• 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
Demographics of the current fleet

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

Mostly Inflexible Constant Pressure Units

Plant age and cycling impact plant reliability

68% of Total fleet is Subcritical

<table>
<thead>
<tr>
<th>Boiler type</th>
<th>Total units</th>
<th>Average net summer capacity (MW)</th>
<th>Fleet average heat rate (Btu/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcritical</td>
<td>751</td>
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<td>1</td>
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<tr>
<td>Adv. USC</td>
<td>0</td>
<td>(e.g.) 600</td>
<td>(pred.) 8,300 – 8,800</td>
</tr>
</tbody>
</table>

*Modeled heat rate not available for 230 subcritical units
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

1. GADS Conventional Plant Data
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)
Major Plants Undergoing Flexible Operations

**Pulverized Coal (PC) Power Plant Schematic**

Common components
- Boiler
- Steam turbine
- Generator

**Natural Gas Combined Cycle (NGCC) Plant Schematic**

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

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

2. [https://www.climatetechwiki.org/technology/sup_crit_coal](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).

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

CHALLENGES

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
<table>
<thead>
<tr>
<th>Title</th>
<th>Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>An overview of problems and solutions for components subjected to fireside of boilers</td>
<td><a href="https://link.springer.com/article/10.1007%2Fs40090-017-0133-0">https://link.springer.com/article/10.1007%2Fs40090-017-0133-0</a></td>
</tr>
<tr>
<td>Inspection, Monitoring, Repair, and Maintenance of HRSGs</td>
<td><a href="https://static1.squarespace.com/static/5304e62de4b00674c06af5d5c/t/5c1bc12b4fa51a06475ccf84/154532796174/Intro-HRSG+Guidelines.pdf">https://static1.squarespace.com/static/5304e62de4b00674c06af5d5c/t/5c1bc12b4fa51a06475ccf84/154532796174/Intro-HRSG+Guidelines.pdf</a></td>
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<tr>
<td>EIA Annual Energy Outlook, 2019</td>
<td>NA</td>
</tr>
<tr>
<td>Benefits of Advanced Material Use for Boiler Tubes in Coal-Fired Power Units</td>
<td>NA</td>
</tr>
</tbody>
</table>
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

<table>
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<th>Boiler type</th>
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</table>

*Modeled heat rate not available for 230 subcritical units
Major Effects of Cyclic Operations

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

32% of Total fleet is Supercritical

Plant age and cycling impact plant reliability

CCNG fleet is relatively young
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)
**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
Reheater tubing | SS304H, SS347 are widely used over T-91 when high-sulfur, corrosive coal is used and due to their easier weldability
Reheater tubing | T-11 and T-91
Waterwall tubing | 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

