Extreme Environment Materials

DOE FE0031562

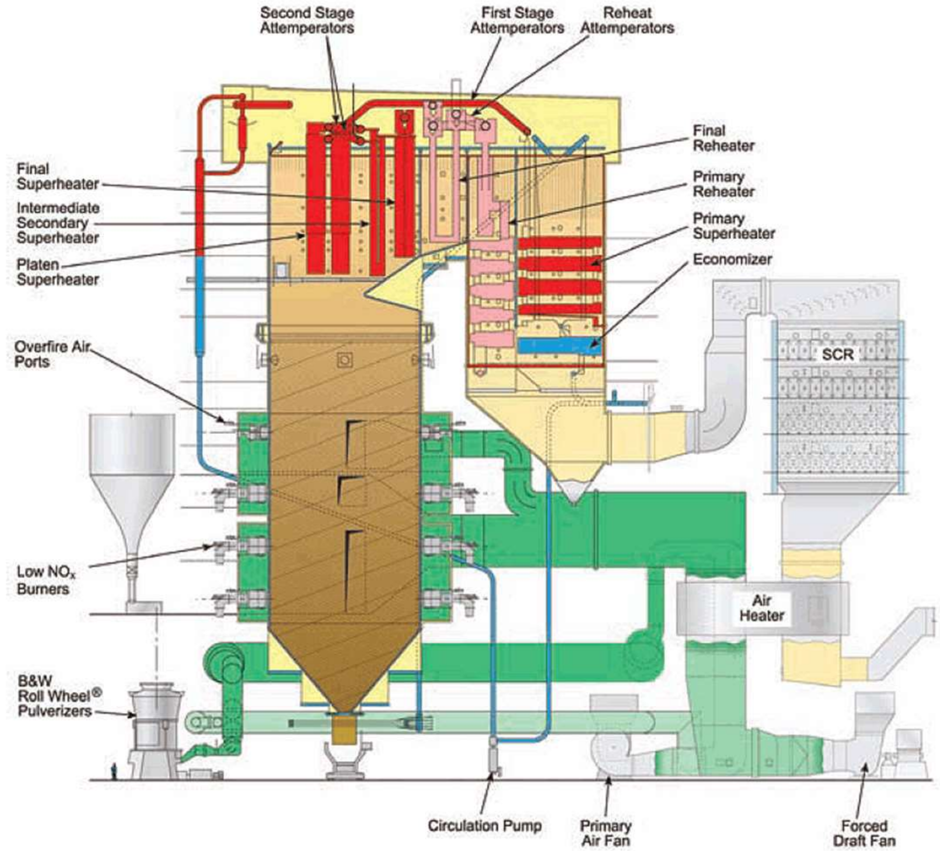
Michael Gagliano
Electric Power Research Institute

DOE Crosscutting Research Program Portfolio Review Meeting

Pittsburgh, PA: April 11, 2018

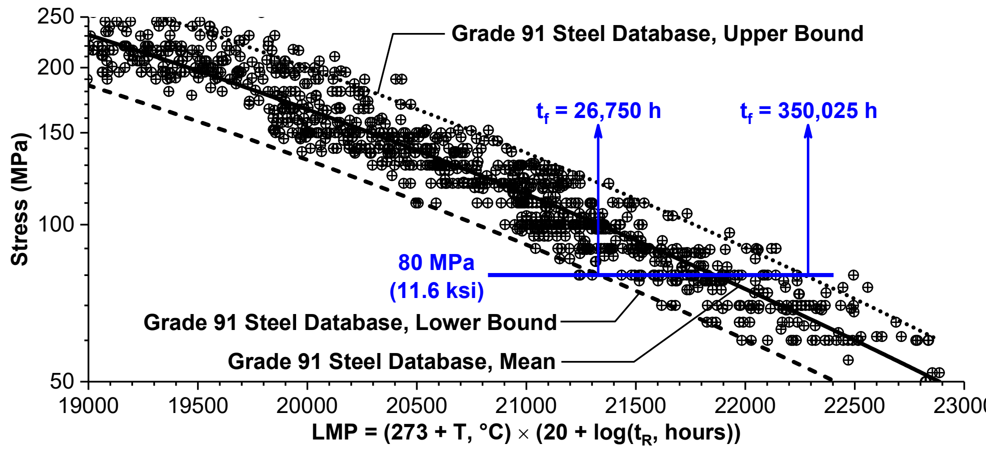
Technical Basis

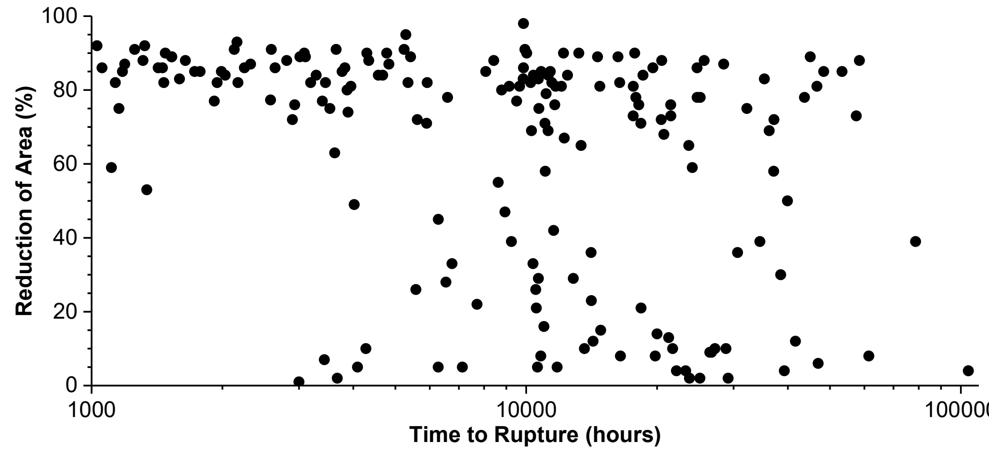
- Existing coal-fired fleet is >39 years
  - Already beyond the original anticipated life
  - Expectation is another 30 years
  - Most were designed for baseload operation; will see some level of flexible operation
    - Intermittent deployment of renewables
    - Low natural gas prices
  - Limited or no information is available from service-aged materials
    - Most models are based on testing of virgin 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



Technical Basis

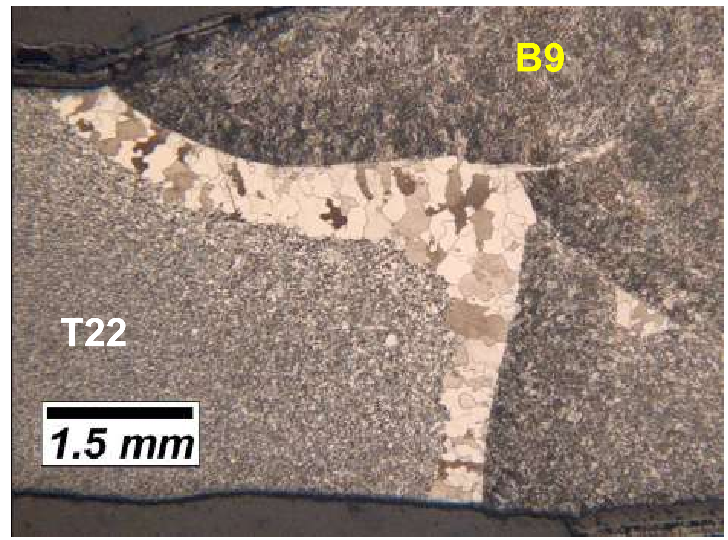
- Life assessment requires a fundamental understanding of:
  - Mechanical properties, design parameters, **stress state**, crack initiation/propagation, failure criteria, etc.
- For traditional materials, creep data alone may be sufficient, but not for CSEF, SS and ASS
  - Metallurgically more complex
  - Large variations in materials behavior
    - Chemical composition, processing, fabrication, heat treatment, etc.
    - Global sourcing
  - Premature failures due to poor creep properties
    - Inclusions, tramp elements, deleterious phases, nucleation and growth of carbides, etc.





Potential Significance of the Results

- Collection of ex-service EEM components
- Comprehensive compendium of materials data from CSEF, SS, ASS, DMWs and nickel-based alloys
  - Mechanical properties
  - Time-Temperature parameter relationships
  - Oxidation behavior
- Will ensure current and future DOE efforts to:
  - Improve plant performance
  - Develop/improve material and mechanical models
  - Validate computational methods for materials design based on sound science
- Facilitate optimization of design rules with Codes and Standards
  - Evaluation of DMW and critical components from different OEMs



EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Project Objectives

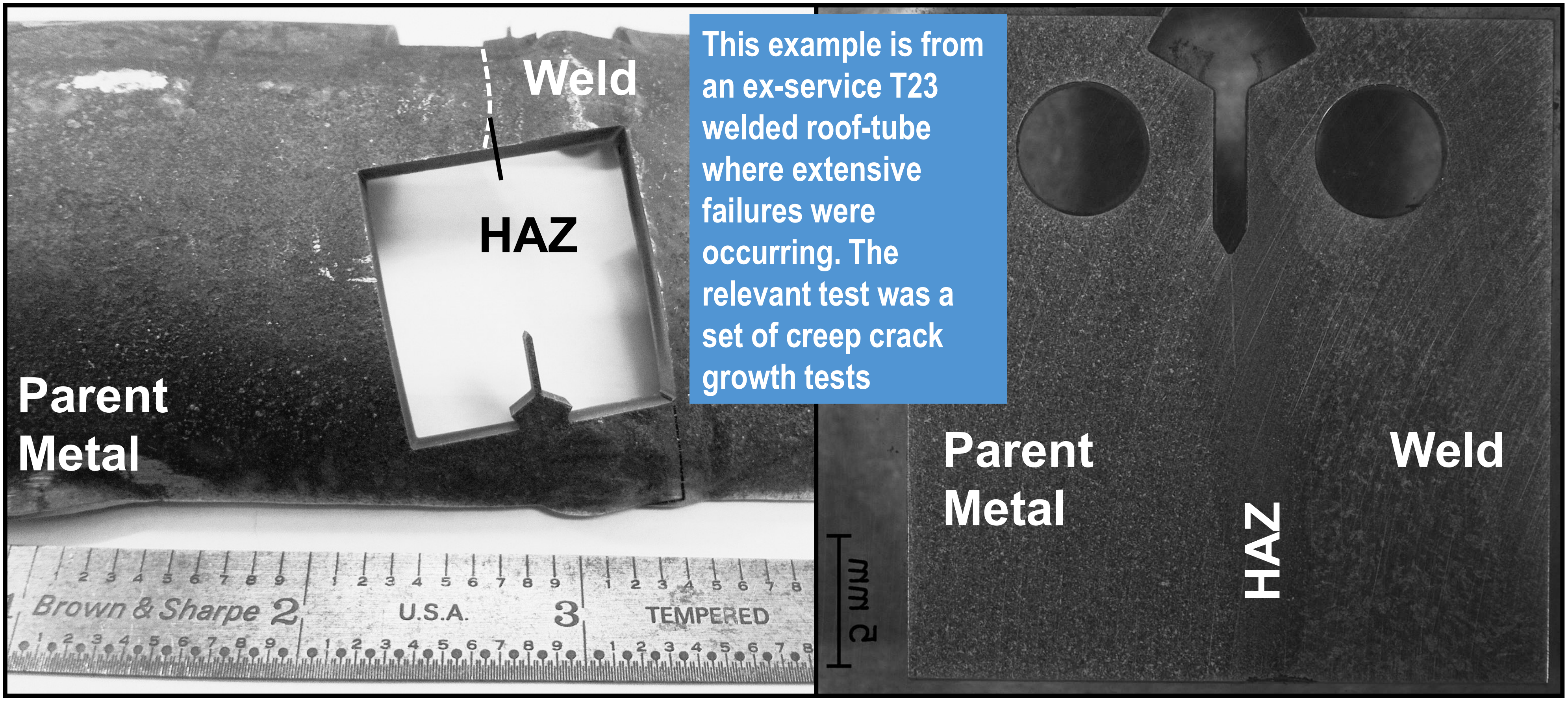
- Obtain sufficient quantity of relevant EEM components and appropriate documentation
  - CSEF steels, 300-series H grade stainless, advanced austenitics, nickel-based materials, and DMWs
  - Time, temperature/pressure, number of cycles, repair history, coal/fuel, etc.
- Perform detailed analysis
  - Mechanical and microstructural characterization
- Link microstructural features to long-term behavior
  - Secondary phases, inclusions, decomposition/evolution, damage
  - Service performance/destructive evaluation, TTP relationships, CDM
- Compare measured degree of degradation with service history based on available models (if applicable)
- Develop a comprehensive database of mechanical properties and quantitative microstructural information
  - Make all data available to DOE/public for future use

Mechanical Testing

The Types of Tests Performed by EPRI

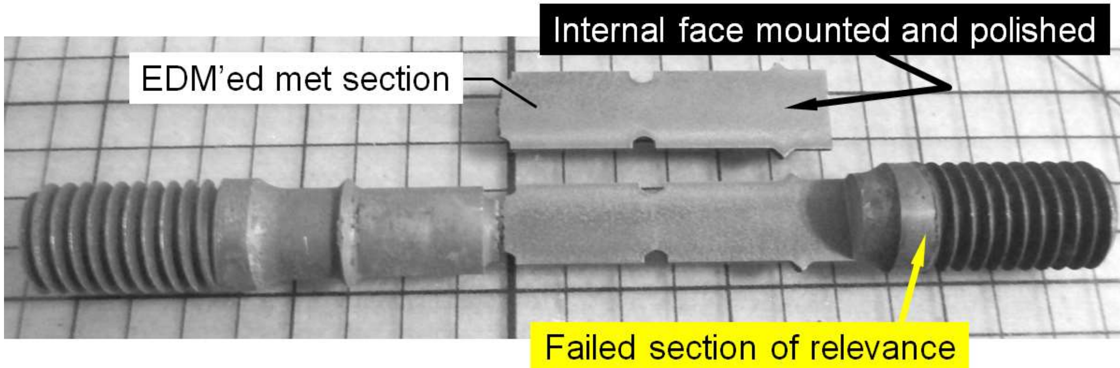
- Time independent
  – Fracture toughness
  – Less relevant tests… tensile, charpy v-notch (may be performed for comparison or informational purposes)
- Time dependent
  – Smooth bar creep
  – Notch bar creep
  – Feature cross-weld
  – Crack growth
  – Creep-fatigue
- Nature of samples and information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

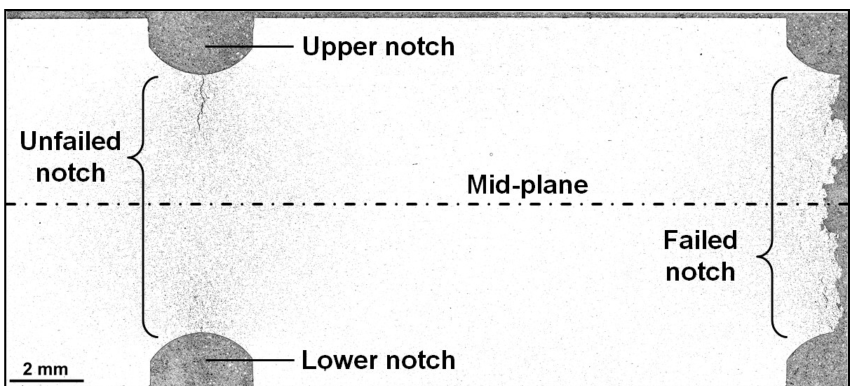
Specialty, In-house Machining Provide Opportunity to Extract Meaningful Samples

