Optimization of Advanced Steels for Cyclic Operation through an Integration of Material Testing, Modeling and Novel Component Test Validation

DE-FE002620, P.O.P. 9/3/15 to 3/30/17

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NETL Project Manager

Project Goals and Objectives

- To develop the needed microstructural processing and performance relationships and associated material models for specific constituents in fabricated weldments (such as the parent material, heat affected zone regions and weld metal),
- Apply these metallurgical relationships through modeling of a welded pressure bearing power plant component subjected to cyclic operational conditions under both mechanical and thermal loading, and
- Validate the model through novel structural feature and component tests.

Milestone Description	Completion Date
Task 1.0 – Kickoff Meeting	11/6/2015
Task 1.0 – Updated Project Management Plan	9/24/2015
Task 1.0 – Submit Final Report	
Task 2.0 – Materials and Processing	1/26/2016
Task 3.0 – Fabrication of Test Coupons	3/1/2016
Task 4.0 – Testing of optimized Grade 92 steel parent material and weldments	In process
Task 5.0 – Microstructural Evaluation of chosen material	In process
Task 6.0 – Design and Modeling of Component Test	In process
Task 7.1 – Conceptual design for a feature test of parent material and weldments under flexible operation	4/29/2016
Task 7.2 – Assemble and complete a check-out test on one experimental test frame for use in Phase 2 follow-on proposal work	In process

Outline

- Motivation for the Research
- Team Assembled, Plan, and Defining Test Conditions & Materials
- Experimental Approach
- Results and Ongoing Characterization
- Future Work and Summary

Motivation for Research

Today's 'Options' for State-of-the-Art HRSGs; Steam ≥ 600°C

<u>**Summary of Key Challenges facing OEMs**</u> [Not limited to]:

- ❑ Steamside Oxidation
- ❑ "Air" Oxidation (high moisture content in exhaust gas)
- ❑ Materials with High Creep Strength
- ❑ Materials with variable Creep Ductility
- ❑ Design by rule is in adequate to achieve the stated life and cycling objectives. Conversely, available Design by Analysis approaches for fatigue, creep or creep-fatigue vary significantly

Option 1a: Stainless Steels

- Advanced grades (principally Super 304H) or 'traditional' 300 series "H" grades (principally 347H)
- **Dissimilar metal welds**

Option 1b: Substitute stainless steel for lean Ni-base alloy

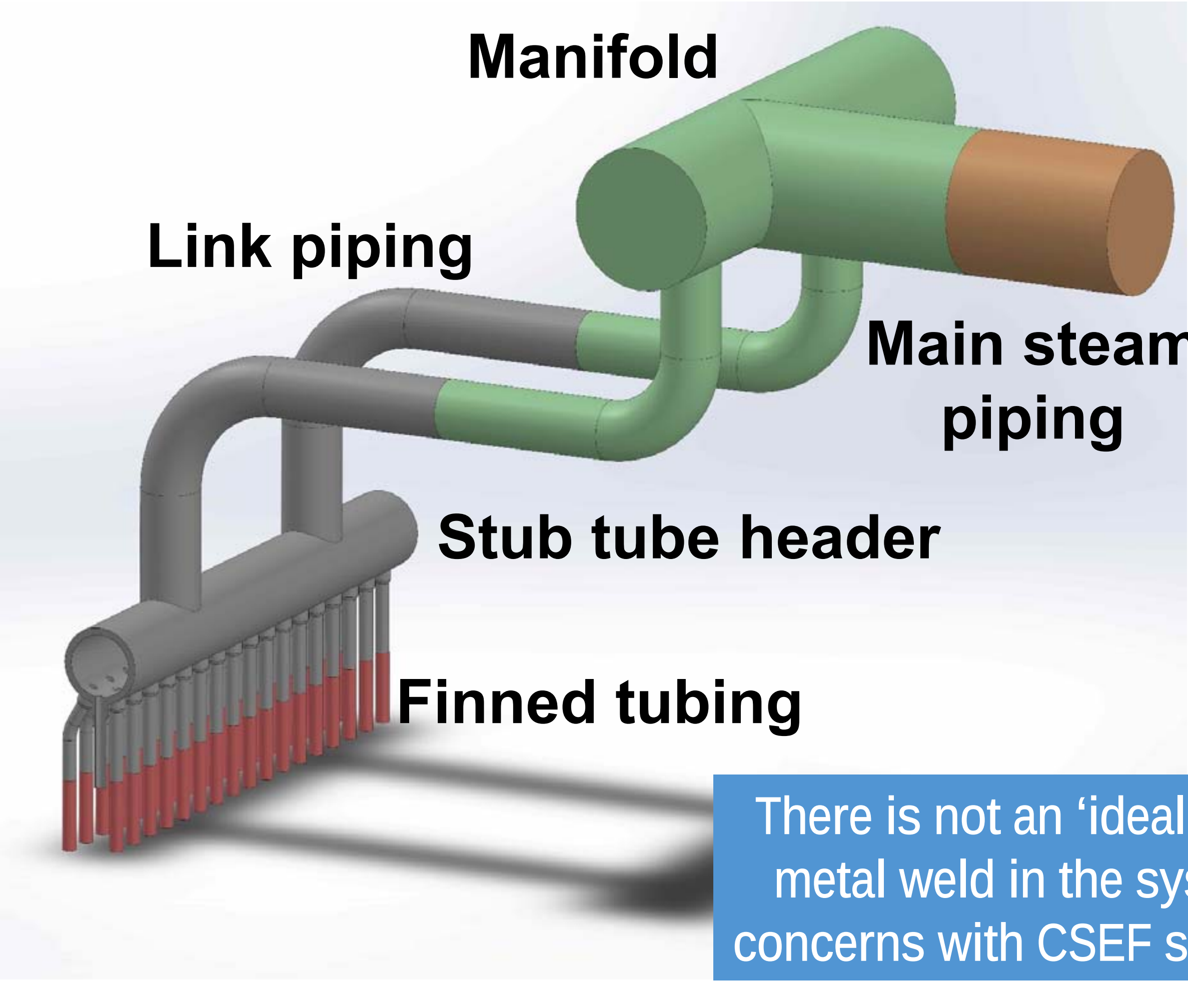
- Lean Ni-base alloy options include HR6W, alloy 800H and potentially others
- **Dissimilar metal welds**

Should avoid DMWs in flexible operation whenever possible

Option 2: 'More' Creep Strength Enhanced Ferritic Steels

- Oxidation resistant 11Cr variants (i.e. THOR 115 and VM12SHC)
- High creep strength 9%Cr variants (i.e. Gr. 92 and SAVE 12AD) and 'pushing the performance envelope' of Gr. 91/Gr. 92

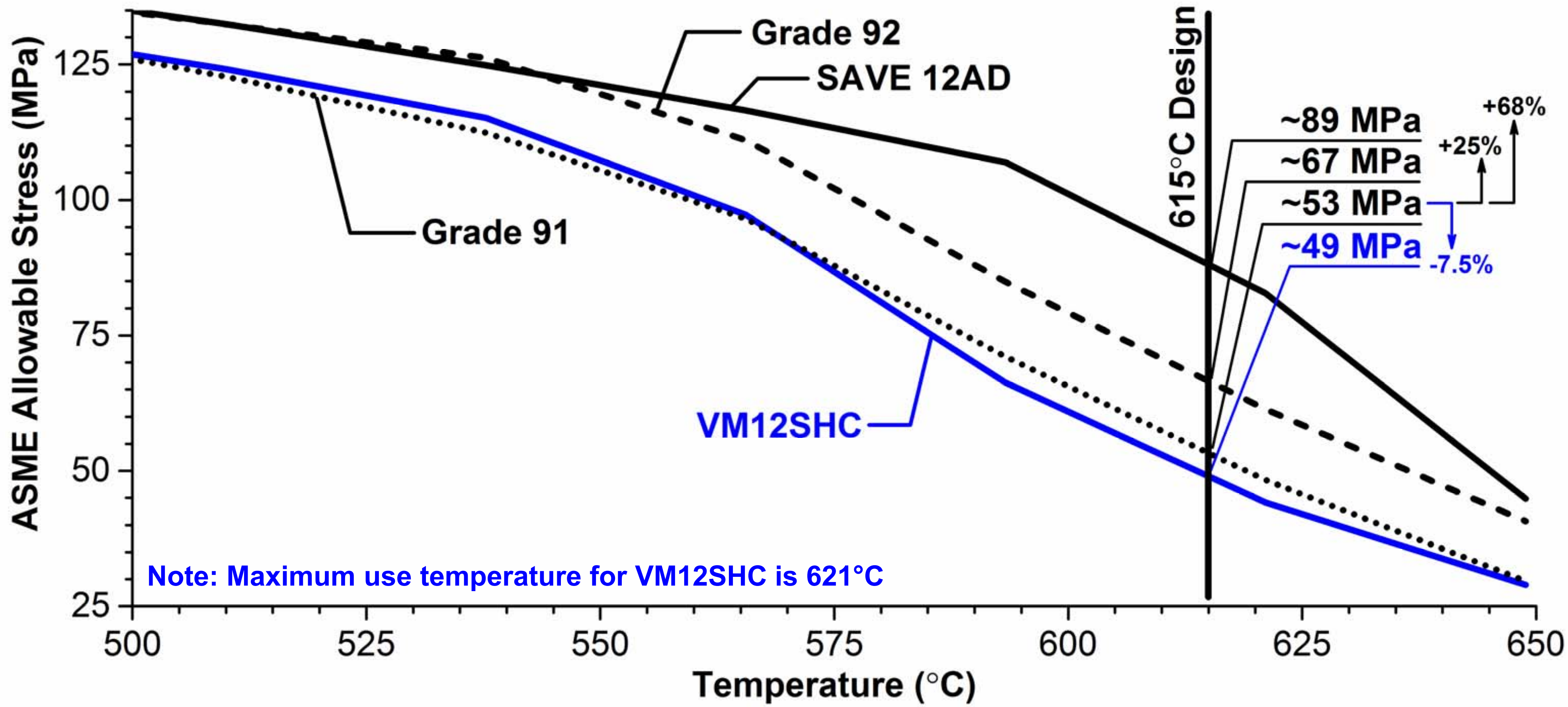
Materials Challenges: HRSG Configuration



