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SUBSECTION HB, Subpart B

Dr. T.-L. (Sam) Sham

TING-LEUNG (SAM) SHAM BIOGRAPHICAL INFORMATION

Dr. T.-L. (Sam) Sham is the Technical Manager for Advanced Reactor Materials in the Nuclear Engineering Division at Argonne National Laboratory. His technical specialty is in deformation and failure of advanced materials and structural mechanics technologies for high temperature reactors. He is the Technology Area Lead of the advanced materials R&D program for the Office of Advanced Reactor Technologies (ART), Office of Nuclear Energy (NE), Department of Energy (DOE). The R&D portfolio cross-cuts the three reactor campaigns on Fast Reactors, Gas-cooled Reactors and Molten Salt Reactors in ART. In addition, Sham leads the DOE-NE international R&D efforts on advanced materials and code qualification for sodium-cooled fast reactor structural applications.

Dr. Sham is a member of the ASME Boiler and Pressure Vessel (BPV) Committee on Construction of Nuclear Facility Components (III). He chairs BPV III Subgroup on Elevated Temperature Design, which is responsible for the development and maintenance of design rules for nuclear components in elevated temperature service. He was elected ASME Fellow in 2000.

Before he joined Argonne in 2015, Dr. Sham was a Distinguished R&D Staff Member at Oak Ridge National Laboratory, held senior positions with AREVA NP Inc. and Knolls Atomic Power Laboratory, and was tenured faculty at Rensselaer Polytechnic Institute. He holds a B.Sc. degree, First Class Honour, in Mechanical Engineering from the University of Glasgow, Scotland, and M.S. and Ph.D. degrees (Mechanics of Solids and Structures) as well as an M.S. (Applied Mathematics) from Brown University in Providence, Rhode Island, USA.

AGENDA

- Subsection HB, Subpart B - Materials
  - Failure Modes
  - Temperature and Service Life Limits
  - HBB Class A Materials
  - Materials Specific Design Parameters
  - Allowable Stress Intensity
  - Stress-to-Rupture
  - Fatigue & Creep Fatigue
  - Material Challenges - MSRs

Section III, Division 5 Organization

Class	Subsection	Subpart	Subsection ID	Title	Scope
General Requirements *					
Class A, B, & SM	HA	A	HAA	Metallic Materials	Metallic
Class SN		B	HAB	Graphite and Composite Materials	Nonmetallic
Class A Metallic Pressure Boundary Components					
Class A	HB	A	HBA	Low Temperature Service	Metallic
Class A		B	HBB	Elevated Temperature Service	Metallic
Class B Metallic Pressure Boundary Components					
Class B	HC	A	HCA	Low Temperature Service	Metallic
Class B		B	HCB	Elevated Temperature Service	Metallic
Class A and Class B Metallic Supports					
Class A & B	HF	A	HFA	Low Temperature Service	Metallic
Class SM Metallic Core Support Structures *					
Class SM	HG	A	HGA	Low Temperature Service	Metallic
Class SM		B	HGB	Elevated Temperature Service	Metallic
Class SN Nonmetallic Core Components *					
Class SN	HH	A	HHA	Graphite Materials	Graphite
Class SN		B	HHB	Composite Materials	Composite

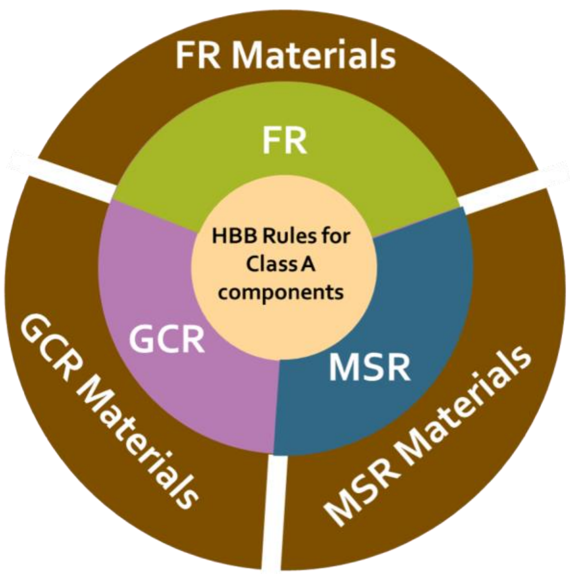
* Class designation being balloted

Class A, Class B and Class SM – Metallic Components

Class A, Elevated Temperature – Subsection HB, Subpart B (HBB)

HBB-1110 Scope

(c) The rules of this Subpart are applicable to Class A components independent of the type of contained fluid — water, steam, sodium, helium, or any other process fluid



- High temperature design methodologies that form the technical bases of the HBB Code rules
- Based on structural failure modes under elevated temperature cyclic service
- Establish what types of material data are required to support Code rules
- These rules cross-cut reactor types (FRs, GCRs and MSRs)
- FRs, GCRs and MSRs have different coolants, neutron irradiation environments and operating conditions (temperature, pressure, and transients)
- Different structural materials are needed to meet different requirements of FRs, GCRs and MSRs

Failure Modes Guarded by HBB Rules

1. Ductile rupture from short-term loadings
2. Creep rupture from long-term loadings
3. Creep–fatigue failure
4. Gross distortion due to incremental collapse and ratcheting
5. Loss of function due to excessive deformation
6. Buckling due to short-term loadings
7. Creep buckling due to long-term loadings

Requirements Outside the Scope of HBB Rules

- Design procedures and materials data not contained in HBB may be required to ensure the integrity or the continued functioning of the structural part during the specified service life
  - e.g., HBB rules do not provide methods to evaluate deterioration that may occur in service as a result of corrosion, mass transfer phenomena, radiation effects, or other material instabilities
  - Owner/operator has the responsibility to demonstrate to Regulators that these effects are accounted for in the design of the component

Temperature and Service Life Limits

- The HBB rules shall not be used for structural parts that will be subjected either to metal temperatures or to times greater than those values associated with the S_{mt} data for the specified material (see Mandatory Appendix HBB-I-14)

Table HBB-I-14.3C
S_{mt} — Allowable Stress Intensity Values, ksi (MPa), Ni-Fe-Cr (Alloy 800H)

U.S. Customary Units

Temp., °F	1 hr	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
800	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
850	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
900	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8
950	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6
1,000	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.1
1,050	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	12.8	11.2
1,100	14.1	14.1	14.1	14.1	14.1	14.1	14.1	13.9	12.0	10.2	8.9
1,150	13.9	13.9	13.9	13.9	13.9	13.9	13.2	11.2	9.6	8.2	7.0
1,200	13.8	13.8	13.8	13.8	13.8	12.4	10.7	9.0	7.7	6.5	5.6
1,250	13.5	13.5	13.5	13.5	12.0	10.1	8.6	7.2	6.2	5.2	4.4
1,300	13.2	13.2	13.2	11.6	9.8	8.2	7.0	5.8	5.0	4.1	3.5
1,350	12.0	12.0	11.3	9.5	8.0	6.7	5.7	4.7	4.0	3.3	2.8
1,400	11.0	10.8	9.3	7.8	6.5	5.4	4.6	3.8	3.2	2.6	2.2

Necessary But Not Sufficient

HBB Class A Materials Base Metals

Permissible Base Metals (Not for Bolting)	Specification No.
304H and 316H (stainless steels, Notes 1, 2, 3)	SA-182, 213, 240, 249, 312, 358, 376, 403, 479, 965, 430
Fe-Ni-Cr (**Alloy 800H**, Fe-base austenitic alloy, Note 4)	SB-163, 407, 408, 409, 564
2¼Cr-1Mo (Grade 22, ferritic steel, Note 5)	SA-182, 213, 234 (Note 6), 335, 336, 369, 387, 691
9Cr-1Mo-V (Grade 91, ferritic martensitic steel)	SA-182, 213, 335, 387
Ni-Cr-Co-Mo (**Alloy 617**, Ni-base alloy, being balloted by ASME for approval)	SB-166, 167, 168, 564
Pressure vessel steels (for short term elevated temperatures)	SA-533 Type B, Class 1; SA-508 Grade 3, Class 1

NOTES

(1) These materials shall have a minimum specified room temperature yield strength of 30,000 psi (207 MPa) and a minimum specified carbon content of 0.04%. **For use above 1100F (595°C), 304H and 316H materials shall have a 0.05% minimum nitrogen, 0.03% maximum aluminum, and 0.04% maximum titanium**

(2) For use at temperatures above 1,000°F (540°C), these materials may be used only if the material is heat treated by heating to a minimum temperature of 1,900°F (1,040°C) and quenching in water or rapidly cooling by other means.

(3) Nonmandatory Appendix HBB-U provides nonmandatory guidelines on additional specification restrictions to improve performance in certain service applications.

(4) These materials shall have a total aluminum-plus-titanium content of at least 0.50% and shall have been heat treated at a temperature of 2,050°F (1,120°C) or higher.

(5) This material shall have a minimum specified room temperature yield strength of 30,000 psi (207 MPa), a minimum specified room temperature ultimate strength of 60,000 psi (414 MPa), a maximum specified room temperature ultimate strength of 85,000 psi (586 MPa), and a minimum specified carbon content of 0.07%.

(6) The material allowed under SA-234 shall correspond to one of: *(a)* SA-335, Grade P 22, *(b)* SA-387, Grade 22, Class 1, *(c)* SA-182, Grade F 22, Class 1 in compliance with Note (4).

