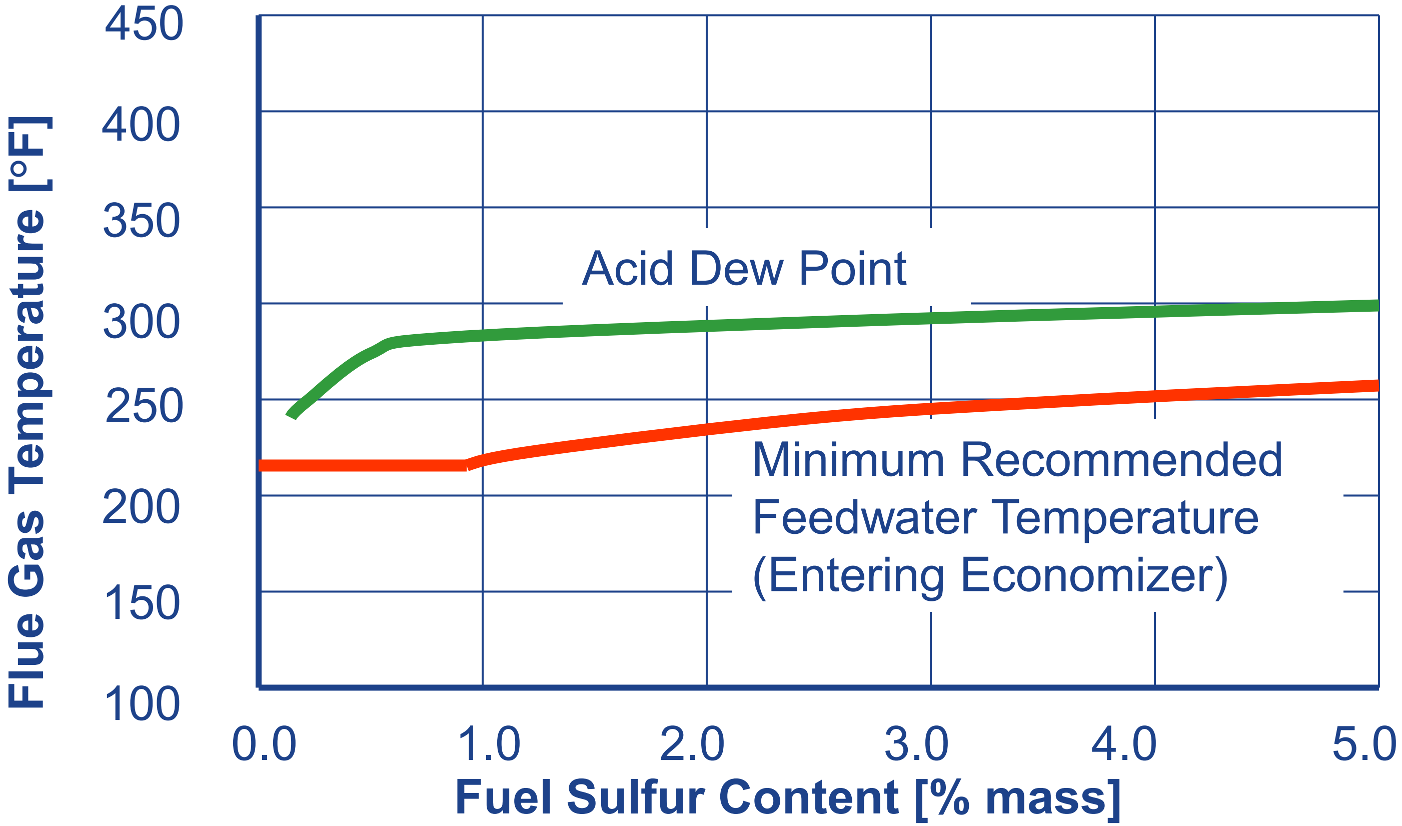
Energy Recovery Components

- Feedwater economizers and combustion air preheaters



Flue Gas Temperature Limitations

- Flue gas temperature is maintained above the dew point of acidic components
  - Fuels containing sulfur produce sulfuric acid
  - All hydrocarbon fuels can produce carbonic acid

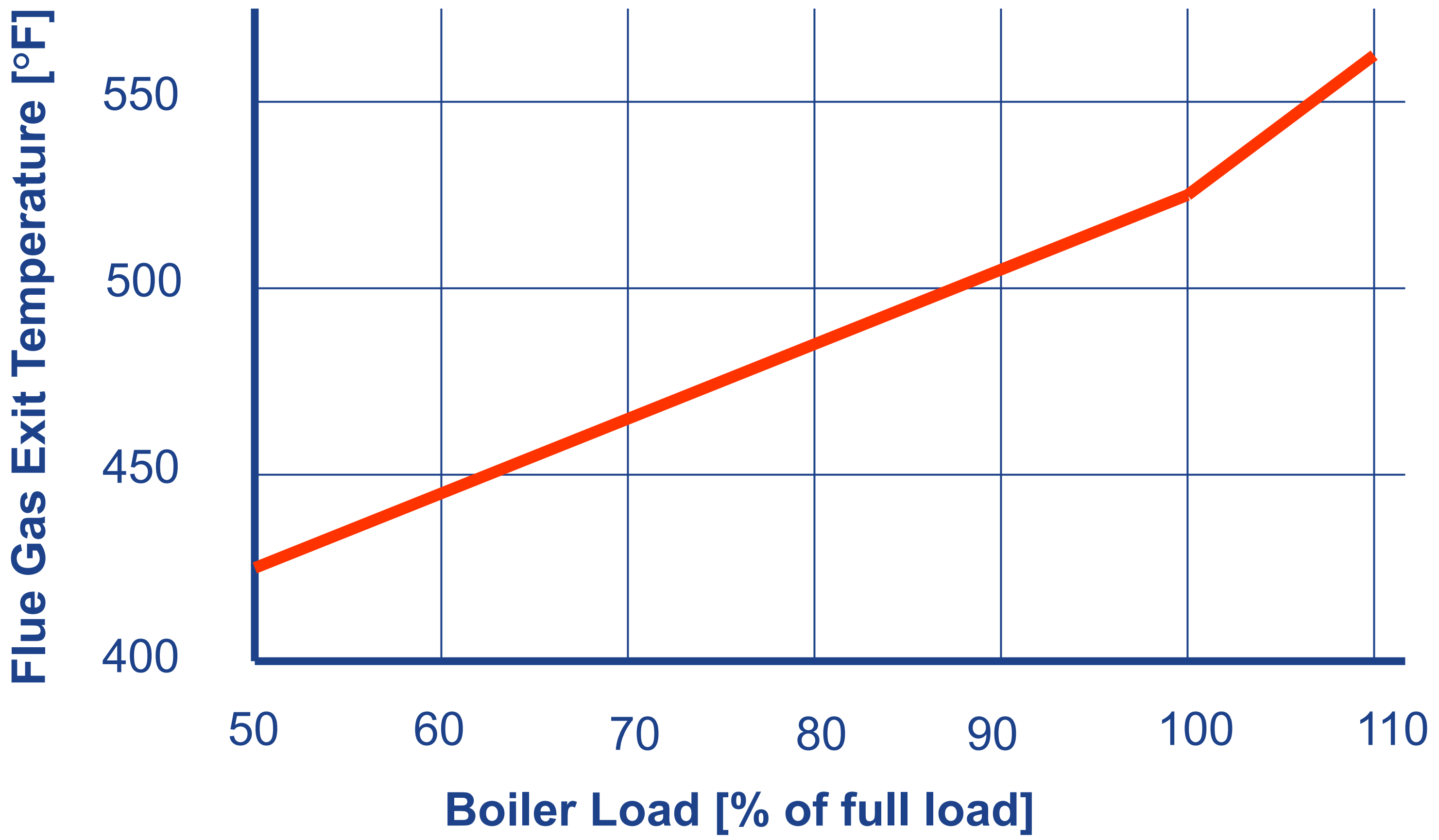


Condensing Economizers

- Condensing economizers can improve boiler efficiency more than 10% in comparison to conventional boilers
  - Final flue gas temperature can approach 75°F
  - Indirect units can heat streams to 200°F
  - Direct units can heat streams to 140°F
  - A significant amount of relatively *low-temperature* energy is recovered
  - Equipment is limited to *clean fuels*

