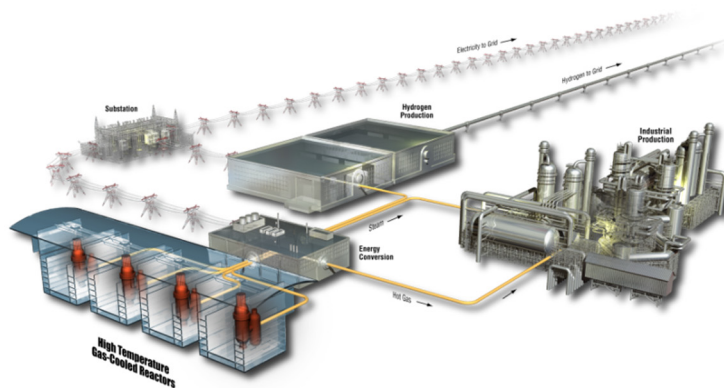# Updated Draft ASME Boiler and Pressure Vessel Code Case for Use of Alloy 617 for Construction of Nuclear Components for Section III, Division 5

R. N. Wright

September 2018

Idaho National
Laboratory

Updated Draft ASME Boiler and Pressure Vessel Code Case for Use of Alloy 617 for Construction of Nuclear Components for Section III, Division 5

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INL ART Program
Idaho Falls, Idaho 83415

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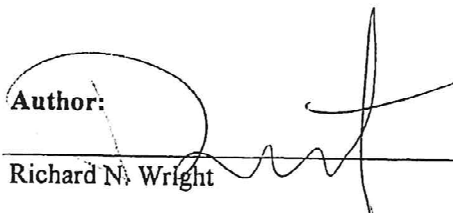
INL ART Program

Updated Draft ASME Boiler and Pressure Vessel Code Case for Use of Alloy 617 for Construction of Nuclear Components for Section III, Division 5

INL/EXT-17-42999
Revision 1

September 2018

Author: _____ Richard N. Wright

9/4/2018
Date

Peer Reviewer: (Confirmation of mathematical accuracy, and correctness of data and appropriateness of assumptions.)

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Thomas Lillo, Idaho National Laboratory
Peer Reviewer
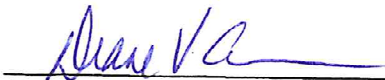
9/4/18
Date

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Mark Messner, Argonne National Laboratory
Peer Reviewer
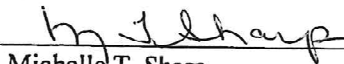
9/4/18
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Approved by:

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Diane V. Croson
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9/4/18
Date

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INL Quality Assurance

9/4/18
Date

REVISION LOG

Rev.	Date	Affected Pages	Revision Description
0	08/15/2017	All	Newly issued document.
1	09/05/2018	Page 3	Progress on Code Case balloting has been updated and the response to comments and editorial issues identified during balloting noted
		Page 24	Editorial correction to Table HBB-I-14.3 to correct transposed numbers at 1 and 10 hours for temperatures of 1,400 and 1450ºF and 775ºC

ABSTRACT

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code currently only allows five materials for use in construction of nuclear components for high temperature service. Since 2005, the United States high temperature gas-cooled reactor program has been characterizing elevated temperature mechanical properties of Alloy 617 as the leading candidate material for the intermediate heat exchanger. After analysis of these experimental results, along with historical data and additional results available through the Generation IV International Forum Very High Temperature Reactor Materials Program Management Board Materials Handbook, a draft ASME Code Case to allow nuclear construction with Alloy 617 has been developed.

This report contains the Code Case for Low Temperature Service Construction Section III, Division 5, Section HB, Subpart A, Class A and Subsection HC, Subpart A, Class B components, which has been approved by the Board of Nuclear Codes and Standards. This Code Case allows use of Alloy 617 up to 800°F (425°C).

This report also contains an updated draft of a Section III, Division 5, Section HB, Subsection B, Code Case for Alloy 617 to qualify it for use in construction of nuclear components up to 1750°F (950°C) for service life up to 100,000 hours. The draft is in the balloting process by the appropriate ASME Committees.

