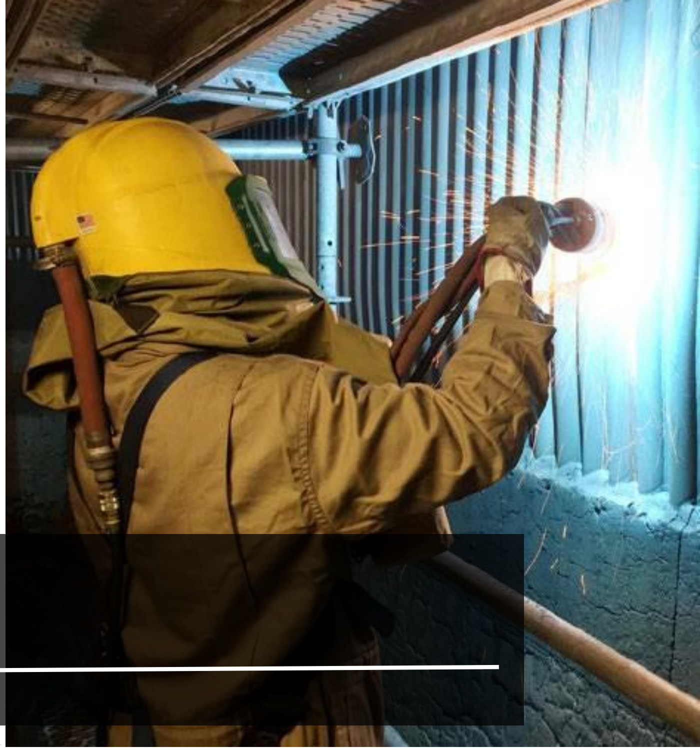


Solutions for Today | Options for Tomorrow

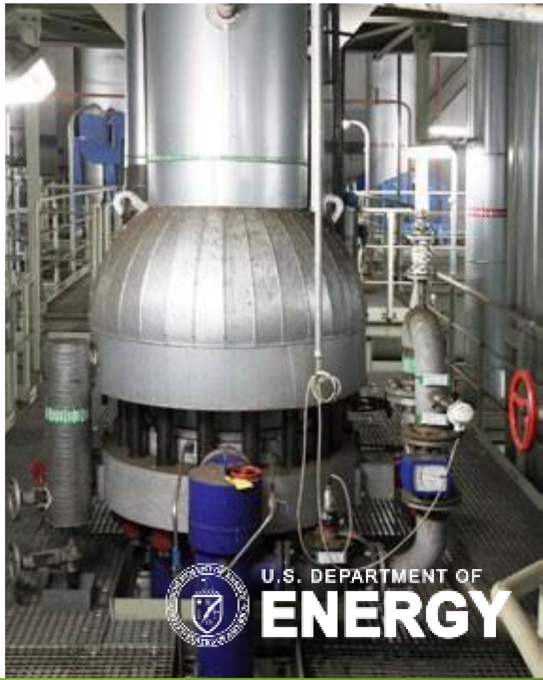
Existing Fleet Materials Analysis

Annual Project Review Meeting

August 25, 2020

Irene Spitsberg

Deloitte



U.S. DEPARTMENT OF ENERGY

About Irene

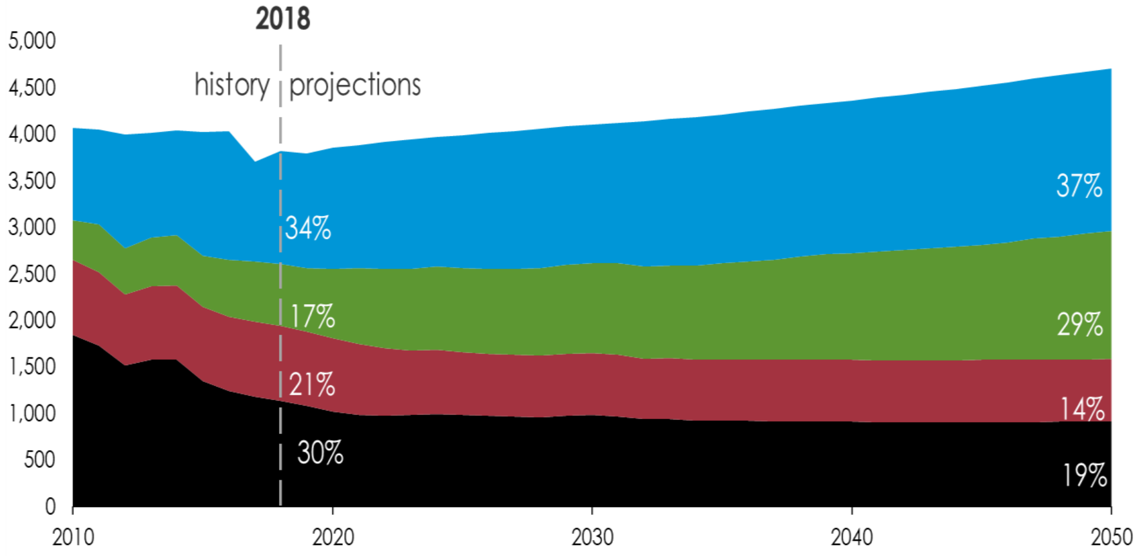
- 10 years with GE Aviation
  - 80+ patents in High Temperature Materials area, publications in peer reviewed journals
  - Lead introduction of new coatings and ceramic composite technologies on commercial and military engines (GEnx, JSF)
  - NASA “Bring Goals to Reality” award
- Leadership R&D Roles in global advanced manufacturing companies
- VP and CTO of AIM Aerospace (now Sekisui Aerospace), a leading advanced composites manufacturer
- R&D strategy and Innovation consulting experience across various industries and government sector
  - “Top 10 in Capability Building” by Global Innovation Institute, 2016
- Ph.D. in Material Science

Strategic Context of Existing Fleet Performance

Life extension and efficiency of existing fleet are critical to the resiliency and reliability of America's electrical supply

- Coal-fired power plants optimized as baseload resources are being increasingly relied on as load following
  - Operating at average 50% capacities
  - Low efficiency due to sub-optimal operating parameters
  - Reduced margins due to minimum loads
  - Increases in operating cost due to extensive repairs and environmental impact management
  - Asset availability reduced by outages by 3%
- Significant penetration of renewable energy will increase the regulation requirement and will force more flexible operations

Coal and NG will continue to provide 56% of domestic energy supply for 2050

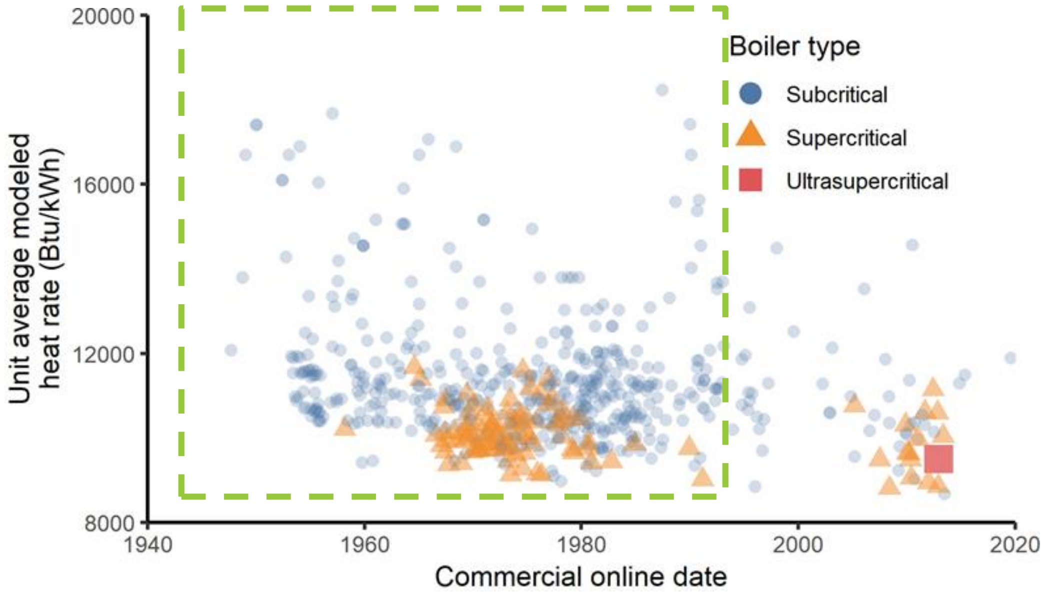


1. EIA, Annual Energy Outlook 2019
2. GADS Conventional and CCGT Plant Data

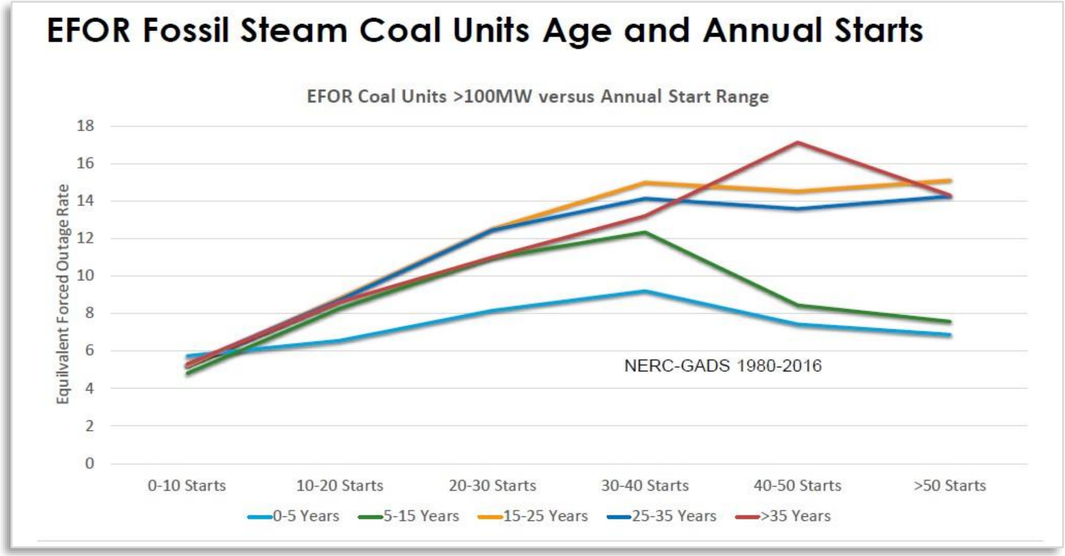
Demographics of the current fleet

Existing fleet dominated by older subcritical units that are performing increasing amounts of cycling, resulting in increase Forced Outages (EFOR)

Mostly Inflexible Constant Pressure Units



Plant age and cycling impact plant reliability



68% of Total fleet is Subcritical

Boiler type	Total units	Average net summer capacity (MW)	Fleet average heat rate (Btu/kWh)
Subcritical	751	235	12,227*
Supercritical	101	740	10,092
Ultrasupercritical	1	609	9,500
Adv. USC	*0*	*(e.g.) 600*	*(pred.) 8,300 – 8,800*

*Modeled heat rate not available for 230 subcritical units

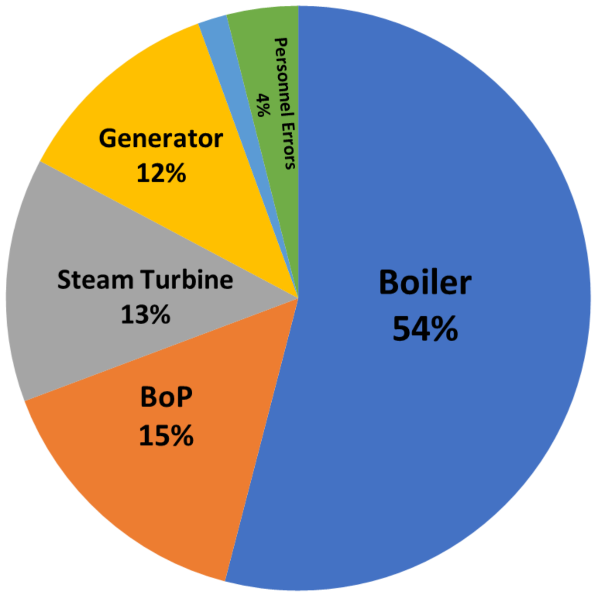
1. A Flexible Future
2. GADS Conventional and CCGT Plant Data

