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

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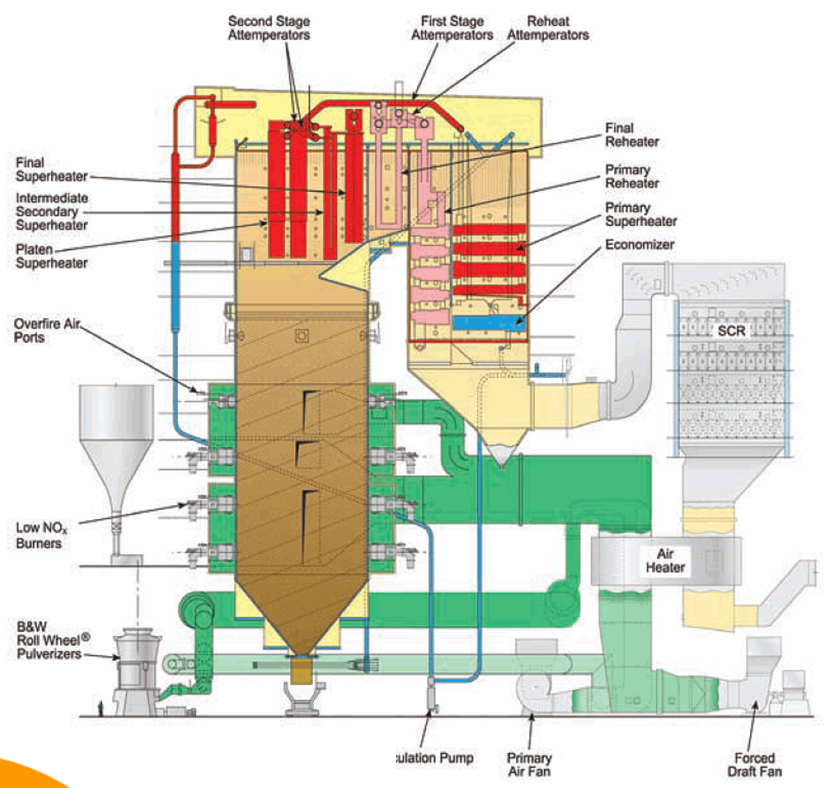
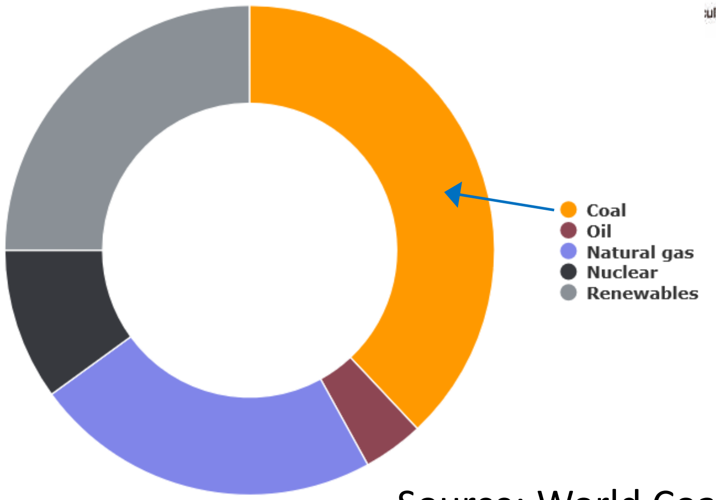
DOE-NETL 2020 FE R&D Project Review Meeting
September 29, 2020