ACKNOWLEDGEMENTS

CONTENTS

ACRONYMS

ART	Advanced Reactor Technologies
ASME	American Society of Mechanical Engineers
BPV	Boiler and Pressure Vessel
INL	Idaho National Laboratory
SC-D	Subcommittee Design
SG-ETD	Subgroup Elevated Temperature Design
SG-ExtPress	Subgroup External Pressure
SG-HTR	Subgroup High Temperature Reactors
SG-MF&E	Subgroup Materials, Fabrication and Evaluation
SG-NFA	Subgroup Nonferrous Alloys
SG-PhysProp	Subgroup Physical Properties
SG-StrengthWeld	Subgroup Strength of Weldments
WG-AM	Working Group Analysis Methods
WG-ASC	Working Group Allowable Stress Criteria
WG-CFNC	Working Group Creep-Fatigue and Negligible Creep

Updated Draft ASME Boiler and Pressure Vessel Code Case for Use of Alloy 617 for Construction of Nuclear Components for Section III, Division 5

Early in the United States' very high temperature reactor program, several candidate nickel alloys were considered for use in construction of the intermediate heat exchanger. Based primarily on technical maturity, a down-selection was made to focus on Alloy 617. After this down-selection, the primary goal of the research and development program was to develop sufficient information on the high temperature properties of the material to qualify it for construction of high temperature nuclear components in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code.

Alloy 617 is a solid-solution strengthened material with nominal Ni-Cr-Co-Mo composition, originally developed for aerospace applications such as burner can liners for turbine engines by Huntington Alloys. (Huntington Alloys is now Special Metals Division of Precision Castparts, Inc.) The ASME BPV Code allows use of Alloy 617 for construction of non-nuclear pressure vessels, and Alloy 617 is used in fossil fired power plants.

Section III, Division 1, Subsection NB of the ASME BPV Code was developed for construction of nuclear components in light water reactors and allows use of ferritic materials up to 700°F and austenitic alloys up to 800°F. Subsection NH of Section III Division 1 was written to allow higher temperature construction with a primary focus on sodium cooled reactors. Recently, a new Division 5 of Section III was published specifically for high temperature reactors (regardless of the primary working fluid) and incorporates both Subsections NB and NH.

There are only five alloys currently allowed for use in high temperature nuclear components: 2.25Cr-1 Mo and V modified 9Cr-1Mo steels, Types 304 and 316 stainless steels, and the high nickel austenitic Alloy 800H. This very sparse set of allowed materials is in contrast with the collection of more than 150 materials that are allowed for use in non-nuclear pressure vessel construction. A draft Code Case to add Alloy 617 to the list of qualified alloys for use in high temperature nuclear design was submitted to ASME in the early 1990s, but it was withdrawn prior to formal Code action.

A great deal of experimental characterization of high temperature properties required for Code qualification has been performed under the Advanced Reactor Technologies (ART) High Temperature Materials program (and its predecessors). Several additional requirements exist for qualification of materials for use in high temperature nuclear construction, compared to conventional pressure vessels. For non-nuclear pressure vessel construction, creep rupture data for 10,000 hours can be used to support qualification up to 100,000 hours of service. For high temperature nuclear construction, extrapolation of rupture life beyond the longest experimental rupture lives is restricted to a factor of 3 to 5. High temperature nuclear construction is also the only area of the Code that requires creep-fatigue characterization.

A Code Case to qualify Alloy 617 for use in nuclear construction under Section III, Division 5, Subsection HB, Subpart A, Class A and Subsection HC, Subpart A, Class B for components designed for use up to 800°F (427°C) was developed under the ART program. This Code Case was approved by the Board of Nuclear Codes and Standards in late 2016. This Code Case for Low Temperature Service Construction is presented in Appendix A.