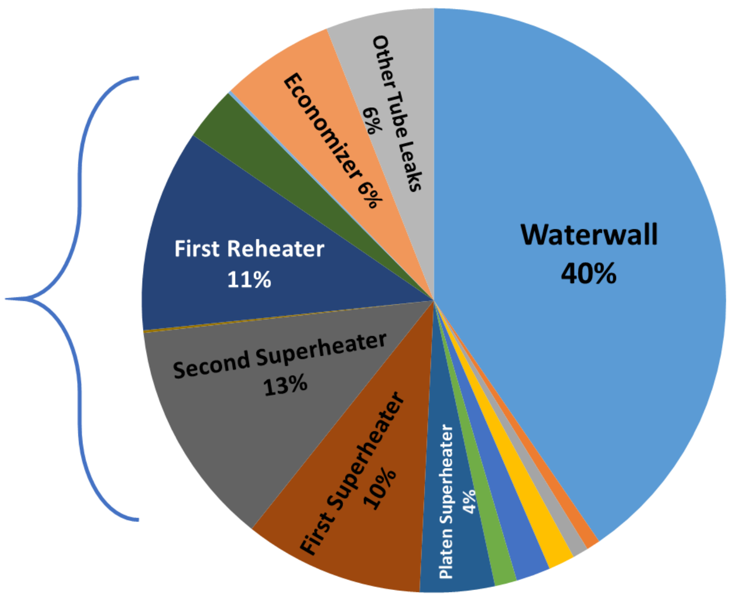
Key Causes of Plant Outages

Waterwalls in boilers are the primary component that fail and cause forced outages, followed by turbine and BoP

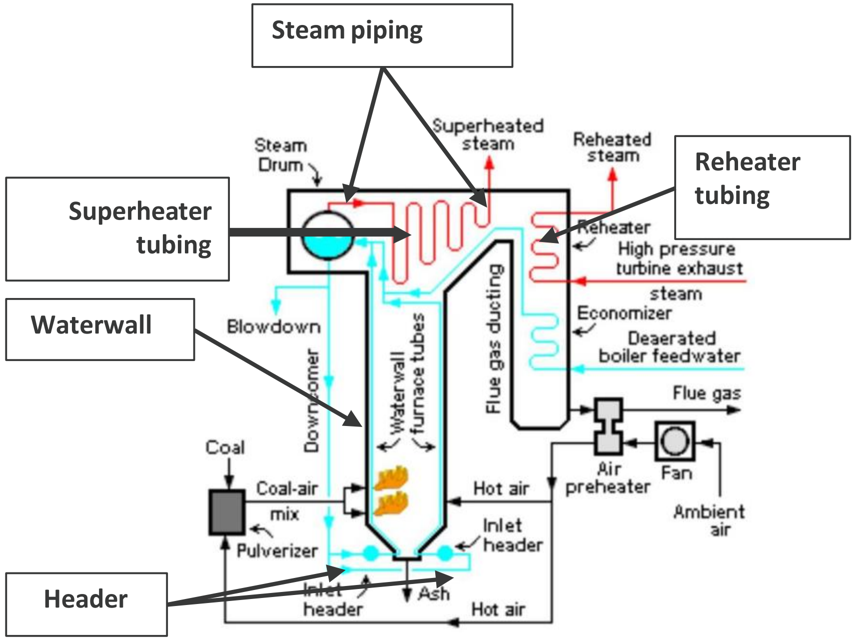
Waterwall boiler tubes are the leading cause of boiler tube leaks

Boiler tube leaks are the largest cause of forced outages across the fleet





Common PC Plant Boiler Diagram



1. GADS Conventional Plant Data
2. https://commons.wikimedia.org/wiki/File:Steam_Generator.png

Failure Mechanisms by Boiler Component

Fatigue is a cause of failure present across all major boiler components

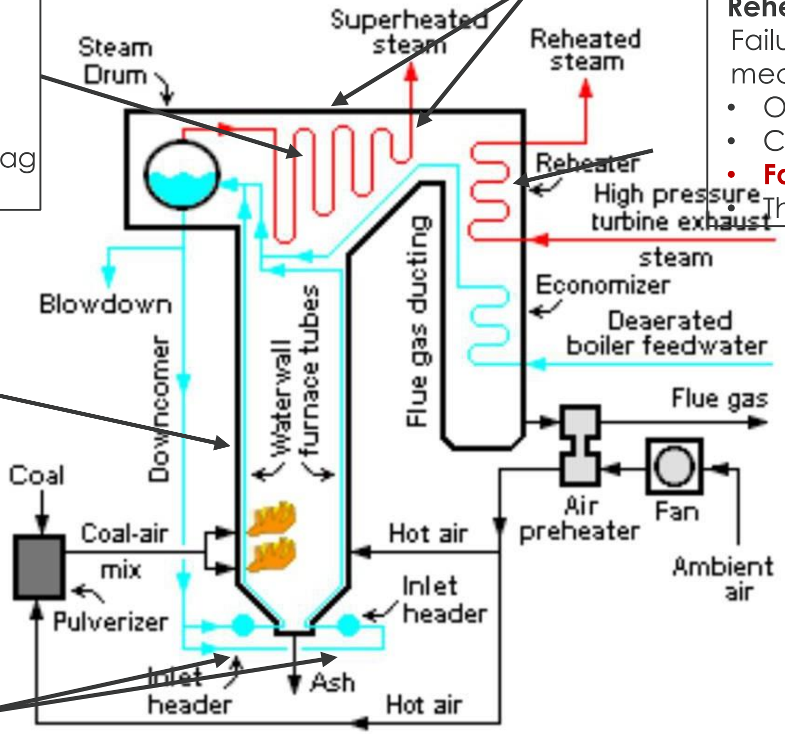
Steam piping
Failure mechanisms:
- Corrosion
- **Fatigue**
- Creep

Superheater tubing
Failure mechanisms:
- **Fatigue**
- Creep
- Thermal fatigue
- Weld defect
- Corrosion from slag
- Fly ash erosion

Reheater tubing
Failure mechanisms:
- Overheating
- Corrosion
- **Fatigue**
- Thermal fatigue

Waterwall
Failure mechanisms:
- **Fatigue**
- Overheating
- Weld defects
- Erosion
- Hydrogen damage

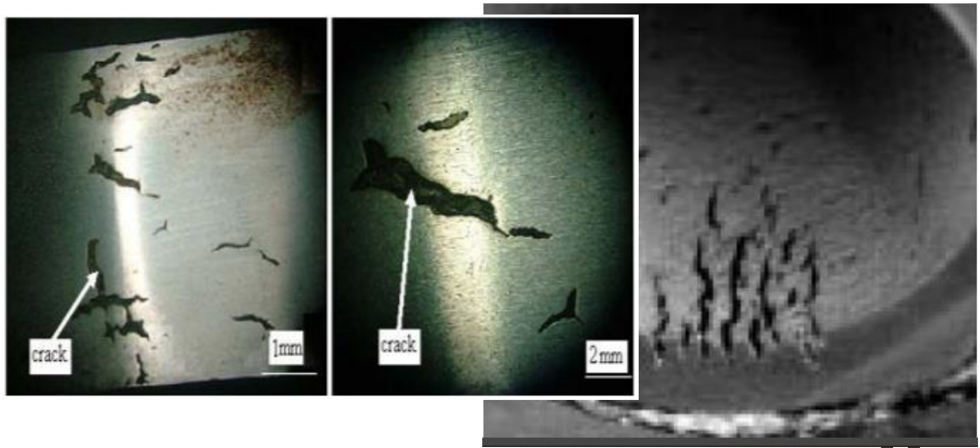
Header
Failure mechanisms:
- **Fatigue**
- Corrosion fatigue
- Thermal fatigue
- Coal particle corrosion



THERMAL FATIGUE

… is more of a concern within the boiler compared to *mechanical fatigue*, particularly in thicker sections of the boiler

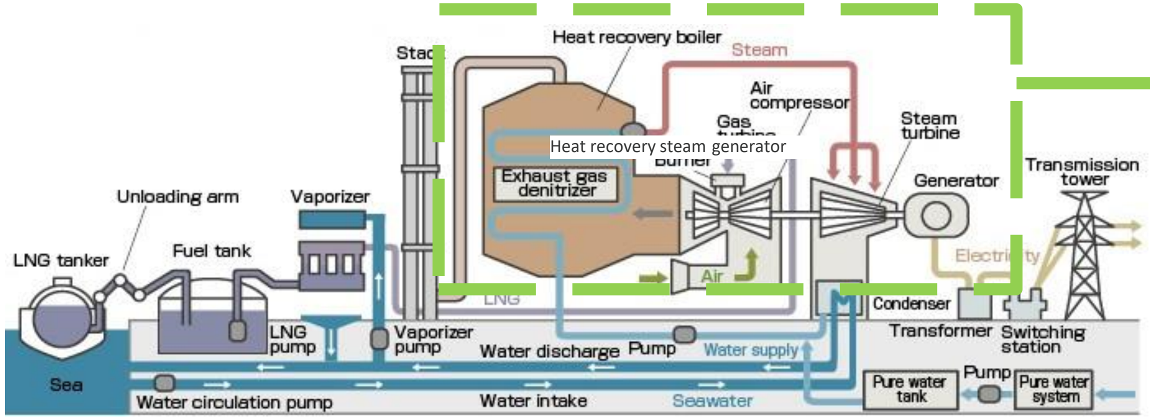
- Influenced by changes in temperature
  - Thick sections are more at risk
  - Turbine and valve casings
  - Superheater and reheater outlet headers
  - Economizer inlet headers
  - Drums
- Openings and high restrain locations
- Propagation of existing damage



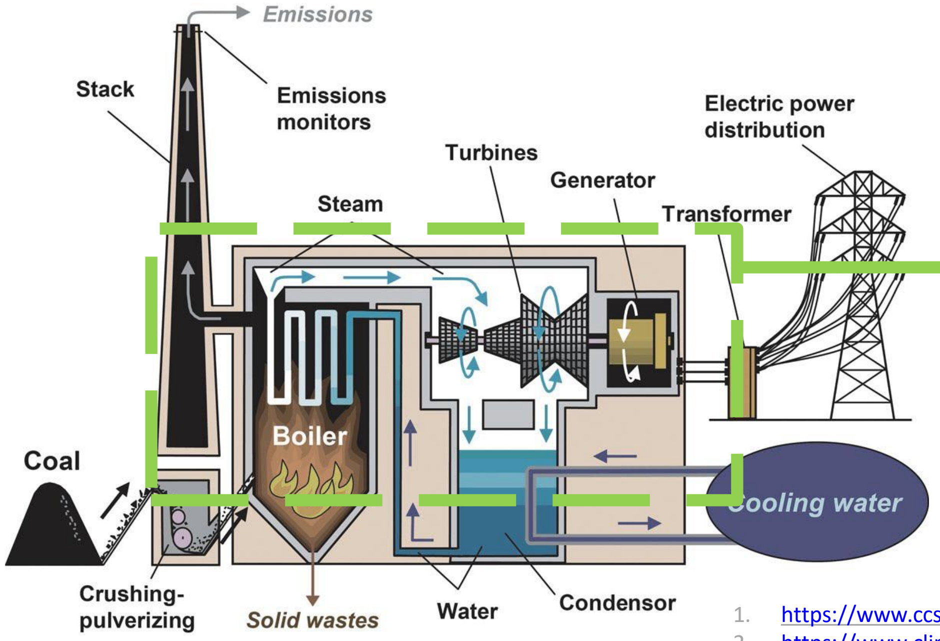
1. Benefits of Advanced Material Used for Boiler Tubes in Coal-Fired Power Unit
2. International Journal of Emerging Technology and Advanced Engineering Website: www.ijetae.com (ISSN 2250-2459, Volume 2, Issue 8, August 2012)
3. https://www.babcock.com/pt-br/resources/learning-center/finding-the-root-cause-of-boiler-tube-failure/#WatersideFailureMechanisms

Major Plants Undergoing Flexible Operations

Pulverized Coal (PC) Power Plant Schematic



Natural Gas Combined Cycle (NGCC) Plant Schematic



Common components
- **Boiler**
- **Steam turbine**
- **Generator**

Common failure mechanisms occurring in HRSGs are similar to those seen in conventional boilers in coal power plants

Component	Low cycle fatigue	Thermal shock	Flow assisted corrosion	Corrosion fatigue	Deposits/corrosion
Superheater headers	H, B	H	H	H	
Superheater tubes	H, B	H	H	H	
Reheater headers	H	H	H	H	
Reheater tubes	H, B	H	H	H	
Evaporator tubes	H		H	H	H
Economizer headers	H		H	H	H
Economizer tubes	H, B		H	H	H
Drum	H		H	H	H
Steam piping*	H, B	H	H	B	
Feed/connecting pipes	H, B		H	H, B	
Casting, liners, duct, etc.	H	H	H		

1. https://www.ccsdualsnap.com/pressure-switches-in-combined-cycle-power-plant-switches/
2. https://www.climatetechwiki.org/technology/sup_crit_coal

Key Industry Challenges from Interviews

Barriers include the financial ability of utilities to invest in predative maintenance and new advanced materials, increasingly complex material behavior in the components under cycling modes, and the lack of data on existing fleet component performance (historic and current).

