INL/MIS-22-70547-Revision-0

Fast Reactor Materials R&D Update

December 2023

Changing the World's Energy Future

Ting-Leung Sham

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Fast Reactor Materials R&D Update

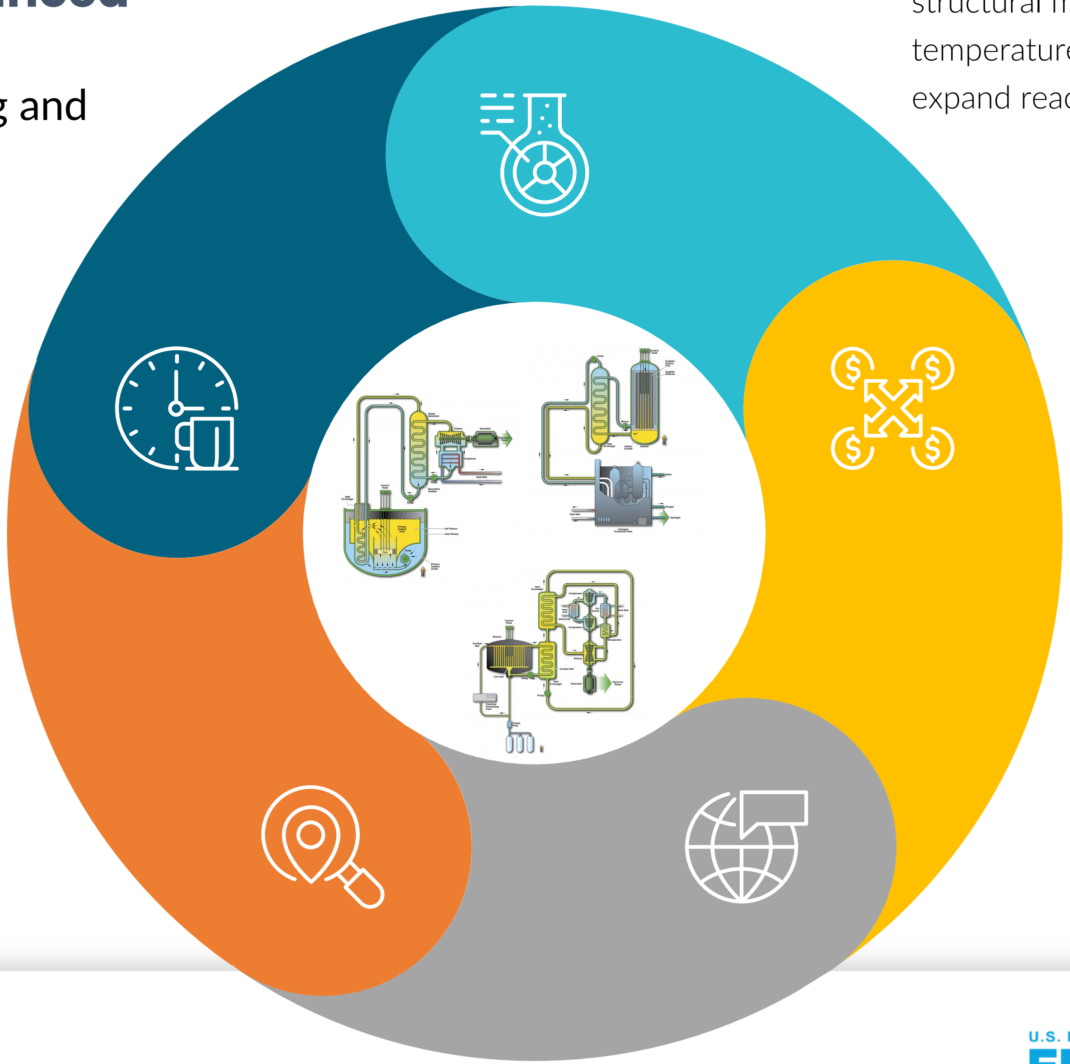
Sam Sham
Idaho National Laboratory

DOE-NE ART Fast Reactor Program Review Meeting
December 13-15, 2022
Argonne National Laboratory, Lemont, IL

ART ADVANCED MATERIALS

Focus on materials and design methods to support advanced reactors deployment

- Design, construction, licensing and operations



High temperature design methodologies

Develop high temperature design methodologies for use of the qualified materials under elevated temperature cyclic service of advanced reactors

Existing qualified materials

Extend qualified lifetimes and usage temperatures of structural materials already approved within the ASME Code for construction of high temperature reactors

Qualify new materials

Qualify additional high performance structural materials for high temperature reactor construction to expand reactor design envelope

NRC licensing

- Understand and predict environmental and irradiation effects relevant to different advanced reactor concepts
- Assess & improve methods to evaluate flaw growth and component lifetime predictions to support plant operations
- Develop in-reactor high temperature structural materials surveillance technology

Innovative materials solutions

Develop material solutions to address highly corrosive working fluids

INTEGRATION, COORDINATION, COLLABORATION

ART Advanced Materials
DEVELOP AND DEPLOY

ADVANCED REACTOR DEMONSTRATION PROGRAM

RESEARCH: NEUP, IRP

REGULATORS: USNRC, CNSC

INTERNATIONAL COLLAB: GIF, CNWG, JSCNEC

GIF VHTR Metals WG: Australia, Canada, China, European Union, France, Korea, Switzerland, United Kingdom

CNWG: Japan (JAEA)

JSCNEC: Argentina (CNEA)

PRIORITIZATION: ASME SWG-HTRS

ARC Clean Energy • Flibe Energy • GE-Hitachi • Kairos Power • TerraPower • Terrestrial Energy • Ultra Safe Nuclear • Westinghouse • Hayward Tyler • Ontario Power Generation • EPRI • USNRC • CNSC • Institute of Nuclear and New Energy Technology, China • JAEA • KAERI • SINAP

iFOA

SBIR, STTR

COORDINATION: AMMT, NEAMS, IMARC, ASI, LWRS

GAIN

INTEGRATION: NRIC

ART ADVANCED MATERIALS PORTFOLIO – METALS

INTEGRATION AND COORDINATION

Funding	Topic	Status	Adv Rx Supported
GCR	Design methods improvement & development	Ongoing	GCR, FR, MSR, MRP
GCR	Extension of design lifetime for Class A materials	Ongoing	GCR, FR, MSR, MRP
GCR	Qualification of A617	Completed	GCR, MRP, FR
GCR	Qualification of advanced A800H welds	Ongoing	GCR, MRP
FR	Qualification of A709	Ongoing	FR, MSR, GCR, MRP
MSR	Surveillance test article development	Ongoing	MSR, FR, GCR
MRP	Qualification of PM-HIP components	Ongoing	MRP, MSR, FR, GCR
GCR	GIF VHTR Materials PMB	Ongoing	GCR
NEAMS	Accelerate A709 qualification with physics-based Mod-Sim & Bayesian model	Initiated in FY23	FR, MSR, GCR, MRP
Coolant Effects on Metals			
GCR	Impure helium effects on A800H and A617	Completed	GCR, MRP
GCR	Crack growth in impure helium – A617	Ongoing	GCR, MRP
GCR	Impure helium effects on A709	To be initiated	GCR, MRP
FR	Sodium effects on G91, A709	G91 completed; A709 ongoing	FR, MRP
MSR	Effects of molten fluoride & chloride salts on stainless steels & Ni alloys	Ongoing	MSR, MRP

- GCR – Gas-cooled Reactors Campaign
- MSR – Molten Salt Reactors Campaign
- FR – Fast Rectors Campaign
- MRP – Microreactor Program
- NEAMS – Nuclear Energy Advanced Modeling and Simulation