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





Source: World Coal Association

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

Type	Material	Source	Component	Vintage/ Hours	Quantity Received
Ferritic	½Cr-½Mo-¼V	Utility #3	CrMoV Turbine lead piping (straights, ends and girth weld)	~270,000 hrs	One lead
	Grade 22	Utility #3	Grade 22 seam-welded HRH piping	435,000	
	Grade 22	Eddystone #2	Main steam piping - large radius Grade 22 bends to SP valve	1960	2 bends (15’ long)
	Grade 91	Utility #2	Grade 91 superheater outlet headers	141,000 hrs	2 headers
	Grade 91	Utility #4	Seam-welded Grade 91 hot reheat outlet header	>100,000 hrs	1 section, 30” long
SS	316H OC	Eddystone #1	Main steam piping from boiler to SP valve, including bends and large and small bore welds	1983	2 sections, 20’long
	316H OC	Eddystone #1	Main steam piping in penthouse (large/small bore welds)	1983	2 sections, 8’ long
	316H	Eddystone #1	Outlet piping from junction header turbine. Straights, large radius bend, girth weld(s) and small bore penetration welds	1963	2 leads, each about 25’ long
	316H	Eddystone #2	Main steam collection header with link piping	1960	2 headers
SS + DMWs	316H, 316H to Grade 22	Eddystone #1	SP valve assembly, with 316H/P22 DMWs	1968	1 assembly, 2 DMWs
	316H, 316H to Grade 22	Eddystone #1	Turbine J-loop piping, with 316H/F22 DMWs	2007	2 loops, 2 DMWs
	316H , 316H to Grade 22	Eddystone #2	Main steam piping, with 316/P22 DMW	early 1990s	2 DMWs
	321H, 321H to Grade 22	Utility #3	Austenitic stainless steel superheater tubing	290,000 hrs	Many
	347H; 347H to Grade 22	Utility #4	347H FSH tubing; DWMs between 347H and T22	~100,00hr	~100 ft
	321H, 321H to Grade 22	Utility #5	Austenitic stainless steel superheater and reheater tubing	>250,000 hrs	Numerous
Turbine	Variable	Eddystone #1	Super pressure rotors	1960	2 rotors

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 Turbine Lead Piping


316H Outlet Piping


316H MS Collection Header


316H to Grade 22 DMW

Task 5 - Mechanical Testing

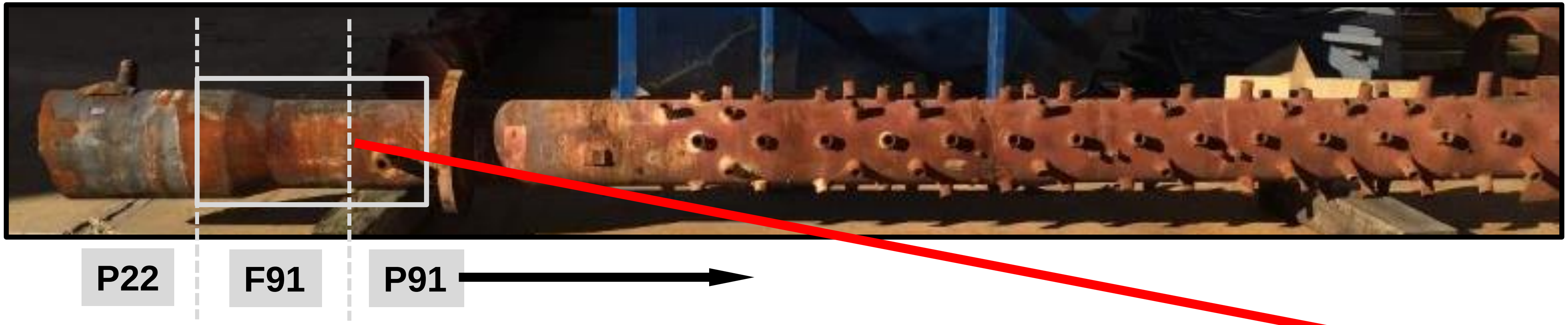
Key Activities

- 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

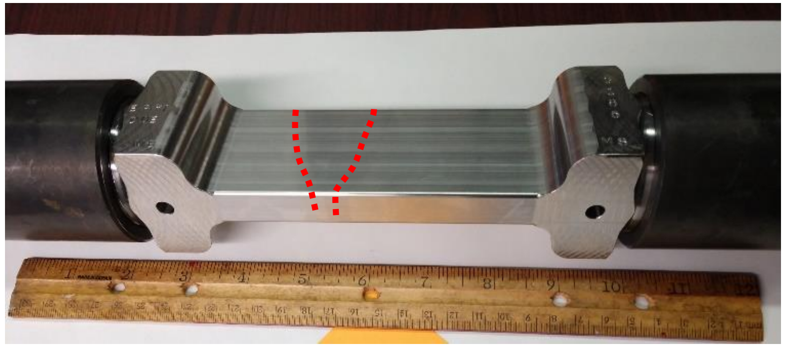
Component Materials

- ❑ 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.)



