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

FE0031562

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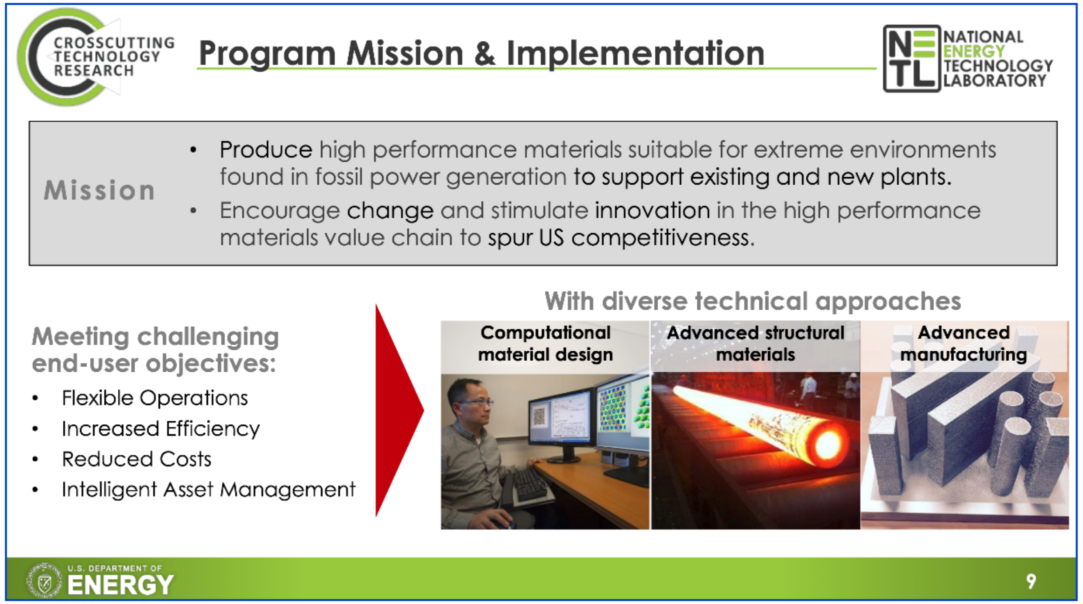
Project Objectives

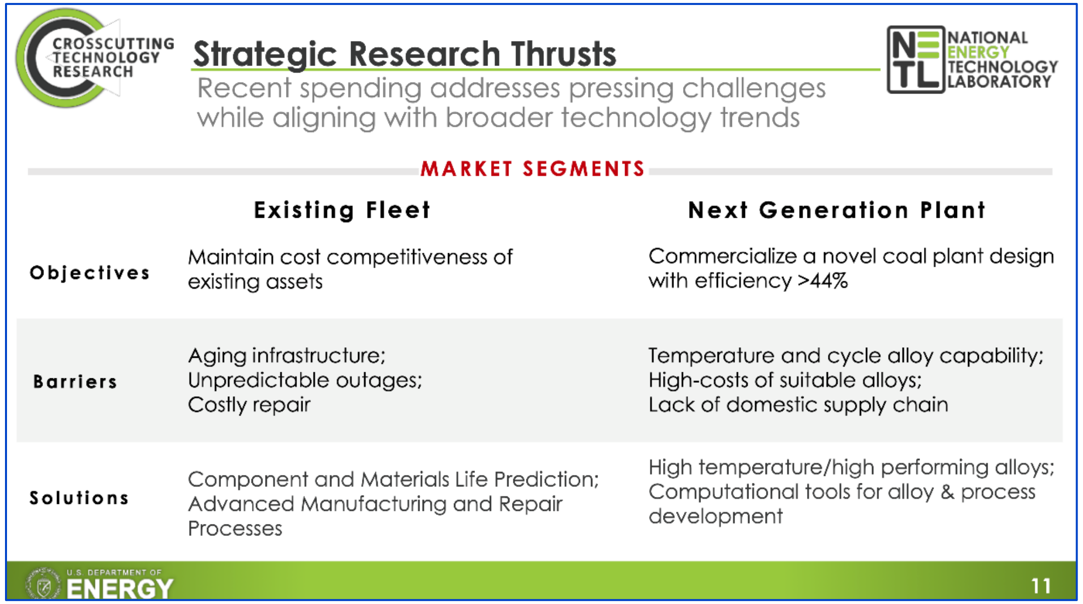
To develop a database of microstructures, mechanical properties, and damage mechanisms for long-term serviced EEM (>*100,000 hours*)

Key Approaches

- Source and acquire EEM components worldwide
- Perform detailed characterization and mechanical testing
  - NDE, macro and microstructures (SEM/EDS, EBSD, TEM), hardness, etc.
  - Time-dependent and time-independent mechanical testing
  - Collaboration with external labs to generate additional mechanical data
- Link compositions and microstructural features to long-term materials behavior
  - Secondary phases, inclusions, decomposition/evolution, damage
- ***Develop a comprehensive database on mechanical properties and microstructures***

Database will be accessible by DOE and other organizations for future materials research and modeling





EEM Project Support **DOE Technical Approaches**:

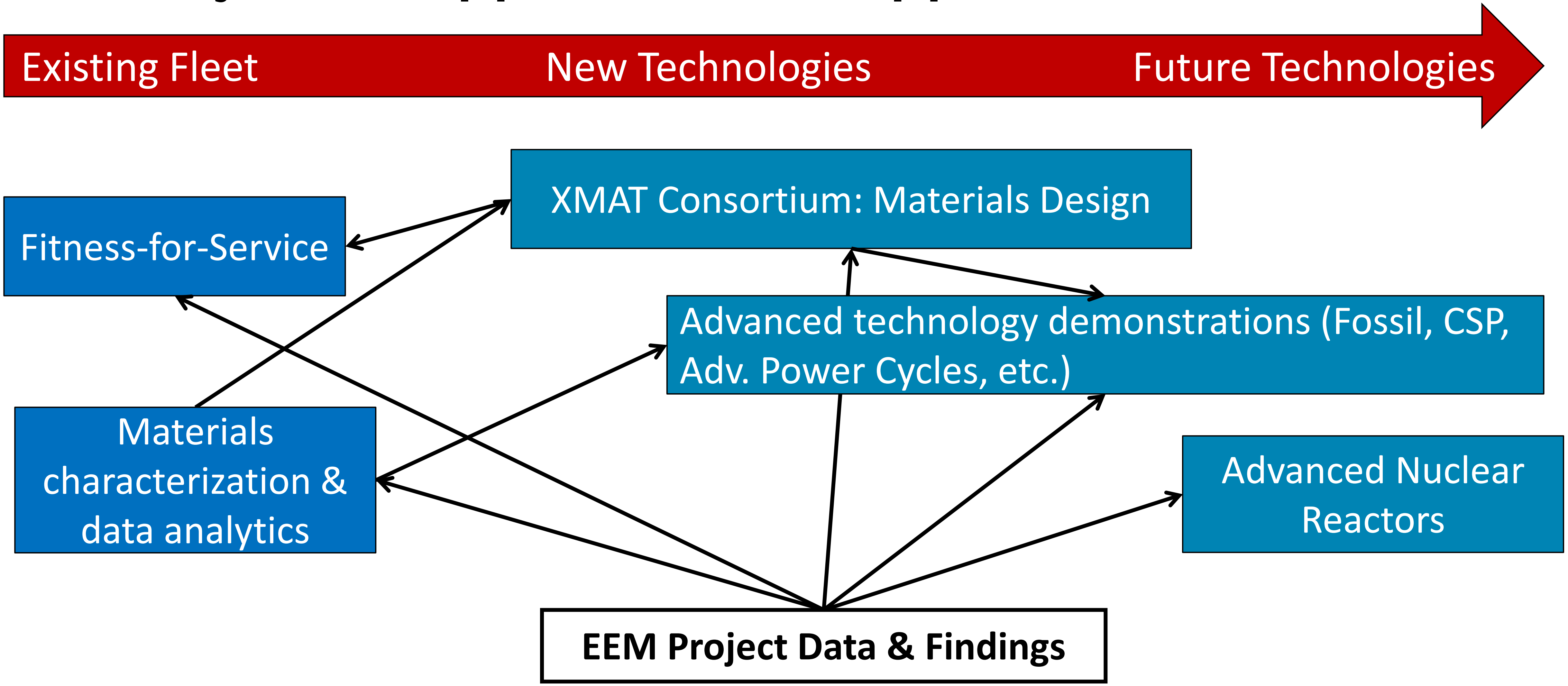
- Microstructural and mechanical data enable improved **computational materials design**
- Detailed knowledge linking material production to long-term high-temperature performance and enabling **advanced structural materials** and **advanced manufacturing**