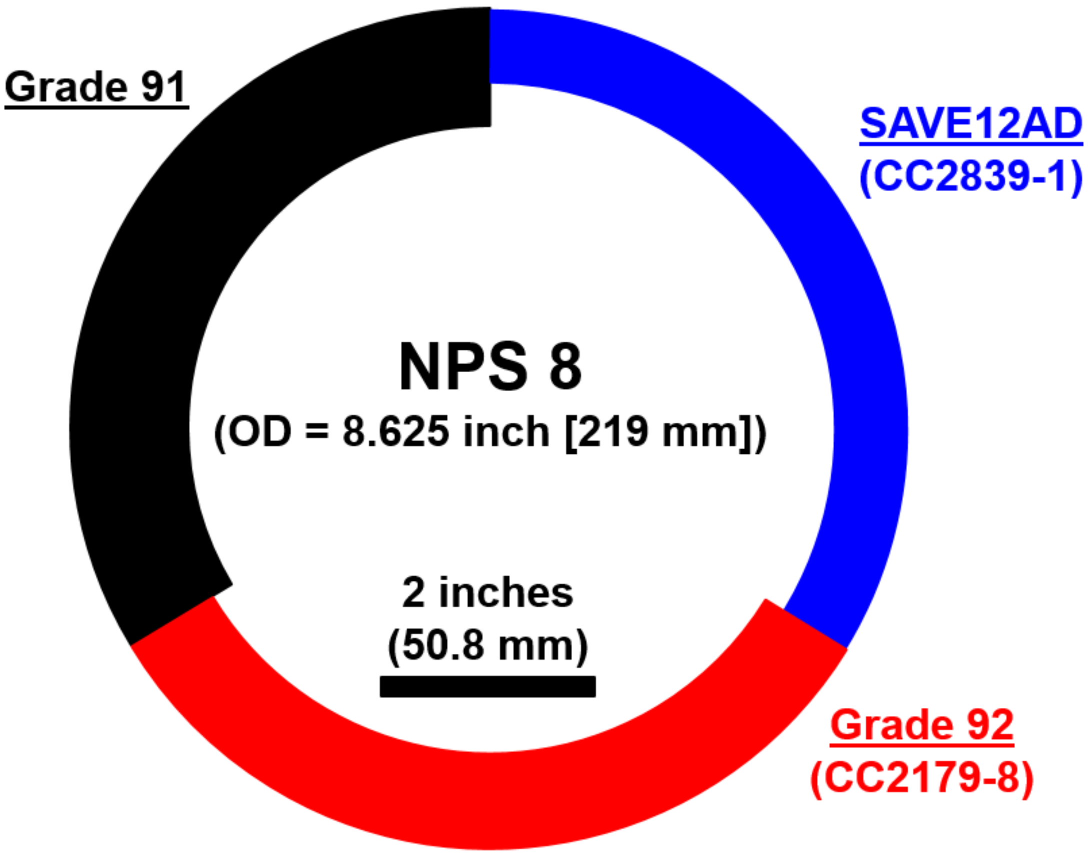
- Practical challenges
  - Where to place DMWs
  - Designing with stainless steels
    - Thermal-fatigue
    - Welding
    - Sensitization
    - Metallurgical risk (sigma phase evolution)

There is not an ‘ideal’ option for placement of a dissimilar metal weld in the system. Although there are significant concerns with CSEF steels, it may be the lesser of two evils

Stress Allowable Comparison for 9Cr and 12Cr Materials [Ref. SA-213 T91, CC2179-8, CC2781, CC2839]



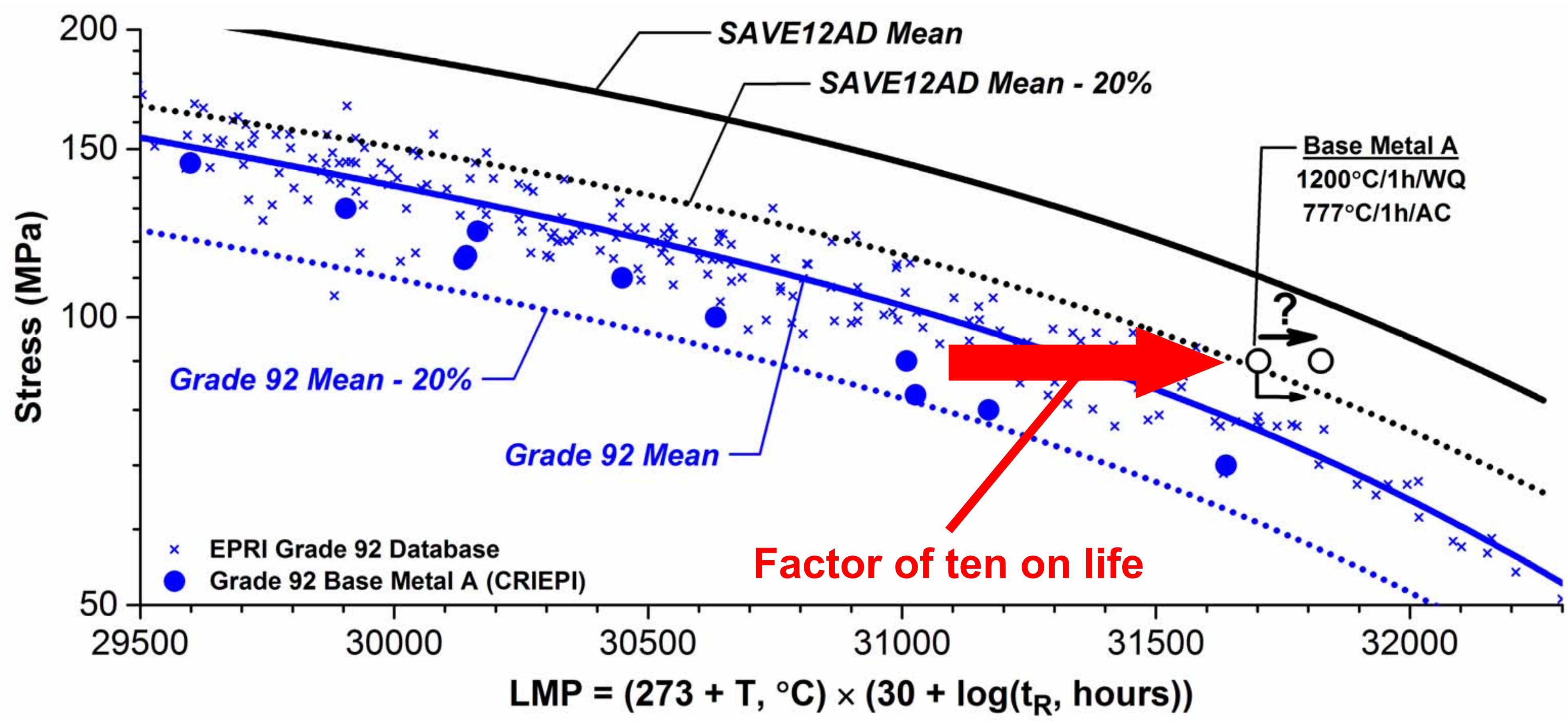
Comparison of Required Wall Thickness for a NPS 8 Superheater Outlet Header



Material	Allowable Stress at 615°C (1140°F) (MPa)	Code required wall thickness (mm)
Grade 91	52.1	30.5
Grade 92 (CC2179-8)	64.7	25.5
Grade 93, SAVE12AD (CC2839-1)	88.6	19.5

Material selection for this application is a balance of oxidation resistance and allowable stress

If both the <u>Composition and Processing</u> are Optimized for Grade 92, we may reasonably Expect Performance within the Scatter-band for SAVE12AD



Formation of In-service Damage is a Function of Three Key Concepts in Martensitic CSEF Steels

- **Damage**
  - Measure = creep ductility [Elongation or reduction of area]
  - Fundamental concept = Void nucleation
  - Key microstructure features = Inclusions/intermetallics
- **Deformation**
  - Measure = creep strength [time to failure, min creep rate, etc.]
  - Fundamental concept = Void growth
  - Key microstructure features = Particles on grain boundaries
- **Stress State**
  - Measure = Equivalent versus principal stress controlled damage
  - Key microstructure features = distribution/extent of damage in carefully controlled tests which introduce multiaxial stress state

Team Assembled, Plan, and Defining Test Conditions & Materials

Tasks

- Task 2.0 – P92 Alloy Procurement and Processing **[Wyman]**
- Task 4.0 – Laboratory Scale Creep, Creep and Thermal Cycling Testing of P92 Samples **[EPRI]**
- Task 5.0 – Microstructural Evaluation of Initial Material, Heat Treatments and as-Tested Samples **[EPRI]**
- Task 6.0 – Development of Constitutive Equations, Creep-Fatigue Models and Design of a Phase II Pressure Vessel Component Test **[Structural Integrity Associates]**
- Task 7.0 – Design and Fabrication of a Structural Feature Scale Creep-Fatigue Test **[ORNL]**

