REINHOLD ENVIRONMENTAL Ltd.

2016 NOx-Combustion-CCR Round Table Presentation

February 1 & 2, 2016, in Orlando, FL / Hosted by OUC

Energy Efficiency - Heat Rate

Presented at the NOx Roundtable
February 2, 2016

Imagination at work

Preview

Heat rate basics

Boiler efficiency effects on heat rate

Boiler steam conditions effects on heat rate

Other interesting (to me) stuff and an example economic calculation

Take away R.O.T. (Rules of thumb)

Questions ? - anytime

What this is not…

Thermodynamic Review of Rankine/Regnerative cycle

- In the regenerative cycle, it is important to add heat to the working fluid in steps at different temperatures and pressures to maximize efficiency.

Detailed Heat Rate Calculations

- The complicated system of HP/IP/LP turbines, superheat and reheat steam, 7 FW heaters, steam turbine extractions, etc. is all designed to maximize the cycle efficiency at an economical cost over the long term. Deviations from design hurt either heat rate or equipment.

Detailed Boiler/Turbine Analysis

Combustion Book has some of the basics on cycles

Heat Rate Definitions

Heat Rate - How much heat (thermal energy, BTU) is required to generate a unit of electrical energy (kW)

- Format - BTU/kW hr
- Less is more, lower is better

100% conversion of heat to electricity

- 3412 Btu/hr = 1 kW hr

Another view - Thermal efficiency

- of the heat input to the boiler, how much is converted to usable electrical energy
- 9645 BTU/kW hr Heat Rate = 35.4 % Thermal Efficiency (3412/9645)=.354

Why Heat Rate and not thermal efficiency?

- It is useful to know how much energy in BTUs we need to make a kW.
- We buy fuel in Million BTUs (MMBTU)
- If we divide the Heat Rate (HR) in BTU/kWh by 1000 we get MMBTU/MWh
- This makes it very easy to calculate things on a per MW basis
  - Fuel at $/MMBTU x HR MMBTU/MW = $/MW
  - Emissions in Lb/MMBTU x HR MMBTU/MW= Lb/MW

Heat Rate - Different Boundaries

Turbine Heat Rate -

- Heat input to turbine / Generator Output (kW hr)

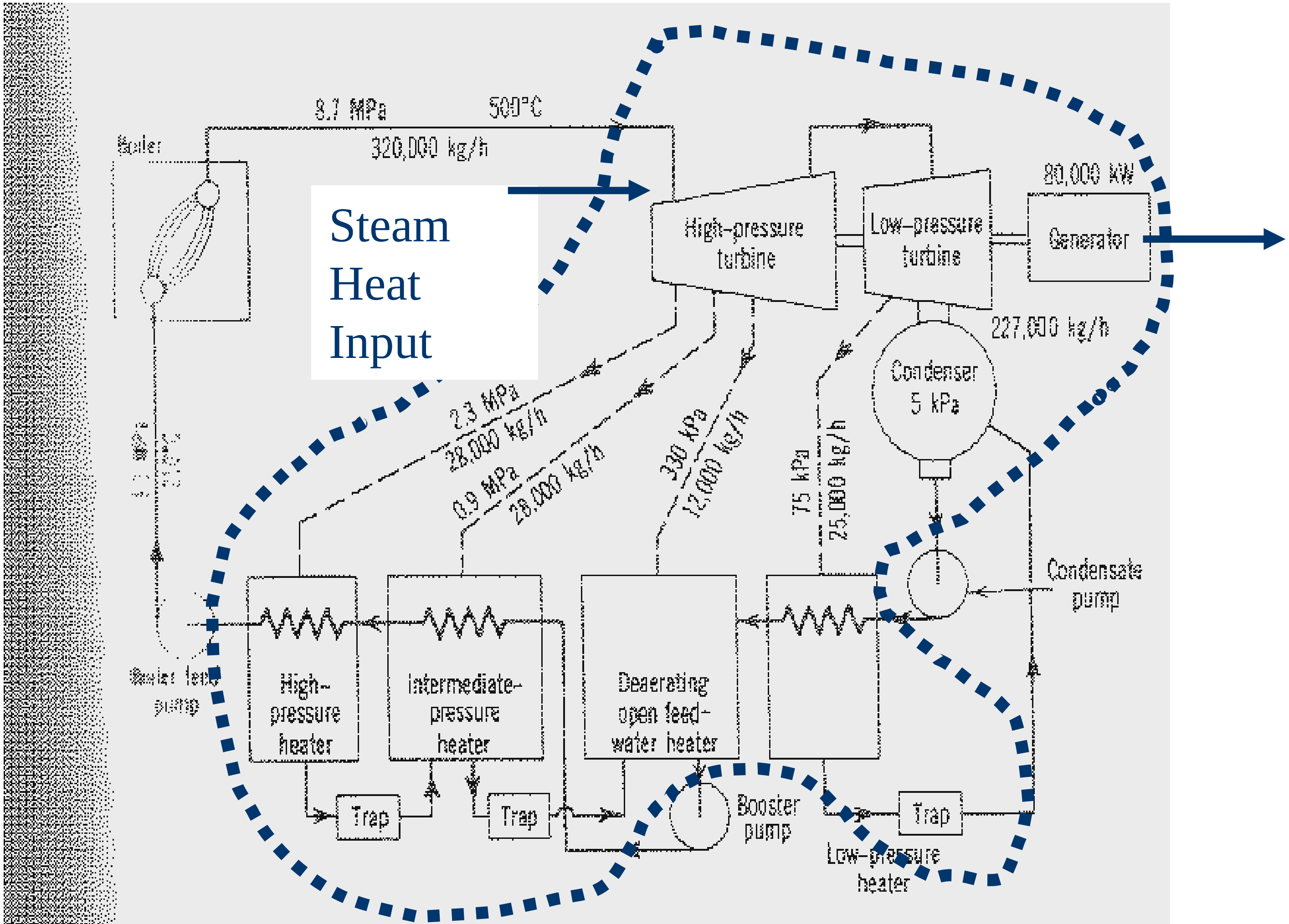
Plant (Gross) Heat Rate

- BTU’s from fuel burned / Generator Output kW/hr
- Factors in boiler efficiency

Net Plant Heat Rate

- BTU’s from fuel burned/Generator Output - Auxiliary Power
- Considers all auxiliary equipment
- Best view of overall plant efficiency

Turbine Heat Rate ("Actual")