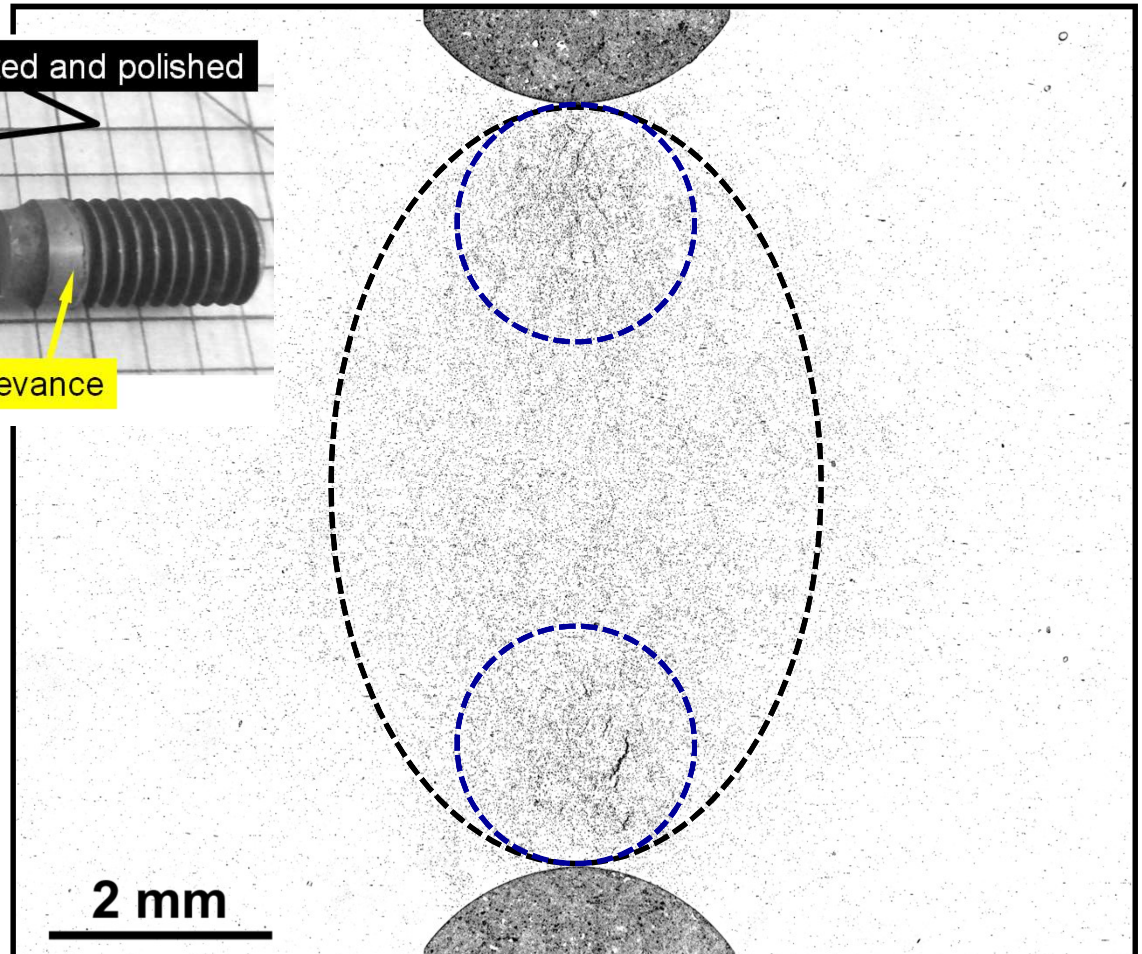


This example is from an ex-service T23 welded roof-tube where extensive failures were occurring. The relevant test was a set of creep crack growth tests

Creep Damage in a Notch Bar Creep Test in a 9%Cr Steel

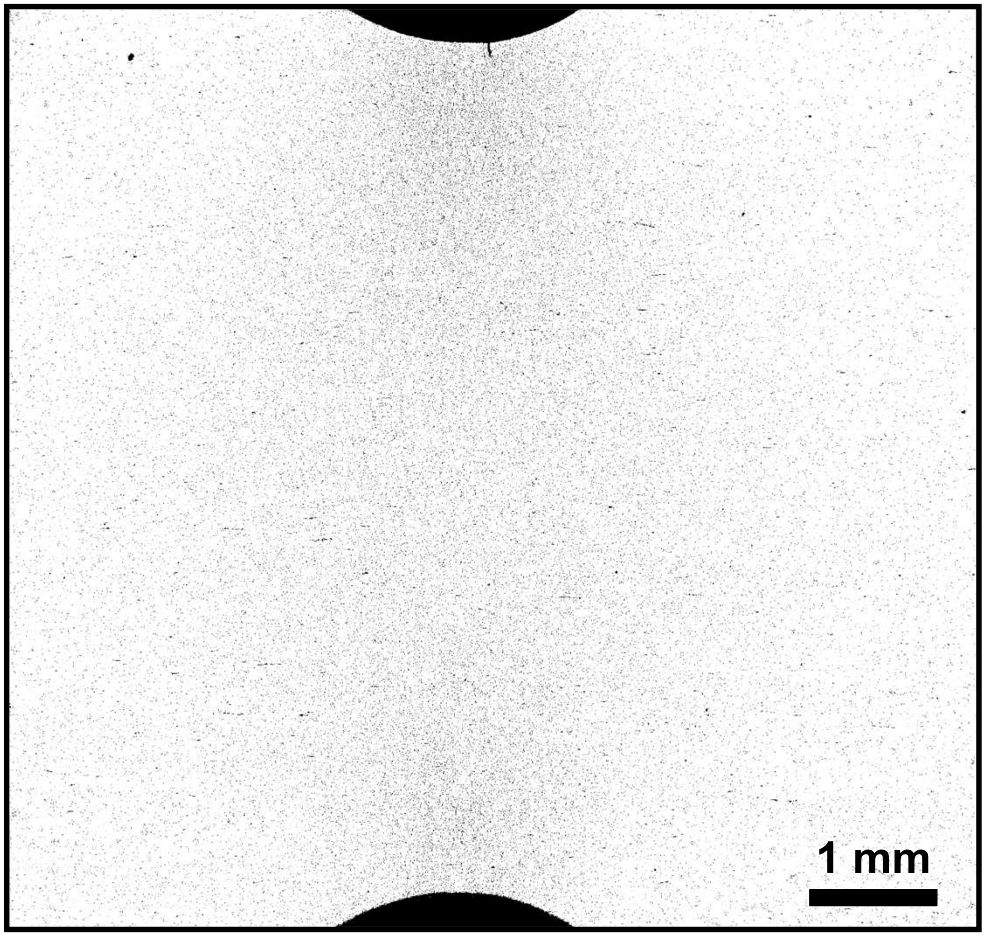


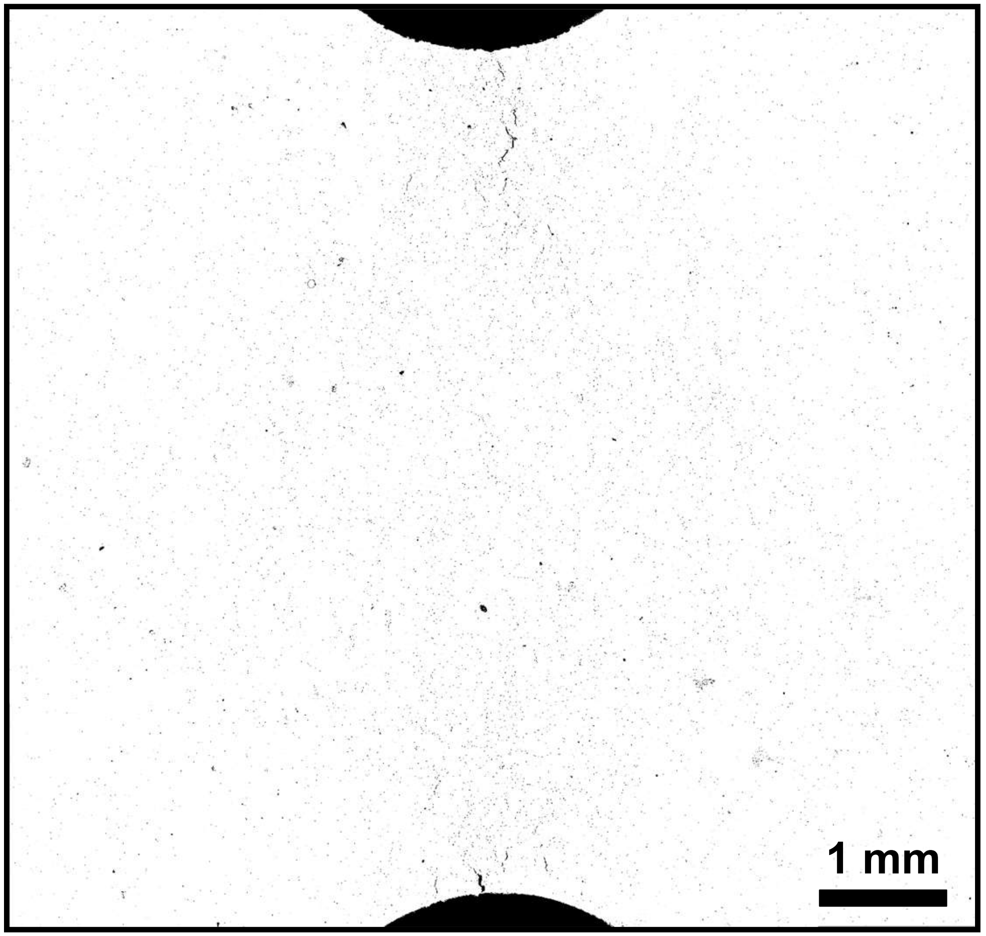




The distribution of damage is not random; this is an indication of stress-state dependency

Damage in B2 (Left) and TP1 (Right); 7.7 mm W X 7.3 mmT

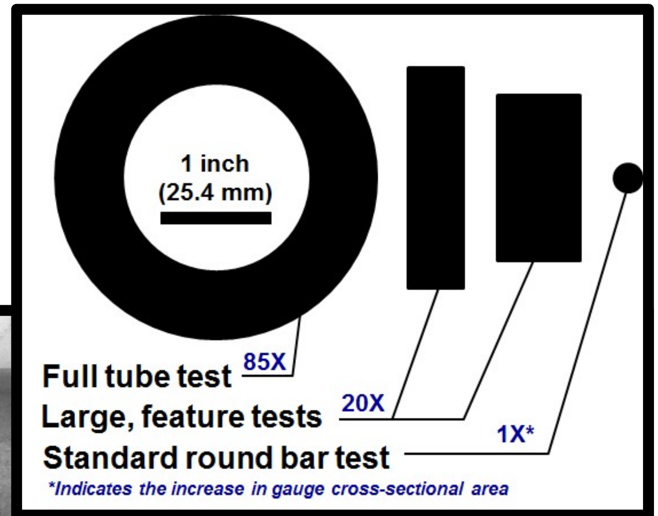




EPRI | ELECTRIC POWER RESEARCH INSTITUTE

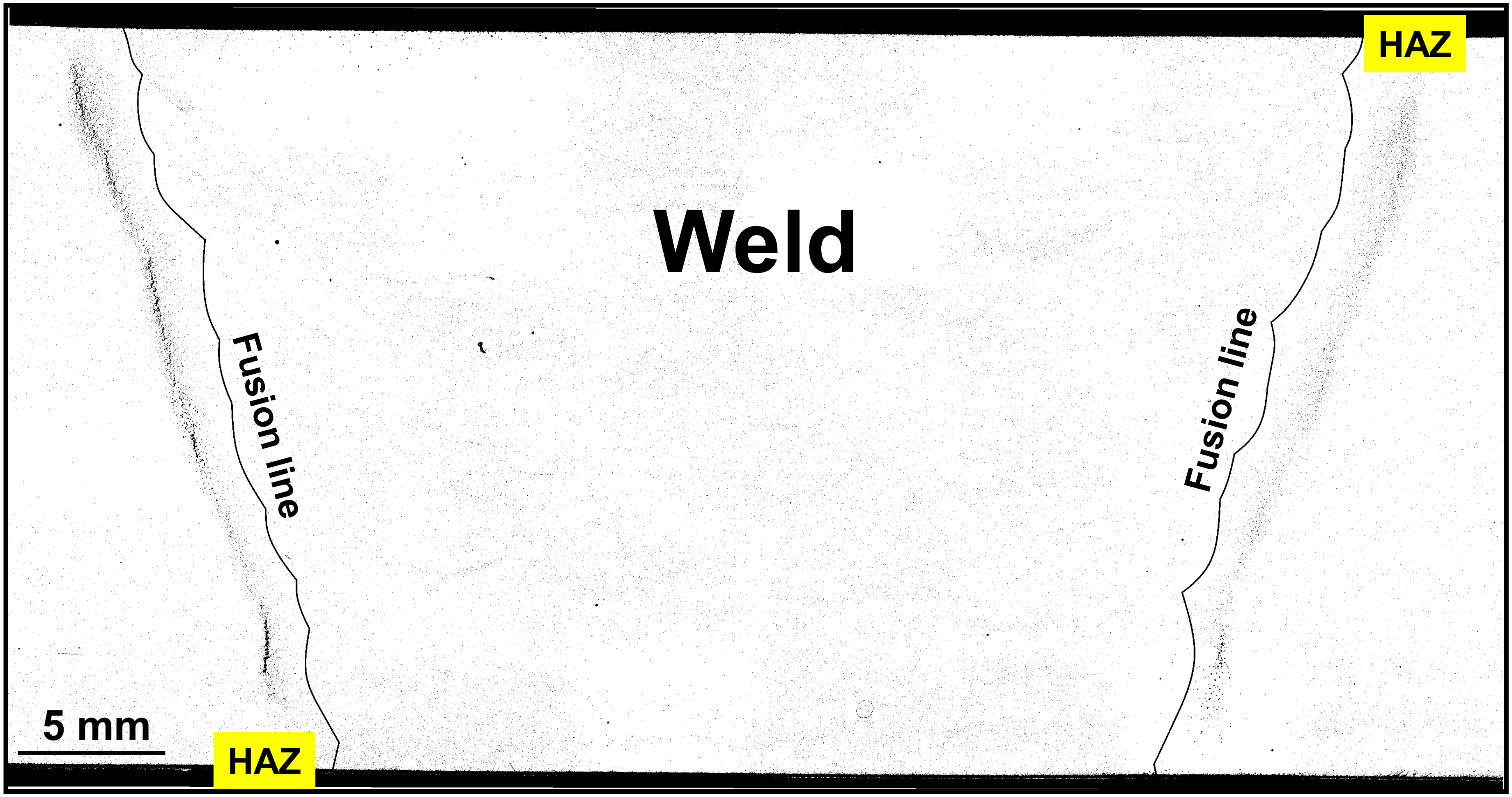
Feature Type Cross-weld Specimens

- Test the entirety of the weld repair including both HAZs
- Provide the opportunity for detailed assessment of the unfailed HAZ



EPRI ELECTRIC POWER RESEARCH INSTITUTE

Creep Damage – Metallurgical Notch (Weldment HAZ)



An Essential Variable in all Testing is Post-test Examination

- It is **impossible to fully validate** and extract meaningful outcomes from testing unless the samples are properly evaluated
- EPRI has developed the expertise and procedures to perform post-test assessment
- It is clear that for more sophisticated tests and/or materials, the emphasis on post-test examination cannot be understated
  - It is EPRI's general opinion that test data are essentially meaningless unless it is accompanied by metallographic assessment.

Materials Characterization

Materials Characterization

- Develop robust characterization procedures
  - Aimed at not only qualitative observations but more importantly **quantitative assessment** of important microstructural features
  - that can be **standardized**
  - using **relevant** techniques
  - that involves **statistical evaluation** of data
  - And eventually **translated to** other characterization **labs** for **consistency** in characterization methodology

Chemical Analysis

Combination of OES-ICP, OES-MS, IGF, combustion

- As a standard procedure, chemical composition of all procured components will be established
  - **Elements identified will be well beyond those listed in specifications**

Example: Composition of Super304H component as per ASME Code case 2328-1

C	Si	Mn	P	S	Cu	Cr	Ni	Sb
0.084	0.202	0.45	0.019	0.0014	2.898	19.13	9.12	0.47

Additional Elements that Should be Assessed

Co	Mo	N	B	Ti	V	W	As	Sb
0.11	0.150	0.105	0.0032	0.007	0.061	0.017	0.009	0.0007
Sn	**O**	**Pb**	**Al**	**Ca**	**La**	**Ta**	**Zr**	**Bi**
0.002	0.006	<0.002	0.005	0.0015	<0.002	<0.002	<0.002	<0.0001

Detailed Assessment Based on Scale of Features

"Macro" Level

- Density of creep cavitation
- Distribution of creep damage
- Hardness distribution across material cross section

- ❑ Light Microscopy
- ❑ LED Microscopy
- ❑ Laser Microscopy
- ❑ Hardness Mapping

Provides insight on the variation of microstructure and properties and distribution of damage

"Micro" Level

- Analysis of phases
- Size and distribution of precipitates
- Association of damage to phases and grain boundaries
- Local variation of composition
- Oxide scale thickness

- ❑ Laser Microscopy
- ❑ SEM – EDS
- ❑ SEM – EBSD

Provides insight on distribution of phases and precipitates.