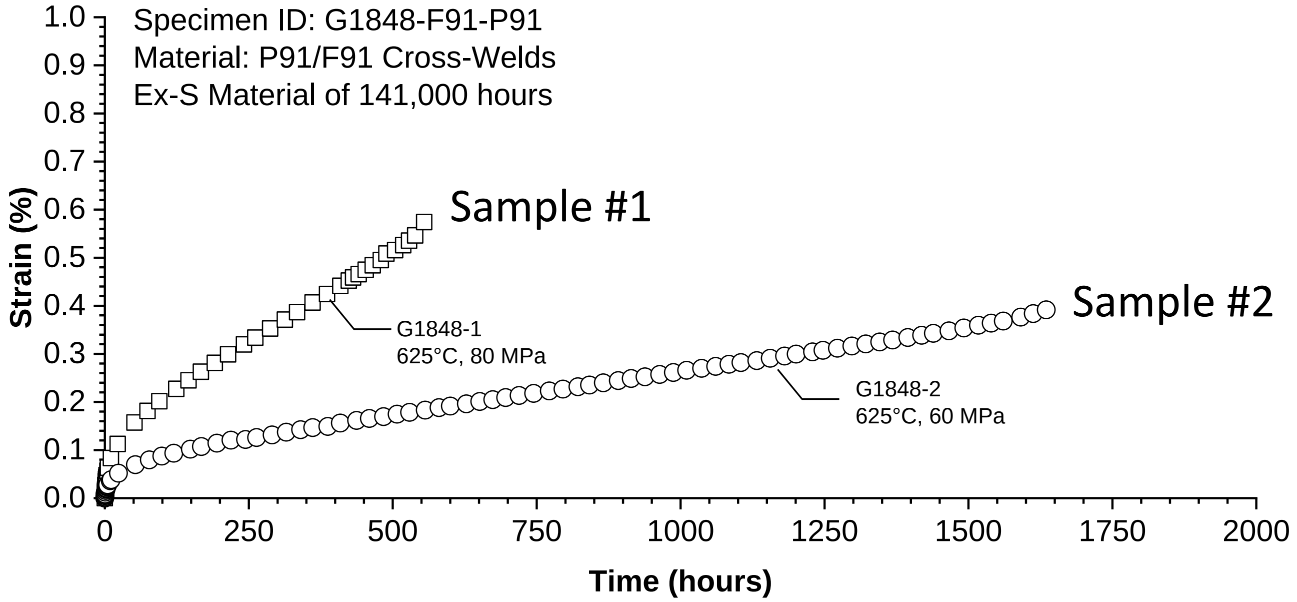
Example 1: Feature-Type Creep Tests for P91/F91 DMW

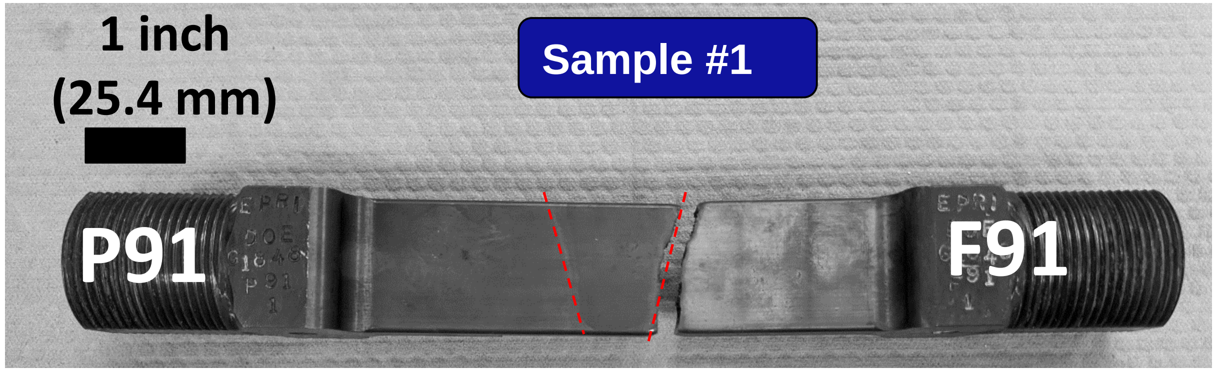
Sample #1: 625°C (1,157°F) and 80 MPa (11.5 ksi)