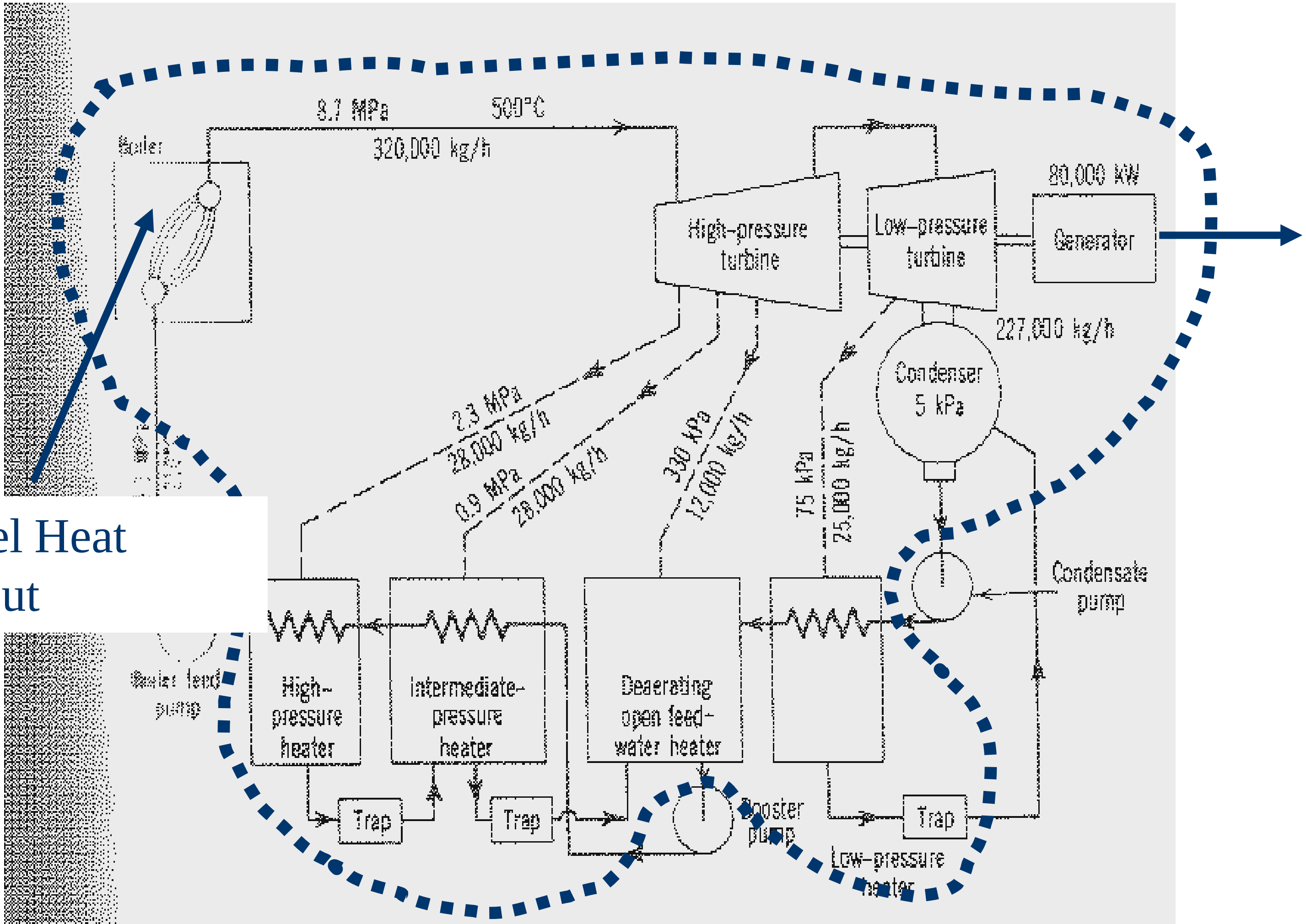


Steam Heat Input

Gross Power Output

Fig. 10.10 Arrangement of heaters in an actual power plant utilizing regenera feedwater heaters.

Plant (Gross) Heat Rate

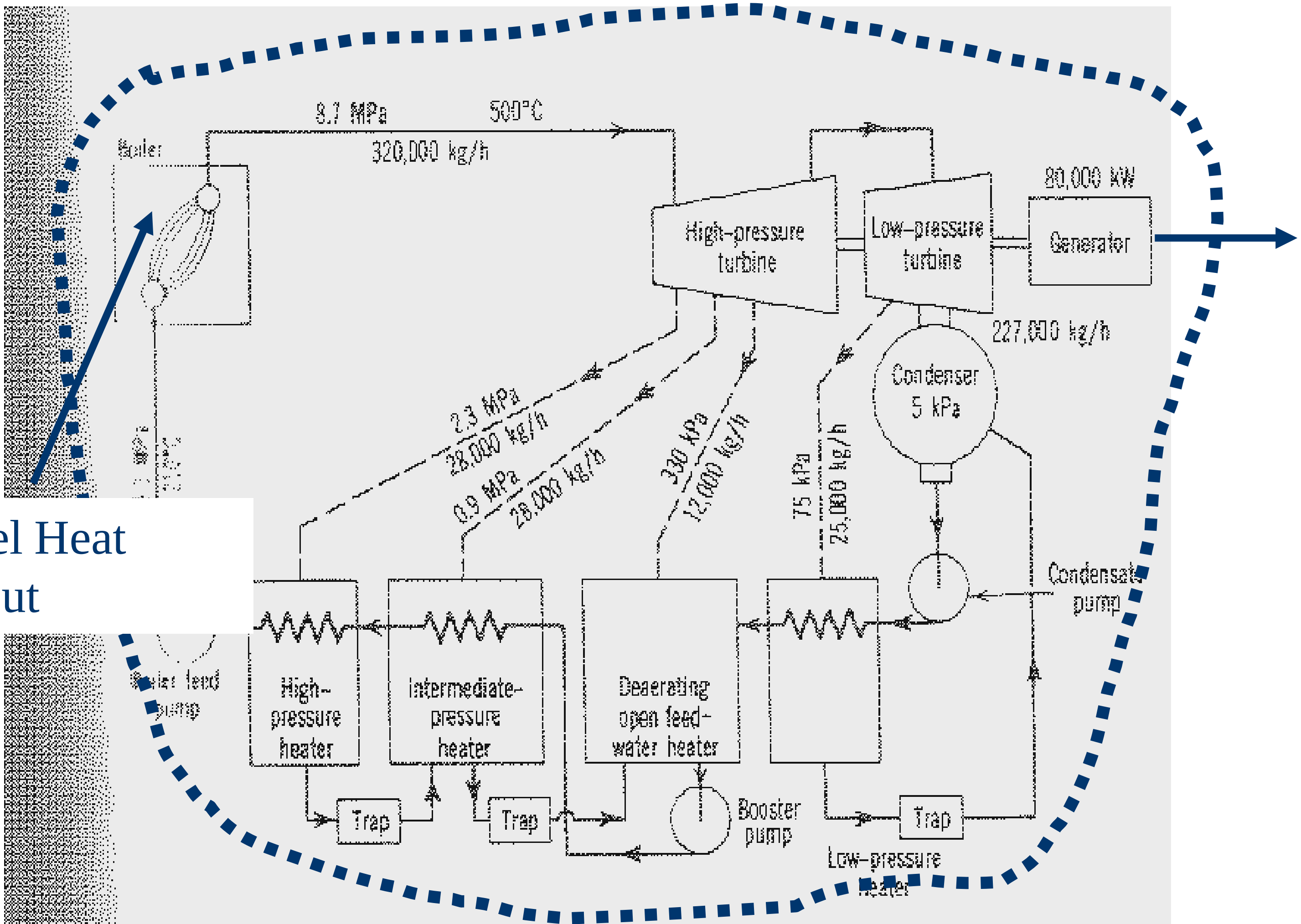


Gross Power Output

Fuel Heat Input

Fig. 10.10 Arrangement of heaters in an actual power plant utilizing regenera feedwater heaters.

Net Plant Heat Rate



Fuel Heat Input

NET

Power Output

Fig. 10.10 Arrangement of heaters in an actual power plant utilizing regenera feedwater heaters.

Example

500 MW net plant,

- 4.8% Auxiliary Power (25 MW)
- 86% Boiler Efficiency
- 7900 BTU/kW Turbine Heat Rate