HBB Class A Materials Weld Metals

Base Materials	Permission Weld Materials (Specification Number; Class)
Type 304 SS and 316 SS	SFA-5.4; E 308, E 308L, E 316, E 316L, E 16-8-2 SFA-5.9; ER 308, ER 308L, ER 316, ER 316L, ER 16-8-2 SFA-5.22; E 308, E 308T, E 308LT, E 316T, E316LT-1 EXXXT-G (16-8-2 chemistry)
Fe-Ni-Cr (Alloy 800H)	SFA-5.11; ENiCrFe-2 SFA-5.14; ERNiCr-3
2¼Cr-1Mo	SFA-5.5; E 90XX-B3 (>0.05% Carbon) SFA-5.23; EB 3, ECB 3 SFA-5.28; E 90C-B3 (>0.05% Carbon), ER 90S-B3 SFA-5.29; E 90T-B3 (>0.05% Carbon)
9Cr-1Mo-V	SFA-5.5; E90XX-B9 SFA-5.23; EB9 SFA-5.28; ER90S-B9
Alloy 617	SFA-5.14; ERNiCrCoMo-1
SA-533 Type B, Class 1; SA-508 Grade 3, Class 1	Associated weld metals

HBB Class A Materials Bolting

Materials	Specification Number	Grades
304 stainless steel	SA-193	B8 Class 1, B8A Class 1A (Note 1)
316 stainless steel	SA-193	B8M Class 1, B8MA Class 1A (Note 1)
Ni-Cr-Fe-Mo-Cb, Alloy 718 (Notes 2, 3 and 4)	SB-637	NO 7718

Notes

1. For use at temperatures above 1,000°F (540°C), these materials may be used only if the material is heat treated by heating to a minimum temperature of 1,900°F (1 040°C) and quenching in water or rapidly cooling by other means
2. Maximum forging diameter shall be limited to 6 in. (150 mm)
3. Welding is not permitted
4. Precautionary Note: In use of Alloy 718, consideration shall be given to a reduction in toughness caused by long-term exposure at a temperature of 1,000°F (540°C) or greater

Deterioration of Material in Service

- Consideration of deterioration of material caused by service is generally outside the scope of HBB
- It is the responsibility of the Owner to select material suitable for the conditions stated in the Design Specifications (NCA-3250), with specific attention being given to the effects of service conditions upon the properties of the material
  - Influence of elements such as copper and phosphorus on the effects of irradiation on the properties of material (including welding material) in the core belt line region of the reactor vessel
  - Effects of the combination of fabrication induced cold working and subsequent elevated temperature service on time-dependent material properties
- Long-time, elevated temperature, service may result in the reduction of the subsequent yield and ultimate tensile strengths
  - The effects are explicitly accounted for in HBB

Delta Ferrite Determination

- Determination of delta ferrite shall be performed on
  - A-No. 8 weld material (Section IX, Table QW-442)
  - Backing filler metal (consumable inserts)
  - Bare electrode, rod, or wire filler metal
  - Weld metal, except for
    - SFA-5.4, Type 16-8-2
    - A-No. 8 weld filler metal to be used for weld metal cladding
- Acceptance Standards
  - Design temperatures ≤ 800F
    - Minimum acceptable delta ferrite shall be 5 FN (Ferrite Number)
  - Design temperatures > 800F
    - Acceptable delta ferrite range, 3 to 10 FN

To Avoid Hot Cracking or Solidification Cracking

Repair By Welding

- The Material Organization may repair by welding material from which defects have been removed, provided the depth of the repair cavity does not exceed one-third of the nominal thickness and the requirements of Division 1, NB-2539.1 through NB-2539.7 are met
- The weld material used to make weld repairs shall meet the requirements of permissible weld materials in Table HBB-I-14.1(b), and Division 1, NB-2400
- Additional requirements may be listed in the Design Specifications

Creep-Fatigue Acceptance Test

- Apply only to 304 and 316 SS components for service where the negligible creep conditions in HBB-T-1324 for Levels A, B, and C are not met
  - I.e., need to consider creep-fatigue interaction
- Acceptance test shall be conducted for each material lot (defined in material spec.)
  - Uniaxial creep-fatigue test shall be performed in air at 1,100°F at an axial strain range of 1.0% with a 1-hr hold period at the maximum positive strain point in each cycle
  - The creep-fatigue test shall exceed 200 cycles without fracture or a 20% drop in the load range
    - Test-specimen location and orientation shall be in accordance with the general guidance of SA-370, paras. 6.1.1 and 6.1.2 and the applicable product specifications
    - Shall follow ASTM E2714−13, Standard Test Method for Creep-Fatigue Testing
  - Retesting - Two additional specimens shall be tested and both specimens must pass the cyclic life requirement. Further retests are not permitted

Non-mandatory Appendix HBB-U Guidelines for Restricted Material Specifications

- Specification restrictions for Types 304 and 316 stainless steels, which will improve the performance in certain elevated temperature nuclear applications where creep effects are significant
- The restrictions have the effect of narrowing chemical composition, grain size, and other aspects of material quality while staying within the broader specification limits

Materials Specific Design Parameters – Base Materials

Base Materials

- Physical properties (CTE, diffusivity and conductivity) and elastic properties (moduli)
- Yield strength S_y and tensile strength S_u
- Allowable stress intensity S_0 (for Design Condition)
- Allowable stress intensity S_t
- Allowable stress intensity S_{mt}
- Expected minimum stress-to-rupture, S_r
- Yield strength and tensile strength reduction factor due to long term prior elevated temperature Service
- Permissible time/temperature conditions for material which has been cold worked >5% and <20% and subjected to short-time high temperature transients
- Negligible creep parameters, r and s
- Stress relaxation strength
- Creep-fatigue interaction parameter D
- Huddleston parameters for determining equivalent stress and K′ factor, both for creep damage evaluation
- Design fatigue curves
- Isochronous stress-strain curves
- Time–temperature limits for application of Section II external pressure charts

Materials specific design parameters are provided in the form of tables and/or charts

Materials Specific Design Parameters Weld and Bolting Materials

Weld Materials	
• Stress rupture factor	• Creep-fatigue reduction factor
Bolting Materials	
• Allowable stress intensity S_0 (for Design Condition) • Allowable stress intensity S_{mt} • Expect minimum stress-to-rupture S_r	• Evaluations for strain limits required • Evaluations for creep-fatigue damage required

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Tensile and Yield Strength

- Permission base materials
  - For metal temperatures up to 1,000F, the tensile and yield strength can be obtained from Section II, Part D, Subpart 1, Table U and Y-1, respectively
  - For metal temperatures above 1,000F and up to the respective maximum use temperature, the tensile and yield strength can be obtained from Table HBB-3225-1 and HBB-I-14.5, respectively
- These strengths shall be modified for long-time, elevated temperature, service due to thermal aging (see subsequent slides)

Determination of $S_y(T)$ and $S_u(T)$

Yield Strength at Temperature

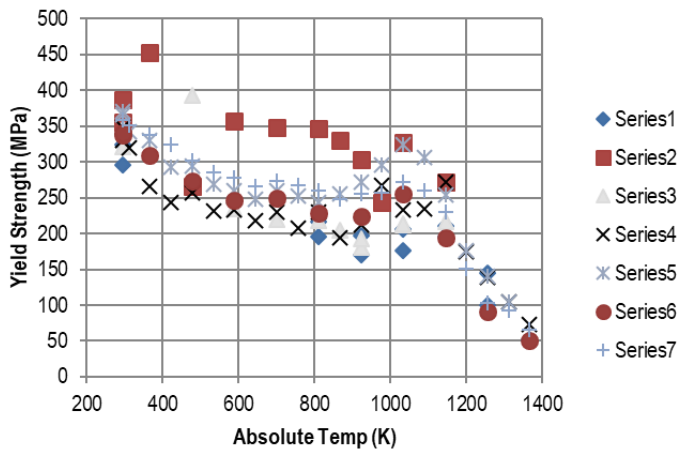
- The yield strength data are normalized by dividing by the average room temperature yield strength for the respective heat.
- A best fit trend curve $R_Y(T)$ is generated for the normalized yield strength data as a function of test temperature.
- The yield strength at temperature is defined as $S_y(T) = S_Y R_Y(T)$, where S_Y is the specification minimum yield strength at room temperature.

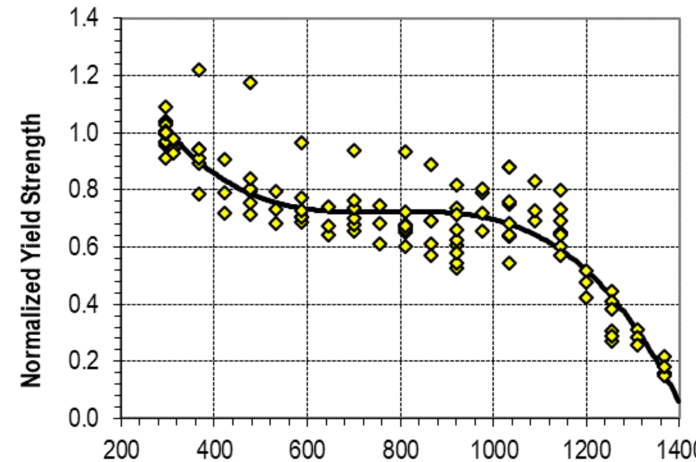
Tensile Strength at Temperature

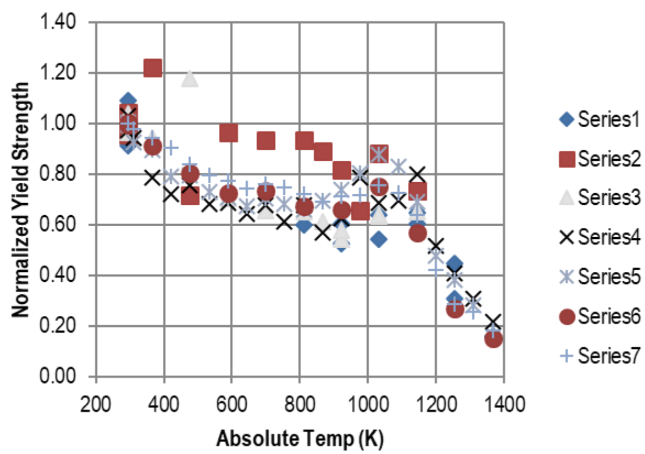
- $S_u(T) = 1.1 \times S_T R_T(T)$, where S_T is the specification minimum tensile strength at room temperature

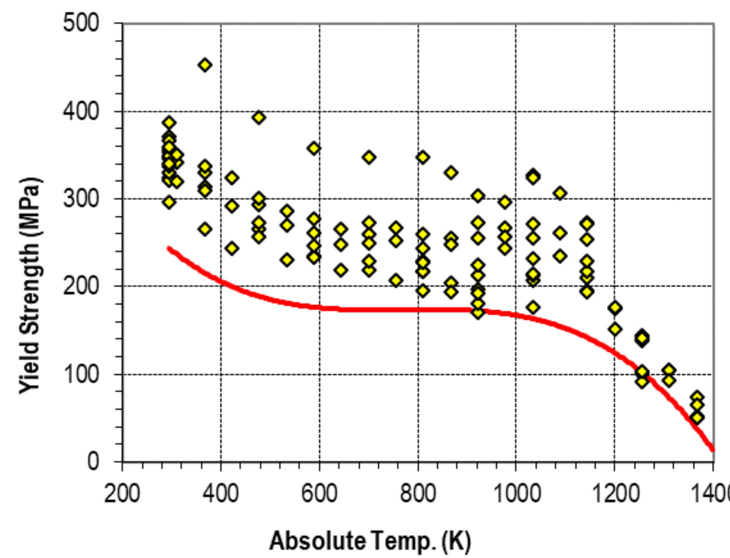
Note: the temperature trend curves are required to be either constant or decreasing with increasing temperature

