GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

July 18, 2024

High Temperature Materials

Heramb Mahajan

Idaho National Laboratory

DOE ART GCR Review Meeting

Hybrid Meeting at INL

July 16–18, 2024

FY-24 Work Packages and Contributors

FY24 Work Packages	R&D topics
High Temperature Design Methodology - ANL, INL, ORNL	• ASME code participation • Continue development of new Class B rules • Variable amplitude fatigue testing to validate the fatigue design rules • Inelastic material models development and limited deformation data generation for all Division 5 Class A materials
Long-Term VHTR Material Qualification – INL, ORNL	• Verification of EPP + SMT method • Continue testing of new Alloy 800H weldment • Creep and creep-fatigue crack growth tests in air and in reactor grade helium

- Contributors
  - Heramb Mahajan, Michael McMurtrey (INL)
  - Yanli Wang, Brad Hall (ORNL)
  - Mark Messner, Hao Deng (ANL)
  - Sam Sham (Now NRC)
  - Bob Jetter, Richard Wright, Bill Corwin (Subject Matter Experts)

Component Construction Rules for Advanced Reactor Designs

NRC Regulatory Guide 1.87 revision 2, Jan 2023		
Components	**Quality Design Standards**	
Traditional Component Classification	Quality Group A	Quality Group B
Pressure Vessels, Piping, Pumps, Valves	Subsection HB, Class A	Subsection HC, Class B
Metallic core support structures	Subsection HG, Class SM	NA
Nonmetallic core support structures	Subsection HH, Class SN	NA

ASME BPVC Section III, Division 5 Code

- Division 5 is organized by Code Classes
- Component classification in different importance levels based on function
- Code classes selection to assure structural integrity

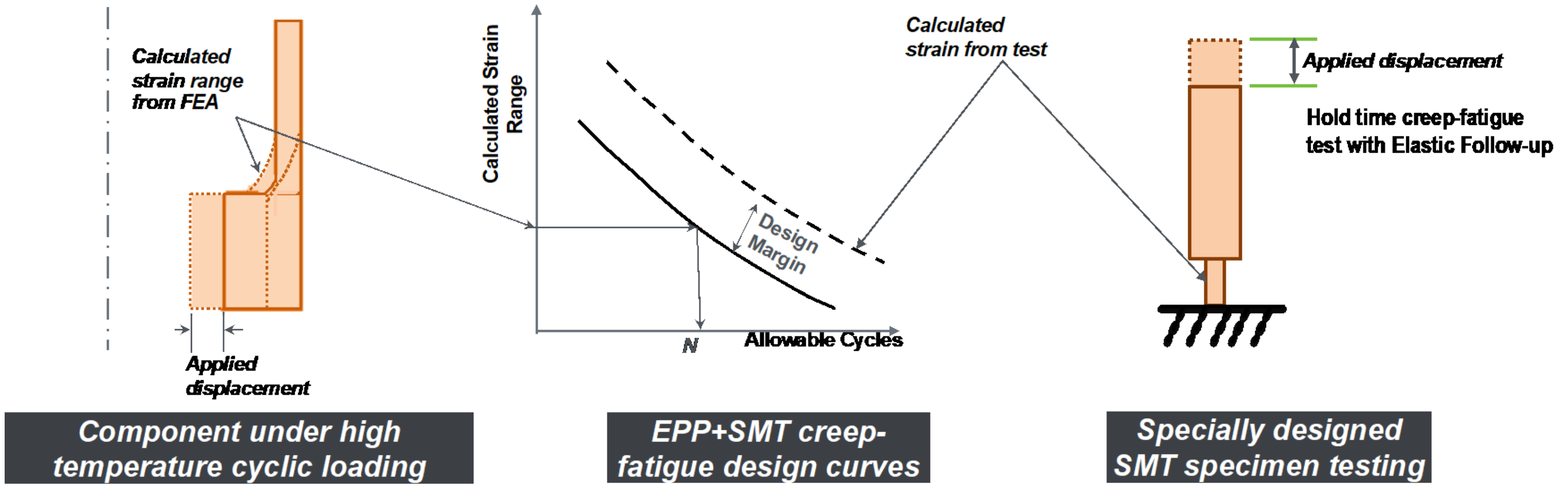
Material Library in Section III, Division 5 for Advanced Reactor Design