Gross Plant Heat Rate

- 7900 / 0.86 = 9186 BTU/kW hr

Net Plant Heat Rate

- 9186 x (525 / 525-25) = 9645 BTU / kW hr

Turbine Heat Balance Diagram - Actual

Features

Reheat Regenerative

6 FW Heaters - One top heater

2520 psig SH Outlet

2400 psig Turbine Inlet

1000ºF SH and RH temp

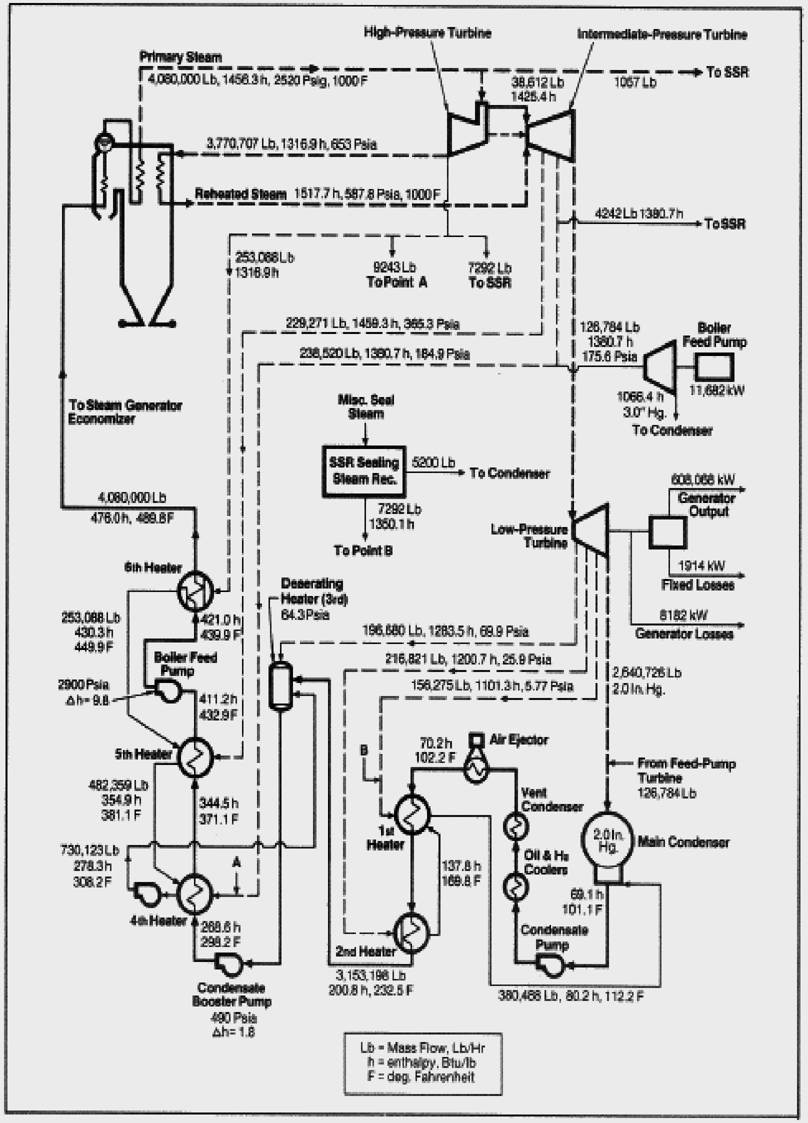


Fig. 6 **Reheat regenerative cycle, 600-MW subcritical-pressure fossil power plant**

Net Plant Heat Rates (Ideal?)

PC - Subcritical (2400 psig, 1000/1000)

- 9550 BTU/kW hr, 35.8%

PC - Supercritical (3500 psig, 1050/1050/1050)

- 8450 BTU/kW hr, 40.5%

PC - ULTRA-Supercritical (5075 psig, 1291/1328)

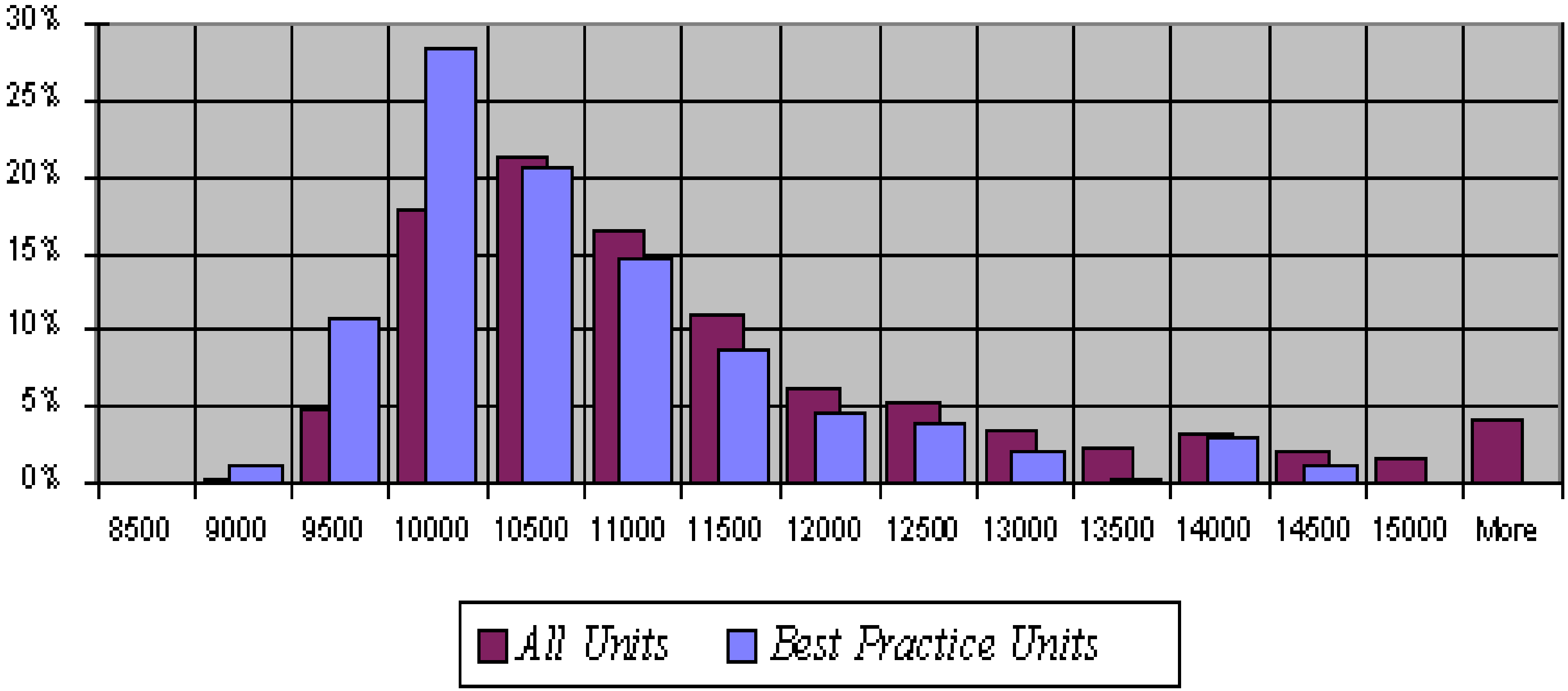
- 7850 BTU/kW hr, 43.6%

Gas Turbine, Combined Cycle

- 5784 BTU/kW hr, 59%
- Comparing PC subcritical to GTCC helps explain why gas can cost 2+ x as much as coal and still be economical

Range of Heat Rates - 1,098 US Boilers

Distribution of Heat Rates for Coal-fired Generating Units



Does Heat Rate Really Matter ?

YES

- All else being equal, a lower heat rate means less emissions and less fuel usage, which means lower cost for generating electricity.

NO

- Controlled Utility - Fuel cost is a pass through, but…..
  - PUC oversight
  - Plant pride / Dispatch order (bonuses?)
- Heat Rate increased with PRB conversion. Cost of PRB is significantly less.
- When electricity is at a premium, MW generation dominates

Heat Rate is only **<u>one</u>** of the key factors in economic decisions made by the plant or downtown.

Boiler Influence on Heat Rate

Boiler Efficiency

- Affects plant heat rate and net plant heat rate
- Straight forward - the better the efficiency, the better the heat rate.

Boiler thermal conditions affect turbine heat rate

- Spray (RH, SH)
- Steam Temperatures (SH, RH)
- Steam Pressure

Power Consumption

There are countless other minor influences

Boiler Efficiency

Each 1% change in boiler efficiency affects heat rate by approximately 108 BTU/kW hr.

- 0.25% change in efficiency equals 27 BTU/kW hr

Boiler/operations influencing efficiency

- Exit O2
- Exit gas temperature
- Unburned carbon

Purchasing influences on efficiency

- Coal type, moisture

Boiler Efficiency

Exit O2 - for each 1% change in O2

- 0.25% Boiler Efficiency or 27 BTU/kW hr

Exit gas temperature, 10 °F change ...