Example Construction of $S_y(T)$









Tensile and Yield Strength Reduction Factor Due to Long Term Thermal Aging

Material	Service Temp., F (C)	YS Reduction Factor	TS Reduction Factor	Remark
304 SS	≥ 900 (480)	1.0	0.8	Selected to correspond to the maximum wall-averaged temperature achieved during any Level A, B, or C Service Loading
316 SS	≥ 900 (480)	1.0	0.8	Ditto
Alloy 800H	≥ 1,350 (730)	0.9	0.9	Ditto
2¼ Cr-1 Mo	≥ 800 (425)	Note 1	Note 1	Based on the specific cumulative time history of the wall-averaged temperature per HBB-2160 (d)
9Cr-1Mo-V	≥ 900 (480)	1.0	Note 2	Ditto
Alloy 617	≥ 800 (425)	1.0	1.0	None
Note 1. See Tables HBB-3225-3A and HBB-3225-3B (time dependent) Note 2. See Table HBB-3225-4 (time dependent)				

Time Independent Allowable Stress Intensity, S_m

- The time independent allowable stress S_m shall be given in Section II, Part D, Subpart 1 for metal temperatures up to 1,000F
- For metal temperatures above 1,000F and up to the respective maximum use temperature, S_m shall be obtained from S_u and S_y of Table HBB-3225-1 and HBB-I-14.5, respectively, according to the lesser of
  - *(a)* one-third of the specified minimum tensile strength at room temperature
  - *(b)* one-third of the tensile strength at temperature
  - *(c)* two-thirds of the specified minimum yield strength at room temperature
  - *(d)* two-thirds of the yield strength at temperature, except that for austenitic stainless steels and nickel alloys, having an *SY/ST* ratio less than 0.625, as indicated in Section II, Part D, Tables 2A and 2B, this value may be as large as 90% of the yield strength at temperature (but never more than two-thirds of the specified minimum yield strength)
- As described in previous slides, it may be necessary to adjust the values of S_m to account for the effects of long-time service at elevated temperature

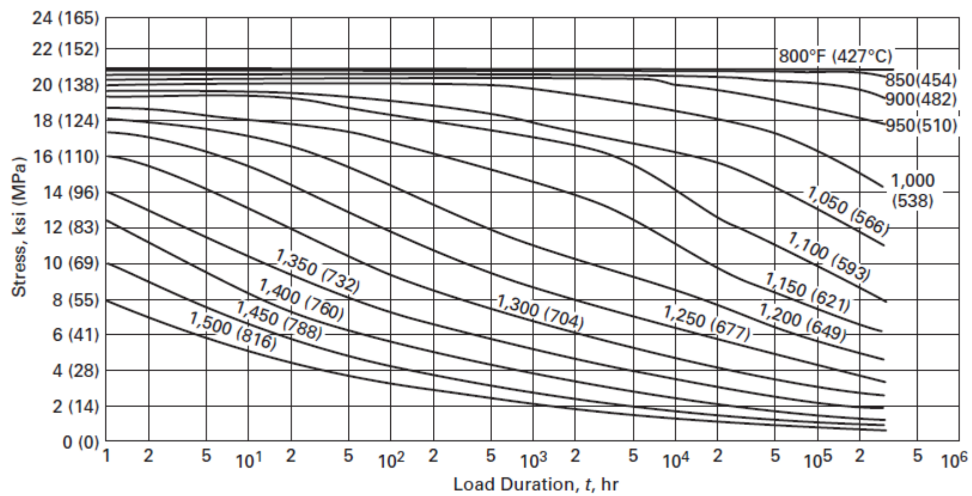
Allowable Stress Intensities S_0 and S_t

- The allowable stress intensities for the Design Condition, S_0, and for the operating conditions, S_t, are developed based on the data from creep rupture tests
- For each creep rupture test at a given temperature and applied load, the strain versus time curve up to creep rupture is used to determine
  - Time to 1% total strain
  - Time to onset of tertiary creep
  - Time to rupture
- Such data from different temperatures and applied loads are used to obtain correlations using time-temperature engineering parameter, the Larson-Miller parameter
- S_0 is based on extrapolated 100,000 h rupture properties
- S_t is base on the lesser of
  - *(a)* 100% of the average stress required to obtain a total strain of 1%
  - *(b)* 80% of the minimum stress to cause initiation of tertiary creep
  - *(c)* 67% of the minimum stress to cause rupture

Allowable Stress Intensity S_0

For Metal Temperature Not Exceeding, °F	304 SS	316 SS	Ni-Fe-Cr (Solution Annealed) UNS N08810	$2^1/_4$Cr-1Mo	9Cr-1Mo-V
700	...	...	...	17.9	26.7
750	...	...	...	17.9	25.9
800	15.2	15.9	15.3	16.6	24.9
850	14.8	15.7	15.1	16.6	23.7
900	14.6	15.6	14.8	13.6	21.9
950	14.2	15.5	14.6	10.8	17.8
1,000	11.1	14.0	14.1	8.0	16.3
1,050	10.1	11.2	11.2	5.7	12.9
1,100	9.8	11.1	10.0	3.8	9.6
1,150	7.7	9.8	9.3	...	7.0
1,200	6.1	7.4	7.4	...	4.3
1,250	4.7	5.5	5.9	...	...
1,300	3.7	4.1	4.7	...	...
1,350	2.9	3.1	3.8	...	...
1,400	2.3	2.3	3.0	...	...
1,450	1.8	1.7	...	...	...
1,500	1.4	1.3	...	...	...

Allowable Stress Intensity S_t: 316H

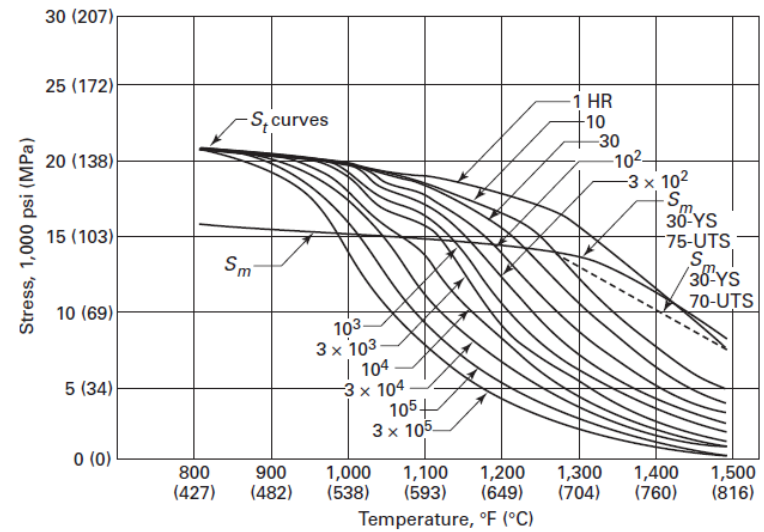


U.S. Customary Units

Temp., °F	1 hr	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
800	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8
850	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.3
900	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.2	19.9	19.3
950	20.1	20.1	20.1	20.1	20.1	20.0	20.0	19.7	19.2	18.4	17.6
1,000	19.8	19.8	19.8	19.8	19.8	19.5	19.0	18.2	17.5	16.2	14.0
1,050	19.4	19.4	19.2	18.7	18.3	17.6	16.8	15.9	14.9	12.5	10.7
1,100	19.1	19.0	18.5	17.8	17.3	16.6	15.9	13.9	11.5	9.5	7.8
1,150	18.5	17.7	17.3	16.4	15.4	14.2	13.0	10.9	8.9	7.2	5.9
1,200	17.8	16.8	15.8	14.2	12.4	10.6	9.4	8.3	6.9	5.5	4.5
1,250	17.1	15.2	13.5	11.5	9.8	8.3	7.3	6.3	5.4	4.2	3.3
1,300	16.1	12.8	10.9	9.1	7.5	6.4	5.6	4.7	3.9	3.1	2.5
1,350	14.2	10.3	8.6	7.0	5.9	5.0	4.2	3.4	2.8	2.1	1.8
1,400	12.0	8.2	6.7	5.4	4.5	3.8	3.1	2.5	2.0	1.5	1.2
1,450	9.7	6.4	5.1	4.1	3.4	2.9	2.2	1.7	1.4	1.0	0.8
1,500	7.8	4.9	3.9	3.2	2.6	2.1	1.6	1.2	0.9	0.65	0.5

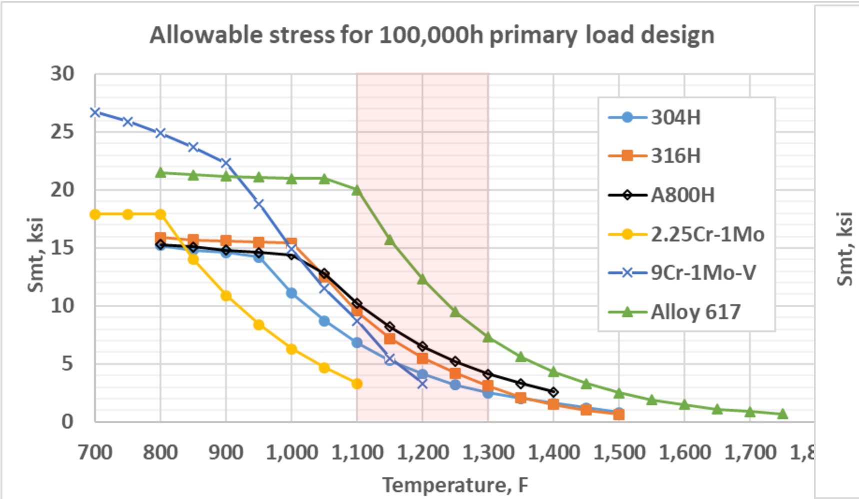
Allowable Stress Intensity S_{mt}

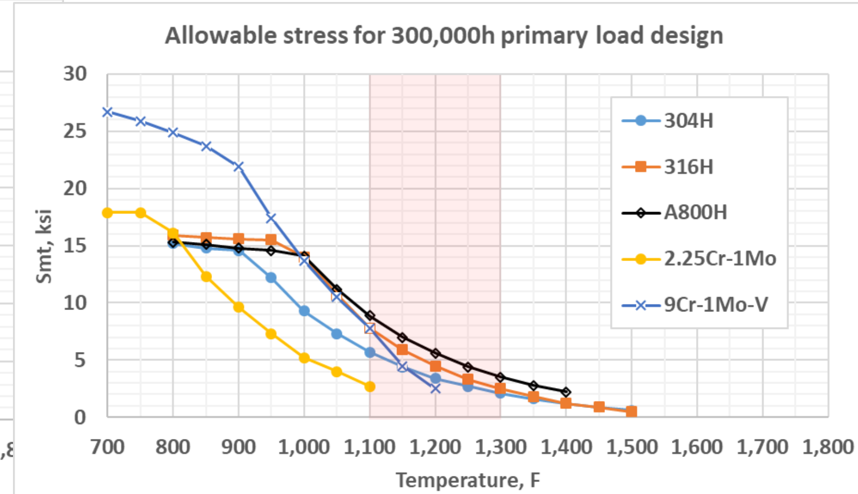
- The allowable stress intensity S_{mt} is given as the lesser of S_m and S_t
- An example for 316H in HBB is shown here