EEM Project Supports **Existing** and **Next Generation** power Plants:

- Reduce materials uncertainty to minimize **unscheduled outages** and **costly repairs**
- Practical context and foundational data for **new material and manufacturing developments**

The EEM Project Provides Valuable Data and Tools to *Reduce Uncertainty* in the Operation of Current Fossil Fleet and *Enable Development* of Future Energy Systems

EEM Project in Support of Other Opportunities



Materials database provides foundational information to other technologies

Project Tasks and Scope

- Task 1: Project Management
- ***Task 2: Identification and Removal of EEM Components***
- ***Task 3: Metallurgical Characterization of Components***
  - 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
  - Charpy V-notch / notch bar impact testing
  - Fracture toughness testing

    } **Time-independent testing**
  - Base-metal creep testing
  - Cross-weld creep testing
  - Creep fatigue testing

    } **Time-dependent testing**
  - Estimation of remaining life
- Task 6: Database and Material Repository

Collaboration with ORNL and CRIEPI* for additional creep data
***The Central Research Institute of Electric Power Industry (Japan)**

Task 2: Component Procurement – A Major Undertaking

- Email solicitations for EEM components
  - >50 domestic and international utilities
- Requests for EEM components at multiple major EPRI events
  - Meetings attended by stakeholders (utilities, OEMs, component manufacturers, etc.)
- Surveys for pedigree/documentation
  - Alloys, hours, temperatures, pressures, cycles, repair history, and fuels
- Initial components reviewed, ranked, and down-selected
  - Decisions made based on operating history, removal schedule, resources, and cost
  - **Seven power plants prioritized (including two major European utilities)**
- Extensive meetings and planning conducted
  - At least one site visit to each power plant
  - More than 5 trips to Eddystone (two sister units)
  - Planning for demolition, subcontracting, and delivery

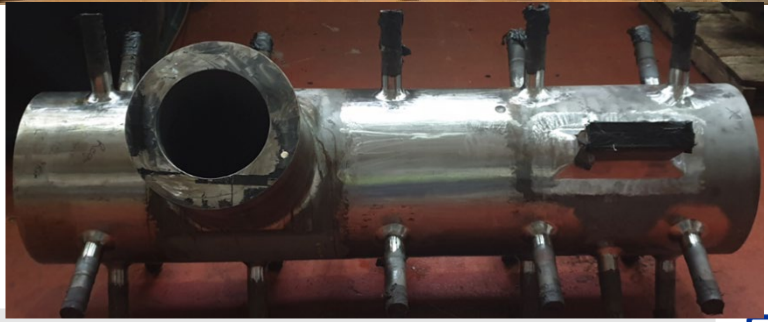
EPRI has demonstrated unique global position to secure EEM components

List of Major Power Plant EEM Components

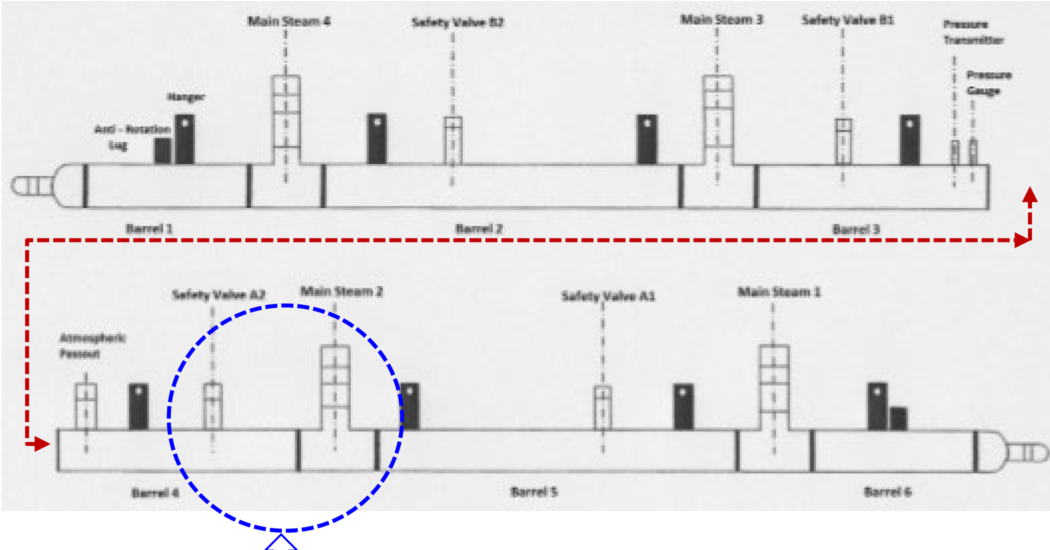
Type	Material	Source	Component	Vintage/ Hours	Quantity Received
Ferritic	½Cr-½Mo-¼V	Utility #3	CrMoV Turbine lead piping (straights, ends and girth weld)	~270,000 hrs	One lead
	Grade 22	Utility #3	Grade 22 seam-welded HRH piping	435,000	
	Grade 22	Eddystone #1	Main steam piping - large radius Grade 22 bends to SP valve	1960	2 bends (15' long)
	Grade 91	Utility #2	Grade 91 secondary superheater outlet header	141,000 hrs	2 headers 1st Set Hdr
	Grade 91	Utility #4	Seam-welded Grade 91 hot reheat outlet header	>100,000 hrs	1 section, 30" long
	Grade 91	**Utility #2**	**Grade 91 secondary superheater outlet header**	**~125,000 hrs**	**4 sections of header** NEW
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

A 2nd Grade 91 SSOH was acquired from a UK utility after ~125,000 hours of service

Staging of Component Samples (partial)



Removal of 2nd Grade 91 SSOH from U.K. Power Plant Unit 9



Approx. view area

Retrieval of large power plant components is a major undertaking

Task 3 - Component Characterization

*"Characterization describes those features of the **composition** and **structure** (including defects) of a material that are significant for a particular preparation, study of properties, or use, and suffice for reproduction of the material"* – ***National Materials Advisory Board*** *(1967)*

Compositional Features

- Bulk Composition
- Macro Segregation
- Inclusion Characterization
    - Type, quantity, and distribution

