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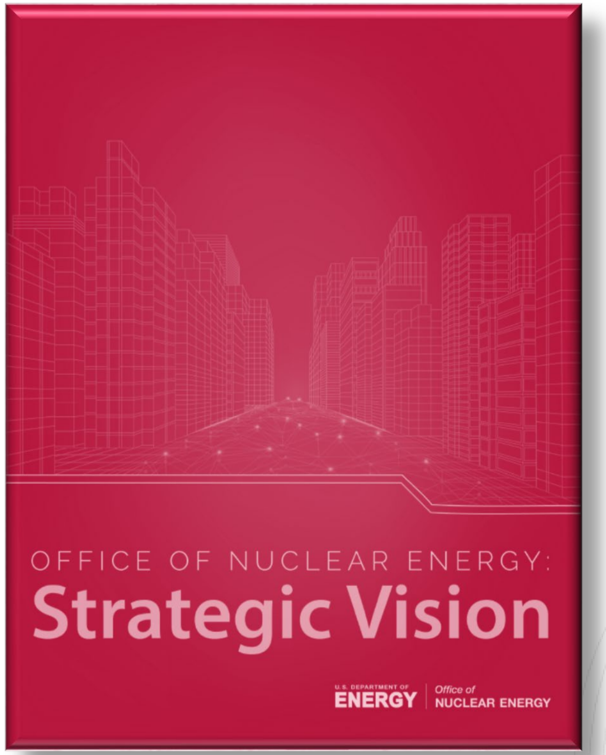
Advanced Materials Program Summary

ART
Advanced Reactor Technologies

DOE Office of Nuclear Energy Strategic Vision

- Vision
  - A thriving U.S. nuclear energy sector delivering clean energy and economic opportunities
- Mission
  - Advance nuclear energy science and technology to meet U.S. energy, environmental, and economic needs
- Goals
  1. Enable continued operation of existing U.S. nuclear reactors
  2. ✓ Enable deployment of advanced nuclear reactors
  3. Develop advanced nuclear fuel cycles
  4. ✓ Maintain U.S. leadership in nuclear energy technology
  5. Enable a high-performing organization