A draft of a Section III, Division 5, Section HB, Subsection B, Code Case for Alloy 617 to qualify it for use in construction of nuclear components up to 1750°F (950°C) for service life up to 100,000 hours is under development and major sections are currently being balloted. A detailed balloting plan has been developed for approval by letter ballot of the high temperature Alloy 617 Code Case, as shown in Figure 1. Record numbers have been established in the ASME information managements system, C&S

Connect, for sections of the Code Case that are related topically. These records contain detailed background files and related data tables to enable working groups and subgroups to evaluate those sections of the Code Case that are relevant to their area of expertise. For example, Record RC-16-994 contains details of eight sections of the Draft Code Case that relate to allowable stresses. This record must be balloted within Section III first by the Working Group Allowable Stress Criteria (WG-ASC). After the record is approved by the working group, it is sent (with revisions as required) to the Subgroup Elevated Temperature Design (SG-ETD). Upon passage by this subgroup, the record is balloted concurrently by the Subgroups High Temperature Reactors (SG-HTR), and Materials, Fabrication and Evaluation (SG-MF&E). Record RC-16-994 also requires approval by Section II Subgroups Nonferrous Alloys (SG-NFA) and Strength of Weldments (SG-StrengthWeld). After approval by the subgroups, the draft will be balloted by the Section II Committee (BPV II). In addition to this specific record, each of the working groups and subgroups that are balloted in both Section II and III receive the entire Draft Code Case (RC-16-1001) for review and comment. After RC-16-994 through RC-16-1000 are approved by the lower tier committees and BPV II, the complete Draft Code Case must be balloted by the Section III Committee (BPV III).

no.	Record/ Project Manager	Alloy 617 Code Case Topics (dry run presentations in TG-A617CC)	Section III, for approval (order of balloting indicated by numbers)	Section II, for approval (order of balloting indicated by numbers)	Review and Comment, accompanying each sub-record
1	RC-16-994 R. Wright	Permissible base materials	1. WG-ASC 2. SG-ETD 3. (SG-HTR, SG-MF&E)	4. (SG-NFA, SG-StrengthWeld) 5. BPV II	RC-16-1001
2		Permissible weld materials			
3		Yield and ultimate (S_y, S_u)			
4		Allowable stresses (S_o, S_m, S_r, S_t, S_{mt})			
5		Stress rupture factor			
6		Relaxation cracking			
7		Aging factor			
8		Cold work and annealing			
9	RC-16-995 R. Wright	Extension of modulus values to higher temperatures	1. WG-ASC 2. SG-ETD 3. (SG-HTR, SG-MF&E)	4. (SG-PhyProp, SG-NFA) 5. BPV II	RC-16-1001
10		Thermophysical properties (CTE, diffusivity, conductivity)			
11	RC-16-996 Jetter	Temp/time limits for buckling charts	1. WG-AM 2. SG-ETD 3. (SG-HTR, SG-MF&E)	4. (SG-ExtPress, SG-NFA) 5. BPV II	RC-16-1001
12	RC-16-997 Jetter	Huddleston parameters	1. WG-ASC 2. SG-ETD 3. (SG-HTR, SC-D)		RC-16-1001
13		Isochronous stress-strain curves			
14	RC-16-998 Jetter	Negligible creep	1. WG-CFNC 2. SG-ETD 3. (SG-HTR, SC-D)		RC-16-1001
15		Creep-fatigue D-diagram			
16		EPP creep-fatigue damage evaluations			
17	RC-16-999 Jetter	EPP strain limits evaluations	1. WG-AM 2. SG-ETD 3. (SG-HTR, SC-D)		RC-16-1001
18	RC-16-1000 Jetter	Fatigue curves	1. (WG-FS, WG-CFNC) 2. SG-ETD 3. (SG-HTR, SG-MF&E, SC-D)		RC-16-1001
19	RC-16-1001 Jetter	Overall Alloy 617 Code Case	1. BPV III		

Figure 1. Balloting plan for approval of the high temperature Alloy 617 Code Case.

The balloting procedure for the high temperature Code Case began in fiscal year 2017. The status of the balloting process is given below. The updated draft Code Case, reflecting changes resulting from balloting, is shown in Appendix B.