Microstructural Features

- Grain Size
- Morphology
- Phase/Precipitate
    - Phase ID, amount, and distribution
- Hardness Map

Task 3 –Approaches in Characterization

- Perform detailed metallurgical analysis on long-term serviced EEM components
- Generate relevant data using state-of-the-art analytical tools to reduce uncertainty and inform future research

Goals:

- ❑ ***Develop robust and informed characterization procedures***
- ❑ ***Generate statistically relevant and large datasets***
- ❑ ***Leverage high-power computing and advanced analytical tools to achieve automated analysis***

Characterization challenges:

- **Most characterization deals with small samples by assuming homogeneity**
- **Engineering materials are inhomogeneous**
- **Local characterization can lead to incorrect or misleading information**
- **Large area analysis with statistical significance is important**

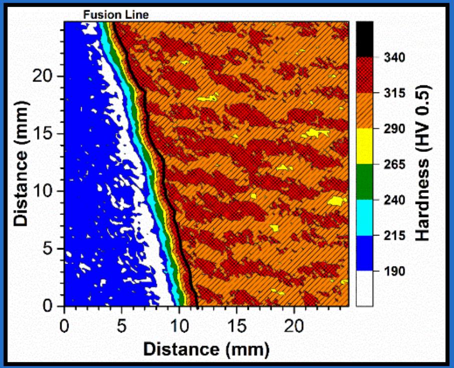
Materials Include:

- ❑ Grade 91 Steel
- ❑ Grade 22 Steel
- ❑ 316H Stainless Steel
- ❑ 347H Stainless Steel
- ❑ 321H Stainless Steel

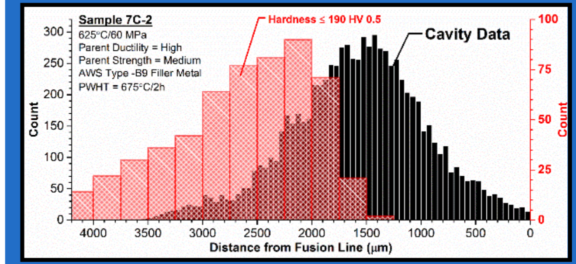
Task 3: Characterization Techniques by Scale