CHALLENGES

General Conclusions

- Preventive maintenance is not prioritized or invested in by utilities
- Lack of historical data on plant components prevents good repair planning
- There is no standard to assess cyclic damage/associated repair needs
- Utilities are not stocking necessary spare parts/components, extending outages

Boiler

- Component material upgrades are not a significant opportunity, but surface technologies are an accepted practice
- Utilities are using cheaper coal, increasing damage to boiler components

Turbine

- Inspections take prohibitively long amount of time; in-situ inspection capability is needed

OPPORTUNITIES

- Boiler component life prediction
- Surface technologies for component life extension
- Business case development for cost benefit analyst investment in extended asset's life
- Coal quality monitoring to optimize operational parameters and minimize damage

Appendices

Resources

Title	Link
Benchmarking Boiler Tube Failures	https://www.powermag.com/update-benchmarking-boiler-tube-failures/
Materials Technology for Advanced Coal Power Plants	https://www.phase-trans.msm.cam.ac.uk/2005/LINK/188.pdf
An overview of problems and solutions for components subjected to fireside of boilers	https://link.springer.com/article/10.1007%2Fs40090-017-0133-0
Boiler Maintenance and Upgrades — Attacking Tube Failures	https://www.power-eng.com/articles/print/volume-108/issue-2/features/boiler-maintenance-and-upgrades-mdash-attacking-tube-failures.html
Utility self-performs on boiler tube replacement	http://www.arcmachines.com/industries-served/pulp-paper/utility-self-performs-boiler-tube-replacement
DOE providing $39 million for coal-fired power fleet research	https://www.power-eng.com/articles/2019/06/doe-providing-39-million-for-coal-fired-power-fleet-research.html
Do You Need To Repair Boiler Tubes?	https://www.thermalspray.com/need-repair-boiler-tubes/
Newer Materials for Supercritical Power Plant Components	https://www.researchgate.net/publication/301294683_Newer_Materials_for_Supercritical_Power_Plant_Components_-_A_Manufacturability_Study
Inspection, Monitoring, Repair, and Maintenance of HRSGs	https://static1.squarespace.com/static/5304e62de4b00674c06afd5c/t/5c1bc12b4fa51a06475ccf84/1545322796174/Intro-HRSG+Guidelines.pdf
Impact of Cycling on the Operation and Maintenance Cost of Conventional and Combined-Cycle Power Plants	https://www.epri.com/#/pages/product/3002000817/?lang=en-US
EIA Annual Energy Outlook, 2019	NA
Benefits of Advanced Material Use for Boiler Tubes in Coal-Fired Power Units	NA
International Journal of Emerging Technology and Advanced Engineering	www.ijetae.com (ISSN 2250-2459, Volume 2, Issue 8, August 2012)
Finding the Root Cause of Boiler Tube Failures	https://www.babcock.com/pt-br/resources/learning-center/finding-the-root- cause-of-boiler-tube-failure/#WatersideFailureMechanisms

Materials Failure and Repair Executive Summary

Opportunity for Government R&D to support business case development for investment In plant assets, component life prediction methodology, advance surface treatments, and coal quality monitoring

- Boilers are the most susceptible component of PC plants to flexible operations damages
- Commercial material and process repair solutions are available, but the greater challenge is implementing predictive maintenance capabilities and obtaining acceptance of the business case for costly but necessary upgrades
- more advanced surface tech., coal quality monitoring, and business case development to support reinvestment into plant assets
- Material and process solutions for PC plant components undergoing FlexOps damage can apply to NGCC plant components seeing similar damages
- Barriers include the financial ability of utilities to invest in predative maintenance and new advanced materials, increasingly complex material behavior in the components under cycling modes, and the lack of data on existing fleet component performance (historic and current).

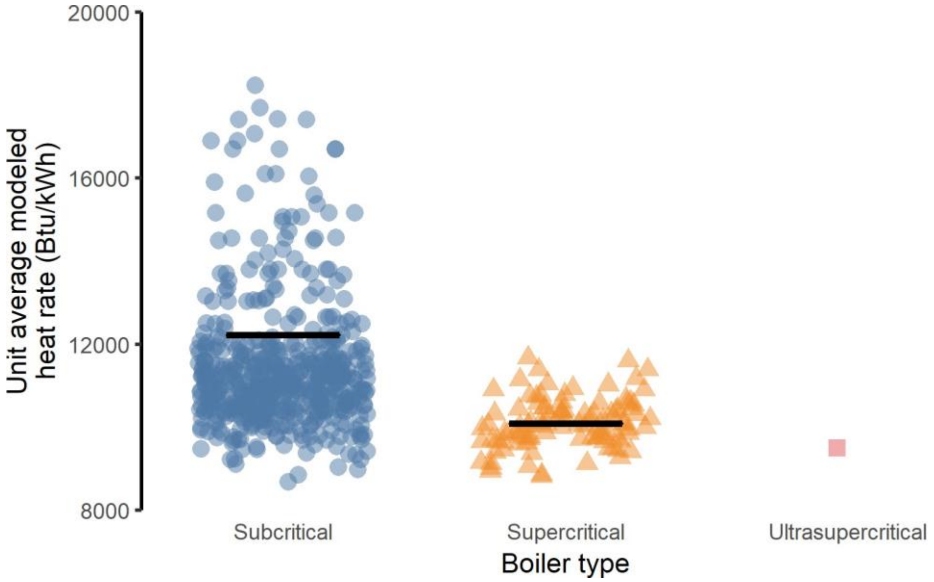
Gap Analysis and R&D Opportunities

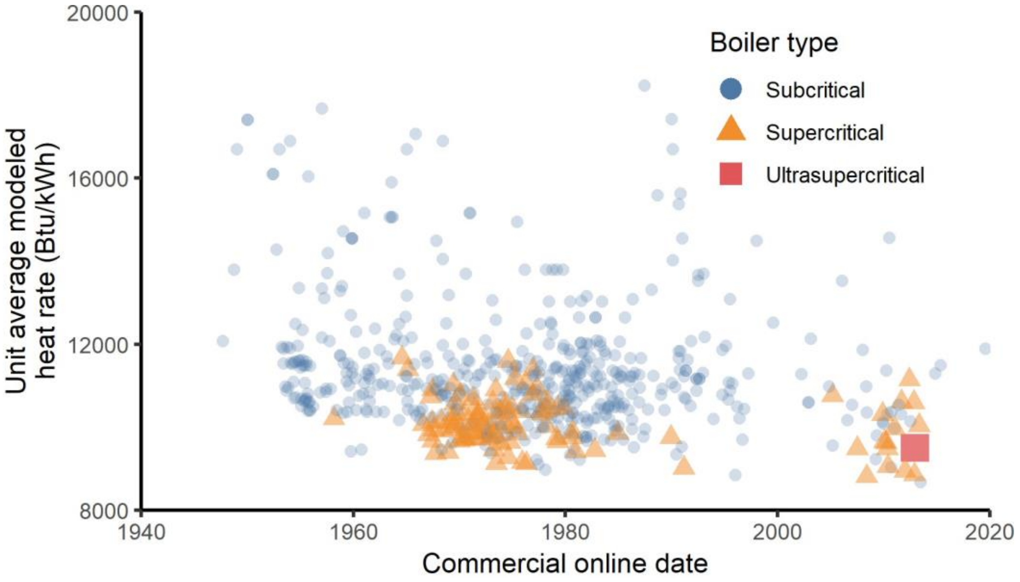
- Boiler Component Life Prediction
  - Objective – develop and integrated methodology to assess the remaining life of the components
  - Scope – Integrate field data analysis, lad test methods, and computational methods to develop empirical and/or computational model that predicts remaining life based on measurable criteria; focused on key material systems and/dissimilar joins
  - Type –consortia with and an industrial lead member(s)
  - Benefit – Remaining life information for repair decision and planning

- Surface Technologies to expend life of components, in-filed application techniques
- Coal quality monitoring for optimizing operation parameters to minimize damage
- Business case development for assessing of cost/benefit of investment in the extended assets life

Demographics of the current fleet

Existing fleet dominated by subcritical units, but considerable supercritical exists





Boiler type	Total units	Average net summer capacity (MW)	Fleet average heat rate (Btu/kWh)
Subcritical	751	235	12,227*
Supercritical	101	740	10,092
Ultrasupercritical	1	609	9,500
Adv. USC	*0*	*(e.g.) 600*	*(pred.) 8,300 – 8,800*

*Modeled heat rate not available for 230 subcritical units

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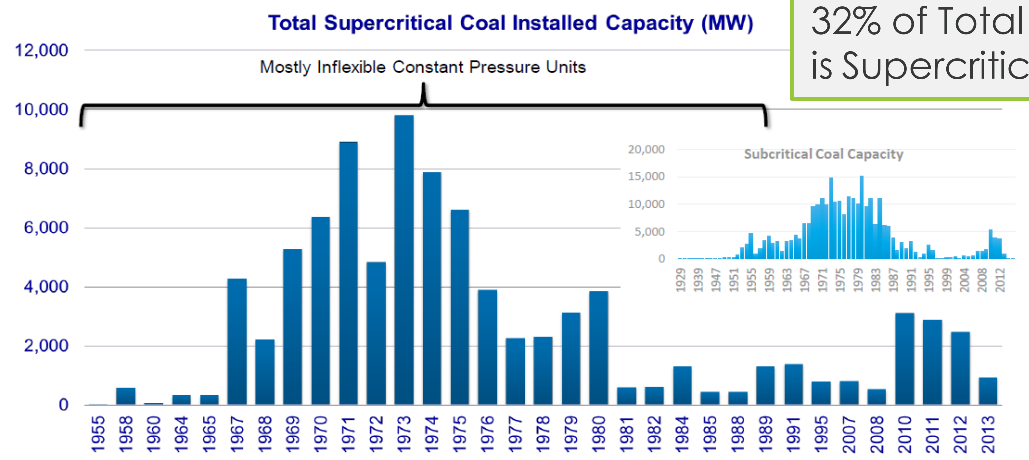
Major Effects of Cyclic Operations

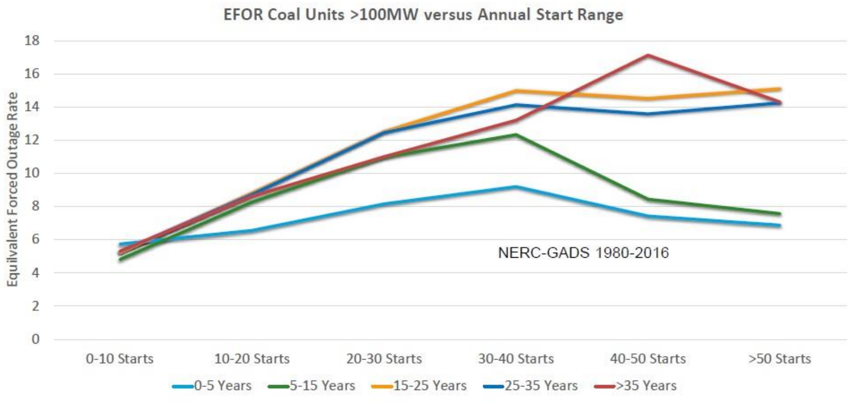
Coal and combined cycle units are performing increasing amounts of cycling, resulting in increase Forced Outages (EFOR)

US Coal Fired Power Plant Fleet (EIA)