- Test ruptured after 556 hours

Sample #2: 625°C (1,157°F) and 60 MPa (8.7 ksi)

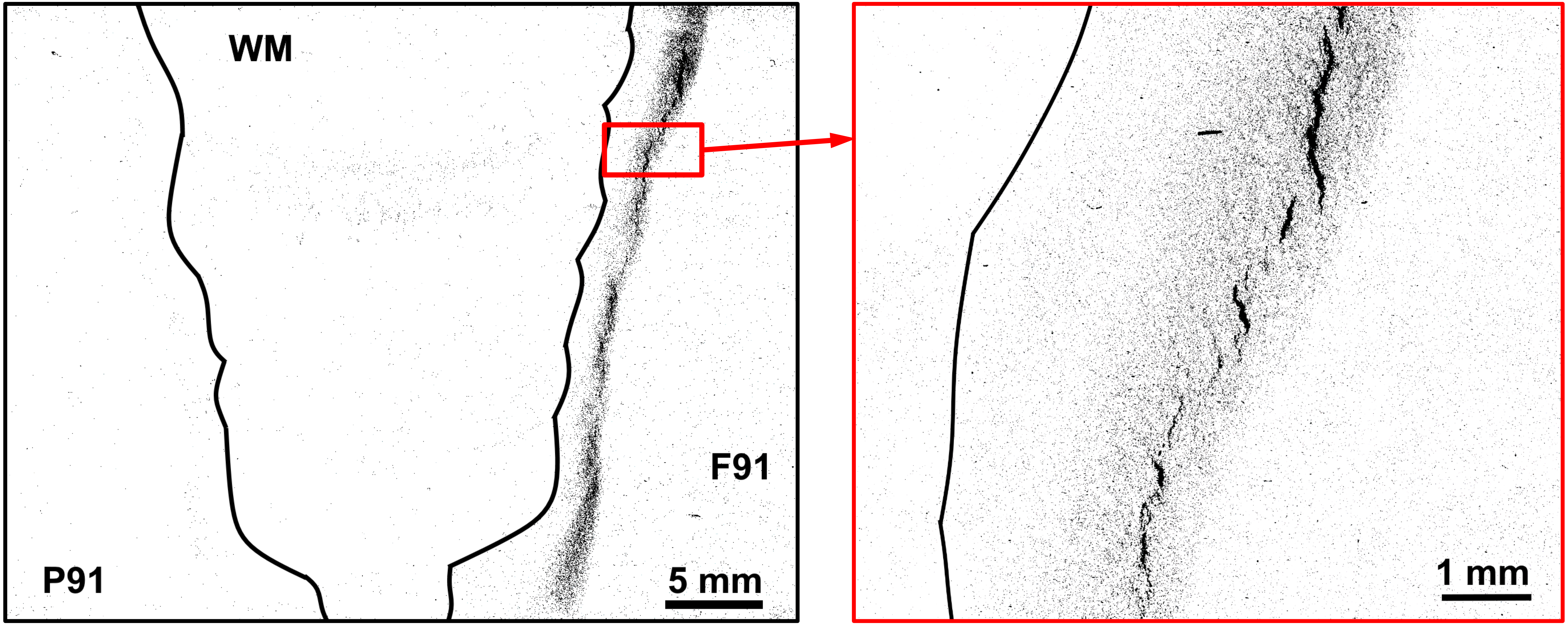
- Test interrupted after 1,637 hours
- Life fraction >98%
- See macro metallography (next slide)





Sample #2 test was interrupted immediately before failure (at >98% life fraction)