Maximum design life	10 Years	20 Year	30 Year	40 Year	50 Years	60 Year
SS 304						
SS 316H				Ongoing	Ongoing	Ongoing
800H				Ongoing	Ongoing	Ongoing
21/4Cr-1Mo (Grade 22)				Ongoing	Ongoing	Ongoing
9Cr-1Mo-1V (Grade 91)						
Alloy 617 (Ni-alloy)		Ongoing	Ongoing			
Alloy 709* (Planned)	Ongoing					

Maximum operation temperature	450C	500C	550C	600C	650C	700C	750C	800C	850C	900C	950C
SS 304											
SS 316H											
800H											
21/4Cr-1Mo (Grade 22)				Limit	Limit						
9Cr-1Mo-1V (Grade 91)											
Alloy 617 (Ni-alloy)											
Alloy 709* (Planned)											

*Currently A709 is not available in ASME Section III, Division 5. A709 Code case is under development.

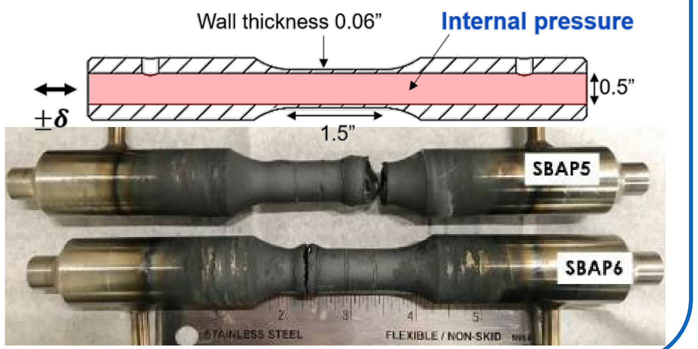
New Creep-Fatigue Evaluation Approach: Simplified Model Test (SMT)



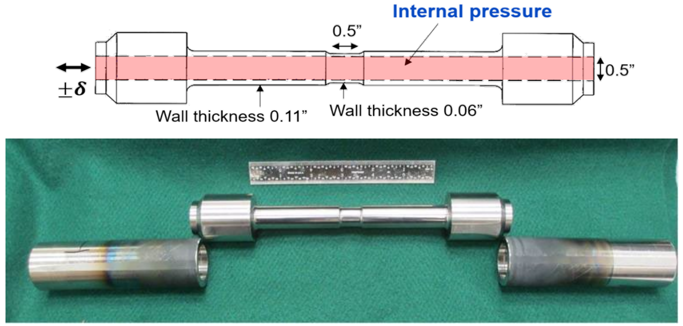
- An alternative to Creep-Fatigue evaluation Approach in the ASME Section III Division 5 Code
- Consider strain accumulation damage at critical locations
- Represents the combined creep-fatigue effects at local stress raisers with multiaxiality

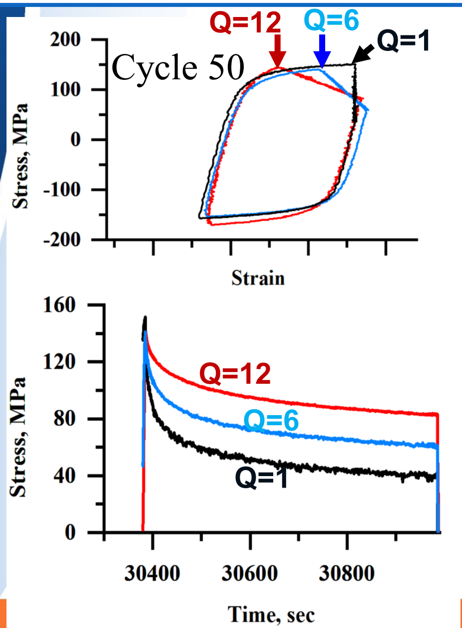
Testing and Developing SMT-based Creep-Fatigue Design Curves