Macro Scale

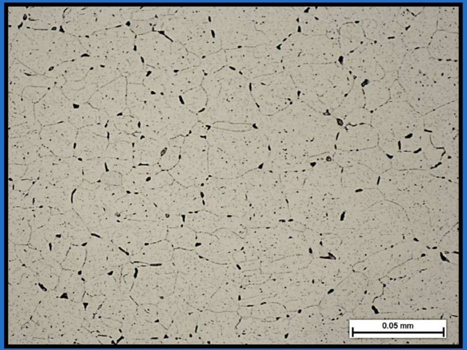
Micro Hardness



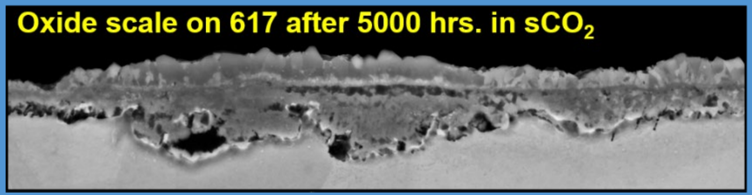
Damage Distribution



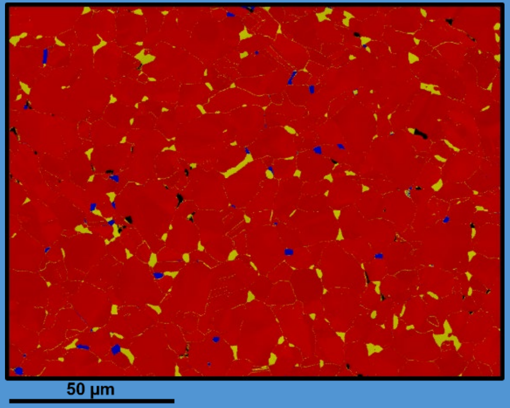
Optical Microscopy



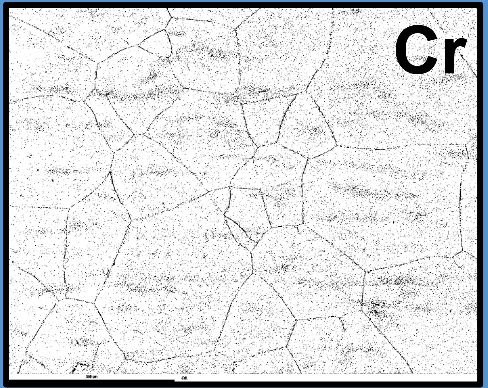
Micro Scale



SEM

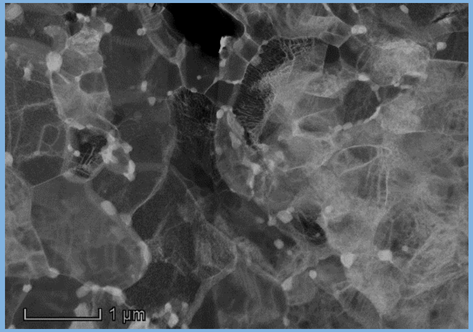


EBSD



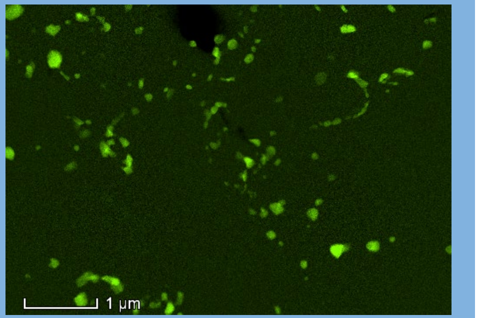
EDS

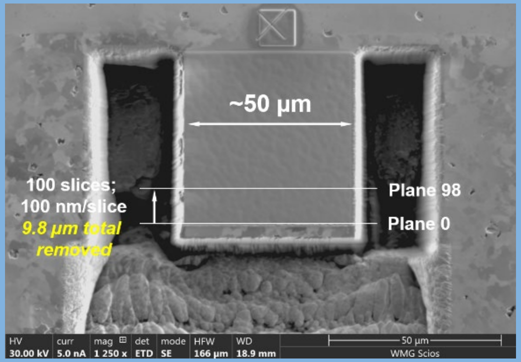
Nano Scale



TEM

TEM- EDS

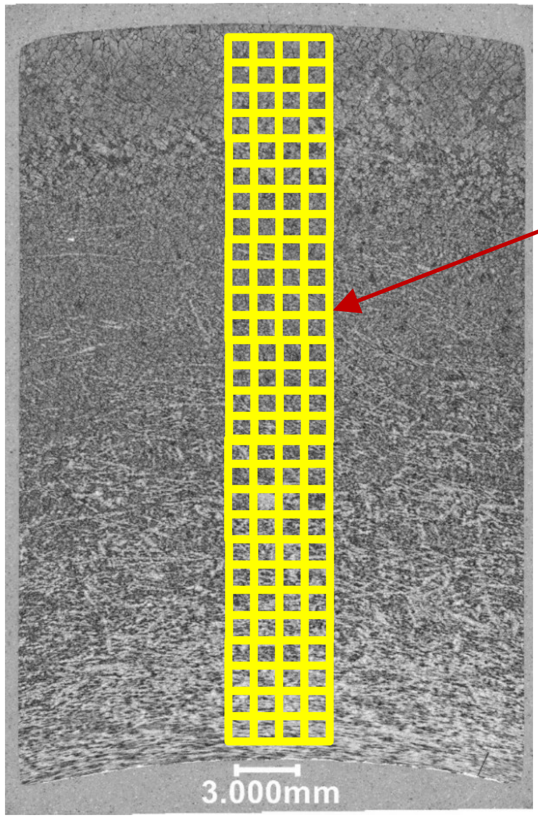


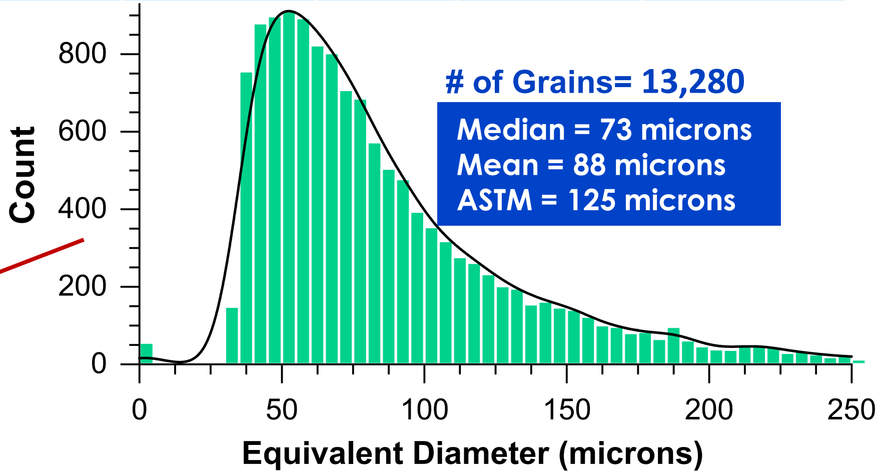


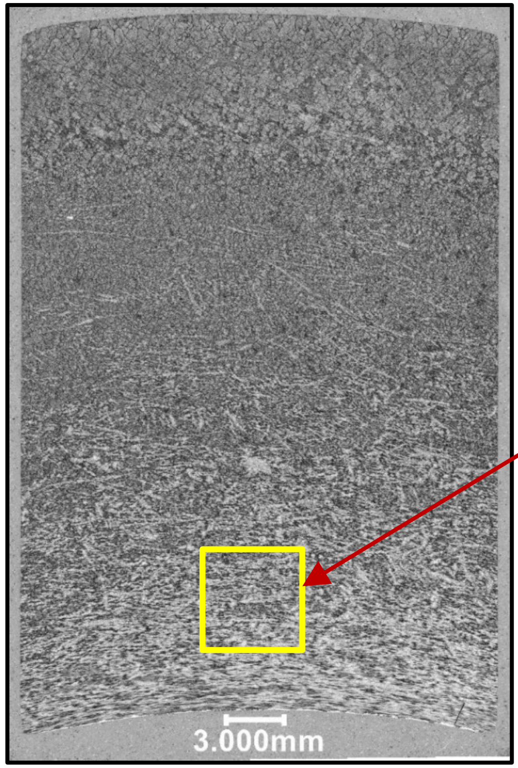
FIB

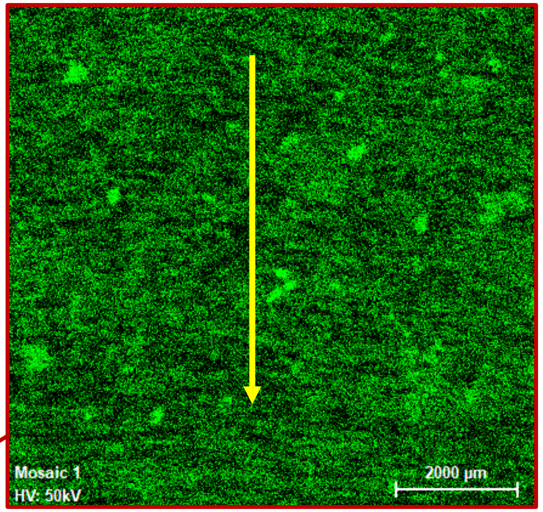
Task 3 Example: 316H Main Steam Piping from Eddystone Unit 2

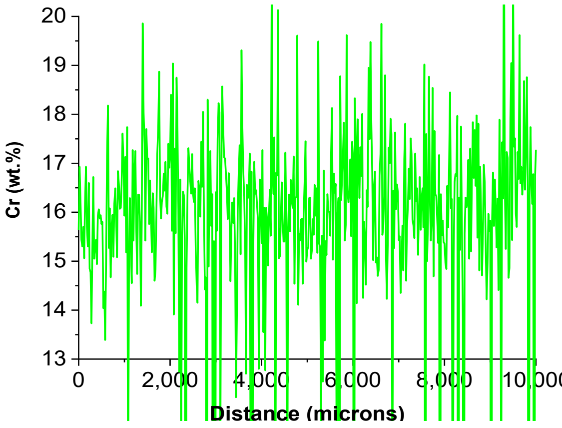
C	Si	Mn	P	S	Ni	Cr	Fe
0.061	0.245	1.57	0.014	0.0086	13.58	16.518	65.71
Co	**Nb**	**Mo**	**N**	**B**	**Ti**	**V**	**W**
0.027	<0.002	2.03	0.0738	<0.0005	0.002	0.018	<0.002
As	**Sb**	**Sn**	**O**	**Cu**	**Al**	**Ca**	**Zr**
0.005	0.0006	0.004	0.0156	0.092	0.005	0.0062	<0.002