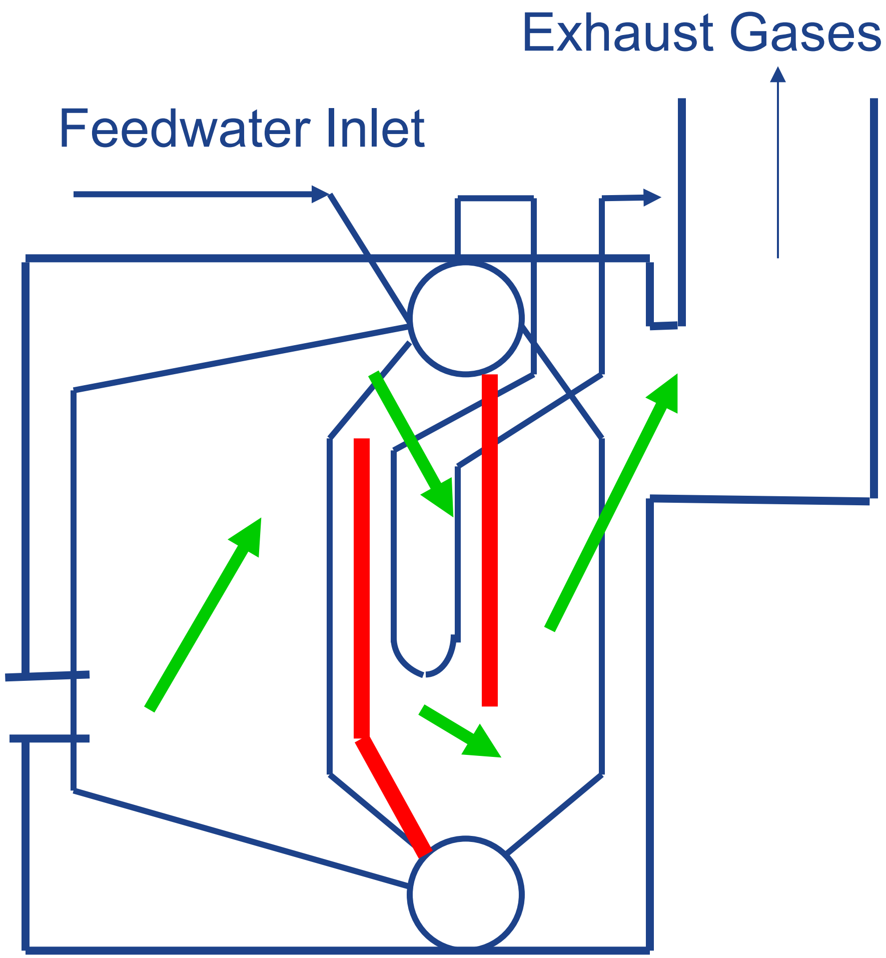
Boiler Load

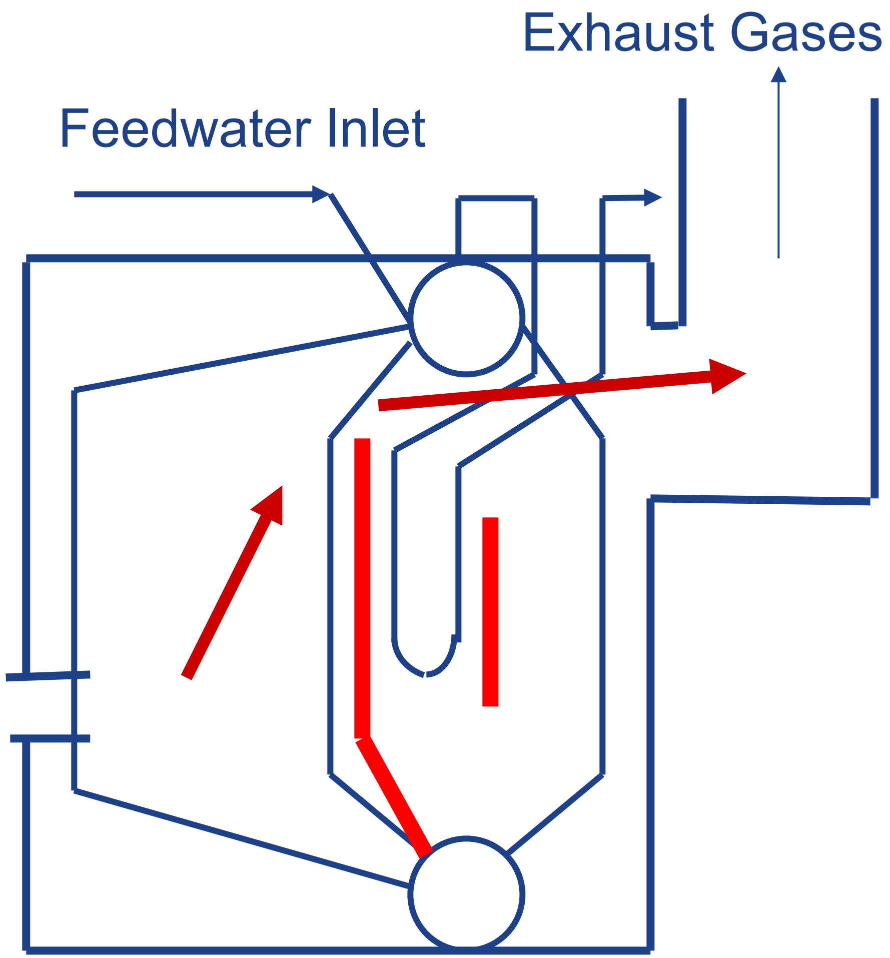
- Flue gas exhaust temperature typically increases as boiler steam production increases



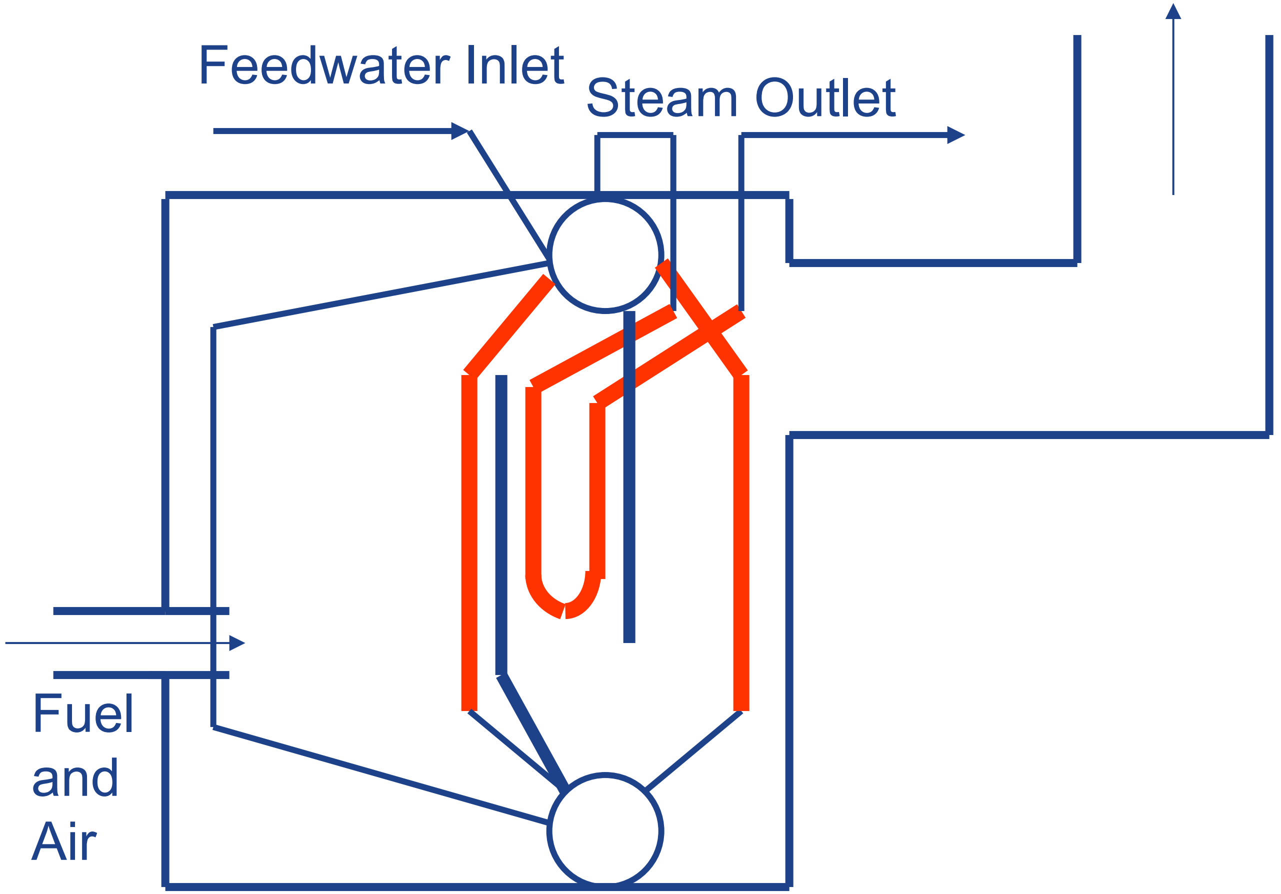
Failed Flue Gas Component

- Internal baffles force the flue gas to pass across the heat transfer surfaces
  - Baffle failures can result in flue gas bypassing surfaces