Pressurized Single Bar SMT specimen

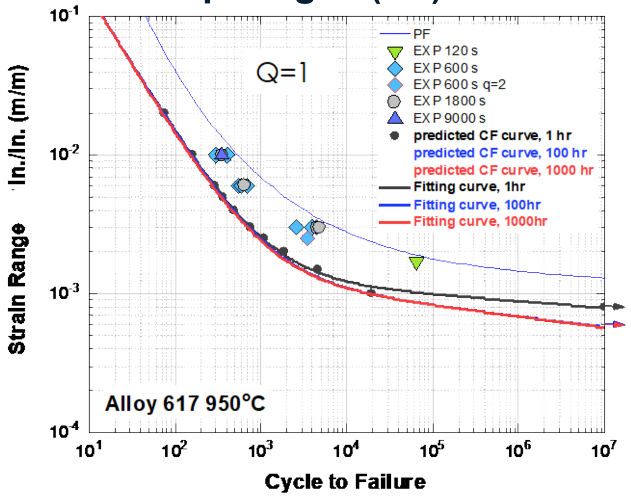


Pressurized SMT specimen



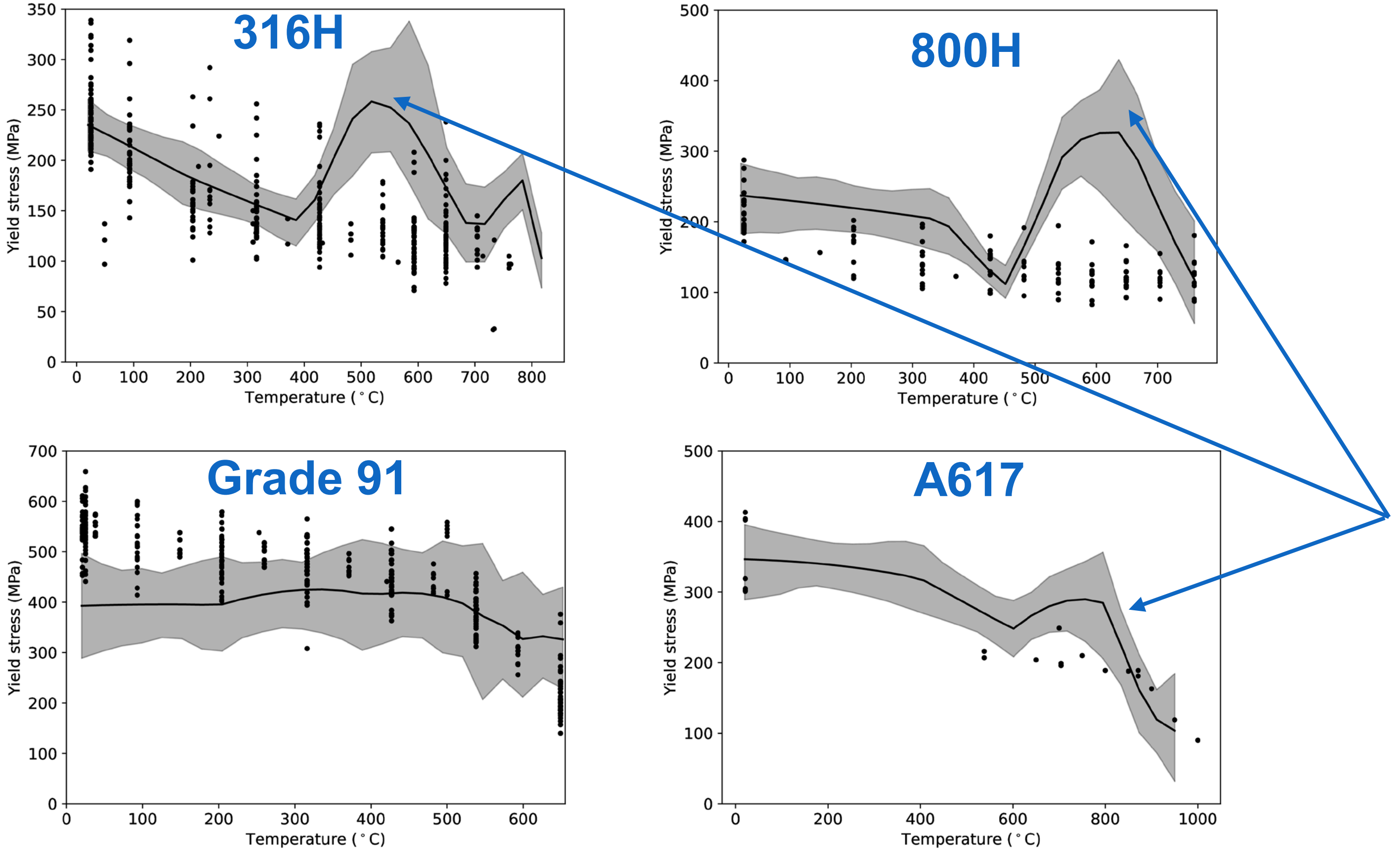


Creep-fatigue (CF) life



- Elastic follow-up effect:
  - Enhanced creep damage
  - Strain accumulation
- Support Elastic perfectly Plastic (EPP+SMT) design methodology
- Dissipation work-based method for CF life prediction
- Ongoing work
  - Design curves at lower temperature are being developed (400-800C)
  - Adopt Dissipated work of CF tests as the conservative design life criteria at lower temperature