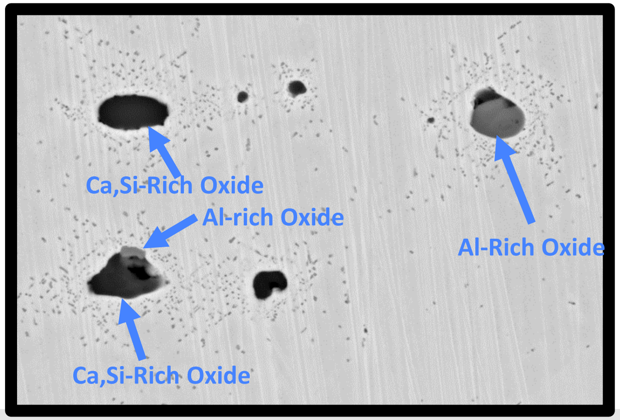






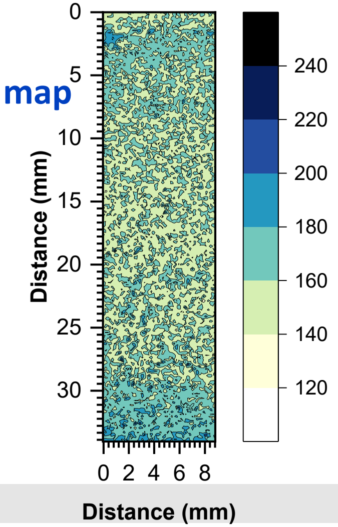


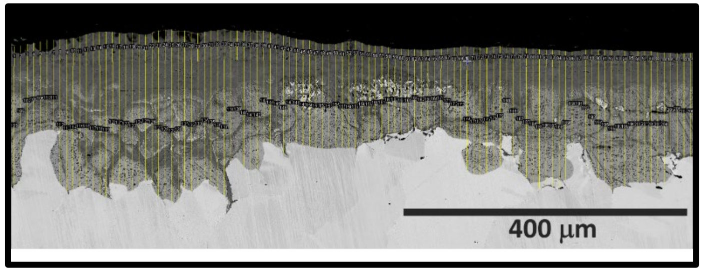




# of inclusions = 4,471 (5 mm x 2.5 mm area)

Hardness map

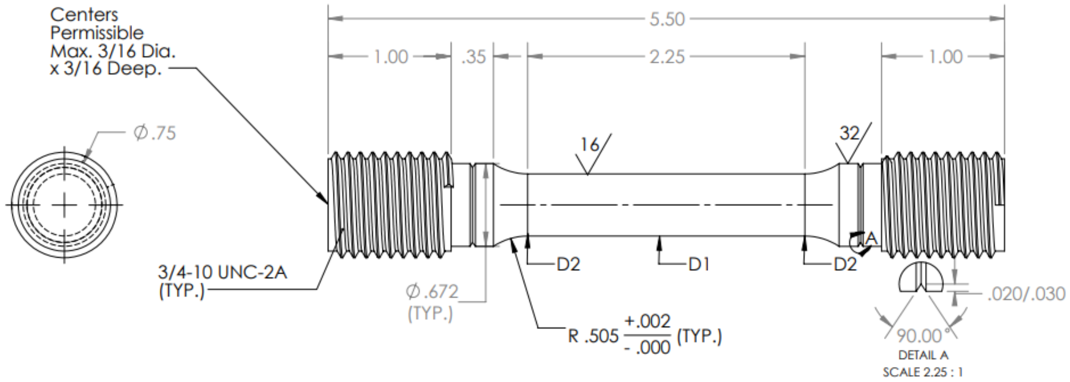


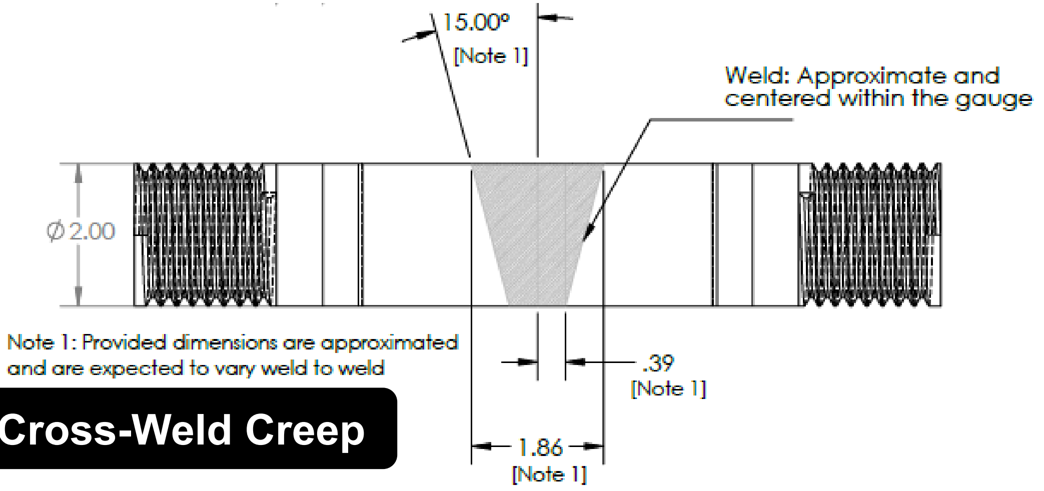


Task 5 – Types of Mechanical Testing

- ***Time-dependent*** testing of Grade 91 and 316H
  - **>31,600** hours on *feature cross-welds*
  - **>58,750** hours on base metals
- ***Time-independent*** testing of Grade 91 and 316H
  - Room and high temperature tensile
  - Charpy impact
  - Fracture toughness

Base Metal Creep





Feature Cross-Weld Creep

To date, >90,000 hours of time-dependent and time-independent data are produced to inform future material research and modeling

Task 5 Example: Grade 91 MS Outlet Header

- 6th stage outlet superheater header
  - P91 outlet header supplied main steam to HP turbine
- Removed from service after 141,000h of service
  - Design (or operation) = 575°C (1,067°F) and 178 bar (2,590 psi)
  - 3,300 starts
  - Retired due to increased stub weld repairs
- Mechanical testing
  - Plain bar creep tests in base metal (F91 & P91)
  - Feature cross-weld creep tests in girth DMW
  - Time-independent tests (tensile, Charpy, hardness)

Chemical Analysis of F91 and P91 Heats

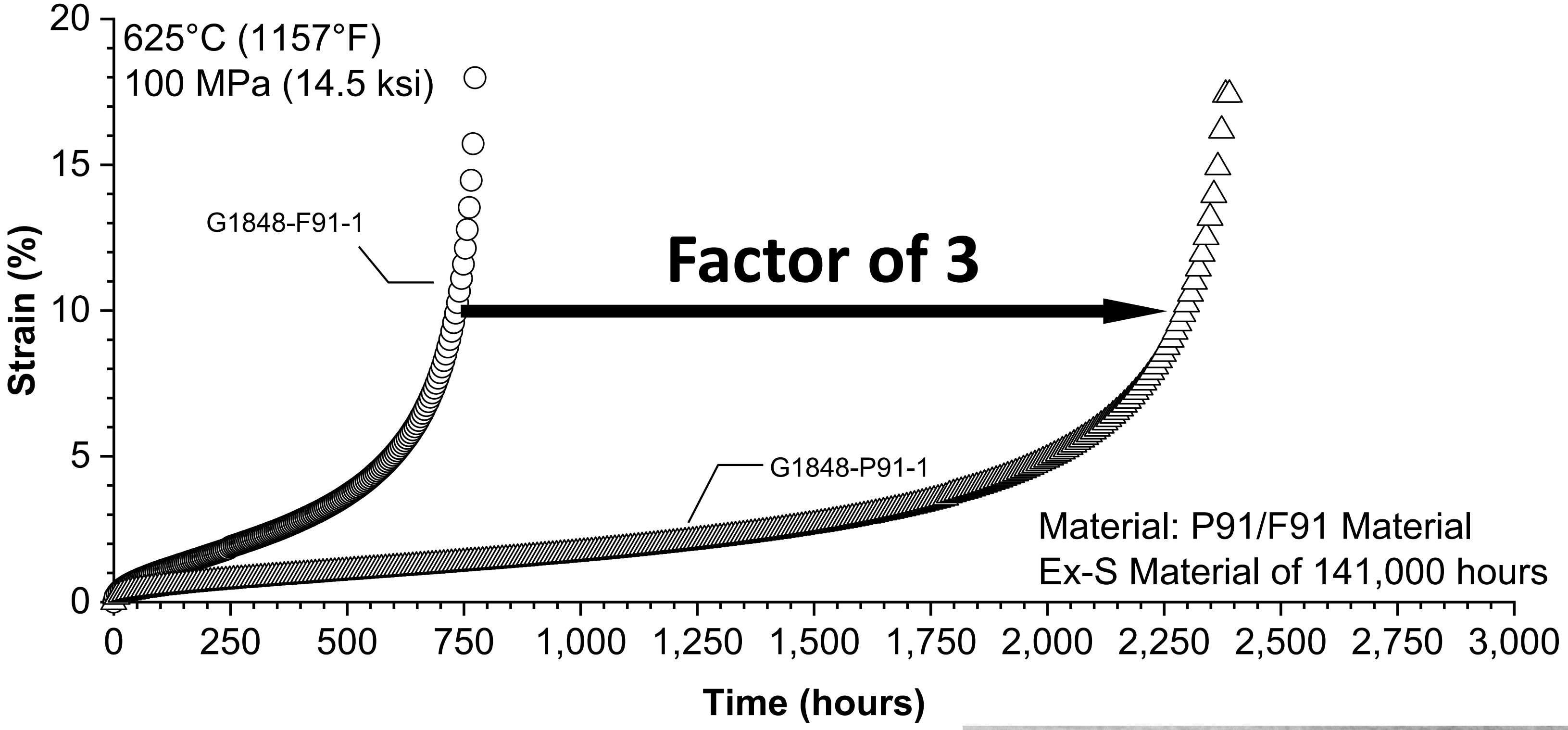
Heat	C	S	O	N	Al	B	Ca
F91	0.103	0.0105	0.0020	0.0378	0.033	<0.0005	<0.0005
P91	0.099	0.0003	0.0011	0.0398	0.007	<0.0005	<0.0005
Heat	**Co**	**Cr**	**Cu**	**Fe**	**La**	**Mn**	**Mo**
F91	0.012	8.148	0.124	89.53	<0.002	0.40	0.89
P91	0.007	9.125	0.032	88.53	<0.002	0.43	0.98
Heat	**Nb**	**Ni**	**P**	**Si**	**Ta**	**Ti**	**V**
F91	0.108	0.11	0.009	0.242	<0.002	0.002	0.200
P91	0.077	0.17	0.021	0.262	<0.002	0.003	0.200
Heat	**W**	**Zr**	**As**	**Bi**	**Pb**	**Sb**	**Sn**
F91	<0.002	<0.002	0.010	<0.0001	0.005817	0.0013	0.008
P91	<0.002	<0.002	0.004	<0.0001	0.00003	0.0002	0.001

