U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

GCR: Class B Code Case

Joint ART Materials/AMMT Program Review

DOE Headquarters, Germantown, MD

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FY23 AT-23IN060402 High Temperature Design Methodology – INL

- **Task 1**
  - Initiate development to revamp the ASME Section III, Division 5 Class B design rules
- **Development Team**
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  - Yanli Wang (ORNL)
  - Robert Jetter (SME)

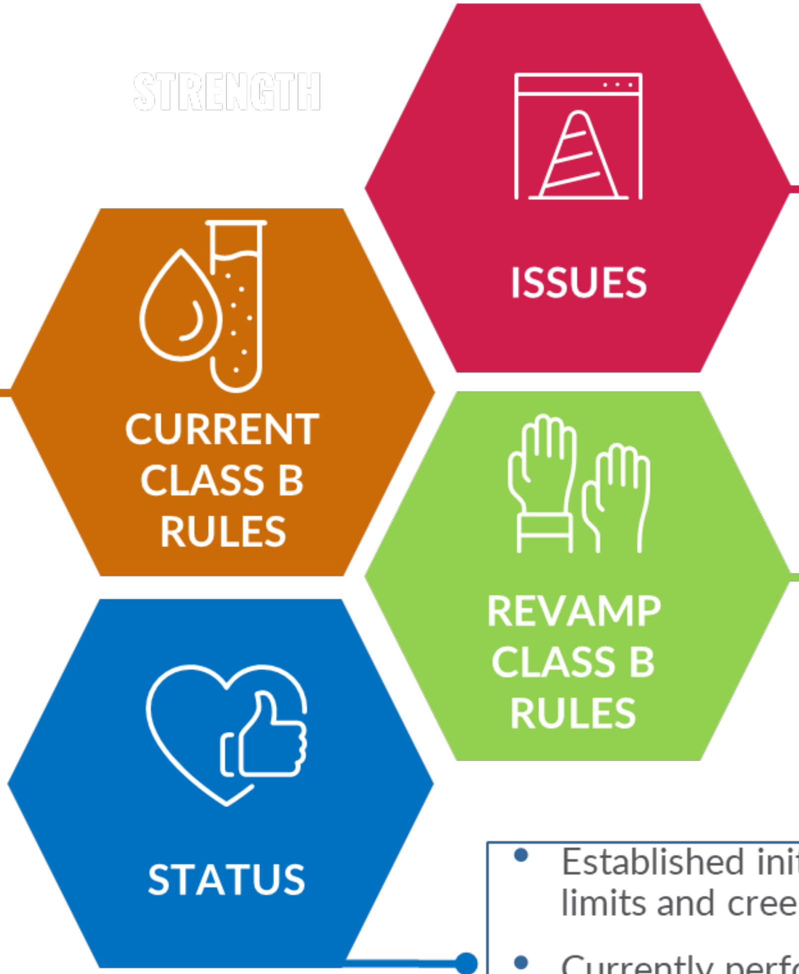
ASME Section III, Division 5 - A Component Construction Code

- Division 5 is organized by Code Classes:
  - Class A, Class B, Class SM for metallic components
  - Class SN for non-metallic components
- Division 5 recognizes the different levels of importance associated with the function of each component as related to the safe operation of the advanced reactor plant
- The Code Classes allow a choice of rules that provide a reasonable assurance of structural integrity and quality commensurate with the relative importance assigned to the individual components of the advanced reactor plant

NRC Regulatory Guide 1.87 revision 2, Jan 2023		
Classification Method	**Component Classification**	
• Traditional	Quality Group A	Quality Group B
• Risk-informed (10 CFR 50.69)	RISC-1	RISC-1
• Risk-Informed (RG 1.233)	SR	SR
Components	**SR Qualify Design Standards**	
Pressure Vessels, Piping, Pumps, Valves, Atmospheric Storage Tanks, Storage Tanks (0-15 psig)	ASME Code, Section III, Division 5, Class A	ASME Code, Section III, Division 5, Class B
Metallic Core Support Structures	ASME Code, Section III, Division 5, Subsection HG	NA
Nonmetallic Core Support Structures	ASME Code, Section III, Division 5, Subsection HH	NA

Revamp ASME Division 5 Class B Construction Rules

- Are extension of construction rules of Section III, Division 1, Class 2 vessel, pump, valve and piping designs to elevated temperature service
- Similar to commercial rules (Section I and Section VIII, Division 1)
- Based on the design-by-rule approach
- Allowable stresses based on extrapolated 100,000-hour creep rupture properties
- Cyclic loading in creep regime (i.e., creep-fatigue interaction) not considered
  - Except for piping, but very conservative rules



- These rules do not provide the design flexibility and are not adequate to address many design and operational characteristics of new high temperature reactors
  - Different design lifetimes, e.g., 7, 20 or 60 years
  - Thermal cycles
  - Limited permissible Class B materials

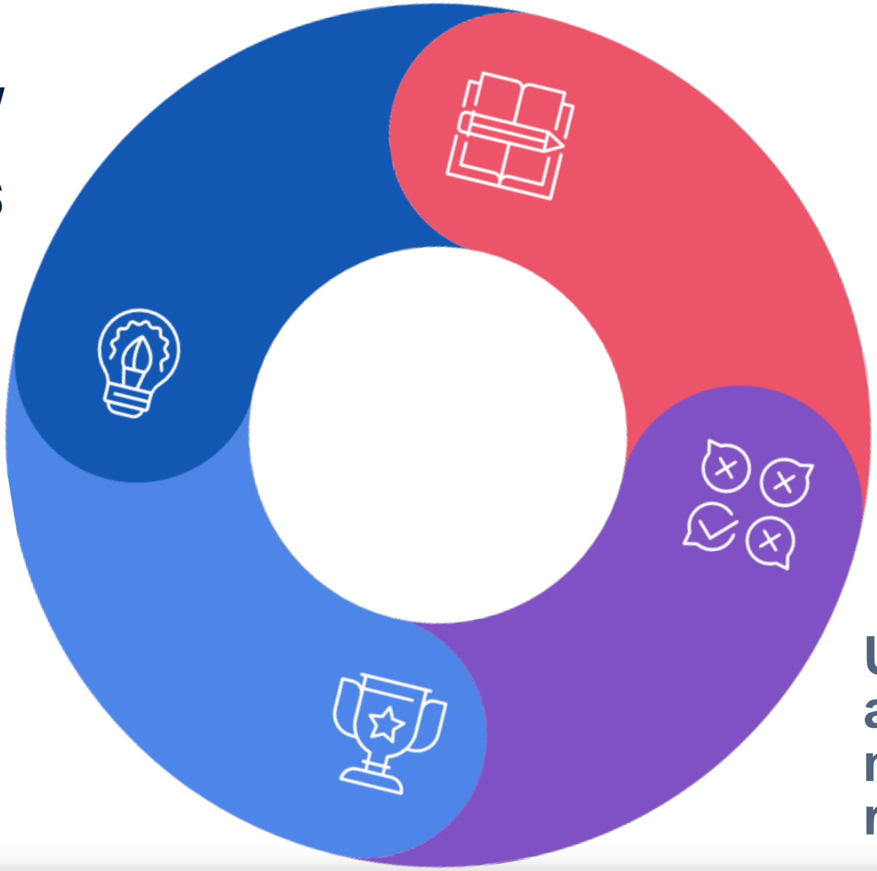
- Incorporate time-dependent allowable stresses and design lifetime concept
- Introduce simplified design-by-analysis approach to address primary load, strain limits and creep-fatigue
- Expand the permissible Class B materials list