Inelastic Model Development: Limitation with pure Chaboche Models

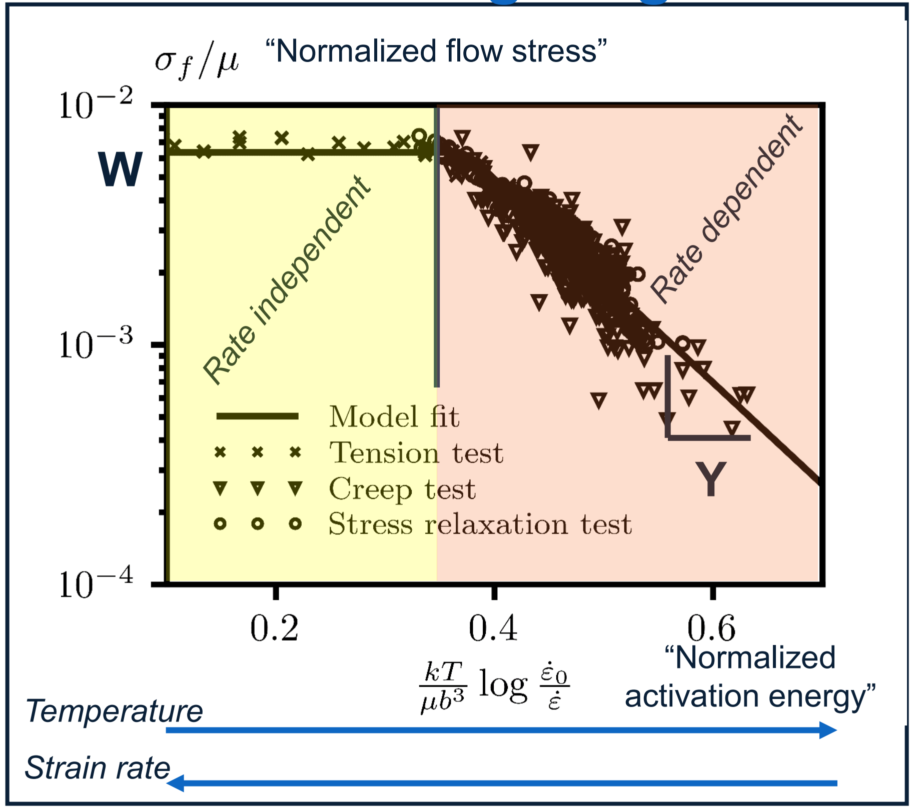


Overshoot at onset of creep regime

Inelastic Model Development: Kocks-Mecking model for Rate Senstivity

- General concept – Material flow stress is controlled by thermally activated processes
- Normalized activation energy describes the energy available for dislocations to overcome
- Tension, creep, and stress relaxation data falls on a bilinear curve

