Characterization of Long-Term Service Coal Combustion Power Plant Extreme Environment Materials (EEMs)

DOE FE0031562

EPRI Program 87 Materials and Repair

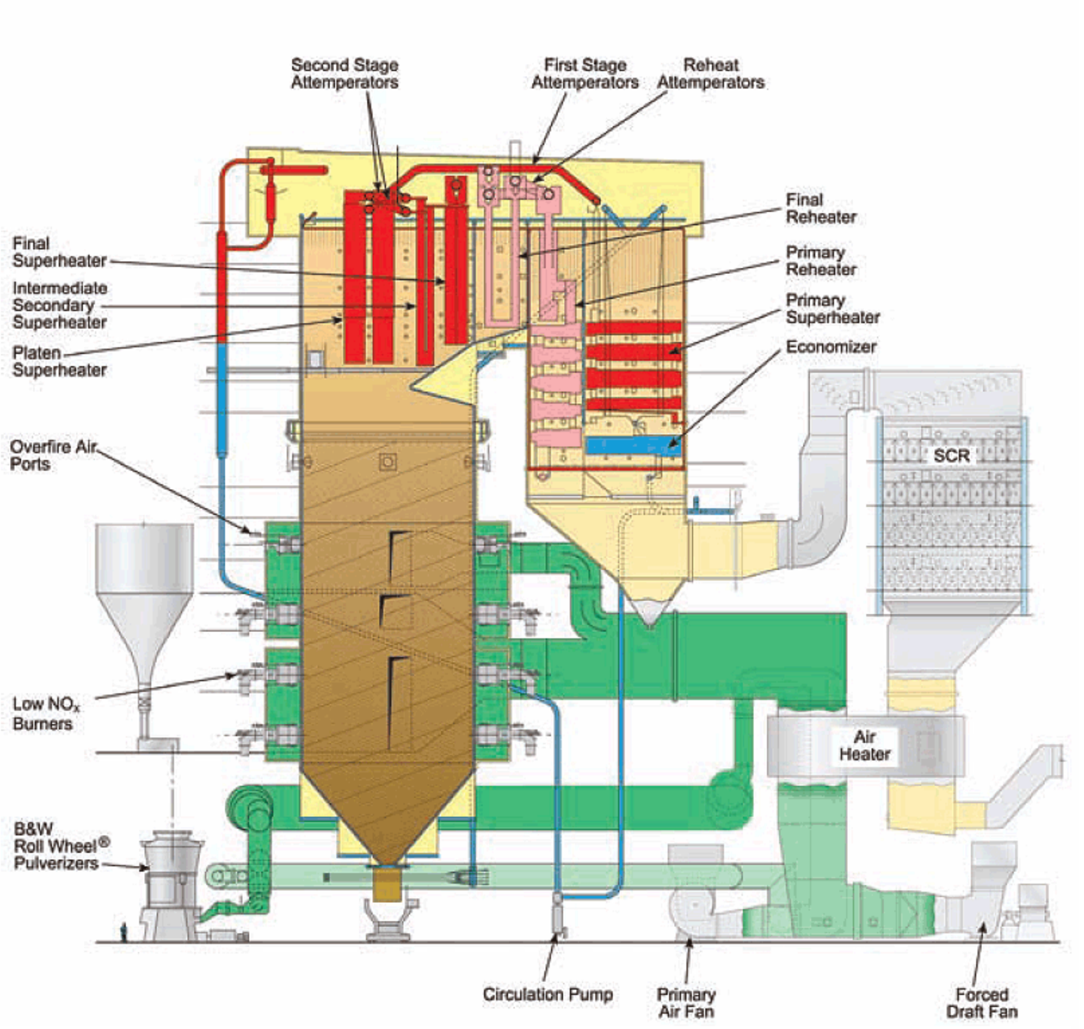
Steven Kung, John Siefert, John Shingledecker