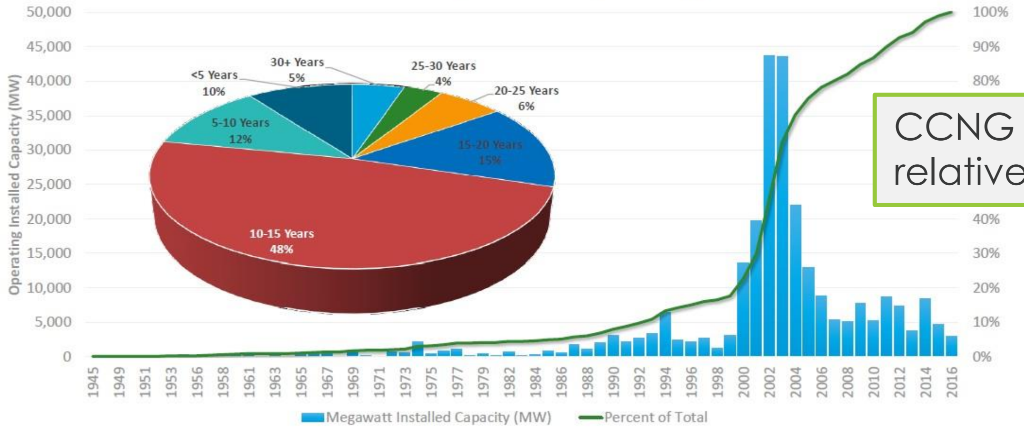
32% of Total fleet is Supercritical

EFOR Fossil Steam Coal Units Age and Annual Starts



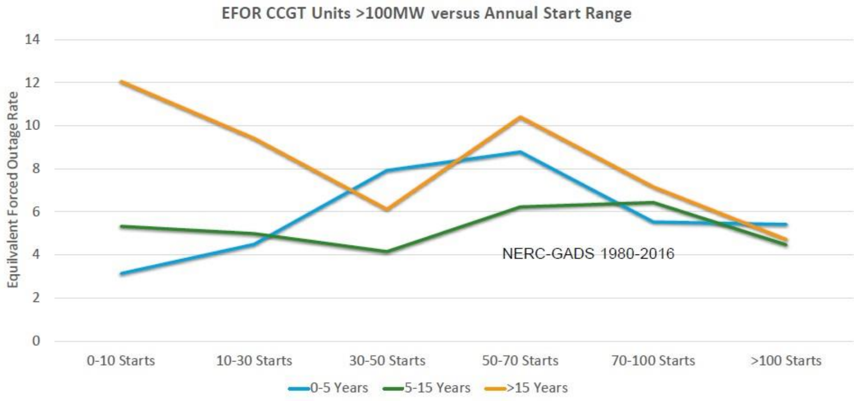
Plant age and cycling impact plant reliability

U.S. Installed Combined Cycle Capacity



CCNG fleet is relatively young

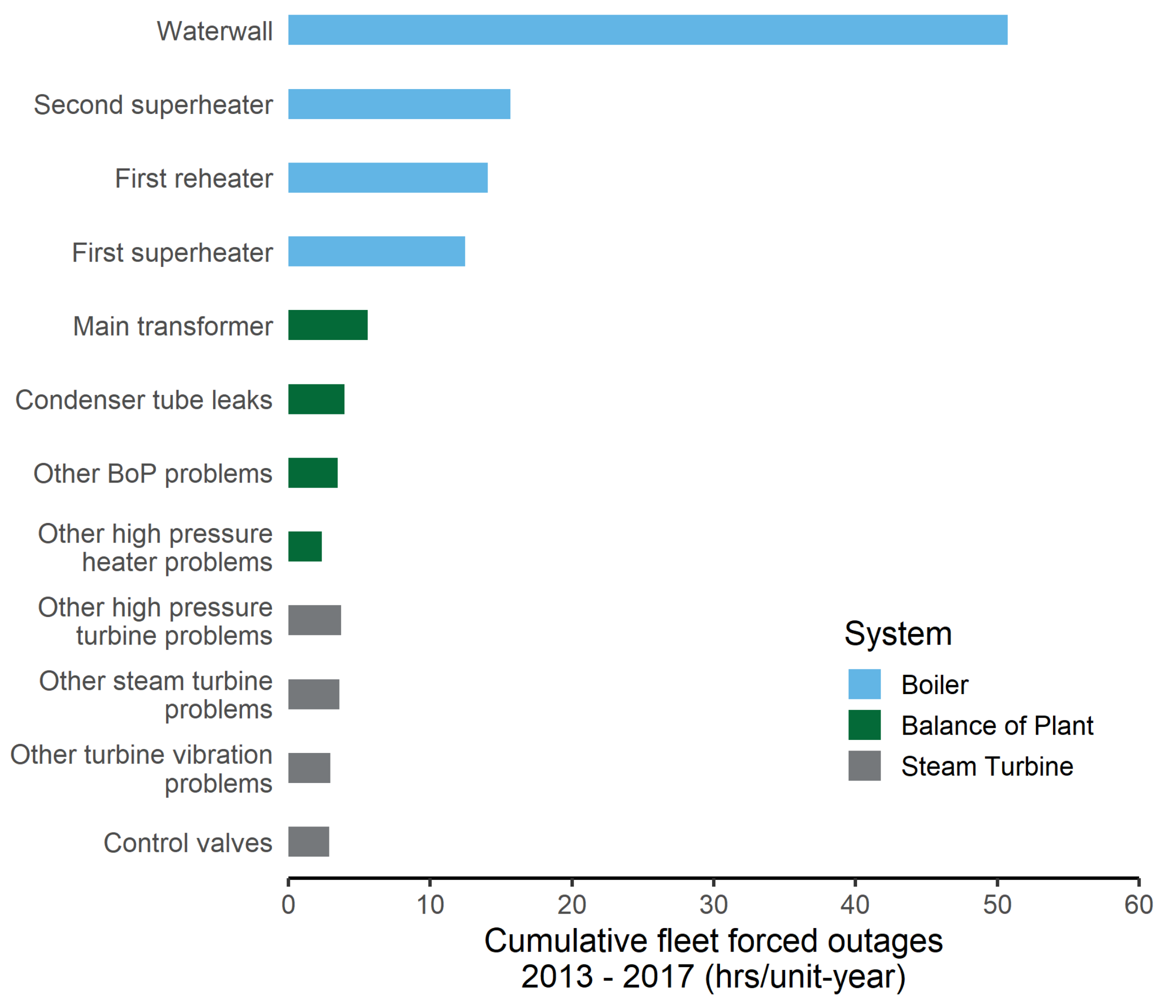
EFOR Fossil Steam CCGT Units Age and Annual Starts



1. A Flexible Future
2. GADS Conventional and CCGT Plant Data

Leading System Causes of Plant Outages

Material failures in boiler, steam turbine, and balance-of-plant componentry accounted for 82% of fleet forced outage hours between 2013 and 2017



Largest cause of forced outages:
Boiler tube leaks
(across the fleet and separate size classifications)

Followed by:
Turbines and Balance-of-Plant Systems

Cause of most boiler tube leaks:
Waterwall boiler tubes
(on a unit-year basis)

Longest time to repair:
Platen superheater
(across the fleet and separate size classifications)

Failure Mechanisms by Boiler Component

Fatigue is a cause of failure present across all major boiler components

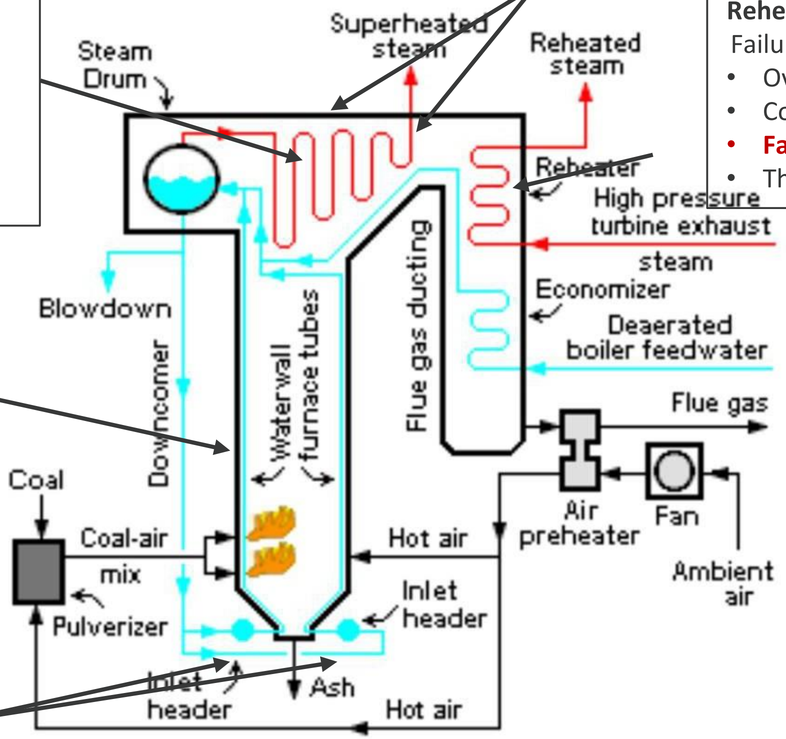
Steam piping
Failure mechanisms:
- Corrosion
- **Fatigue**
- Creep

Superheater tubing
Failure mechanisms:
- **Fatigue**
- Creep
- Thermal fatigue
- Weld defect
- Corrosion from slag
- Fly ash erosion

Reheater tubing
Failure mechanisms:
- Overheating
- Corrosion
- **Fatigue**
- Thermal fatigue

Waterwall
Failure mechanisms:
- **Fatigue**
- Overheating
- Weld defects
- Erosion
- Hydrogen damage

Header
Failure mechanisms:
- **Fatigue**
- Corrosion fatigue
- Thermal fatigue
- Coal particle corrosion

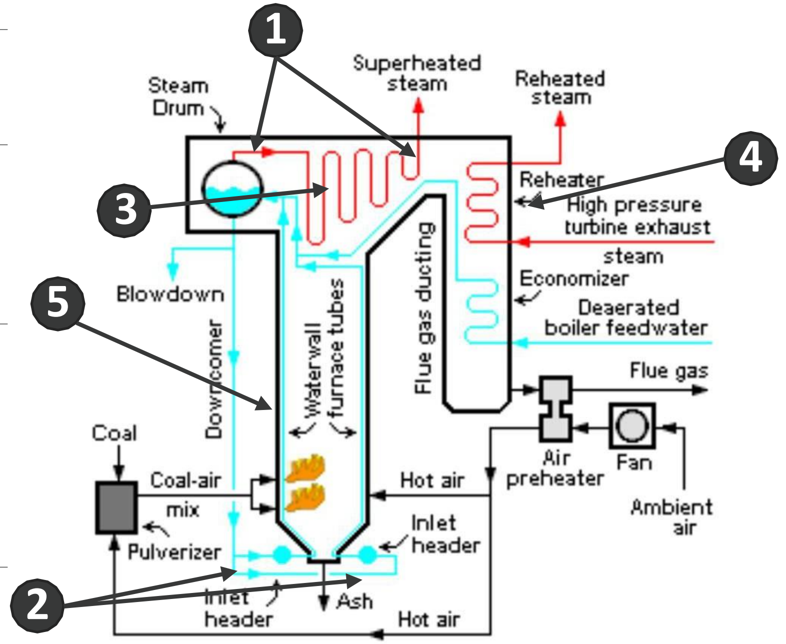


Component	Material in Supercritical Boiler
Steam piping	**P91 or P92*** *(in steam pipes the temperature can become 25-39° C higher than the steam)*
Header	**P91 steel***
Superheater tubing	**SS304H, SS347, or T-91** *SS304H, SS347 are widely used over T-91 when high-sulfur, corrosive coal is used and due to their easier weldability*
Reheater tubing	
Waterwall tubing	**T-11 and T-91** *T-11 has been used but insufficient creep strength. T-91 is available but requires post-weld heat treatment. T-91 overlaid or clad with high Cr alloys is common to reduce corrosion due to the retrofitting of boilers with low NOx burners*