- 16-994 Allowable stress criteria: approved WG-ASC, SG-ETD, SG-HTR, Sg-MF&E, SG-NFA and SG-Strength of Weldments; awaiting ballot by Section II Committee

- 16-995 Physical properties: approved WG-ASC, SG-ETD, SG-HTR, SG-MF&E, SG-Physical Properties and SG-NFA; awaiting ballot by Section II Committee

- 16-996 Buckling Charts: verbal approval WG-ASC; awaiting formal ballot

- 16-997 Isochronous Stress Strain Curves and Huddleston parameters: verbal approval WG-ASC; awaiting formal ballot

- 16-998 Creep-fatigue: approved WG-CFNC, SG-HTR, SG-ETD and SC-D

- 16-999 PP strain limits: approved WG-AM, SG-HTR, SG-ETD and SC-D

- 16-1000 Design fatigue curves: approved WG-FS, WG-CFNC, SG-ETD; out for ballot SG-HTR and SG-MFE

As a result of comments during balloting an editorial change has been made to Table HBB-I-14.3F S_{mt} – Allowable Stress Intensity Values in the high temperature Code Case for both the customary and metric tables. For the customary table, for allowable stress at 1,400 and 1,450°F the values at 1 and 10 hours were transposed. That editorial error has been corrected. A similar correction was made in the metric table for 775°C.

During development of this Code Case it was determined in discussion with the Section II Subgroup Non-Ferrous alloys that existing values for Alloy 617 allowable stresses that are published in Section II D "Materials Properties" would be incorporated into the Code Case where appropriate. Table HBB-I-14.2 "S_o – Maximum Allowable Stress Intensity" values in this Code Case were directly incorporated from the time dependent allowable stress values in Table 1B from Section II D. The origin of the values in Table 1B is uncertain, but likely derive from the database developed by Huntington Alloys when Alloy 617 was originally code qualified for non-nuclear construction. It has recently been noted that the Table 1B values are not consistent with values that would be derived from the more current and expanded data set used elsewhere in this Code Case. This issue has been discussed with Section II Subgroup Non-Ferrous Alloys and it was determined that it is appropriate to continue using the Table 1B values until a complete analysis is carried out. If it is determined that Table 1B is in need of modification an official ballot item to make the necessary changes to Section II D Table 1B will be taken out and the Code Case can be amended subsequent to that action to reflect the revised values.

Provisional buckling charts and isochronous stress-strain curves are included for completeness. This information has received review and verbal approval from Section III Working Group Allowable Stress Criteria, but the figures have not yet been formally balloted and may be subject to revision as balloting proceeds.

Appendix A

Case N-XXX: Use of Alloy 617 (UNS N06617) for Low Temperature Service Construction
Section III, Division 5

Appendix A

Case N-XXX: Use of Alloy 617 (UNS N06617) for Low Temperature Service Construction
Section III, Division 5

Inquiry: May 52Ni–22Cr–13Co–9Mo Alloy 617 (UNS N06617) in the solution annealed condition be used in the construction of components conforming to the requirements of Section III, Division 5, Subsection HB, Subpart A, Class A and Subsection HC, Subpart A, Class B?

Reply: It is the opinion of the Committee that 52Ni–22Cr–13Co–9Mo Alloy 617 (UNS N06617) conforming to the product specifications shown in Table A-1 may be used in the construction of Section III, Division 5, Subsection HB, Subpart A, Class A and Subsection HC, Subpart A, Class B components provided the following requirements are met:

(a) The maximum use temperature shall not exceed 800°F (425°C).

(b) The design stress intensity values and yield and tensile strength values for Class A shall be as shown in Table A-2.

(c) The maximum allowable stress values and yield and tensile strength values for Class B shall be as shown in Table A-3.

(d) The moduli of elasticity shown in Section II, Part D, Table TM-4 shall apply.

(e) The values of Poisson's ratio and density shown in Section II, Part D, Table PRD shall apply.

(f) The coefficients of thermal expansion shown in Table A-6 shall apply.

(g) The nominal coefficients of thermal conductivity and thermal diffusivity shown in Table A-8 shall apply.

(h) All other requirements of Section III, Division 5, Subsection HB, Subpart A for Class A components, and Subsection HC, Subpart A for Class B components shall be met.

(i) The design fatigue curve shown in Section III Appendices, Mandatory Appendix I, Figure I-9.5 and Table I-9.5 shall apply.

(j) External pressure chart Figure NFN-4 and values in Table NFN-4 of Section II, Part D shall apply.