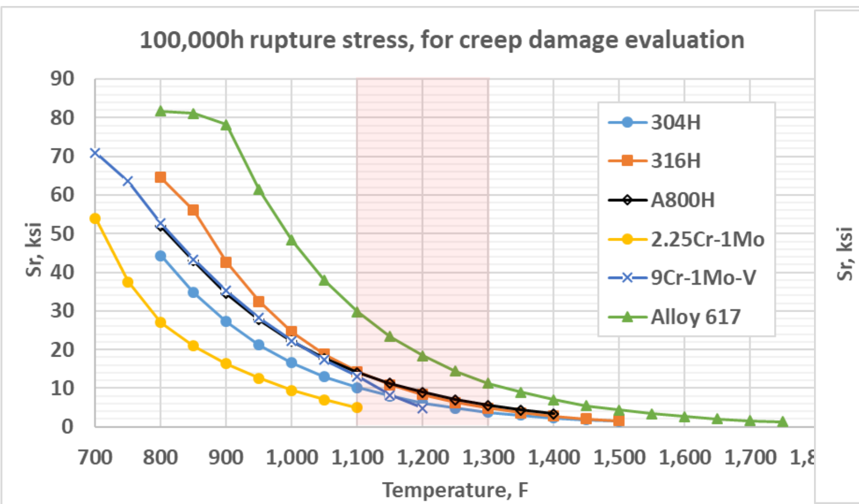


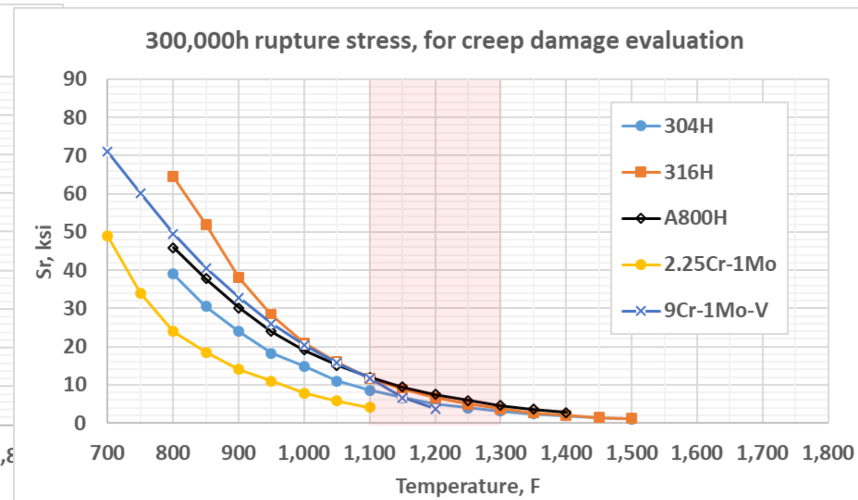
Temp., °F	1 hr	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
800	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9
850	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
900	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
950	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
1,000	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	14.0
1,050	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	14.9	12.5	10.7
1,100	14.8	14.8	14.8	14.8	14.8	14.8	14.8	13.9	11.5	9.5	7.8
1,150	14.7	14.7	14.7	14.7	14.7	14.2	13.0	10.9	8.9	7.2	5.9
1,200	14.6	14.6	14.6	14.2	12.4	10.6	9.4	8.3	6.9	5.5	4.5
1,250	14.2	14.2	14.2	11.5	9.8	8.3	7.3	6.3	5.4	4.2	3.3
1,300	13.8 (13.4)	12.8	10.9	9.1	7.5	6.4	5.6	4.7	3.9	3.1	2.5
1,350	12.8 (11.9)	10.3	8.6	7.0	5.9	5.0	4.2	3.4	2.8	2.1	1.8
1,400	11.3 (10.5)	8.2	6.7	5.4	4.5	3.8	3.1	2.5	2.0	1.5	1.2
1,450	9.7 (9.0)	6.4	5.1	4.1	3.4	2.9	2.2	1.7	1.4	1.0	0.9
1,500	7.8 (7.7)	4.9	3.9	3.2	2.6	2.1	1.6	1.2	0.9	0.65	0.5

Allowable Stresses Comparison

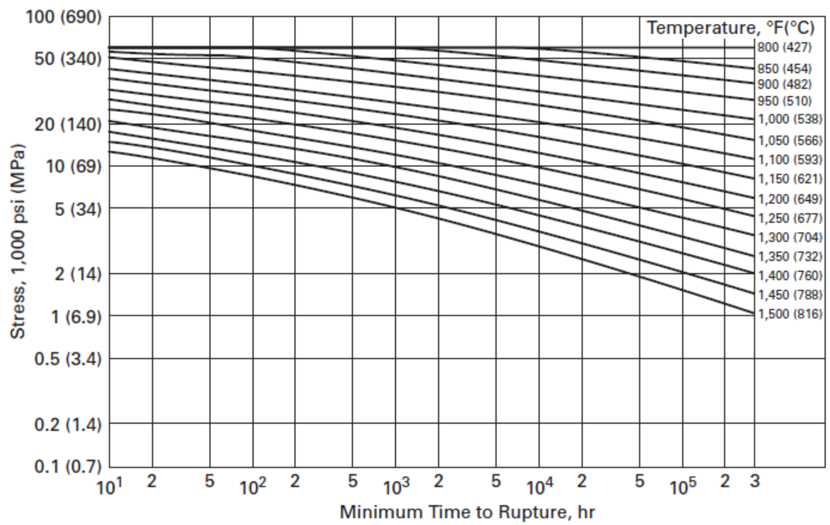








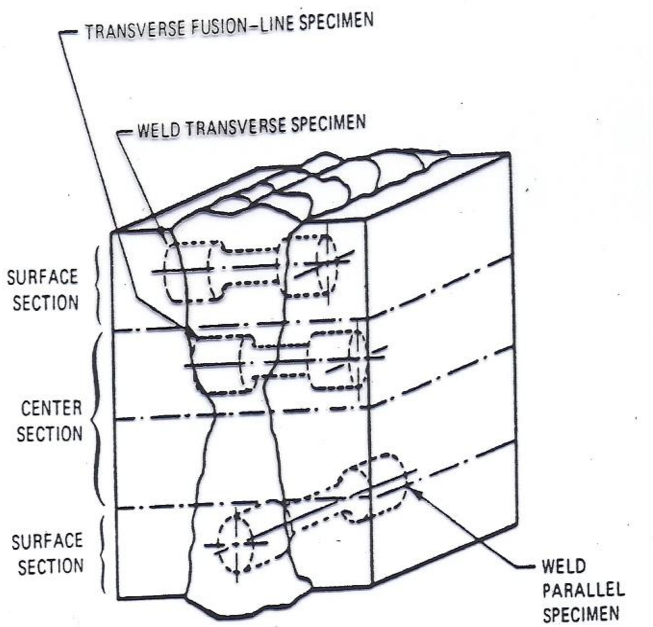
Expected Minimum Stress-to-Rupture S_r – 316H



Temp., °F	1 hr	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
800	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5
850	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	60	56	52
900	62.2	62.2	62.2	62.2	62.1	62	58	54.1	48	42.6	38
950	60	60	60	60	56	51.6	46.5	42.6	37.5	32.4	28.3
1,000	58.5	58.5	55	51.7	47	42.1	37.5	33.6	28.8	24.6	21
1,050	56	52.9	47.5	43.4	38.2	34.4	30.2	26.4	22.3	18.8	16
1,100	53.5	45.1	40	36.4	32.2	28.1	24.2	20.8	17.3	14.3	11.7
1,150	46.5	38.4	34	30.5	26.6	23.0	19.5	16.4	13.4	10.9	8.8
1,200	40	32.7	29	25.6	22	18.8	15.6	12.9	10.3	8.3	6.7
1,250	35	27.8	24.3	21.4	18.1	15.4	12.7	10.2	8.1	6.3	4.9
1,300	30	23.7	20.8	18.0	15	12.5	10.0	8.0	6.2	4.8	3.7
1,350	26	20.0	17.5	15.0	12.7	10.4	8.2	6.4	4.9	3.6	2.7
1,400	22.5	17.1	14.8	12.4	10.2	8.4	6.6	5.0	3.8	2.8	2.1
1,450	19.5	14.6	12.6	10.5	8.6	6.8	5.2	3.9	2.9	2.1	1.5
1,500	17	12.5	10.6	8.8	7.2	5.6	4.2	3.1	2.3	1.6	1.2

Stress Rupture Factor - Weldment

- The stress rupture factor is defined as the ratio of creep rupture strength of weldment to that of base material
- Creep rupture weldment data from the following types of specimens are generally required
- For materials that are susceptible to Type IV cracking, cross-weld specimens shall be used
- Creep rupture strength correlation for weldment is generally developed from Larson-Miller analysis



Stress Rupture Factors Example

Stress Rupture Factors for Type 316 Stainless Steel Welded With SFA-5.22 E 308T and E 308L T; SFA-5.4 E 308 and E 308L; and SFA-5.9 ER 308 and ER 308L

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	1.00	0.98	0.95	0.95	0.95	0.94	0.92	0.92	0.92	0.92
900	1.00	0.94	0.88	0.88	0.88	0.87	0.84	0.84	0.82	0.82
950	1.00	0.90	0.81	0.81	0.81	0.80	0.77	0.76	0.73	0.72
1,000	1.00	0.87	0.75	0.75	0.74	0.73	0.70	0.68	0.64	0.62
1,050	1.00	0.89	0.78	0.78	0.77	0.76	0.74	0.72	0.67	0.60
1,100	1.00	0.90	0.81	0.81	0.79	0.79	0.76	0.73	0.69	0.63
1,150	0.90	0.88	0.86	0.82	0.79	0.77	0.74	0.70	0.64	0.57
1,200	0.81	0.80	0.79	0.79	0.76	0.75	0.70	0.64	0.57	0.49
1,250	0.79	0.78	0.76	0.74	0.72	0.68	0.63	0.56	0.48	0.39
1,300	0.75	0.73	0.70	0.68	0.63	0.59	0.53	0.46	0.38	0.30

