Characterization of Long-Term Serviced Coal Combustion Power Plant Extreme Environment Materials

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Challenges for Coal Fleet

Avg age of existing U.S. coal fleet is >40 years

- Many already operated beyond the original design lives
- Expectation is to continue for another 30 years
- Most units were designed for baseload operation
- Practice of some level of flexible operation
  - Intermittent deployment of renewables
  - Low natural gas prices/CC
Project Objectives and Approaches

To develop a database for microstructures, damage mechanisms, and mechanical properties of long-term serviced EEM (>100,000 hours)

- Perform detailed characterization and mechanical testing
  - NDE, macro and microstructures, and various mechanical testing
- Link compositions and microstructural features to long-term behaviors of materials
  - Secondary phases, inclusions, decomposition/evolution, damage
- Develop a comprehensive database on mechanical properties and microstructural information

Database will be shared with DOE and 3rd-party researchers in future materials research and modeling
Key Tasks

- Task 1: Project Management
- Task 2: Identification and Removal of Material Components
- Task 3: Metallurgical Characterization of Component Alloys
  - Engineering materials are not homogenous
- Task 4: Fabrication of Test Samples for Mechanical Testing
- Task 5: Mechanical Testing and Remaining Life Assessment of Components
  - Uniaxial tensile testing
  - Fracture toughness testing
  - Charpy V-notch / notch bar impact testing
  - Fracture toughness testing
  - Base-metal creep testing
  - Cross-weld creep testing
  - Creep fatigue testing
  - Estimation of remaining life
- Task 6: Data and Material Repository
### List of Power Plant EEM Components

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Source</th>
<th>Component</th>
<th>Vintage/Hours</th>
<th>Quantity Received</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferritic</td>
<td>½Cr-¾Mo-½V</td>
<td>Utility #3</td>
<td>CrMoV Turbine lead piping (straights, ends and girth weld)</td>
<td>~270,000 hrs</td>
<td>One lead</td>
</tr>
<tr>
<td></td>
<td>Grade 22</td>
<td>Utility #3</td>
<td>Grade 22 seam-welded HRH piping</td>
<td>435,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grade 22</td>
<td>Eddystone #2</td>
<td>Main steam piping - large radius Grade 22 bends to SP valve</td>
<td>1960</td>
<td>2 bends (15’ long)</td>
</tr>
<tr>
<td></td>
<td>Grade 91</td>
<td>Utility #2</td>
<td>Grade 91 superheater outlet headers</td>
<td>141,000 hrs</td>
<td>2 headers</td>
</tr>
<tr>
<td></td>
<td>Grade 91</td>
<td>Utility #4</td>
<td>Seam-welded Grade 91 hot reheater outlet header</td>
<td>&gt;100,000 hrs</td>
<td>1 section, 30” long</td>
</tr>
<tr>
<td>SS</td>
<td>316H OC</td>
<td>Eddystone #1</td>
<td>Main steam piping from boiler to SP valve, including bends and large and small bore welds</td>
<td>1983</td>
<td>2 sections, 20’ long</td>
</tr>
<tr>
<td></td>
<td>316H OC</td>
<td>Eddystone #1</td>
<td>Main steam piping in penthouse (large/small bore welds)</td>
<td>1983</td>
<td>2 sections, 8’ long</td>
</tr>
<tr>
<td></td>
<td>316H</td>
<td>Eddystone #1</td>
<td>Outlet piping from junction header turbine. Straights, large radius bend, girth weld(s) and small bore penetration welds</td>
<td>1963</td>
<td>2 leads, each about 25’ long</td>
</tr>
<tr>
<td></td>
<td>316H</td>
<td>Eddystone #2</td>
<td>Main steam collection header with link piping</td>
<td>1960</td>
<td>2 headers</td>
</tr>
<tr>
<td>SS + DMWs</td>
<td>316H, 316H to Grade 22</td>
<td>Eddystone #1</td>
<td>SP valve assembly, with 316H/P22 DMWs</td>
<td>1968</td>
<td>1 assembly, 2 DMWs</td>
</tr>
<tr>
<td></td>
<td>316H, 316H to Grade 22</td>
<td>Eddystone #1</td>
<td>Turbine J-loop piping, with 316H/F22 DMWs</td>
<td>2007</td>
<td>2 loops, 2 DMWs</td>
</tr>
<tr>
<td></td>
<td>316H, 316H to Grade 22</td>
<td>Eddystone #2</td>
<td>Main steam piping, with 316/P22 DMW</td>
<td>early 1990s</td>
<td>2 DMWs</td>
</tr>
<tr>
<td></td>
<td>321H, 321H to Grade 22</td>
<td>Utility #3</td>
<td>Austenitic stainless steel superheater tubing</td>
<td>290,000 hrs</td>
<td>Many</td>
</tr>
<tr>
<td></td>
<td>347H; 347H to Grade 22</td>
<td>Utility #4</td>
<td>347H FSH tubing; DMWs between 347H and T22</td>
<td>~100,00hr</td>
<td>~100 ft</td>
</tr>
<tr>
<td></td>
<td>321H, 321H to Grade 22</td>
<td>Utility #5</td>
<td>Austenitic stainless steel superheater and reheater tubing</td>
<td>&gt;250,000 hrs</td>
<td>Numerous</td>
</tr>
<tr>
<td>Turbine</td>
<td>Variable</td>
<td>Eddystone #1</td>
<td>Super pressure rotors</td>
<td>1960</td>
<td>2 rotors</td>
</tr>
</tbody>
</table>