"Nano" Level

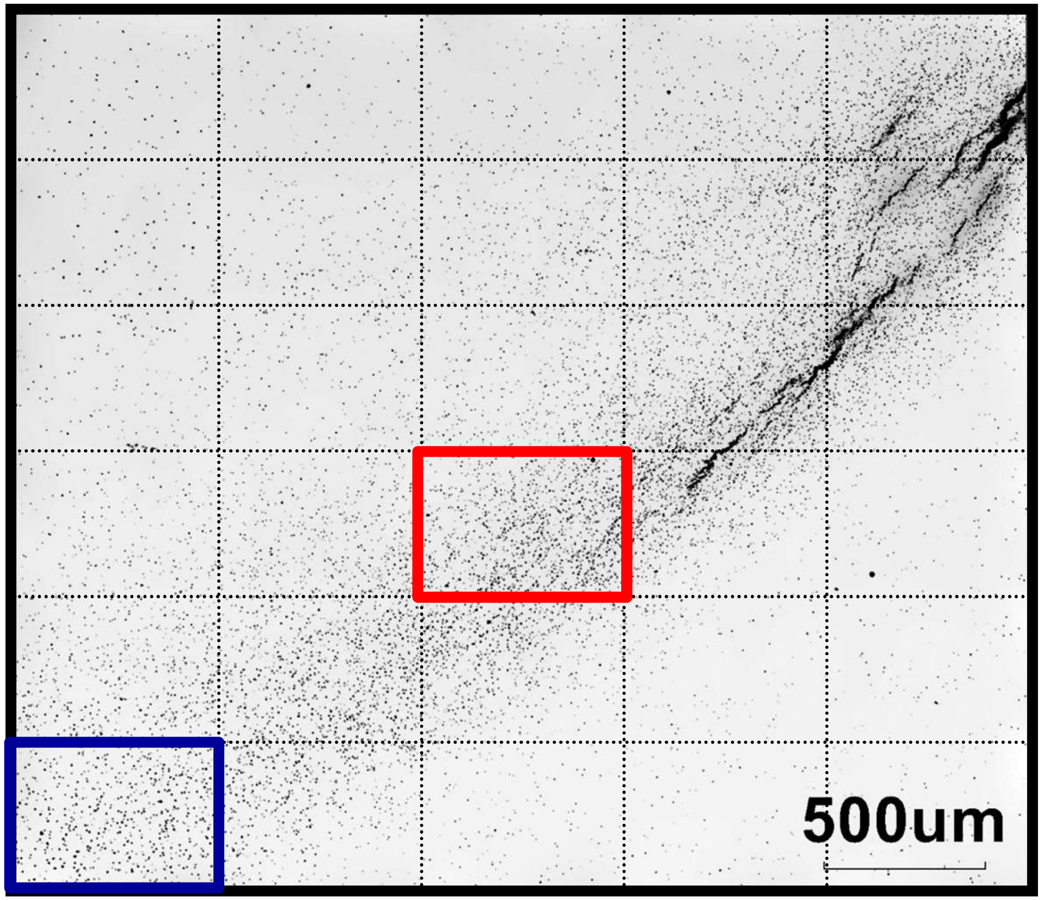
- Determination of precipitate structure and composition
- Association of damage to particles/ features
- Local composition around damage

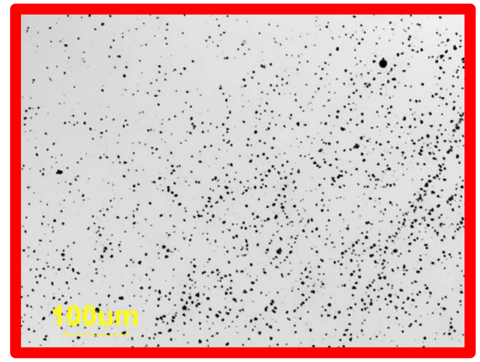
- ❑ Focused Ion Beam
- ❑ Transmission electron microscopy

Provides insight on particles controlling nucleation of cavities

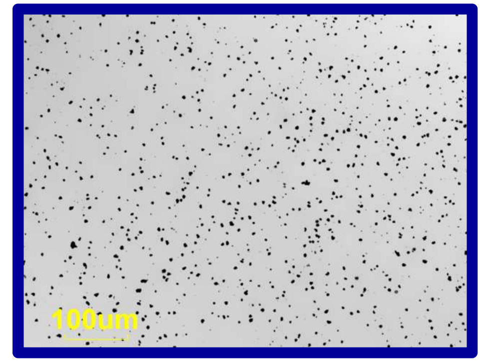
Evaluation of Damage (Stub to Header Weld - Rugeley Heat 1)

Compiled from 30 - 20X images





4,320 voids/mm^2



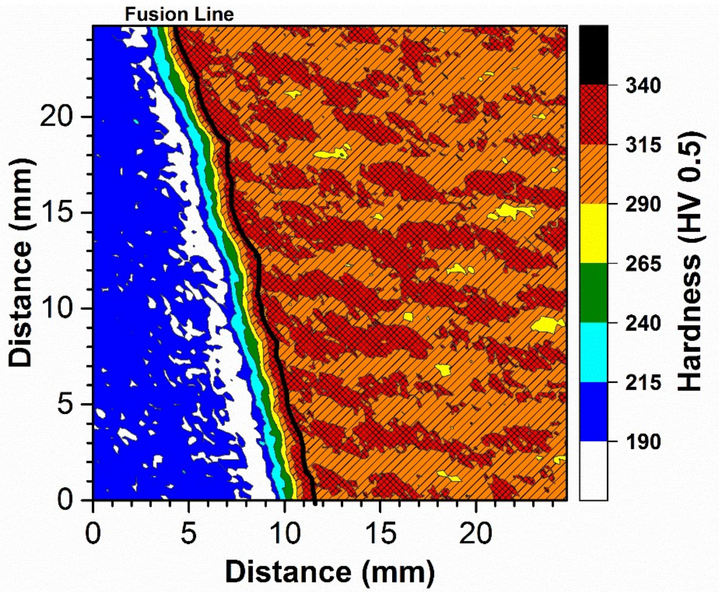
2,528 voids/mm^2

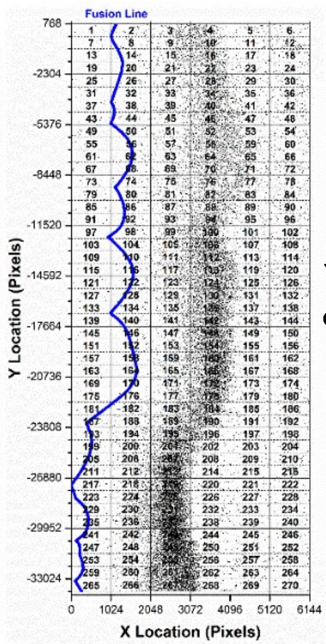
Observed damage is almost twice as extensive relative to typical behavior in 9%Cr steel uniaxial samples; e.g. this heat of Gr. 91 steel is particularly prone to damage when subject to triaxial stresses

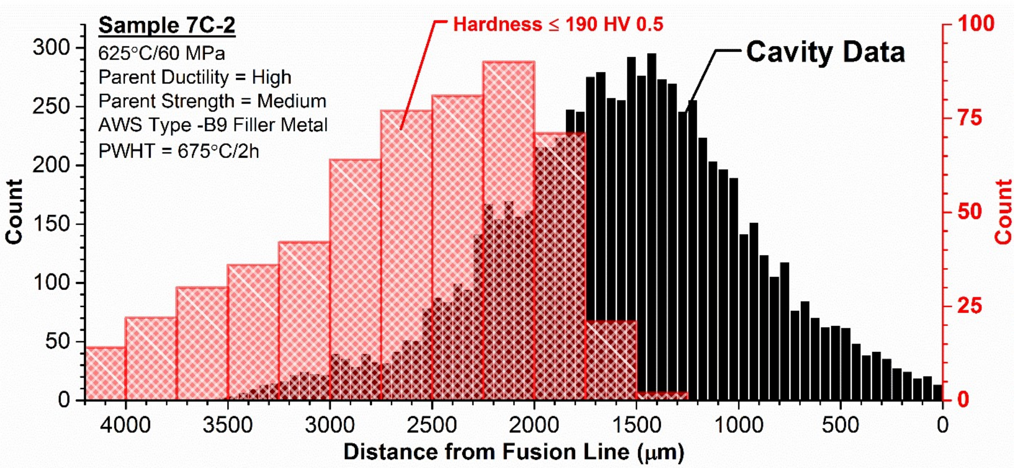
EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Combining Microhardness and Damage Distribution Plots

Distribution of hardness at welded joints







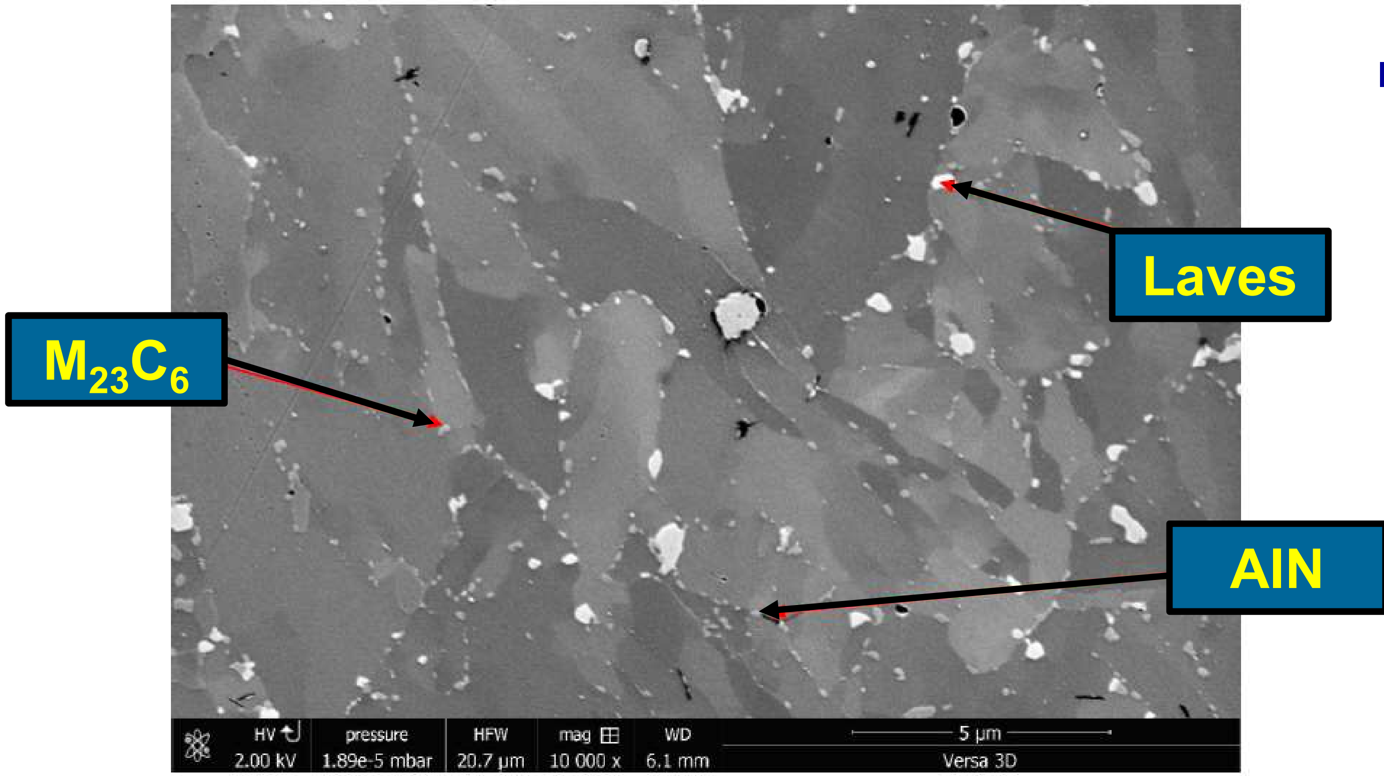
Hardness Mapping

Damage Distribution Analysis

Combining hardness and damage distribution data to understand association of damage to hardness

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

SEM Backscatter Image - Laves and $M_{23}C_6$ in Grade 92



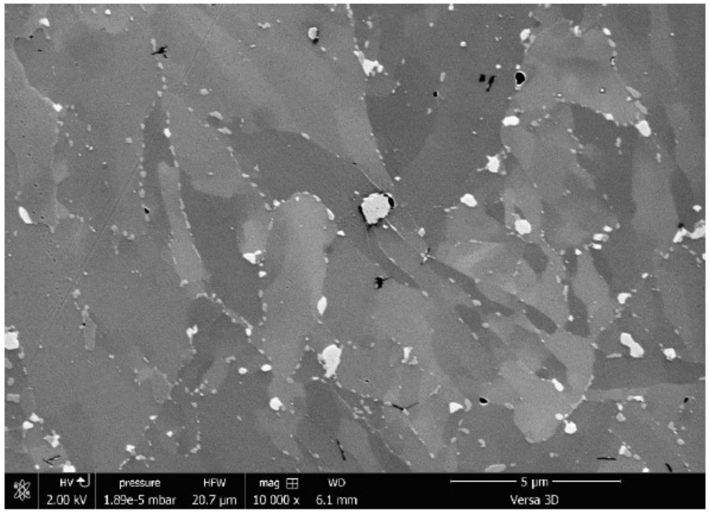
- Parameters to be optimized
  - Voltage
  - Magnification
  - Brightness/ contrast

- How to quantify different types of precipitates?

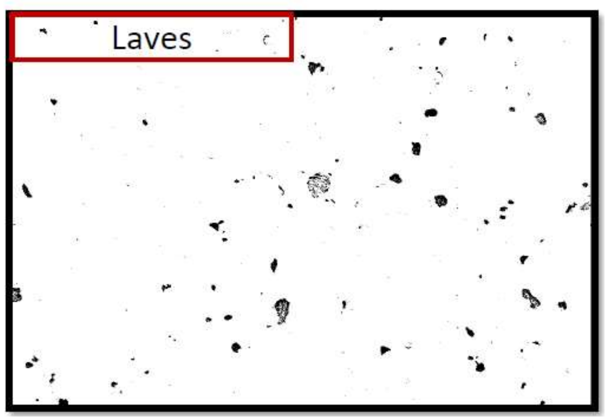
Analysis performed by University of Warwick

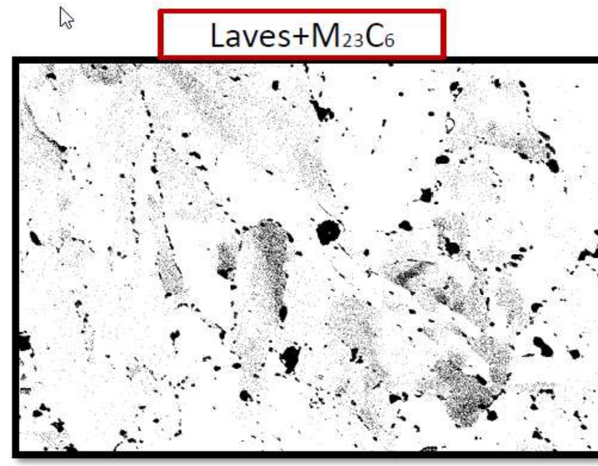
EPRI ELECTRIC POWER RESEARCH INSTITUTE

How to quantify different precipitates?