- Established initial rules for primary load, strain limits and creep-fatigue
- Currently performing assessment of the new rules using sample problems

Strategic Steps to Address Current Gaps in Class B Methodology

Propose new Class B rules

Targeting current gaps and based on engineering judgments



Evaluate proposed rules (I)

Compare with available test data, e.g., from key-feature testing

Evaluate proposed rules (II)

Use sample problems to compare against other design analysis methods, e.g., Division 5 Class A rules – elastic, EPP, inelastic

Revise rules if necessary for improvement

New Class B Rules – Primary Load & Strain Limits

- **Primary stress limit**
  - Design condition assessment
    - Elastic-perfectly plastic analysis based on time and temperature dependent pseudo yield stress
  - Service condition assessment
    - Same as new Class A EPP primary load Code Case (without local check)
    - Time and temperature dependent pseudo yield stress

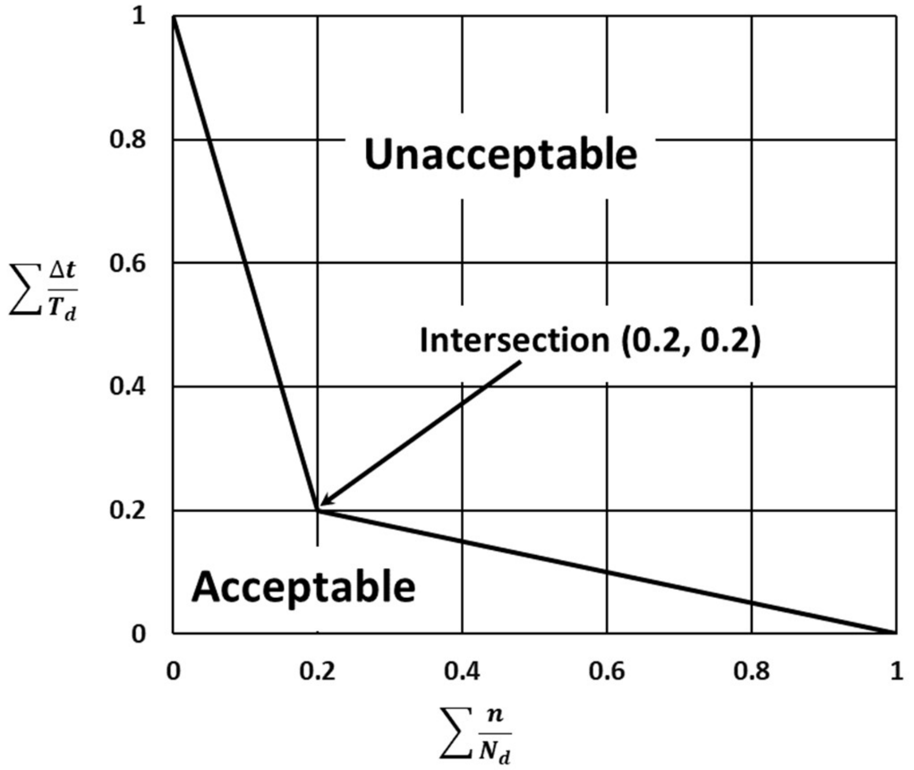
- **Cyclic load assessment in elevated regime**
  - Strain limits –
    - Pseudo yield stress from simplified Isochronous Stress-Strain Curves (ISSCs) – time and temperature dependent
    - EPP plastic shakedown without explicit strain limits

New Class B Rules – Creep-Fatigue

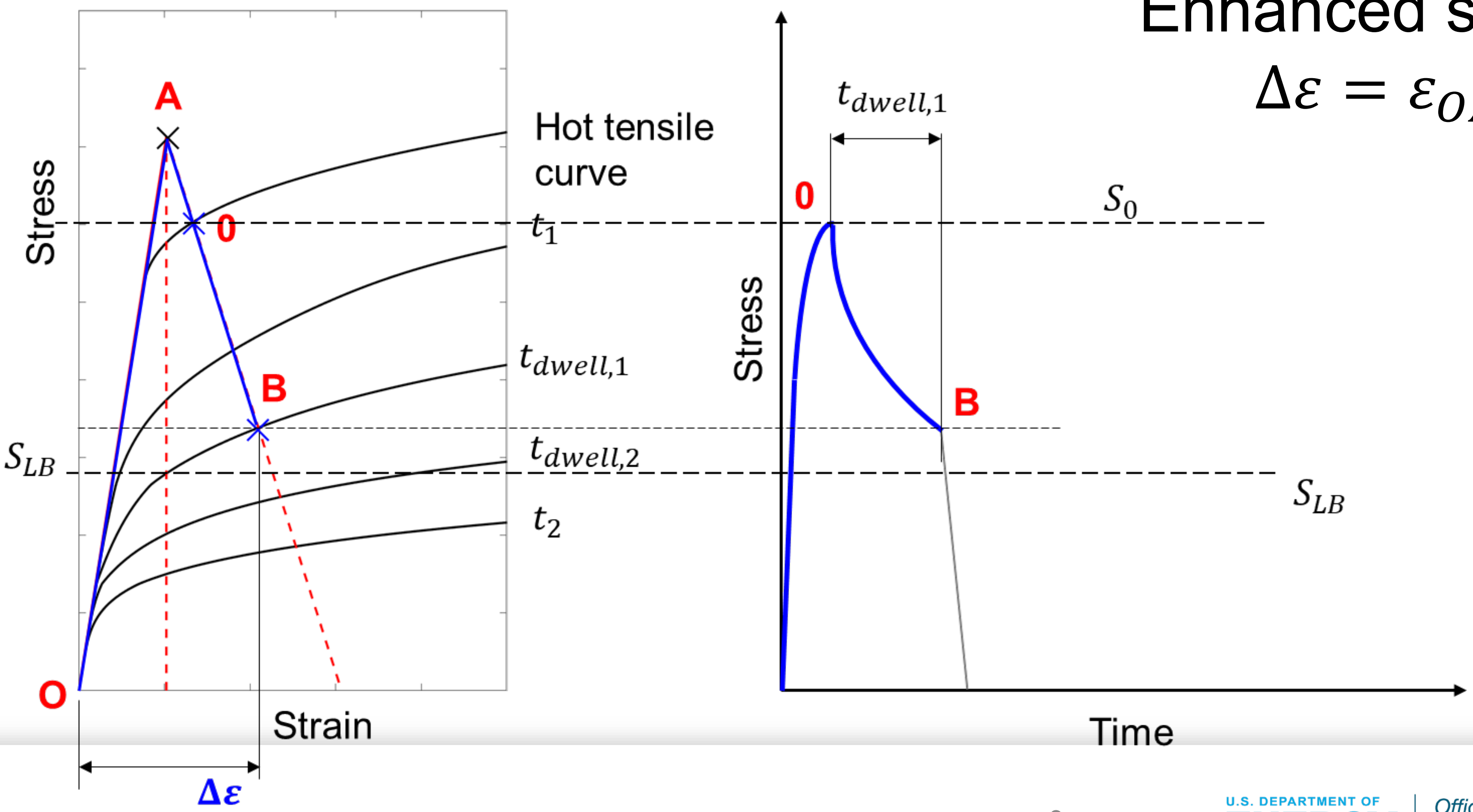
- **Creep Damage Evaluation**
  - Determine stress history σ from elastically calculated peak stress by stress relaxation using simplified isochronous stress-strain curves (ISSCs), **but with elastic follow-up**
    - Impose lower bound stress on stress relaxation history
  - Creep damage per cycle time calculated using time-fraction, stress relaxation history, σ, and creep rupture time, T_d
    - $d_c = \int_0^{t_h} \frac{dt}{T_d(\sigma, T, t)}$
- **Fatigue Damage Evaluation**
  - Calculate enhanced strain range using stress relaxation history σ
  - Use strain range to determine allowable fatigue cycles from fatigue design curves
  - Calculate fatigue fraction