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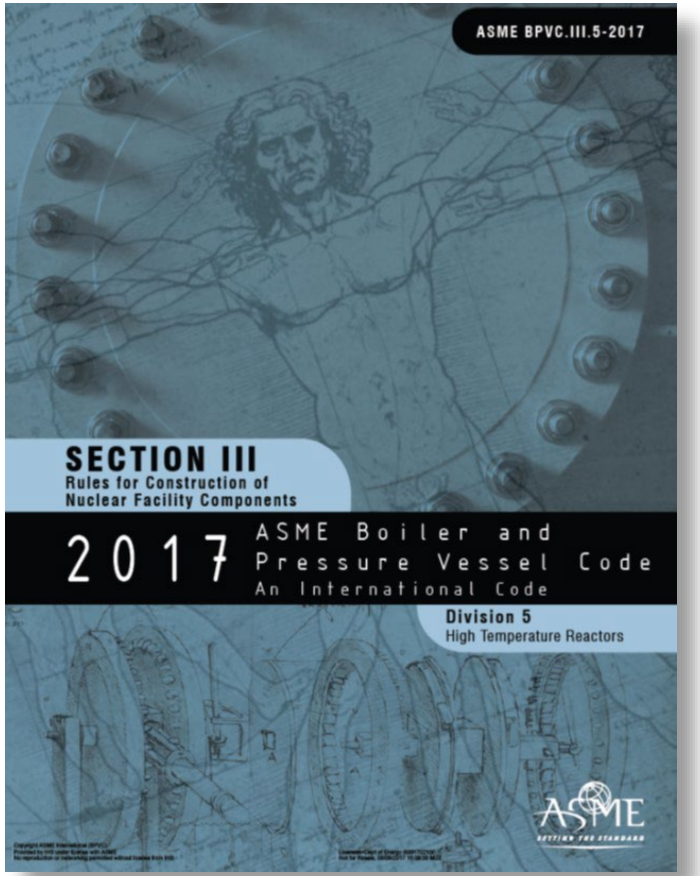
NRC ENDORSEMENT OF ASME SECTION III, DIVISION 5

STATUS

- US Nuclear Regulatory Commission (NRC) is currently assessing ASME Section III, Division 5 (2017 Edition), the EPP strain limits and creep-fatigue evaluation Code Case and the Alloy 617 Code Case for endorsement
- Technical review completed, and endorsement pending final review by the NRC Office of General Council
- Endorsement by NRC will be made, with exceptions and limitations, through the Regulatory Guide 1.87, rev 2



DIVISION 5 CLASS A MATERIAL CODE CASES

Current Division 5 Class A Materials

- Type 304 and 316 stainless steels
- Alloy 800H
- Grade 91 (9Cr-1Mo-V)
- 2¼Cr-1Mo (solution annealed)
- Alloy 617
- SA 508 Grade 3 and SA 533B reactor pressure vessel steels (for short term, elevated temperature excursions)

New Material Code Cases

- Lessons-learned from Alloy 617 Code Case effort have streamlined the balloting workflow for Class A material code cases
- After requester submitted material design parameters and supporting data package to ASME, Division 5 could turn around a material code case in about three Code Week cycles (less than a year)
- Data requirements for new materials are described in Division 5, “Nonmandatory Appendix HBB-Y, Guidelines For Design Data Needs For New Materials”

EXTEND DESIGN LIFE TO 60 YEARS

SUPPORT ADVANCED REACTOR DEPLOYMENT

	304SS	316SS	A800H	2¼Cr-1Mo	Grade 91
Extend Time Dependent Design Parameters to Support 60-year Design – Part of the Division 5 Optimization Effort (Priorities Identified with Stakeholders input)					
Time Dependent Allowable Stress	To be balloted	To be balloted	Partial	N	Y
Rupture Stress	To be balloted	To be balloted	Y	N	Y
Aging Factor	Partial	Partial	N	N	Y
Stress Rupture Factor (Weldment)	N	N	N	N	Y
ISSCs	Partial	Partial	Partial	Partial	Y
Temp-Time Limits on NB Buckling Charts	Y	Y	Y	Y	Y
Other Code Rules Optimization					
Strain Limits and Creep-Fatigue (EPP)	Y	Y	Y	Y	Y
Primary Load (EPP + Simplified Inelastic)	Y	Y	Y	Y	Y
Unified Viscoplastic Material Model	Partial	Y	Partial	N	Y

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FY23 PLANNED WORK FOR FAST REACTOR MATERIALS

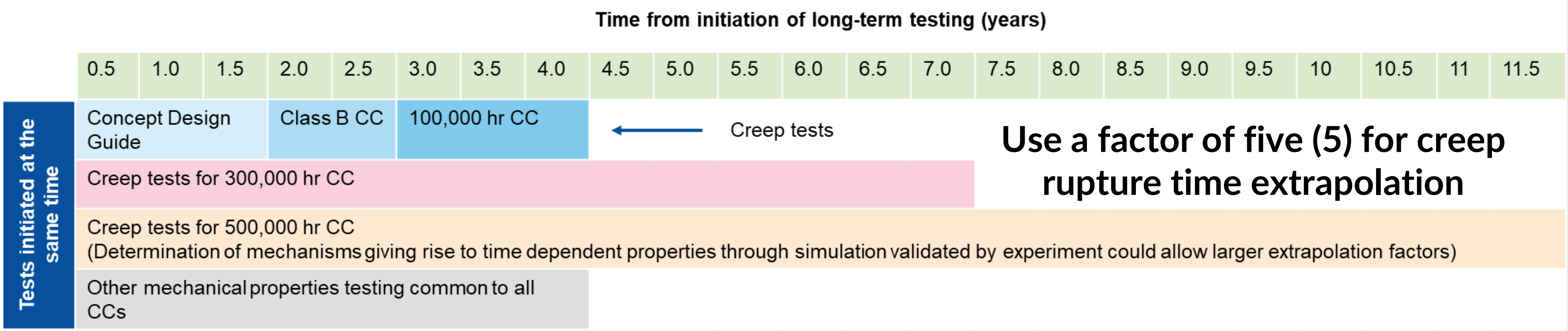
FY23 Work Packages

- RD-23AN040401, A709 Development – ANL
- RD-23IN040402, A709 Development - INL
- RD-23OR040403, A709 Development – ORNL
- RD-23AN040404, A709 Code Case Testing – ANL
- RD-23IN040406, A709 Code Case Testing - INL
- RD-23OR040407, A709 Code Case Testing – ORNL
- RD-23OR040408, A709 Weldment Testing – ORNL
- RD-23AN040409, A709 Sodium Testing- ANL
- RD-23IN040410, A709 Design Rules - INL

Fast Reactor Materials Technical Staff

- Xuan Zhang, Yiren Chen (ANL)
- Ryann Bass, Mike McMurtrey, Heramb Mahajan, Sam Sham (INL)
- Yanli Wang, Zhili Feng, Grace Burke, Peijun Hou (ORNL)
- Richard Wright, John Grubb (Subject Matter Expert)

A "STAGED" APPROACH FOR QUALIFICATION OF ALLOY 709 MATERIAL CODE CASE



A three/four-year testing program, without resource constraints, would have sufficient time to generate data package to support:

- Conceptual design (first 2 years)
  - Conceptual Design Guide for 500,000-hour lifetime
- Preliminary design
  - 100,000-hour Class A code case (3 to 4 years)
  - Class B material code case (first 2 to 3 years)

Additional creep data only at 7-year mark from start:

- Final design
  - 300,000-hour Class A code case

Additional creep data only at 12-year mark from start:

- Nth-of-a-kind
  - 500,000-hour Class A code case

CODE CASE REQUIREMENT FOR QUALIFICATION – THREE COMMERCIAL HEATS

- **First commercial heat received in FY17**
  - Totaling about 45,000 lbs
  - Nine process conditions
  - ASTM grain size range 5-8
  - Down-selected ESR-1150SA melt practice followed by a precipitation treatment (PT)

Photograph of first commercial heat A709 plates in as-rolled condition

- **Second commercial heat received in FY21**
  - Totaling about 40,000 lbs
  - ESR melt practice
  - Hot rolled into 1.75” and 2” plate product form
  - ASTM grain size range 4-7

Photograph of second commercial heat in solution-annealed condition

- **Third commercial heat received in FY22**
  - Totaling about 38,000 lbs
  - ESR melt practice
  - Hot rolled into plate product form
  - Characterization in progress