Fouling



- Fire-side fouling is managed through soot-blowing and periodic off-line cleaning
- Water-side fouling (scale) is typically managed through water treatment efforts

Potential Energy Loss Resulting from Scale Deposits			
Scale Thickness [inches]	Fraction of Total Fuel Input Energy Loss [%]		
	Scale Type		
	Normal	High Iron	Iron + Silica
1/64	1.0	1.6	3.5
1/32	2.0	3.1	7.0
3/64	3.0	4.7	--
1/16	3.9	6.2	--
National Institute of Standards and Technology, Handbook 115, Supplement 1			

Flue Gas Oxygen (Excess Air) Limits

- Primary factors affecting oxygen (excess air) are:
  - Fuel type
  - Monitoring and control method
  - Oxygen sensing location
  - Burner condition
  - Boiler load

Theoretical Air - Stoichiometric Combustion

- In a perfect world air and fuel would mix thoroughly and complete combustion would occur
  - Each molecule of fuel would find exactly the correct amount of oxygen for the combustion reaction to continue to completion

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Energy Release}$$

Actual Combustion

- In actual combustion processes fuel and oxygen do not react perfectly

- Un-reacted CH_4, CO, and H_2 are *fuels* resulting from incomplete combustion

$$CH_4 + 2O_2 \underbrace{\rightarrow}_{\text{Energy Release}} \alpha CO_2 + \beta H_2O + \gamma CO + \delta H_2 + \varepsilon CH_4 + \zeta O_2$$

Stack Loss Evaluation

- Measurements required to determine stack loss:
  1. Flue gas exit temperature
  2. Combustion zone exit oxygen content
  3. Ambient temperature
  4. Fuel composition
  5. Flue gas combustibles concentration
- Stack loss tables are one method that can be used to determine stack loss

Stack Loss - Natural Gas

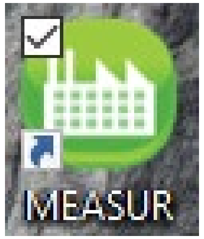
Stack Loss Table for Natural Gas												
Flue Gas Oxygen Content Wet Basis [%]	Stack Loss [% of fuel higher heating value input] Net Stack Temperature [∆°F] {Difference between flue gas exhaust temperature and ambient temperature}											
	155	180	205	230	255	280	305	330	355	380	405	430
1.0	13.1	13.6	14.1	14.7	15.2	15.8	16.3	16.9	17.4	18.0	18.5	19.1
2.0	13.2	13.8	14.3	14.9	15.5	16.1	16.6	17.2	17.8	18.4	18.9	19.5
3.0	13.4	14.0	14.6	15.2	15.8	16.4	17.0	17.6	18.2	18.8	19.4	20.0
4.0	13.6	14.2	14.8	15.5	16.1	16.7	17.4	18.0	18.7	19.3	20.0	20.6
5.0	13.8	14.5	15.1	15.8	16.5	17.2	17.8	18.5	19.2	19.9	20.5	21.2
6.0	14.1	14.8	15.5	16.2	16.9	17.6	18.3	19.1	19.8	20.5	21.2	22.0
7.0	14.4	15.1	15.9	16.6	17.4	18.1	18.9	19.7	20.5	21.2	22.0	22.8
8.0	14.7	15.5	16.3	17.1	17.9	18.8	19.6	20.4	21.2	22.1	22.9	23.7
9.0	15.1	16.0	16.8	17.7	18.6	19.5	20.4	21.2	22.1	23.0	23.9	24.8
10.0	15.5	16.5	17.4	18.4	19.4	20.3	21.3	22.2	23.2	24.2	25.2	26.1
Actual Exhaust T [°F]	225	250	275	300	325	350	375	400	425	450	475	500
Ambient T [°F]	70	70	70	70	70	70	70	70	70	70	70	70

Reference: Combustion model developed by Greg Harrell, Ph.D., P.E.

Stack Loss using US DOE MEASUR

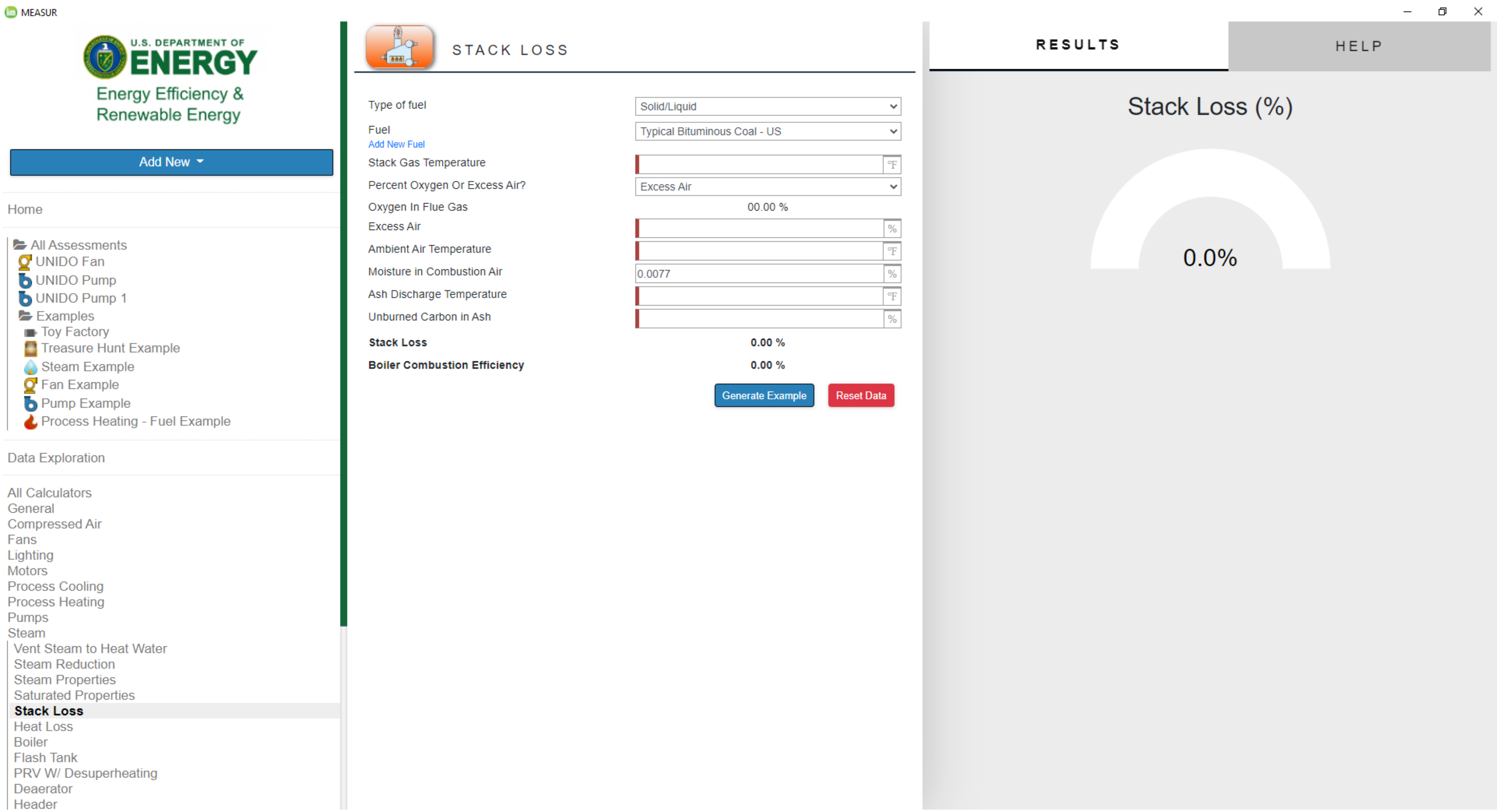
- Use US DOE MEASUR to determine stack loss and combustion efficiency