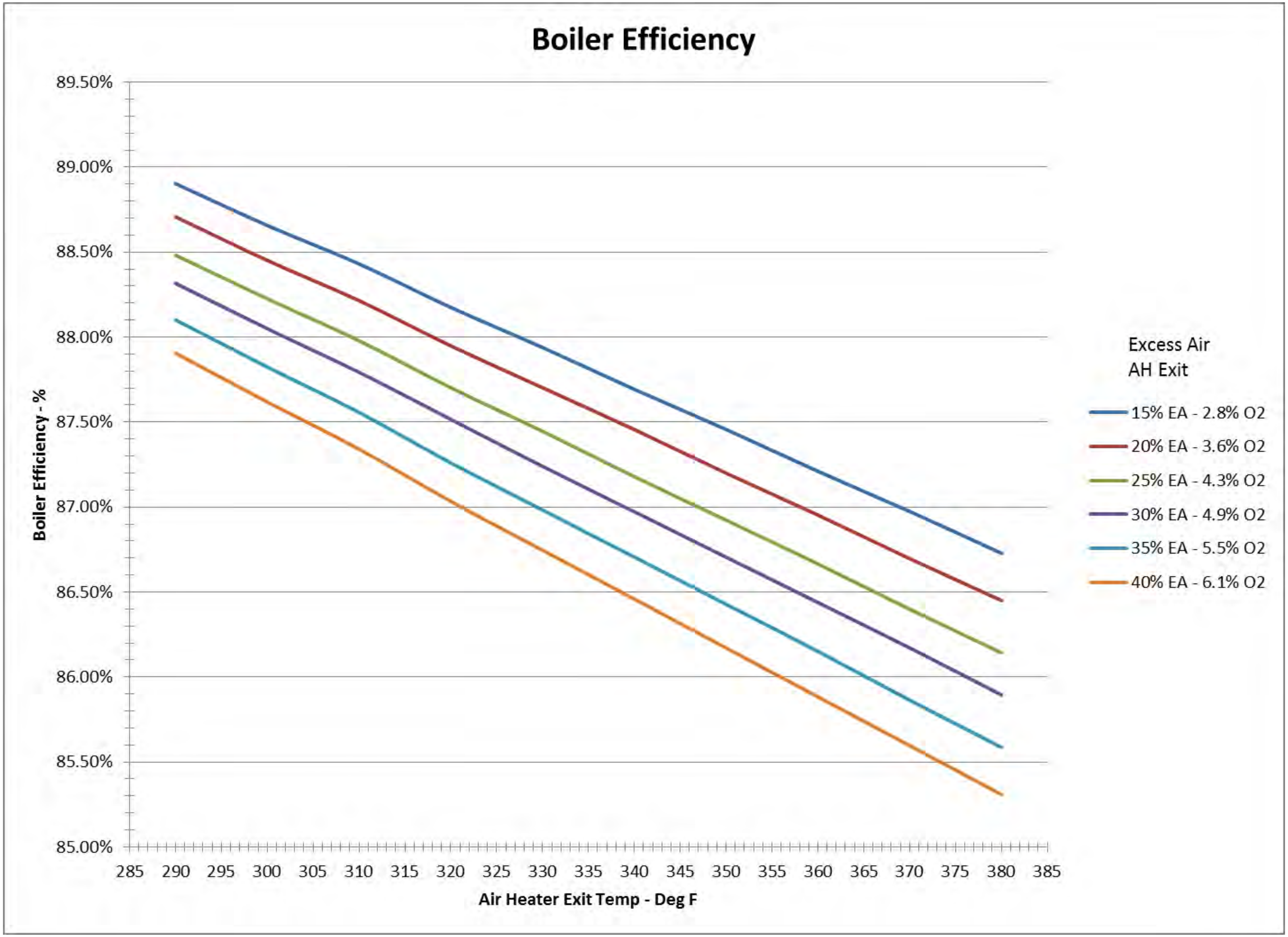
- E Bit. - 0.25% boiler eff. or 27 BTU/kW hr
- PRB - 0.28% boiler eff. or 31 BTU/kW hr

Unburned carbon

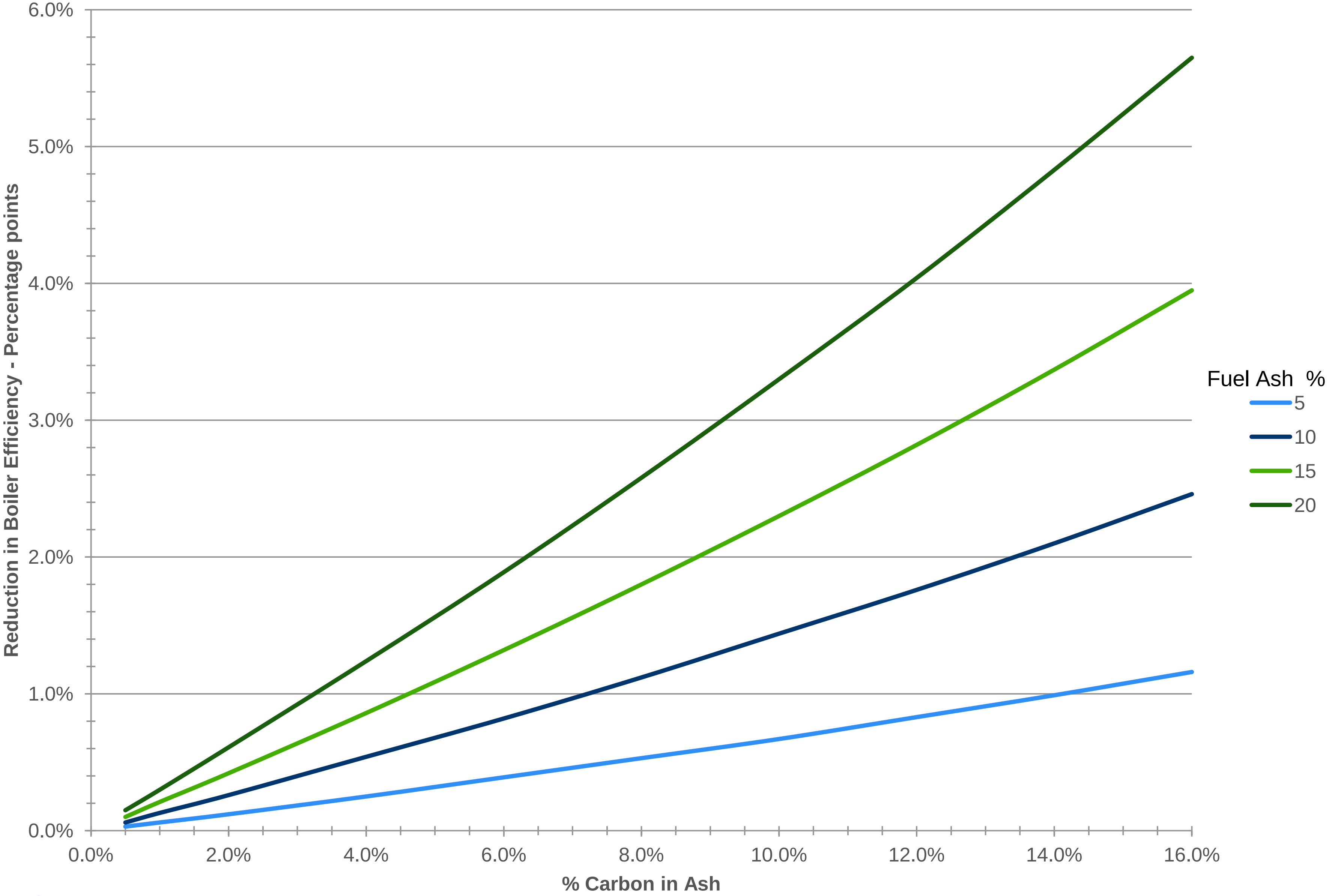
- Very fuel dependent, can be affected by operation