Photograph of third commercial heat in solution-annealed condition

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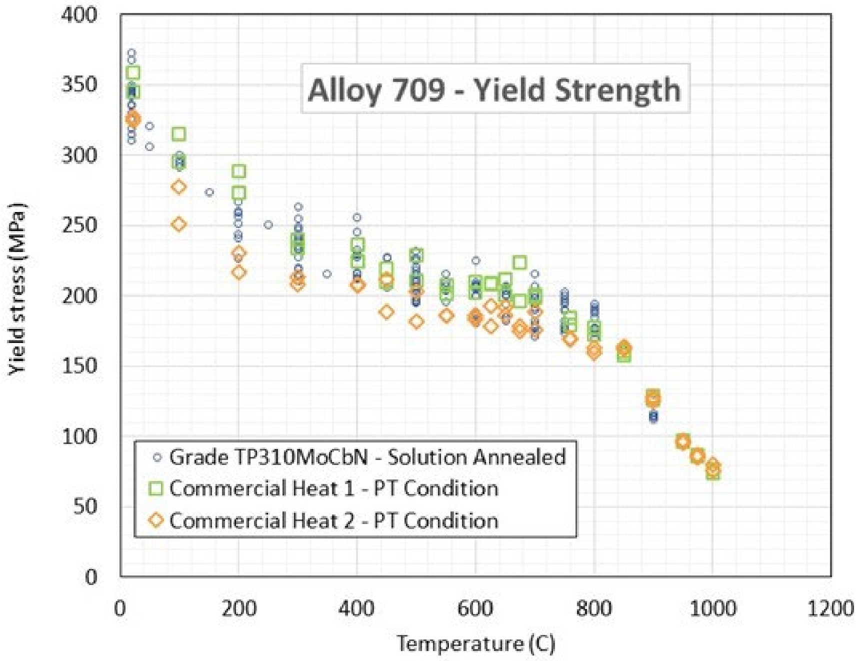
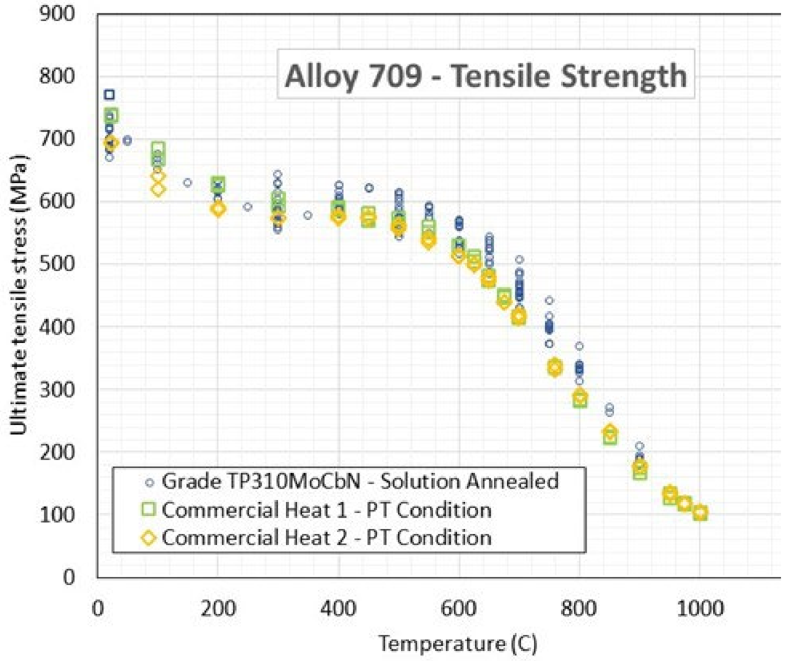
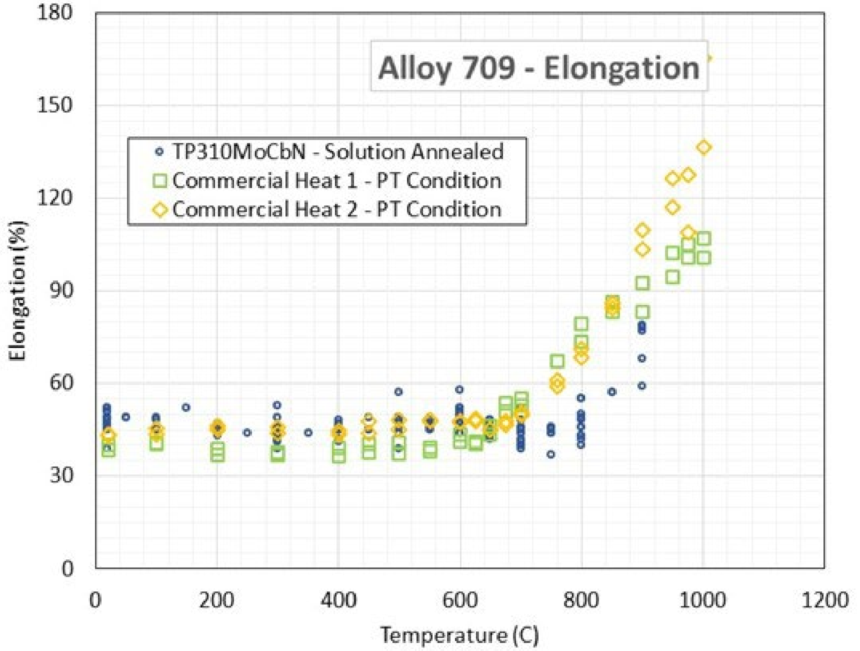
ELEVATED TEMPERATURE TENSILE DATA GENERATED TO-DATE