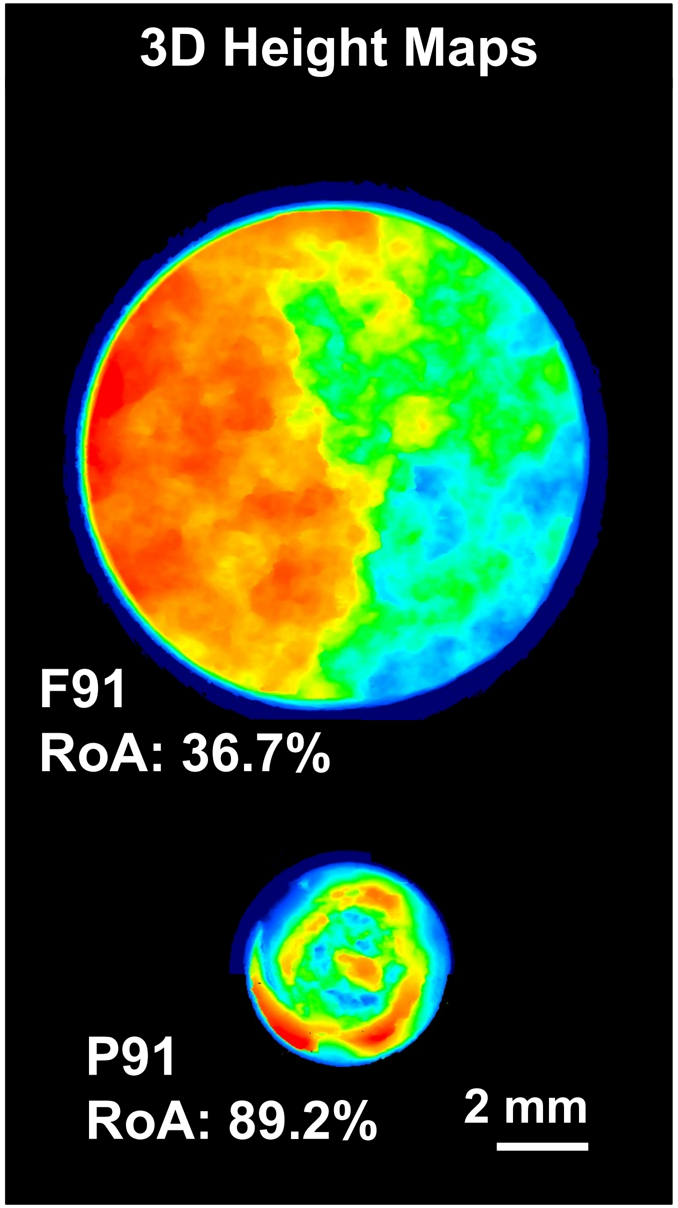
EPRI Recommendation	
Element	**wt %**
N:Al	**>4.0**
Al	<0.02
Cu	<0.10
S	<0.005
As	<0.010
Sb	<0.003
Sn	<0.010
Pb	<0.001

F91 Forging — **N:Al= 1.15**, **Sn+As+Sb+Pb= 0.0251**

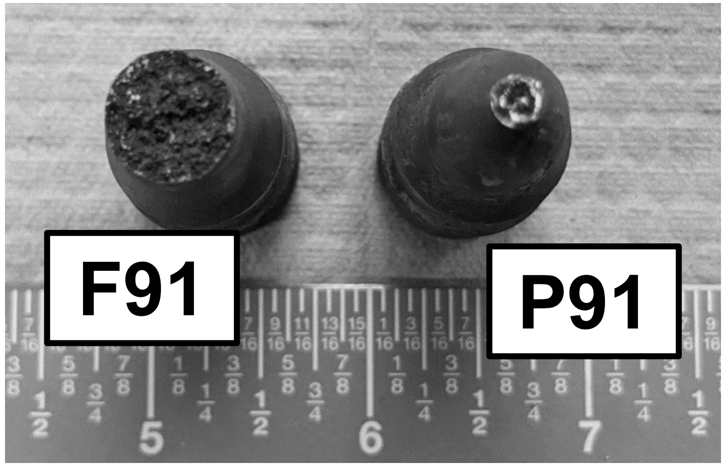
P91 Piping — **N:Al= 5.69**, **Sn+As+Sb+Pb= 0.0052**