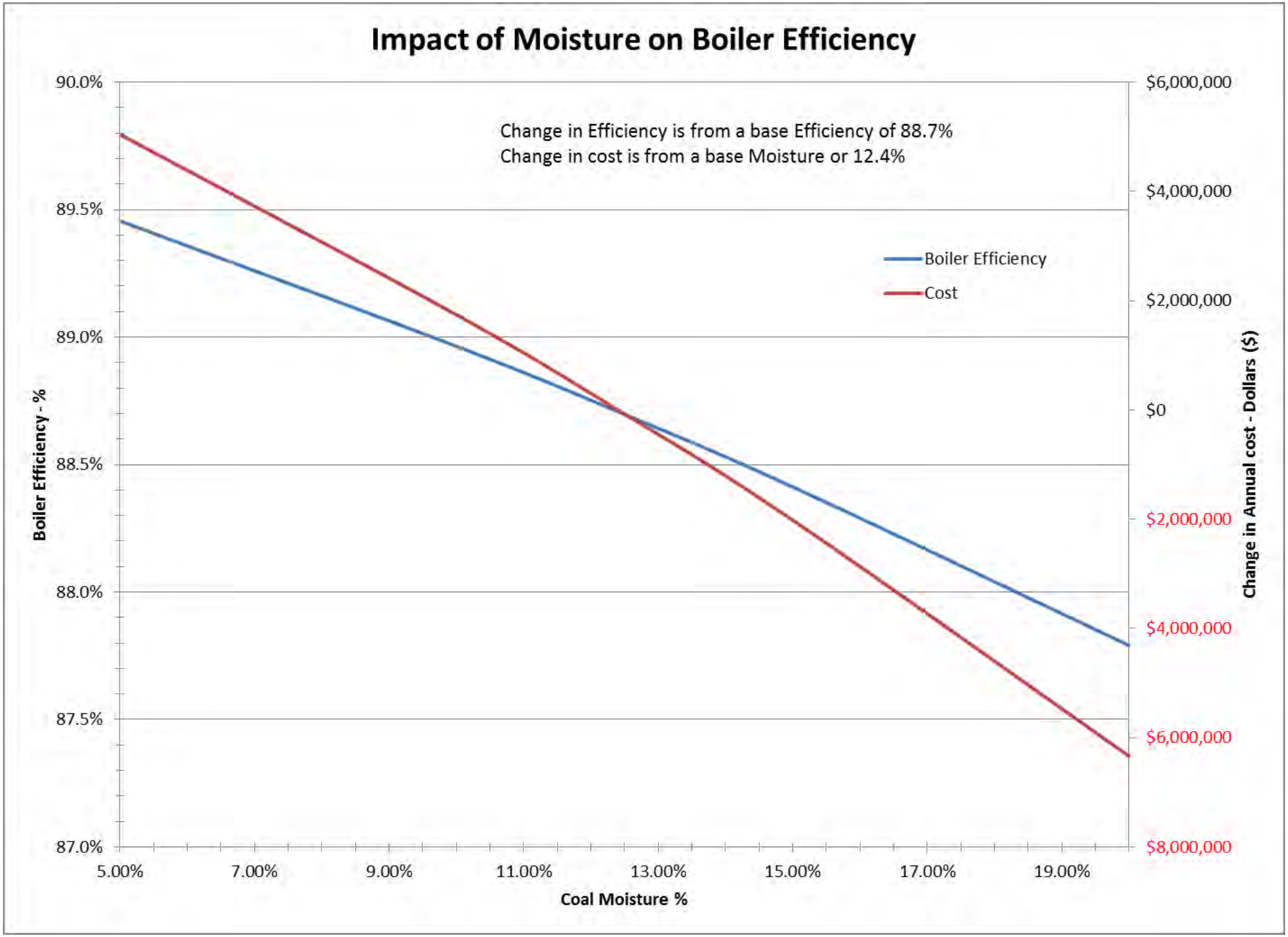
Coal moisture

- again, fuel dependent
- Coal price dominates PURCHASING decision
- 8 BTU/kW hr for each 1% change in coal moisture


Boiler Efficiency
Boiler Efficiency - %
89.50%
89.00%
88.50%
88.00%
87.50%
87.00%
86.50%
86.00%
85.50%
85.00%
285
290
295
300
305
310
315
320
325
330
335
340
345
350
355
360
365
370
375
380
385
Air Heater Exit Temp - Deg F
Excess Air
AH Exit
15% EA - 2.8% O2
20% EA - 3.6% O2
25% EA - 4.3% O2
30% EA - 4.9% O2
35% EA - 5.5% O2
40% EA - 6.1% O2

Carbon in Ash impact on Boiler Efficiency




Impact of Moisture on Boiler Efficiency
Change in Efficiency is from a base Efficiency of 88.7%
Change in cost is from a base Moisture or 12.4%
Boiler Efficiency
Cost
Boiler Efficiency - %
90.0%
89.5%
89.0%
88.5%
88.0%
87.5%
87.0%
Change in Annual cost - Dollars ($)
$6,000,000
$4,000,000
$2,000,000
$0
$2,000,000
$4,000,000
$6,000,000
$8,000,000
Coal Moisture %
5.00%
7.00%
9.00%
11.00%
13.00%
15.00%
17.00%
19.00%

Opportunities

Boiler Efficiency

Lower O2

- Integration with low NOx Neural Net System
- Firing Systems / Tech Service Expertise
- Expansion joints - Reduce inleakage

Lower Gas Temperature

- Economizer Redesign
- Air Heater upgrades
- Sootblower

Unburned Carbon - Work with Pulverizer Eng.

Fuel Switching - optimize efficiency

Steam Temperature

The higher the temperature, the better (lower) the heat rate

Metallurgy of boiler and steam turbine are limiting factors

SH temperature - Each 10°F low is 0.15% HR change (14 BTU/kW hr on a 9645 basis)

RH temperature - Each 10°F low is 0.14% HR (13 BTU/kW hr)

Steam temperature control :

- Spray
- Tilts
- Excess Air
- Backpass Dampers

RH Spray

All spray water bypasses steps in the boiler cycle (FW heater(s) and/or economizer) which decreases turbine heat rate.

RH Spray also bypasses the high pressure turbine

RH Spray increases flow through the IP and LP turbines, increasing Power Output (at a cost)

Based on 1% RH Spray (of MSF)

- 0.20 % heat rate increase (8-10x importance of SH spray)
- 19 BTU/kW hr (based on 9645 BTU/kW hr)

Leaking Spray Valves

Control of spray - Can be important

SH Spray

All spray water bypasses steps in the boiler cycle (FW heater(s) and/or economizer) which decreases turbine heat rate.

As the spray water goes through the HP turbine the cycle loss is very small compared to RH spray

Based on 1% of MSF:

- Spray from BFP 0.025% or 2.5 BTU/kW hr
- Spray from top htr. 0.008% or 0.7 BTU/kW hr

Control of SH Spray - No biggie, but in sub-critical units excessive spray puts impurities in the SH

Steam Pressure

The higher the pressure, the lower the heat rate at VWO

Critical Pressure (3208 psia) is the transition point in terms of capital costs (3-5% more material $)

- Practically - 2850 psig drum pressure is limit

Boiler circulation issues

Each 10 psig

- 0.04% - 3 BTU/kW hr

Note that temperature is more sensitive than pressure

- Some units slide pressure at low load to maintain temperature

Opportunities

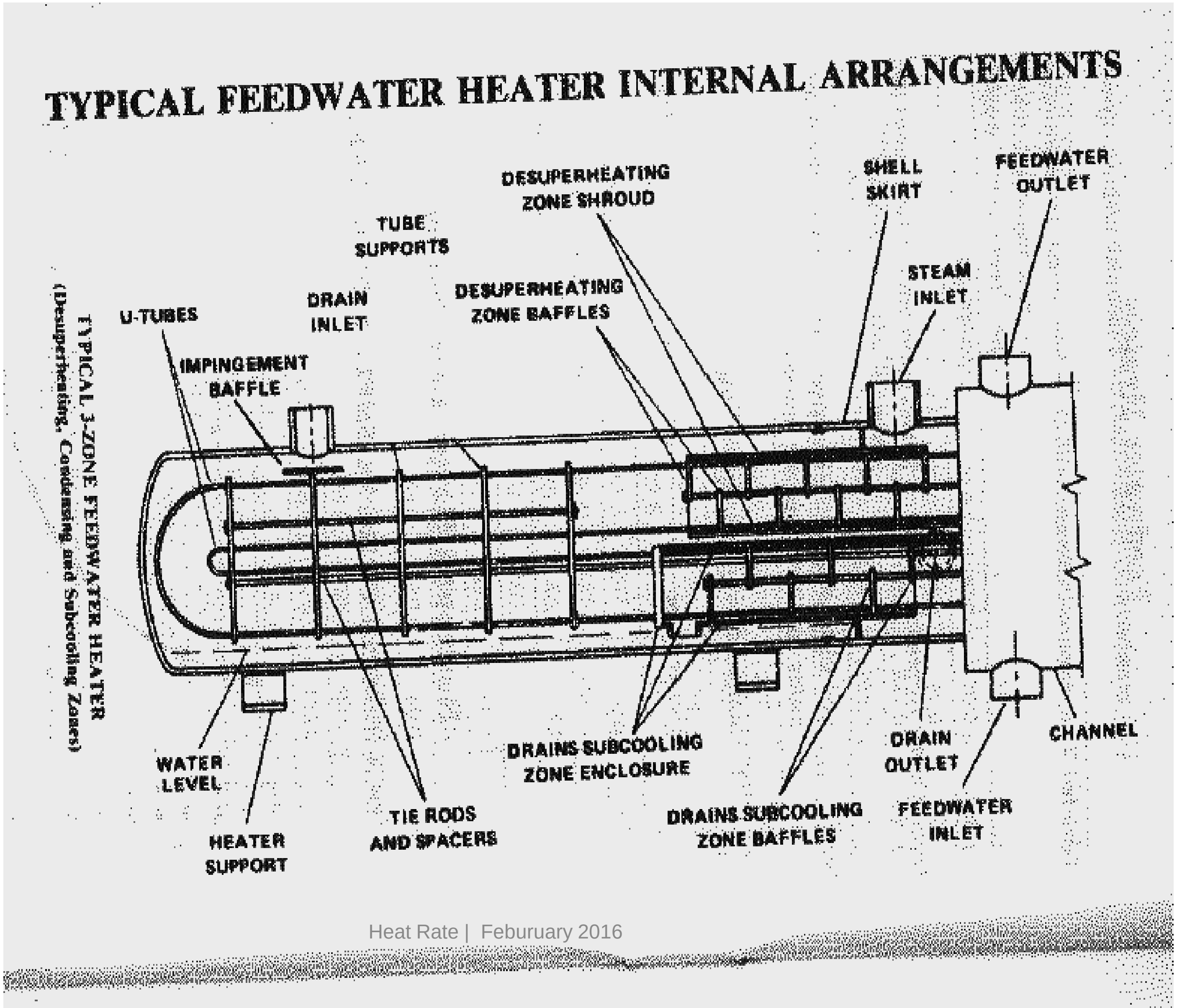
To regain steam temperature or reduce spray