Grade 92 Material

Analysis	C	Mn	P	S	Si	Ni	Cr	Mo	V
Cert	0.10	0.49	0.013	0.002	0.28	0.18	8.79	0.41	0.202
Ind. Analysis	0.084	0.47	0.008	0.0013	0.238	0.17	8.693	0.43	0.192
EPRI Rec.		0.30-0.50	<0.020	<0.005	0.20-0.40	<0.20			
Analysis	**Cu**	**Al**	**As**	**Sn**	**W**	**B**	**Sb**	**Nb**	**N**
Cert	0.18	0.005	0.007	0.011	1.77	0.0029	0.001	0.069	0.0418
Ind. Analysis	0.152	0.002	0.004	0.007	1.86	0.0023	0.0012	0.064	0.0480
EPRI Rec.	<0.10	<0.010	<0.010	<0.010			<0.003		

- Starting material = Grade 92; USA-sourced
  - Section size = 508 mm (20 inch) OD X 134 mm (5.27 inch) WT
  - As-received (1065°C target/air cool + 775°C/air cool)
  - **Optimized (1125°C minimum/oil quench + 775°C/air cool)**

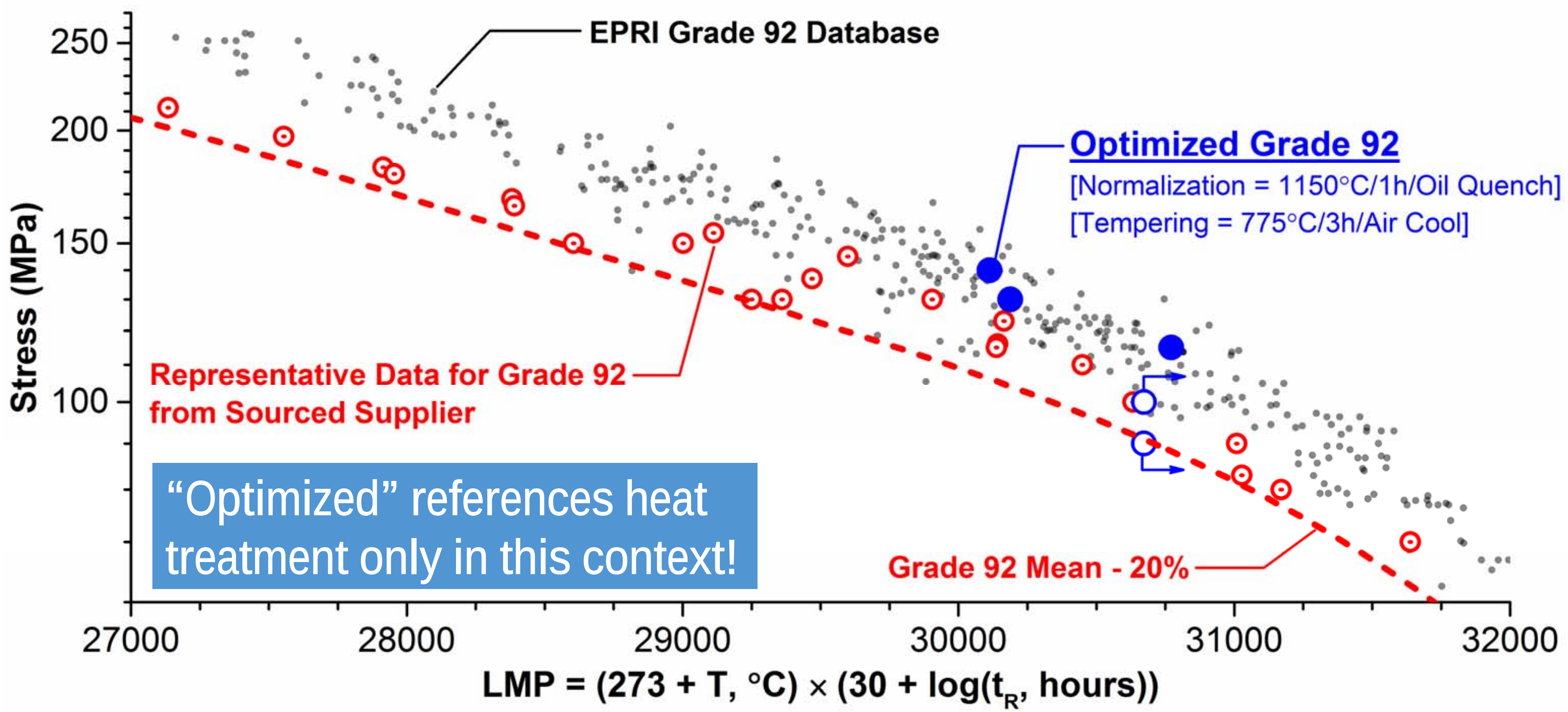
Test Program – Emphasis on Relevance

- Smooth bar creep (for database comparison)
  - Parent metal
  - Simulated HAZ (T_{peak} ~900°C/1m/AC + PWHT)
- Parent metal notch bar creep (multiaxial stress state)
  - *Including a strict Code of Practice to ensure results are consistent*
- Feature type cross-weld creep (multiaxial stress state)
- Sequential testing to separate creep, fatigue and tensile damage mechanisms
  - Fatigue + creep
  - Creep + tensile

Evaluation of all samples to define deformation-damage-stress state effects

Results and On-going Studies

Comparison of Optimized to Conventional Grade 92



“Optimized” references heat treatment only in this context!

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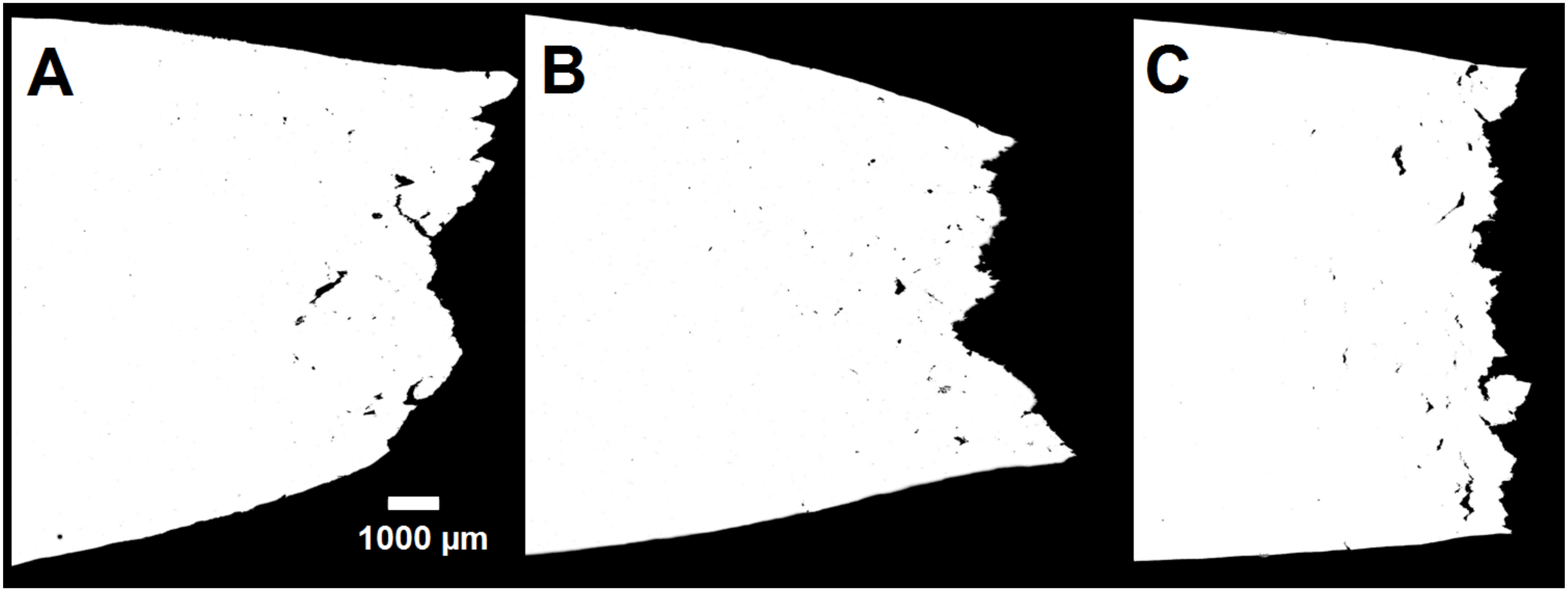
Smooth Bar Creep Tests in Optimized Parent Metal