ART Advanced Materials R&D Supports Goals 2 and 4

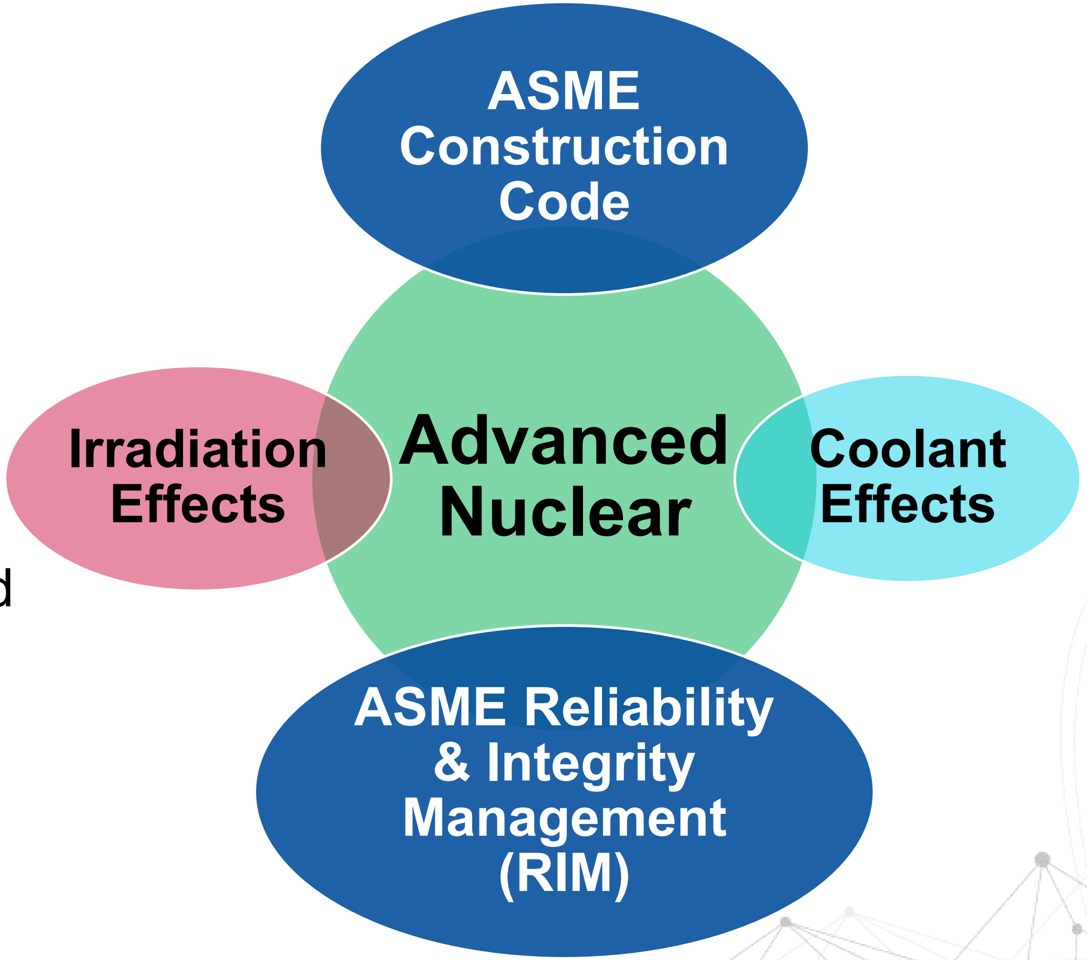


Advanced Reactor Technologies (ART) Advanced Materials Program

- Provide material solutions to enabling design, construction, and operation of licensable advanced reactors
  - Including Gas-cooled Reactors, Fast Reactors, Molten Salt Reactors (solid or liquid fuel)
  - Could be of modular design, and from 350 to 1 Mwe
- Conduct developmental R&D on structural materials that are best addressed by the national program
  - Integrate program-directed work at national labs and universities and collaboration with international partners to address advanced reactor developer needs
  - Provide qualification data (to NQA-1 or equivalent) on structural materials and develop and validate improved high temperature design methodology
  - Utilize consensus standards organizations when appropriate (e.g., ASME, ASTM, etc.)
- Target resolution of issues needed for near to mid-term deployment of advanced reactors

Interrelated Design, Construction and Operation Considerations for Structural Materials

- Topics directly related to ASME Section III, Division 5 for High Temperature Reactors
  - Metallic
    - High temperature design methodology
    - Alloy qualification
    - Fabrication and examination
  - Graphite
    - Qualification and codification
- Additional topics required for licensing approval and plant operations
  - Corrosion effects
    - Gas (He, SCO_2), liquid metal, molten salt
  - Irradiation effects
  - Materials degradation management
  - Flaw evaluations



Integration and Coordination of ART Advanced Materials R&D Portfolio - Metals

Funding Source	Topic	Status	Advanced Reactor Supported
GCR, MRP	Design methods improvement and development	Ongoing	GCR, FR, MSR, MRP
GCR, MRP	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, MRP, GCR
MRP	Qualification of PM-HIP 316H	Ongoing	MRP, MSR, GCR, FR
MSR	Surveillance test article development	Ongoing	MSR, FR, GCR
GCR	GIF VHTR Materials PMB	Ongoing	GCR
FR, MRP	CNWG Advanced Reactors - Material (G91)	Completing	FR, MRP, GCR