2019 Crosscutting Research Review Meeting
Pittsburgh, PA
April 10, 2019

Technical Basis

Existing coal-fired fleet is >39 years

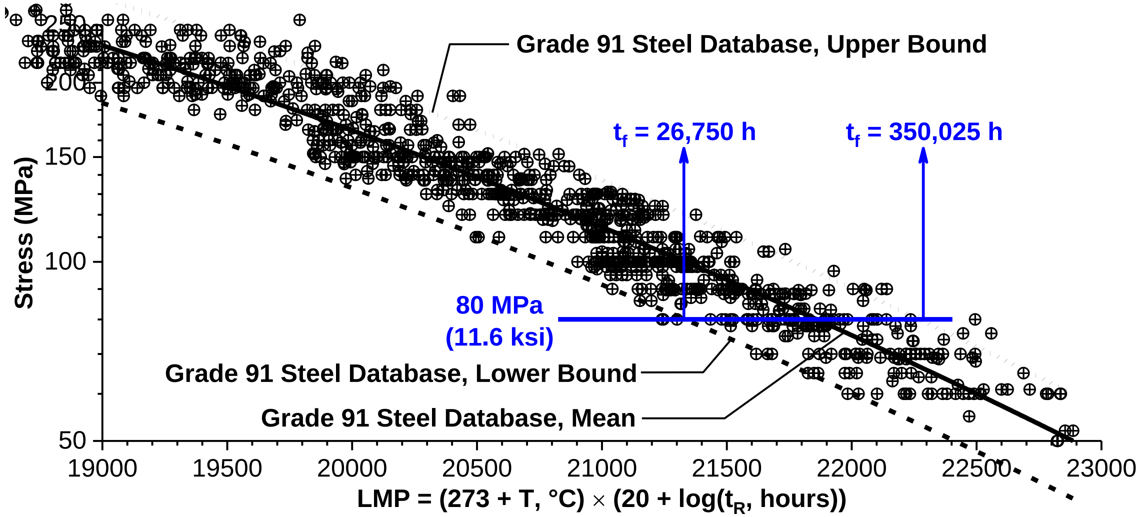
- Many already beyond the original anticipated design life
- Expectation is another 30 years
- Most units were designed for baseload operation
- Experience of some level of flexible operation
    - Intermittent deployment of renewables
    - Low natural gas prices

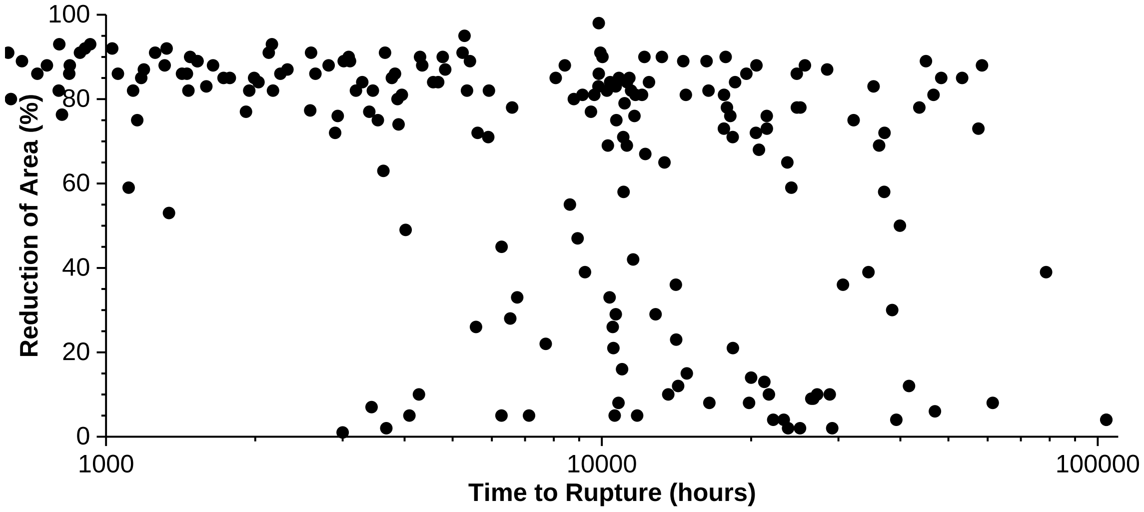


Challenges

Limited or no information is available from service-aged materials

- Most lifing models are based on testing of new materials
- There is a need for large scale evaluation/characterization of post-service materials/components
  - Establish links between microstructure and long-term performance
  - Provide a body of data for development/validation of lifing models