FlexOps Effect on Boiler Components

NATIONAL ENERGY TECHNOLOGY LABORATORY

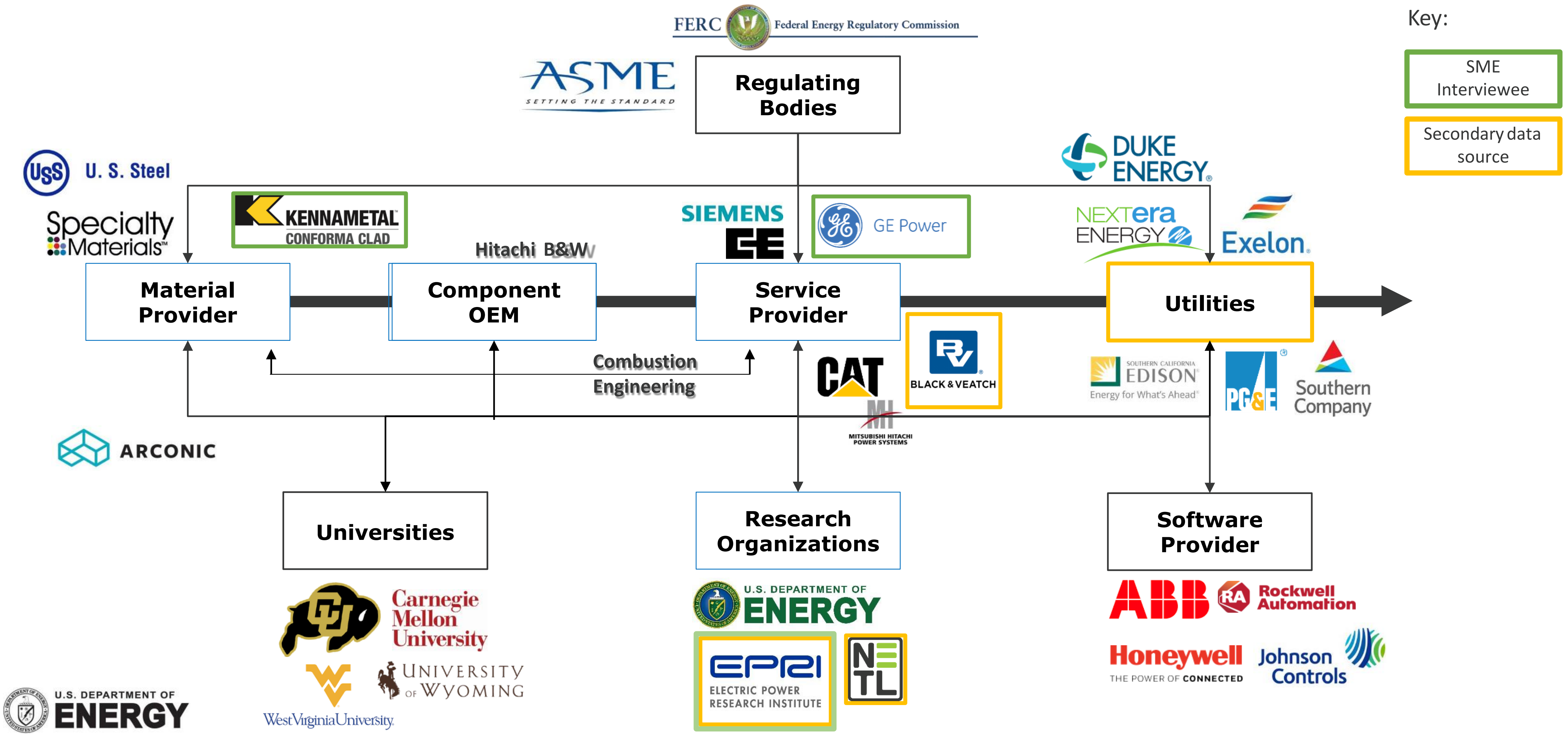
Component	Subcritical Boiler	Supercritical Boiler	AUSC Boiler	Challenges to Advance
1. Steam piping	Austenitic steels - Low alloy steels like P11 and P22*	P91 or P92* *(in steam pipes the temperature can become 25-39° C higher than the steam)*	Inconel 740 *(requires meticulous heat treatment during fabrication)*	High fireside corrosion
2. Header	Austenitic steels - Low alloy steels like P11 and P22*	P91 steel*	Ni based alloys	High fireside corrosion, Ni content must be optimized to ensure strong welds
3. Superheater tubing	T-22 ferric steel - T22(2.25Cr-1Mo)	SS304H, SS347, or T-91. *SS304H, SS347 are widely used over T-91 when high-sulfur, corrosive coal is used and due to their easier weldability*	Inconel 740 (requires meticulous heat treatment during fabrication), Haynes 230, Haynes 282	High fireside corrosion, Creep strength
4. Reheater tubing			Ni based alloys	High fireside corrosion, reheater temperatures typically get higher than superheater temperatures, so creep strength is an even greater concern, difficulty welding Ni alloys
5. Waterwall tubing	T-11 (1.25Cr, 0.5Mo) steel	T-11 and T-91. *T-11 has been used but insufficient creep strength. T-91 is available but requires post-weld heat treatment. T-91 overlaid or clad with high Cr alloys is common to reduce corrosion due to the retrofitting of boilers with low NOx burners*	T-91/T-92 *(have strength and corrosion resistance but require careful heat treatment)* or Inconel 617 *(satisfies all requirements but is very expensive)*	High fireside corrosion resistance, steam side oxidation resistance



1. Materials Technology for Advanced Coal Power Plants
2. Newer Materials for Supercritical Power Plant Components

Industry Landscape

Repair and maintainence are performed by certified service providers. Repair processes comply with approved ASME standards



U.S. DEPARTMENT OF ENERGY

State of the Industry Plant Services

Service providers serve coal power plants in a variety of ways, but innovation and advancement in these categories is limited by plant willingness to pay for non-basic repairs

Outage Services
Providing high-quality spare parts and conducting cost-effective repairs and maintenance

Multi-year Service Agreements
Delivering tailored services to yield specific outcomes beneficial to particular plant and financial situations

Upgrades
Implementing a comprehensive suite of upgrades to achieve more output, improved emissions, extended asset life, or operational flexibility

Operations and Maintenance
Providing customizable advisory or repair services to enhance or perform daily operations, increase productivity, and decrease operating costs

Digital
Transforming the data environment of the power industry by creating a common data network, creating modular applications, machine learning, and network optimization

Full Plant Rehab/Relocation
Conducting full plant, "flange-to-flange" upgrades to improve a plant's turbine and other units in need of conditioning

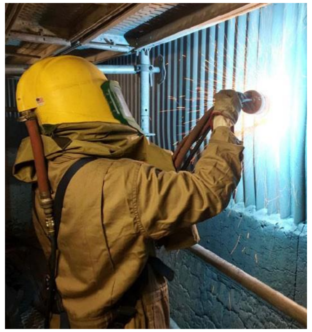
State of the Art Materials Repairs

Based on the current industrial landscape, material and repair process opportunities exist through material retrofits, tube section replacement and patching

Tube Section Replacement

- State of the art welding process
- Required ASME standard and certified vendor
- Process is very challenging
- Replacement is with the same materials not yielding the future service life improvement
- Coatings and Surface Technologies extensively used

10, 11. **Old tube section removed,** header hole is cleaned up (left) before dutchman is welded in (right)



Tube Patch and Shield Protections

- State of the art patch welding process as a temp repair
- Companies offer shielding fixtures (armor) for erosion protection

Tubes

Shielding Fixtures

Coal Riffles

Burner Components

Retrofit with Better Material

- Better alloys development is driven by AUSC
- Advanced materials are too expensive and will not be accepted

Opportunity : Evaluate tube section repair with better alloys
Challenge : welding of dissimilar materials, life prediction of the weld, ASME certification

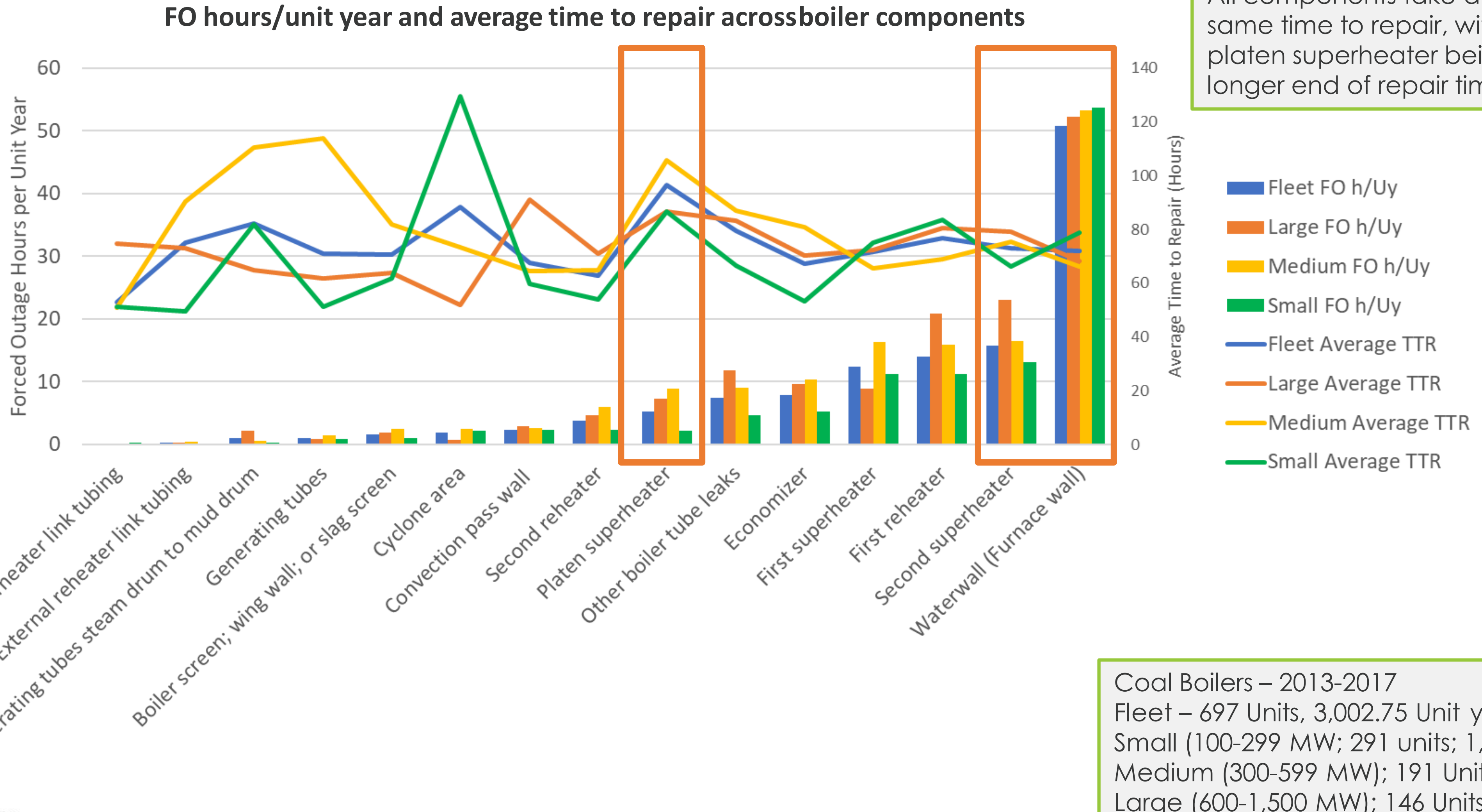
Opportunity : Evaluate additive manufacturing techniques for functionally graded materials for section of the tubes
Challenge : welding of dissimilar materials, life prediction of the weld, ASME certification

Opportunity : Better performing coatings

Challenges Appendix

Key Causes of Plant Outages

Boiler tube leaks in the waterwall are greatest cause of forced outage hours across the fleet and separate size classifications, followed by superheaters



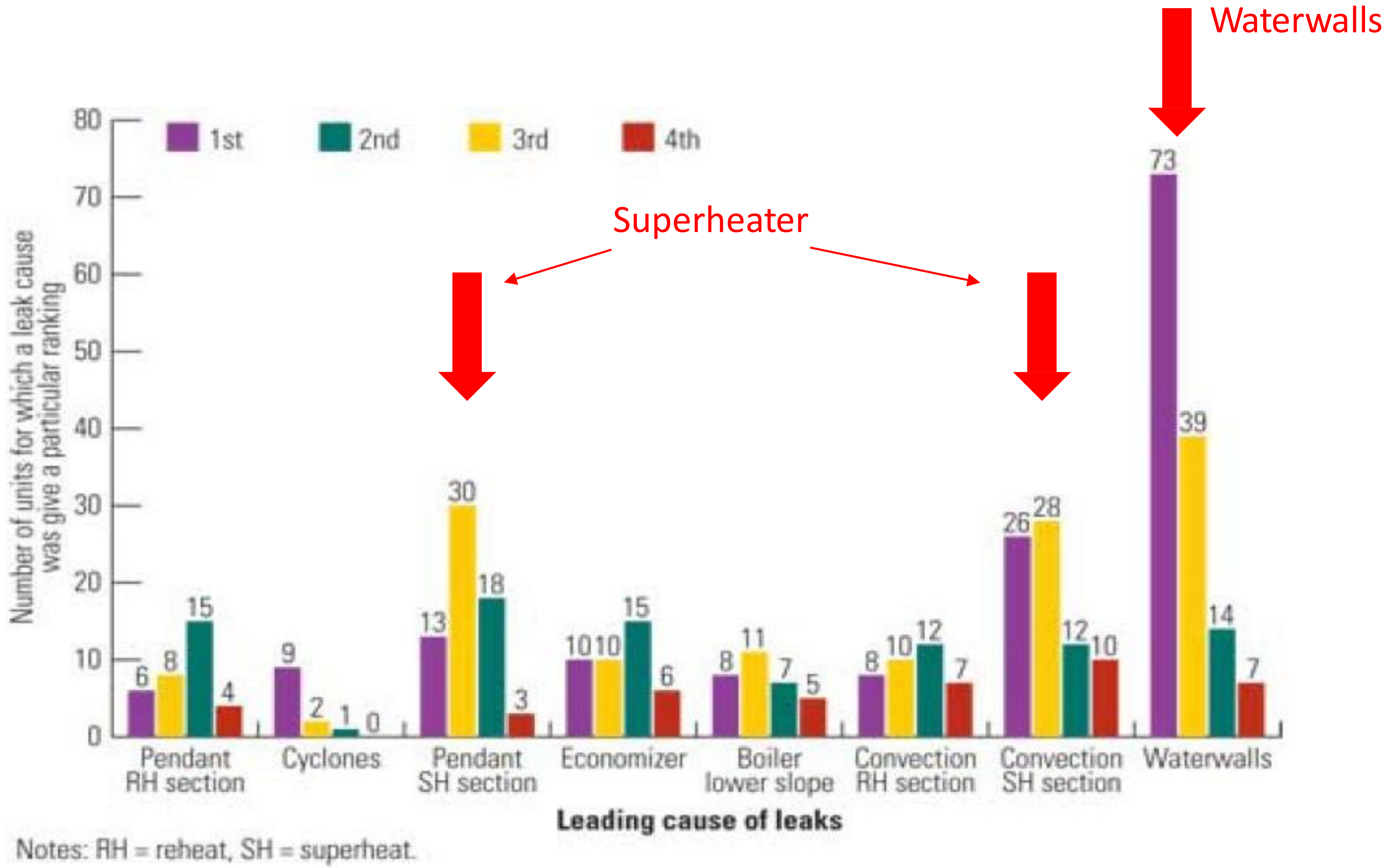
All components take about the same time to repair, with the platen superheater being on the longer end of repair times