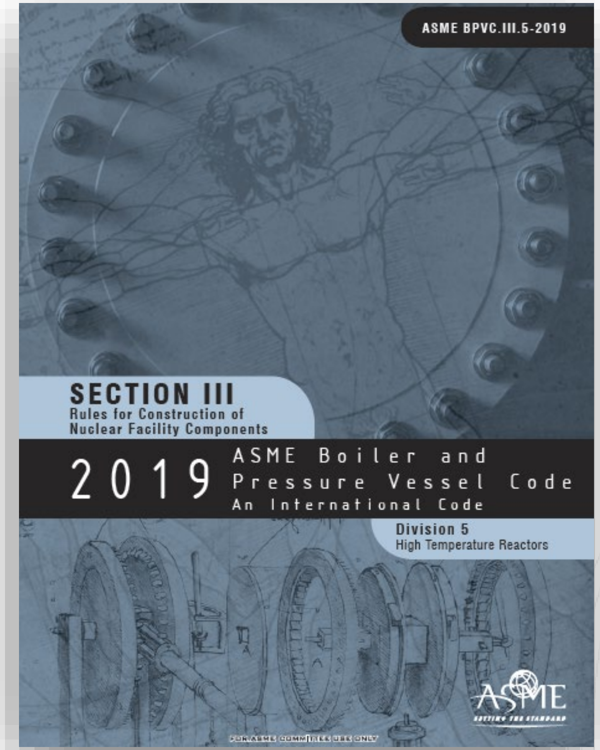
- GCR – Gas-cooled Reactors Campaign
- FR – Fast Rectors Campaign
- MSR – Molten Salt Reactors Campaign
- MRP – Microreactors Program

ART Advanced Materials R&D Portfolio – Coolant Effects on Metals

Funding Source	Topic	Status	Advanced Reactor Supported
GCR	Impure helium effects on A800H and A617	Completed	GCR, MRP
GCR	Fatigue and creep-fatigue crack growth in impure helium – A617	Ongoing	GCR, MRP
FR	Sodium effects on G91, 316H, A709	Ongoing	FR, MRP
MSR	Effects of molten fluoride and chloride salts on stainless steels and nickel alloys	Ongoing	MSR, MRP

NRC Endorsement of ASME Section III, Division 5 - Status

- Nuclear Regulatory Commission (NRC) is currently assessing ASME Section III, Division 5 (2017 Edition) and accompanying Code Cases for endorsement
- Draft Regulatory Guide (DG-1380) and draft NUREG are scheduled to be issued for public comment by June 2021, per update by NRC staff
- The DG is likely to include a number of conditions, in the areas of general requirements, mechanical design, metallic materials allowable stresses, and graphite materials/design
- DG-1380 is a revision to RG 1.87, Revision 1, 1975 (which endorsed the 159X series of ASME Code Cases with conditions)
- Parallel effort to review and endorse the two Alloy 617 code cases
- A technical basis document will be developed, and the results of the review will be merged into the final RG



Overview of GCR FY21 Accomplishments

- Contributors
  - Michael McMurtrey, Ryann Rupp, Joseph Bass, Richard Wright, Sam Sham (INL)
  - Mark Messner (ANL)
  - Yanli Wang (ORNL)

Division 5 Design Rules

Extension of Design Lifetime to 60 Years

Class A Material	Time Dependent Allowable Stress	Minimum Expected Stress-to-Rupture	Thermal Aging Factor	Stress Rupture Factor (Weldment)	Isochronous Stress-Strain Curves
Type 304 SS	Ongoing	Ongoing	TBD	TBD	Ongoing
Type 316 SS	Ongoing	Ongoing	TBD	TBD	Ongoing
A800H	Ongoing	Completed	TBD	TBD	Ongoing
G91	Completed	Completed	Balloting	Balloting	Ongoing