Project Objectives

- Obtain sufficient quantity of relevant EEM components and appropriate documentation
  - CSEF steels, 300-series H grade stainless, advanced austenitic SS, nickel-based alloys, and DMWs
  - Time, temperature/pressure, number of cycles, repair history, coal/fuel, etc.
- Perform detailed analysis
  - NDE and microstructural and mechanical characterization
- Link composition and microstructural features to long-term behavior
  - Secondary phases, inclusions, decomposition/evolution, damage
  - Service performance/destructive evaluation, TTP relation, CDM
- Compare measured degradation with service history based on available models (when applicable)
- Develop a comprehensive database of mechanical properties and quantitative microstructural information
  - **Make all data available to DOE and 3rd-party researchers for future modeling**

Project Tasks 1-3

- **Task 1: Project Management and Planning**
  - Reporting and managing activities in accordance with the PMP
  - Technical workshop to facilitate technical exchange of
- **Task 2: Identification and Removal of Material Components**
  - Literature survey
  - Component sampling plan / Characterization and mechanical testing plan
    - **Eddystone Unit 1 is highest priority**!
    - 25 – 30 component samples identified
  - Removal and Transport of Materials
- **Task 3: Metallurgical Characterization of Component Samples**
  - Perform macro-scale assessment
    - Photography, dimensional measurements, 3D scanning (when possible), NDE
  - Perform micro-scale analysis
    - Chemical, oxide thickness, hardness, grain size, phase analysis, advanced characterization

Project Tasks 4-6

- **Task 4: Fabrication of Test Samples for Mechanical Testing**
- **Task 5: Mechanical Testing and Estimate Remaining Life of Component Samples**
  - Uniaxial tensile testing
  - Fracture toughness testing
  - Charpy V-notch / notch bar impact testing
  - Fracture toughness testing
  - Base metal creep
  - Cross weld creep
  - Creep fatigue
  - Estimation of remaining life

  (Base metal creep, cross weld creep, creep fatigue:)
  - Limited based on size, shape, conditions, cost, etc.
  - ~20 creep tests are anticipated
- **Task 6: Data and Material Repository**
  - Sample inventory and uniform data labeling system
  - Consistent structure to link data from each test sample to individual component
  - Web-based portal for data collation/retention (or NETL EDX data sharing site)
  - On-site storage/repository for physical samples

Selected Components for Investigation

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

Component Samples

Factors considered for material evaluation

- The **metallurgical** properties associated with selected component materials after long-term service at high temperatures and pressures:
  - Tensile strength and ductility
  - Creep strength and ductility including stress-state effects
  - Thermal fatigue resistance
    - normally only an issue for thick sections or severe transient cycles
  - Fracture resistance
    - to assess critical crack size
  - Steamside oxidation and exfoliation resistance
  - Wear resistance (particularly for coatings/surface treatment or hardfacing)
  - Weldability –frequently linked to δ-ferrite content in the weld metal for austenitic stainless steels
  - Effects of fabrication and processing on properties

High Level Perspective of Testing Plan

Component Description	Heat of Material	3D Dimension	NDE for Damage	Microstructure for Damage	Detailed Microstructure	Mechanical Property Testing
Eddystone Unit 1	316 (1960)	✓	✓	✓		
	316 (1968)	✓	✓	✓		
	316OC (1983)	✓	✓	✓	✓	✓
Eddystone Unit 2	316 (1960)	✓	✓	✓	✓	
	DMW Gr. 22-316H	✓	✓	✓	✓	✓
Utility #2 Unit 2	Grade 91 HDR body	✓		✓	✓	✓
	Grade 91 forging	✓				
	P22-F91 Girth Weld	✓	✓	✓	✓	
	F91-P91 Girth Weld	✓	✓	✓	✓	
	P91 End Cap	✓	✓	✓	✓	