Creep Data Extrapolation

- No verified, unique way to specify the allowable limits of time-wise extrapolation of test data
- General guidance
  - Well-behaved, solid-solution alloys may require data at 100°F (50°C) intervals extending to times that will require an extrapolation in time of no more than a factor of five to reach the intended life
  - Metastable alloys, such as the creep-strength enhanced ferritic/martensitic steels, may require data at 50°F (25°C) intervals in the region of expected instability
  - Extrapolations by more than a factor of three will require metallurgical justification
- Extrapolation generally based on Larson-Miller parameter

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Example Larson-Miller Analysis

$$LMP = T(\log_{10} tr + C), \quad T = \text{absolute temp}$$

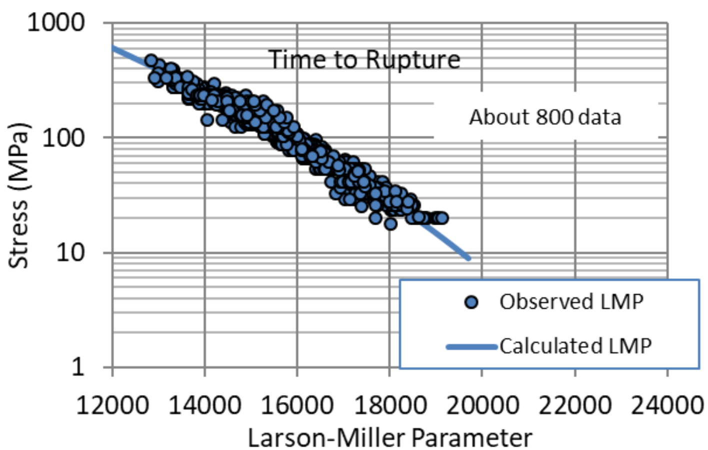
$$tr = \text{rupture time}, \; C = \text{LM constant}$$

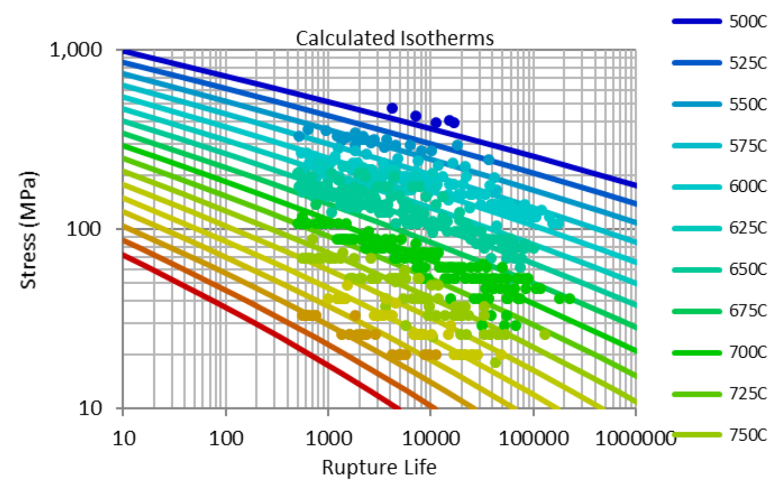
$$LMP = a_0 + a_1 \log_{10} \sigma + a_2 (\log_{10} \sigma)^2, \quad \sigma = \text{rupture stress}$$

$$\text{regression parameters: } a_0, a_1, a_2, C$$

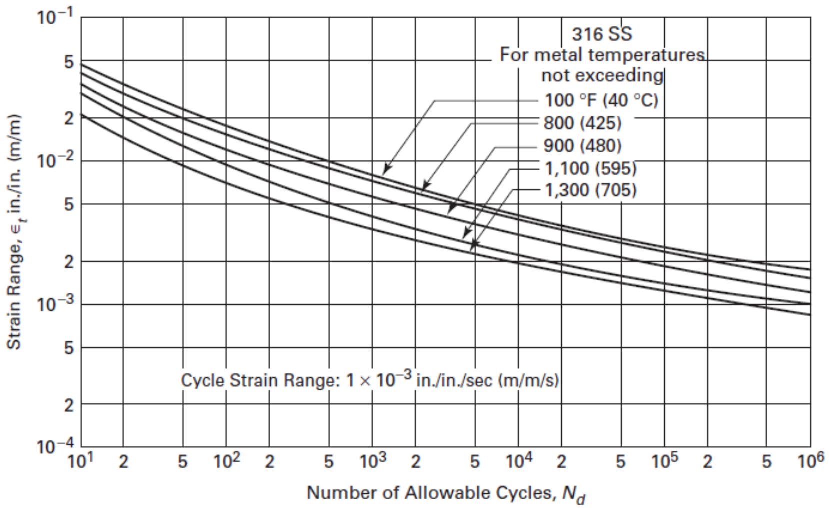
$$tr = 10^{\left[a_0 + a_1 log\ \sigma + a_2 (log\ \sigma)^2\right]/T - C - 1.65 \times SEE}$$