Coal Boilers – 2013-2017
Fleet – 697 Units, 3,002.75 Unit year
Small (100-299 MW; 291 units; 1,194.75 Unit year
Medium (300-599 MW); 191 Units; 899 Unit year
Large (600-1,500 MW); 146 Units; 660 Unit year

1. MESA 202.015 – Initial Boiler GADS Analysis
2. Benefits of Advanced Material Used for Boiler Tubes in Coal-Fired Power Units

Leading System Causes of Plant Outages

Waterwalls are confirmed independently in the EUCG as one of the leading causes of leakages and forced plant outages



Leading Locations of Leaking, 164 units surveyed

1. Benefits of Advanced Material Used for Boiler Tubes in Coal-Fired Power Units

FlexOps Effect on Boiler Components

Common failure modes and their associated causes throughout the boiler are identified and organized, the waterwall being identified as most susceptible to cracking

Failure Mode	Cause	Component/location
Longitudinal Cracking	Corrosion, fatigue	Waterwall, Economizer, Superheater
	Overheating	Waterwall, Reheater
Transverse Cracking	Creep	Superheater, Dissimilar Welds
	Hydrogen damage	Waterwall
	Thermal fatigue	Waterwall
Hole	Corrosion/fatigue	Furnace Riser Tubes, Fireside
	Weld defect	Waterwall, Superheater
	Caustic gauging	Economizer, waterside
Deformation	Corrosion from slag	Superheater
Surface Thinning	Fly ash erosion	Superheater, Reheater, Waterwall

Evaluation of common failure modes again identified two main locations of failure:

Superheater **Waterwall**

1. Materials Technology for Advanced Coal Power Plants
2. Newer Materials for Supercritical Power Plant Components

Failure Modes of the Superheater and Waterwall

The main failure modes per the main locations of failure provide more insight into how they can be addressed and improved

Component	Failure Mode	Location
Superheater	Creep cracking	Dissimilar Metal Welds (DMW)
	Cracks in DMW	DMW
	Complete disintegration of welds	DMW
	Longitudinal cracks from overheating	Not at DMW
Waterwall	Corrosion fatigue	Welds Attachment
	Cracking at bend	Dissimilar Welds
	Cracking at hot spots	Not near welds

Technology Appendix

Standard Boiler Tube Repair Options

When tube failure occurs, standard repair options include the following:

Option **a**

Do standard install of a new tube section

- This option is typically viewed as the most effective type of tube repair
- Replacement can take longer than other repair methods
- Access to the point of failure can be difficult, perhaps limiting repair to only very thin welders

Option **b**

Use a window weld to install new tubing

- Welders may be required to cut through non-failed tubes to create requisite space to weld the failed tube, called a window weld
- Window welds can be used to minimize required time and cost to install new tubing, but are technically difficult and more prone to failure

Option **c**

Conduct a pad weld on the failure

- This weld is an overlay of material matching the boiler tube chemistry on the damaged area
- The damaged area must be thick enough to withstand the pad welding process
- Pad welds are among the fastest repairs, but are typically considered temporary until a failed section can be replaced

10, 11. Old tube section removed, header hole is cleaned up (left) before dutchman is welded in (right)

Pad weld

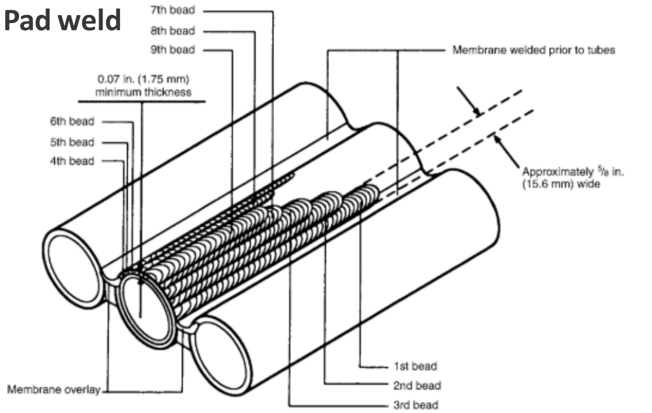


Fig. 10.21 Overlay weld beads applied to cover the waterwall during GMAW overlay welding process. The indicated bead sequence number is for illustration purposes. The actual overlay welding of the waterwall may not follow the bead sequence number indicated here. The weld bead typically progresses in a vertical down mode from top (left side of the schematic) to the bottom (right side of the schematic). Courtesy of Welding Services Inc.

State of the Industry Boiler Technologies

Service providers do offer more advanced boiler technologies, but they do not garner as much plant interest as the most basic repairs

Advanced cladding for waterwall protection

- Cladding provides **waterwall protection** in boilers that may suffer from **high temperature gaseous corrosion** or other erosion
- High velocity continuous combustion application process resists cracking, spalling, and stress

Application of thermal spray cladding

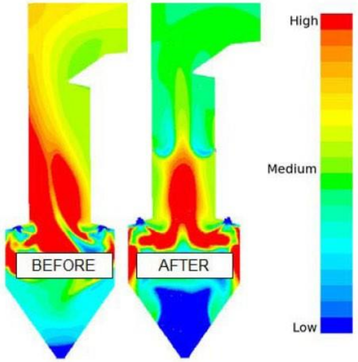
Boiler tuning for flexible operation

- **Assesses the design** of the boiler system to identify potential **problem areas or opportunities** for improved operation
- Services and upgrades customized to the boiler system of interest to **enhance performance** and **lifetime profitability**

Example economizer outlet gas temperature control setup in a plant

Economizer gas temperature controls

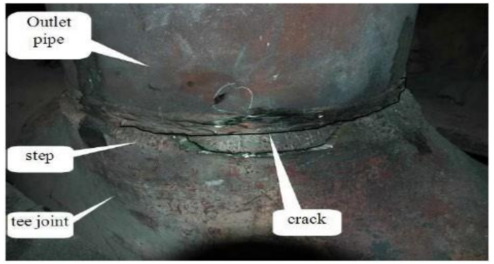
- **Controls the gas temperature** to the SCR, enabling **operation at low load** with **compliance to environmental restrictions**
- Options for **subcritical** and **supercritical boilers** to control gas temperature
- Enables increased **boiler flexibility,** and **decreased boiler wear and tear** due to decreased startup/shutdown cycles



Sample analysis during boiler tuning

Advanced Boiler Tube Repair Technology

Automated orbital welding (AOW) helps service providers address plants' demands for cheaper and quicker services, drastically reducing labor cost and repair time buying the equipment



Automated orbital welding significantly decreases the time required during setup and practice

Compact welding heads can be placed in difficult to reach areas for welders

Identify tear/leak/erosion spot within boiler equipment → Apply pre-weld heat treatment to the area → Determine appropriate welding tools, weld parameters, and skilled welder → Practice welding techniques for area and physical position of welder

→ Once approach is practiced and verified, conduct weld → Continuously verify the quality of each welding spot → Clear potential defects in the weld and re-weld → Setup and conduct post-weld heat treatment → Completed weld

*Automated orbital welding is roughly **50% quicker**[1] than manual welds, and reduces physical strain on welders*

Welder spending a brief time in this position, rather than hours, to check the automated orbital weldingset-up

*Automated orbital welding results in **~99% acceptance rate**[2] of welds, saving time, materials, and money*

Automated orbital welding equipment will easily capture all data related to the weld

1. Utility Self-Performs on Boiler Tuber Replacement
2. The Art of Welding – Orbital Welding Handbook

Automated Orbital Welding Capabilities

Orbital welding is where the welding torch is mechanically rotated 360° around a static workpiece, like a tube or pipe

Automated orbital welding process:

Determine weld parameters (e.g. position, materials, dimensions, temperatures) → Create welding program in the welding system → Set up appropriate welding head (using integrated or external wire feeder) → Run welding program → Obtain captured weld data through power supply or from connection to external computer → Completed weld and documentation

AMI's M217 Orbital Welding power supply

Graphical user interface of AMI M217 Orbital Welding power supply

Welding head conducting the actual weld programmed into the power supply

Benefits

- Enables a **repeatable, high-quality weld**
- Significantly **decreases** or eliminates **welder error and defects,** to < 1%
- **Accelerates the repair process** by completing satisfactory welds quicker than the manual process
- **Investment** in this equipment and accompanying training of employees **decreases potential future down-time**
- **Readily** and quickly **documents the weld** and captures associated data

Challenges

- **Higher upfront cost** for repair
- **Upfront time requirement** to determine weld procedures and exact values of **weld parameters** to control process
- A **skilled welder is still necessary** to monitor and control the process, and will need skill to properly **identify variables** between welding targets

Overview of Boiler Coating Methods

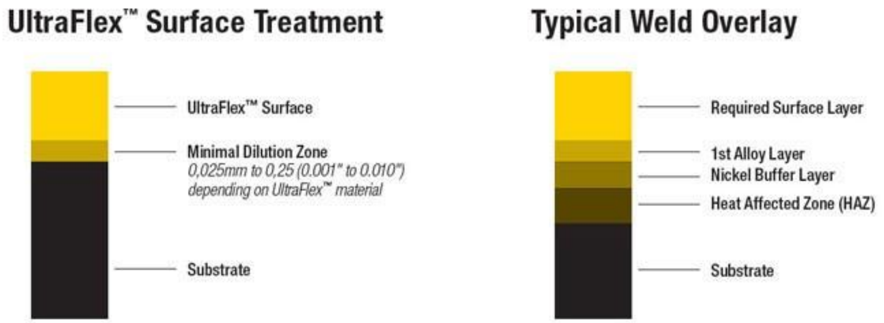
Thermal spray coatings and their various application methods are the current state of the art that for improving surfaces and boiler tube performance

- Thermal Spray Coatings
  - Flame Spray
    - Flame Powder
    - Flame Wire
    - HVOF
    - D-GUN
  - Electric Arc
    - Air
    - Inert
    - Chamber
  - Plasma Spray
    - Conventional
    - Vacuum
  - Kinetic Energy
    - Cold Spray

Commercial Treatments for Plant Boilers

NATIONAL ENERGY TECHNOLOGY LABORATORY

Treatment	Application Technology	Material	Advantages	Location
Kennametal, Conforma Clad and UltraFlex Brazed Cladding	Vacuum furnace braze infiltration process and metallurgical bond	Tungsten carbide	Applicable to complex geometries, thin conformable layer forms metallurgical bond to substrate, minimal diffusion of deposited alloy, does not need buffer layers between alloy and substrate	Gas circulation areas, soot blowers, boiler tubes
		From tungsten carbide to Stellite (range of cobalt-chromium) alloys		Gas circulation areas, soot blowers, boiler tubes, and hard to reach areas/complex geometries
GE, AMSTAR 888* Thermal Spray Cladding	Thermal spraying of melted/heated materials	Patented GE alloy	Able to quickly provide thick coatings on large surface area, minimal heat input	Boiler waterwalls where susceptible to gas corrosion and/or erosion
Praxair Surface Technologies	Laser deposition of material to the surface of target area	Stainless steels (alloy type 309L, 312) and Ni-based alloys (alloy type 625, 622, 52)	Precise process, wide array of applicable materials, minimal heat input, low dilution of deposited alloy	Boiler waterwall panels
GreenShield	Ceramic Boiler Tube Coating	Non-toxic water based coating	Cheaper to apply than other technologies, environmentally safe material with no volatile organic compounds, non-catalytic technology ensures no molten ash impacting the layering	Boiler tubes, economizer, stainless steel tubes,