High Level Perspective of Testing Plan

Component Description	Heat of Material	3D Dimension	NDE for Damage	Microstructure for Damage	Detailed Microstructure	Mechanical Property Testing
Utility #3 Unit 3	347H SH Tubing			✓		
	347H to T22 DMWs (SH Tubing)			✓	✓	✓
Utility #3 Unit 4	Gr. 22 HRH Pipe	✓				
Utility #3 Unit 5	1/2Cr-1/2Mo-1/4V pipe w/ Girth welds	✓	✓	✓	✓	
Utility #4	347H Tubing			✓		
Utility #5 Unit 1	321H SH Tubing with WO			✓		
Utility #4 Unit 2	LSW HRH Hdr Sample		✓	✓		

Microstructural Assessment

316H Components – Based on 'Material Heats'

Details	1960 Vintage, Unit 1	1968 Vintage, Unit 1 (cast valve body)	1983 Vintage, Unit 1	1960 Vintage, Unit 2	1983 bend to valve body weld	Additional weld TBD	Cracked sections identified by NDE
Bulk composition	✓	✓	✓	✓	✓	✓	✓
Macro imaging	✓	✓	✓	✓	✓	✓	✓
Hardness	✓	✓	✓	✓	✓	✓	✓
Microstructure	✓	✓	✓	✓	✓	✓	✓
Oxide scale thickness	✓			✓			
Large area grain size evaluation	✓	✓	✓	✓			
Local inclusion analysis	✓			✓			
Inclusion type/distribution	✓	✓	✓	✓			
Oxide scale composition	✓			✓			
Bulk phase mapping	✓			✓			
Assessment of segregation	✓	✓	✓	✓			
Particle mapping	✓			✓			
Local particle composition	✓			✓			
Local phase confirmation	✓			✓			

Grade 91 and DMW Components – Based on 'Material Heats'

Details	Grade 91 Forging	Grade 91 Header Body	Girth Weld b/w Header Body and Forging	Tube to Header Weld w/ Damage	DMW b/w Gr. 22 and 316H
Bulk composition	✓	✓	✓	✓	✓
Macro imaging	✓	✓	✓	✓	✓
Hardness	✓	✓	✓	✓	✓
Microstructure	✓	✓	✓	✓	✓
Oxide scale thickness	✓	✓		✓	✓
Large area grain size evaluation	✓	✓			
Local inclusion analysis	✓	✓			
Inclusion type/distribution	✓	✓			
Oxide scale composition	✓	✓			
Bulk phase mapping	✓	✓			
Assessment of segregation	✓	✓			✓
Particle mapping	✓	✓			
Local particle composition	✓	✓			
Local phase confirmation	✓	✓			✓

Mechanical Testing

Mechanical testing

- **Time independent**
  - Fracture toughness
  - Less relevant tests… tensile, charpy v-notch (may be performed for comparison or informational purposes)
- **Time dependent**
  - Smooth bar creep
  - Notch bar creep
  - Feature-type cross-weld
  - Crack growth
  - Creep-fatigue
- **Nature of samples and information dictate test plan**
  - Testing will be based on relevance to in-service damage and/or operation

Testing Plan – High Level Summary

Item	Number of Tests
Bulk composition analysis	~20
Base metal creep testing	~10
Low temperature testing	TBD
Cross-weld creep testing	~10

- Emphasis on creep testing
  - Likely to find examples of service-induced fatigue damage for evaluation
    - May not need to develop this type of test data
    - For example, notable craze cracking seen in the 316H valve body
  - Additional (low T) tests such as tensile, charpy, fracture will be performed to help communicate the need/value for creep testing