Example 1: Damage in P91/F91 DMW

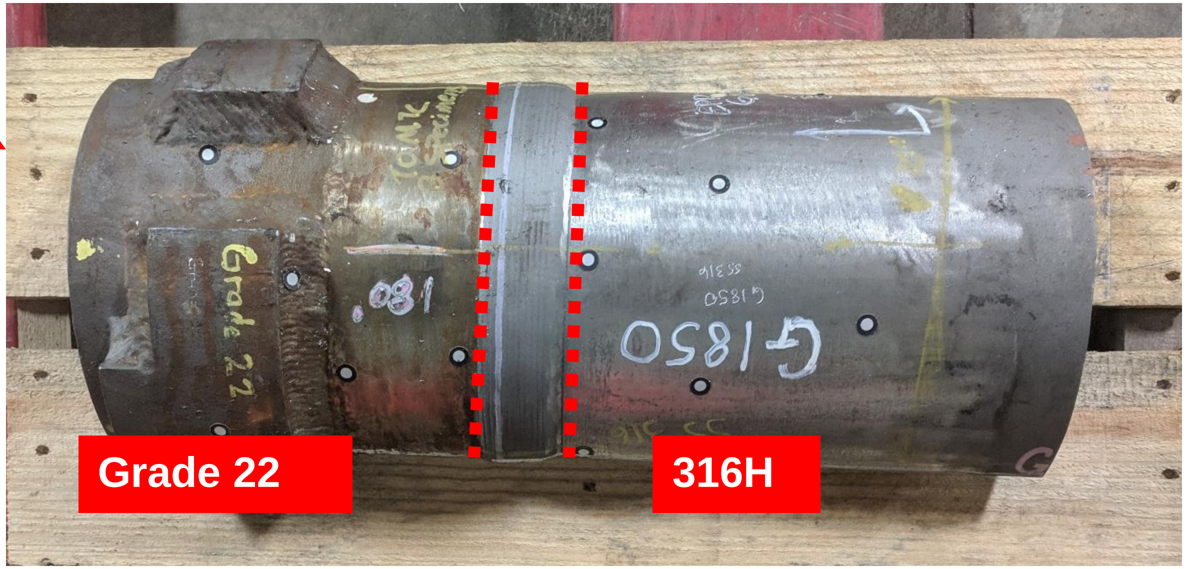


Damage in F91 HAZ is extensive with macro-cracking (>1 mm) near end-of-life

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