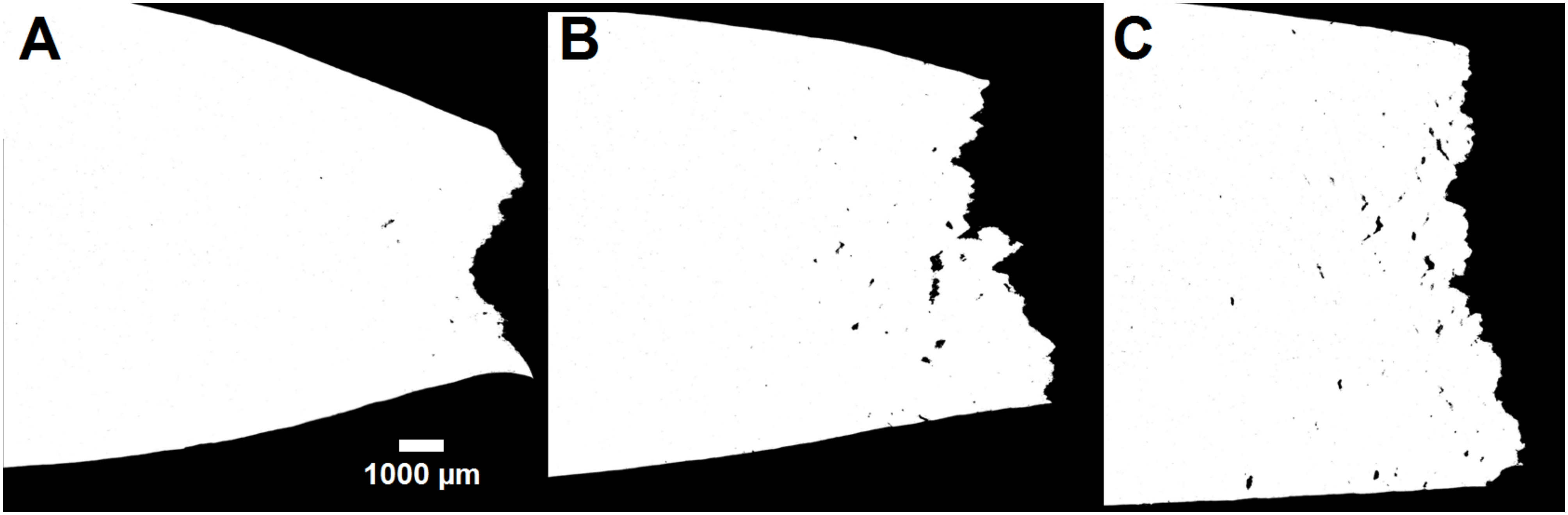


- SB-1, 650°C, 140 MPa
- 422h to failure
- 66.6% ROA

- SB-2, 650°C, 130 MPa
- 509h to failure
- 64.1% ROA

- SB-3, 650°C, 115 MPa
- 2182h to failure
- 31.9% ROA

Smooth Bar Creep Tests in Simulated HAZ

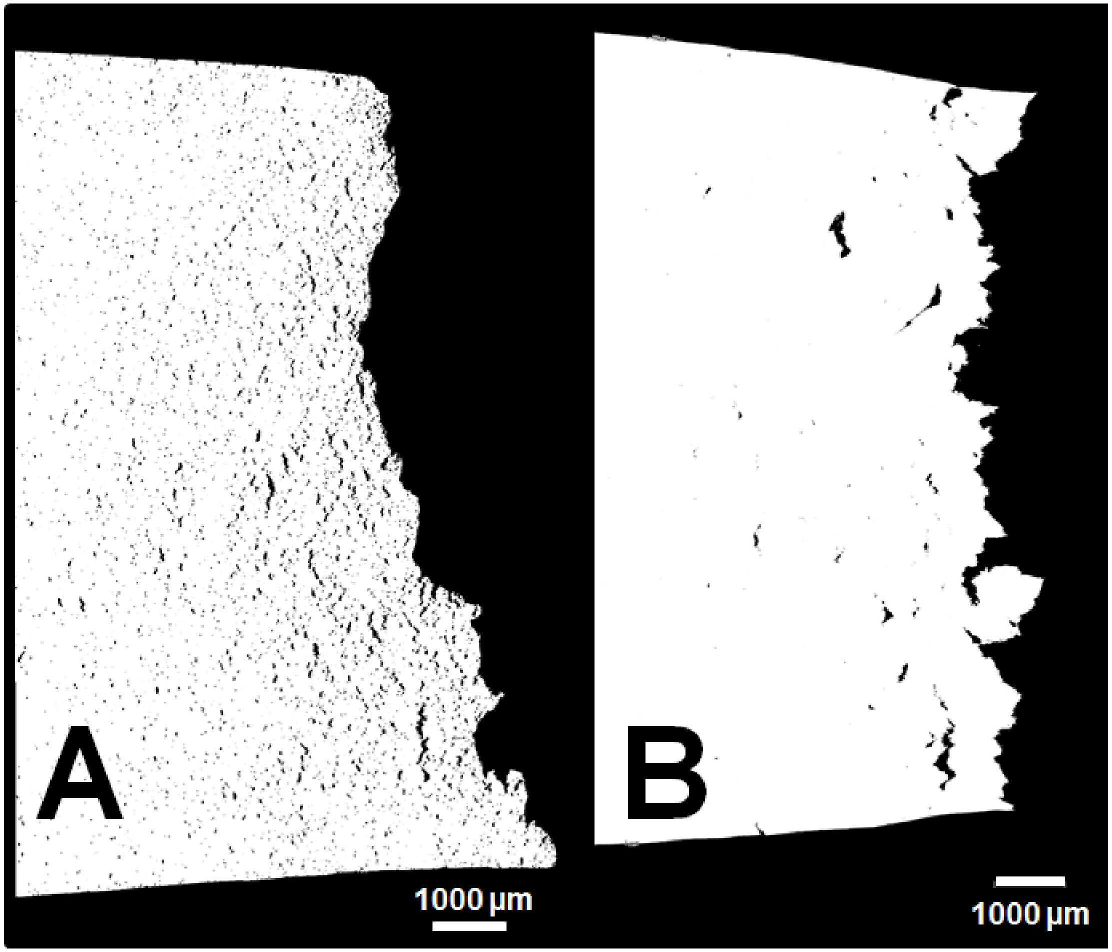


- SB-SHAZ-1a
- 650°C, 115 MPa
- 271h to failure
- 75% ROA

- SB-SHAZ-2a
- 650°C, 100 MPa
- 897h to failure
- 56% ROA

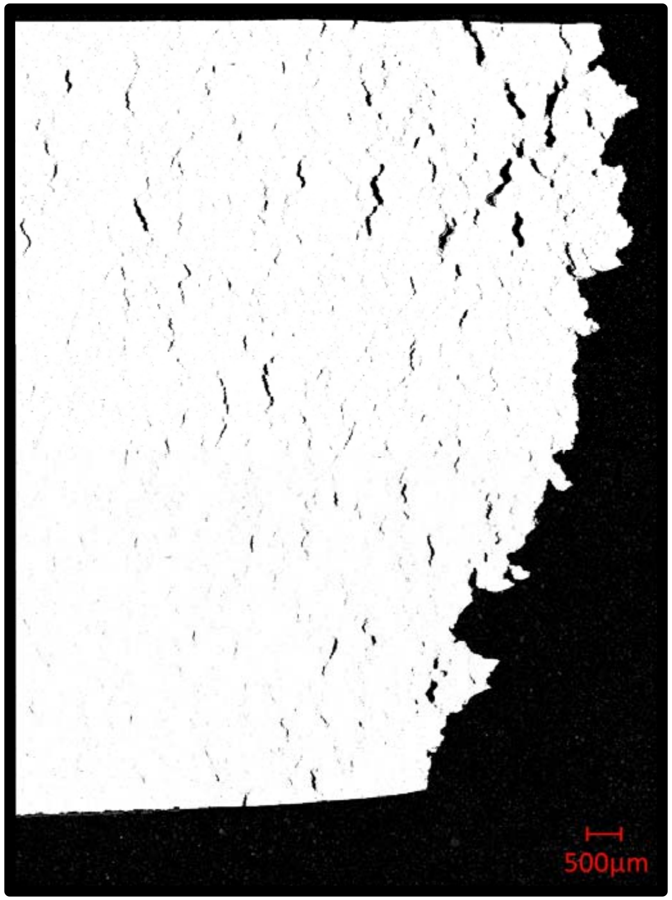
- SB-SHAZ-3a
- 650°C, 90 MPa
- 1832h to failure
- 37% ROA

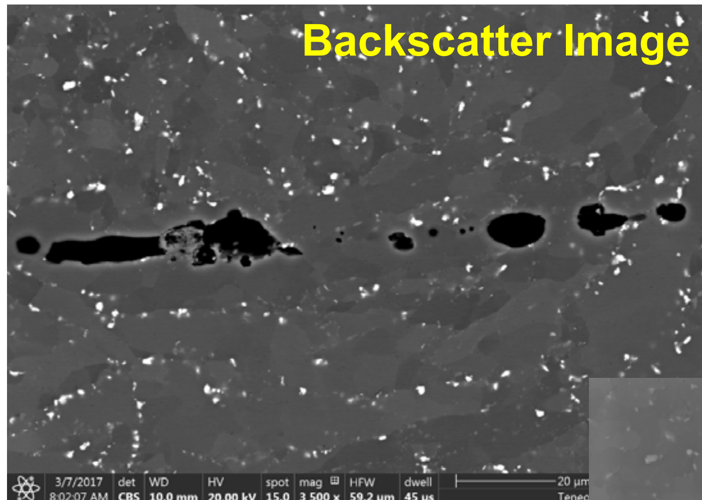
Comparison of Low Ductility Behavior in 9%Cr Steels