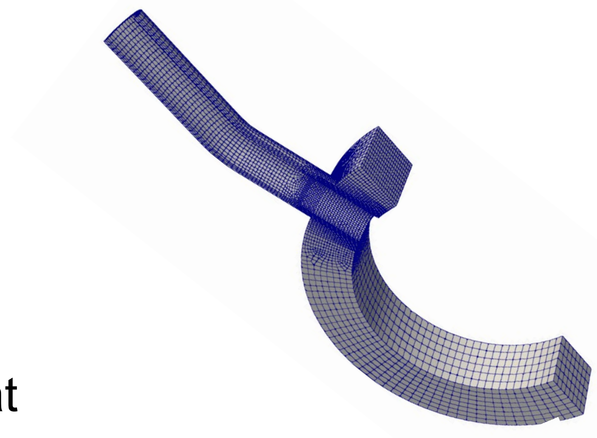
EPP Code Case	Class A materials covered	Status
Primary Load	Types 304 and 316 SS, A800H, G91, 2¼Cr-1Mo, A617	ASME Committees Balloting
Strain Limits	Types 304 and 316 SS, G91, A617 (A800H, 2¼Cr-1Mo ongoing)	Code cases issued by ASME
Creep-Fatigue	Types 304 and 316 SS, G91, A617 (A800H, 2¼Cr-1Mo ongoing)	Code cases issued by ASME

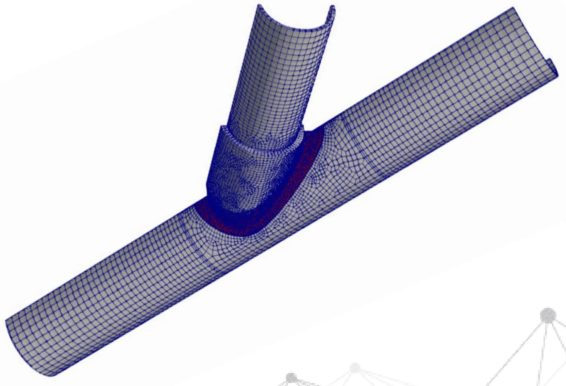
Inelastic Material Models

Class A materials	Status
New Appendix HBB-Z: General guidance, G91 viscoplastic model	ASME Committees Balloting

Inelastic Analysis Methods

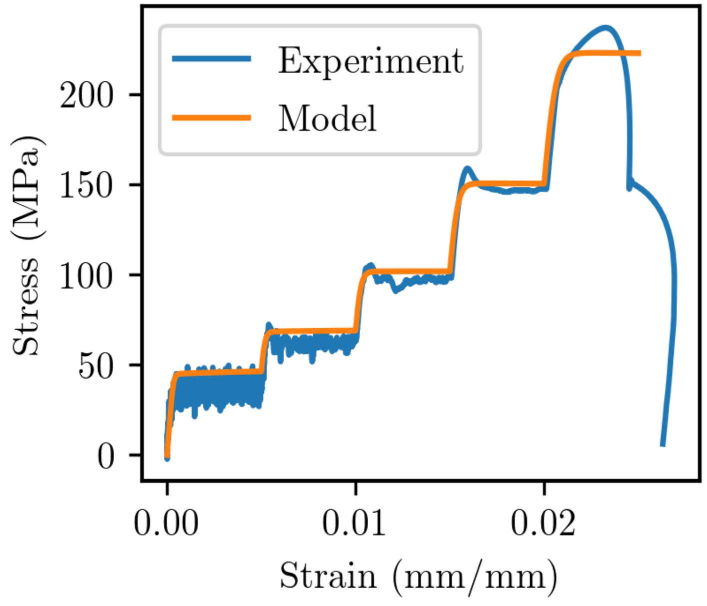
- Current Division 5 status
  - Division 5 does not provide reference inelastic models for any of the Class A materials
  - Specification of the material model left to owner's Design Specification or designers
  - Limits application of the inelastic rules
    - Significant barrier to use inelastic analysis methods to support licensing effort
- Historical experience on the Clinch River Breeder Reactor Project shows that inelastic analysis is:
  - The least over-conservative of the Division 5 design evaluation options
  - Necessary in critical locations where design by elastic analysis is too conservative to produce a reasonable design
- Development status
  - Guidance on inelastic material models development has been drafted
  - Unified viscoplastic constitutive model for G91 steel has been developed
  - Both are included in a new Division 5, Appendix HBB-Z and the Code proposal is under Code Committees ballots