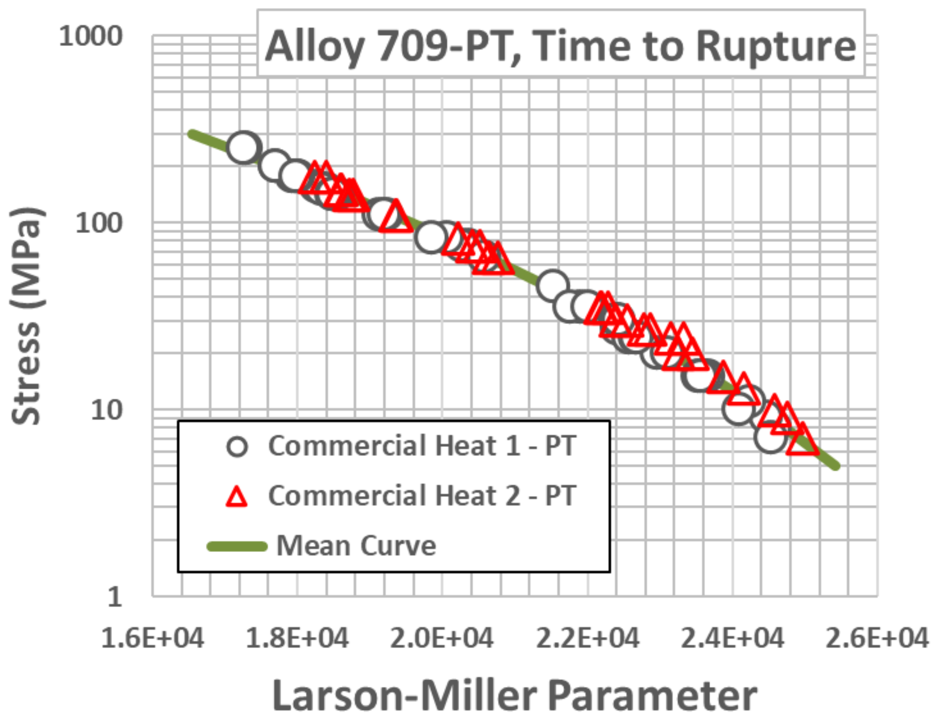


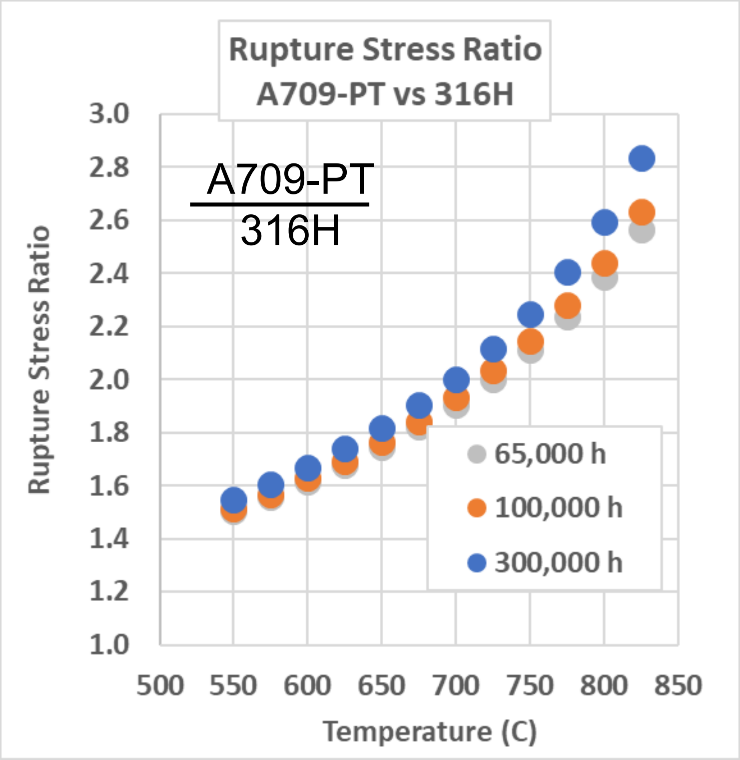


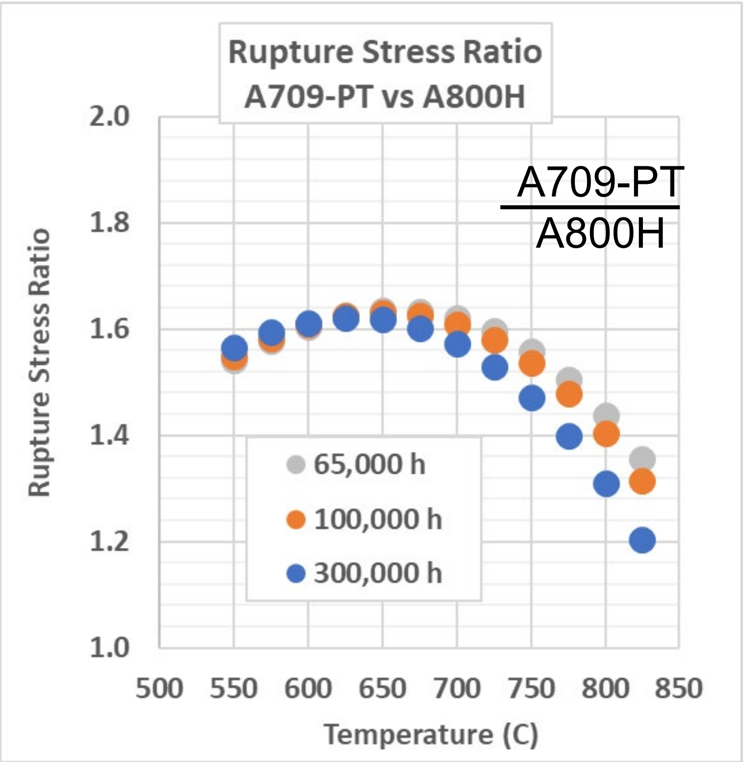


- Elevated-temperature tensile properties of A709-PT are comparable to Grade TP310MoCbN-SA (Nippon Steel, NF709)
- At higher temperatures, the elongations from A709-PT are significantly higher than those from Grade TP310MoCbN-SA, indicating higher tensile ductility

CREEP RUPTURE STRENGTHS OF A709-PT, 316H AND A800H

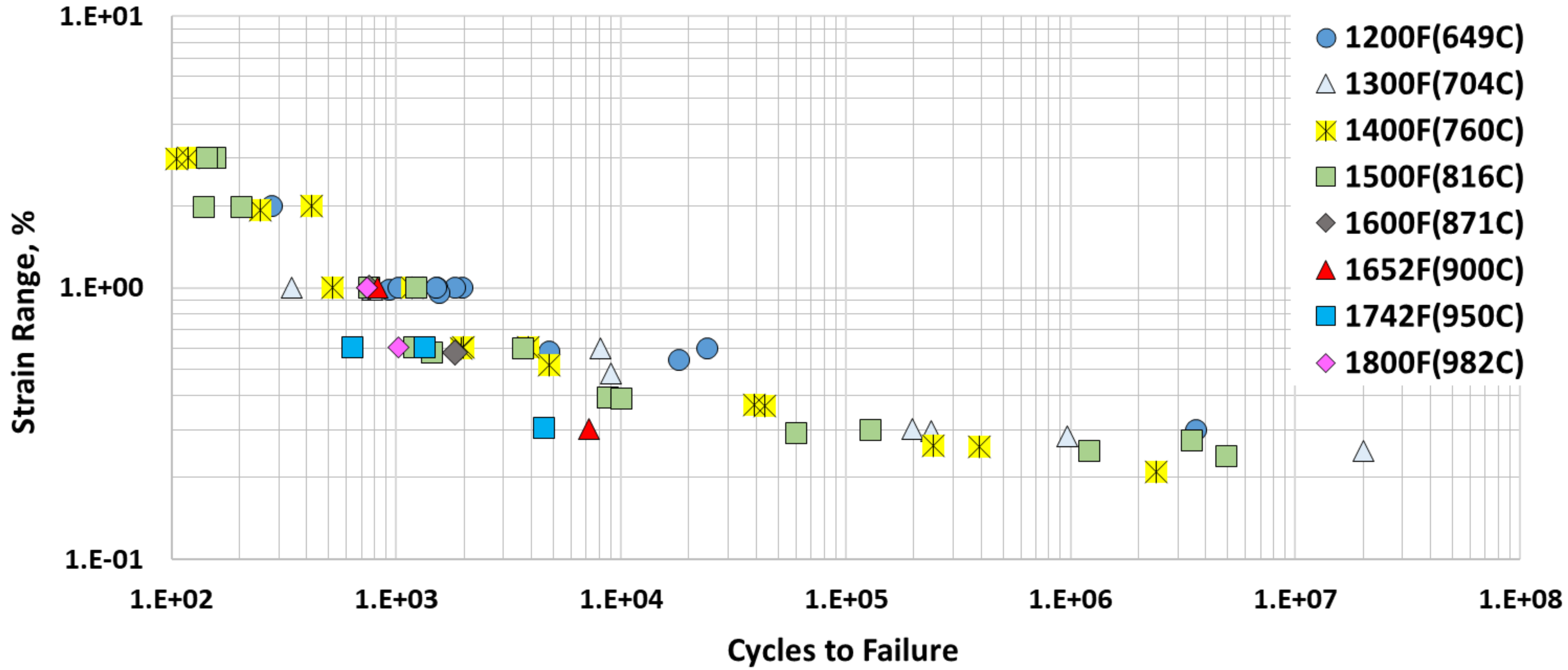






- The trends show that the creep rupture strengths of precipitation-treated A709 are significantly higher than those of 316H stainless steel, and are also higher than those of A800H