$$SEE = \text{standard error of estimate}$$



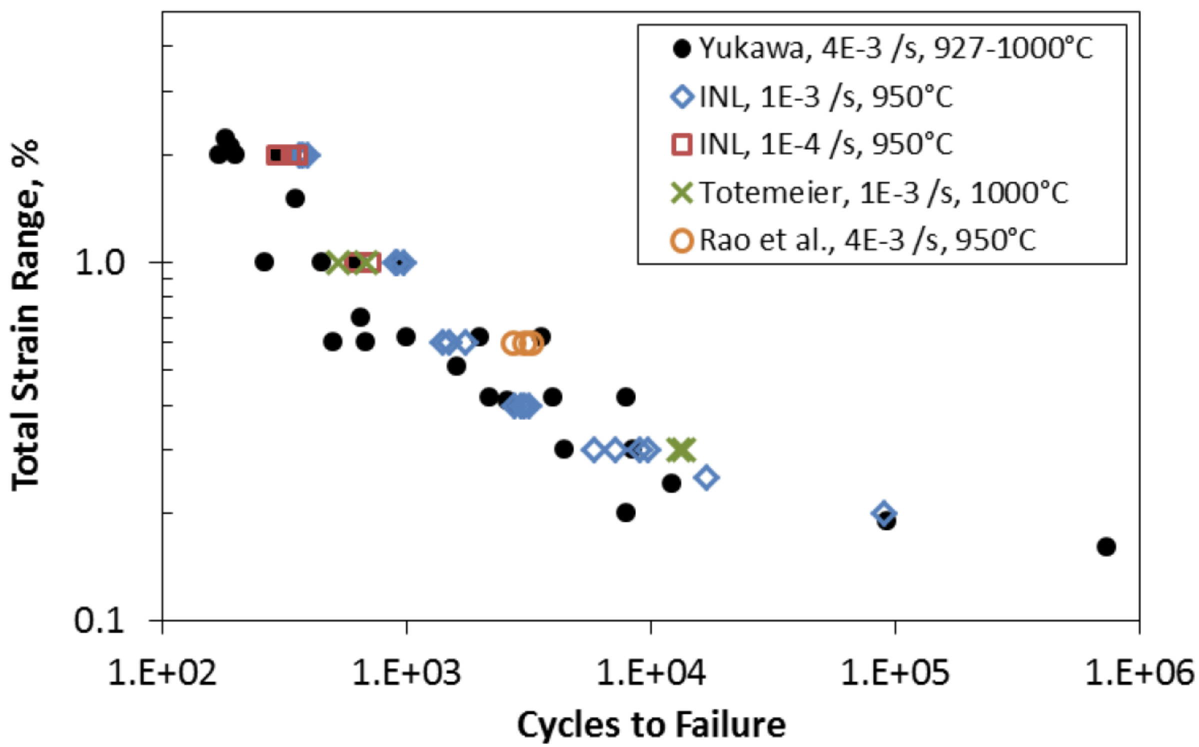


Design Fatigue Curves: 316H

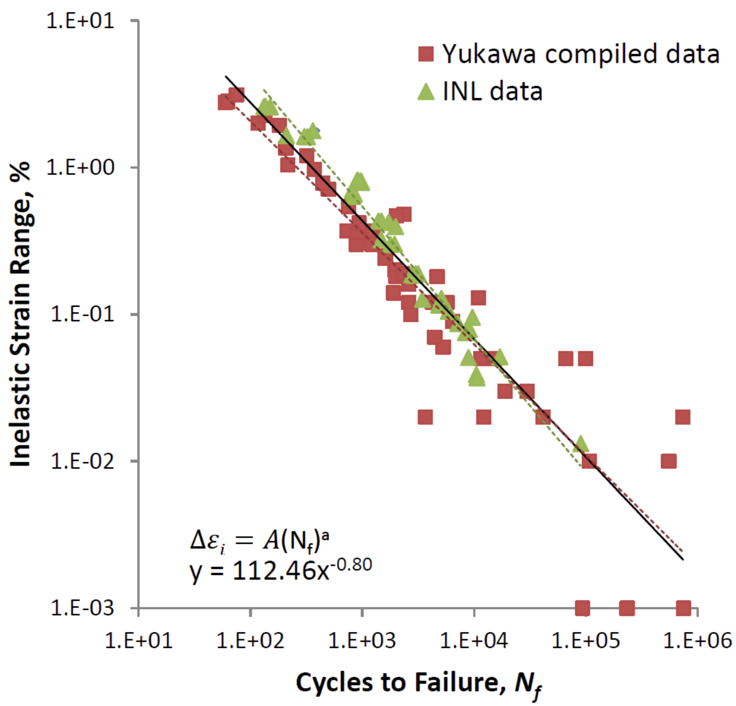


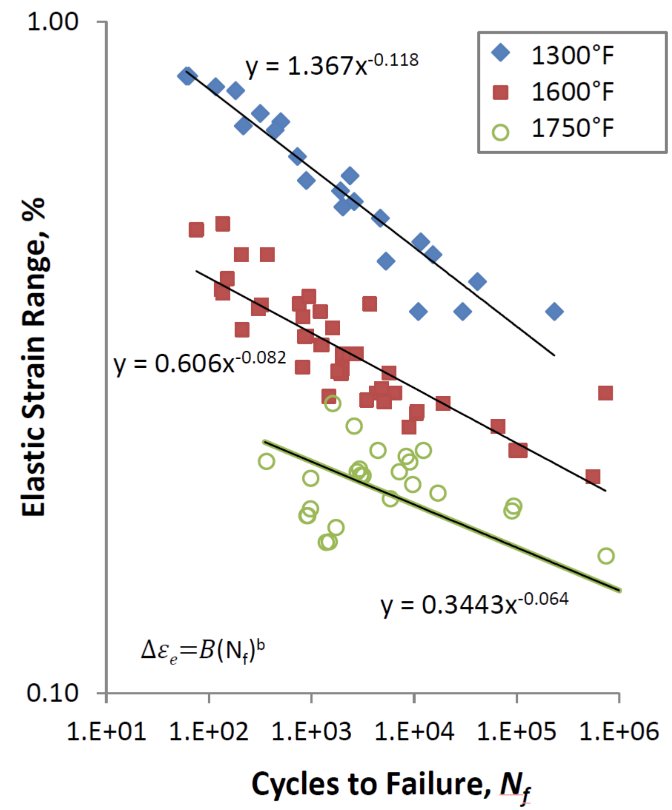
Number of Cycles, N_d [Note (1)]	Strain Range, ϵ_t, in./in., at Temperature 100°F	800°F	900°F	1,000°F–1,200°F	1,300°F
10^1	0.0507	0.0438	0.0378	0.0318	0.0214
2×10^1	0.0357	0.0318	0.0251	0.0208	0.0149
4×10^1	0.026	0.0233	0.0181	0.0148	0.0105
10^2	0.0177	0.0159	0.0123	0.00974	0.00711
2×10^2	0.0139	0.0125	0.00961	0.00744	0.00551
4×10^2	0.0110	0.00956	0.00761	0.00574	0.00431
10^3	0.00818	0.00716	0.00571	0.00424	0.00328
2×10^3	0.00643	0.00581	0.00466	0.00339	0.00268
4×10^3	0.00518	0.00476	0.00381	0.00279	0.00226
10^4	0.00403	0.00376	0.00301	0.00221	0.00186
2×10^4	0.00343	0.00316	0.00256	0.00186	0.00162
4×10^4	0.00293	0.00273	0.00221	0.00161	0.00144
10^5	0.00245	0.00226	0.00182	0.00136	0.00121
2×10^5	0.00213	0.00196	0.00159	0.00121	0.00108
4×10^5	0.00188	0.00173	0.00139	0.00109	0.000954
10^6	0.00163	0.00151	0.00118	0.000963	0.000834

Fatigue Test Data



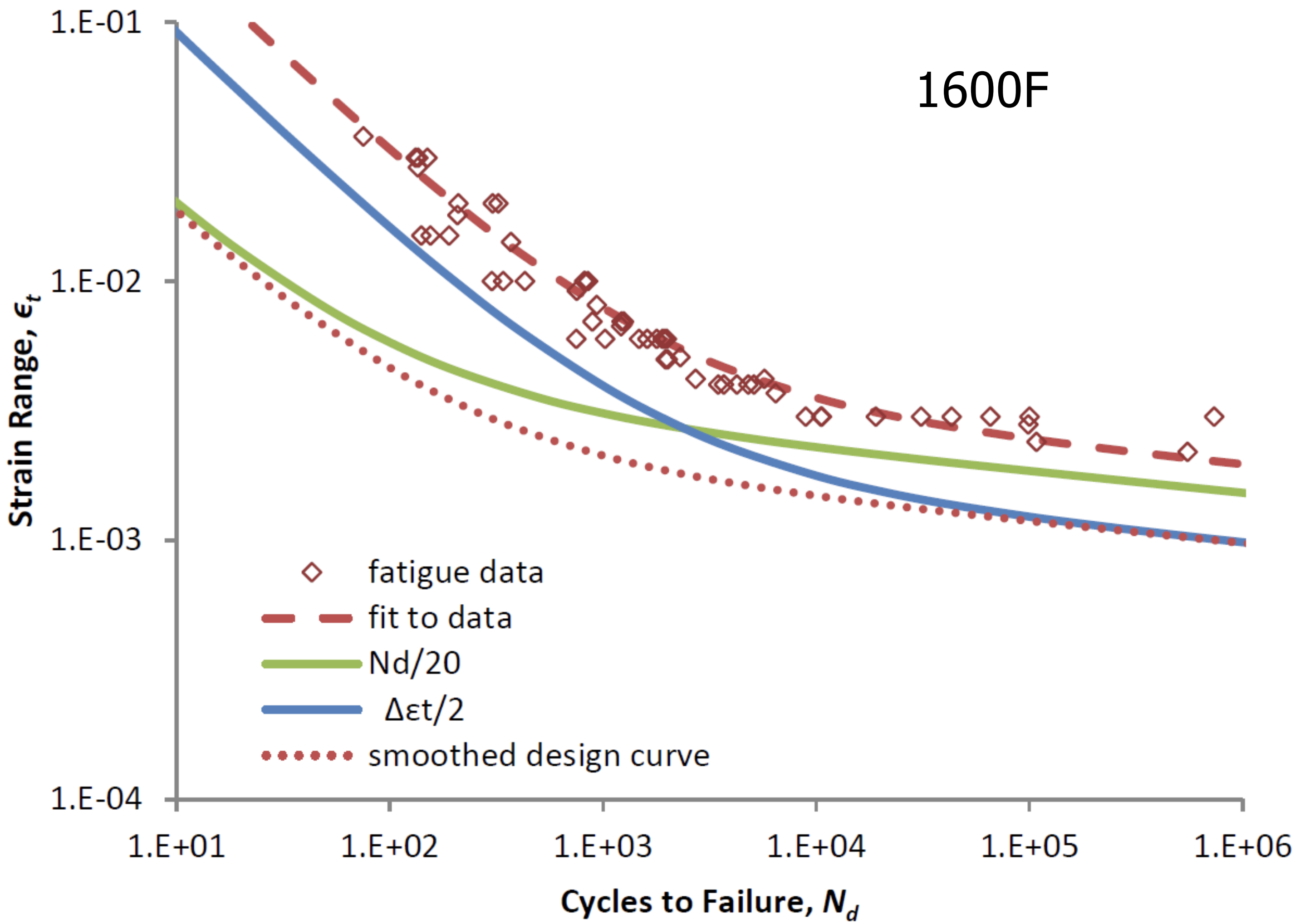
Fatigue Data Analysis



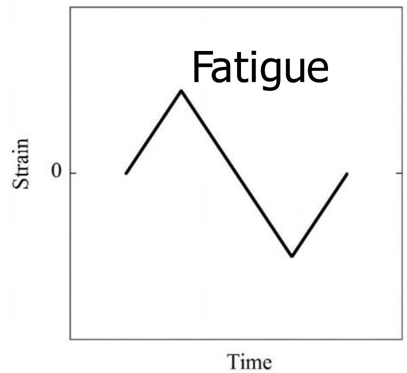


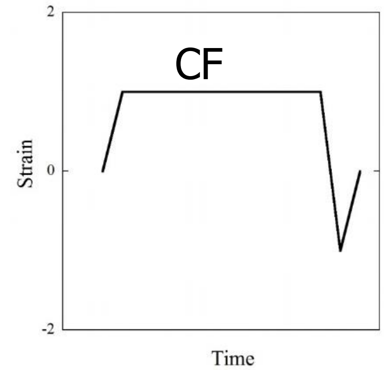
$$\underbrace{\Delta\varepsilon_t}_{\text{Total Strain Range}} = \underbrace{A\,(N_f)^a}_{\textit{Inelastic}} + \underbrace{B\,(N_f)^b}_{\textit{Elastic}}$$

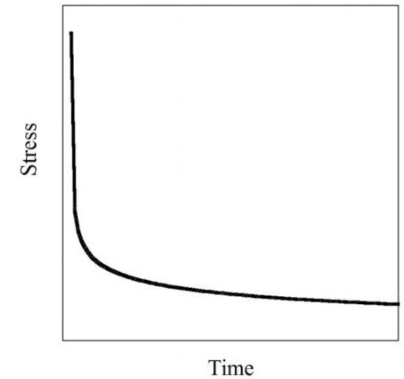
Design Fatigue Curve
Two and Twenty

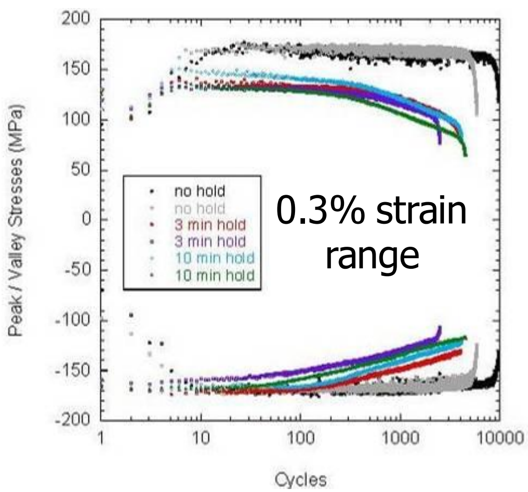


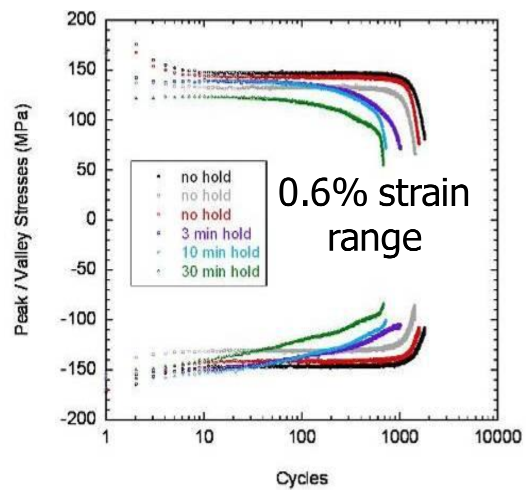
Creep-fatigue Data for Interaction Diagram

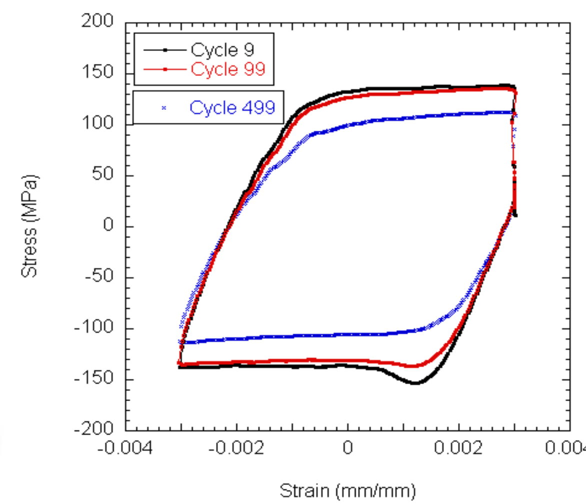












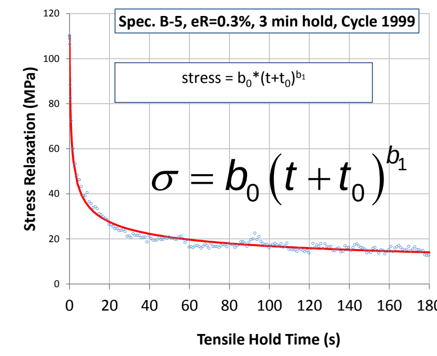
Hysteresis loops, 0.6% strain range, 10 min. hold