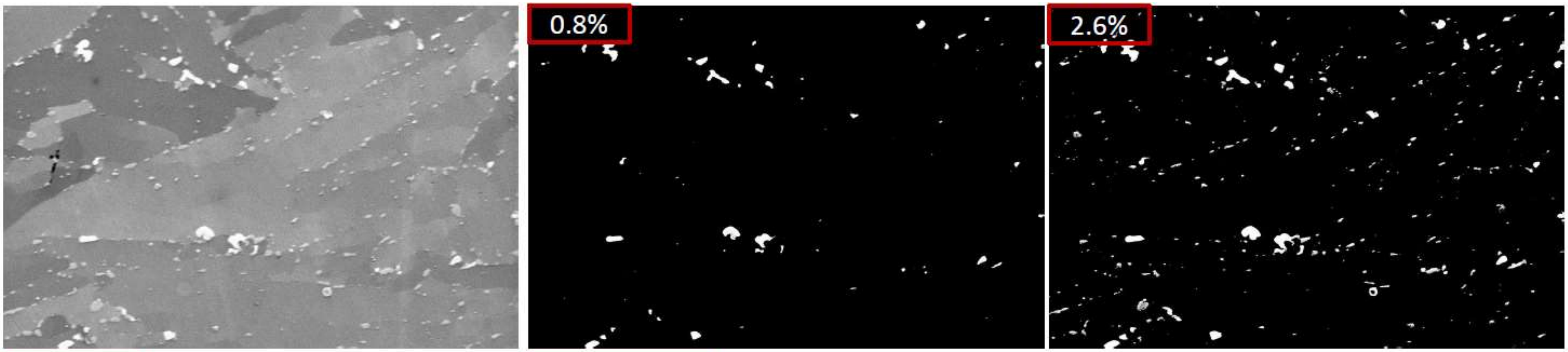
- Three precipitates have different compositions, which shows different intensities in a good Backscattered image
- By selecting different threshold values, AlN and Laves precipitates can be easily separated
- The difficulty is to separate Laves and M23C6

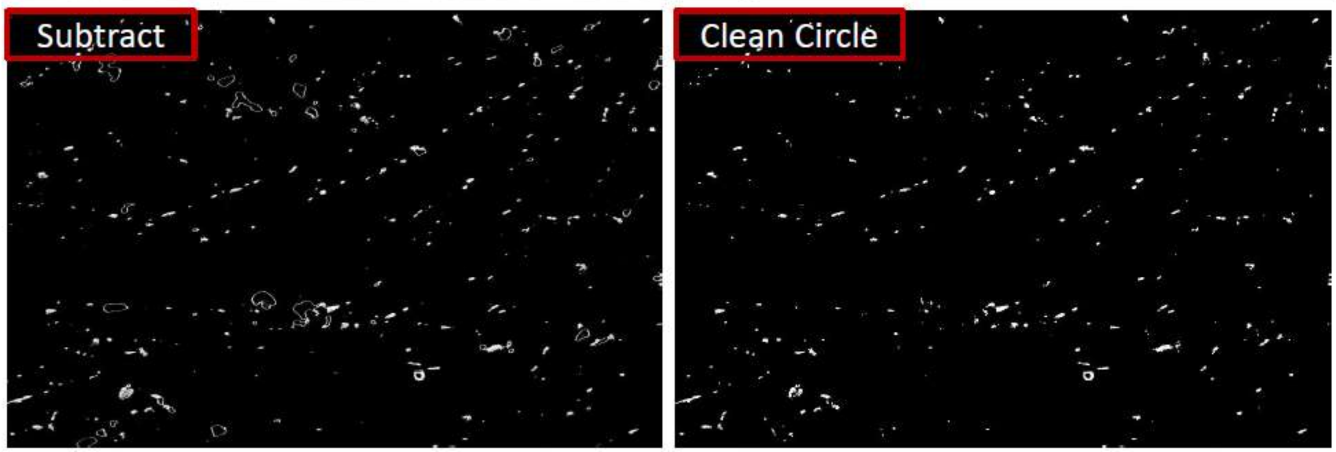




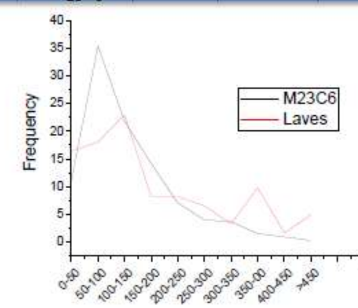
Analysis performed by Loughborough University

Quantification using Image J Analysis





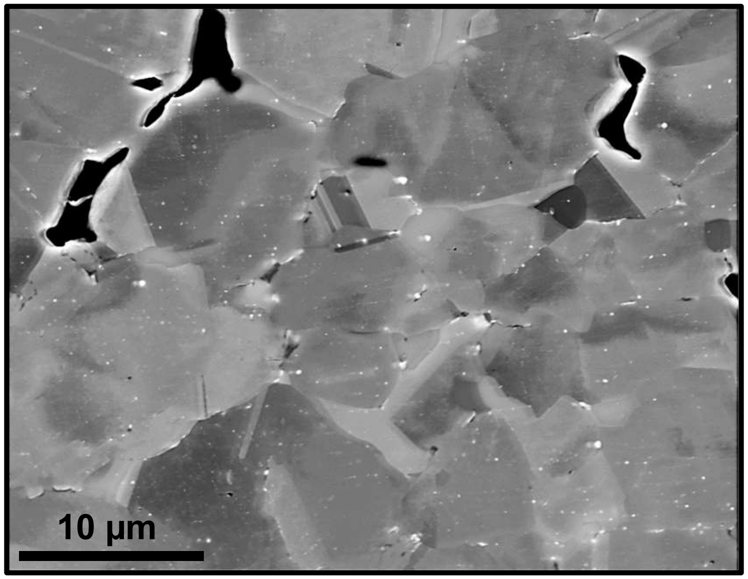
	Precipitates	Count	Total Area	%Area	Feret (um)
0.8	Laves	67	2.187	0.757	0.225±0.213
Subtract	$M_{23}C_6$	328	2.607	0.903	0.135±0.095

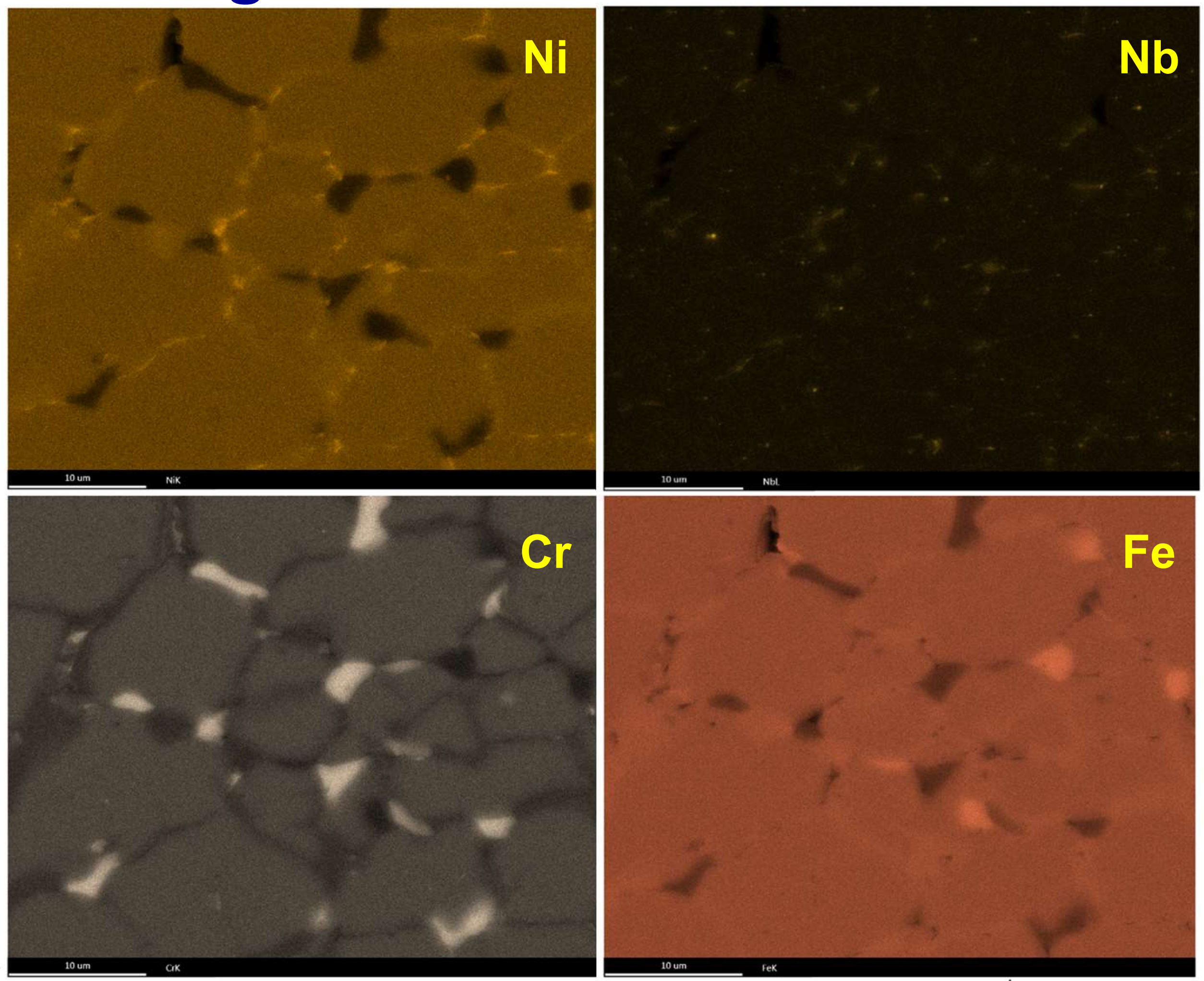


Analysis performed by Loughborough University

Local element distribution using EDS

Associating elements to phases

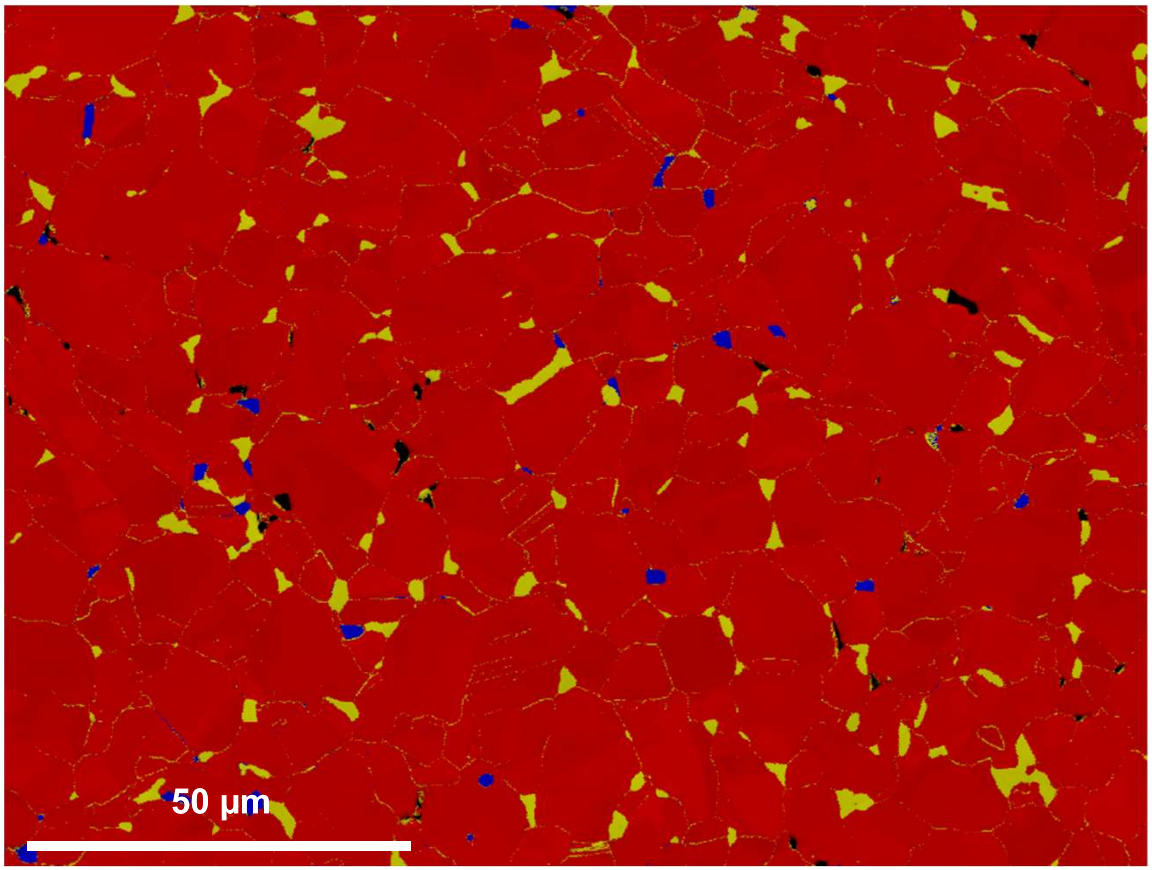




- Distinct sites with local compositional segregation at the boundaries
- Indication of multiple phases