Creep-Fatigue Damage Envelope

- Use material independent universal damage envelope, with (0.1,0.1) or (0.2,0.2) as intersection point
- Can use less limiting damage envelope when creep-fatigue data are available



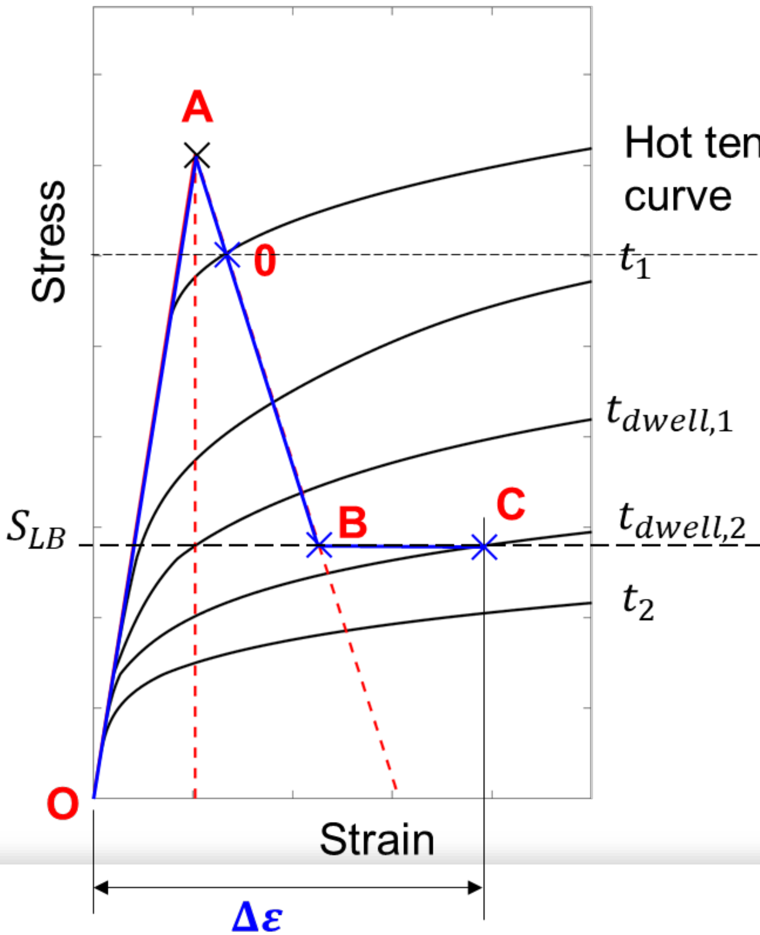
Enhanced Strain Range Calculation – Short Dwell Time