Comparison of Base-Metal Creep for F91 and P91 Heats



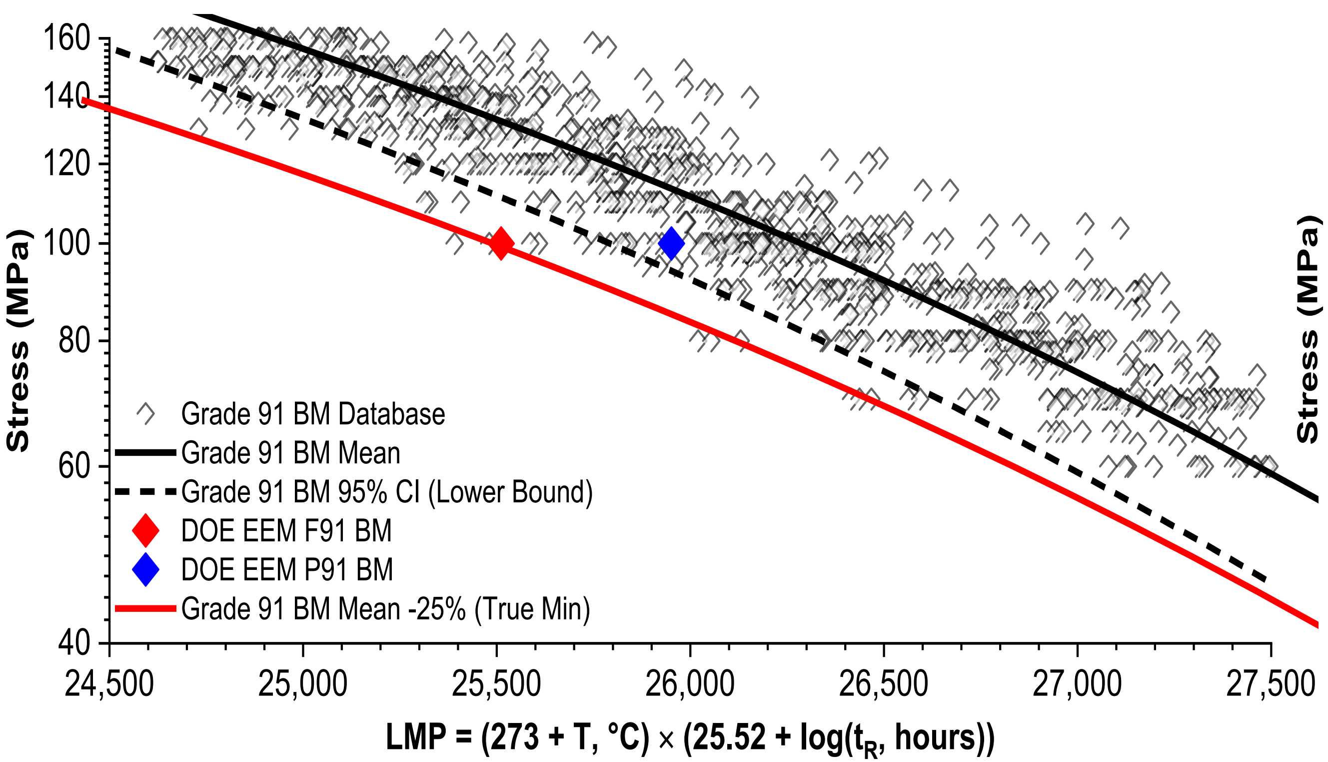


F91 heat exhibits a significant reduction in both *creep strength* and *creep ductility*