An additional Grade 91 outlet header was identified and being acquired from UK after ~125,000 hours of service.
316H SP Valve & MS Piping

316H MS Piping

Grade 91 Outlet Header

316H Outlet Piping

316H Turbine Lead Piping

316H MS Collection Header

316H to Grade 22 DMW
Task 5 - Mechanical Testing

Key Activities

- Perform testing on select materials
  - Time-dependent testing
    - creep
  - Time-independent testing
    - tensile, impact, fracture toughness, etc.
- Detailed characterization
  - Macro-scale evaluation of damage locations and features
  - Detailed SEM/TEM micro-scale evaluations
- External collaboration
  - ORNL – Grade 91 and 316H components
  - CRIEPI (Japan) – Grade 91 outlet header

Component Materials

- Grade 91 Steel
- Grade 22 Steel
- ½Cr½Mo¼V Steel
- 316H Stainless Steel
- 347H Stainless Steel
- 321H Stainless Steel
Example 1: Grade 91 Main Steam Outlet Header

- SH outlet header to HP turbine
- Pedigree:
  - 141,000 hours of service
  - 575°C (1,067°F) and 178 bar (2,590 psi)
  - ~3,300 starts
- Testing Performed:
  - Round-bar creep tests in base metal (F91 and P91)
  - Feature-type cross-weld creep tests (DMW)
  - Standard, time-independent tests (tensile, charpy, hardness, etc.)
Example 1: Feature-Type Creep Tests for P91/F91 DMW

Sample #1: 625°C (1,157°F) and 80 MPa (11.5 ksi)
  - Test ruptured after 556 hours

Sample #2: 625°C (1,157°F) and 60 MPa (8.7 ksi)
  - Test interrupted after 1,637 hours
  - Life fraction >98%
  - See macro metallography (next slide)

Sample #2 test was interrupted immediately before failure (at >98% life fraction)
Example 1: Damage in P91/F91 DMW

Damage in F91 HAZ is extensive with macro-cracking (>1 mm) near end-of-life.
Example 2: Eddystone Unit 2 Main Steam Piping

316H/Gr. 22 DMW Piping
- Main steam piping to super pressure valve
- Early 1990s vintage
- Operating temperature: 1050°F (565°C)
- Operating pressure: 3750 psig

- 316H base-metal creep tests
- DMW cross-weld creep tests
Example 2: P22/316H DMW Test Results

DMW creep testing conditions
- 575°C and 80 MPa
- 600°C and 60 MPa
- 625°C and 40 MPa

Distinct difference in failure mode under different testing conditions
- Fusion line & ductile failure in 80 MPa test
- HAZ and fusion line damage in 60 MPa test

Results reveal different failure modes of common Gr-22/SS DMW in power plants
Characterization Methods

Development of unique techniques and procedures

- Through-wall grain size analysis and mapping
- Through-wall hardness distribution
  - ~80,000 indent locations
- Through-wall sigma phase mapping
  - ~100,000 features (location, size, shape)
- Inclusion mapping using EDS automation
- Large-area elemental mapping using X-Ray fluorescence
- Oxide scale characterization
  - Elemental distribution of oxide scales
  - Automated oxide thickness measurements
Status of Mechanical Testing Task

- Creep testing
  - >42,300 hours in base-metal creep tests
  - >30,000 hours in feature-type cross-weld creep tests
  - Metallography conducted for every sample after test

- ORNL collaboration
  - >1,400 hours in Grade 91 cross-weld and base-metal tests
  - Additional creep tests for 316H planned

- CRIEPI collaboration
  - >12,000 hours in Grade 91 base-metal creep tests
Work performed under agreement
DE-FE0031562
NETL Project Manager: Vito Cedro

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Removal of Grade 91 Outlet Header
Together...Shaping the Future of Electricity