Creep Damage Calculations Example

$$\underbrace{\sum_j \left(\frac{n}{N_d}\right)_j}_{\text{Cyclic Damage}} + \underbrace{\sum_k \left(\frac{\Delta t}{T_d}\right)_k}_{\text{Creep Damage}} \leq D$$

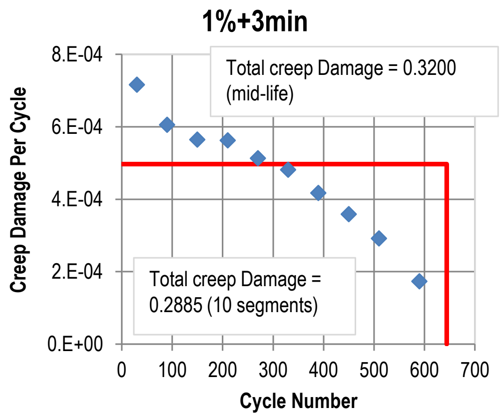
creep damage, k^{th} cycle

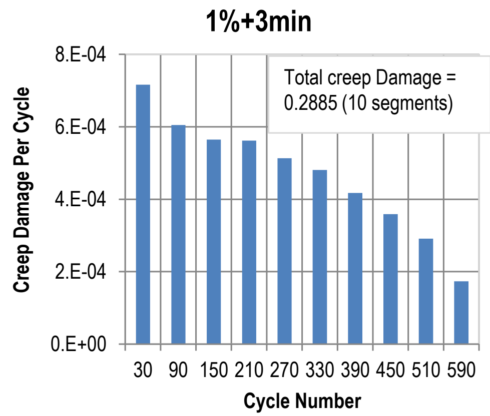
$$= D_k^c = \int_{hold\ time} \left(\frac{1}{T_d}\right)_k dt$$



creep rupture correlation

$$\log_{10}\left(T_d\right) = a_0 + \frac{a_1}{T} + a_2 \log_{10}\left(\sigma\right) + \frac{a_3}{T}\log_{10}\left(\sigma\right)$$

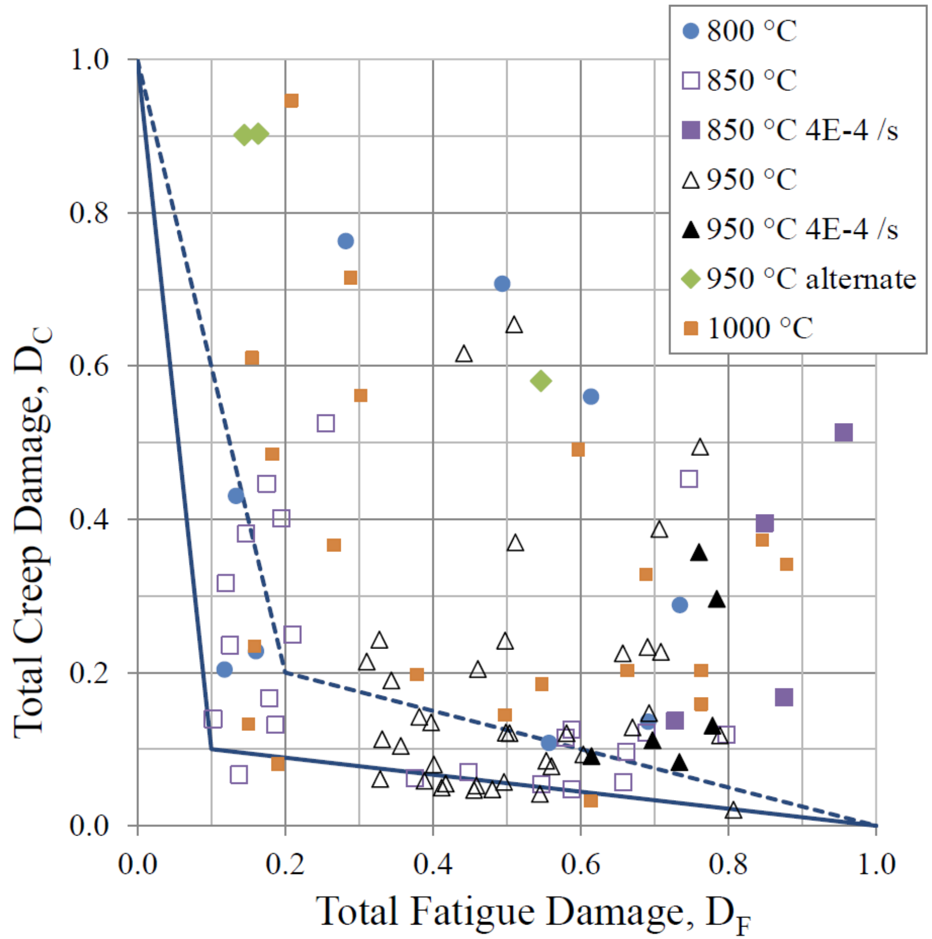




Calculated creep damage for selected cycles

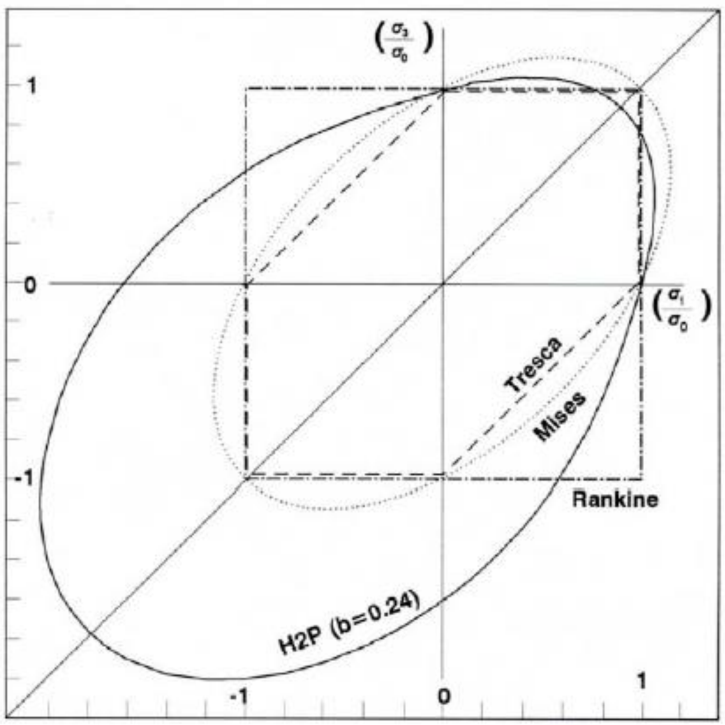
CF Test	Total Creep Damage	Total Creep Damage (based on Mid-Life)
1	0.3972	0.4166
2	0.2885	0.3200
3	0.1965	0.2175
4	0.1296	0.1424
5	0.2729	0.2908

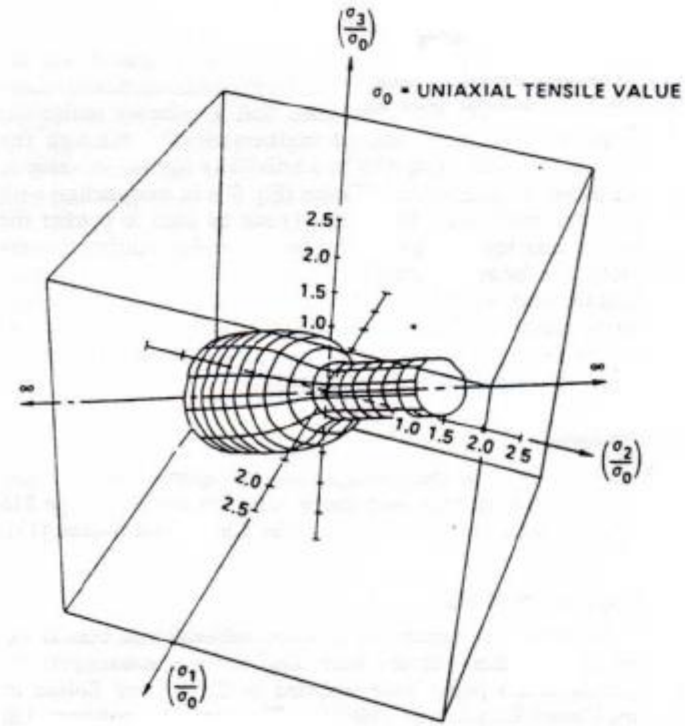
Calculated CF Interaction Data Example



Huddleston Creep Failure Criterion

$$\sigma_e = \bar{\sigma}\exp\left[b\left(\frac{J_1}{S_s}-1\right)\right]$$





Huddleston 3D "Wine bottle" failure surface
b=0.28, compressive to tensile creep strength = 1.75

Testing to Determine Huddleston Constants

Table 4.10. Data Set 4: *averaged* biaxial creep-rupture data of annealed Type 316 stainless-steel cylindrical specimens tested at 1112°F (600°C) in air by Chubb and Bolton[10].

Biaxial Stress Ratio	σ_x (ksi)*	σ_y (ksi)*	σ_z (ksi)*	T_r (h)	Specimen Loading Mode
2.0	17.389	34.777	–0.425	1068	P
1.0	25.443	25.443	–0.360	4202	Z+P
0.5	31.669	15.835	–0.225	629	Z+P
0.0	27.492	0.000	0.000	1958	Z
–0.5	23.365	0.000	–11.561	2460	Z+W
–1.0	19.607	0.000	–19.607	2844	W

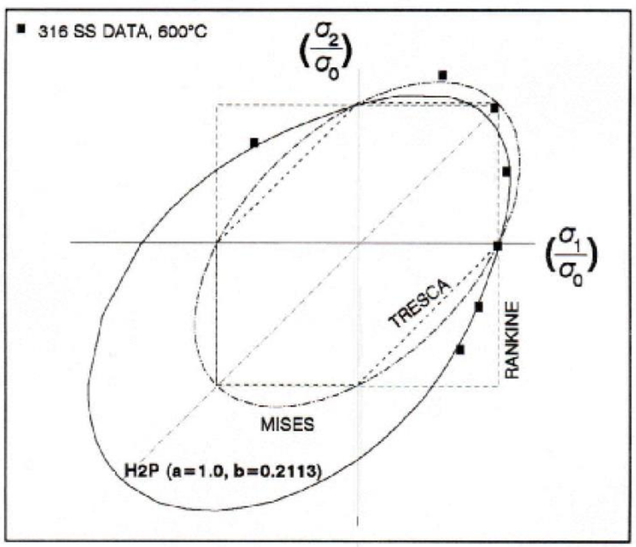


Figure 4.11. Correlation of Type 316 stainless-steel biaxial stress-rupture data with 2-D isochronous stress-rupture contours.