(k) This Case number shall be listed on the Data Report Form for the component.

Table A-1. Product specifications.

Product Form	Spec. No.
Rod, bar and wire	SB-166
Seamless pipe and tube	SB-167
Plate, sheet and strip	SB-168
Forgings	SB-564

Table A-2. Design stress intensity values and yield and tensile strength values for Section III, Division 5, Class A.

For Metal Temperature Not Exceeding, °F	Design Stress Intensity S_m, ksi (Note a)	Yield Strength S_y, ksi	Tensile Strength S_u, ksi
100	23.3	35.0	95.0
200	23.3	31.1	95.0
300	23.3	28.9	95.0
400	23.3	27.1	95.0
500	23.3	25.9	95.0
600	22.5	25.0	93.2
650	22.1	24.6	92.3
700	21.9	24.3	91.4
750	21.7	24.1	90.6
800	21.5	23.8	89.9

a. Due to the relatively low yield strength of this material, the higher stress values were established at temperatures where the short-time tensile properties govern to permit the use of these alloys where slightly greater deformation is acceptable. The stress values in this range exceed 66⅔% but do not exceed 90% of the yield strength at temperature. Use of these stresses may result in dimensional changes due to permanent strain. These stress values are not recommended for the flanges of gasketed joints or other applications where slight amounts of distortion can cause leakage or malfunction. For Section III applications, Table Y-2 lists multiplying factors that, when applied to the yield strength values shown in Table A-2 above, will give allowable stress values that will result in lower levels of permanent strain.

Table A-3. Design stress intensity values and yield and tensile strength values for Section III, Division 5, Class A.

For Metal Temperature Not Exceeding, °C	Design Stress Intensity S_m, MPa (Note a)	Yield Strength S_y, MPa	Tensile Strength S_u, MPa
40	161	241	655
65	161	227	655
100	161	212	655
125	161	205	655
150	161	199	655
175	161	193	655
200	161	188	655
225	161	183	655
250	161	180	655
275	160	177	651
300	157	174	647
325	154	171	640
350	152	169	635
375	151	167	629
400	150	166	624
425	148	164	620

a. Due to the relatively low yield strength of this material, the higher stress values were established at temperatures where the short-time tensile properties govern to permit the use of these alloys where slightly greater deformation is acceptable. The stress values in this range exceed 66⅔% but do not exceed 90% of the yield strength at temperature. Use of these stresses may result in dimensional changes due to permanent strain. These stress values are not recommended for the flanges of gasketed joints or other applications where slight amounts of distortion can cause leakage or malfunction. For Section III applications, Table Y-2 lists multiplying factors that, when applied to the yield strength values shown in Table A-3 above, will give allowable stress values that will result in lower levels of permanent strain.

Table A-4. Maximum allowable stress values and yield and tensile strength values for Section III, Division 5, Class B.

For Metal Temperature Not Exceeding, °F	Maximum Allowable Stress S, ksi	(Note a)	Yield Strength S_y, ksi	Tensile Strength S_u, ksi
100	23.3	23.3	35.0	95.0
200	20.8	23.3	31.1	95.0
300	19.2	23.3	28.9	95.0
400	18.1	23.3	27.1	95.0
500	17.2	23.3	25.9	95.0
600	16.6	22.5	25.0	93.2
650	16.4	22.1	24.6	92.3
700	16.2	21.9	24.3	91.4
750	16.0	21.7	24.1	90.6
800	15.9	21.5	23.8	89.9

a. Due to the relatively low yield strength of this material, the higher stress values were established at temperatures where the short-time tensile properties govern to permit the use of these alloys where slightly greater deformation is acceptable. The stress values in this range exceed 66⅔% but do not exceed 90% of the yield strength at temperature. Use of these stresses may result in dimensional changes due to permanent strain. These stress values are not recommended for the flanges of gasketed joints or other applications where slight amounts of distortion can cause leakage or malfunction. For Section III applications, Table Y-2 lists multiplying factors that, when applied to the yield strength values shown in Table A-4 above, will give allowable stress values that will result in lower levels of permanent strain.