Kocks-Mecking diagrams

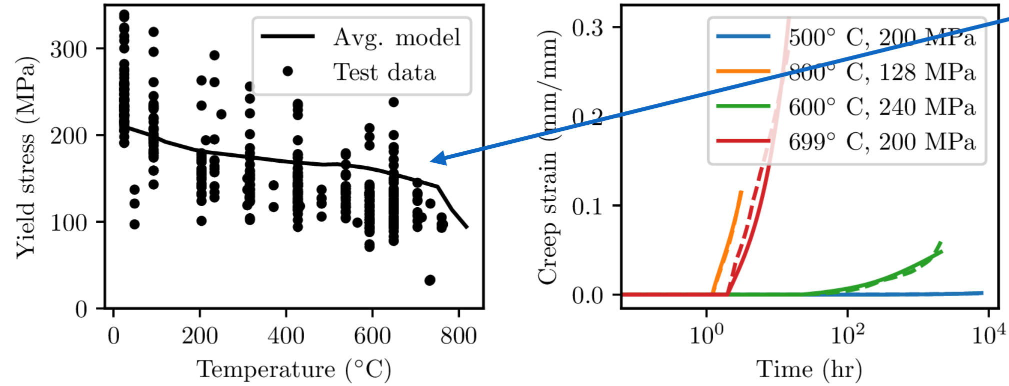


Mecking, H., and U. F. Kocks. "Kinetics of flow and strain-hardening." Acta metallurgica 29.11 (1981): 1865-1875.

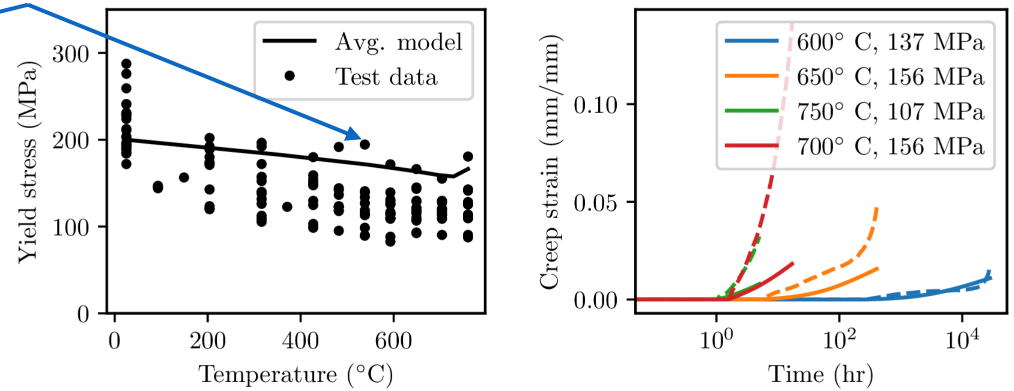
Inelastic Model Development: Chaboche hardening with Kocks-Mecking Flow Rule