Unified Viscoplastic Constitutive Model Development for A617

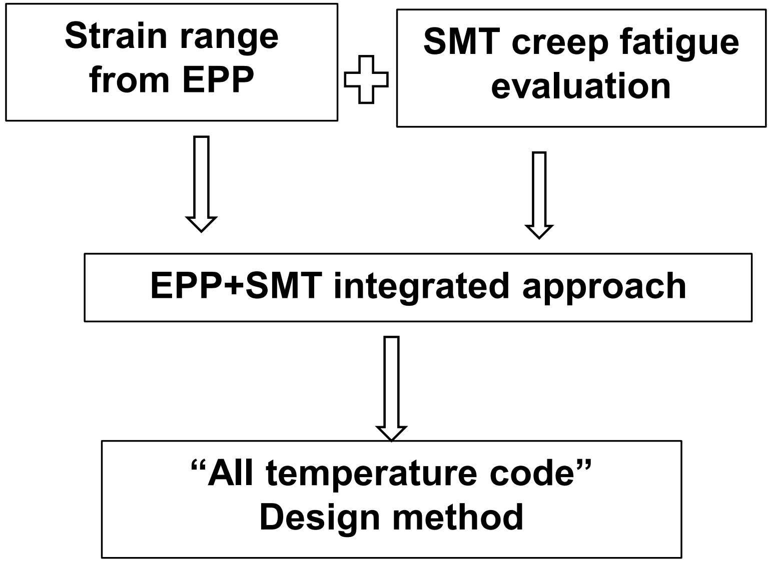
- Model akin to Type 316 stainless steel but with additional needed modeling capabilities:
  - Chaboche kinematic/Voce isotropic hardening
  - Mechanism to switch from rate dependent behavior at high temperature/slow rates to rate independent behavior at low temperatures/fast rates
  - Hayhurst-Leckie damage to model tertiary creep
- Main source of calibration data
  - Data collected at INL and elsewhere for the Alloy 617 Code Case effort
- Validations performed:
  - Strain rate jump
  - Thermomechanical tests
  - ORNL pressurized-SMT data
- A617 viscoplastic model completed
  - Will introduce Type 316 stainless steel and Alloy 617 models in Appendix HBB-Z for balloting in FY22

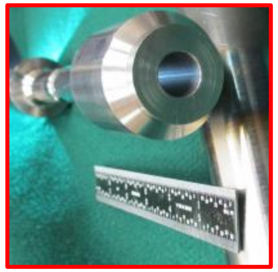


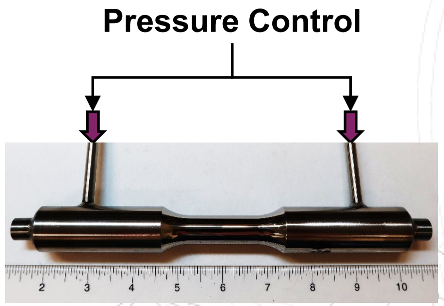
INL strain rate jump test at 950C

New Integrated EPP + SMT Creep-Fatigue Design Procedure

- Integrated approach combines advantages of EPP and SMT methodologies
  - EPP eliminates stress classification
    - Approved for Type 304 SS, Type 316 SS, G91 and integrated into alloy 617 Code Case
    - In the process of integrating A800H and 2.25Cr-1Mo
  - SMT eliminates separation of creep and fatigue damage (no creep-fatigue damage diagram)
- EPP+SMT improves the accuracy and implementation of creep-fatigue damage evaluation
- Will submit EPP+SMT Code Case to ASME for approval in FY22





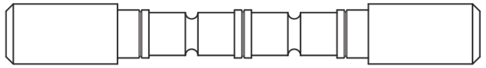


Notch Strengthening vs. Weakening of Alloy 617 – Impact of Multiaxial Stress, Discontinuities, Notch on Creep Rupture