Table A-5. Maximum allowable stress values and yield and tensile strength values for Section III, Division 5, Class B.

For Metal Temperature Not Exceeding, °C	Maximum Allowable Stress S, MPa	(Note a)	Yield Strength S_y, MPa	Tensile Strength S_u, MPa
40	161	161	241	655
65	152	161	227	655
100	142	161	212	655
125	136	161	205	655
150	132	161	199	655
175	129	161	193	655
200	125	161	188	655
225	122	161	183	655
250	120	161	180	655
275	117	160	177	651
300	115	157	174	647
325	114	154	171	640
350	113	152	169	635
375	111	151	167	629
400	110	150	166	624
425	110	148	164	620

a. Due to the relatively low yield strength of this material, the higher stress values were established at temperatures where the short-time tensile properties govern to permit the use of these alloys where slightly greater deformation is acceptable. The stress values in this range exceed 66⅔% but do not exceed 90% of the yield strength at temperature. Use of these stresses may result in dimensional changes due to permanent strain. These stress values are not recommended for the flanges of gasketed joints or other applications where slight amounts of distortion can cause leakage or malfunction. For Section III applications, Table Y-2 lists multiplying factors that, when applied to the yield strength values shown in Table A-5 above, will give allowable stress values that will result in lower levels of permanent strain.

Table A-6. Thermal expansion for Alloy 617.

Temperature, °F	Coefficients for N06617		
	A	B	C
70	7.0	7.0	0
100	7.1	7.0	0.3
150	7.1	7.1	0.7
200	7.2	7.1	1.1
250	7.3	7.1	1.6
300	7.4	7.2	2.0
350	7.5	7.2	2.4
400	7.6	7.3	2.9
450	7.7	7.3	3.4
500	7.8	7.4	3.8
550	7.9	7.4	4.3
600	8.0	7.5	4.8
650	8.2	7.5	5.3
700	8.3	7.6	5.8
750	8.4	7.6	6.3
800	8.6	7.7	6.8

GENERAL NOTE: Coefficient A is the instantaneous coefficient of thermal expansion $\times$ 10^{-6} (in./in./°F). Coefficient B is the mean coefficient of thermal expansion $\times$ 10^{-6} (in./in./°F) in going from 70°F to indicated temperature. Coefficient C is the linear thermal expansion (in./100 ft) in going from 70°F to indicated temperature.

Table A-7. Thermal expansion for Alloy 617.

Temperature, °C	Coefficients for N06617		
	A	B	C
20	12.6	12.6	0
50	12.8	12.7	0.4
75	12.9	12.7	0.7
100	13.0	12.8	1.0
125	13.2	12.9	1.4
150	13.3	12.9	1.7
175	13.5	13.0	2.0
200	13.6	13.1	2.4
225	13.8	13.2	2.7
250	14.0	13.2	3.0
275	14.2	13.3	3.4
300	14.4	13.4	3.8
325	14.6	13.5	4.1
350	14.8	13.6	4.5
375	15.0	13.7	4.9
400	15.2	13.8	5.2
425	15.4	13.9	5.6

GENERAL NOTE: Coefficient A is the instantaneous coefficient of thermal expansion $\times 10^{-6}$ (mm/mm/°C). Coefficient B is the mean coefficient of thermal expansion $\times 10^{-6}$ (mm/mm/°C) in going from 20°C to indicated temperature. Coefficient C is the linear thermal expansion (mm/m) in going from 20°C to indicated temperature.

Table A-8. Nominal coefficients of thermal conductivity and thermal diffusivity for Alloy 617.

Temperature °F	Thermal Conductivity Btu/hr-ft-°F	Thermal Diffusivity ft²/hr
70	6.0	0.112
100	6.2	0.114
150	6.6	0.118
200	6.9	0.122
250	7.2	0.125
300	7.5	0.129
350	7.8	0.132
400	8.1	0.136
450	8.4	0.139
500	8.7	0.142
550	9.0	0.145
600	9.3	0.149
650	9.5	0.152
700	9.8	0.155
750	10.0	0.158
800	10.3	0.161

Table A-9. Nominal coefficients of thermal conductivity and thermal diffusivity for Alloy 617.