No overshoot at onset of creep regime

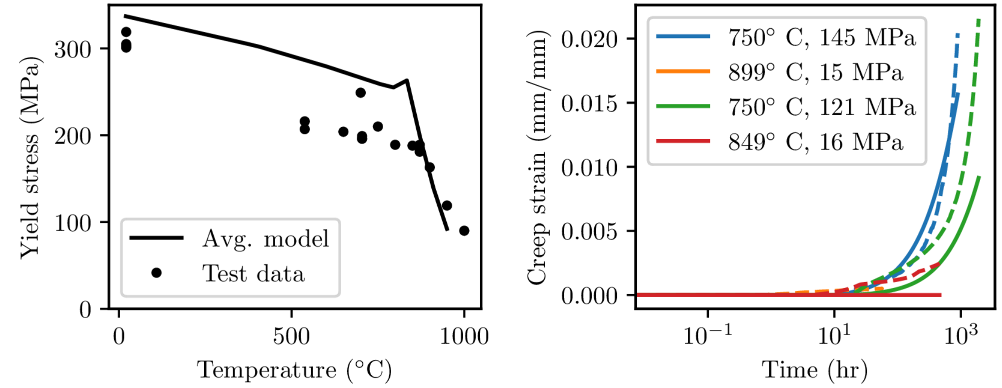
316H



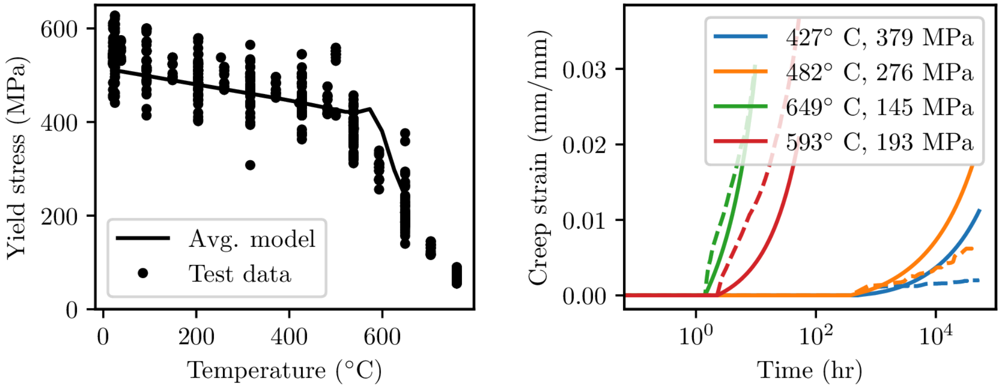
800H



A617



Grade 91



Class B Code Case Development: Allowable Stress Development

- Material list – 316H, A617, 304H, 800H, Gr.91, Gr. 22
- Use all available data in Section III Division 5 Class A to develop Class B allowable stresses
- Develop allowable stresses

Creep Test Data

All available data, extensive information

Data extrapolation options

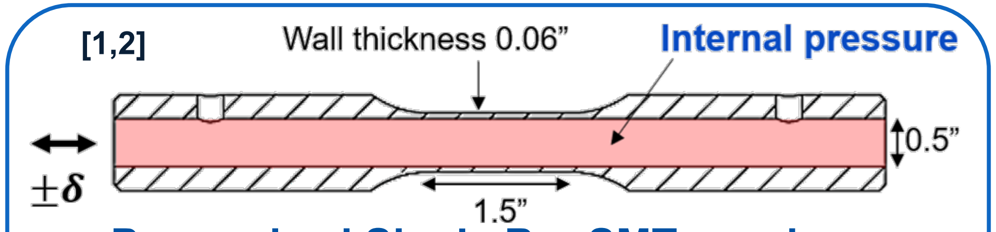
Larson-Miller with fixed confidence levels (Standard approach)

Allowable stress

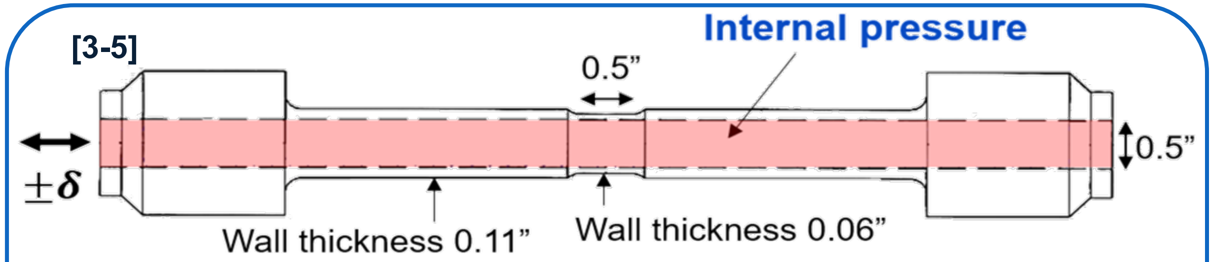
Time- and temperature dependent up to design time of 500,000 hours

Class B Code Case Development: Evaluation against Experimental Data

- Simplified Model Test (SMT) specimen to capture component response
- Test data and rupture life from literature [1-5]
- Material: Alloy 617



Pressurized Single Bar SMT specimen captures elastic follow-up through software-controlled test protocols