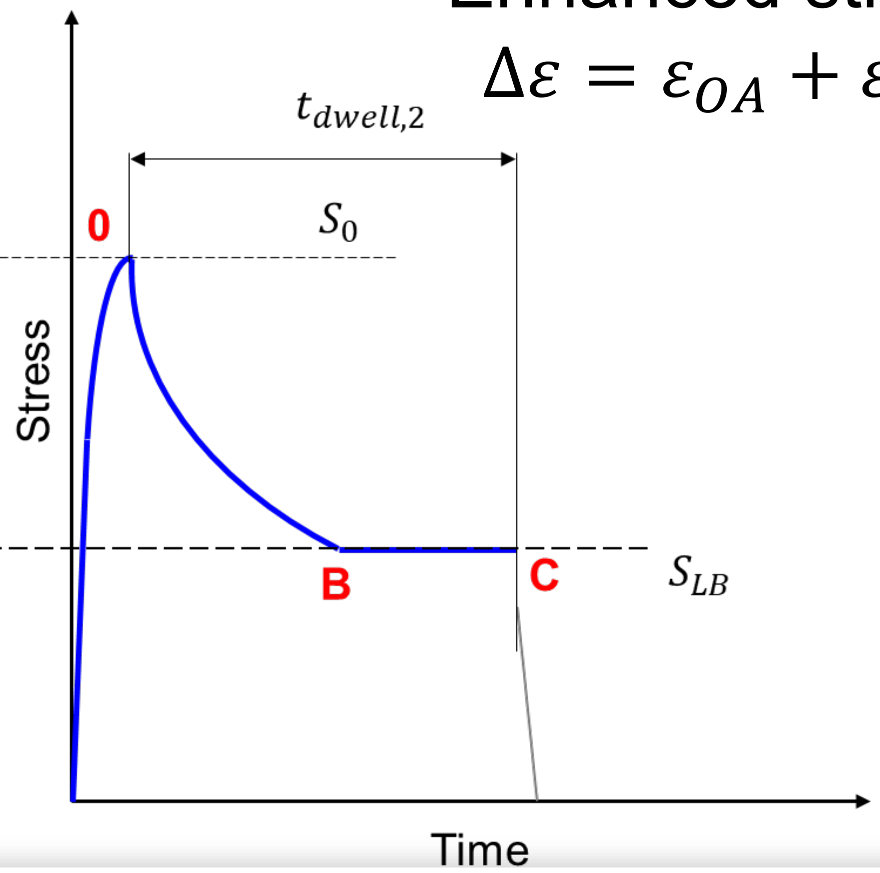


Enhanced strain range

$$\Delta\varepsilon = \varepsilon_{OA} + \varepsilon_{AB}$$

Enhanced Strain Range Calculation – Long Dwell Time



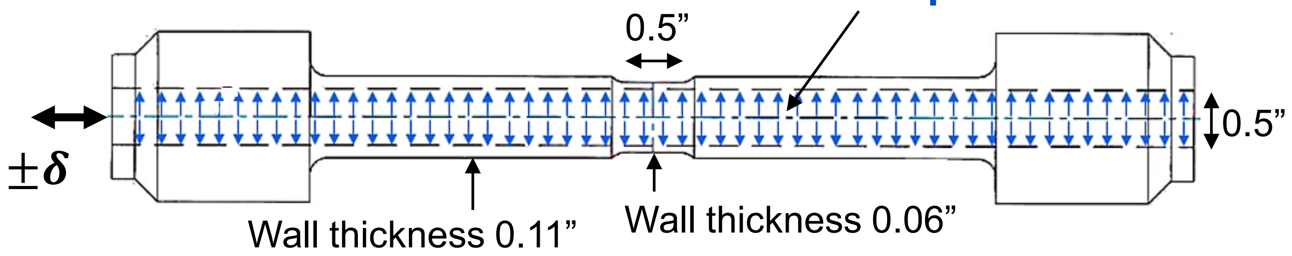


Enhanced strain range

$$\Delta\varepsilon = \varepsilon_{OA} + \varepsilon_{AB} + \varepsilon_{BC}$$

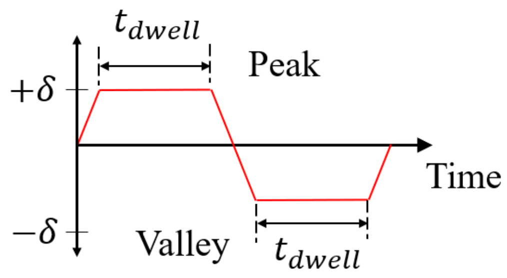
Test Data – Pressurized Simplified Model Test (p-SMT)

- **Capture elastic follow-up**
- **Failure data available**
- **Good benchmark to validate new Class B rules**
- **Material – Alloy 617**



Test specimen geometry of p-SMT [1]

[1] ORNL/TM-2019/1224



Displacement load profile

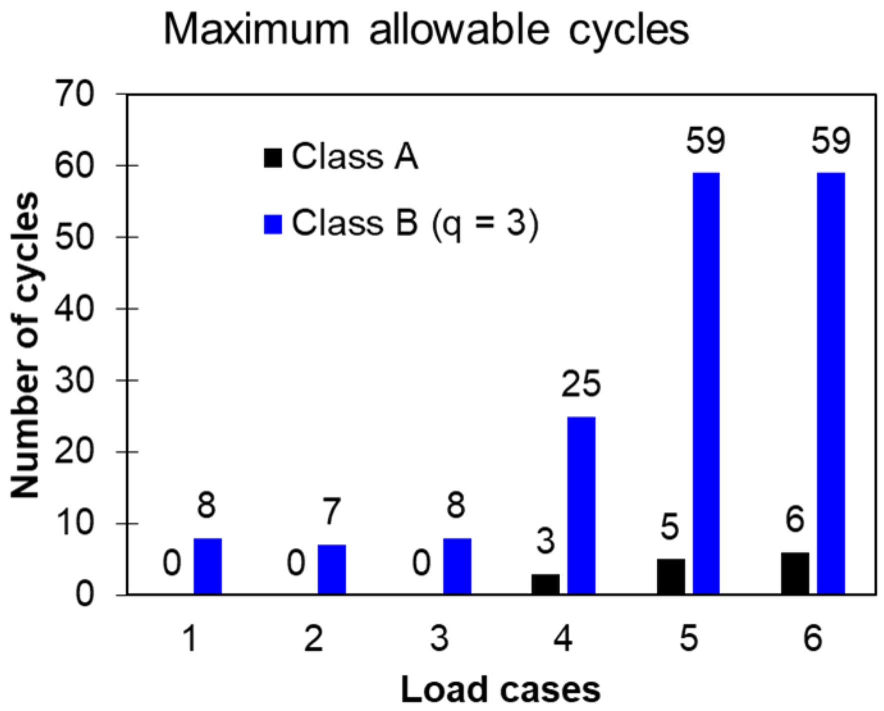
Loading
- Constant temperature
- Constant pressure
- Cyclic end displacement

pSMT – Comparison of Results from Class A and New Class B Rules

Summary of load profiles from pSMT tests

ID	Load Case	Temp (℃)	$\pm\delta$ (mm)	Hold time (s)		P (MPa)	N_f [1]
				Peak	Valley		
P01	1	950	0.1143	600	0	0.01	220
P05	2	950	0.1143	600	600	0.01	320
P02	3	950	0.1143	600	0	1.38	220
P12	4	950	0.0635	600	0	0.01	1360
P14	5	850	0.0762	600	0	2.76	3440
P15	6	850	0.0762	600	0	0.14	3460

[1] ORNL/TM-2019/1224



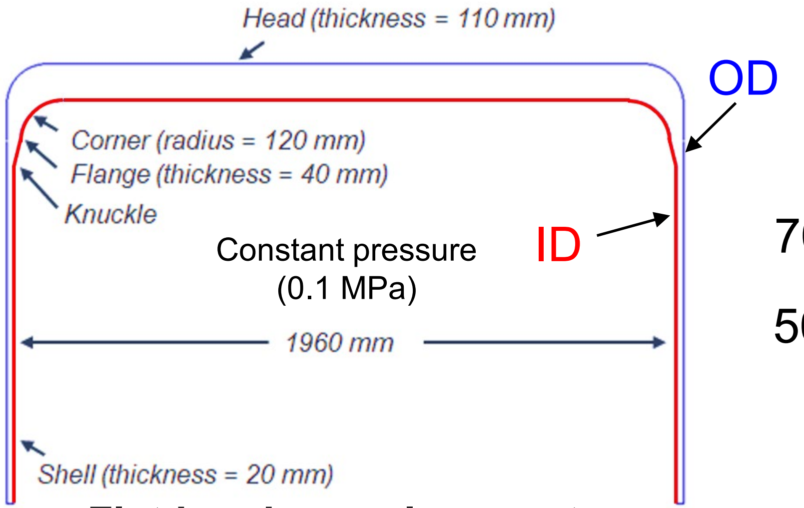
Class A analysis: D-diagram intersection for Alloy 617 is (0.1,0.1)