- New SH, RH surfaces
- Sootblowing – Smart Sootblowing
- Integrate with low NOx Circulation emphasis
- Tilt Upgrades
- Sliding pressure studies

Condenser

- Backpressure has the biggest impact on heat rate
- Air infiltration and air binding reduce effective surface
- Fouling major factor
- Reduced cooling water flow
- High heat sink temperatures
- Plugged tubes

Feedwater Heater



TYPICAL FEEDWATER HEATER INTERNAL ARRANGEMENTS

TYPICAL 3-ZONE FEEDWATER HEATER (Desuperheating, Condensing and Subcooling Zones)

FW Temperature

Feedwater Heaters are designed to add heat at the highest possible temperature

Final FW Temperature - 5 °F

- 0.10% HR or 9 BTU/kW hr

FW temp drop can result in higher SH steam temp.

Limit is economizer outlet - subcooled 30-50 °F

During peak power demand, Owners will bypass the top heater(s) and push more steam through IP / LP turbine. Most CE boiler are not designed for this.

- 5 °F FW temp = .4% More MW

Other Factors

Auxiliary Power

- Any auxiliary power reduces the net plant heat rate
- Fans are big users of aux. power.

  High efficiency, variable pitch (axial fans), variable speed fans.
- Minimize Pulverizers in service, BFP in service
- BWCP (Dings by competition, however we have higher pressures)

Air infiltration

- Air infiltration can reduce load, boiler efficiency and cause increased fan load; Air heater, expansion joints, roof seals, casing, open doors, etc.

Other Factors

Steam Consumption

- Sootblowers
- Steam driven boiler feed pumps

Blowdown

- Heat loss and requires make up water

Turbine Efficiency - Cleanliness, leakage, SPE, etc.

BFP Efficiency

Leaking valves, steam leaks, drains - CYCLE isolation

- Typical Plant 1-2% heat rate loss. Extremely cost effective, but never ending.

Improving Existing Plant Performance

Establish Target Performance

Test Existing Unit

- Using ASME PTC 46 Methodology

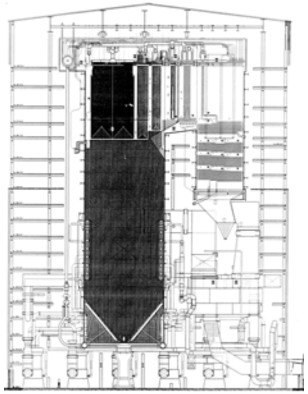
Analyze Differences

Identify Root cause of performance Issues

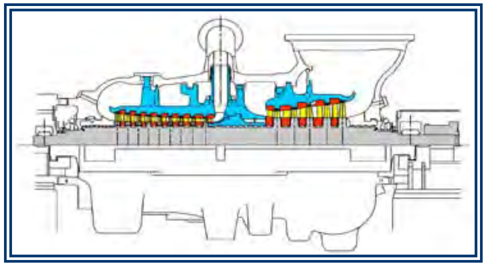
Plan and Implement repairs

EPRI Heat Rate Approximate Impacts for Various Deviations on Plant Performance

HP Turbine Efficiency	**18.8**	**BTU/kWh/%**	**19.8**	**kJ/kWh/%**
IP Turbine Efficiency	**14.5**	**BTU/kWh/%**	**15.3**	**kJ/kWh/%**
Throttle Temperature	**1.4**	**BTU/kWh/°F**	**2.7**	**kJ/kWh/°C**
Throttle Pressure	**0.35**	**BTU/kWh/Psi**	**5.36**	**kJ/kWh/bar**
RH Temperature	**1.3**	**BTU/kWh/°F**	**2.5**	**kJ/kWh/°C**
SH Spray Flow	**0.246**	**BTU/kWh/kLb/Hr Flow**	**0.03**	**kJ/kWh/kg/s**
RH Spray Flow	**2.15**	**BTU/kWh/kLb/Hr Flow**	**0.29**	**kJ/kWh/kg/s**
Excess O2	**29.4**	**BTU/kWh/%**	**31.0**	**kJ/kWh/%**
AH Outlet Temp	**2.7**	**BTU/kWh/°F**	**5.1**	**kJ/kWh/°C**
Condenser Backpressure	**204**	**BTU/kWh/In. Hg**	**6.36**	**kJ/kWh/mbar**
Make Up	**24**	**BTU/kWh/%**	**25.3**	**kJ/kWh/%**
Top FW Htr	**2.1**	**BTU/kWh/Deg F(TTD)**	**4.0**	**kJ/kWh/°C(TTD)**
Next to Top FW Htr	**0.54**	**BTU/kWh/Deg F(TTD)**	**1.03**	**kJ/kWh/°C(TTD)**
Top FW Htr out of Service	**94**	**BTU/kWh**	**99**	**kJ/kWh**



14.504	PSI	=	1	bar	=	100	kPa
7.937	klb/h	=	1	kg/s			
0.948	BTU	=	1	kJ			



Efficiency Improvement Options (Steam Power Plants)

Plant Efficiency = (Boiler Efficiency) x (Steam Cycle Efficiency) x (1- Auxiliary power fraction)

Boiler Efficiency Improvements

- Reduce Stack Loss
  - Reduce Stack Temperature
    - Air Heater Upgrade
    - Inc Air Flow Through AH
      - Minimize Tempering air flow
      - Minimize air leakage
    - Condensing Heat Exchanger
    - Sootblowing Optimization
      - Timing
      - Sequence
      - Locations
      - Nozzles
      - Pressure
      - Medium
  - Reduce Stack Flow
    - Low Excess Air
      - Reduced Air Infiltration
  - Reduce Stack Moisture
    - Fuel Change
- Reduce Other Losses
  - Less Unburned Carbon / CO etc.
    - Flyash carbon separation/combustion
    - OFA / Burner / Mill optimization
  - Better Insulated Unit
  - Heat Recovery from Ash
  - Pulverizer Rejects

Steam Cycle Efficiency Improvements

- Higher Steam Conditions
  - Pressure, Temperature
  - Additional Reheat Stages
- Additional Regeneration
  - More FWH's
  - Topping De-superheaters
- Lower Condenser Pressure
  - Cooling Tower Improvements
- Better Steam Expansion
  - Blade Profile Improvements
  - Minimize leaks
  - Reduce Exhaust Loss
    - Larger LP Turbines
- Lower Pressure Drops
  - Steam and Water
- Better Pump Efficiency
  - Boiler Feed Pump
  - Condensate Pump
  - Cooling System Pumps
- Smaller Leakage Quantities
- Minimize De-superheater Spray Quantities
  - Reheater(s)
  - Superheater