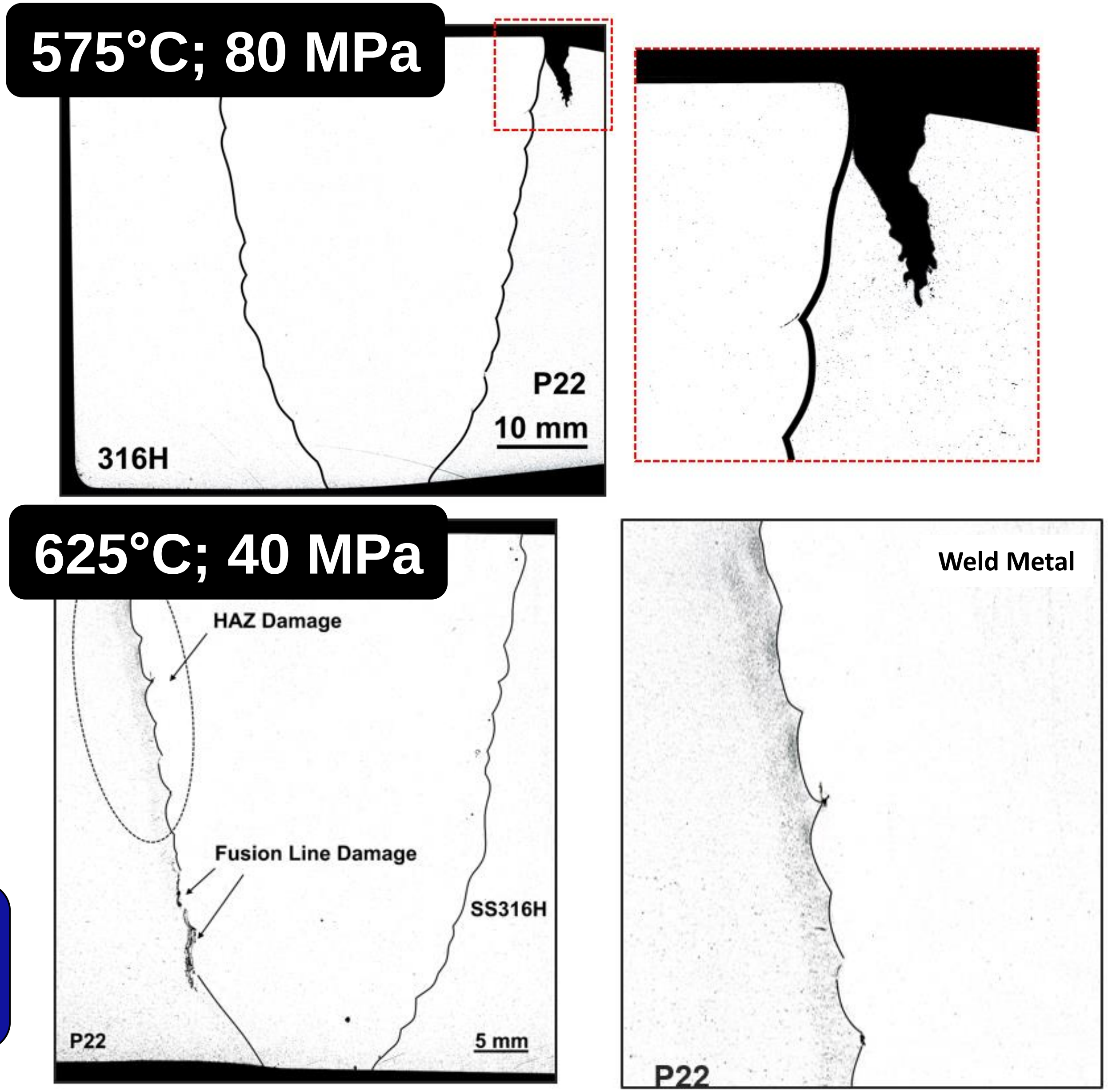
DMW creep testing conditions

- 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

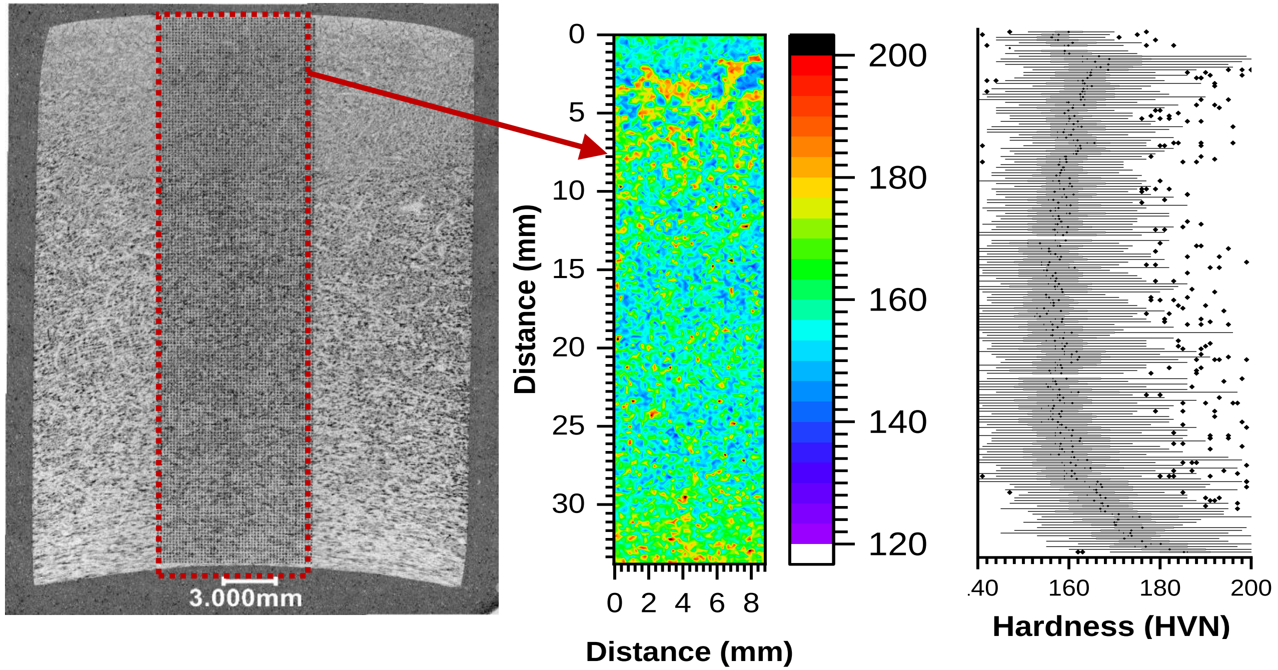
Results reveal different failure modes of common Gr-22/SS DMW in power plants