New Class B creep-fatigue rules: D-diagram intersection is (0.2,0.2)

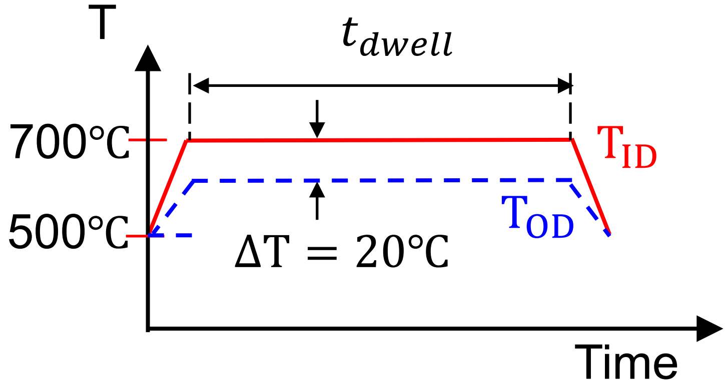
Predictions from both Class A rules and new Class B rules are conservative compared with pSMT data

Sample Problem – Flat Head Vessel

- Temperature cycle with hold (dwell) time
- Linear temperature gradient across thickness
- Constant pressure
- Geometrical discontinuity



Flat head vessel geometry

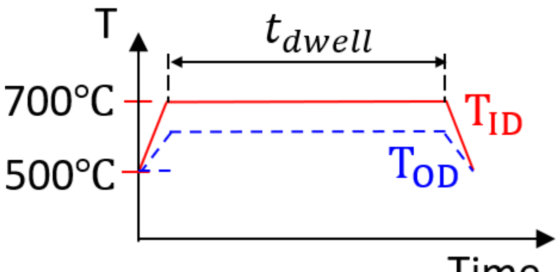


Temperature cycle

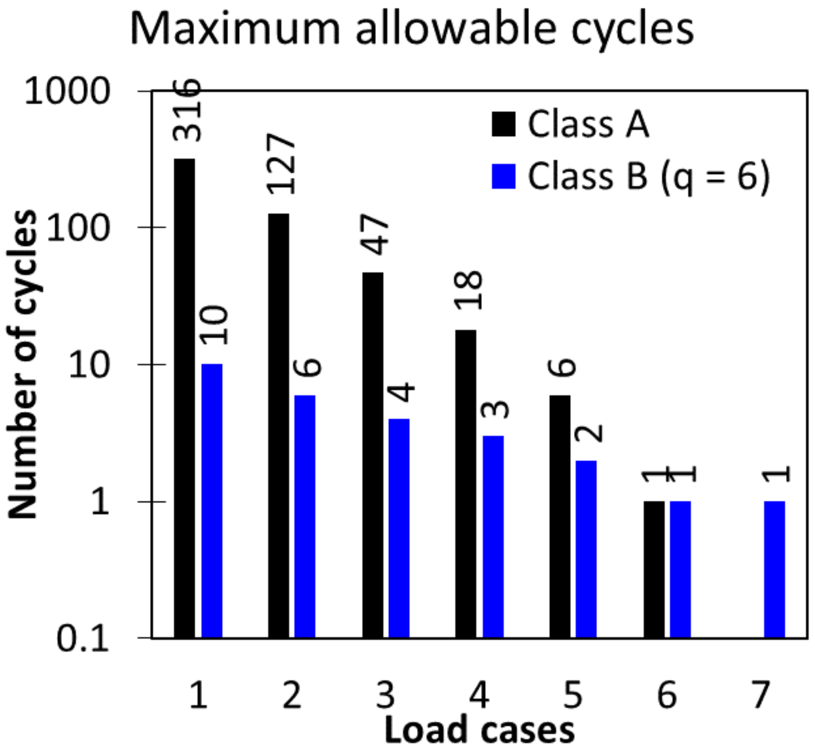
Material: 316H

Flat Head Vessel – Comparison of Results from Class A and Class B Rules

Load Case	t_{dwell} (hr)
1	10
2	30
3	100
4	300
5	1000
6	3000
7	10000



Temperature cycle



New Class B creep-fatigue rules might be too conservative for stress concentrations

Class A analysis: D-diagram intersection for 316H is (0.3,0.3)

New Class B creep-fatigue rules: D-diagram intersection is (0.2,0.2)

Current Class B Allowable Stresses for Primary Load Design

- **Current Class B allowable stresses are provided in ASME Section II, Part D tables**
- **Based on extrapolated creep properties for 100,000 h, irrespective of component design lifetimes**
    - Time extrapolation factors are typically 3 to 5
- **Criteria: Lesser of**
    - lesser of $(0.67 \times S_Y, 0.67 \times S_y, S_T\ /\ 3.5, S_u\ /\ 3.5\ )$
    - 100% of the average stress to produce a creep rate of 0.01%/1,000 h
    - $100 \times F_{avg}\%$ of the average stress to cause rupture at the end of 100,000 h
    - 80% of the minimum stress to cause rupture at the end of 100,000 h

New Class B Time-Dependent Allowable Stresses for Primary Load Design

- **Use the same allowable stress criteria as the current Class B rules, except extrapolation is done for different lifetimes, not just 100,000 h**
- **Creep data are still similar to current Section II requirements for 100,000 h, but with different extrapolation factors**

	Time Extrapolation Factors		
Design Lifetime	100,000 h	300,000 h	500,000 h
Ferritic, Ferritic-martensitic	3	9	15
Stainless, nickel alloys	5	15	25

Lower Bound of Creep Rupture Properties Depends on Lifetime

- **Current Larson-Miller lower bound calculation**

$$log_{10}t_r = \left(\frac{1}{T_a}\sum_{p=0}^{n} a_p \Sigma^p\right) - C - 1.645 \times SEE, \qquad SEE = \text{standard error of estimate}$$