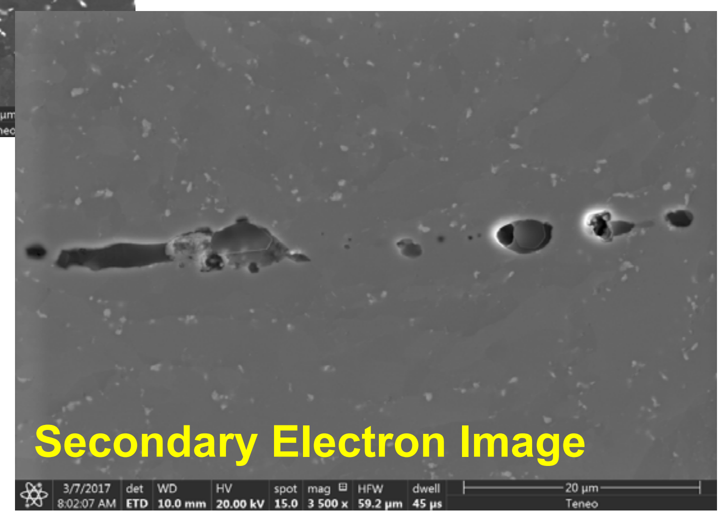


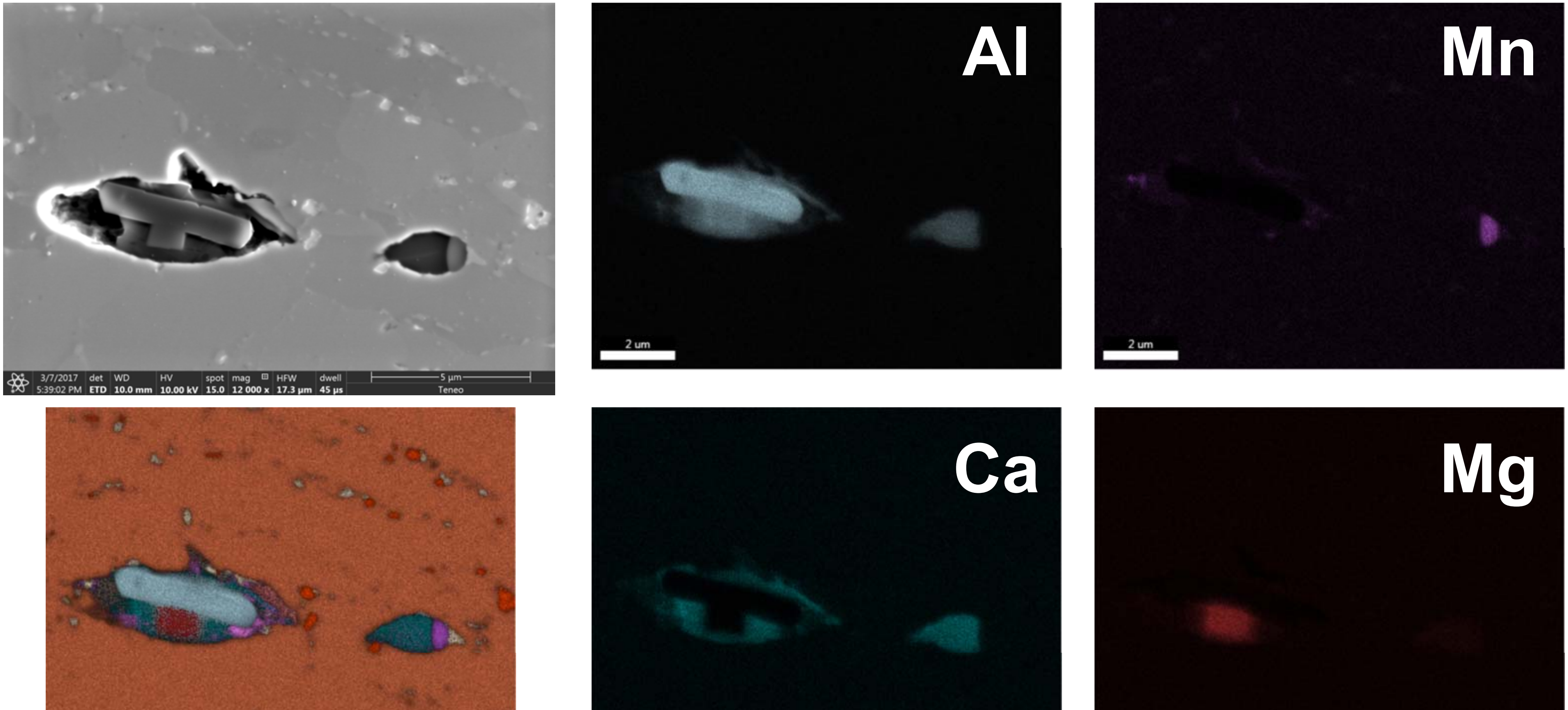
- Both the parent metal and simulated HAZ samples are trending to low creep ductility (HAZ is NOT immune!)
- However, there may be two low ductility mechanisms
  - A – Cavitation dominated
  - B – Local concentration of strain at grain boundaries

SEM Evaluation of Longest Duration Sample SB-SHAZ-4a (650°C, 80 MPa, 3191h to failure, 20% ROA)



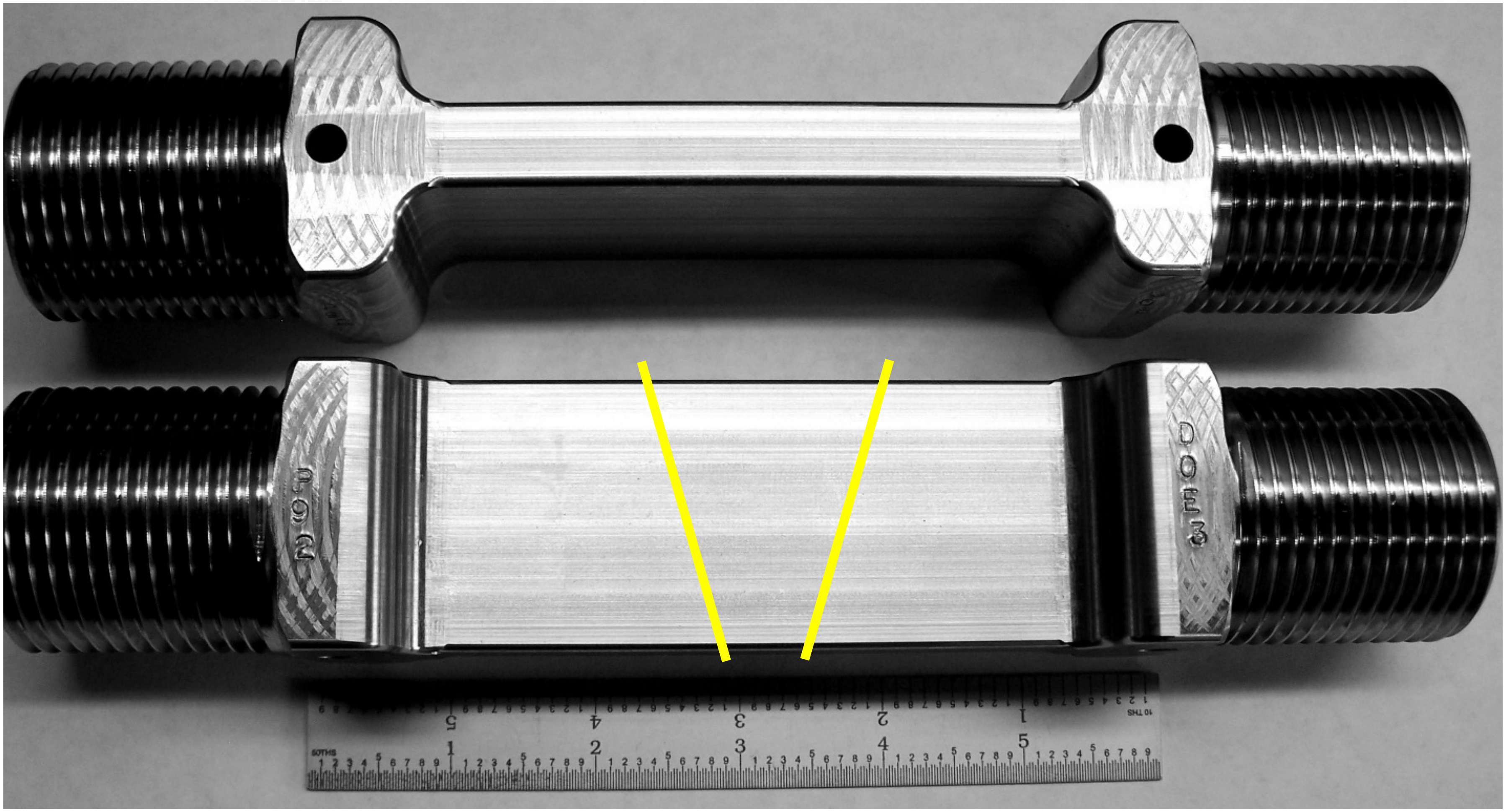






Damage is consistently observed at inclusions; careful observation clearly shows large particles in these voids. Inclusions consistently >1 µm

Feature Cross-weld Creep Test As-machined Sample



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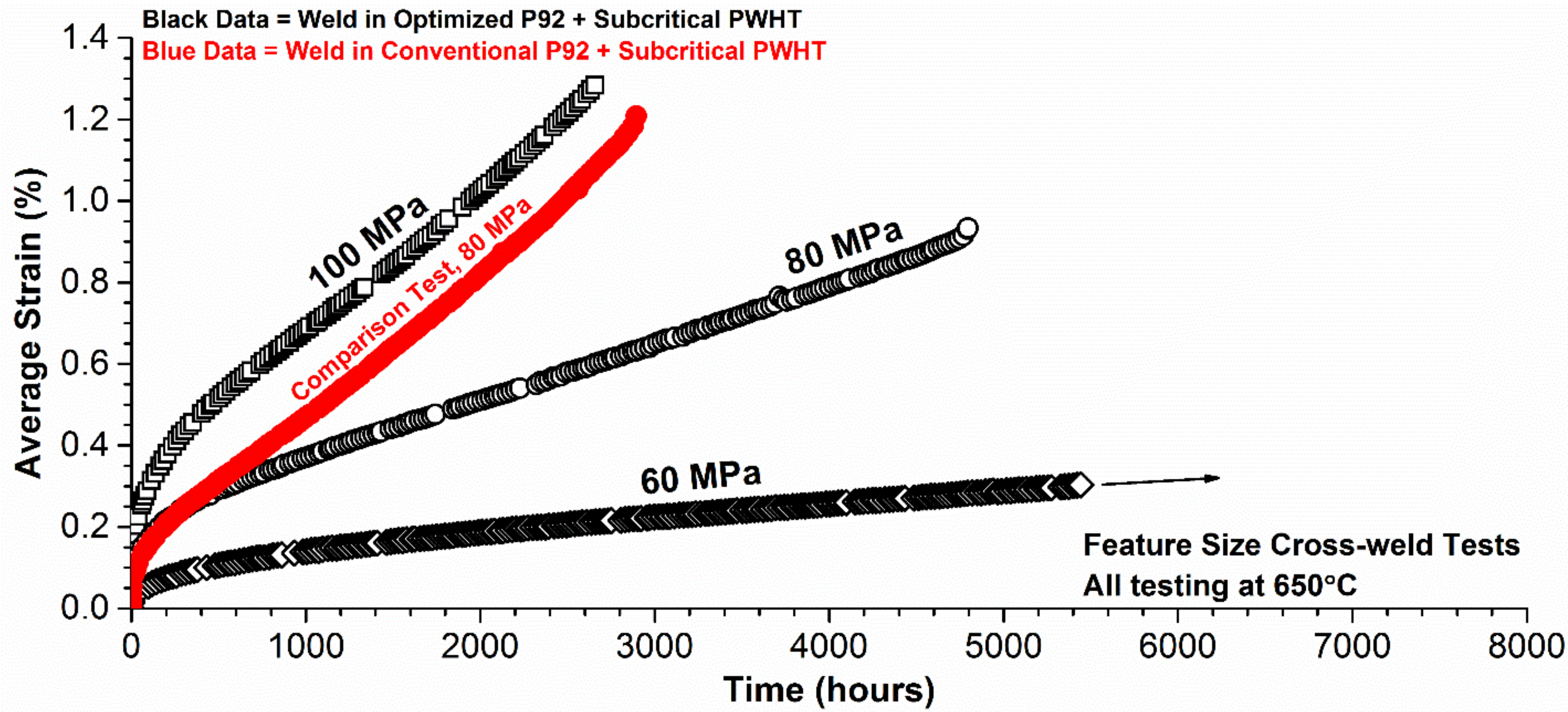
Cross-weld Creep Strain:Time Data