EBSD - Phase Quantification

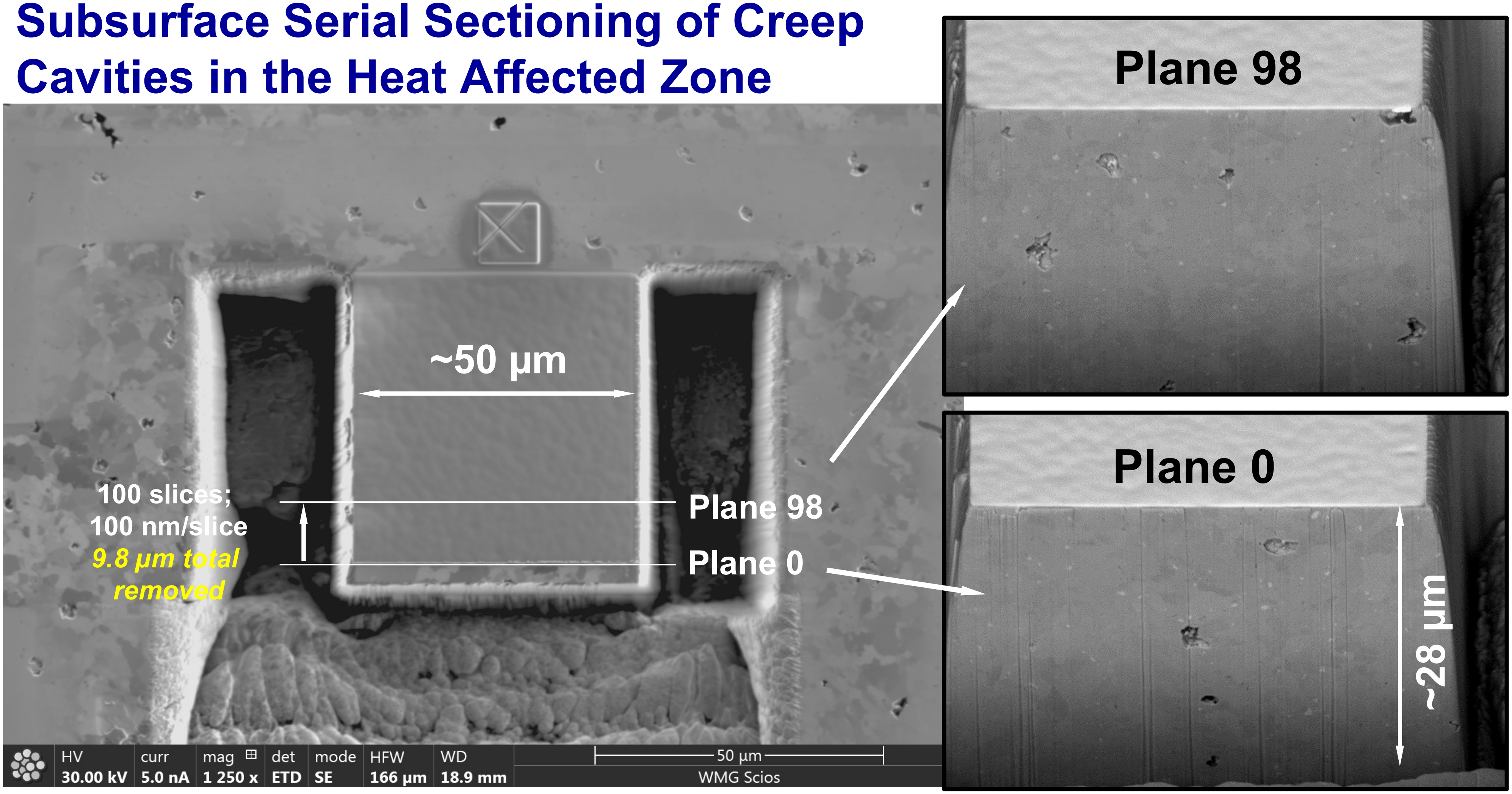
Determination of phases in 347H SH tube



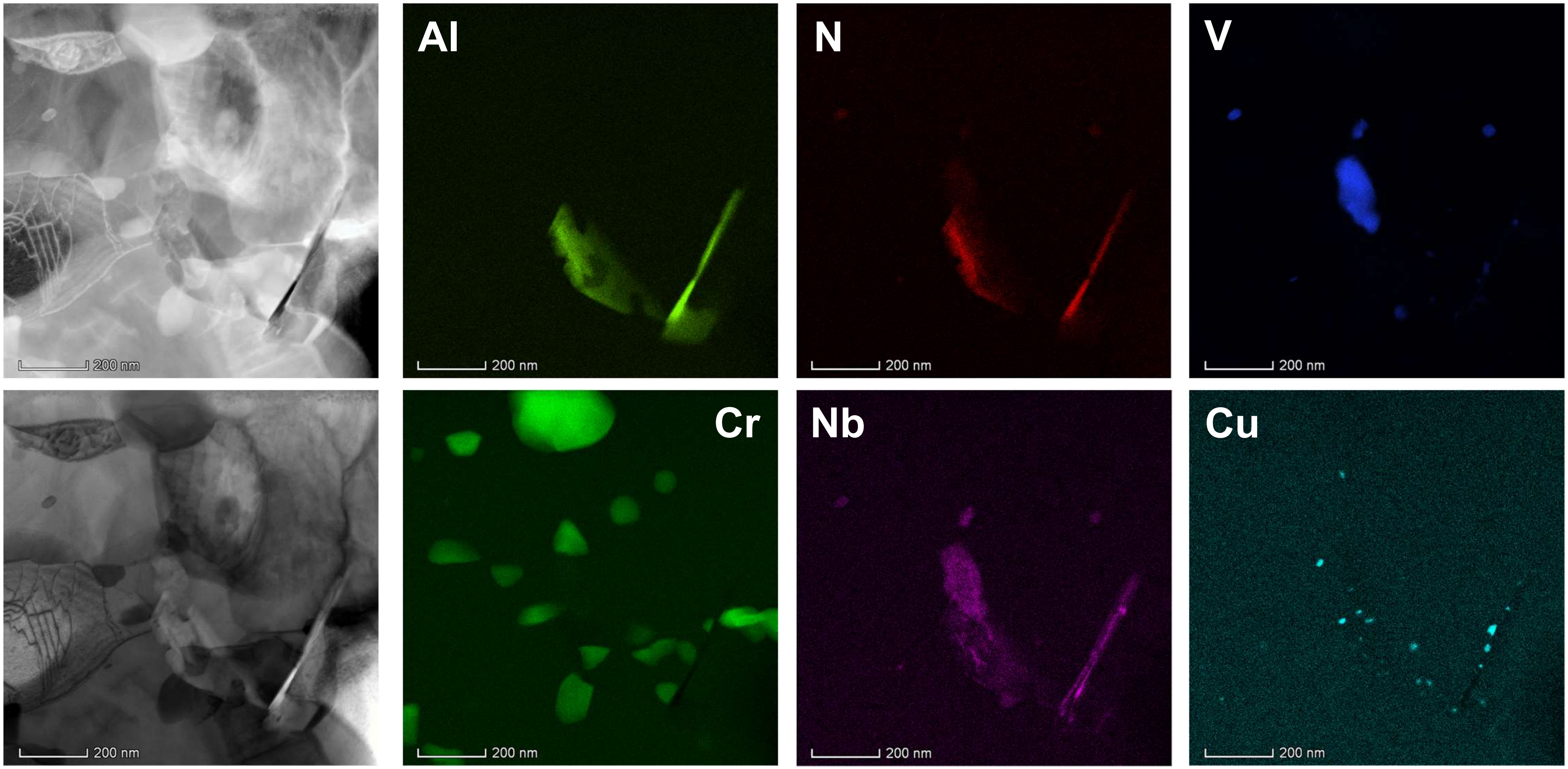
Delta Ferrite
Sigma
Austenite
Voids

- **Within the scanned area, fraction of:**
  - **Delta Ferrite = 0.46%**
  - **Voids = 0.31%**
  - **Sigma = 2.5%**

Subsurface Serial Sectioning of Creep Cavities in the Heat Affected Zone



Area for STEM-EDS Mapping



Summary- Evaluation of ex-service and post-test samples

- Multiple characterization techniques and procedures are available for evaluation of materials that have operated in extreme environment conditions

- Most effective outcome from this project can be achieved by characterization of ex-service material and post-test evaluation of specimen

Project Schedule and Status

Project Schedule

Task	Start	End	Budget Period 1				Budget Period 2				Budget Period 3			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1 – Project Management	1/2018	1/2021	■	■	■	■	■	■	■	■	■	■	■	■
Task 2 – Component Removal	1/2018	12/2018	■	■	■	■								
2.1: Literature Survey			■	■										
2.2-2.3: Sampling and Characterization Plan				■	■									
2.4: Delivery of EEMs					■	■								
Task 3 - Characterization	7/2018	10/2020			■	■	■	■	■	■	■	■	■	■
3.1: Macro Characterization					■	■	■	■						
3.2: Micro Characterization					■	■	■	■	■	■	■	■	■	■
3.3: Nano Characterization						■	■	■	■	■	■	■	■	■
Task 4 – Specimen Machining	7/2018	3/2019			■	■	■							
Task 5 – Mechanical Testing	8/2018	10/2020			■	■	■	■	■	■	■	■	■	■
5.1: Tensile Tests					■	■	■	■						
5.2: Fracture Toughness Tests						■	■	■	■					
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	10/2018	11/2020	■	■	■	■	■	■	■	■	■	■	■	■

Identified Components from Eddystone

Location	Unit	Component	Material	Vintage	Available
1	1	Superheater Outlet Header	316H, OC	1986	1
2/3	1	Main steam piping, straight sections	316H, OC	1983	4 heats
2	1	Main steam bends	316H, OC	1983	2 bends
2	1	Large bore girth welds	316H, OC	1983	3
2/3	1	Small bore penetrations	316H, OC	1983	7
4	1	SP Valve Assembly	316H	1968	1
4	1	DMW between SP Valve Assembly and Bypass Line	316H to P22	1968	1
5	1	Junction header	316H, OC	2007	1
6	1	Outlet piping from JH to turbine straight section and girth welds	316H	1963	2
7	1	Turbine stop valve assemblies	316H	1983	4
8	1	Turbine DMW between F22 and 316H	316H to F22	2007	2
8	1	Turbine J-loop piping	316H	1960	2

Identified Components from Eddystone

Location	Unit	Component	Material	Vintage	Available
2	1	Large bore girth welds	316H, OC	1983	3
2/3	1	Small bore penetrations	316H, OC	1983	7
4	1	SP Valve Assembly	316H	1968	1
9	1	Bolting materials	Unknown	Unknown	Dozens
10	1	Casing	2.25Cr-Mo-V	1960	1
11	2	SHOH with tube penetrations and link piping	316H	1960	2
12	2	Main Steam collection header with link piping	316H	1960	2
13	2	Small bore penetration welds and girth welds	316H	1960	2
14	2	Main steam DMWs	316H to P22	early 1990s	2
15	2	Grade 22 bends	P22	1960	2
16	1	Rotors	Variable	1960	2
	1	Long seam welds	Grade 22	1960	~200 feet
	1	HP furnace wall panel	T91/T22/HCM12	1988	20’
	1	LP furnace wall panel	T91/T22/HCM12	1988	20’

Identified Components from Eddystone

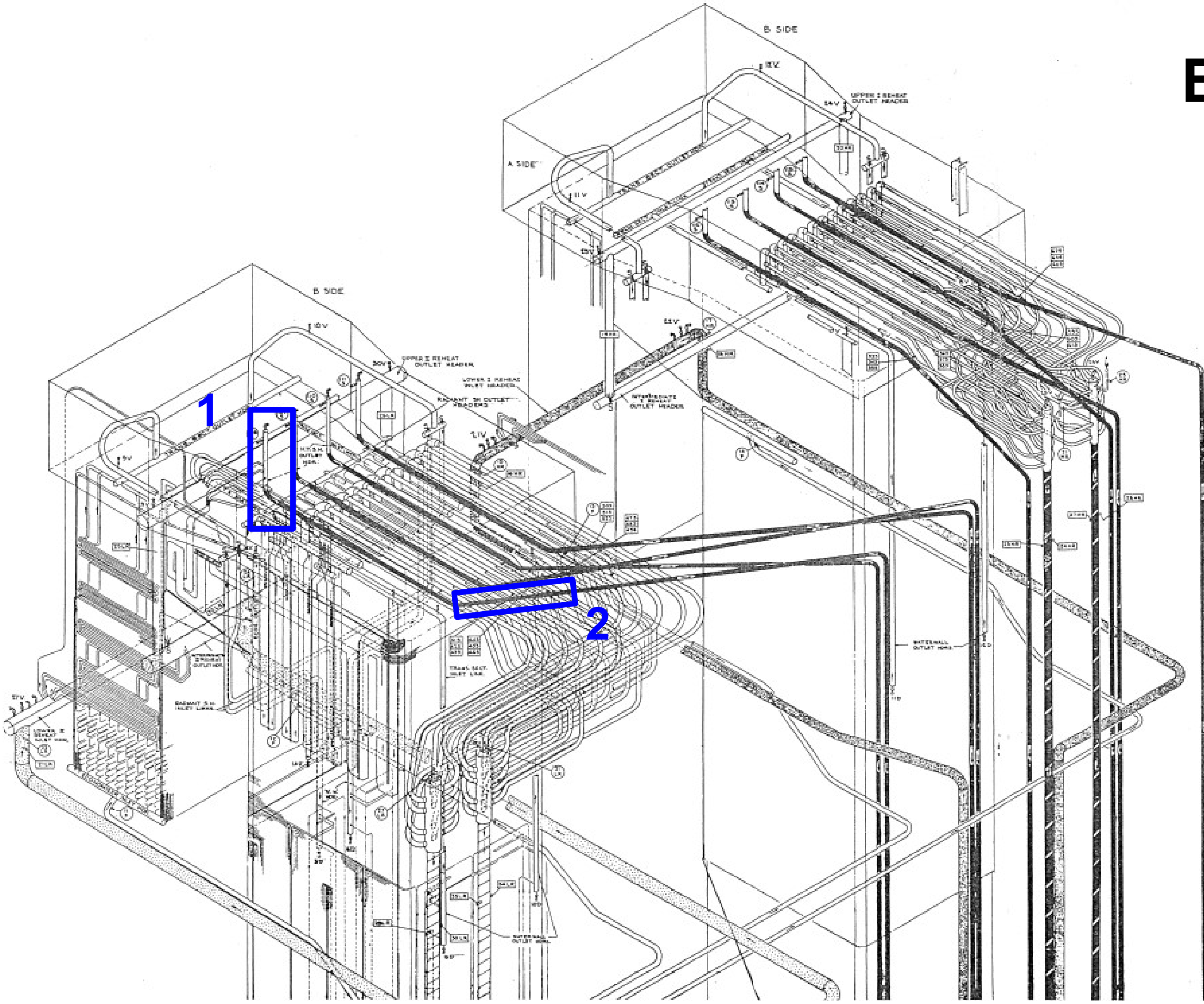
Component	Material	Vintage	Quantity	time (hrs)
FSH DMW 347H to T22	347H to T22	Unknown	Dozens	Unknown
FSH straight and bend sections	347H to T22	1980	200 ft	253,000
HRHOH (LSW)	Grade 91	~1990	Unknown	Unknown
Main steam piping	Grade 91	~1990	Unknown	Unknown
Valves	Grade 91	Unknown	Several	Unknown
FSH tube bends	321H	1980	Numerous	Unknown
Turbine piping spool pieces	Grade 91	Late 1990s	Unknown	~100,000
DMWs X20 to 91 (B9)	X20 to Grade 91	Late 1990s	Unknown	~100,000
DWMs 91 Tee to P22 (B3)	Grade 91 to P22	2001	2	59,000
RH piping (seamless)	Grade 22	Unknown	Several	270,000
RH piping (LSW, girth welds)	Grade 22	Unknown	Several	270,000
RH piping (bends and welds)	0.5Cr-0.5Mo-0.25V	Unknown	Several	270,000
RH piping (seamless)	Grade 22	Unknown	Several	425,000
RH piping (LSW, girth welds)	Grade 22	Unknown	Several	425,000

Currently Available Materials in EPRI's Archive

Type of Component	Extent of Material	Material(s)	Temp	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

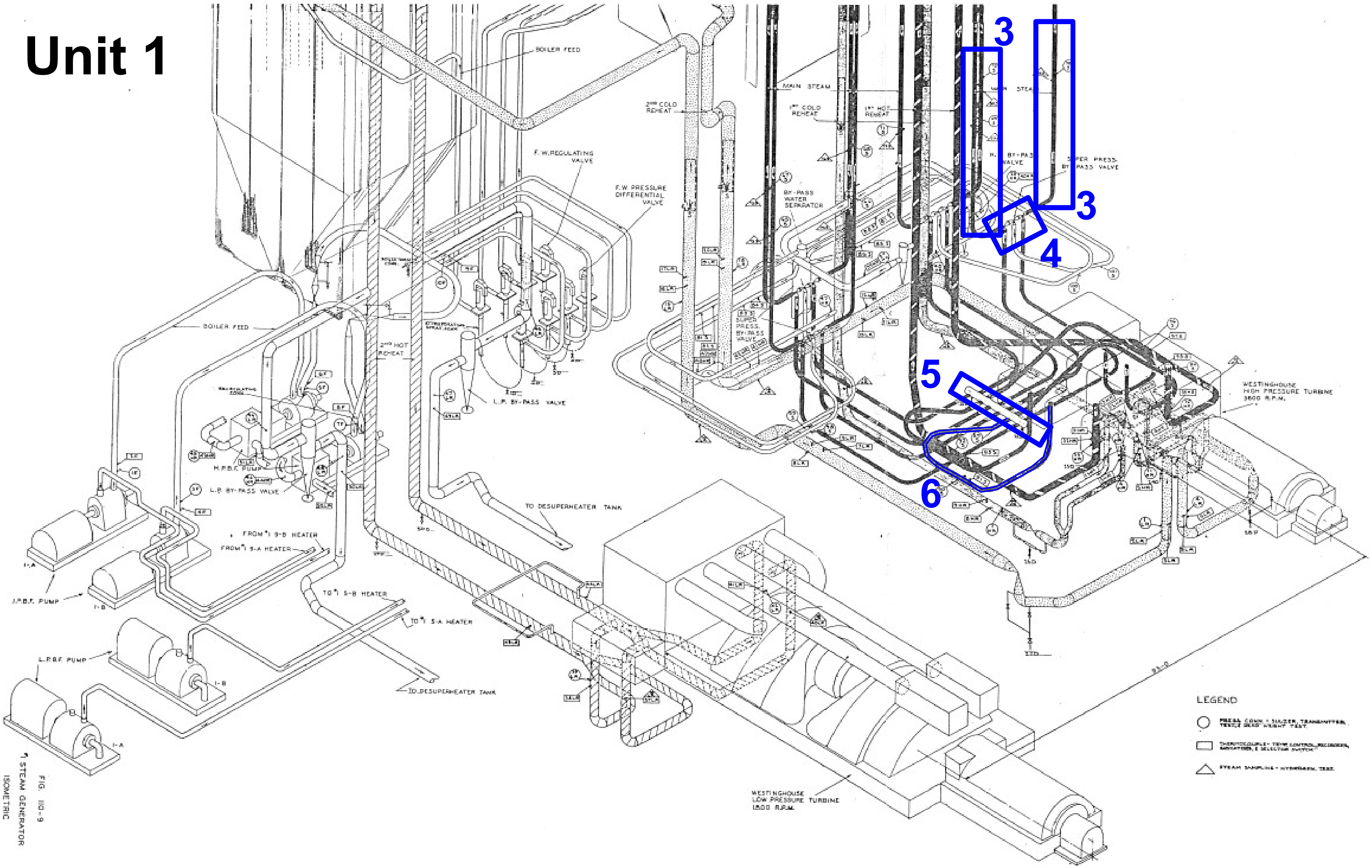
Together…Shaping the Future of Electricity