Auxiliary Power Reductions

- Lower Excess Air
- Lower Pressure Drops
  - Air and Gas Side
    - CFB combustor, FBHE
    - Less combustor inventory
  - Water Steam Side
- Better Component Efficiencies
  - Fans
    - Pressurized unit (no ID fan)
  - Pulverizers
  - Pumps
  - Generator
  - Transformer
  - Drive Motors
- Air Pollution Control System
  - Adipic acid addition
  - Coarser limestone
  - Reduce flue gas bypass
  - ESP instead of Fabric Filter
- Miscellaneous
  - Sootblowing Optimization
  - Reduce Air Heater Leakage

Proven New Technologies to help improve Efficiency

- New Unit Technologies – Supercritical and Ultra Supercritical
- Turbine upgrades with new higher efficiency blading
- New Condenser Designs
- New Cooling Tower designs
- New Controls
- Boiler design changes to reflect current operation
- Pulverizers – Dynamic Classifiers etc, to reduce Carbon Loss
- AH – Leakage control, high efficiency baskets
- Variable speed drives for Fans, CW pumps for part load operation

Turbine OPR

Current Turbine Technology is better…

- More efficient - blades, steam path design

Concept is to simultaneously optimize the boiler steam conditions and turbine boundary conditions

- Larger “steam swallowing capacity”
- Can optimize for heat rate
- Maximize MW generation
- Some combination within outside restriction

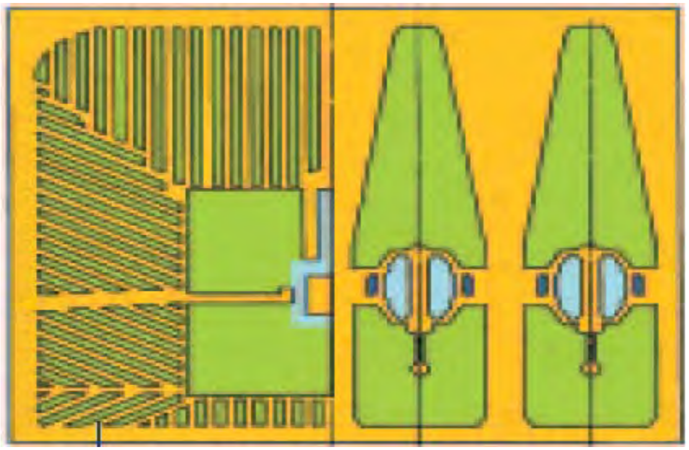
Optimized Plant Retrofit Objectives & Scope

- Maximize potential of existing power plant assets
  - Identify latent steam generating capability of boiler
  - Determine requirements for turbine to accept full boiler output
- Optimize increase in Heat Rate, Efficiency, & Power Output
- Assess Balance of Plant capabilities/limitations
    - Assess BOP systems and components (fans, pumps, ash handling, water handling, etc.) to support boiler turbine island
- Reduce Relative Emissions with Efficiency and/ or Equipment Improvements

New Condenser Design

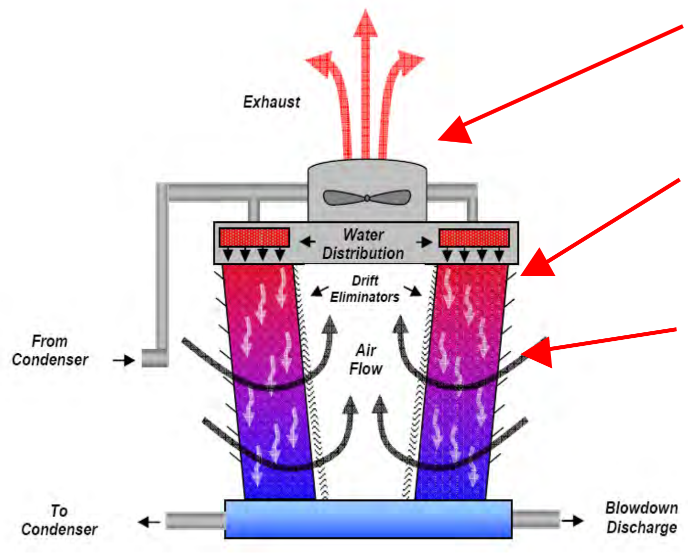
Optimizes Thermal Performance

- Minimizes air binding
- Less Condensate sub cooling



Cooling Tower Improvements

Improvement Cell Cooling Towers



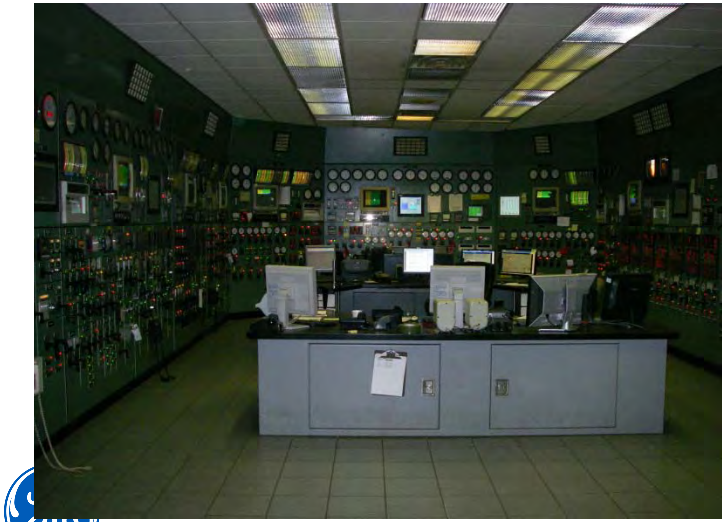
Increase Fan Power

Retrofit Fills

Reduction Of Plume Recirculation

Controls Modification

- Modern DCS Controls
- Neural Net Controls
- Intelligent Sootblowing
- Advanced Steam Temperature Control



Before and After Controls Upgrade

Boiler Modifications to Improve Efficiency

Optimizing Boiler Pressure Parts Surfaces

- Attaining Full Steam Temperatures
- Optimizing Sprays
- Controlling Exit Gas Temperature
- Optimizing Excess Air Levels

Air Heater Heat Transfer Surface Development

Cold End - DNF® Surface

Old NF profile

Upgrade

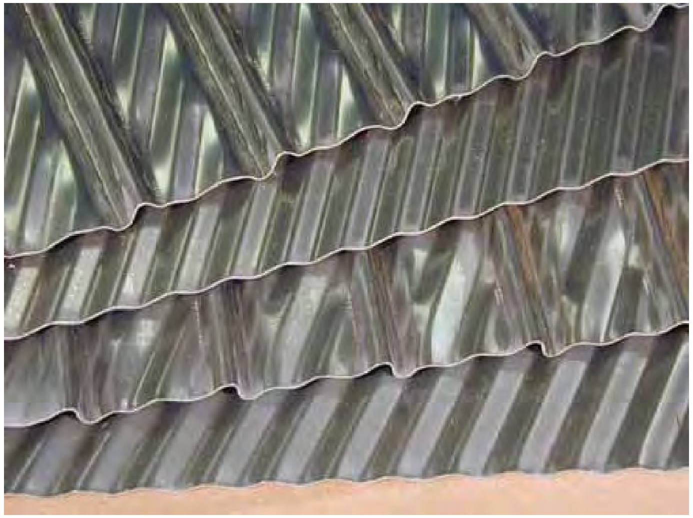
Latest DNF® profile

Upgrading the cold end layer to the latest design of DNF® heat transfer surface profiles can enhance thermal recovery while maintaining closed channel cold end cleanability of the surfaces.