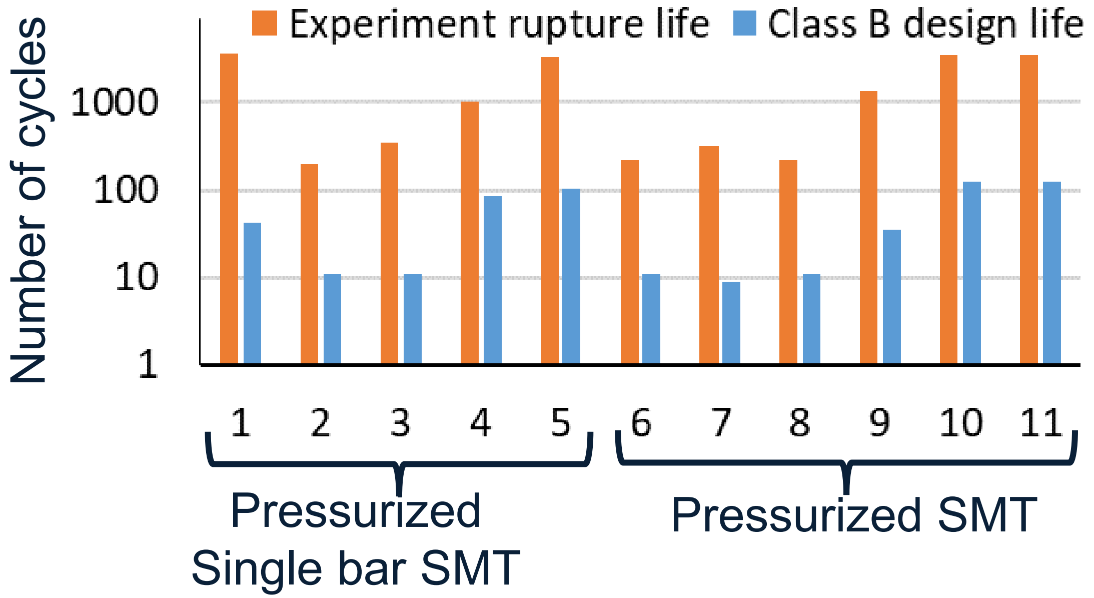


Pressurized SMT specimen captures elastic follow-up through test specimen geometry and external load

[1] Wang Y., Hou, P., Jetter R.I. and Sham T.L., “Evaluation of Primary-load Effects on Creep-Fatigue Life of Alloy 617 Using Simplified Model Test Method”, Proceedings of the ASME 2021 Pressure Vessels and Piping Conference, PVP2021-61658, July 2021.
[2] Wang, Y., Hou, P., Jetter, R.I. and Sham, T.L., “Report on FY2020 Test Results in Support of the Development of EPP Plus SMT Design Method.” ORNL/TM-2020/1620, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, 2022.
[3] Wang Y., Jetter R.I. and Sham T.L., “Pressurized Creep-Fatigue Testing of Alloy 617 Using Simplified Model Test Method”, Proceedings of the ASME 2017 Pressure Vessels and Piping Conference, PVP2017-65457, July 2017.
[4] Wang, Y., Jetter, R.I., Messner, M.C. and Sham, T. L., “Report on FY19 Testing in Support of Integrated EPP-SMT Design Methods Development.” ORNL/TM-2019/1224, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, 2019.
[5] Wang Y., Jetter R. I. and Sham T.L., “Effect of Internal Pressurization on the Creep-Fatigue Performance of Alloy 617 Based on Simplified Model Test Method”, PVP2019-93650, July 2019.