$$\eta_{combustion} = 100 - \lambda_{stack}$$



https://measur.ornl.gov

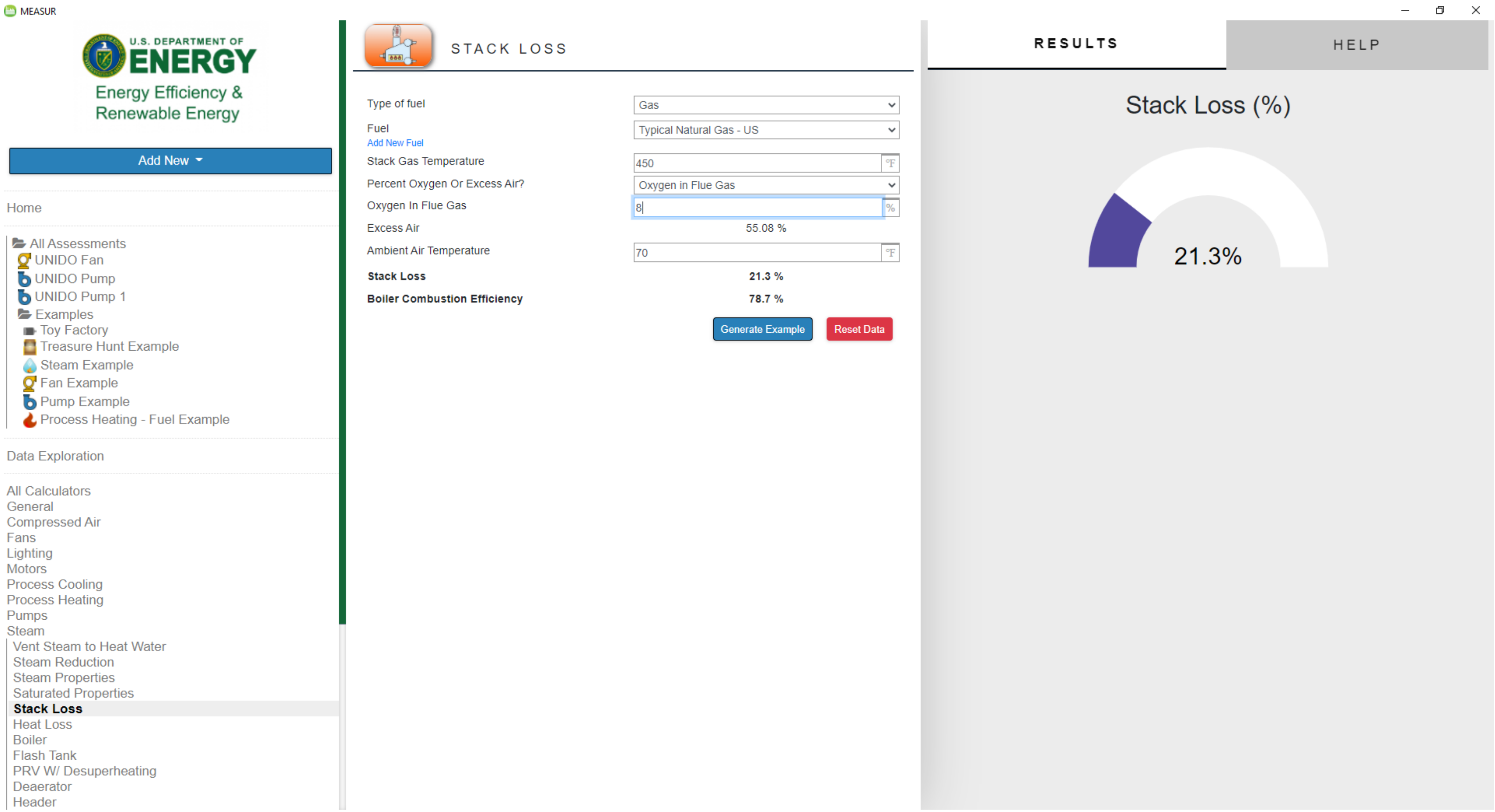
Stack Loss – US DOE MEASUR



Stack Loss Example

- Determine the Stack Loss (Natural Gas)
- Flue gas O_2 content 8% by volume
- Flue gas CO content ~0 ppm
- Flue gas unburned fuel ~0%
- Flue gas temperature 450°F
- Intake air temperature 70°F
- Fuel temperature 70°F
- 380°F net flue gas temperature

Stack Loss - Natural Gas



Stack Loss Example

- Determine the Stack Loss (Natural Gas)
- Flue gas O_2 content 8% by volume
- Flue gas CO content ~0%
- Flue gas unburned fuel ~0%
- Flue gas temperature 450°F (380°F net)
- Intake air temperature 70°F
- Fuel temperature 70°F
- Stack Loss 21.3%
- Combustion efficiency 78.7%

Polling Questions

Polling Questions

1) Do you monitor stack temperature of your boiler(s)?
   A. Yes
   B. No
   C. Don't know

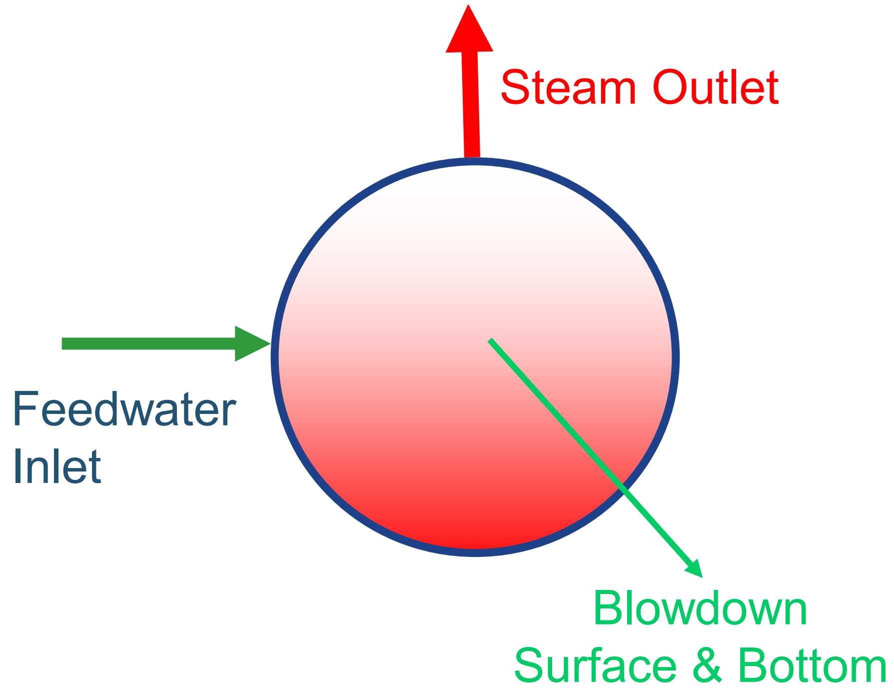
2) Do you monitor flue gas oxygen in your boiler(s)?
   A. Yes
   B. No
   C. Don't know