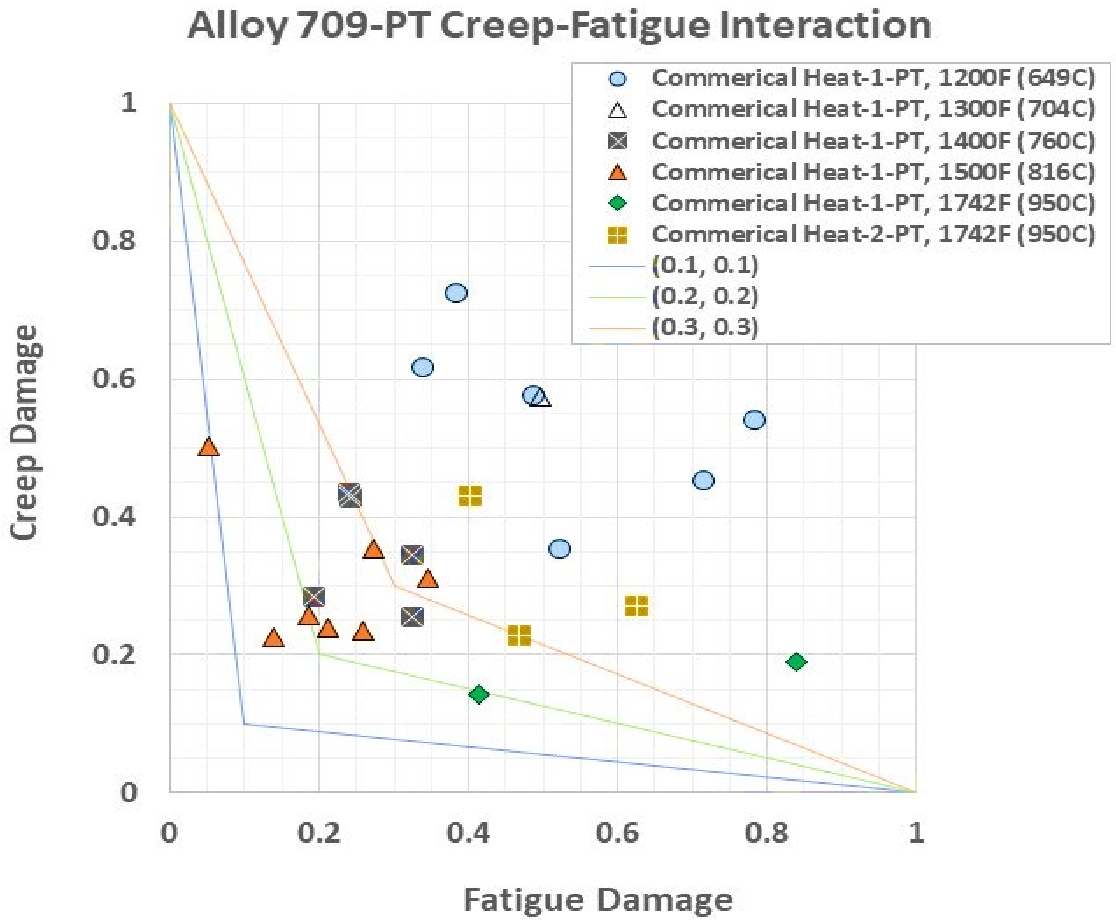
FATIGUE DATA GENERATED TO-DATE



- The initial set of fatigue data were generated to establish the general trends of the fatigue resistance of A709-PT

CREEP-FATIGUE DATA GENERATED TO-DATE

- Strain-controlled creep-fatigue tests on the A709-PT materials were conducted to generate creep-fatigue data for the construction of the creep-fatigue interaction diagram, or the D-diagram
- The fatigue and creep-fatigue data generated to date for A709-PT were used to determine the creep- and fatigue-damage fractions and are shown in the figure on the right
- Various bi-linear creep-fatigue interaction envelopes are added to the figure to provide a visual guide
- D-diagram data generated to-date on A709-PT show good creep-fatigue resistance



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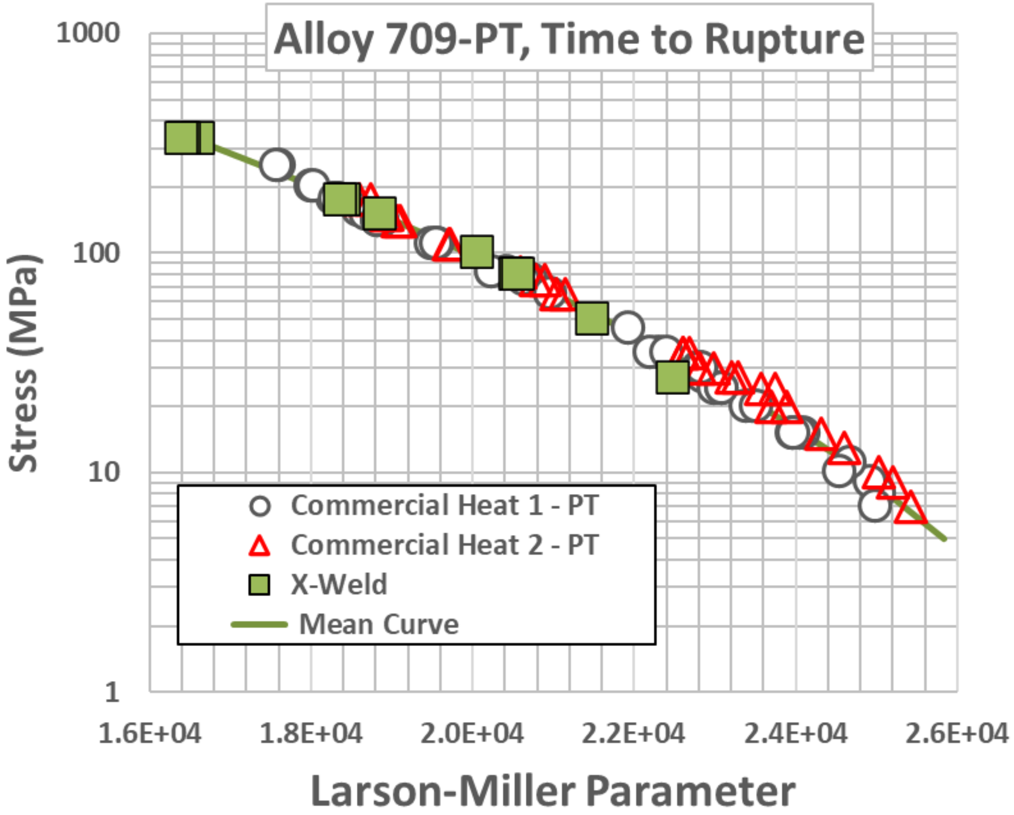
PRELIMINARY CREEP RUPTURE TEST RESULTS ON A709 WELDS



- Preliminary cross-weld creep test results on A709 test welds fabricated with GTAW on commercial heat 1 plates (Carlson with 140 ppm P) continue to show little or no creep strength reduction relative to the base metal
- Comprehensive creep Code Case testing on the two A709 production welds is on-going.

Cross-Weld (X-Weld) Data

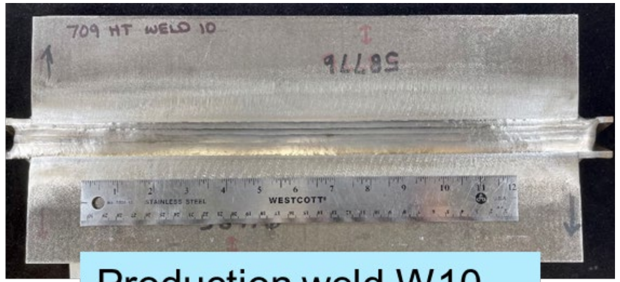
W2: low P weld wire (< 20 ppm P) on solution annealed Carlson plate with 140 ppm P

W5: 140 ppm P weld wire on solution annealed Carlson plate with 140 ppm P

W6: low P weld wire (< 20 ppm P) on Precipitation-Treated Carlson plate with 140 ppm P

FABRICATION OF A709 PRODUCTION WELDS FOR CODE CASE

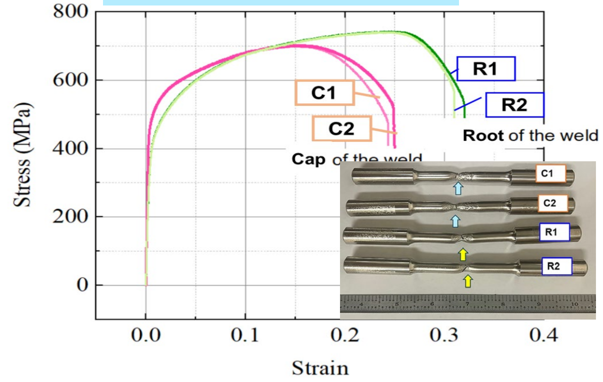
Production welds for Code Case Testing	Weld Wire			Base Metal Plate Precipitation Treatment Applied	Base metal plate thickness (in)	ASME Sec. IX Weld Qualification		
	P Level (wppm)	Original Heat No.	Wire dia. (in)			X-Ray	Side Bend	RT Tensile
W10	< 20 (Low P)	011367-08	0.035	Commercial heat 1 plate (Carlson)	1.12	Pass	Pass	Pass
W11	< 20 (Low P)	011367-08	0.035	Commercial heat 2 plate (ATI)	2.05	Pass	Pass	Pass