Eddystone - Unit 1



- 325MW
- Commissioned in 1960
- 1200F / 5000psig Design
- 1130F / 5000psig (~1965)
  - 316 MS piping
  - Grade 22 HRH
  - “Experimental” WW Materials

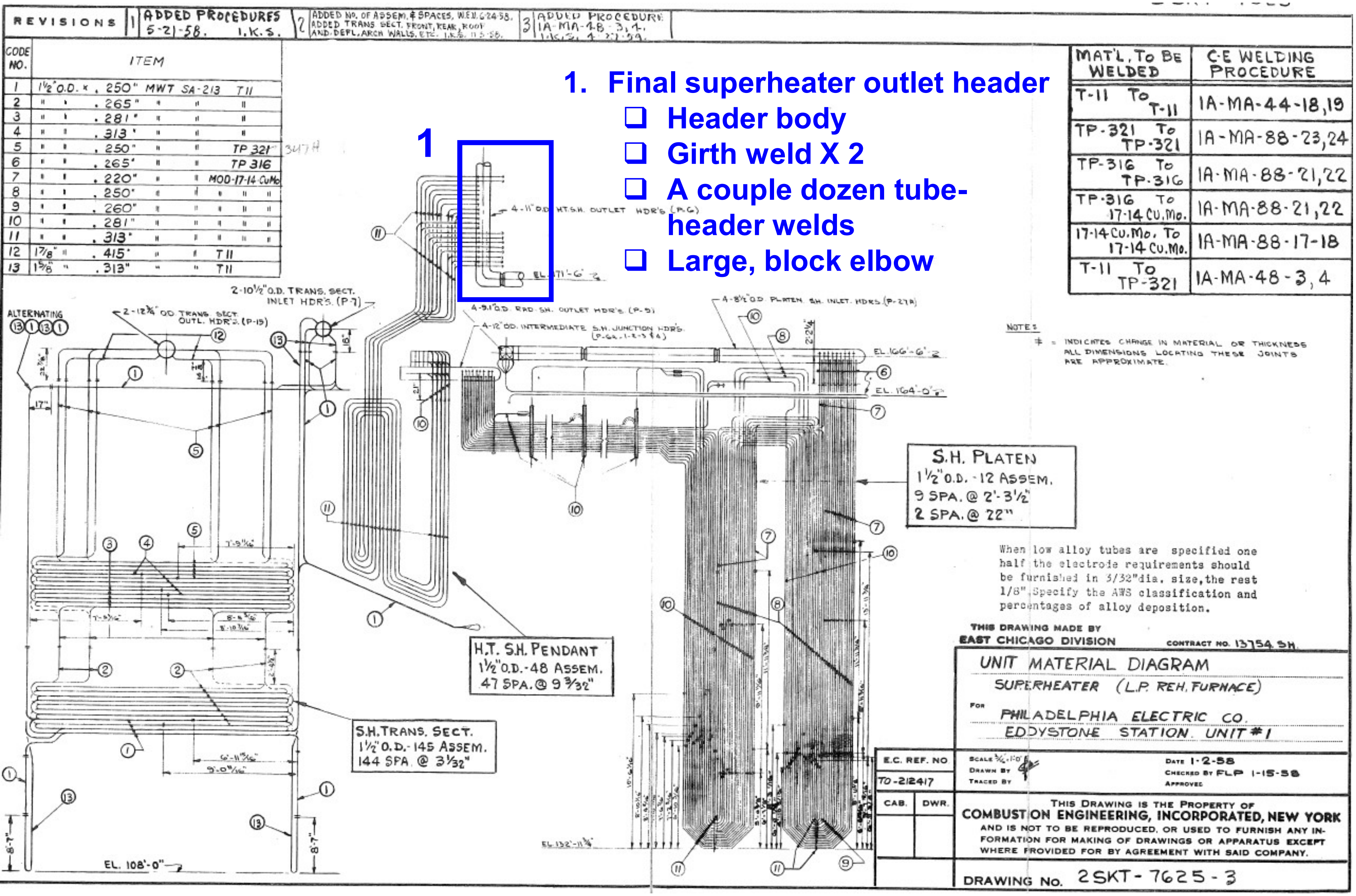
Unit 1



ELECTRIC POWER RESEARCH INSTITUTE

1. Final superheater outlet header

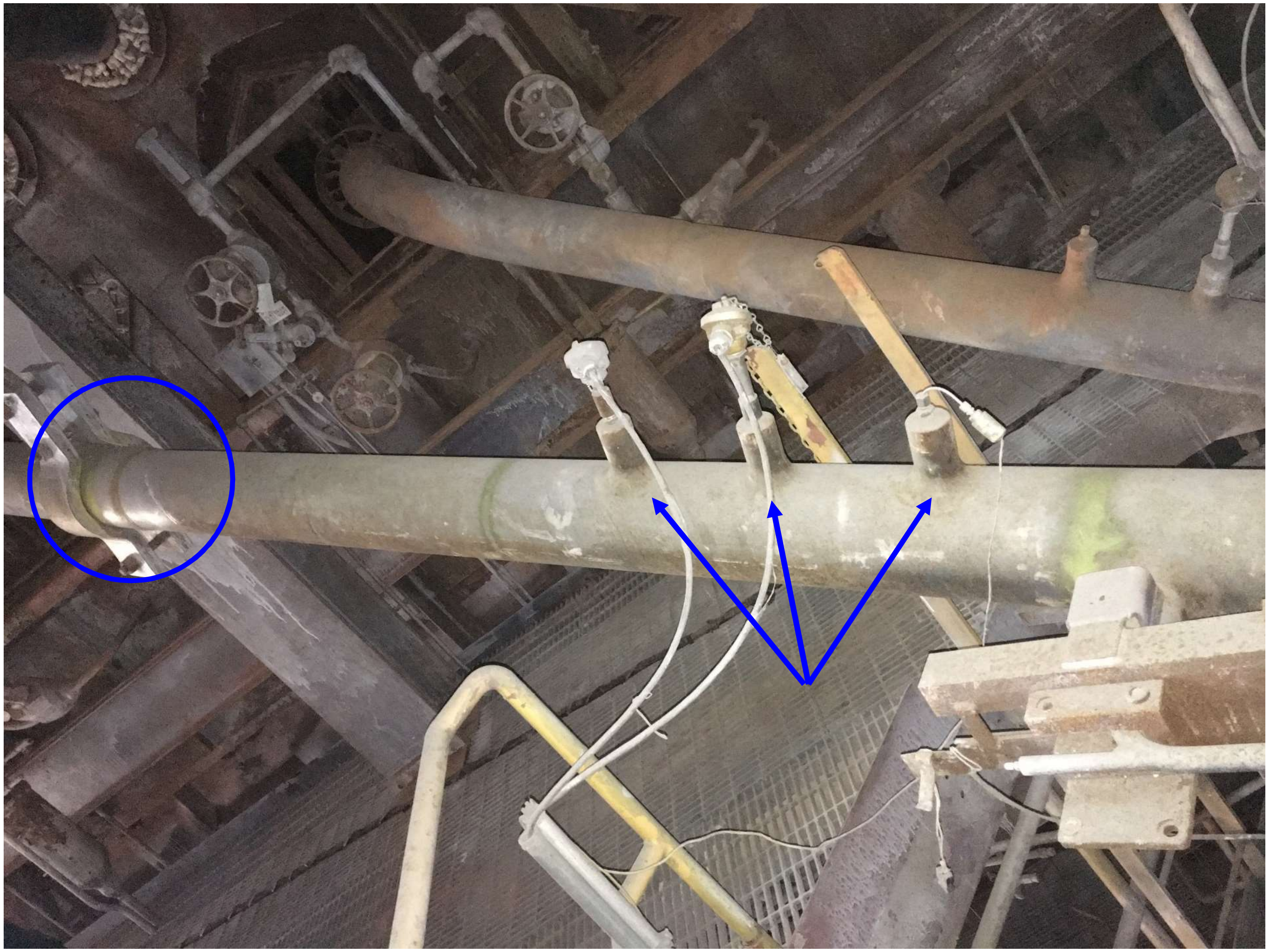
- Header body
- Girth weld X 2
- A couple dozen tube-header welds
- Large, block elbow



CODE NO.	ITEM
1	1½" O.D. x .250" MWT SA-213 T11
2	" " .265" " " "
3	" " .281" " " "
4	" " .313" " " "
5	" " .250" " " TP 321 (347H)
6	" " .265" " " TP 316
7	" " .220" " " MOD-17-14-CuMo
8	" " .250" " " " " "
9	" " .260" " " " " "
10	" " .281" " " " " "
11	" " .313" " " " " "
12	1⅞" " .415" " " T11
13	1⅝" " .313" " " T11

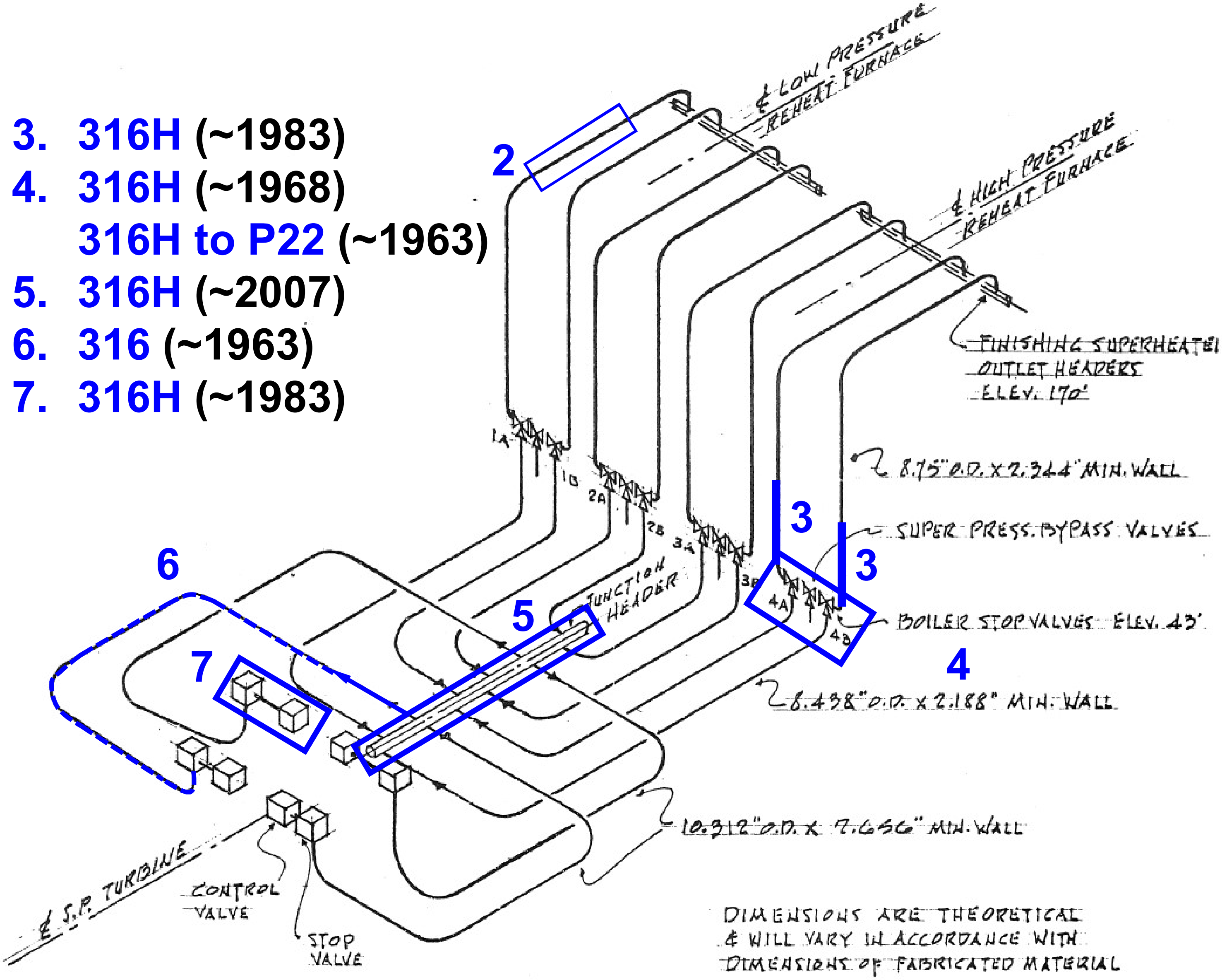
MAT'L. TO BE WELDED	C-E WELDING PROCEDURE
T-11 To T-11	1A-MA-44-18, 19
TP-321 To TP-321	1A-MA-88-23, 24
TP-316 To TP-316	1A-MA-88-21, 22
TP-316 To 17-14 Cu.Mo.	1A-MA-88-21, 22
17-14 Cu.Mo. To 17-14 Cu.Mo.	1A-MA-88-17-18
T-11 To TP-321	1A-MA-48-3, 4

1. Final superheater outlet header (~1986)
   - ❑ Header body
   - ❑ Girth weld X 2
   - ❑ A couple dozen tube-header welds
   - ❑ Large, block elbow



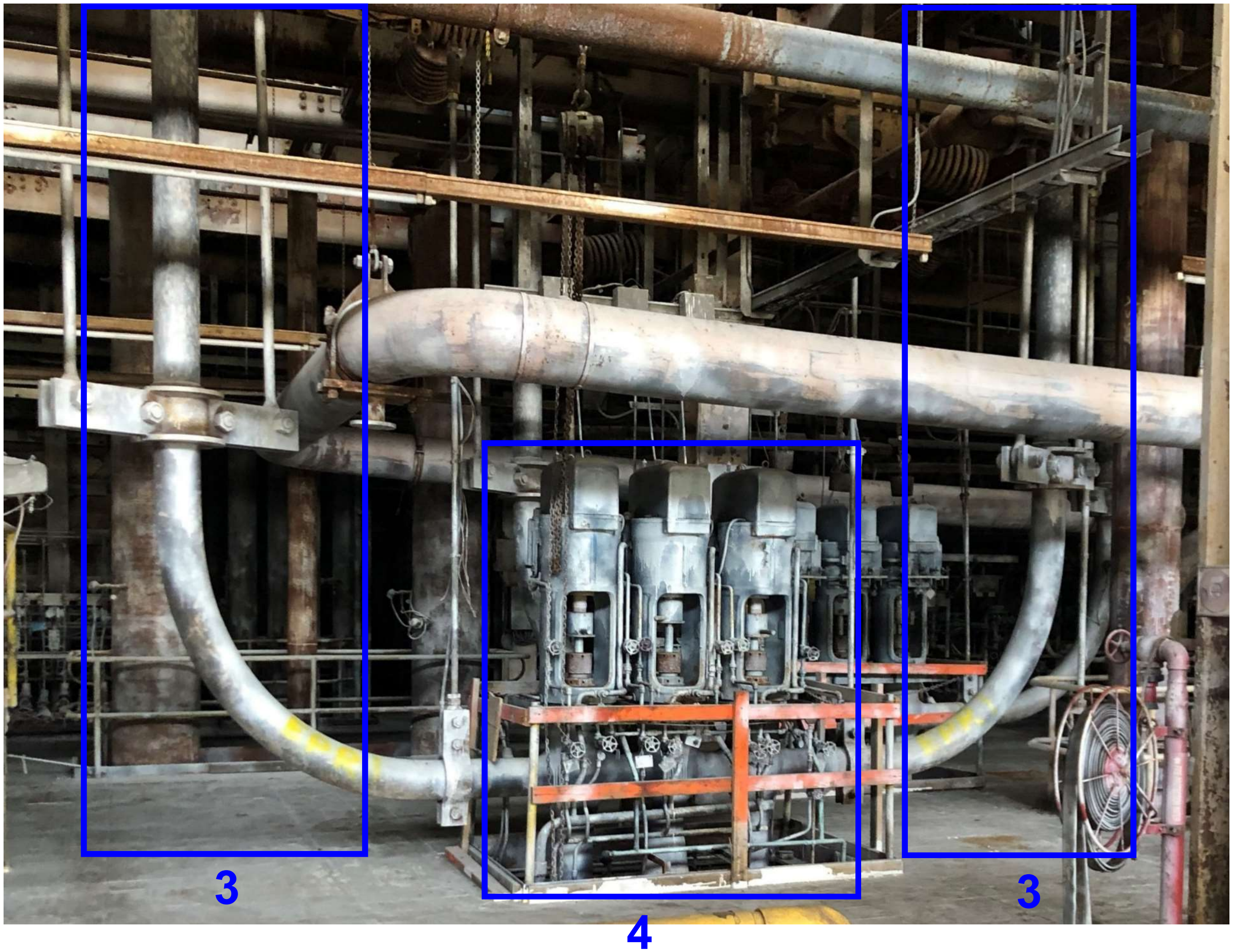
2. Main steam piping, penthouse (1983)
   - ❑ Straight sections
   - ❑ Girth weld
   - ❑ Three small bore penetrations