Heat Transfer Surface Development

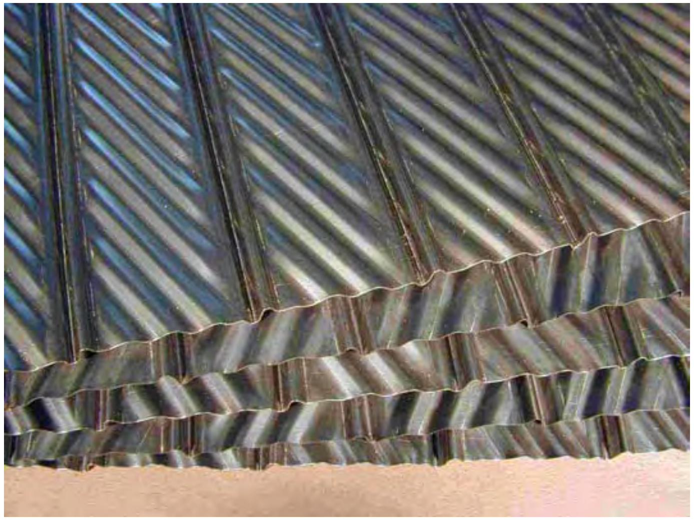
Hot End - DN7™ Surface

Old DU profile



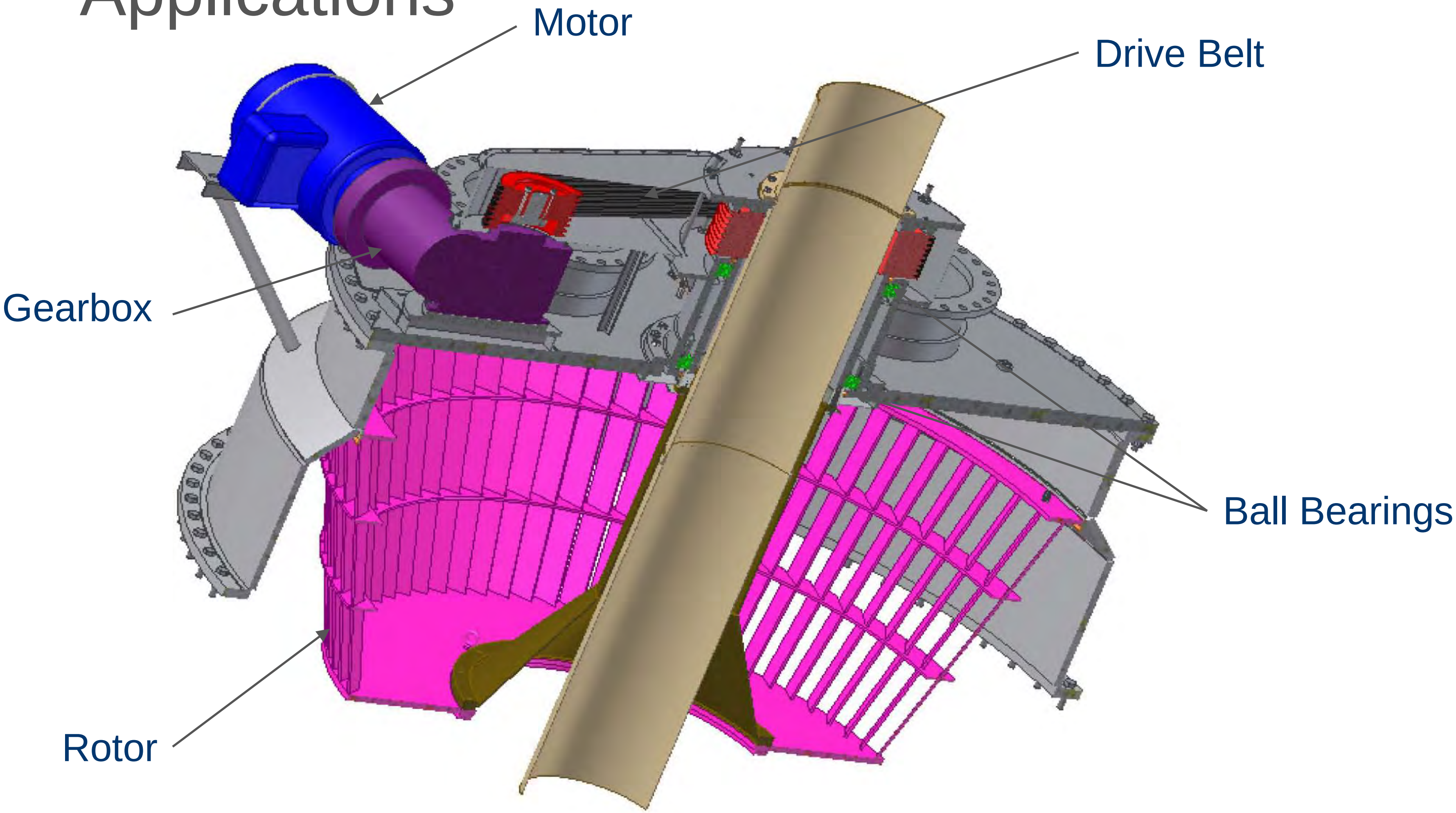
Upgrade

Latest DN7™ profile



Upgrading the hot end layers to the latest design of DN7™ heat transfer surface profiles can enhance thermal recovery, and improve flow distribution through the layers.

Pulverizer DYNAMIC™ Classifier Applications



DYNAMIC™ Classifier Applications – Case Study

Unit # 2

Test	Base Line Test	Guarantee
% UBC	6.24%	2.85%
% UBC Reduction		54%
% Thru 200 Mesh	58.5% to 68.4%	81.1% to 88.1%
% Thru 50 Mesh	97.9% to 99.1%	99.9% to 99.97%

What is it worth?

Our Mythical Plant

- 500 MW
- NPHR of 9645 BTU/kW hr.
- Capacity Factor - 85%

Yearly Heat Input

- 500,000 kW x .85 (c.f.) x 9645 BTU/kW hr x 365 days x 24
- 35,909,634 MMBtu/yr.

What is it worth?

Cost of Fuel

- Eastern Bituminous Coal 11,860 Btu/LB
- $ 38 per ton
- 11,860 x 2000 = 23.72 MMBtu per ton
- $38/23.72 = $1.6 / MBtu
- This equals $57,528,081 yearly fuel cost.

A 100 BTU/kW hr savings is 100/9645 or ~1%

1% Savings is $575,000 per year

What is it worth? (500 MW example)

Each 96 Btu/kw Hr (1%) savings is $575,000 per year

10º F Exit Gas Temp	- $161,700
1% O2	- $176,000
1% RH Spray (=38.2klb/hr)	- $ 491,000
10º F SH Steam Temp	- $ 83,800
10º F RH Steam Temp	- $ 77,800

Takeaways

Net Plant Heat Rate

- Total Heat Input / Total NET Power Output - BTU/kW hr
- Lower is better
- Directly affects fuel costs

Subcritical Heat Rate ranges (best practice)

- 9,500 - 10,000 BTU/kW Hr

Supercritical Heat Rate (best practice)

- 8,500 - 9,000 BTU/kW Hr

Takeaways

Parameter	Value	Heat Rate Effect
Outlet gas temp	10 ^{o}F	0.25%
• 12,000 Btu/lb coal		
Outlet gas temp	10 ^{o}F	0.35%
• 8,000 Btu/lb coal		
Outlet O2	1%	0.27%
Main steam temp	10 ^{o}F	0.15%
• subcritical unit		
Main steam temp	10 ^{o}F	0.15%
• supercritical unit		
Hot RH temp	10 ^{o}F	0.14%

Takeaways

Parameter	Value	Heat Rate Effect
Main Steam Press. • Constant Valve pos.	10 psi	0.04%
Superheat Spray • BFP Discharge	1% MSF	0.025%
Superheat Spray • From final FW	1% MSF	0.008%
Reheat Spray	1% MSF	0.20%

Takeaways

Parameter	Value	Heat Rate Effect
Coal Moisture	1%	0.10%
• 12,000 BTU		
Coal Moisture	1%	0.17%
• 8,000 BTU		
Air Heater		
• Leakage	1%	0.05%
• Effectiveness	1%	0.15%

Takeaways

Parameter	Value	Heat Rate Effect
Condenser Backpressure	1 In Hg	208 BTU/kWHr
Top FW Htr Out		94 BTU/kWHr
Make Up Water	1% MU	24 BTU/kWHr
Top FW Htr TTD	1 Deg F	2.1 BTU/kWHr
Next toTop Htr TTD	1 Deg F	0.54 BTU/kWHr

Questions?

matt.dooley@ge.com

Trivia Question 1

Why do Feedwater Heaters in a Rankine Cycle plant improve cycle efficiency?

Trivia Question 2

Why do Combined Cycle Plants not have Feedwater heaters?

The End