Kennametal weld layering compared to traditional weld layering

AmStar 888* cladding on the left tube after 3.5 years of operation compared to an unprotected adjacent (right) tube in service for only 18 months

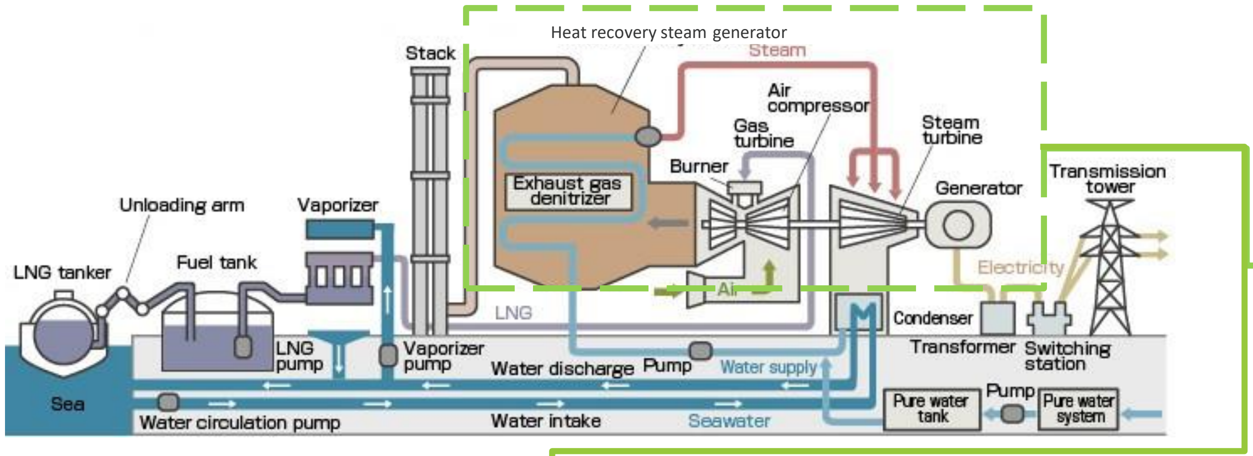
Synergies with NGCC Appendix

Major Plants Undergoing Flexible Operations

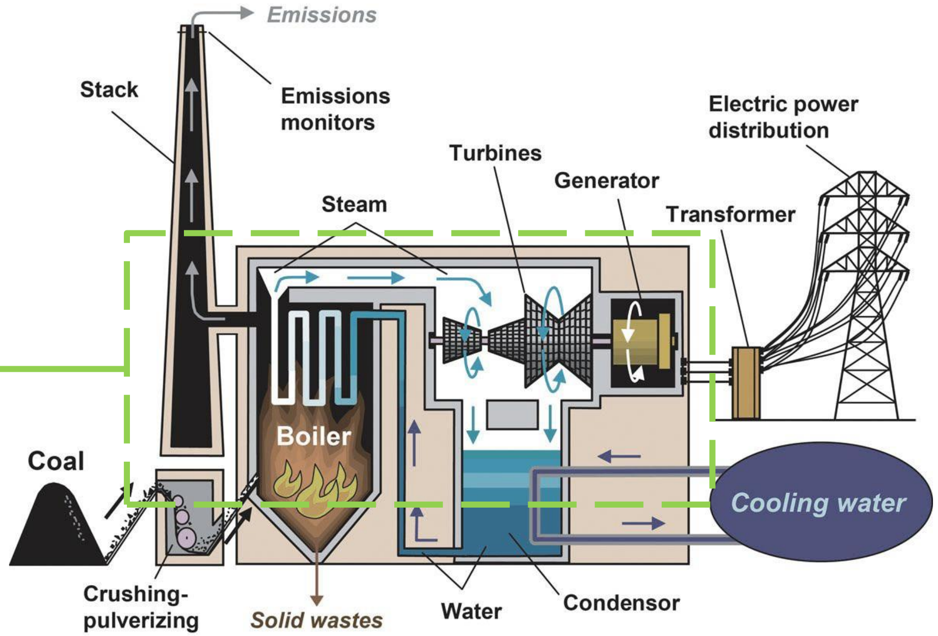
NGCC and PC power plants are both seeing damages from FlexOps, yet their common components provide an opportunity for NETL to support both

NATIONAL ENERGY TECHNOLOGY LABORATORY

Natural Gas Combined Cycle (NGCC) Plant Schematic



Pulverized Coal (PC) Power Plant Schematic



Common components
- Boiler
- Steam turbine
- Generator

Common failure mechanisms occurring in HRSGs are similar to those seen in conventional boilers in coal power plants

U.S. DEPARTMENT OF ENERGY

1. https://www.ccsdualsnap.com/pressure-switches-in-combined-cycle-power-plant-switches/
2. https://www.climatetechwiki.org/technology/sup_crit_coal

Major Flexible Operation Damage Mechanisms

Comparison of damage mechanisms across coal plant conventional boilers and NGCC heat recovery steam generators

Component	Low cycle fatigue	Thermal shock	Flow assisted corrosion	Corrosion fatigue	Deposits/corrosion	Oxidation/exfoliation	Gas-side corrosion	Gas-side erosion	Thermal expansion
Superheater headers	H, B	H	H	H					
Superheater tubes	H, **B**	H	H	H		H		B	
Reheater headers	H	H	H	H					
Reheater tubes	H, B	H	H	H		H		B	
Evaporator tubes	H		H	H	H		H		
Economizer headers	H		H	H	H				
Economizer tubes	H, **B**		H	H	H		H		
Drum	H		H	H	H				
Steam piping*	H, **B**	H	H	**B**				B	
Feed/connecting pipes	H, **B**		H	H, **B**					
Casting, liners, duct, etc.	H	H	H				H	H	H

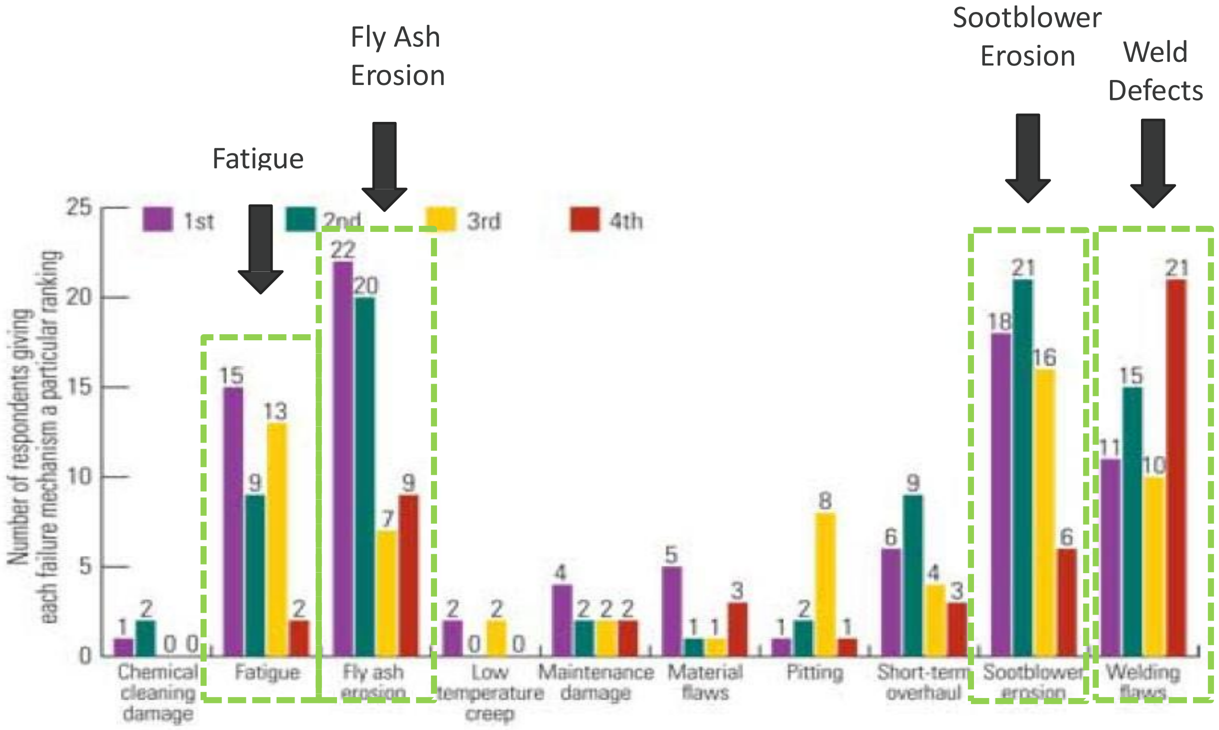
KEY
H – indicates applicable to HRSGs
B – indicates applicable to conventional boilers

1. GADS, FlexOps Proceedings
2. Impact of Cycling on the Operation and Maintenance Cost of Conventional and Combined-Cycle Power Plants, EPRI

Frequent Damage Mechanisms

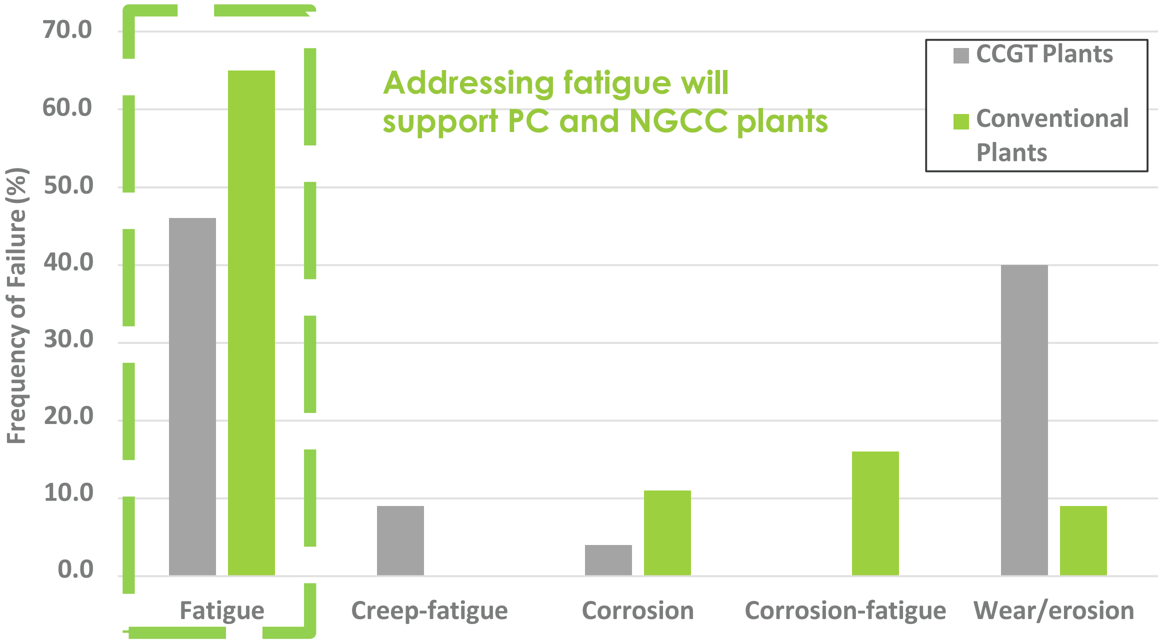
When looking at just the conventional boiler and a comparison of the conventional boiler to the NGCC HRSG, fatigue stands out as a significant challenge

Leading Causes of Leaking in Boilers



Data set represents 164 surveyed units

Comparison of Damage Mechanisms between Conventional and CCGT Plants Undergoing Cyclic Operations