3. **316H** (~1983)
4. **316H** (~1968)
   316H to P22 (~1963)
5. **316H** (~2007)
6. **316** (~1963)
7. **316H** (~1983)

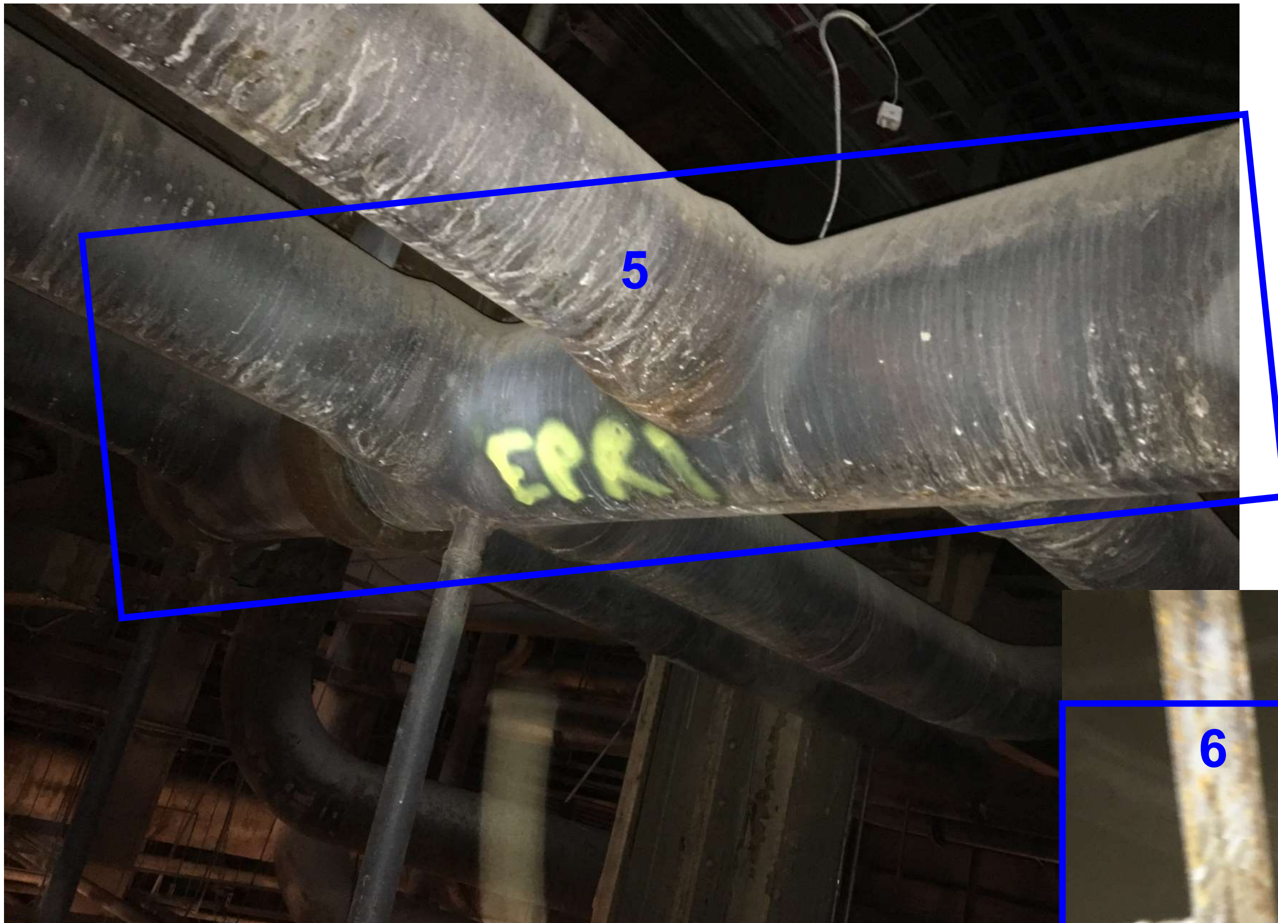


2. **Main steam piping, penthouse**
   - ❑ Straight sections
   - ❑ Girth weld
   - ❑ Three small bore penetrations
3. **Main steam piping**
   - ❑ Straight sections
   - ❑ Girth weld
   - ❑ Large radius bend
4. **Super pressure boiler stop – bypass valve assembly 4**
   - ❑ Girth welds
   - ❑ Repairs on bypass upper branch X 3
   - ❑ DMW on bypass outlet
5. **Junction header**
6. **Main steam junction header outlet lead [E1M1A2]**
   - ❑ Straight sections
   - ❑ Girth weld
   - ❑ Large radius bend
   - ❑ Small bore penetrations
7. **Super pressure turbine stop-control valve assemblies**
   - ❑ Castings
   - ❑ Hardfaced seats
   - ❑ One girth weld

3. Main steam piping (316H – 1983)
   - ❑ Straight sections
   - ❑ Girth weld
   - ❑ Small bore penetrations

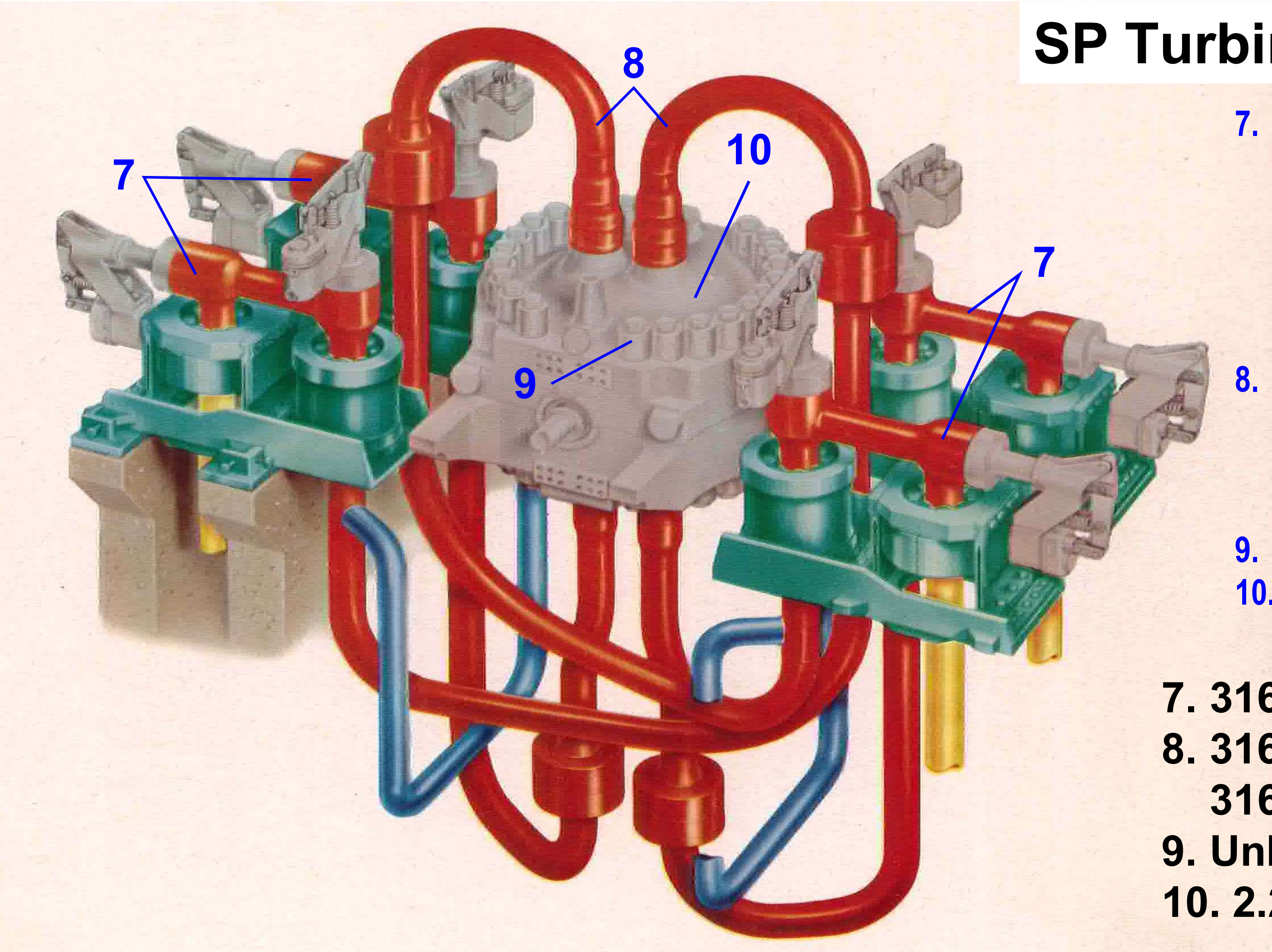


3. **Main steam piping** (1983)
   - ❑ **Straight sections**
   - ❑ **Girth weld**
   - ❑ **Large radius bend**
4. **SP boiler stop – bypass valve assembly 4** (1968)
   - ❑ **Girth welds**
   - ❑ **Repairs on bypass upper branch X 3**
   - ❑ **DMW on bypass outlet**



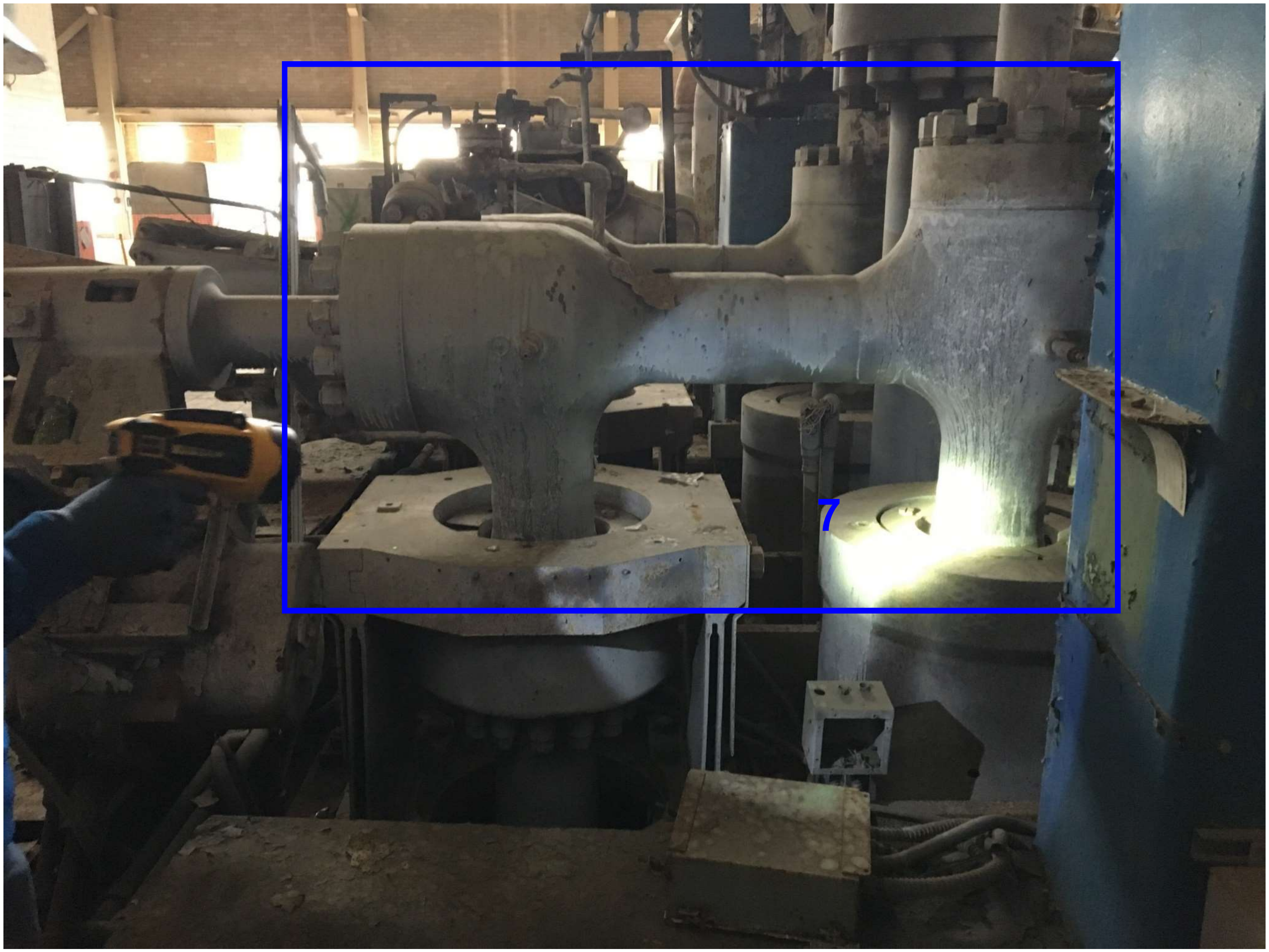
5. **Junction header** (2007)
6. **Main steam junction header outlet lead [E1M1A2]** (~1963)
   - ❑ **Straight sections**
   - ❑ **Girth weld**
   - ❑ **Large radius bend**
   - ❑ **Small bore penetrations**