**Failure Mechanisms by Boiler Component**

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

**Steam piping**
- **Fatigue**
- **Creep**
- **Corrosion**

**Header**
- **Fatigue**
- **Corrosion**
- **Weld defect**
- **Thermal fatigue**

**Superheater tubing**
- **Fatigue**
- **Creep**
- **Corrosion from slag**
- **Fly ash erosion**
- **Thermal fatigue**

**Reheater tubing**
- **Overheating**
- **Corrosion**
- **Fatigue**
- **Thermal fatigue**

**Waterwall tubing**
- **Fatigue**
- **Overheating**
- **Weld defects**
- **Erosion**
- **Hydrogen damage**

**Waterwall**
- **Fatigue**
- **Overheating**
- **Weld defects**
- **Erosion**
- **Hydrogen damage**

**Waterwall**
- **Fatigue**
- **Overheating**
- **Weld defects**
- **Erosion**
- **Hydrogen damage**

**Header**
- **Fatigue**
- **Corrosion fatigue**
- **Thermal fatigue**
- **Coal particle corrosion**

**Benefits of Advanced Material Used for Boiler Tubes in Coal-Fired Power Units**
## FlexOps Effect on Boiler Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Subcritical Boiler</th>
<th>Supercritical Boiler</th>
<th>AUSC Boiler</th>
<th>Challenges to Advance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Steam piping</td>
<td>Austenitic steels - Low alloy steels like P11 and P22*</td>
<td>P91 or P92* (in steam pipes the temperature can become 25-39°C higher than the steam)</td>
<td>Inconel 740 (requires meticulous heat treatment during fabrication)</td>
<td>High fireside corrosion</td>
</tr>
<tr>
<td>2. Header</td>
<td>Austenitic steels - Low alloy steels like P11 and P22*</td>
<td>P91 steel*</td>
<td>Ni based alloys</td>
<td>High fireside corrosion, Ni content must be optimized to ensure strong welds</td>
</tr>
<tr>
<td>3. Superheater tubing</td>
<td>T-22 ferric steel - T22 (2.25Cr-1Mo)</td>
<td>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</td>
<td>Inconel 740 (requires meticulous heat treatment during fabrication), Haynes 230, Haynes 282</td>
<td>High fireside corrosion, Creep strength</td>
</tr>
<tr>
<td>4. Reheater tubing</td>
<td>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</td>
<td>T-91/T-92 (have strength and corrosion resistance but require careful heat treatment) or Inconel 617 (satisfies all requirements but is very expensive)</td>
<td>Ni based alloys</td>
<td>High fireside corrosion, reheater temperatures typically get higher than superheater temperatures, so creep strength is an even greater concern, difficulty welding Ni alloys</td>
</tr>
<tr>
<td>5. Waterwall tubing</td>
<td>T-11 (1.25Cr, 0.5Mo) steel</td>
<td></td>
<td></td>
<td>High fireside corrosion resistance, steam side oxidation resistance</td>
</tr>
</tbody>
</table>
Industry Landscape

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

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

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

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

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

- **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

**Tube Patch and Shield Protections**
- State of the art patch welding process as a temp repair
- Companies offer shielding fixtures (armor) for erosion protection

**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
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.

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

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
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

Waterwalls

Superheater
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.

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

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

- **Superheater**
- **Waterwall**
# 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

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure Mode</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superheater</td>
<td>Creep cracking</td>
<td>Dissimilar Metal Welds (DMW)</td>
</tr>
<tr>
<td></td>
<td>Cracks in DMW</td>
<td>DMW</td>
</tr>
<tr>
<td></td>
<td>Complete disintegration of welds</td>
<td>DMW</td>
</tr>
<tr>
<td></td>
<td>Longitudinal cracks from overheating</td>
<td>Not at DMW</td>
</tr>
<tr>
<td>Waterwall</td>
<td>Corrosion fatigue</td>
<td>Welds Attachment</td>
</tr>
<tr>
<td></td>
<td>Cracking at bend</td>
<td>Dissimilar Welds</td>
</tr>
<tr>
<td></td>
<td>Cracking at hot spots</td>
<td>Not near welds</td>
</tr>
</tbody>
</table>
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

![Image 1](https://example.com/image1.png)

![Image 2](https://example.com/image2.png)

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

**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.

**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.
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.

1. Utility Self-Performs on Boiler Tube Replacement

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.

Practice welding techniques for area and physical position of welder.

Determine appropriate welding tools, weld parameters, and skilled welder.

Clear potential defects in the weld and re-weld.

Setup and conduct post-weld heat treatment.

Completed weld.

Once approach is practiced and verified, conduct weld.

Apply pre-weld heat treatment to the area.

Continuously verify the quality of each welding spot.

Identify tear/leak/erosion spot within boiler equipment.

Automated orbital welding is roughly 50% quicker\(^1\) than manual welds, and reduces physical strain on welders.

Automated orbital welding results in \(\sim99\%\) acceptance rate\(^2\) of welds, saving time, materials, and money.

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

Weaver spending a brief time in this position, rather than hours, to check the automated orbital welding set-up.