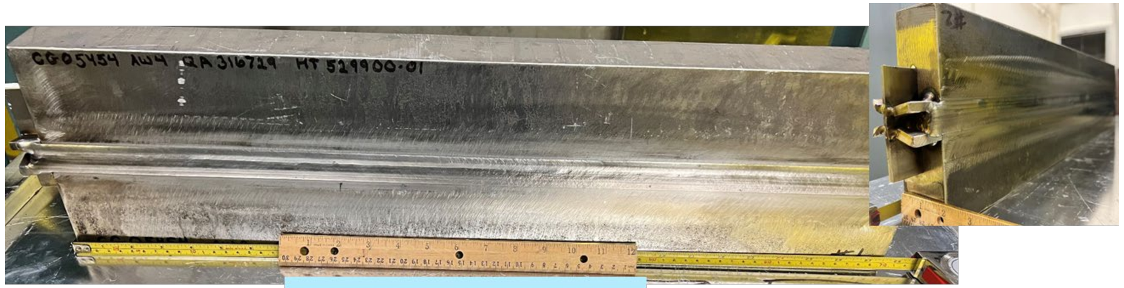


Production weld W10

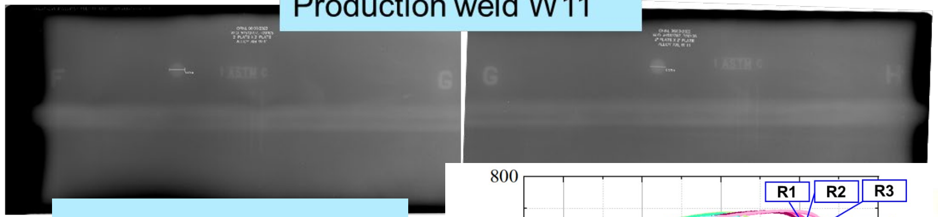
Side bend

RT Tensile

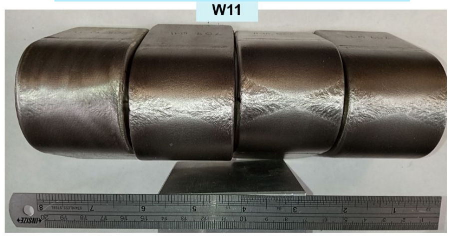


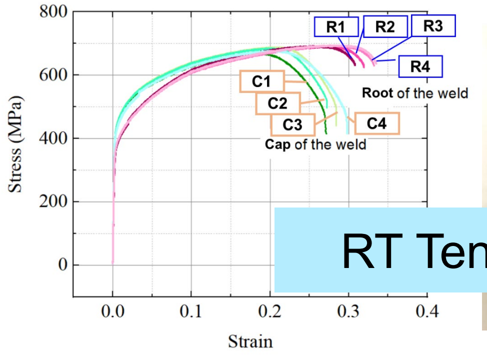


Production weld W11

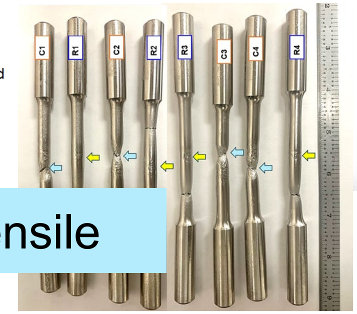


Side bend



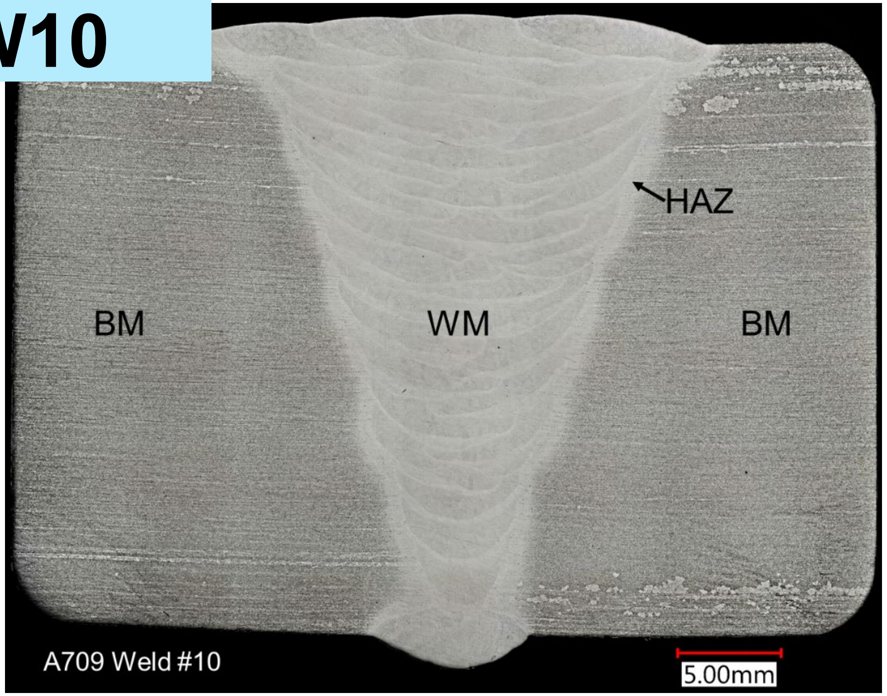


RT Tensile

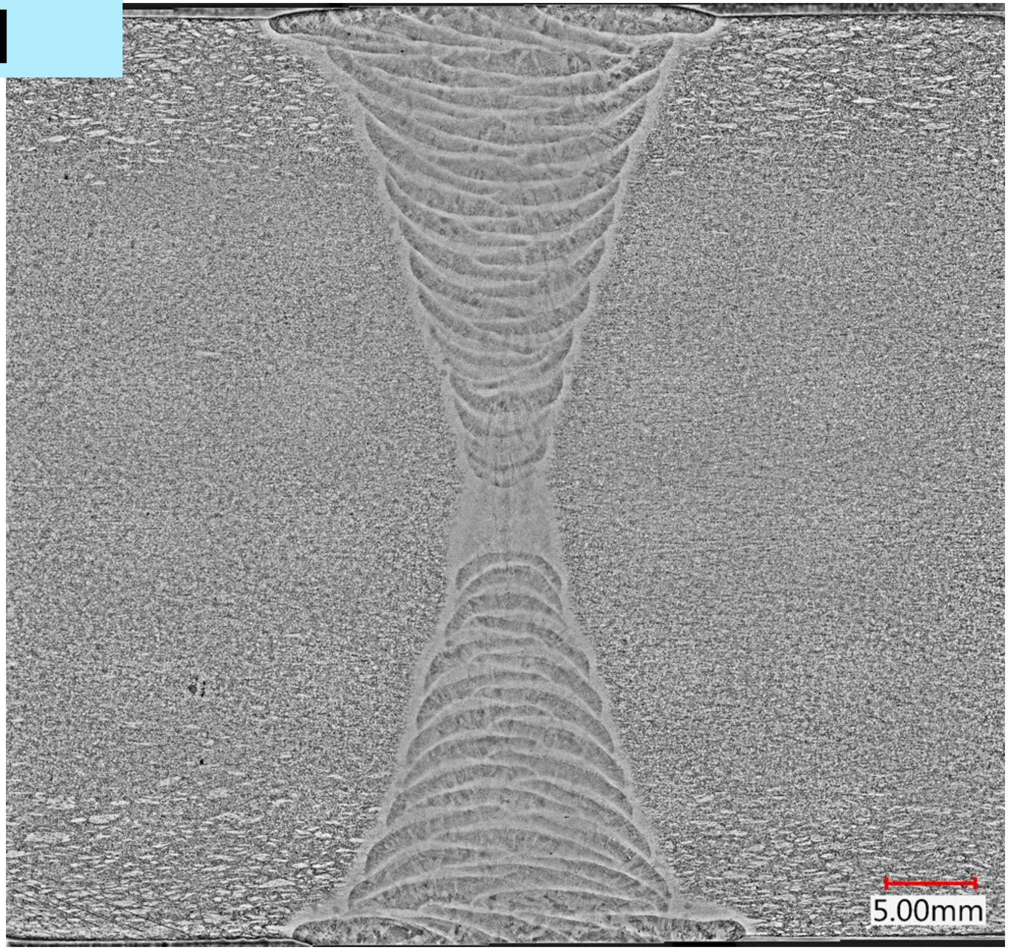


MICROSTRUCTURE OF THE A709 PRODUCTION WELDS

W10



W11



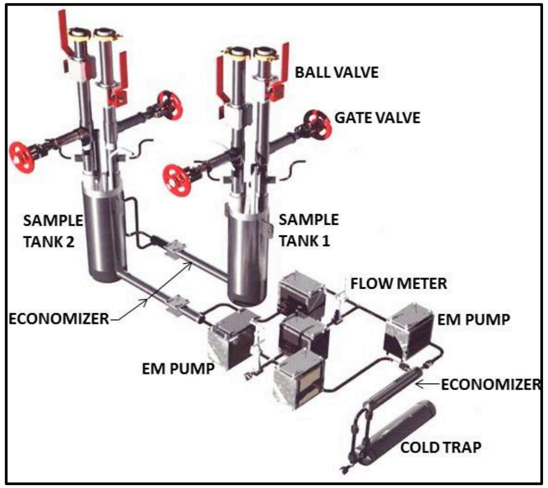
- Additional microstructure analyses of both production welds did not review solidification cracks
- Confirmed the good quality of these production welds

ASTM STANDARDS SPECIFICATION FOR A709

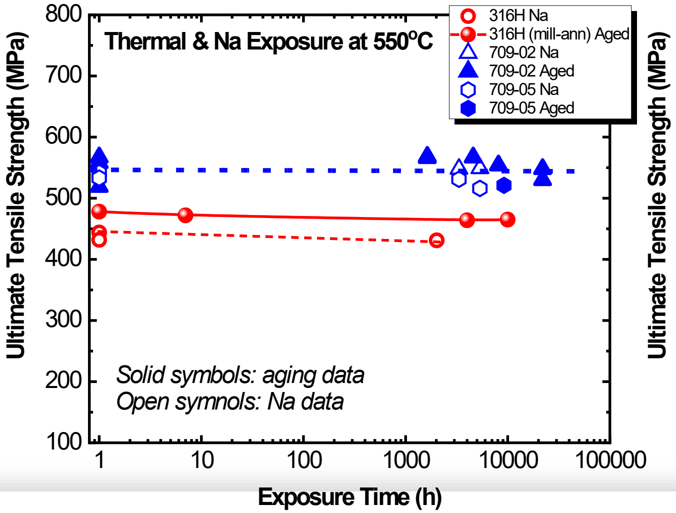
STATUS

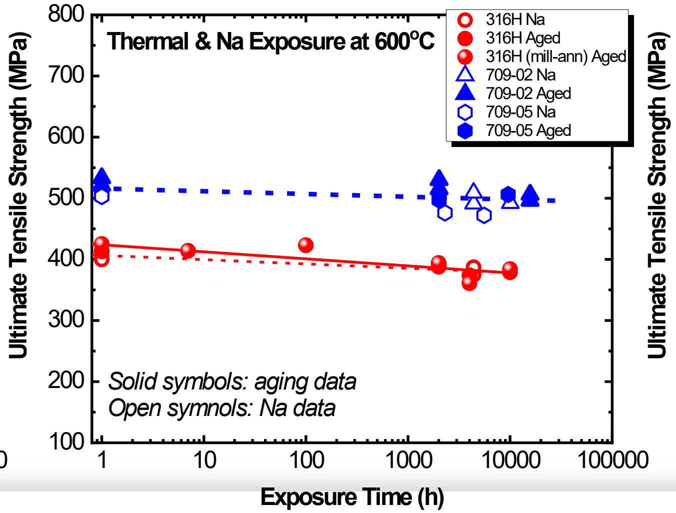
- ASME Division 5 requires new material to have a specification in Section II, Part A or Part B, which incorporates the specification from the ASTM Standards
- Alloy 709 conforms to UNS 31025 with slight modifications