- **New Larson-Miller lower bound calculation will depend on lifetime**

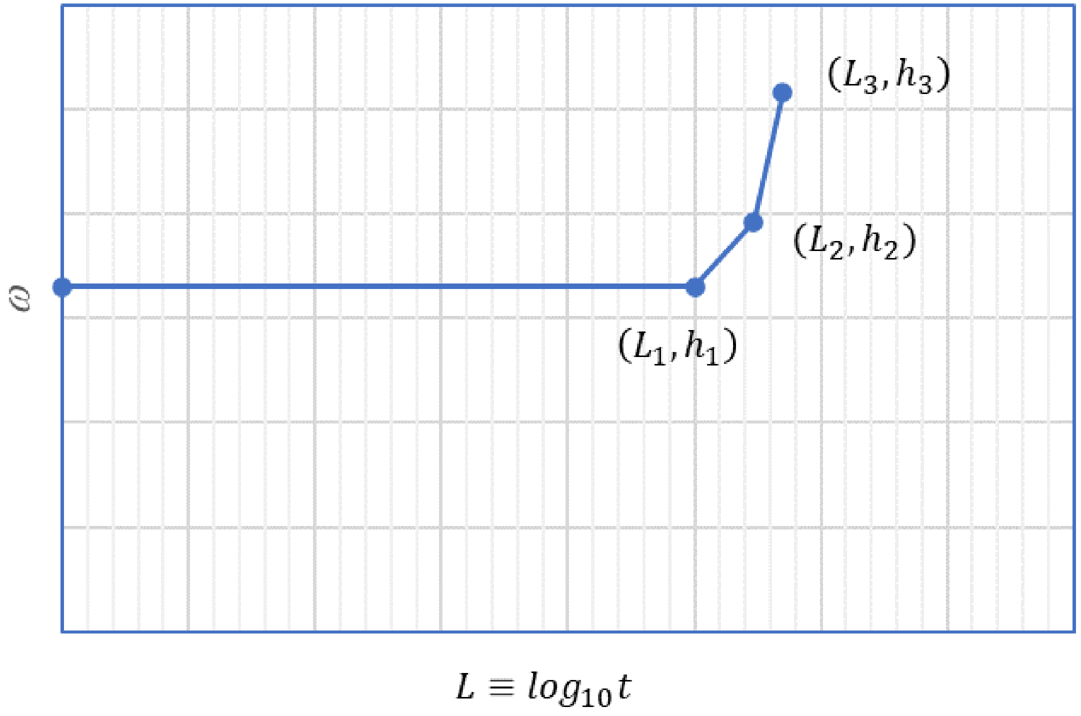
$$log_{10}t_r = \left(\frac{1}{T_a}\sum_{p=0}^{n} a_p \Sigma^p\right) - C - \omega \times SEE, \qquad \omega = \begin{cases} h_1, & 0 \ll L \ll L_1 \\ h_1 + \frac{h_2 - h_1}{L_2 - L_1}(L - L_1), & L_1 < L \ll L_2 \\ h_2 + \frac{h_3 - h_2}{L_3 - L_2}(L - L_2), & L_2 < L \ll L_3 \end{cases}$$

$$L_1 \equiv log_{10}(100{,}000), L_2 \equiv log_{10}(300{,}000),\ L_3 \equiv log_{10}(500{,}000), L \equiv log_{10}(t)$$

$$h_1 = 1.645,\ h_2 = 1.960,\ h_3 = 2.576$$

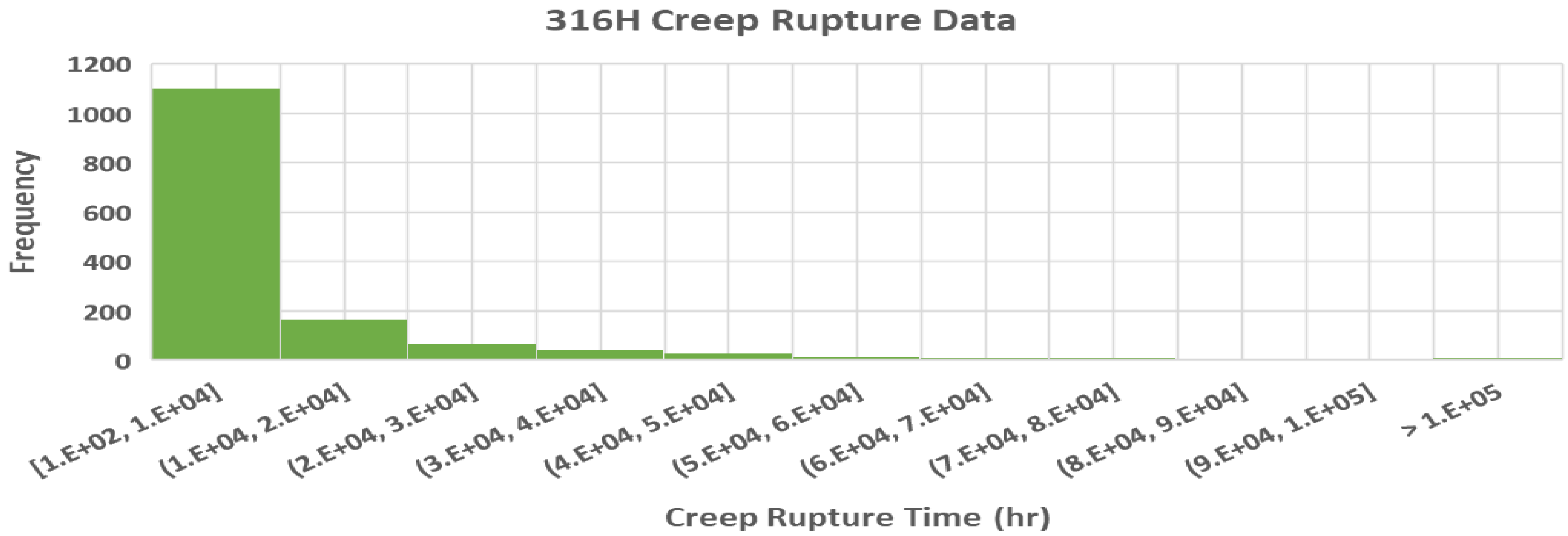
New Time Extrapolation of Lower Bound Creep Rupture Lives

- Higher confidence levels for larger time extrapolation factors
- 90, 95 and 99% confidence levels for 100,000, 300,000 and 500,000 h lifetime, respectively