Temperature °C	Thermal Conductivity W/(m·°C)	Thermal Diffusivity × 10-6 m²/sec
20	10.3	2.88
50	11.0	2.99
75	11.6	3.08
100	12.1	3.17
125	12.6	3.25
150	13.1	3.33
175	13.6	3.41
200	14.0	3.49
225	14.5	3.57
250	14.9	3.64
275	15.3	3.71
300	15.8	3.79
325	16.2	3.86
350	16.6	3.93
375	17.0	4.01
400	17.4	4.08
425	17.8	4.15

Appendix B

Case N-XXX: Use of Alloy 617 (UNS N06617) for Class A Elevated Temperature Service Construction Section III, Division 5

Appendix B

Case N-XXX: Use of Alloy 617 (UNS N06617) for Class A Elevated Temperature Service Construction Section III, Division 5

Inquiry: May 52Ni-22Cr-13Co-9Mo, Alloy 617 (UNS N06617) be used at elevated temperatures in the construction of components conforming to the requirements of Section III, Division 5, Subsection HB, Subpart B "Elevated Temperature Service"?

Reply: It is the opinion of the Committee that 52Ni-22Cr-13Co-9Mo, Alloy 617 (UNS N06617) may be used in the construction of components conforming to the requirements of Section III, Division 5, Subsection HB, Subpart B "Elevated Temperature Service" providing the following requirements are met:

(a) The modifications and additions to the rules provided in Subsection HB, Subpart B defined in this Code Case shall be met.

(b) The service temperature shall be limited to 1,750°F (950°C) and below.

(c) Service time shall be limited to 100,000 hours.

(d) All other applicable requirements of Section III, Division 5, Subsection HB, Subpart B shall be met.

(e) This Case number shall be listed on the Data Report Form for the component.

This Code Case was written to be used in conjunction with Section III, Division 5, Subsection HB, Subpart B and all requirements of it shall be met except when these requirements are modified by the corresponding numbered paragraphs of this Code Case or when new requirements are added with new numbered paragraphs of this Code Case. All general notes contained in Section III, Division 5 shall apply to the corresponding figures and tables in this Code Case. References within Section III, Division 5 to figures and tables in Appendix HBB-I-14, design fatigue curves or isochronous stress-strain curves should be extended to include corresponding figures and tables for Alloy 617 within this Code Case.

Thermal expansion, thermal diffusivity, and thermal conductivity are not currently contained in Section II for Alloy 617 (UNS N06617). Values for these properties are shown in Tables TE-4 and TCD of this Code Case. Elastic modulus values for Alloy 617 are currently included in Section II Part D (Table TM-4) for temperatures up to 1,500°F (850°C), but the temperature range must be increased to 1,750°F (950°C). Elastic modulus values are shown in Table TM-4 of this Code Case.

ARTICLE HBB-2000
MATERIAL

HBB-2100

HBB-2160 DETERIORATION OF MATERIAL IN SERVICE

(d) Long-time, elevated temperature, service may result in the reduction of the subsequent yield and ultimate tensile strengths.

    (3) When the yield and ultimate tensile strengths are reduced by the elevated temperature service, it is necessary to appropriately reduce the values of S_{mt} and S_m. To reflect the effects of long-time elevated temperature service, the S_{mt} values of Tables HBB-I-14.3A through HBB-I-14.3F shall be redefined as the lower of *(-a)* through *(-g)* below, and the values of S_m shall be defined as the lower of *(-b)* through *(-g)* below:

        (-g) for Alloy 617, the product of the yield strength at temperature (Table HBB-I-14.5) and the yield strength reduction factor (Table HBB-3225-2).

ARTICLE HBB-3000
DESIGN

HBB-3200 Design by Analysis

HBB-3210 Design Criteria

HBB-3212 Basis for Determining Stress, Strain, and Deformation Quantities

(d) An additional material of this Subsection, Alloy 617, has several unique characteristics that should be recognized and reflected in multiaxial stress-strain relationships. These include the following:

    (1) There is not a clear distinction between time-independent elastic-plastic behavior and time-dependent creep behavior.

    (2) Flow stresses are strongly strain-rate sensitive at elevated temperatures.