U-Notch, Base Metal

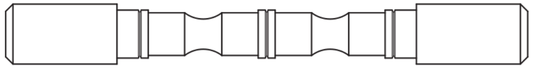
Small radius

$$\frac{d_{no}}{r_{no}} = 4.83$$

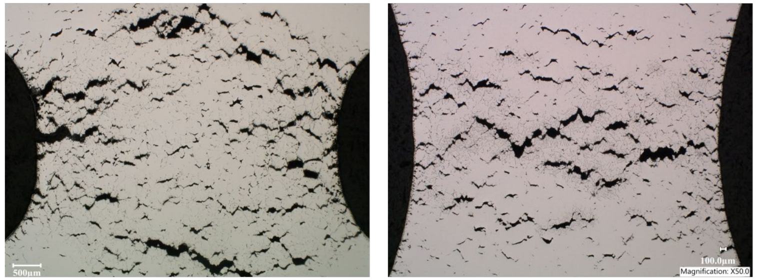


Large radius

$$\frac{d_{no}}{r_{no}} = 1$$



U-Notch, 1,000C, 20 MPa

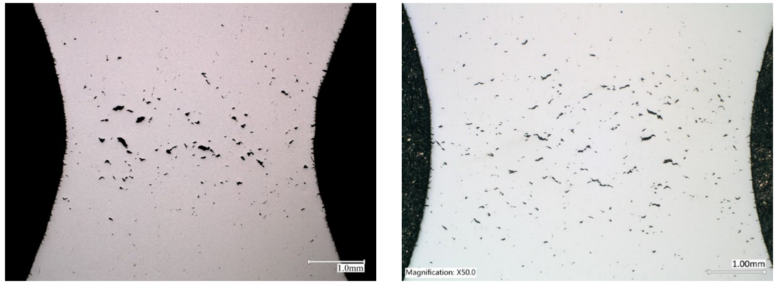


Small Radius
t = 3,415 h

Large Radius
t = 1,580 h

1 mm

U-Notch, Large Radius, 800C



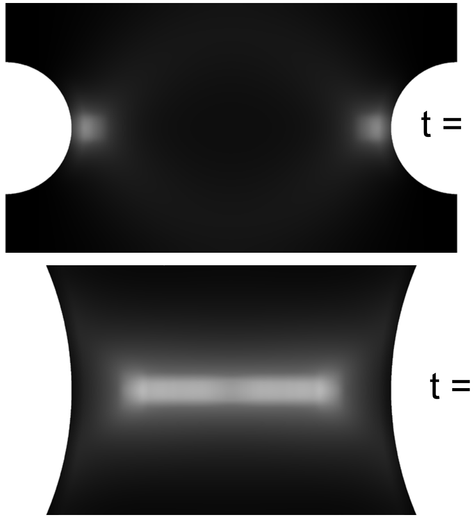
80 MPa, t = 2,114 h

60 MPa, t = 10,837 h

Mod-Sim with damage model

Experiment, 750C, 145 MPa

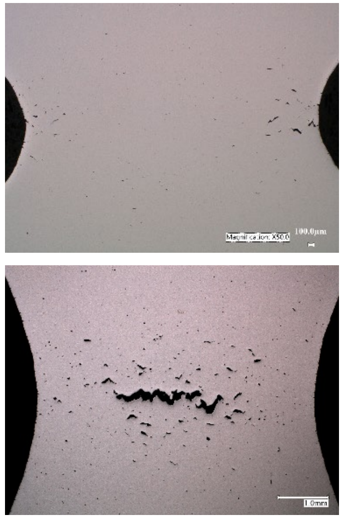
U-Notch
Small Radius



t = 12,463 h

U-Notch
Large Radius

t = 5,732 h



- Data showed notch strengthening behavior for short and intermediate term rupture
- Long term (100,000 h) notch strengthening/weakening tests ongoing
- Similar notch studies for A617 weld

Performance of Permissible A800H Welds Not Optimum

Table HBB-I-14.10C-1
Stress Rupture Factors for Alloy 800H Welded With SFA-5.11 ENiCrFe-2 (INCO A)