Project Status

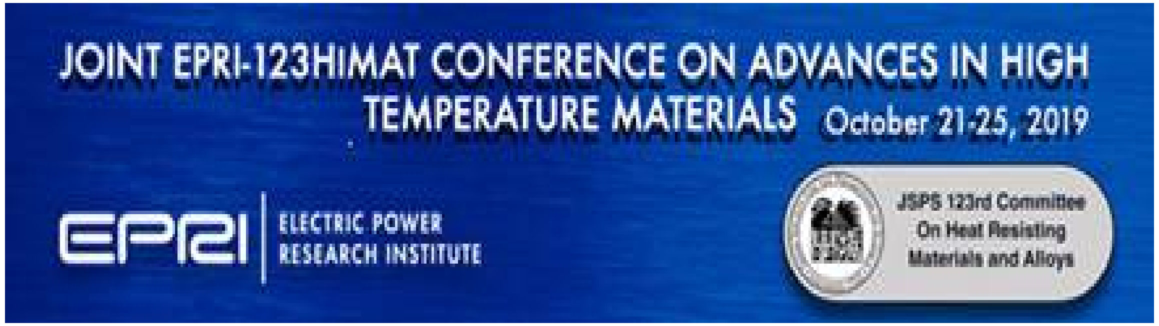
- **Task 2 – Component Retrieval**
  - Complete
- **Task 3 - Characterization**
  - Metallurgical evaluation initiated
    - 316H main steam piping from Eddystone Unit 2
  - NDE in progress
    - Information helps selection of specific locations on components for detailed analyses
    - Two Eddystone components completed (top two on right)
- **Task 4: Fabrication of Mechanical Samples**
  - Sections cut off from components for specimen machining

DOE Extreme Environment Materials – Preliminary Schedule Eddystone NDE

Eddystone Unit 1 - Turbine DMWs and J Loop Piping (G188)			
	Surface conditioning of G188 to be complete	17-Jan-19	Shop Team
	Deliver G188 to building 3	17-Jan-19	Daniel Duggins
	Data Acquisition G188 Complete	11-Feb-19	Nuc. NDE
	Return G188 to building 1	12-Feb-19	Daniel Duggins
Eddystone Unit 1 - Super Pressure Valve and Main Steam Piping (G185)			
	Surface conditioning of G185 to be complete	11-Mar-19	Shop Team
	Deliver G185-1 and G185-2 to Building 3	12-Feb-19	Daniel Duggins
	Data Acquisition G185 Complete	15-Mar-19	Nuc. NDE
	Return G185 to building 1	16-Mar-19	Daniel Duggins
Eddystone Unit 1 - Main Steam Junction header Outlet Lead (G1810)			
	Surface conditioning of G1810 complete	2-Apr-19	Shop Team
	Deliver G1810 to Building 3	16-Mar-19	Daniel Duggins
	Data Acquisition G1810 Complete	8-Apr-19	Nuc. NDE
	Return G1810 to Building 1	9-Apr-19	Daniel Duggins
Eddystone Unit 2 - Main Steam Collection Header (G186)			
	Surface Conditioning of G186 complete	3-Apr-19	Shop Team
	Deliver G186 to Building 3	9-Apr-19	Daniel Duggins
	Data Acquisition G186 Complete	10-Apr-19	Nuc. NDE
	Return G186 to Building 1	11-Apr-19	Daniel Duggins
Eddystone Unit 1 - Main Steam Oultet Material: Penthouse (G1813)			
	Surface Conditioning of G1813 complete	4-Apr-19	Shop Team
	Deliver G1813 to Building 3	11-Apr-19	Daniel Duggins
	Data Acquisition G1813 Complete	11-Apr-19	Nuc. NDE
	Return G1813 to Building 1	12-Apr-19	Daniel Duggins
Eddystone Unit 2 - Main Steam Piping: Grade 22 o 316H DMW (G1850)			
	Surface Conditiong of G1850 Complete	9-Apr-19	Shop Team
	Deliver G1850 to Building 3	12-Apr-19	Daniel Duggins
	Data Acquisition G1850 Complete	15-Apr-19	Nuc. NDE
	Return G1850 to Building 1	16-Apr-19	Daniel Duggins

Planned Technology Transfer in 2019

- **Project Update**
  - Meeting with DOE-NETL: March
  - DOE-NETL Crosscutting Review Meeting: April
  - P87 Tech Transfer Week (for utility members): June
  - Joint EPRI-123HIMAT Conference on High Temperature Materials: October
- **Collaboration**
  - **Opportunity for engagement from research community**
  - If interested, let us know