- ASTM Standards define specific characteristics the alloy must meet, these definitions are the basis for receiving inspection for material from a vendor as part of a NQA-1 quality program
- The alloy has been approved under standard ASTM A213/213M-21b, “Standard Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes”
- A consultant with considerable experience standardizing austenitic stainless steels has been sub-contracted to aid with this effort
- Necessary modifications on chemistry and microstructure will be defined
- Acceptance criteria will be determined; this will likely include a creep-fatigue acceptance test for elevated temperature applications

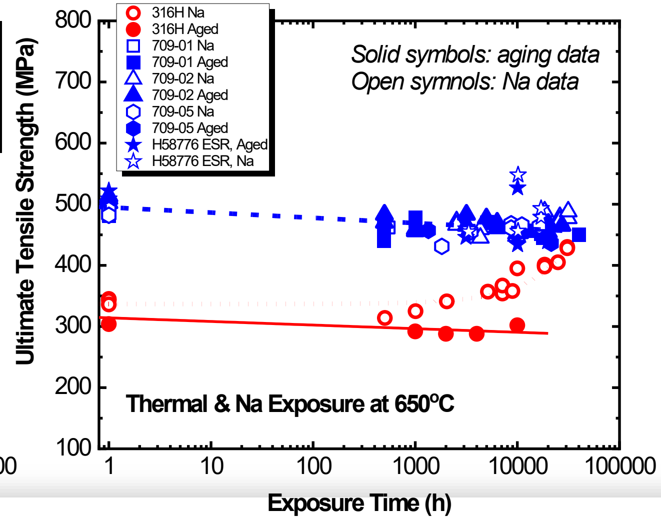
EFFECT OF SODIUM EXPOSURE ON TENSILE STRENGTH OF A709 AND 316H STAINLESS STEEL



Data of lab heats and preliminary results of the 1st commercial heat show that sodium compatibility of A709 is similar or better than the reference 316H stainless steel