Class B Code Case Development: Evaluation against Experimental Data

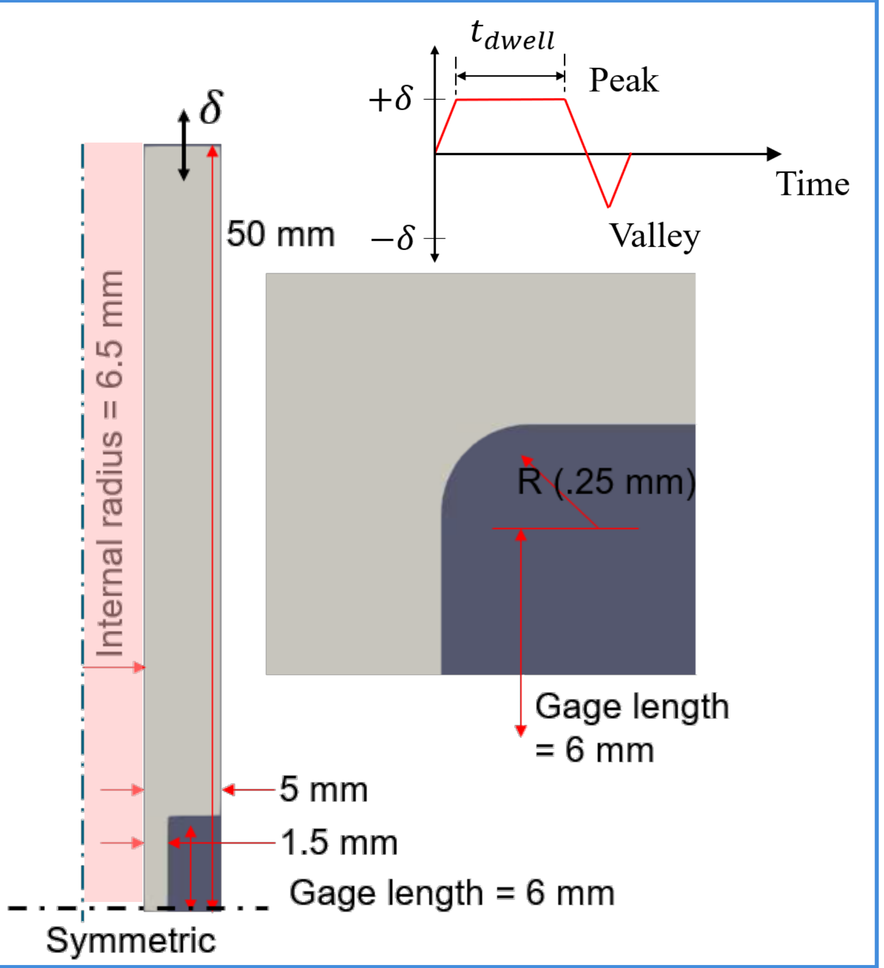
Specimen Geometry	ID	Test Name	T (°C)	Internal Pressure (MPa)	q
Pressurized Single bar SMT [1-2]	1	SBAP4	950	0.01	6.1
	2	SBAP5	950	1.03	3.4
	3	SBAP6	950	0.01	3.5
	4	SBAP9	950	1.03	2.0
	5	SBAP7	950	0.01	2.0
Pressurized SMT [3-5]	6	P01	950	0.01	3.8
	7	P05	950	0.01	3.5
	8	P02	950	1.38	3.8
	9	P12	950	0.01	4.1
	10	P14	850	2.76	3.5
	11	P15	850	0.14	3.5



Class B creep-fatigue assessment is conservative compared to the rupture life

[1] Wang Y., Hou, P., Jetter R.I. and Sham T.L., "Evaluation of Primary-load Effects on Creep-Fatigue Life of Alloy 617 Using Simplified Model Test Method", Proceedings of the ASME 2021 Pressure Vessels and Piping Conference, PVP2021-61658, July 2021.
[2] Wang, Y., Hou, P., Jetter, R.I. and Sham, T.L., "Report on FY2020 Test Results in Support of the Development of EPP Plus SMT Design Method." ORNL/TM-2020/1620, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, 2022.
[3] Wang Y., Jetter R.I. and Sham T.L., "Pressurized Creep-Fatigue Testing of Alloy 617 Using Simplified Model Test Method", Proceedings of the ASME 2017 Pressure Vessels and Piping Conference, PVP2017-65457, July 2017.
[4] Wang, Y., Jetter, R.I., Messner, M.C. and Sham, T. L., "Report on FY19 Testing in Support of Integrated EPP-SMT Design Methods Development." ORNL/TM-2019/1224, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, 2019.
[5] Wang Y., Jetter R. I. and Sham T.L., "Effect of Internal Pressurization on the Creep-Fatigue Performance of Alloy 617 Based on Simplified Model Test Method", PVP2019-93650, July 2019.

Class B Code Case Development: Evaluation with Sample Problem



Maximum allowable design cycles

ID	Stress concentration factor	Section III Division 5 Class A analysis methodologies			Proposed Class B rules
		Elastic	EPP	Inelastic	
A	1.44	101	705	503	282
B	1.71	34	294	282	183
C	2.64	4	88	155	99

Proposed Class B rules adopt simplified procedure without excessive conservatism

Future Work – Tasks for FY24

Continued Support for Code Rule Development

- Continue design curve development for alternative CF method at lower temperature range
- Continue the model training and optimization work. Plan to finish the four models by end of FY and support the ASME Code change for the 2027 edition
- Finish the draft Class B Code case by end of FY and continue the allowable stress development for candidate Class B materials

GAS-COOLED REACTOR

ADVANCED REACTOR TECHNOLOGIES PROGRAM

Thank You

Heramb Mahajan

Heramb.Mahajan@inl.gov

U.S. DEPARTMENT OF ENERGY