Generation Area

- Boiler Blowdown Loss

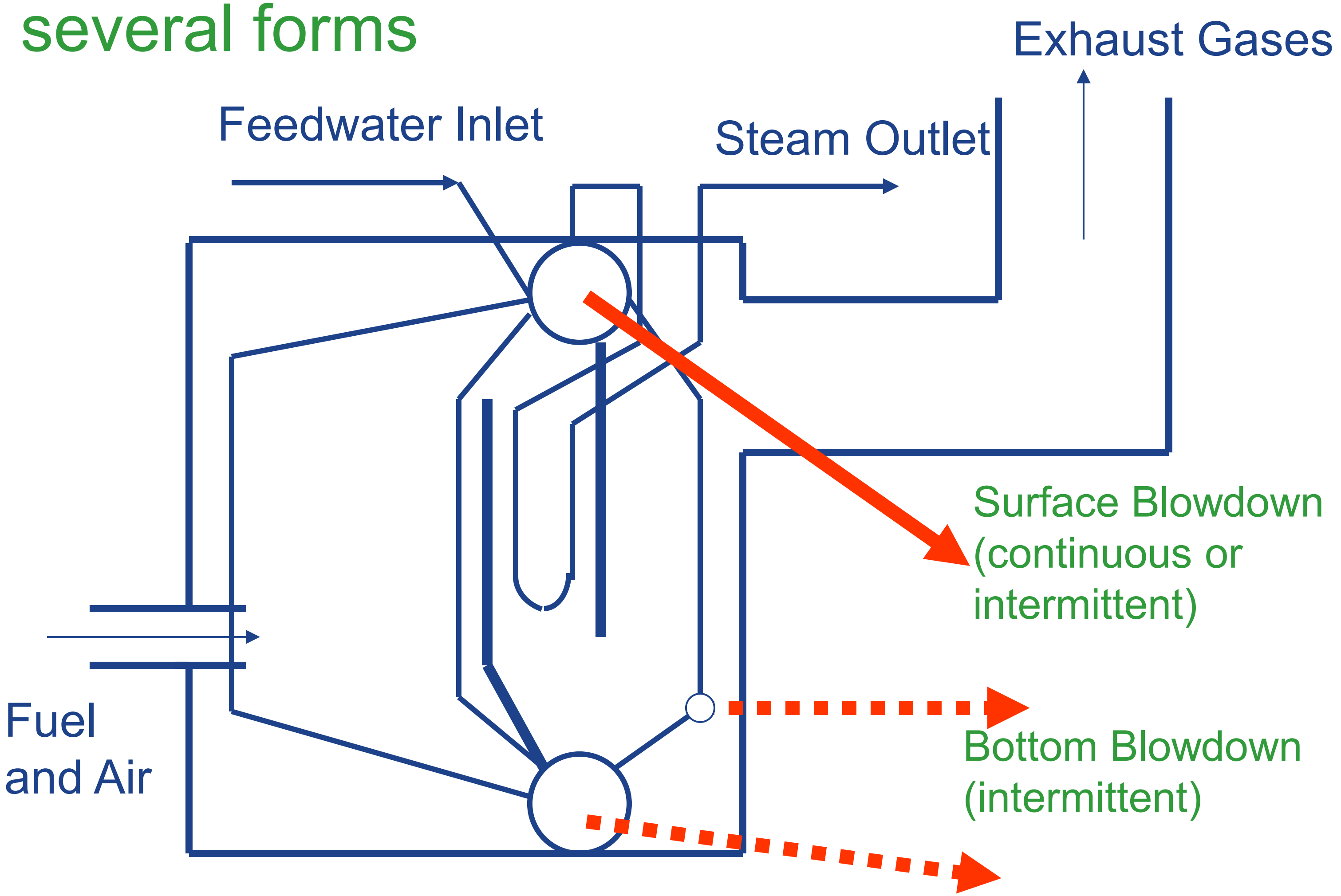
Blowdown Losses

- Boiler water contains dissolved minerals that are insoluble in steam
  - These minerals do NOT leave with steam
  - As steam is produced the concentration of these chemicals increases
- Blowdown is the removal of liquid water from the boiler to maintain proper water chemistry
  - Dissolved and precipitated chemical concentrations are controlled
- Blowdown is **required** to reduce the concentration of dissolved chemicals to keep them in solution
  - If boiler water chemistry is not properly maintained significant problems result



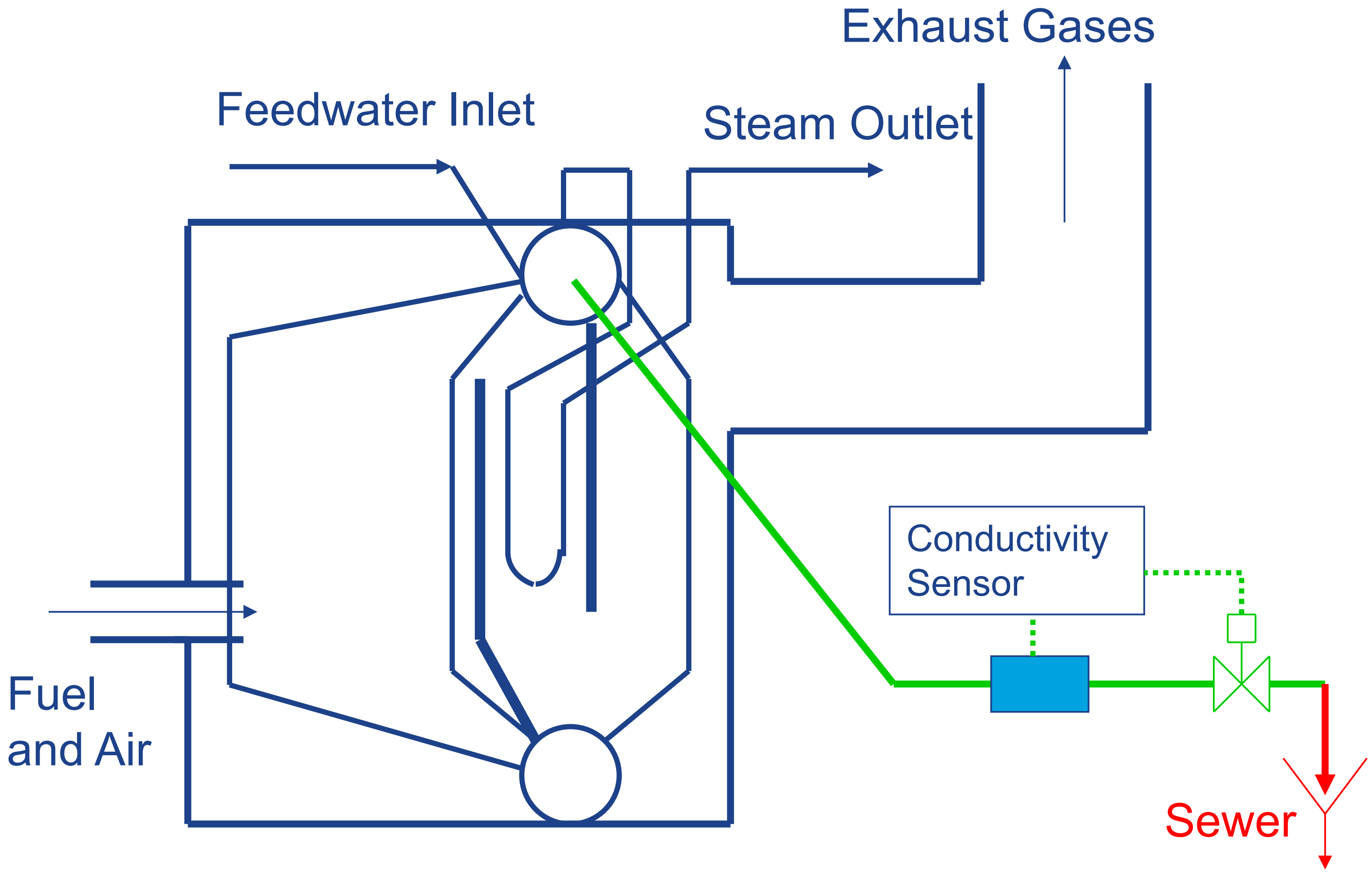
Boiler Blowdown

- Boiler blowdown takes several forms
  - Surface
    - Continuous
    - Intermittent
  - Bottom
    - Intermittent



Blowdown Control

- Primary control of surface blowdown is typically based on boiler water conductivity
- Conductivity must be correlated to actual water quality through specific analysis



Blowdown Loss & Management

- Blowdown amount is primarily dependent on:
  - Water quality
  - Boiler operating pressure

- Blowdown loss calculation begins with *measurement*
  - Typically, blowdown amount is estimated from boiler water chemical analysis

- Blowdown rates can be less than $1\%_{mass}$ in high quality water systems or higher than $10\%_{mass}$ in low quality water systems

Example Boiler

- Boiler fired with natural gas
  - HHV is 1,000 Btu/scf
- Steam conditions: 400 psig, 700°F
- Output: 100,000 lb/hr (steady)
- Rating: 120,000 lb/hr (maximum continuous)
- Feedwater: 600 psig, 242°F
- Fuel supply: 149,000 scf/hr
- Fuel cost: $\$5.00/10^6$ MMBtu
- Fuel related operating cost: ~$6,500,000/yr