U.S. Customary Units

Temp., °F	10 hr	30 hr	100 hr	300 hr	1,000 hr	3,000 hr	10,000 hr	30,000 hr	100,000 hr	300,000 hr
850–900	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
950	1.00	1.00	1.00	1.00	0.98	0.95	0.92	0.90	0.86	0.83
1,000	1.00	1.00	1.00	1.00	0.98	0.94	0.90	0.86	0.82	0.78
1,050	1.00	1.00	1.00	1.00	0.98	0.94	0.89	0.85	0.81	0.76
1,100	1.00	1.00	1.00	1.00	0.98	0.94	0.89	0.84	0.79	0.75
1,150	1.00	1.00	1.00	1.00	0.98	0.93	0.88	0.83	0.77	0.72
1,200	1.00	1.00	1.00	1.00	0.98	0.93	0.87	0.81	0.75	0.70
1,250	1.00	1.00	1.00	1.00	0.98	0.92	0.85	0.80	0.73	0.68
1,300	1.00	1.00	1.00	1.00	0.97	0.91	0.84	0.77	0.71	0.65
1,350	1.00	1.00	1.00	1.00	0.96	0.89	0.82	0.75	0.68	0.62
1,400	1.00	1.00	1.00	1.00	0.95	0.87	0.80	0.73	0.65	0.59

INCO A, SRF = 0.59 @ 1,400F, 300,000 h

Table HBB-I-14.10C-2
Stress Rupture Factors for Alloy 800H Welded With SFA-5.14 ERNiCr-3 (INCO 82)