Initial results suggest some increase in cross-weld creep performance is realized

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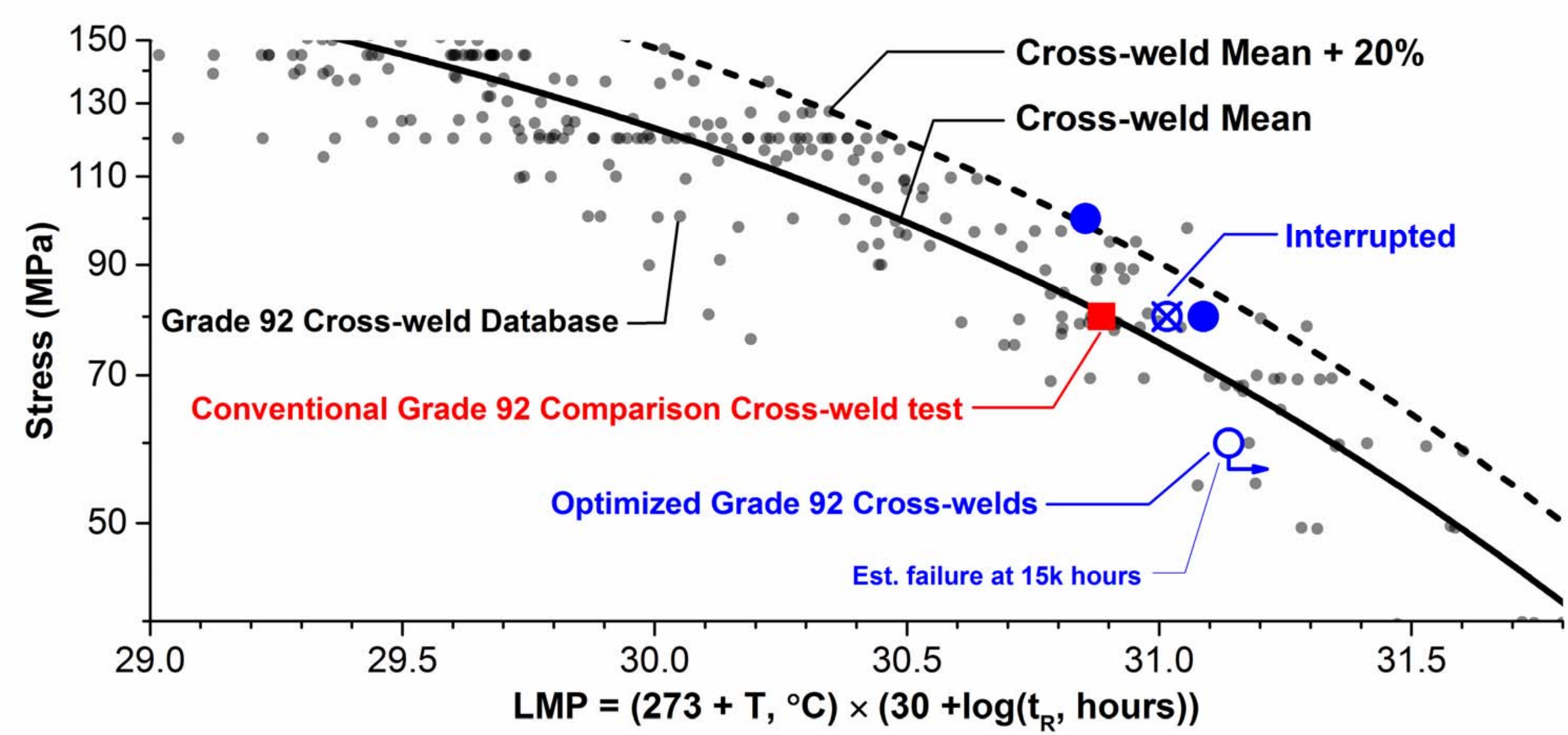
Cross-weld LMP Comparison