**P (internal pressure).

Z (axial tension)

W (torsion).

Temperatures and Lifetimes - Class A

Base Metal	Smt and Sr temp. range and time	Fatigue curve temp. range	Stress rupture factor temp. range and time
304H	>800-1,500F; 300,000h	>800-1,300F	308; >800-1,250F; 300,000h 16-8-2; >800-1,200F; 300,000h 316; >800-1,400F; 300,000h
316H	>800-1,500F; 300,000h	>800-1,300F	308; >800-1,300F; 300,000h 16-8-2; >800-1,200F; 300,000h 316; >800-1,400F; 300,000h
A800H	>800-1,400F; 300,000h	>800-1,400F	NiCrFe-2; >800-1,400F; 300,000h NiCrFe-3; >800-1,400F; 300,000h
2¼Cr-1Mo	>700-1,100F; 300,000h >1100-1,200F; 1,000h	>700-1,000F	90C-B3, 90XX-B3, B 3, CB 3 (> 0.05C), 90T1-B3; >700-1,200F; 300,000h
9Cr-1Mo-V	>700-1,200F; 300,000h	>700-1,000F	90S-B9, 90XX-B9, B9; >700-1,200F; 300,000h
A617	>800-1,750F, 100,000h	>800-1,750F	NiCrCoMo-1; >800-1,750F; 100,000h
SA533B SA508	Smt: >700-800F; 3,000h (Level B) >800-1,000F; 1,000h (Level C or D) Sr: >700-1,000F; 100,000h	>700-1,000F	Associated weldments >700-1,000F

Material Qualification

ASME Construction Rules for Nuclear Facility Components (Section III)	
Within HBB Scope • Data requirements to support design properties determination per Division 5 Appendix HBB-T • Testing performed in air and at elevated temperatures	Outside HBB Scope • Corrosion • Mass transfer phenomena • Radiation • Fission product Support development of design procedures and materials data to characterize **effects of material deterioration on HBB design properties**
Approved by ASME Section III for incorporation into Division 5, HBB	Approved by Regulator • Support construction license application

Appendix HBB-Y "Guidelines for Design Data Needs for New Materials"

Required testing to introduce a new structural material into Section III, Division 5, or a Division 5 Code Case

- HBB-Y-2100 Requirement For Time-independent Data
- HBB-Y-2110 Data Requirement for Tensile Reduction Factors for Aging
- HBB-Y-2200 Requirement for Time-Dependent Data
- HBB-Y-2300 Data Requirement for Weldments
- HBB-Y-3100 Data Requirement for Isochronous Stress-Strain Curves
- HBB-Y-3200 Data Requirement for Relaxation Strength
- HBB-Y-3300 Data Requirement for Creep-Fatigue
- HBB-Y-3400 Data Requirement for Creep-Fatigue of Weldments
- HBB-Y-3500 Data Requirement for Cyclic Stress-Strain Curves
- HBB-Y-3600 Data Requirement for Inelastic Constitutive Model
- HBB-Y-3700 Data requirement for Huddleston multiaxial failure criterion
- HBB-Y-3800 Data Requirement for Time-Temperature Limits for External Pressure Charts
- HBB-Y-4100 Data Requirement for Cold Forming Limits
- Validation of Elastic-Perfectly Plastic (EPP) Simplified Design Methods for the new alloy

Backup

Materials Challenges Molten Salt Reactors

- **Fast Spectrum** Vs **Thermal Spectrum**
  - Fast Spectrum: Higher point defect generation rate
  - Thermal Spectrum: Lower point defect generation rate

- **Different salt chemistries and their reactions with metals**
  - Chloride salts Vs Fluoride salts

- **Liquid fuel** Vs **Solid fuel**
  - Liquid fuel: Fuel salt, fission products Vs Coolant salt
  - Solid fuel: Primary coolant salts Vs Secondary coolant salts

- **Drastically different design lives**
  - 4 yrs Vs 30 to 60 yrs

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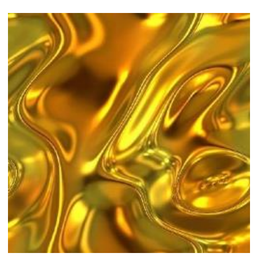
Corrosion of Structural Materials in Molten Salts Differs from Other Coolants

Molten Fluoride Salts

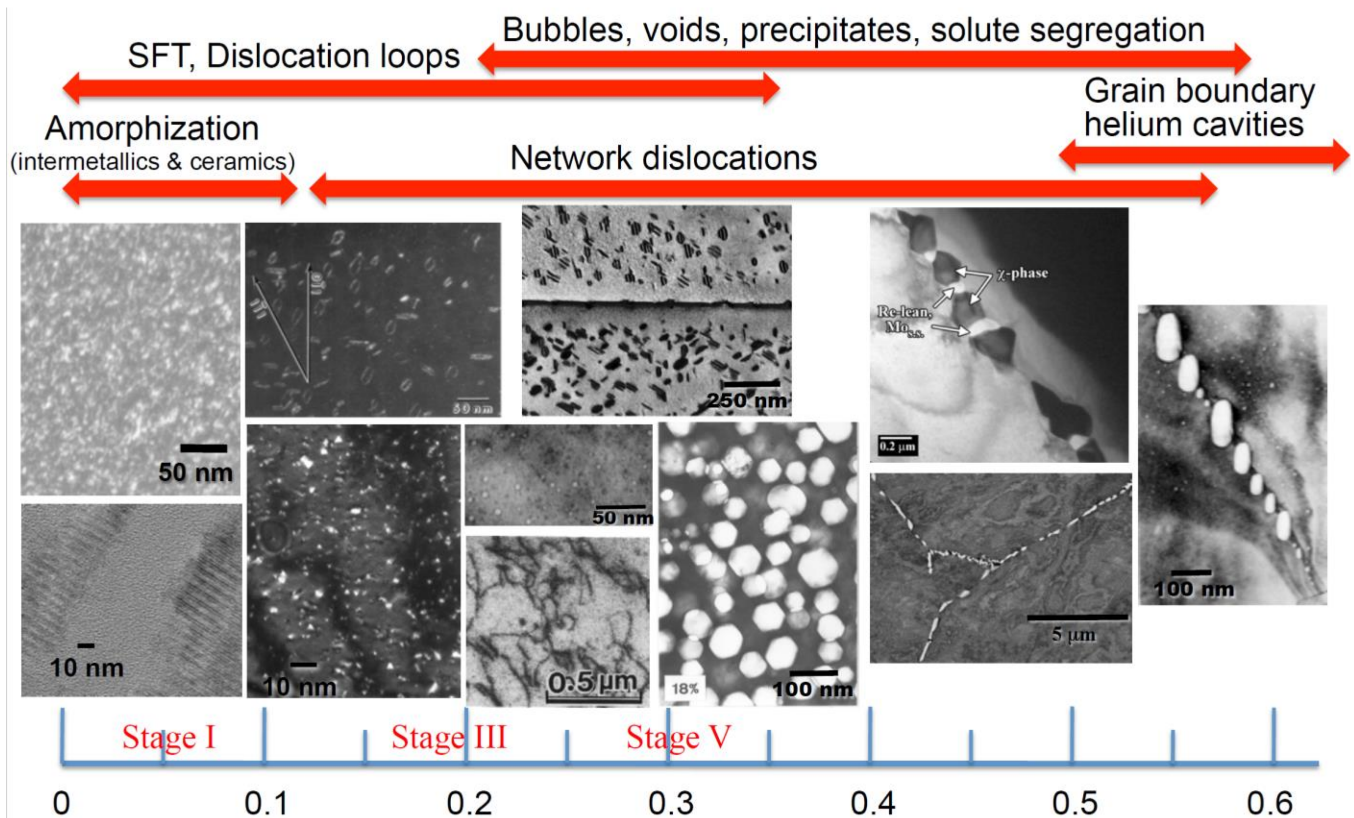
- Fluorides remove oxide layers from metals
- Mass transfer due to thermal & activity gradient in MSR circuits
- Selective dissolution of Cr near alloy surface and along grain boundaries in Cr-bearing alloys
- Intergranular cracking in Hastelloy N due to tellurium corrosion from fission product
- Corrosion accelerated by presence of impurities



Molten Chloride Salts

- Oxide layers can form on metal surface in molten chloride salts but mostly porous and non-protective
- Formation of a stable passivating oxide layer is much more challenging
- Corrosion is due to depletion of Cr in alloy matrix underneath oxide layer and the intergranular corrosion
- Generally, nickel-based alloys have better corrosion resistance than stainless steels
- Very few studies on effects of actinides and fission products on the materials corrosion

MSR Structural Component Doses Range from less than 1 dpa to 25 dpa



Irradiation Temperature (T/T_M)

Zinkle & Snead, Ann. Rev. Mater. Res. 44 (2014) 241

Irradiation damage of MSR materials must be assessed

Cladded Component Concept to Support Near-Term MSR Deployment (Ongoing Code Effort)

- Clad corrosion and irradiation resistant materials on ASME Division 5 Class A components which are already code qualified
  - Initial focus - weld overlay, co-extrusion (other possible fabrication processes, e.g., explosion bonding)
- Issues to be addressed
  - Clad/base metal thermomechanical interaction (thermal expansion mismatch)
  - Clad/base metal metallurgical interaction (mass diffusion, formation of intermetallic)
  - New design rules and evaluation methods
  - Acceptance testing and criteria for clad/base metal system
- Goal
  - Enable MSR designers to deploy ASME Code-compliant cladding/base metal combinations, including non-Code qualified cladding materials, for Class A components that could be licensed for vendor-specific MSR designs, without the need of very long term data generation

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High Temperature In-Situ Passive Material Surveillance Methodology

- The use of surveillance specimens was identified in a HTGR roadmap (Sims, 2010, ASME HTGR Code Development Roadmap, STP-NU-045, ASME), developed with funding from NRC

- Creep rupture, long term strain accumulation, creep-fatigue damage, and their interaction with environmental effects require significant extrapolation from shorter term tests

- From a regulatory perspective, in-situ passive material surveillance program, with appropriate protocol and acceptance criteria, will be very helpful to support licensing reactors with long design lifetimes or for deployment of new materials for elevated temperature service

High Temperature In-Situ Passive Material Surveillance Methodology

- Surveillance specimens in a test reactor could be used to evaluate the performance and validate the design basis of existing or new materials to support their near-to-mid-term deployment in advanced high temperature reactors
- Appropriately designed surveillance test specimens could be placed in an operating plant at different key locations to accumulate damage either as a result of prototypical reactor operating conditions or under some accelerated loading conditions

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