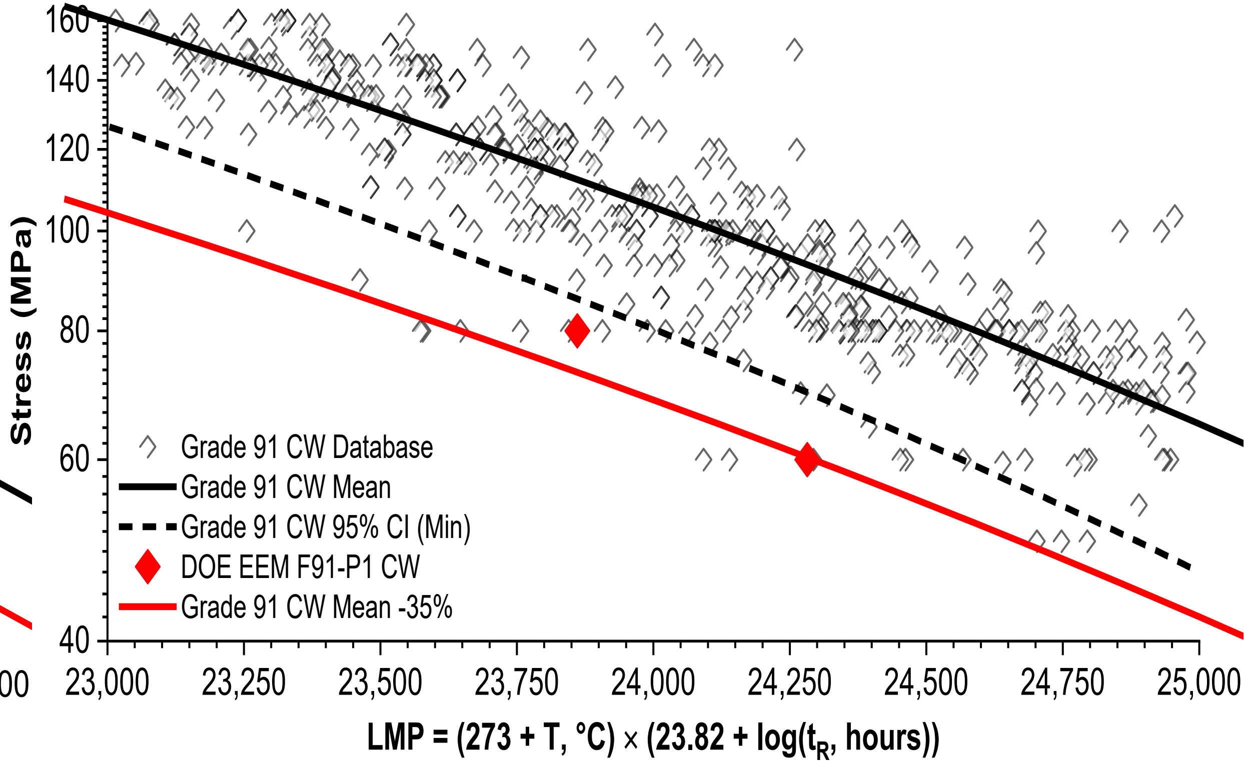


Comparison of F91 and P91 Heats in SSOH with EPRI Databases

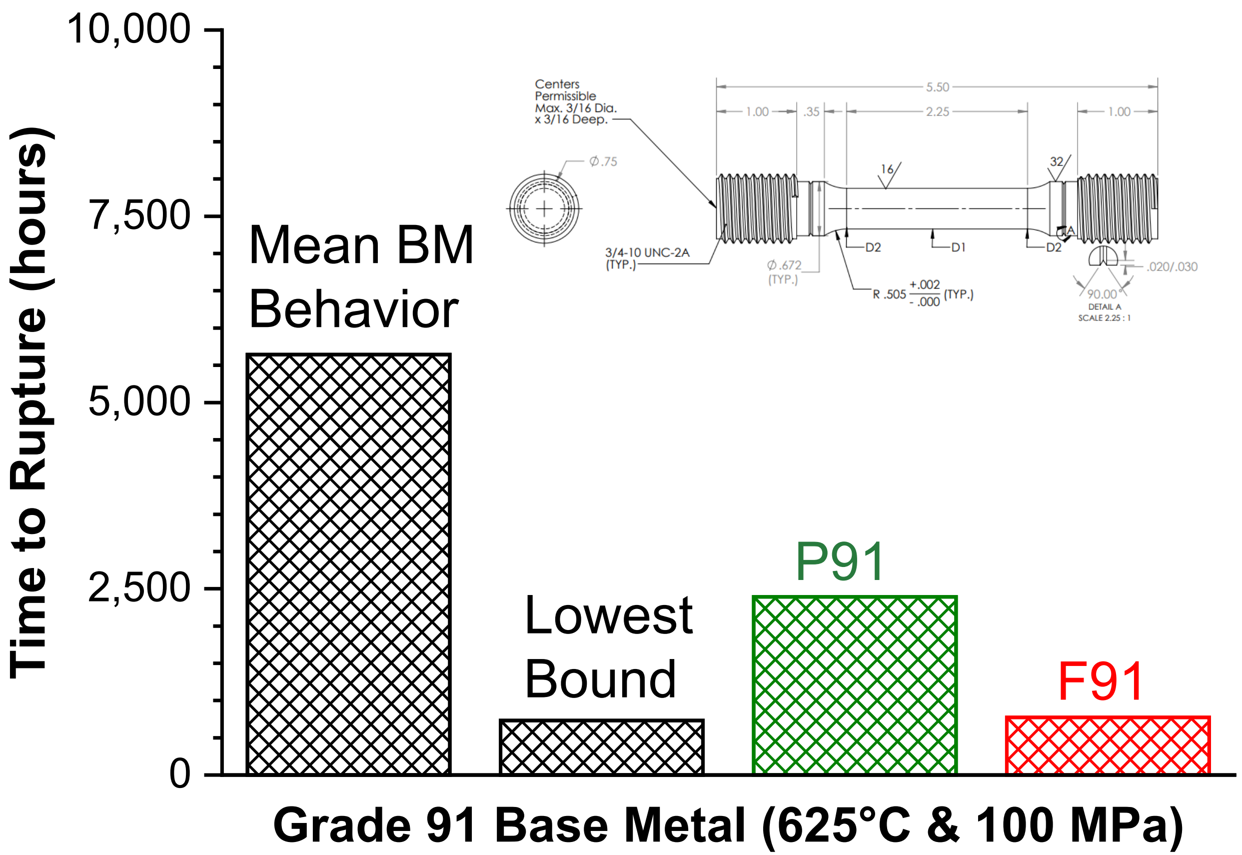
Base Metal Creep

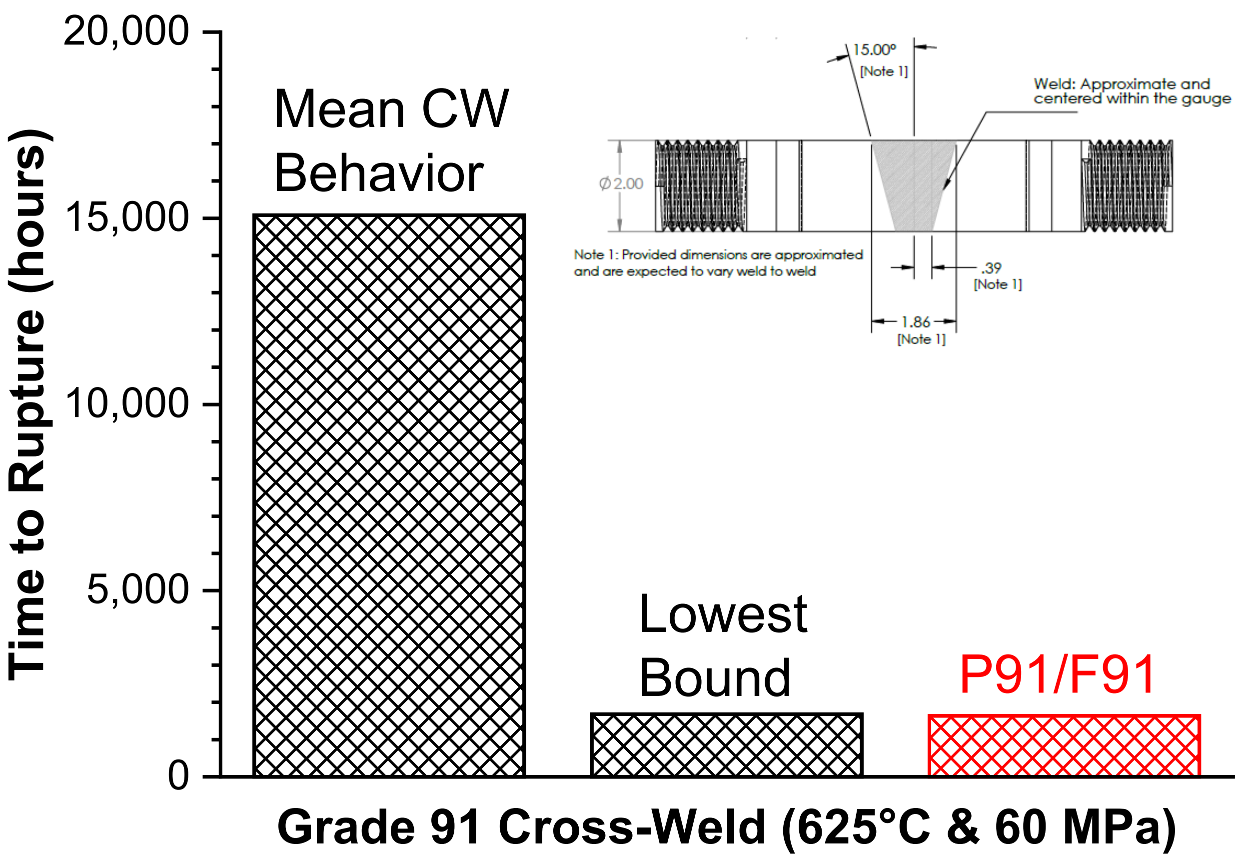


Cross Weld Creep



Comparison of Creep Test Results for Grade 91 SSOH





- F91 base metal shows lowest bound behavior
- Cross-weld shows lower bound behavior with failure on F91 side

Collaboration with External Laboratories

- Additional creep data being generated by **CRIEPI** and **ORNL**
- Collaboration opportunity exists
  - ***Project is open to expanded engagement with research community***

ORNL - Grade 91 Header (Cross-Weld and Base Metal)			
Temp. °C	**Stress MPa**	**Min hours**	**Mean hours**
600	120	1,000	2,500
600	100	2,000	5,500
600	80	5,500	15,000
625	100	325	100
625	90	500	1,500
625	80	1,000	3,000
625	70	1,800	5,000
625	60	3,500	12,000
650	80	150	500

ORNL - 316H Piping			
Temp. °C	**Stress MPa**	**Min hours**	**Mean hours**
650	150	400	1,500
650	120	1,500	5,500
650	100	4,400	15,000
675	120	450	1,600
675	100	1,250	4,500
700	100	400	1,335
700	90	700	2,400
700	80	1,335	4,250
700	70	2,500	8,500
700	60	6,000	18,000

CRIEPI (Japan) - Grade 91 Header (Base Metal Only)			
Temp. °C	**Stress MPa**	**Min hours**	**Mean hours**
600	140	1,200	3,700
600	120	3,350	10,000
600	100	9,600	28,000
625	100	2,000	6,000
625	80	6,350	18,500
625	60	24,100	70,000

Project Status

- **Task 2 – Component Procurement and Retrieval**
  - Complete
  - Archived at EPRI; available for future DOE projects
- **Task 3 - Characterization**
  - NDE: complete (including 2nd Grade 91 SSOH)
    - Information used to select specific locations for component evaluation
  - Metallurgical evaluation: ongoing
- **Task 5: Mechanical Testing**
  - Components received before 2021: mostly complete
  - 2nd Grade 91 SSOH received in 2021: in progress (section machining complete)

Project has developed state-of-the-art characterization procedures, mechanical data, and case studies useful for future model development and validation

Acknowledgement and Disclaimer

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NETL Project Manager: V. Cedro

Together…Shaping the Future of Electricity