SP Turbine Inlet Piping

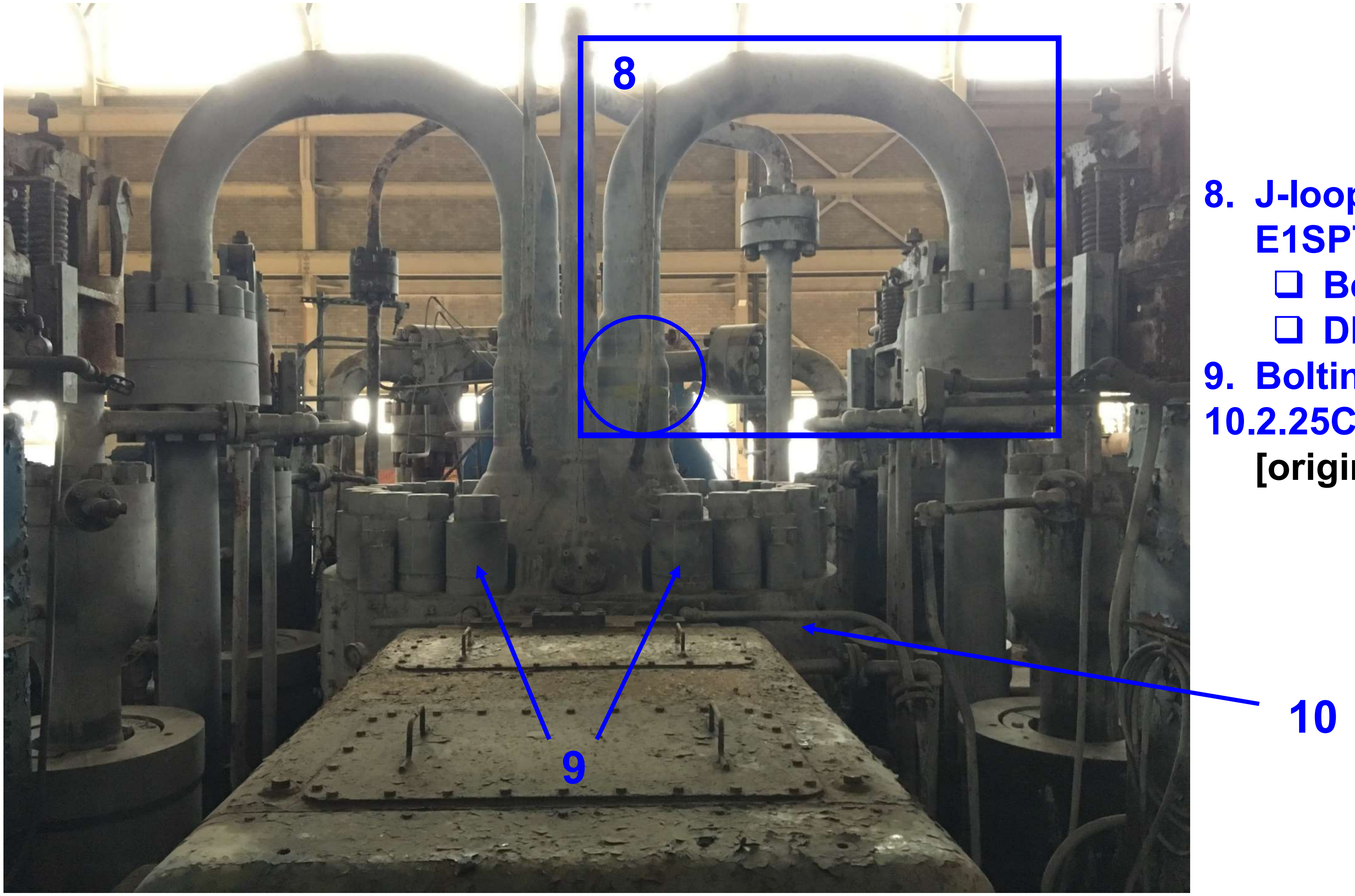


7. Super pressure turbine stop-control valve assemblies A-1, A-2, B-1 and B-2
   - ❑ Castings
   - ❑ Hardfaced seats
   - ❑ One girth weld
8. J-loop turbine inlet piping E1SPTA1 and E1SPTB1
   - ❑ Bend [original]
   - ❑ DMW [2007]
9. Bolting
10. 2.25Cr-1Mo-V Casing

7. 316H (~1983)
8. 316H (~1960)
   316H to P22 (2007)
9. Unknown (unknown)
10. 2.25Cr-Mo-V (1960)



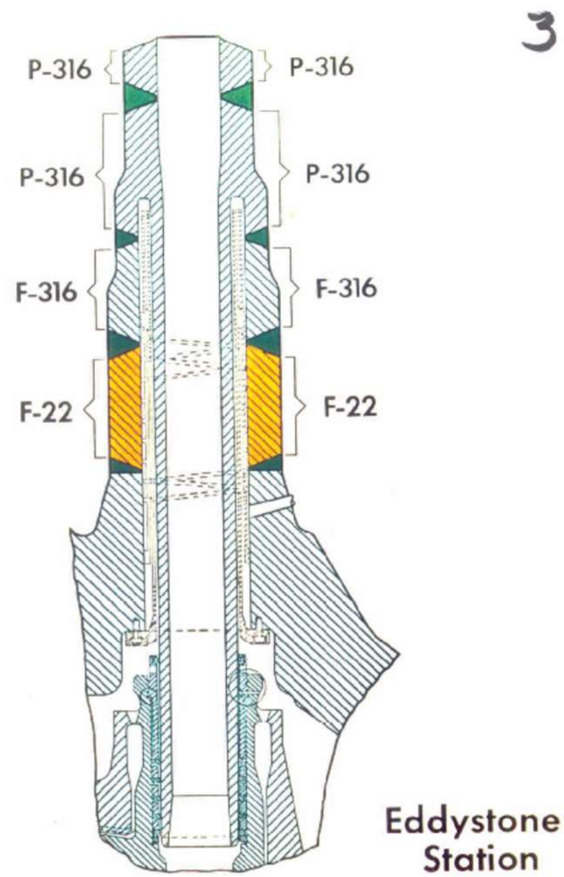
7. **SP turbine stop-control valve assemblies A-1, A-2, B-1 and B-2** (1983)
   - **Castings**
   - **Hardfaced seats**
   - **One girth weld**



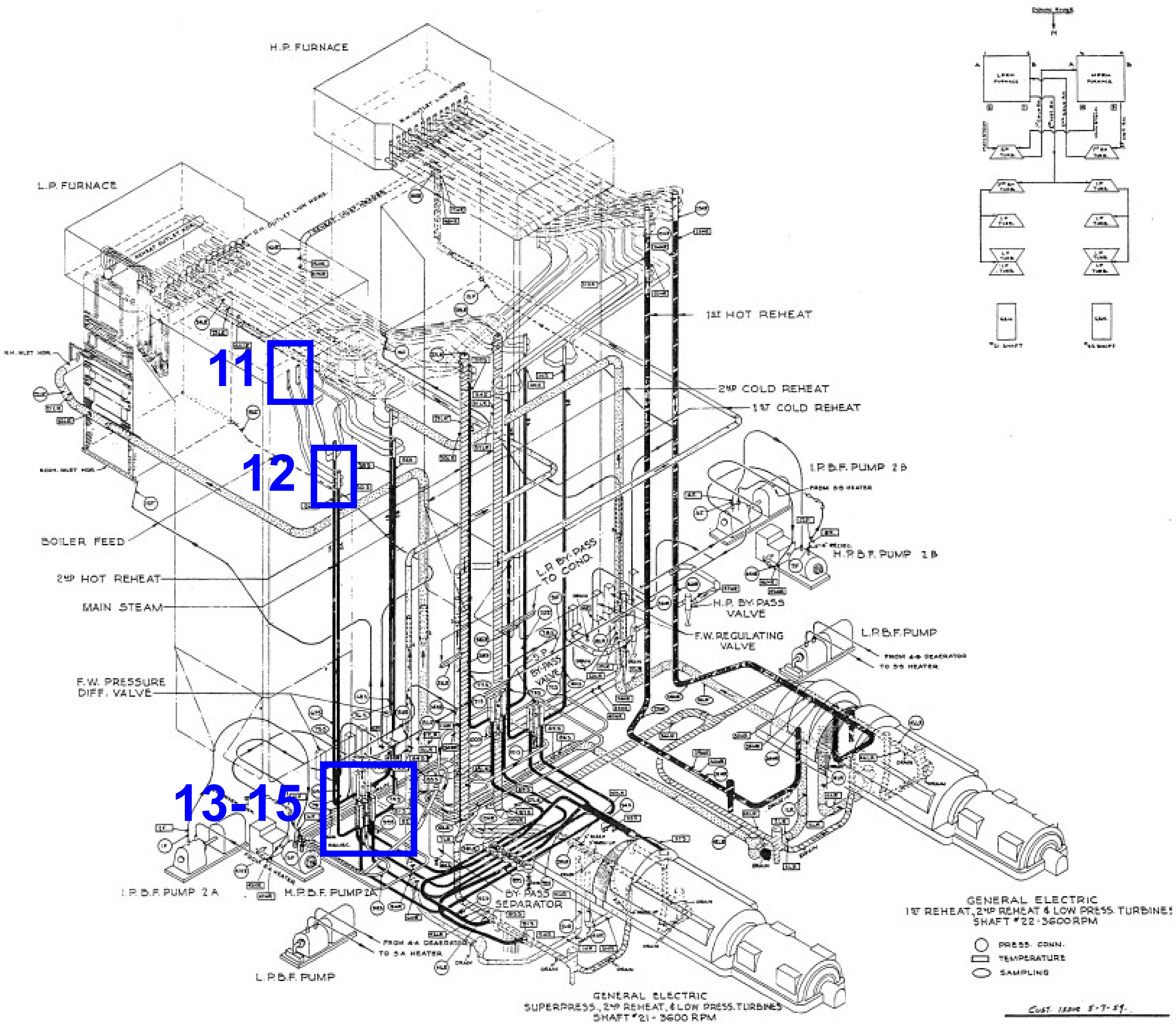
8. J-loop turbine inlet piping E1SPTA1 and E1SPTB1
   - ❑ Bend [original]
   - ❑ DMW [2007]
9. Bolting [unknown]
10. 2.25Cr-1Mo-V Casing [original]

J-Loop DMWs

- Operational data for the top leads show that these operated at higher temperature throughout the life of the plant; operational data – reported as skin temperature and then extrapolated to steam temperature – from 1978 is given below
- 13” OD X 2.5” WT
- The lower DMWs consistently showed the most damage throughout the life of the plant, as reported and summarized in 1978 and as noted by the catastrophic failure in 2007
  - (6) Top, up-river – skin temperature on OD = **1010-1013°F**
  - (4) Top, down-river – skin temperature on OD = **1004-1006°F**
  - (5) Bottom, up-river – skin temperature on OD = **968-969°F**
  - (7) Bottom, down-river – skin temperature on OD = **957-970°F**
  - Average steam temperature **~1110 to 1135°F**
  - Note the thermal sleeve which reduces the overall temperature at the DMW by design



#1 UNIT SP TURBINE
Outer Cylinder Steam Leads



STEAM FLOW DIAGRAM

FIG. 210-2

Unit 2

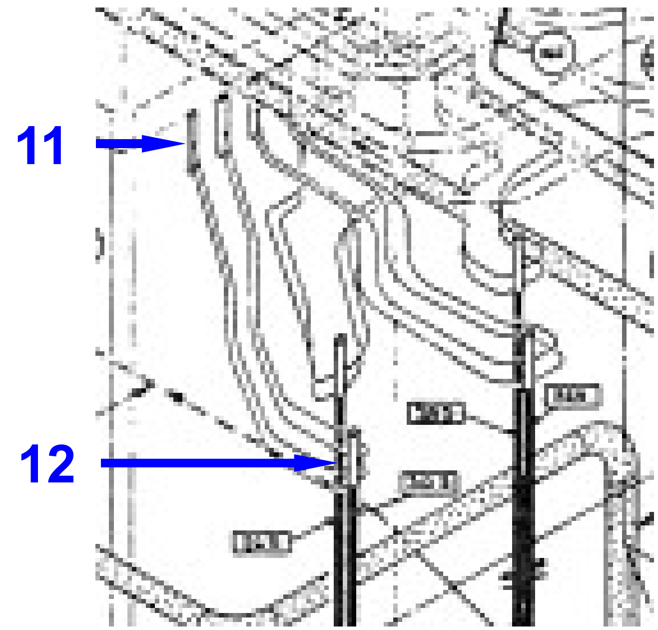
11. 316H SHOH (original)
    - Tube-to-header welds
    - Pipe-to-header welds
12. 316H Connection piping to main steam line (original)
    - Several pipe-to-header welds
    - Girth weld to MS line
    - Small bore penetrations
13. 316H straight pipe section (original)
    - Two small bore welds
    - Straight section (2 heats)
    - One girth weld
14. Dissimilar metal weld [early 1990s]
15. Grade 22 large radius bend (original)

11.316H SHOH (original)
- Tube-to-header welds
- Pipe-to-header welds

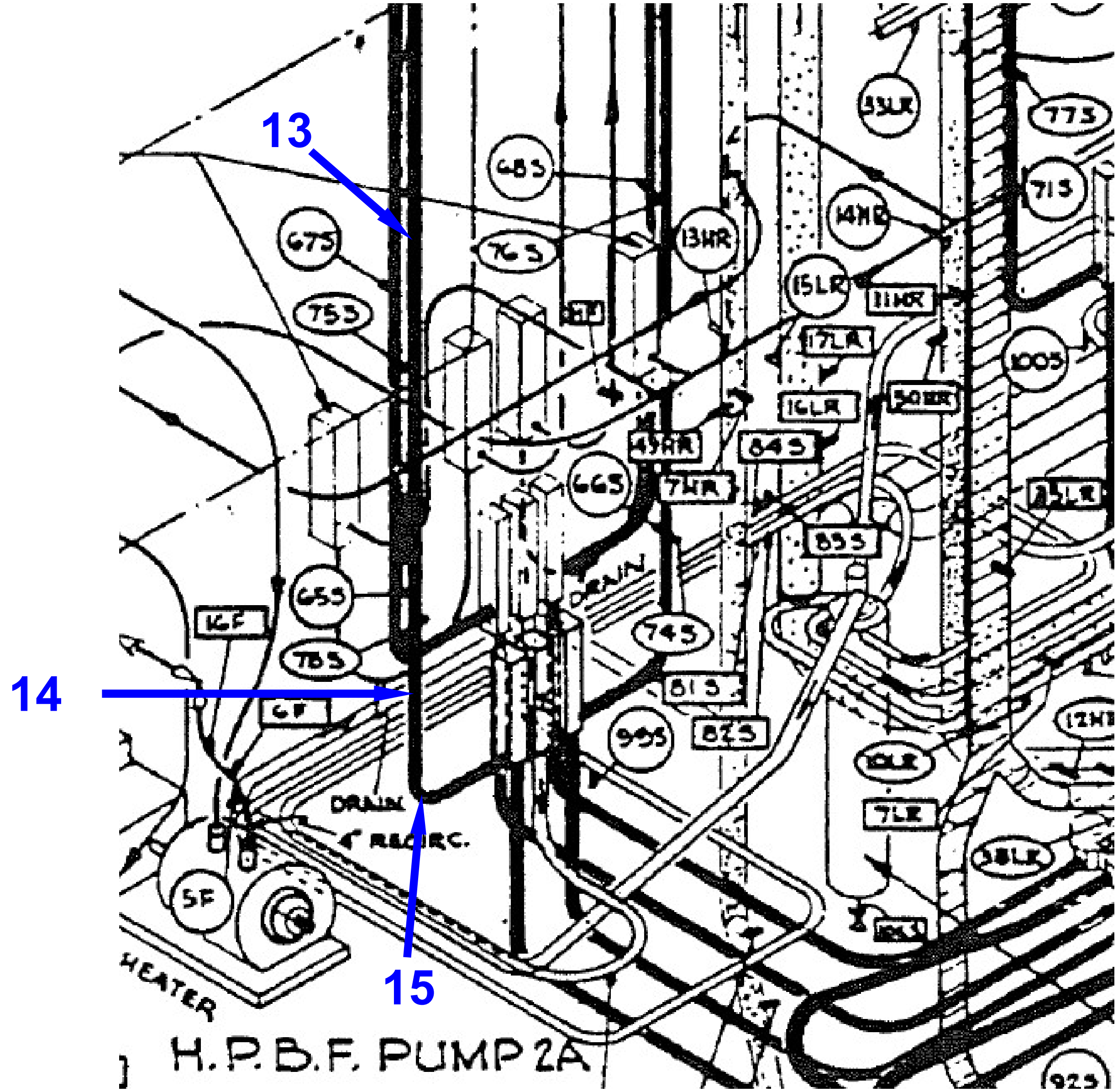
12.316H Connection piping to main steam line (original)
- Several pipe-to-header welds
- Girth weld to MS line
- Small bore penetrations

11

12



13. 316H straight pipe section (original)
    - Two small bore welds
    - Straight section (2 heats)
    - One girth weld
14. Dissimilar metal weld (~1990)
15. Grade 22 large radius bend (original)



13

14

13. 316H straight pipe section(original)
  - ❑ Two small bore welds
  - ❑ Straight section (2 heats)
  - ❑ One girth weld

14. Dissimilar metal weld (~1990)

15.Grade 22 large radius bend (original)

16.SP Rotors – Unit 1(original)