Project Tasks and Schedule

			Budget Period 1 (1/25/18 – 1/24/19)				Budget Period 2 (1/25/19 – 1/24/20)				Budget Period 3 (1/25/20 – 1/24/21)				
Task	Start	End	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
Task 1 - Project Management	1/15/2018	1/15/2020													
Task 2 - Component Retrieval	1/15/2018	12/31/2018													
2.1: Literature Survey															
2.2-2.3: Sampling and Characterization Plan															
2.4: Delivery of EEMs															
Task 3 - Characterization	7/1/2018	10/31/2020													
3.1: Macro Characterization															
3.2: Micro Characterization															
3.3: Nano Characterization															
Task 4 - Speciment Machining	7/1/2018	12/31/2019													
Task 5 - Mechanical Testing	8/1/2018	10//31/2020													
5.1: Tensile Tests															
5.2: Fracture Toughness Tests Test															
5.3: Impact Toughness Tests															
5.4: Parent Metal Creep Tests															
5.5: Cross Weld Creep Tests															
5.6: Creep-Fatigue Tests															
5.7: Remaining Life Estimates															
Task 6 - Data Management	1/1/2018	11/30/2020													

Together…Shaping the Future of Electricity

Selected Components for Creep Test Evaluation

Material Type	Component Description	Creep Test Evaluation
316H; 1960 vintage	Eddystone Unit 1 turbine piping between junction header and turbine stop valves	Yes
316H; 1960 vintage	Eddystone Unit 2 base metal upstream from DMW	Yes
316H; 1968 vintage casting	Eddystone Unit 1 super pressure valve body #4	Yes
316H; 1983 replacement pipe	Eddystone Unit 1 bend into super pressure valve body #4	Yes
316H cross-weld	Eddystone Unit 1 weld between super pressure valve body and replacement piping	Yes
316H cross-weld	Eddystone Unit 1 original weld in turbine piping	Yes
Grade 91 header body	Utility #2 outlet header	Yes
Grade 91 forging	Utility #2 outlet header	Yes
Grade 91 header body to Grade 91 forging	Utility #2 outlet header	Yes
Grade 91 tube to header weld	Utility #2 outlet header; location to be informed by NDE	No

Base Metal Creep Testing – Based on 'Material Heats'

Sample ID	Temp °F (°C)	Stress ksi (MPa)	Est. Time to Failure (hours)
Gr 91-1	1157 (625)	14.5 (100)	5,000
Gr 91-2	1157 (625)	14.5 (100)	5,000
316H-1	1247 (675)	13.05 (90)	5,000
316H-2	1247 (675)	13.05 (90)	5,000
316H-3	1247 (675)	13.05 (90)	5,000
316H-4	1247 (675)	13.05 (90)	5,000
316H-5	1247 (675)	13.05 (90)	5,000
316H-6	1247 (675)	13.05 (90)	5,000
316H-7	1247 (675)	13.05 (90)	5,000
316H-8	1247 (675)	13.05 (90)	5,000

Cross-Weld Creep Testing – Based on ‘Material Heats’

Sample ID	Temp °F (°C)	Stress ksi (MPa)	Est. Time to Failure (hours)
316H-W1-1	1247 (675)	13.05 (90)	5,000
316H-W2-1	1247 (675)	13.05 (90)	5,000
316H-W3-1	1247 (675)	13.05 (90)	5,000
316H-W4-1	1247 (675)	13.05 (90)	5,000
316H-W5-1	Spare*		
Gr91-1	1157 (625)	11.6 (80)	4,000
Gr91-2	Spare*		
DMW-1	1067 (575)	11.6 (80)	4,000
DMW-2	1157 (625)	5.8 (40)	4,000
DMW-3	Spare*		