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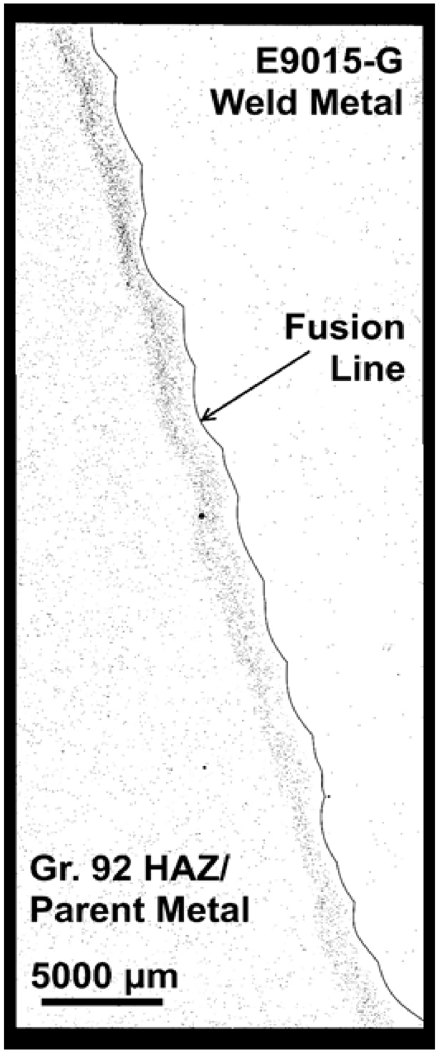
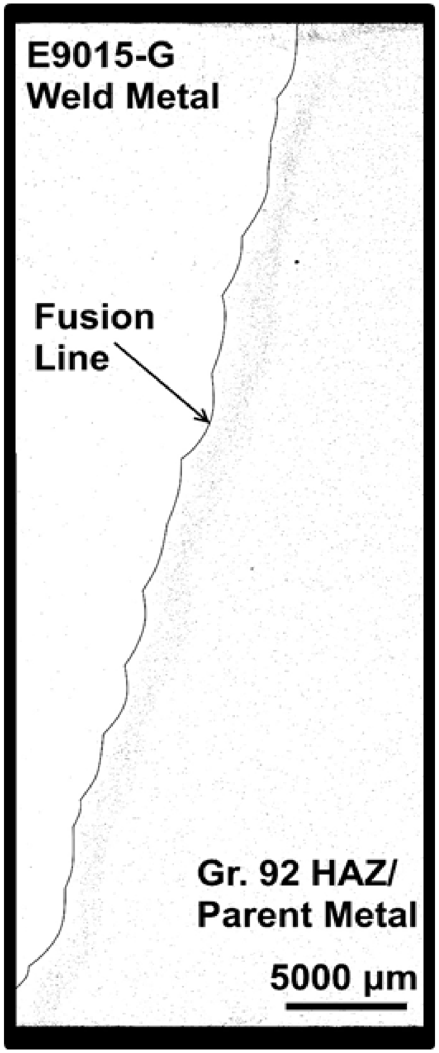
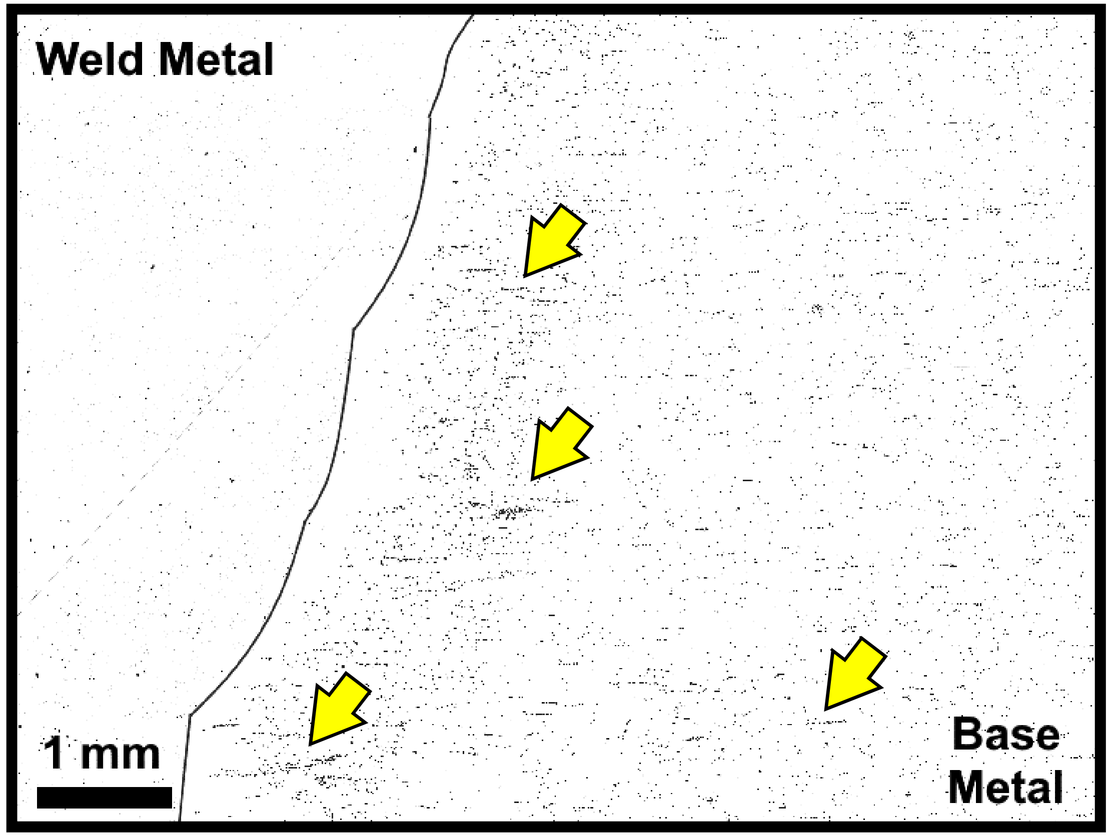
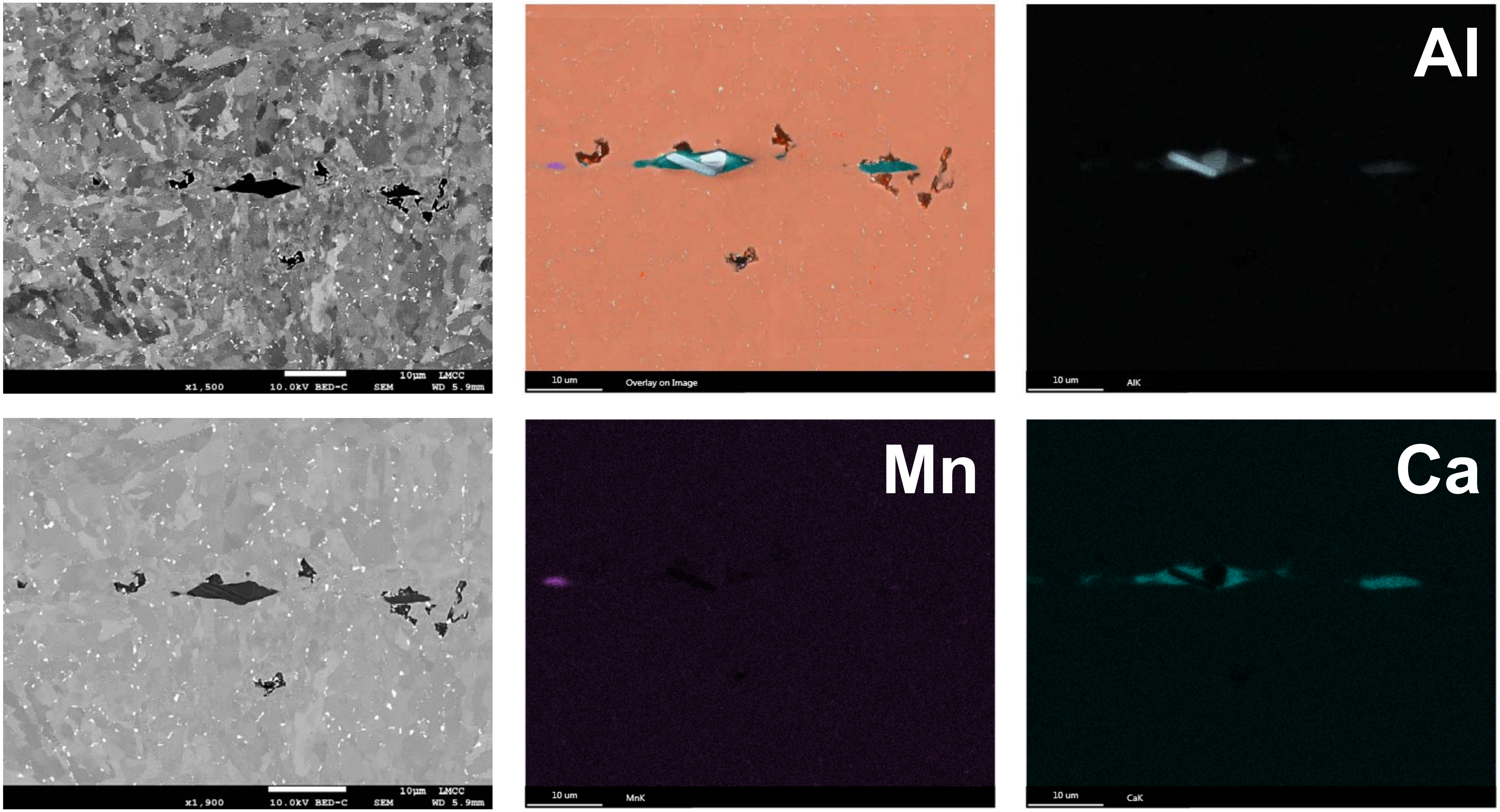
Damage in Cross-weld Creep Test