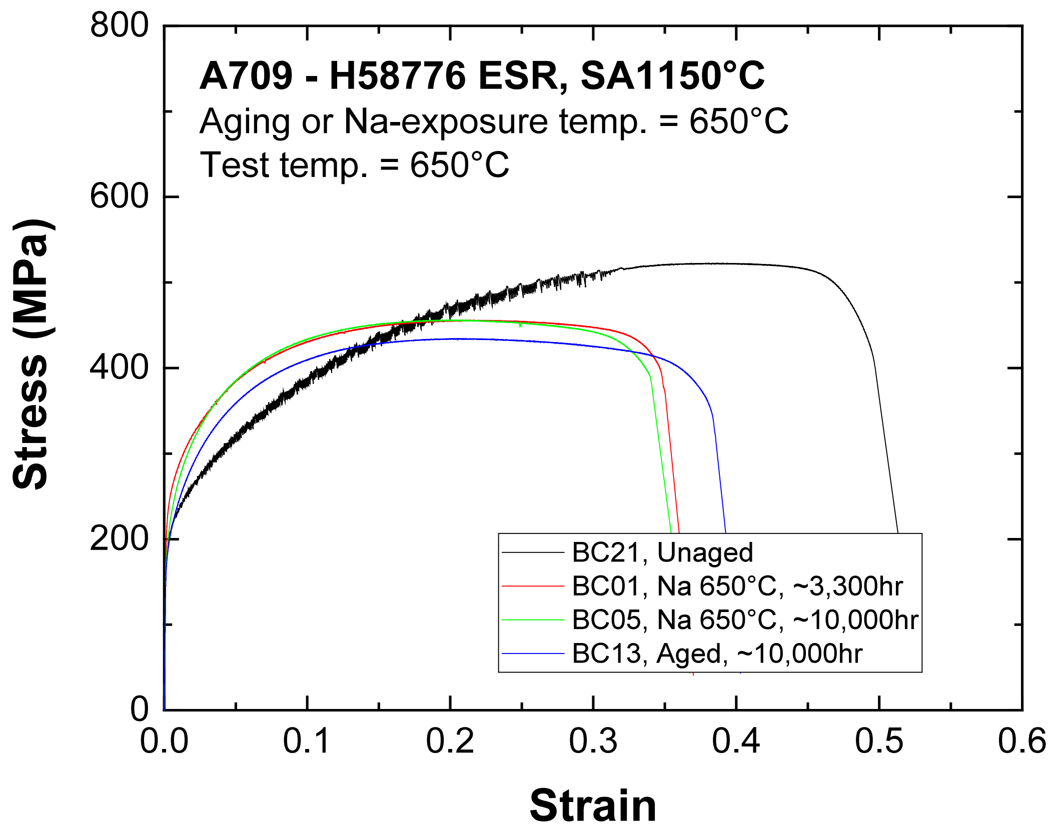




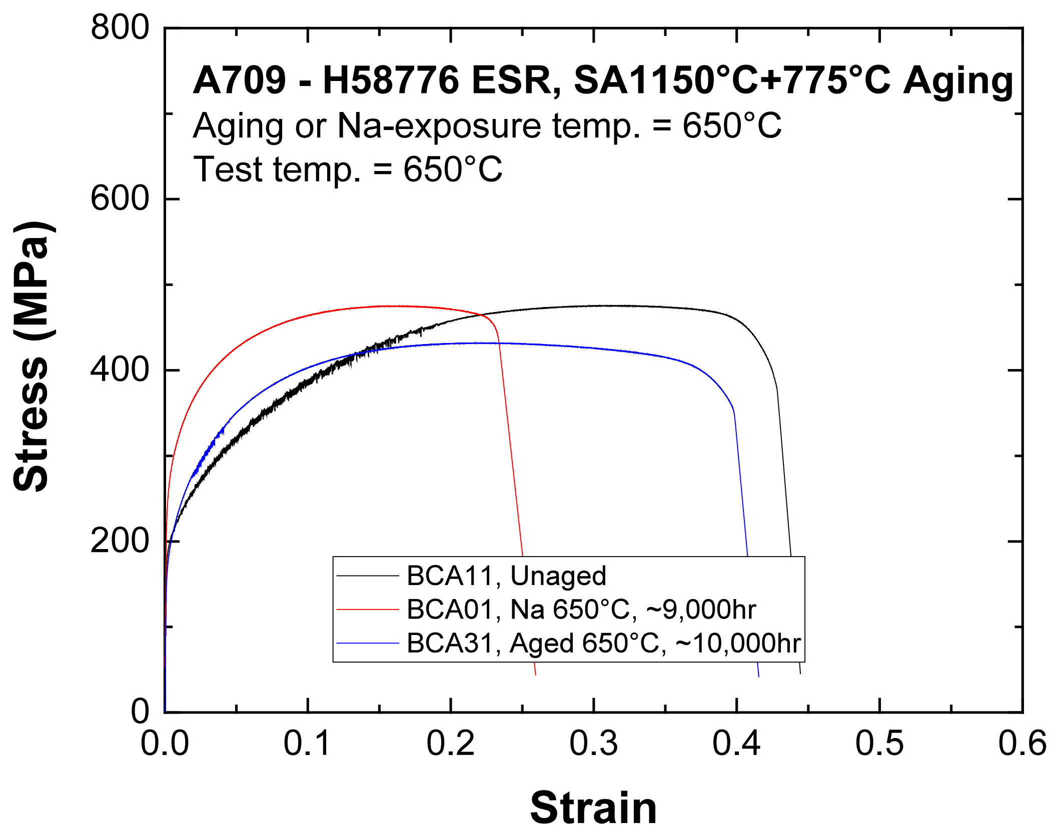
550°C 600°C 650°C **Sodium Exposure Temperature**

NEW SODIUM COMPATIBILITY DATA FOR PRECIPITATION-TREATED A709

Solution-Annealed



Solution-Annealed + Precipitation Treatment



650C exposure and tensile test at 650C after exposure

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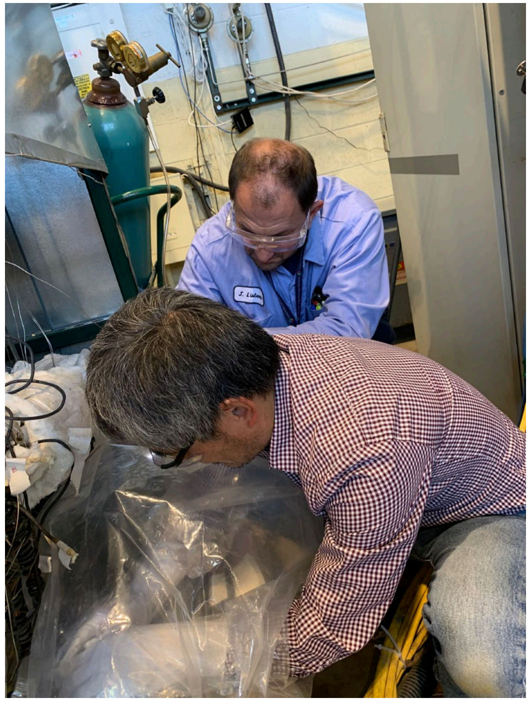
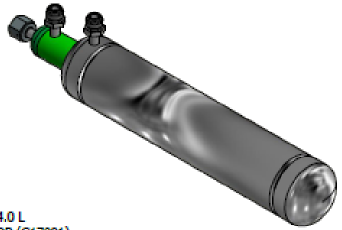
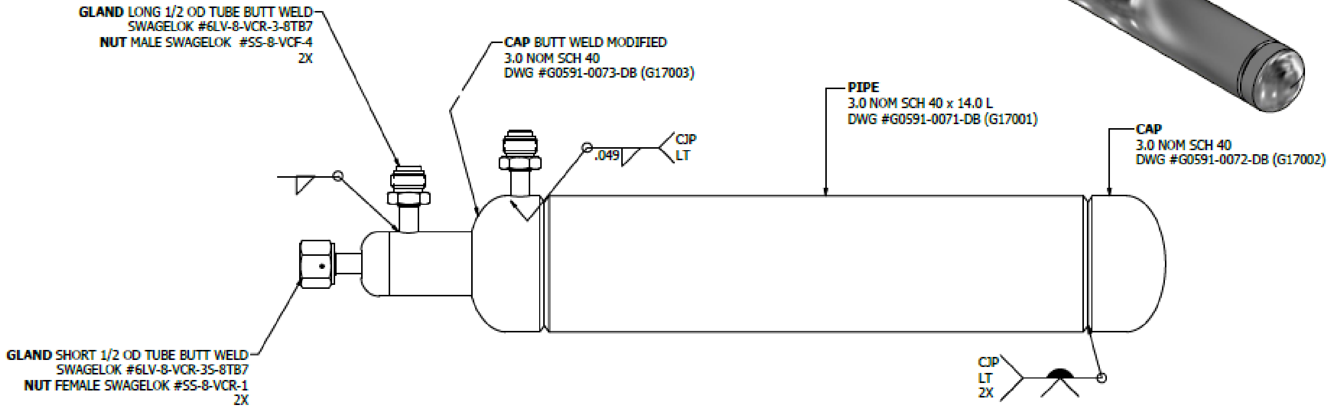
COLD-TRAP REPLACEMENT IN SMT-1 AND SMT-2



- The two sodium material test loops have been operating for 10 years or longer
- Two new cold traps with improved design were fabricated
- The cold trap for SMT-2 has been replaced
- The replacement work for SMT-1 is underway





FY23 PLANNED WORK SCOPE FOR FAST REACTOR MATERIALS

- Complete the initial characterization of the third commercial heat (from ATI)
- Continue A709 Code Case testing of the first two commercial heats
- Initiate testing on the third commercial heat
- Initiate weldment testing on the "production" weldments
- Add A709 filler metal welding wire specification per the American Welding Society (AWS) classification requirements
- Initiate effort to develop design parameters from test data for
  - "Conceptual Design Guide" (planned for FY23)
  - A709 Class B code case (planned for FY24)
  - A709 Class A code case (planned for FY25)
- Work with SME to add A709 plate specification to ASTM and then ASME Section II, Part A
- Continue Alloy 709 sodium compatibility testing

Thank you for your attention

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