Blowdown Estimate

- Chemical concentrations (such as chlorides and other chemicals) can be measured to determine blowdown rate
- For the *example boiler* chloride concentration in the feedwater is measured to be 15 ppm
  - Chloride concentration in the blowdown is measured to be 250 ppm

$$\% \, Blowdown = \frac{C_{feedwater}}{C_{blowdown}}(100) = \frac{15 \; ppm}{250 \; ppm}(100)$$

$$\% \, Blowdown \approx 6.0\%_{mass} \; of \;\; feedwater \; flow$$

Blowdown Estimate

- Boiler water conductivity can provide an indication of blowdown rate

$$\%\ Blowdown \approx \frac{Feedwater\ Conductivity}{Blowdown\ Conductivity} = \frac{C_{feedwater}}{C_{blowdown}}$$

$$\beta \approx \frac{150\ \frac{\mu mho}{cm}}{2{,}500\ \frac{\mu mho}{cm}}(100)$$

$$\beta \approx 6.0\%_{mass}$$

Blowdown Flow Rate

- The blowdown flow rate is determined from a mass balance completed on the boiler

$$\dot{m}_{blowdown} = \left(\frac{\beta}{1-\beta} \right) \dot{m}_{steam}$$

$$\dot{m}_{blowdown} = \left(\frac{0.06}{1-0.06} \right) 100{,}000 \,\tfrac{lbm}{hr} = 6{,}400 \,\tfrac{lbm}{hr}$$

Blowdown Loss Estimate for the Boiler

$$\lambda_{blowdown} = \frac{m_{blowdown} \times (h_{blowdown} - hf_{eedwater})}{m_{fuel} \times HHVf_{uel}}$$

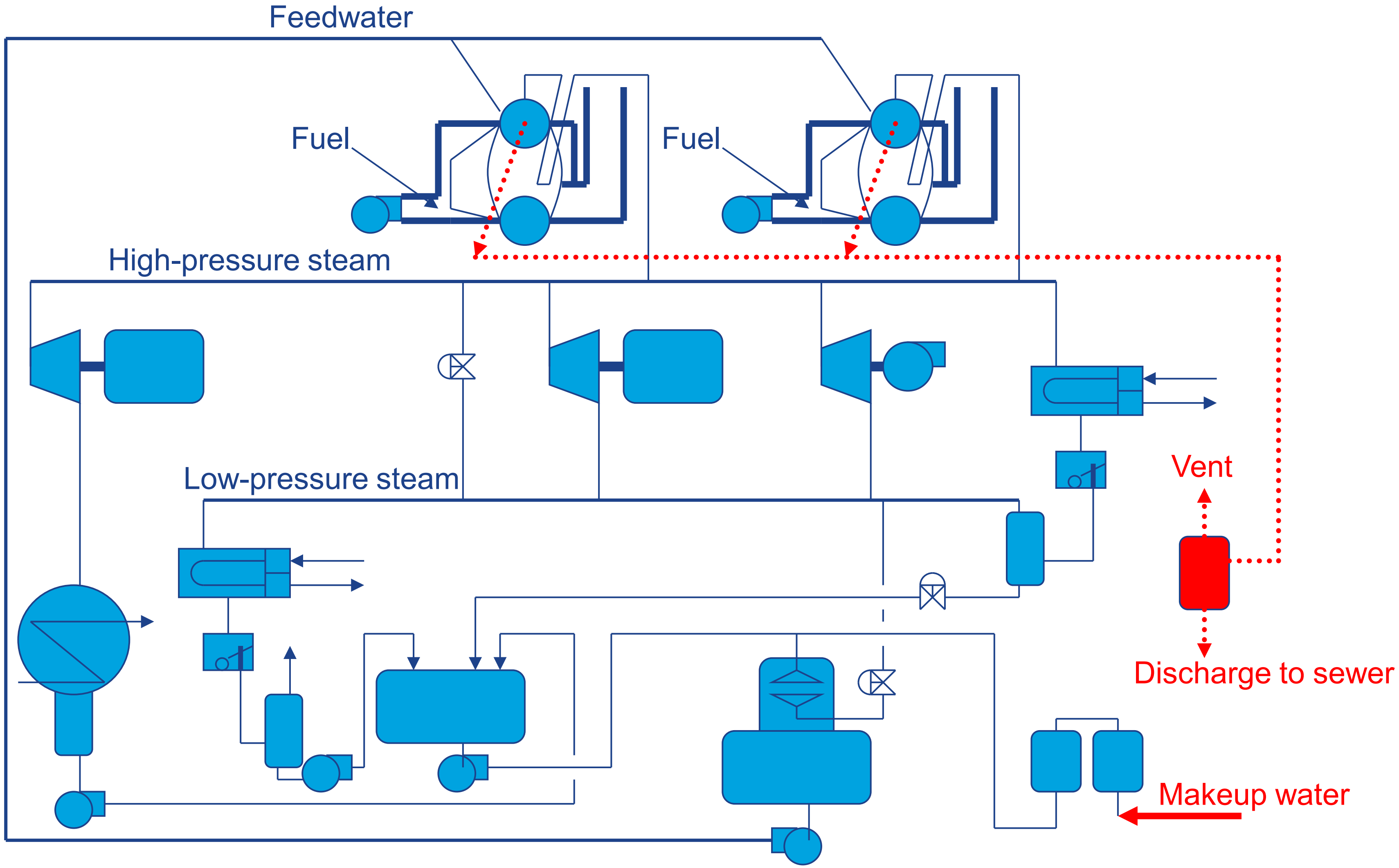
242°F feedwater

$$\lambda_{blowdown} = \frac{6{,}400 \times (428.2 - 211.74)}{149{,}000 \times 1{,}000}$$

$$\lambda_{blowdown} = 0.0093 \quad \text{or} \quad 0.93\%$$

~1.0% of the total fuel input energy resides in the blowdown stream

Blowdown Related System Loss



Blowdown Loss Estimate for the System

$$\lambda_{blowdown} = \frac{m_{blowdown} \times (h_{blowdown} - hm_{akeup})}{m_{fuel} \times HHVf_{uel}}$$

75°F makeup water

$$\lambda_{blowdown} = \frac{6{,}400 \times (428.2 - 43.1)}{149{,}000 \times 1{,}000}$$

$$\lambda_{blowdown} = 0.0165 \quad \text{or} \quad 1.65\%$$

~1.7% of the total fuel input energy resides in the blowdown stream when the *system* impact is considered

Generation Area

- **Boiler Shell (Radiation & Convection) Loss**

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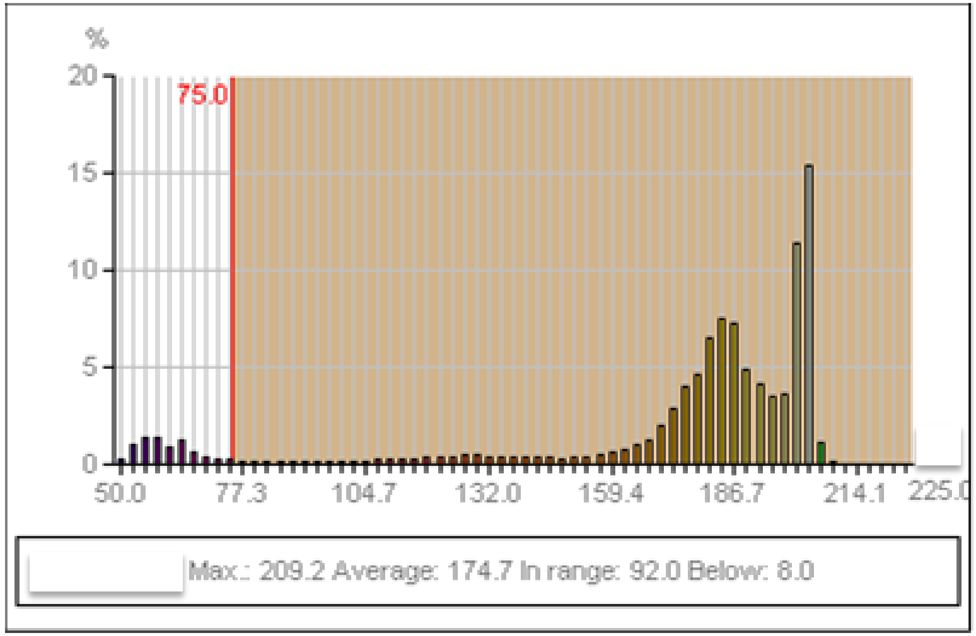
Shell Loss Magnitude

- The American Society of Mechanical Engineers (ASME) Power Test Code 4 (PTC-4) identifies a calculation procedure to *estimate* boiler shell loss
  - ASME PTC-4-2008, Section 5.14.9, pages 91-92