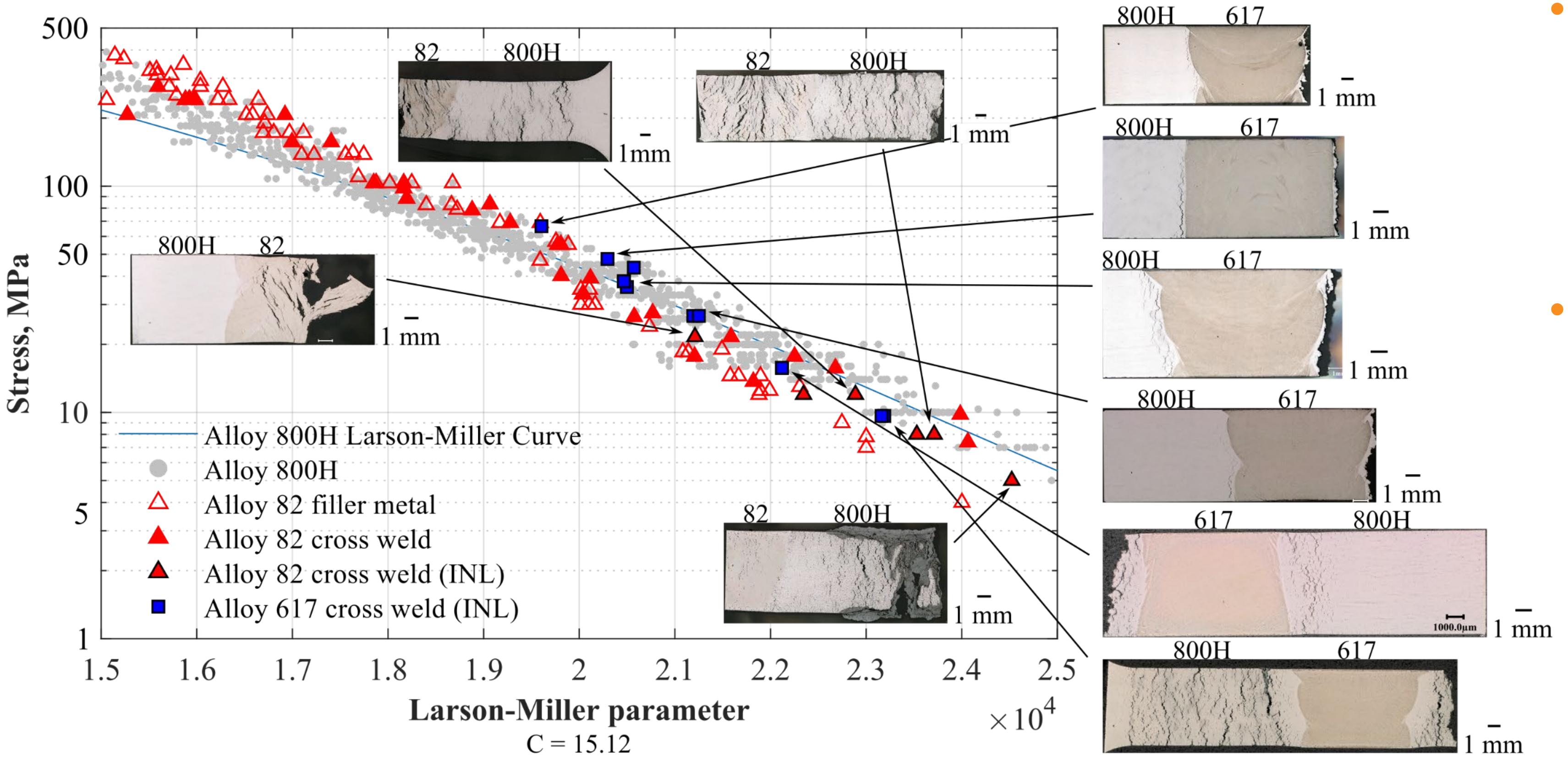
U.S. Customary Units

Temp., °F	10 hr	30 hr	100 hr	300 hr	1,000 hr	3,000 hr	10,000 hr	30,000 hr	100,000 hr	300,000 hr
850–900	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
950	0.89	0.90	0.90	0.90	0.89	0.89	0.88	0.87	0.86	0.86
1,000	0.85	0.86	0.86	0.86	0.85	0.85	0.84	0.84	0.82	0.81
1,050	0.88	0.88	0.88	0.88	0.87	0.86	0.85	0.84	0.83	0.81
1,100	0.91	0.91	0.91	0.90	0.89	0.88	0.87	0.85	0.83	0.81
1,150	0.94	0.93	0.93	0.92	0.90	0.89	0.87	0.85	0.83	0.81
1,200	0.96	0.96	0.95	0.93	0.92	0.90	0.88	0.86	0.83	0.81
1,250	0.99	0.98	0.96	0.95	0.93	0.91	0.88	0.85	0.82	0.80
1,300	1.00	1.00	0.98	0.96	0.93	0.91	0.88	0.85	0.82	0.78
1,350	1.00	1.00	0.99	0.96	0.94	0.91	0.87	0.84	0.77	0.68
1,400	1.00	1.00	1.00	0.97	0.94	0.89	0.79	0.71	0.62	0.54

INCO 82, SRF = 0.54 @ 1,400F, 300,000 h

- The stress rupture factors (SRFs) for the two permissible filler metals for A800H may impede construction at high temperature and long service lives

Advanced A800H Filler Metals



- Investigated overmatched filler metal, Alloy 617
  - Only slight performance gain over current permissible welds
- Next step: Investigate matching filler metal, UTP A 2133 Mn
  - Aiming for similar creep strength as base metal

Summary

- ART Advanced Materials R&D for metals involves integration and coordination of activities of GCR, FR, MSR, MRP
- Significant accomplishments under GCR funding
- Expected GCR FY22 accomplishments
  - Approval of primary load code case
  - Approval of Appendix HBB-Z and G91 viscoplastic model
  - Submit revised allowable stresses and rupture stresses for Type 304 and 316 SS for approval
  - Submit Type 316 SS and A617 viscoplastic models for approval
  - Submit EPP strain limits and creep-fatigue code cases to include A800H for approval
  - Complete EPP+SMT creep-fatigue development and submit code case for approval
  - Initiate development on A800H viscoplastic model
  - Continue notch testing of A617
  - Initiate cross weld creep rupture testing of A800H/A21.33 Mn weldment
  - Initiate A617 fatigue and creep-fatigue crack growth tests in impure helium
  - Initiate development of improved Class B design rules to include design-by-analysis and time-dependent allowable stresses

Idaho National Laboratory