Example on 316H Creep Rupture

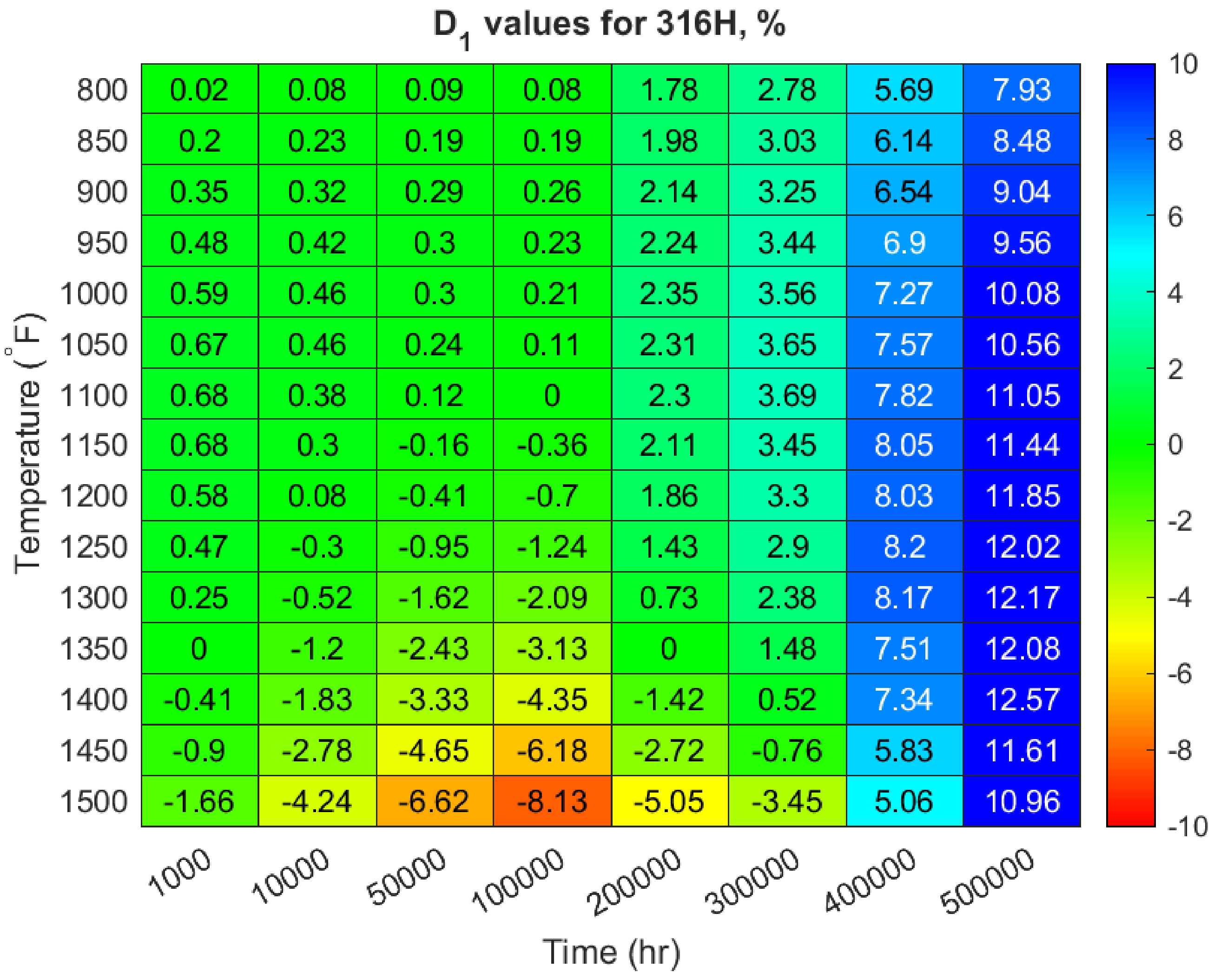
- Very large 316H creep rupture database, with some long-term rupture data from 100,000 to 200,000 h for Division 5, Class A consideration
- Formed Class B database by extracting rupture data of 20,000 h or less



Results of LM Regression

316H Larson-Miller Parameters for Rupture (U.S. Customary Units)		
	Class A creep database	**Class B creep database**
a_0	4.3393529502E+04	4.3943390248E+04
a_1	-6.1859858045E+03	-6.6024131061E+03
a_2	-1.5591228059E+03	-1.4445717270E+03
C	1.6282175397E+01	1.6424454855E+01
SEE	3.4958041854E-01	3.4795968837E-01