- Tiered pipes
- Step
- Te joint
- Crack
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**

**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.
## Commercial Treatments for Plant Boilers

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Application Technology</th>
<th>Material</th>
<th>Advantages</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kennametal, Conforma Clad and UltraFlex Brazed Cladding</td>
<td>Vacuum furnace braze infiltration process and metallurgical bond</td>
<td>Tungsten carbide</td>
<td>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</td>
<td>Gas circulation areas, soot blowers, boiler tubes</td>
</tr>
<tr>
<td>GE, AMSTAR 888* Thermal Spray Cladding</td>
<td>Thermal spraying of melted/heated materials</td>
<td>Patented GE alloy</td>
<td>Able to quickly provide thick coatings on large surface area, minimal heat input</td>
<td>Boiler waterwalls where susceptible to gas corrosion and/or erosion</td>
</tr>
<tr>
<td>Praxair Surface Technologies</td>
<td>Laser deposition of material to the surface of target area</td>
<td>Stainless steels (alloy type 309L, 312) and Ni-based alloys (alloy type 625, 622, 52)</td>
<td>Precise process, wide array of applicable materials, minimal heat input, low dilution of deposited alloy</td>
<td>Boiler waterwall panels</td>
</tr>
<tr>
<td>GreenShield</td>
<td>Ceramic Boiler Tube Coating</td>
<td>Non-toxic water based coating</td>
<td>Cheaper to apply than other technologies, environmentally safe material with no volatile organic compounds, non-catalytic technology ensures no molten ash impacting the layering</td>
<td>Boiler tubes, economizer, stainless steel tubes,</td>
</tr>
</tbody>
</table>

### UltraFlex™ Surface Treatment

- **UltraFlex™ Surface**  
  - Minimal Dilution Zone: 0.030 in. (0.76 mm) to 0.060 in. (1.52 mm) depending on UltraFlex™ material  
  - Substrate

### Typical Weld Overlay

- **Required Surface Layer**  
  - 1st Alloy Layer  
  - Nickel Buffer Layer  
  - Heat Affected Zone (HAZ)  
  - Substrate

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.

**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.
## Major Flexible Operation Damage Mechanisms

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Low cycle fatigue</th>
<th>Thermal shock</th>
<th>Flow assisted corrosion</th>
<th>Corrosion fatigue</th>
<th>Deposit/corrosion</th>
<th>Oxidation/efoliation</th>
<th>Gas-side corrosion</th>
<th>Gas-side erosion</th>
<th>Thermal expansion</th>
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<tr>
<td>Superheater headers</td>
<td>H, B</td>
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<td>Feed/connecting pipes</td>
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<td>Casting, liners, duct, etc.</td>
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**KEY**

- **H** – indicates applicable to HRSGs
- **B** – indicates applicable to conventional boilers
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

- Fatigue
- Fly Ash Erosion
- Sootblower Erosion
- Weld Defects

Data set represents 164 surveyed units.

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

Addressing fatigue will support PC and NGCC plants.

Frequency of Failure (%)

- Fatigue
- Creep-fatigue
- Corrosion
- Corrosion-fatigue
- Wear/erosion
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**
  - **BoP 28%**
  - **Steam Turbine 23%**
  - **Generator 16%**
  - **Gas Turbine 14%**
  - **HRSG 9%**

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

CC Block Fleet BoP FO Hours
- Condensing System
- Circulating Water System
- Waste Water System
- Other circulating Water
- Condensate System
- Feedwater System
- Heater Drain Systems
- Extraction Steam
- Electrical
- Power Station Switchyard
- Auxiliary Systems
- Miscellaneous (BoP)

CC Block Electrical FO Hours
- Transformers 72%
- Circuit Breakers 4%
- Protection Devices 11%
- Feedwater 9%
- Electrical 53%
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

HRSG Failure Mechanisms:

<table>
<thead>
<tr>
<th>Component</th>
<th>Low cycle fatigue</th>
<th>Thermal shock</th>
<th>Creep</th>
<th>Flow induced corrosion</th>
<th>Crevice corrosion</th>
<th>Crevice stress corrosion</th>
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</tbody>
</table>

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

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