Shell Loss Estimation

- Search for "hot spots"
- Simple (but could get complex) methodology
  - Measure boiler surface temperatures – Infrared camera
  - Calculate surface area
  - Use histogram, if needed
  - Heat transfer model (3EPlus)
- Another estimation method
  - Identical boiler on hot standby
  - Measure fuel consumption
  - Generally, easier to do with gas and fuel oil-based fuels



First Order Shell Loss **Guide**

Shell Loss Gross Estimate Field Evaluations				
Boiler Type	**Steam Production Rating**		**Boiler Full-Load Shell Loss Estimate**	
	Minimum [lb/hr]	**Maximum [lb/hr]**	**Maximum [% fuel input energy]**	**Minimum [% fuel input energy]**
Water-tube	10,000	100,000	2.0	0.3
Water-tube	100,000	1,000,000	0.6	0.1
Water-tube	1,000,000	10,000,000	0.2	0.1
Fire-tube	1,000	40,000	1.0	0.1

Example Boiler Shell Loss

- From an *ASME type* investigation the radiation and convection loss of the example boiler is approximately 0.5% of the total fuel energy input to the boiler
  - This represents a loss of approximately $33,000/yr

Generation Area

- **Boiler Efficiency**

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Indirect Efficiency Summary

$$\eta_{indirect} = 100 - \sum_{Losses} \lambda_i$$

$$\eta_{indirect} = 100 - \lambda_{stack} - \lambda_{blowdown} - \lambda_{shell} \_ \lambda_{misc}$$

$$\eta_{indirect} = 100 - 21.3 - 0.9 - 0.5 - 0$$

$$\eta_{indirect} = 77.3\%$$

Direct (Classic) Efficiency Calculation

This evaluation is also known as *direct* efficiency

$$\eta_{boiler} = \frac{m_{steam} \times (h_{steam} - hf_{eedwater})}{m_{fuel} \times HHVf_{uel}}$$

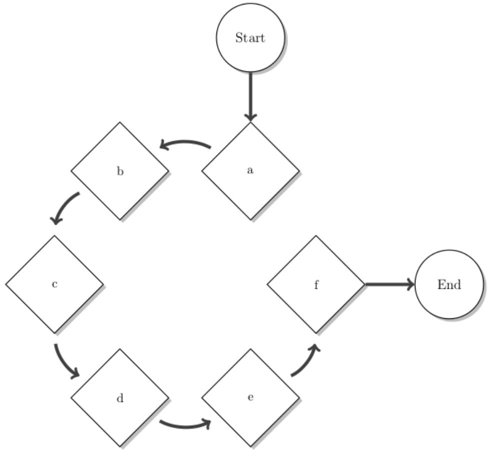
$$\eta_{boiler} = \frac{100{,}000 \times (1362.02 - 211.74)}{149{,}000 \times 1{,}000}$$

$$\eta_{boiler} = 0.772 \quad \text{or} \quad 77.2\%$$

Which Method should be used?

Polling Question

Direct Method



InDirect Method

Boiler Efficiency Evaluation – Direct Method

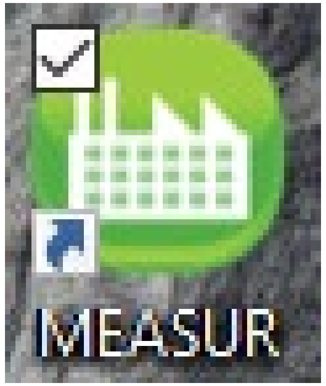
- Advantages
  - All-in-one
  - Very quick and easy – minimal data required
  - Can be done for instantaneous, hourly, daily, monthly, annually or any time period
  - Trends, dashboards – programmable for operators
- Disadvantages
  - Need flow rates (steam and fuel) – maybe difficult to obtain – larger time periods needed with totalizers
  - Can have significant errors – calibration + human
  - No information on how to improve boiler efficiency

Boiler Efficiency Evaluation – InDirect Method

- Advantages
  - Can be very accurate since errors in measurements are very minimal
  - Provides gap analysis for boiler efficiency improvement
  - Stack loss, blowdown can be trended and programmed – main variable losses
- Disadvantages
  - Significant data collection (in-situ and portable instruments + human intervention)
  - Mostly done instantaneously or over shorter periods of time only
  - Boiler shutdown maybe needed to initiate data collection

Example Boiler – US DOE MEASUR

- Boiler fired with natural gas
  - HHV is 1,000 Btu/scf
- Steam conditions: 400 psig, 700°F
- Output: 100,000 lb/hr (steady)
- Fuel cost: $5.00 per MMBtu
- Blowdown: 6%
- Deaerator: 10 psig
- Combustion efficiency: 78.7%
  - Shell loss can be added to more accurately reflect the energy flow numbers but it is generally not an impact parameter



Example Boiler – US DOE MEASUR

BOILER

Deaerator Pressure	10 psig
Combustion Efficiency	78.7 %
Calculate Efficiency	
Blowdown Rate	6 %

Steam

Pressure	400 psig.
Known Variable	Temperature
Temperature Value	700 °F
Steam Mass Flow	100000 klb/hr

Generate Example   Reset Data

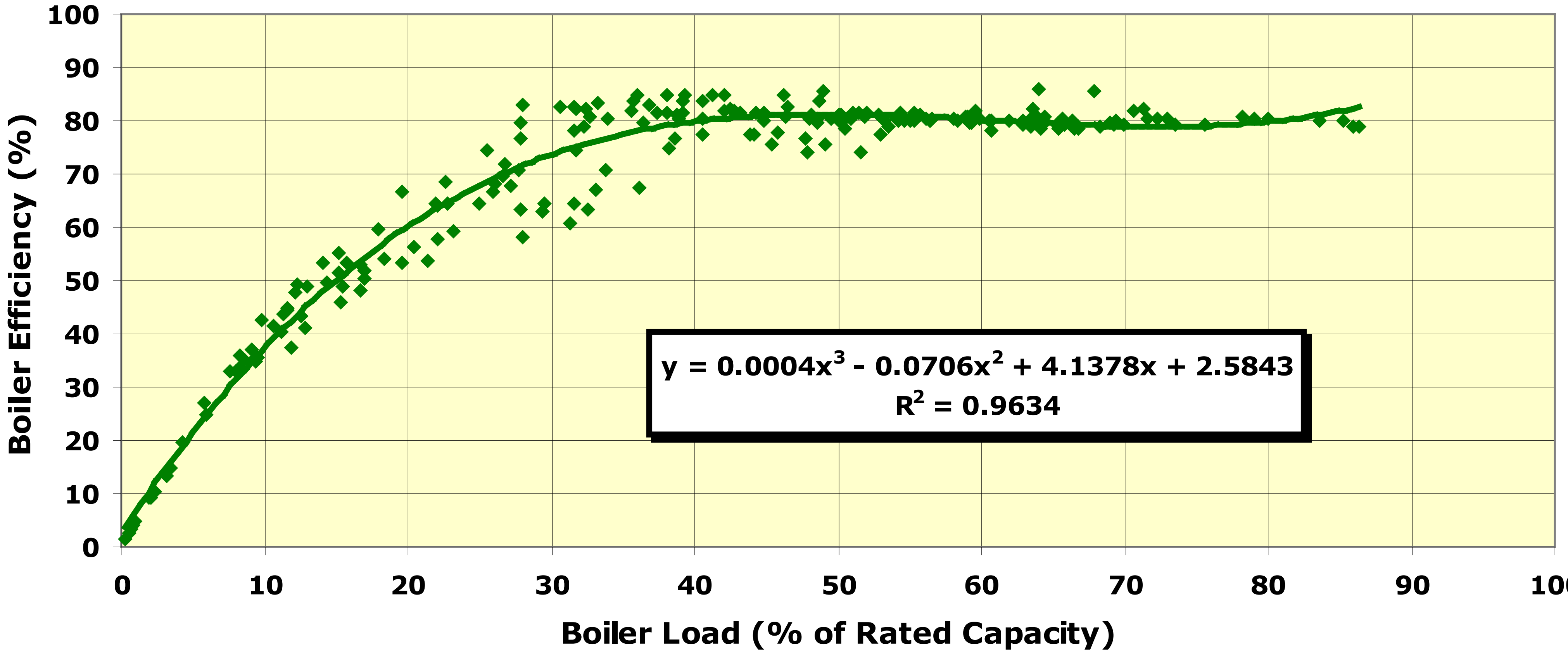
RESULTS   HELP

Blowdown Rate	6 %
Boiler Energy	116,825.4 MMBtu/hr
Combustion Efficiency	78.7 %
Fuel Energy	148,444 MMBtu/hr