Class A vs New Class B Extrapolation

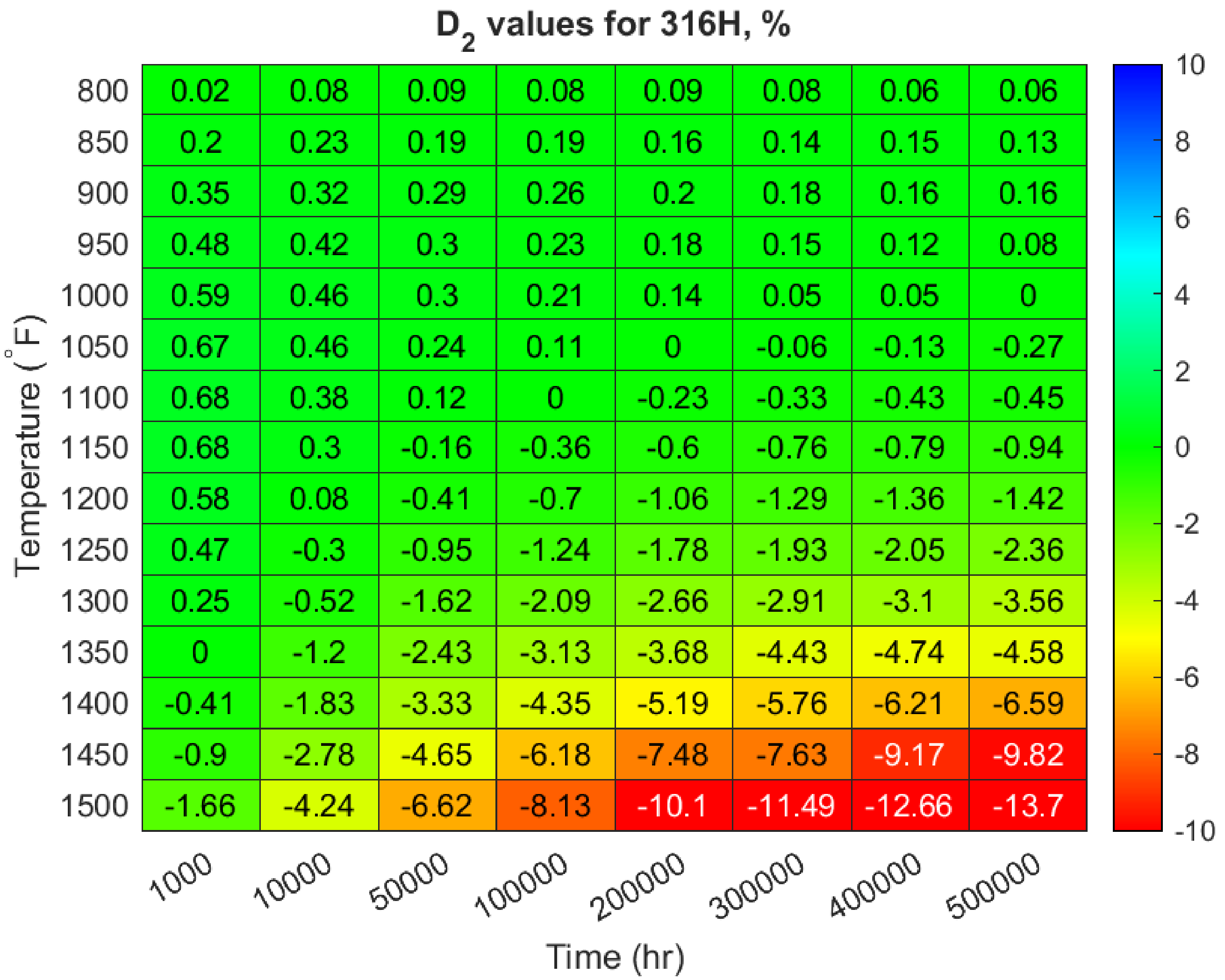


Temperature (°F) \ Time (hr)	1000	10000	50000	100000	200000	300000	400000	500000
800	0.02	0.08	0.09	0.08	1.78	2.78	5.69	7.93
850	0.2	0.23	0.19	0.19	1.98	3.03	6.14	8.48
900	0.35	0.32	0.29	0.26	2.14	3.25	6.54	9.04
950	0.48	0.42	0.3	0.23	2.24	3.44	6.9	9.56
1000	0.59	0.46	0.3	0.21	2.35	3.56	7.27	10.08
1050	0.67	0.46	0.24	0.11	2.31	3.65	7.57	10.56
1100	0.68	0.38	0.12	0	2.3	3.69	7.82	11.05
1150	0.68	0.3	-0.16	-0.36	2.11	3.45	8.05	11.44
1200	0.58	0.08	-0.41	-0.7	1.86	3.3	8.03	11.85
1250	0.47	-0.3	-0.95	-1.24	1.43	2.9	8.2	12.02
1300	0.25	-0.52	-1.62	-2.09	0.73	2.38	8.17	12.17
1350	0	-1.2	-2.43	-3.13	0	1.48	7.51	12.08
1400	-0.41	-1.83	-3.33	-4.35	-1.42	0.52	7.34	12.57
1450	-0.9	-2.78	-4.65	-6.18	-2.72	-0.76	5.83	11.61
1500	-1.66	-4.24	-6.62	-8.13	-5.05	-3.45	5.06	10.96

$$D_1 \equiv \frac{\sigma_{standard\ creep} - \sigma_{Class\ B\ creep}}{\sigma_{standard\ creep}} \times 100\%$$

- **New Class B extrapolation is adequately conservative**

Class A vs Old Class B Extrapolation

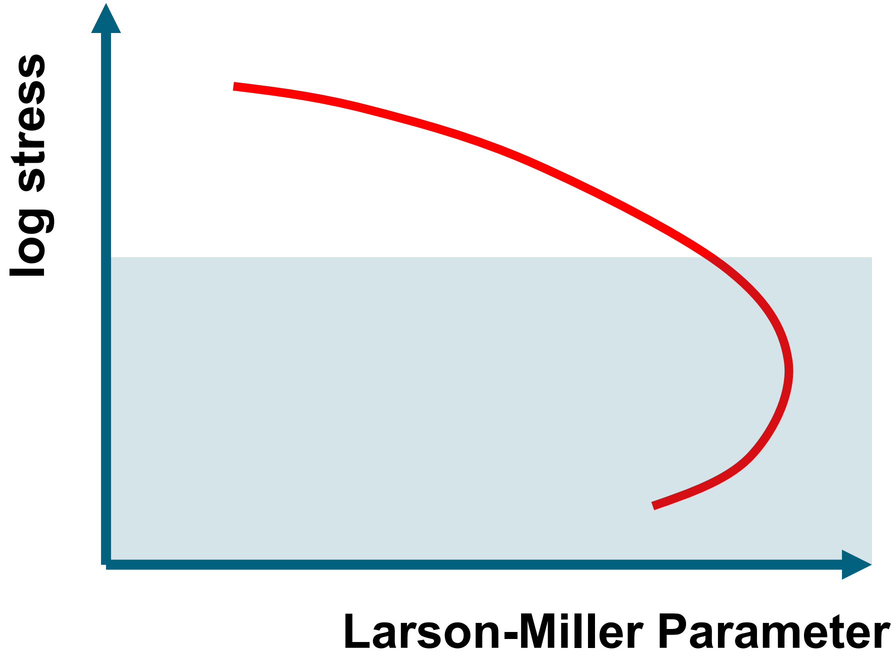


$$D_2 \equiv \frac{\sigma_{standard\ creep} - \sigma_{Class\ B\ creep;\ h=1.645}}{\sigma_{standard\ creep}} \times 100\%$$

- Confidence level is fixed at 90%, i.e., *h* = 1.645
- Use of fixed confidence level for lower bounds is increasingly more unconservative as the lifetime is increased beyond 100,000 h

Further Thoughts on Class B Extrapolation – (I)

- The Larson-Miller model sometimes produces a "turn-around" in the correlation for low stresses
- This behavior is undesirable when extrapolating for long design lives, or using large extrapolation factors, as in the new Class B extrapolation method
- Will assess a different correlation model, e.g., the Wilshire model, that does not have such a "turn-around" feature



Further Thoughts on Class B Extrapolation – (II)

- The acceptability of very long-time extrapolations, particularly for 500,000 h design lifetime (up to a factor of 25), should be assessed on a case-by-case basis and consider the metallurgical stability of the alloy
- This could be done via experimental assessments (e.g., time-temperature-transformation) diagrams
- Or via CALPHAD-type of computational materials modelling to confirm the phase stability and/or the kinetics of deleterious phase formation

Candidate Materials Identified for Incorporation into the New Class B Code Case

Creep data in Section III, Division 5	Creep Data in Section II (non-nuclear)	None of the above
• 304H, 316H, Alloy 800H, Grade 22 (solution annealed), Grade 91, Alloy 617	• 316L, 316Ti, Ti-mod 304 (TP321), 304N, 316N • Alloy 690, Hastelloy X, Alloy 625, Hastelloy N, Haynes 230, Haynes 242, Haynes 282, Inconel 740H • Grade 92, Grade 22 (N&T)	• Alloy 709 • XM-19 (NITRONIC 50) • Haynes 244 • HT-9 • 15-15-Ti

Plan for FY24

- **Continue new Class B design rules development**
  - Modify new Class B creep-fatigue rules to remove excessive conservatism
  - Assess Larson-Miller vs Wilshire for the new Class B extrapolation method using those Class A materials where long-term creep rupture data are available
  - Investigate alternative strain range evaluations for fatigue damage
  - Evaluate universal Class B intersection point in D-diagram relative to material-specific Class A intersection points
  - Evaluate the new Class B rules against Class A rules based on Elastic-Perfectly Plastic (EPP) methodology and full inelastic analysis method, using sample problems

Thank you

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