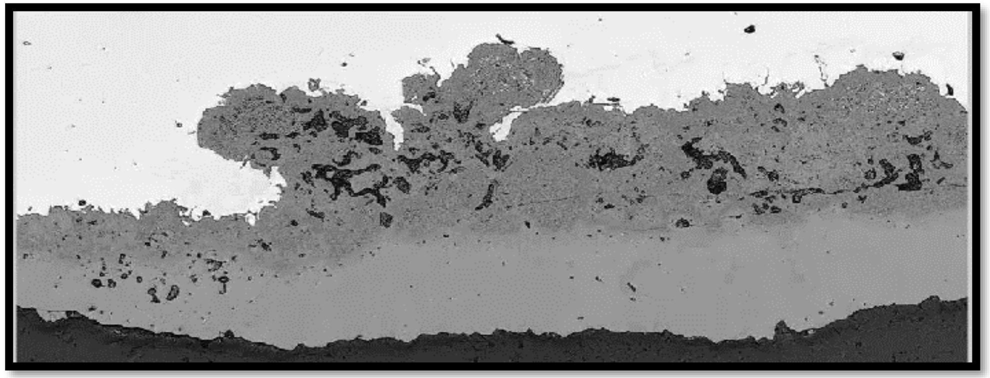


Characterization Methods

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





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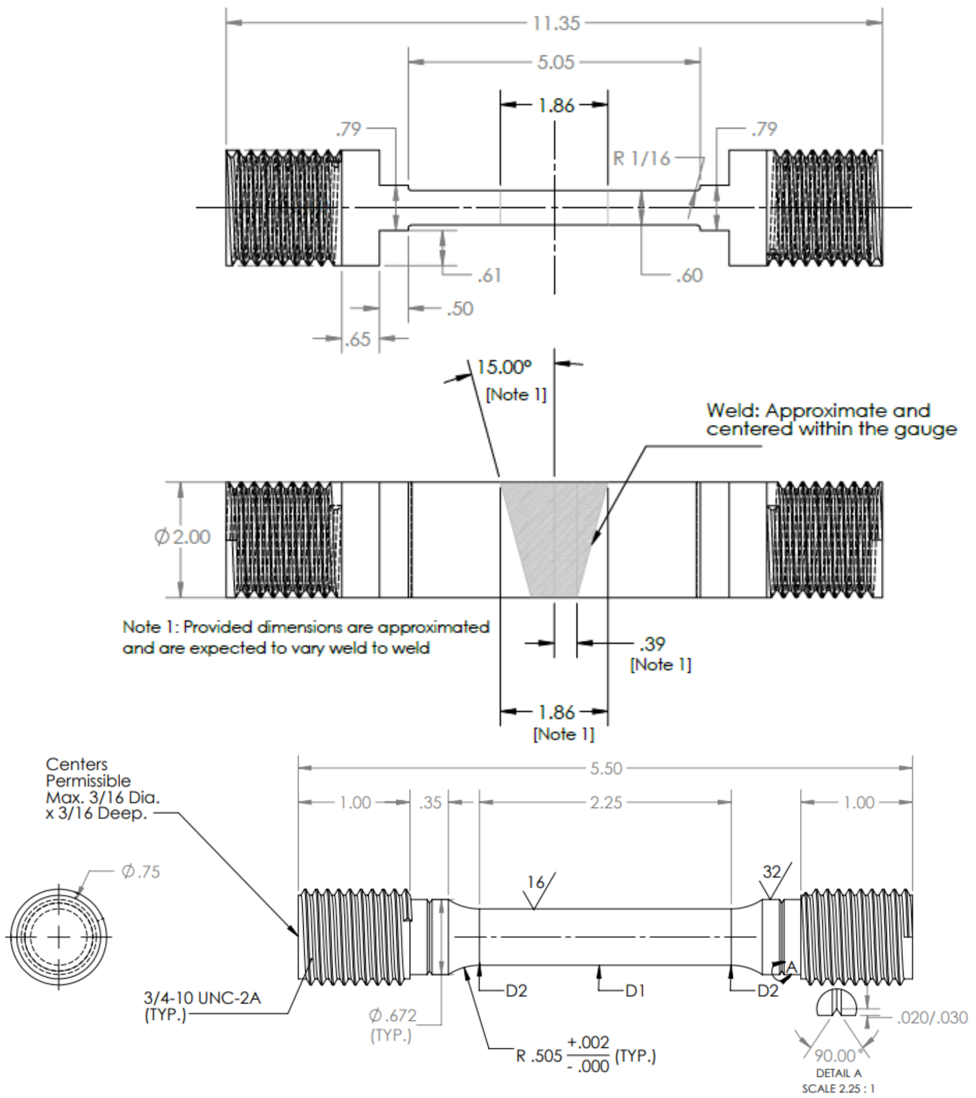
Status of Mechanical Testing Task