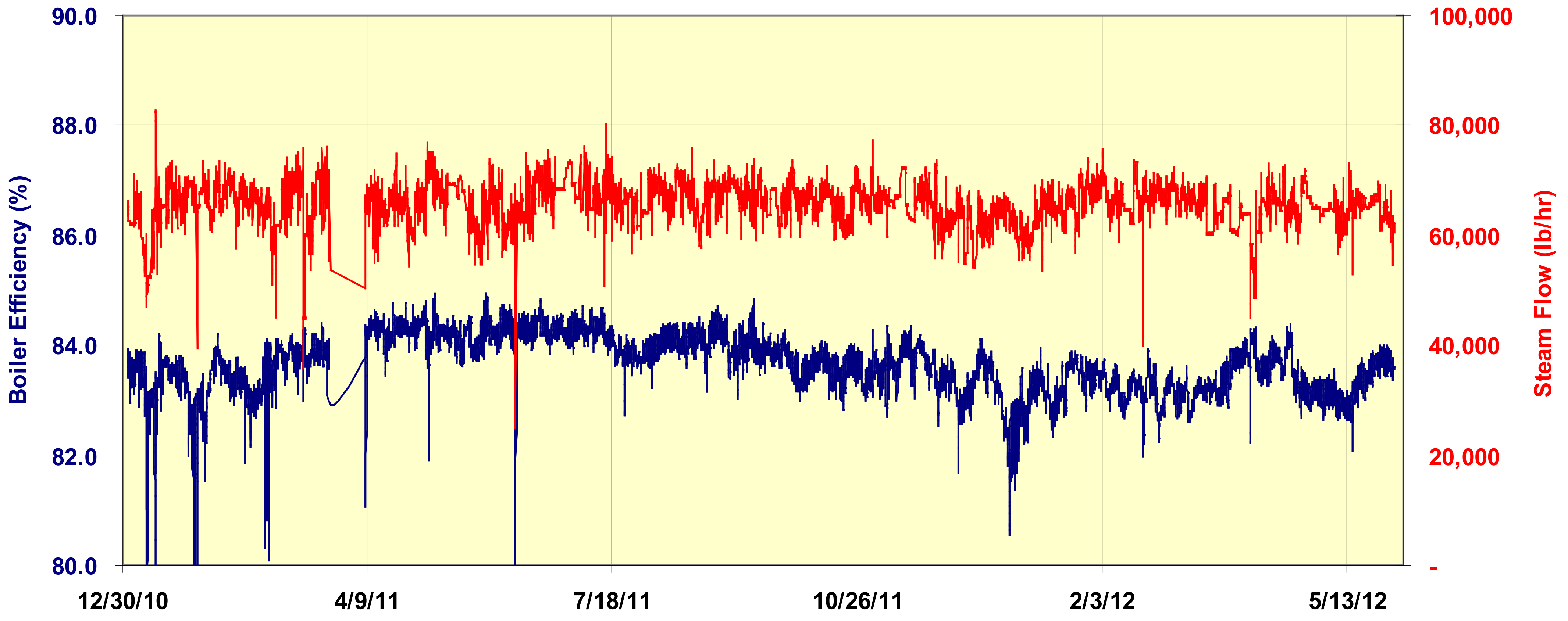
	Feedwater	Blowdown	Steam
Pressure (psig)	10	400	400
Temperature (°F)	239.4	448.2	700
Saturated	Liquid	Liquid	Gas
Mass Flow (klb/hr)	106,382.98	6,382.98	100,000
Sp. Enthalpy (Btu/lb)	207.8	428.2	1,362
Sp. Entropy (Btu/lb-°F)	0.352	0.626	1.636
Energy Flow (MMBtu/hr)	22,108.6	2,732.9	136,201.2

Copy Table

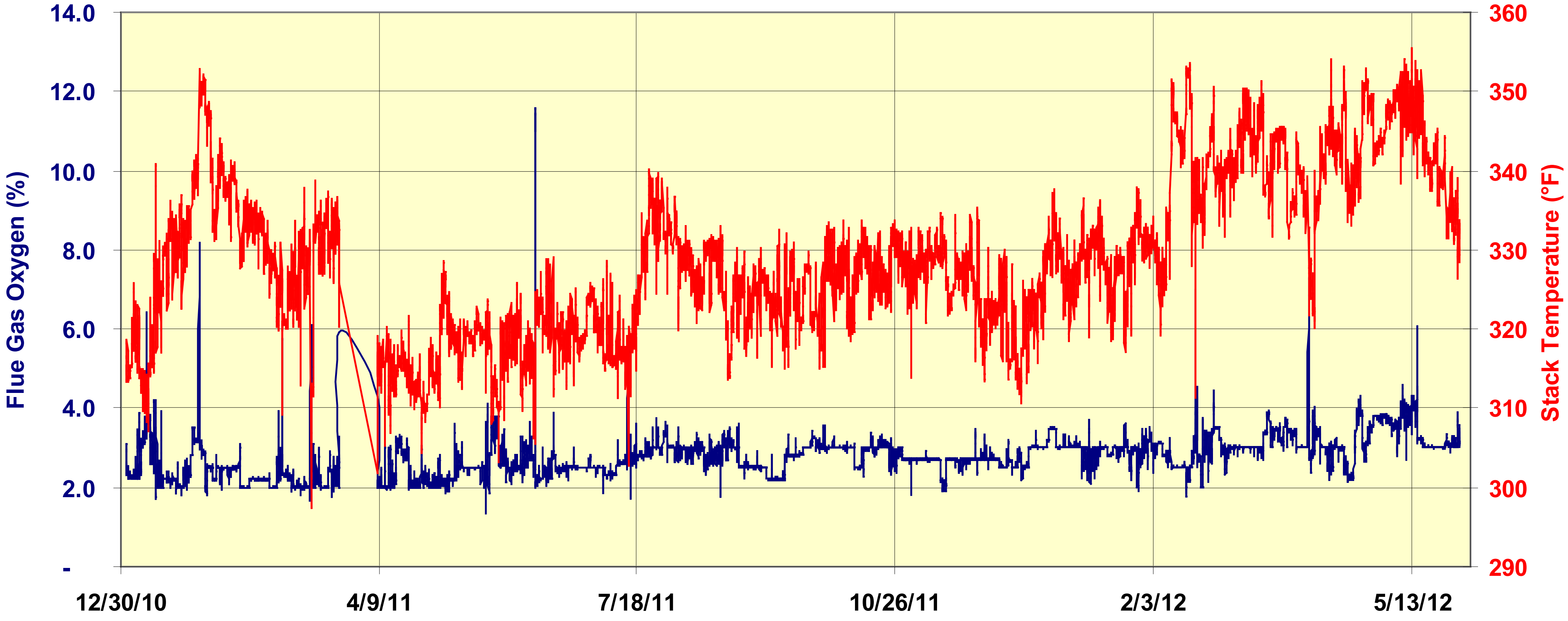
Typical Boiler Efficiency Curve



Boiler Efficiency Curve



Boiler Efficiency – Key Parameters Monitoring



What about Boiler Plant Direct Efficiency?

- If the fuel is the same for all boilers and boilers have same steam generation conditions and feedwater conditions

$$\eta_{plant} = \frac{m_{total-steam}\left(h_{steam} - h_{feedwater}\right)}{m_{total-fuel} \times HHV_{fuel}} \times 100$$

- If the fuel is different for boilers and boilers have different steam generation conditions and feedwater conditions

$$\eta_{plant} = \frac{\sum_1^n m_{steam}\left(h_{steam} - h_{feedwater}\right)}{\sum_1^n m_{fuel} \times HHV_{fuel}} \times 100$$

Homework #2

- Pay a visit to your boiler plant (generation) area and make a list of all the boilers, their design steam flow, pressure, fuel used and heat (input or output) rating.
- Understand how the boiler plant is controlled – how many boilers are running, how many are hot standby, etc. How does seasonality and production change the operations of these boilers.
- Pick one or more boilers and complete the exercise to calculate direct boiler efficiency and indirect boiler efficiency with specific boiler losses. You can use 2Q or 3Q 2024 average data or representative operating data.
- Calculate your steam cost ($/klb).

Thank You all for attending today's webinar.

See you all on Wednesday – October 16, 2024 – 10 am ET

If you have specific questions, please stay online and we will try and answer them.

Alternately, you can email questions to me at paparra@ornl.gov

U.S. DEPARTMENT OF ENERGY