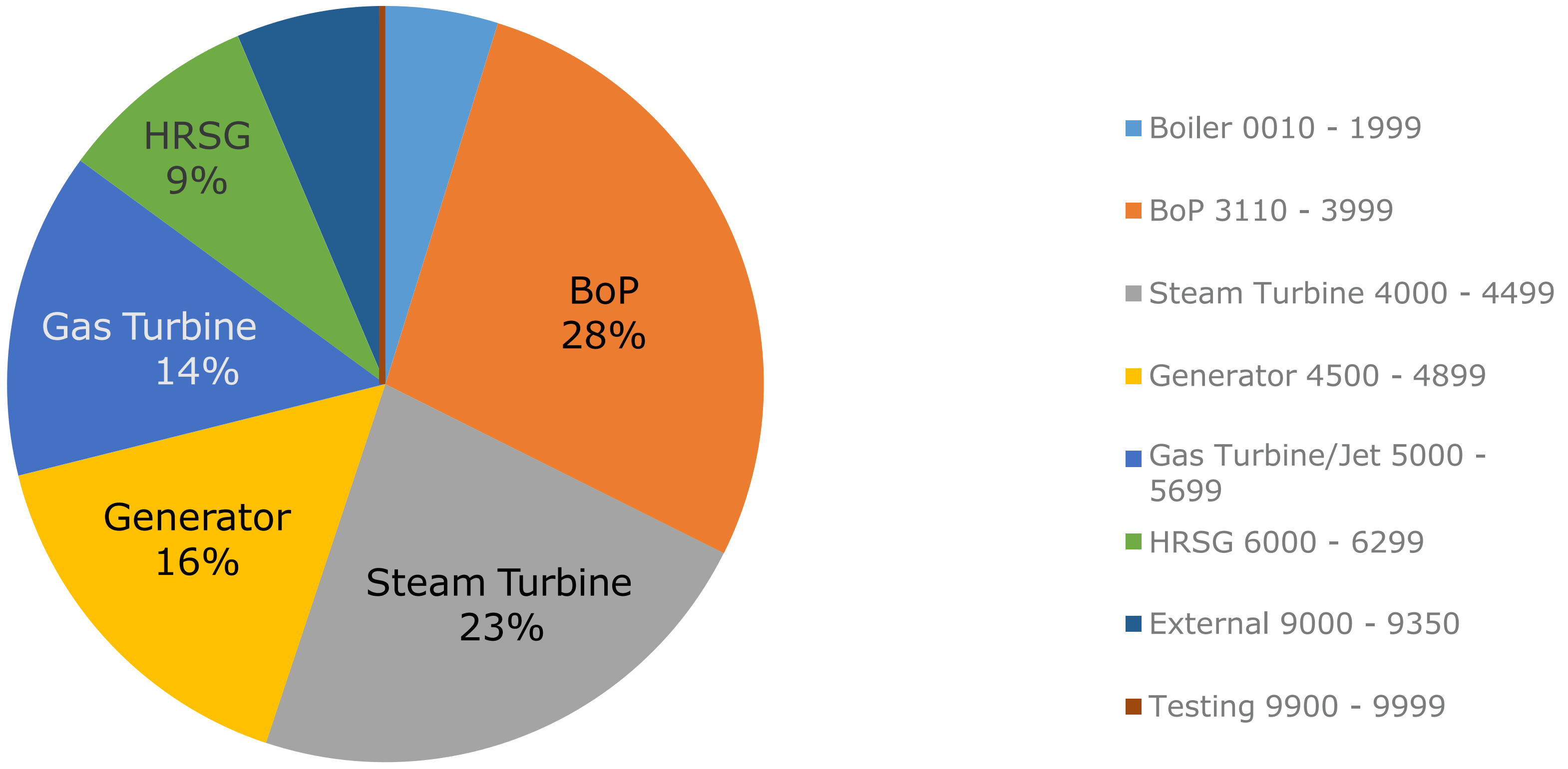


2. Impact of Cycling on the Operation and Maintenance Cost of Conventional and Combined-Cycle Power Plants, EPRI

Steam Turbine is 2nd Greatest Cause of FOs

Steam turbines are the second leading cause of forced outage hours and, after the HRSG, is the second most comparable component to pulverized coal plants

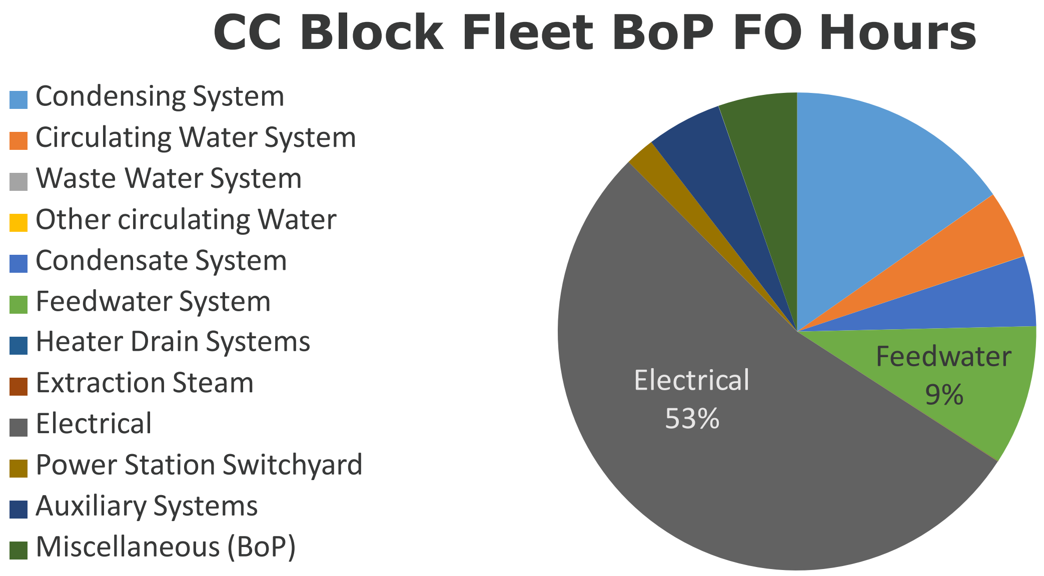
Combined Cycle Block Fleet Forced Outage (FO) Hours

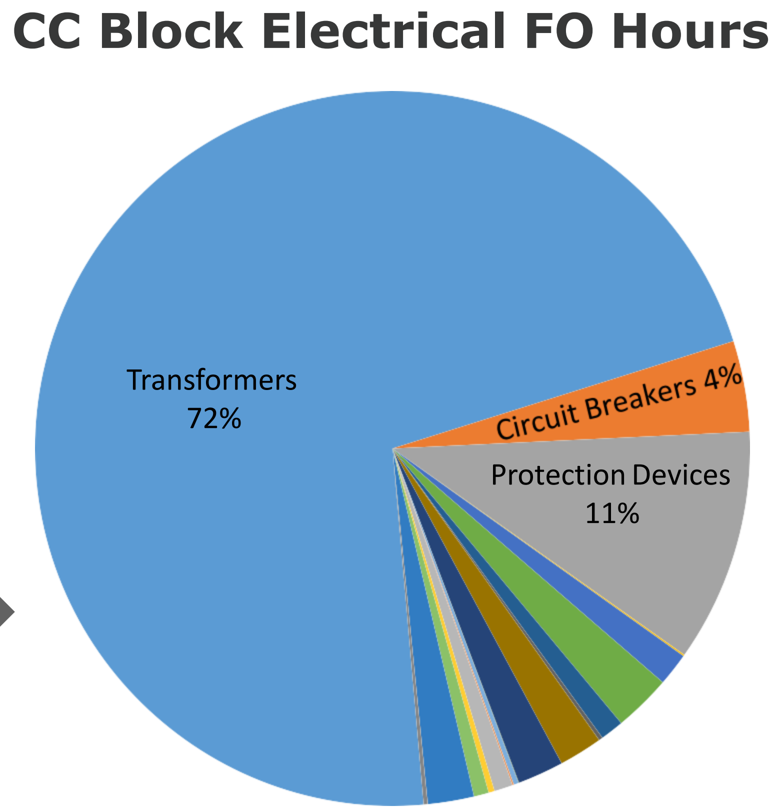


NGCC data can be reported at the “Block” level or at the “CCGT” level. The block includes gas & steam turbine and equipment supporting the production of electricity. The CCGT format reports individual combined unit events. Details can be found at https://www.nerc.com/pa/RAPA/gads/DataReportingInstructions/Appendix_L1_Calculating_Combined_Cycle_and_Co-Generation_Block_Data_Using_Synthesis_Event_Performance_Method_2019_DRI.pdf

Electrical FO hours can be broken down

Transformers are a main source of electrical-component caused forced outages

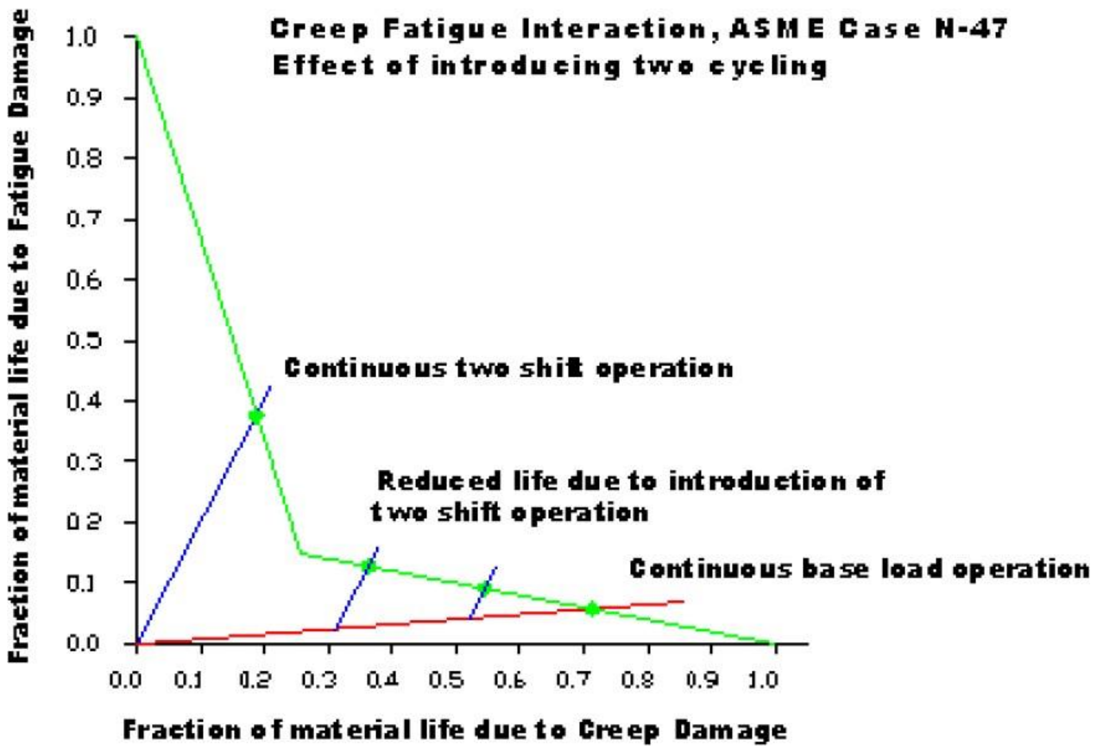




Steam Turbine Cyclic Failure Mechanisms

Damage for steam turbines in conventional and CCGT plants are generally similar

- **Thermal fatigue and associated creep-fatigue**
  - Due to thermal shock and thermal cycling from mismatches of incoming steam temperature and equipment temperature
- **Mechanical fatigue**
  - Load and speed variations
  - Vibrations from ramping up and down
- **Erosion**
  - By particulates due to oxide scales at the front end
  - By water droplets at the back end
- **Fouling and stress corrosion**
  - Due to carryover of boiler water salts and impurities because of less controlled environments during cyclic operation



The red line indicates the effective operation of the component, and the actual component life is given by the point at which it intersects with the green line under various operational procedures

HRSG and Boiler Failure Similarities

Although the 5th most likely cause of FOs in CCGT plants, HRSGs are the most comparable CCGT component to conventional coal plants

Both HRSGs and conventional boilers:

- Are damaged by cyclic operations
- See tube failures as the main source of breakdowns
- Suffer thermal fatigue, corrosion fatigue
- Have difficult to reach tube failures requiring advanced or creative welding solutions to maintain and repair

Common failure mechanisms occurring in HRSGs are similar to those seen in conventional boilers in coal power plants

HRSG Failure Mechanisms:

Component	Low cycle fatigue	Thermal shock	Creep	Flow assisted corrosion	Corrosion fatigue	Deposits/ corrosion	Oxidation/ Exfoliation	Gas-side corrosion	Gas-side erosion	Thermal expansion
Superheater headers	X	X	X							
Superheater tubes	X	X	X				X			
Reheater headers	X	X	X							
Reheater tubes	X	X	X				X			
Evaporator tubes	X			X	X	X		X		
Economizer headers	X	X		X	X	X				
Economizer tubes	X	X		X	X	X		X		
Drum	X	X		X	X	X				
Steam Piping	X	X	X							
Feed / connecting pipes	X			X	X					
Casing, liners, duct, etc	X	X	X					X	X	X

1. Inspection, Monitoring, Repair, and Maintenance of HRSGs
2. EPRI Cycling Costs