- 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

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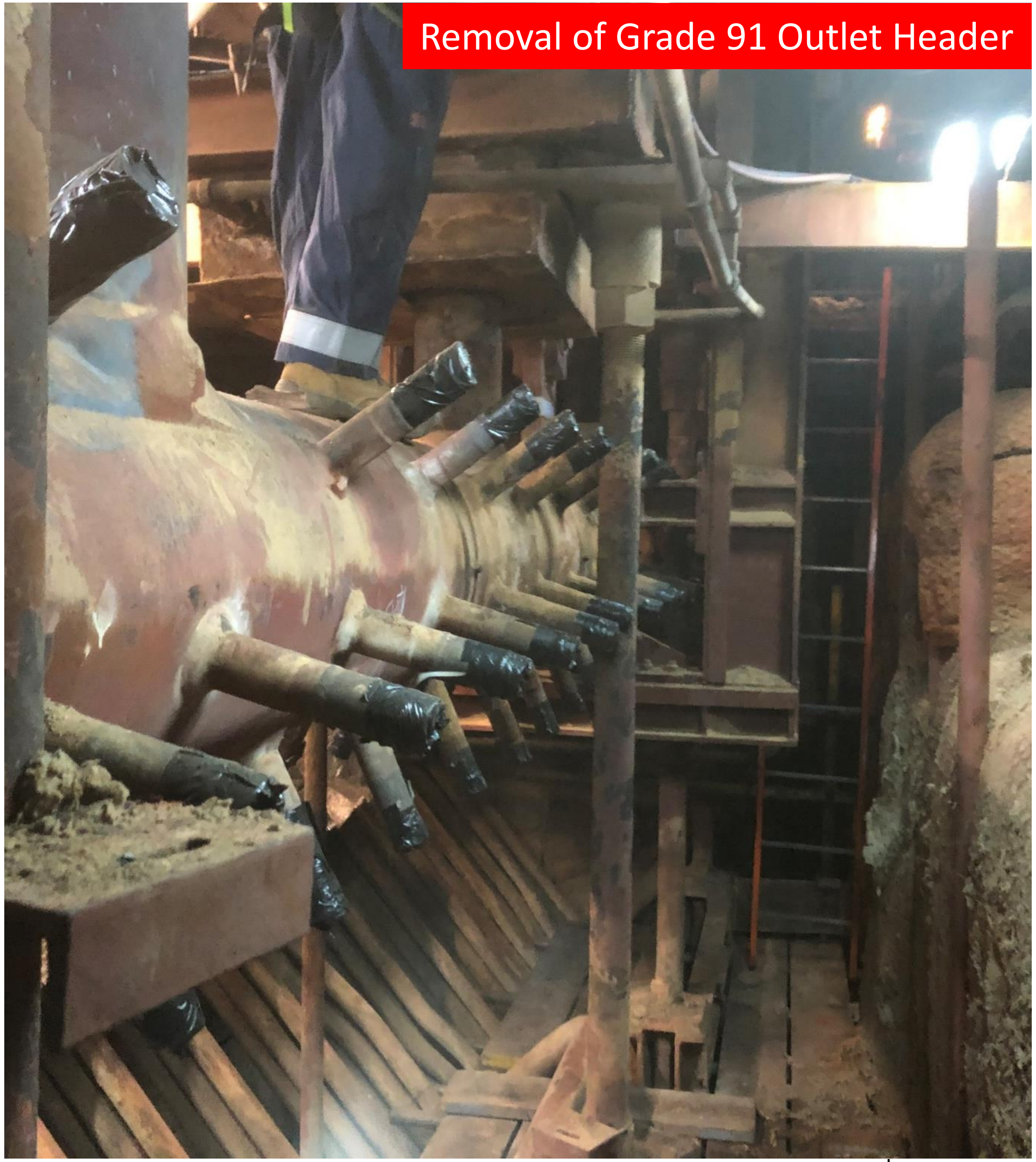

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