Pedigree Information

Unit	Heats of Material	Run-Hours	# Starts	Steam Temperature	Steam Pressure	Operation History	Remarks
Exelon Eddystone Unit 1	316 (1960)	1960 – 2/1983 130,520 1997-2011 ~83,890	1960 – 2/1983 ~311 1997-2011 ~329	1200°F (to 1965) 1130°F**	5000 psi (to 1965) 4496 psi**	Base Loaded	Information from 1983-1997 has been requested. Current response from Exelon is "Chase That's a tough one. I don't think we kept a running tally on starts and run hours and the folks that may have any direction on that have all retired. Dennis"
	316 (1968)	1997-2011 ~83,890	1997-2011 ~329				
	316OC (1983)	1997-2011 ~83,890	1997-2011 ~329	1130°F**	4496 psi**		
Exelon Eddystone Unit 2	316 (1960)	~298,000	~740	1050°F**	3523 psi**	Base Loaded	
	DMW b/w Gr. 22 and 316H	1997-2011 ~90,749	1997-2011 ~483	1050°F**	3523 psi**	Base Loaded	Weld replaced circa 1990
Utility #2 Unit 2	Grade 91 header body	~141,000	~3,300	1067°F***	2590 psi***	Base Loaded 1991-1995 Cycled 1995-2011	In Service 1991 - 2015
	Grade 91 forging	~141,000	~3,300	1067°F***	2590 psi***		
	P22-F91 Girth Weld	~141,000	~3,300	1067°F***	2590 psi***		
	P91 End Cap	~106,000	~2,900	1067°F***	2590 psi***	Base Loaded 2011-2015	Replaced in 1997

* Nominal Design Conditions ** Nominal Plant Operating Conditions *** Nominal Component Operating Conditions

Pedigree Information

Unit	Heats of Material	Run-Hours	# Starts	Steam Temperature	Steam Pressure	Operation History	Remarks
Utility #3 Unit 3	347H SH Tubing	415,725	N/A	1050°F (~250k hrs.) 1025°F (~165k hrs.)**	1800 psi**	Base Loaded	
	347H – LAS DMWs (SH Tubing)						
Utility #3 Unit 4	Gr. 22 HRH Pipe	412,140	N/A	1050°F (~251k hrs.) 1025°F (~161k hrs.)**	1800 psi**	Base Loaded	
Utility #3 Unit 5	1/2Cr-1/2Mo-1/4V w/ Girth welds	266,701	N/A	1050°F (~142k hrs.) 1025°F (~125k hrs.)**	2400 psi**	Cycled	Temperature Excursion in 2003 – Reached 1470°F
Utility #4	347H Tubing	85,328	85	~975°F***	~3700 psi***	Base Loaded	
Utility #5 Unit 1	321H SH Tubing with Weld Overlays	293,081	591	1000°F**	2800 psi**		We currently have limited information on these tubes.
Utility 4 Unit 2	LSW HRH Hdr Sample						

* Nominal Design Conditions

** Nominal Plant Operating Conditions

*** Nominal Component Operating Conditions

Base Metal Creep Testing Perspective for 316H (Data per EPRI correlation of 316H database)

- 100 MPa @ 675°C = 899 or 3,644 hours
- 90 MPa @ 675°C = 1,619 or 6,565 hours
- 80 MPa @ 675°C = 3,126 or 12,677 hours
- 70 MPa @ 700°C = 1,920 or 7,787 hours
- Note: design hoop stress ~70 MPa

- Comparison of 16-8-2 weld metal and 316H data overlap for database of available information. Thus, assumed lives for base metal above are assumed for cross-weld tests

Additional Materials in EPRI Archive

Type of Component	Extent of Material	Material(s)	Temperature	Time	Damage
SH Outlet Header	Large Sections	P91	565°C	130,000 hours	Unknown
SH Outlet Header	Minimal Sections	P91	540°C	115,000 hours	Unknown
SH Outlet Header	Large Sections	P91	585°C	89,000 hours	Extensive
SH Outlet Header	Large Sections	P91	568°C	79,000 hours	Extensive
DMW	~15	T23 to SS	540°C	115,000 hours	Unknown
DMW	~15	T23 to T91	540°C	115,000 hours	Unknown
DMW	Minimal sections	T91 to SS	540 to 650°C	103,000 hours	Yes, variable
Hot RH Branch Connection	Ring Sample	P92	605°C	70,000 hours	Through-wall leak
SH Outlet Branch Connection	Large Section	P91	540°C	70, 000 hours	Through-wall leak