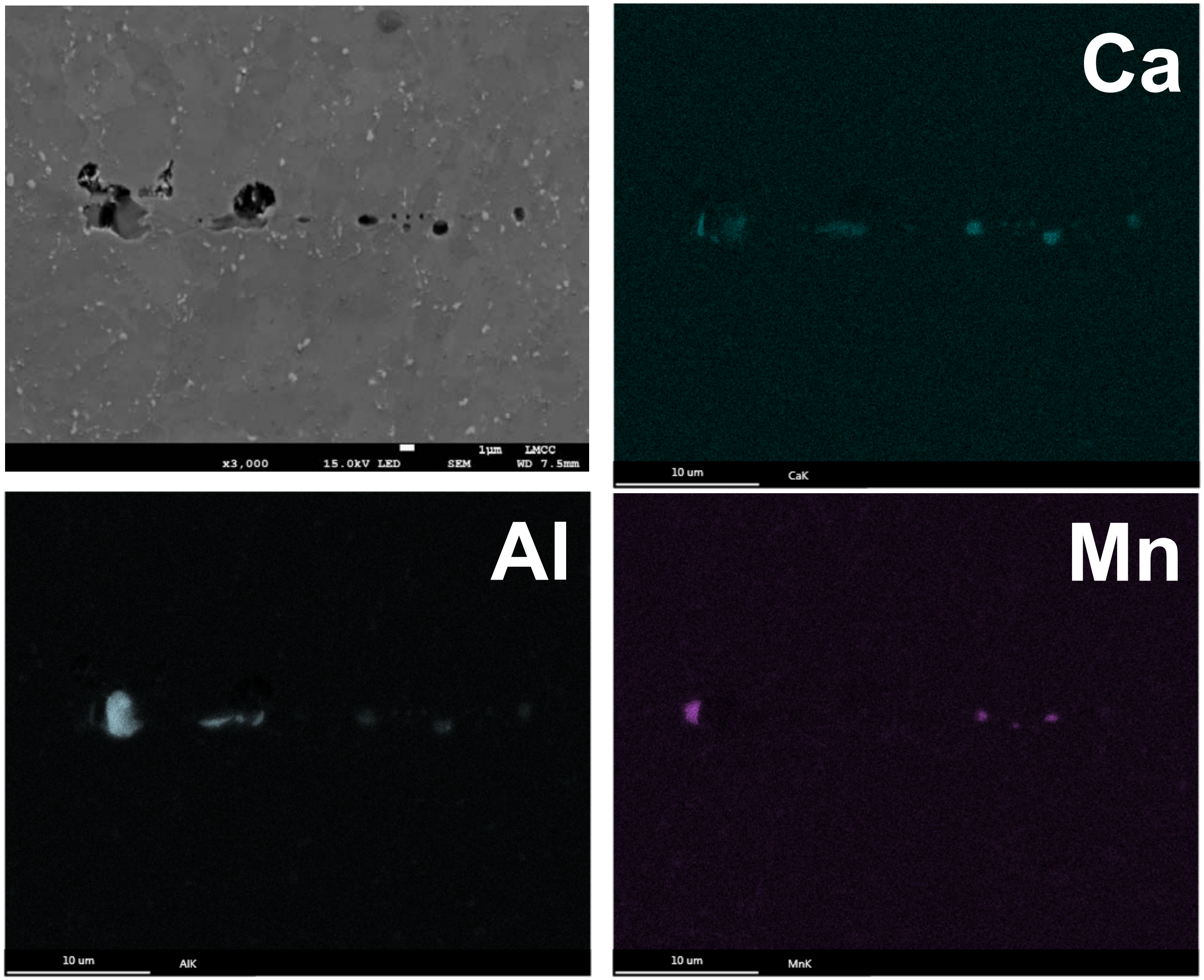






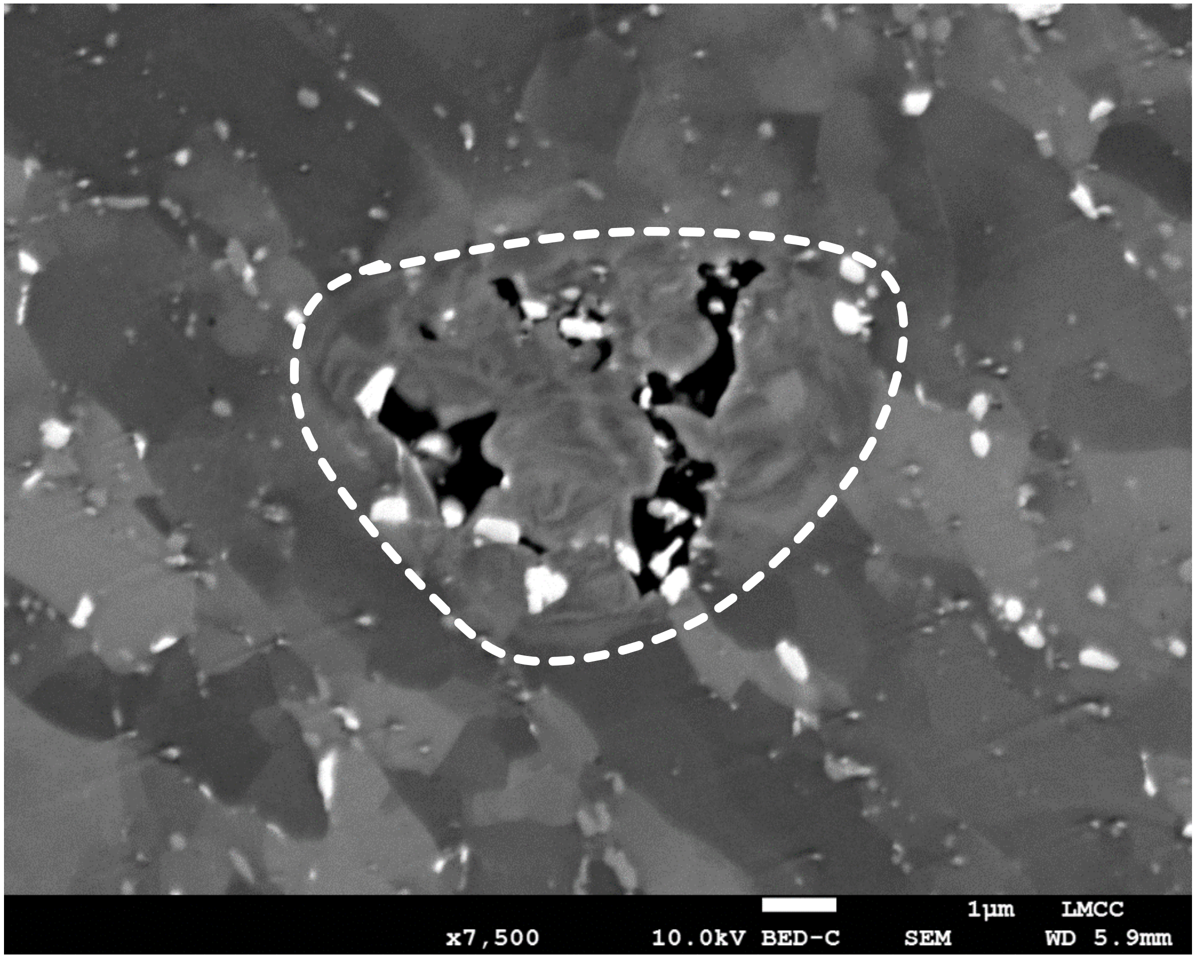
Note the strong, linear association of damage with apparent inclusion stringers


10µm LMCC
x1,500 10.0kV BED-C SEM WD 5.9mm
10 um
Overlay on Image
Al
10 um
AlK
10µm LMCC
x1,900 10.0kV BED-C SEM WD 5.9mm
Mn
10 um
MnK
Ca
10 um
CaK



Just as in the simulated HAZ sample, damage is noted in the HAZ of cross-weld creep tests and associated with inclusions. There is a strong association of inclusions with Al and Ca; to a lesser degree with Mn. This is not surprising since this heat of Grade 92 has low sulfur (e.g. lower MnS can be expected)

Evidence of Strain Localization at Cavities in HAZ



From a 2D-perspective the damage in the HAZ is being identified not just at inclusions but in also some cases at grain boundaries.

It is not yet clear, for the example shown here, if an inclusion exists beneath this plane

Standard Inclusion Analysis

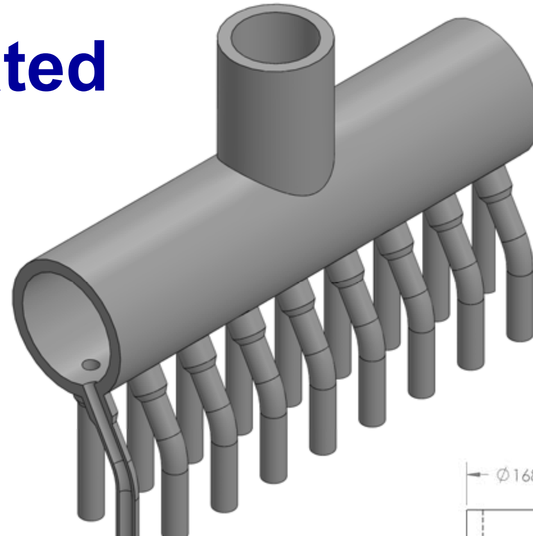
Type	DOE P92
Al-type	40
S-rich	253
MnSi-type	16
Nb-type	134
Ti-type	254
Ca-type	1,295
Mg-type	0
High Si	51
Complex Spinel	142
Unclassified	40
Inclusions Analyzed	2,225
Total Features	4,016

- Grade 91 steel database
  - Total inclusions range from 877 to 5,950
  - General susceptibility to damage for heats with numbers >2,000
- Ca-rich inclusions are not put into solution through high temperature normalization
  - Although the high temperature normalization is sufficient to dissolve BN, it cannot overcome other inclusions

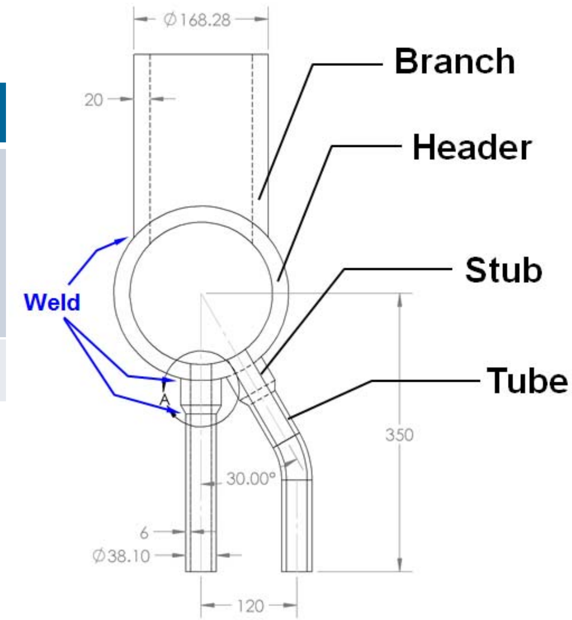
Future Work and Summary

Conceptual Drawings for Simulated Header Configuration [Task 6]

- In this configuration, a number of potential fabricated components can be life-limiting, e.g.
  - Branch to header weld
  - End-cap to header weld
  - Stub to header weld
  - Tube to stub weld
- Need to balance material degradation mechanisms
  - Oxidation (OD and ID)
  - Creep (deformation and damage)
  - DMWs (if applicable; in this study the stated objective is to avoid ferritic to austenitic DMWs)



Component	Material
Branch	SAVE12AD
Header	
Stub	
Tube	VM12SHC



Pressurized Tube Tests [Task 7]

- Tests to include:
  - Parent metal and
  - Cross-weld test
- Loading
  - Pressure only
  - Pressure + End Load

Summary

- Phase I – evaluate the influence of renormalization
  - Where BN is present, normalization ≥1125°C and accelerated cooling can put the nitrogen and boron back into solution
  - However, damage susceptibility cannot be improved if other inclusions are present in sufficiently high quantities
    - Ca- and Al-rich have a stability >melting
    - MnS has a stability ~≥1400°C
- The influence of the renormalization is not having a greater benefit in multiaxial tests and simulated HAZ tests because we have not been able to fully remove the nucleation sites for damage which are shown to be Ca-rich

The influence of damage governs behavior in the long-term for 9%Cr martensitic steels

Summary

- Phase II [will not be funded] – combine renormalization with controlled composition to
  - Reduce impurities (e.g. Cu, As, Sb, Sn) to low levels and
  - Reduce inclusion content (e.g. restrict S, Al and others, Ca for example) through controlled melting process
- The approach is still promising provided composition and steel-making can be tailored to reduce inclusion content
- A key driver for improvement of Grade 92 as opposed to adoption of new materials are driven by practical considerations such as Code acceptance, cost and alloying additions which decrease formability or introduce rare earths

Together…Shaping the Future of Electricity

On Available Materials for Operation ≥ 600°C

- 9%Cr CSEF Steels
  - **Grade 91** – Insufficient steamside oxidation; recently reduced stress allowable values
  - **Grade 92** – Insufficient steamside oxidation; low damage resistance
  - **SAVE12AD** – Recently approved; material availability; consistency in stated performance; rare earth addition adds cost/complexity; limited manufacturing base
- 11-12%Cr CSEF Steels
  - **VM12SHC** – Similar stress allowable values to Grade 91 steel; restricted section sizes; limited manufacturing base
  - **THOR 115** – In-process within ASME; similar stress allowable values to Grade 91 steel