HBB-3214 Stress Analysis

HBB-3214.2 Inelastic Analysis

[Note: Add the following paragraph as a new last paragraph to HBB-3214.2]

For Alloy 617, decoupling of plastic and creep strains in the classical constitutive framework is generally a poor representation of the true material behavior. Unified constitutive equations, which do not distinguish between rate-dependent plasticity and time-dependent creep, represent the rate dependence and softening that occur, particularly at higher temperatures.

HBB-3220 Design Rules and Limits for Load-controlled Stresses in Structures other than Bolts

HBB-3225 Level D Service Limits

The following temperature-dependent tensile strength values, S_u, for Alloy 617 are added in Table HBB-3225-1 of this Code Case.

The following tensile and yield strength reduction factors due to long-time prior elevated temperature service for Alloy 617 are added in Table HBB-3225-2 of this Code Case.

Table HBB-3225-1
Tensile Strength Values, S_u

U.S. Customary Units, ksi	
	See Section II, Part D, Subpart 1, Table U for Values up to 1,000°F
For Metal Temperature Not Exceeding, °F	UNS N06617
1,050	85.2
1,100	83.4
1,150	81.2
1,200	78.4
1,250	75.2
1,300	71.3
1,350	66.9
1,400	62.0
1,450	56.6
1,500	50.8
1,550	44.7
1,600	38.5
1,650	32.4
1,700	26.4
1,750	21.0

SI Units, MPa	
	See Section II, Part D, Subpart 1, Table U for Values up to 538°C
For Metal Temperature Not Exceeding, °C	UNS N06617
550	593
575	584
600	572
625	557
650	540
675	520
700	496
725	470
750	440
775	408
800	373
825	336
850	298
875	260
900	221
925	185
950	151

GENERAL NOTES:
(a) The tabulated values of tensile strength and yield strength are those which the Committee believes are suitable for use in design calculations required by this Subsection. At temperatures above room temperature, the values of tensile strength tend toward an average or expected value which may be as much as 10% above the tensile strength trend curve adjusted to the minimum specified room temperature tensile strength. At temperatures above room temperature, the yield strength values correspond to the yield strength trend curve adjusted to the minimum specified room temperature yield strength. Neither the tensile strength nor the yield strength values correspond exactly to either *average* or *minimum* as these terms are applied to a statistical treatment of a homogeneous set of data.
(b) Neither the ASME Material Specifications nor the rules of this Subsection required elevated temperature testing for tensile or yield strengths of production material for use in Code components. It is not intended that results of such tests, if performed, be compared with these tabulated tensile and yield strength values for ASME Code acceptance/rejection purposes for materials. If some elevated temperature test results on production material appear lower than the tabulated values by a large amount (more than the typical variability of material and suggesting the possibility of some error), further investigation by retest or other means should be considered.

Table HBB-3225-2
Tensile and Yield Strength Reduction Factor Due to Long-Time Prior Elevated Temperature Service

Material	Temp. °F (°C)	YS Reduction Factor	TS Reduction Factor
617	≥ 800 (425)	1.0	1.0

GENERAL NOTE: No reduction factor required for service below the indicated temperature.

ARTICLE HBB-4000
FABRICATION AND INSTALLATION
HBB-4200

HBB-4210

HBB-4212   Effects of Forming and Bending Processes

(a) Post fabrication heat treatment [in accordance with *(b)* below] of materials that have been formed during fabrication, shall be required for fabrication induced strains greater than 5%.

(b) When required, the post fabrication heat treatment shall be in accordance with the following:

   (3) For Alloy 617, the post fabrication heat treatment shall consist of the heat treatment specified in the base material specification.

HBB-4800 Relaxation Cracking

Components that will see service between 932°F (500°C) and 1436°F (780°C) shall be given a heat treatment of three hours at 1796°F (980°C) to eliminate relaxation cracking after post fabrication heat treatment, if needed according to HBB-4212. This heat treatment is required for material in either a welded or solution annealed condition.

MANDATORY APPENDIX HBB-I-14
TABLES AND FIGURES

The following Tables and Figures have Alloy 617 data added as indicated.

Table HBB-I-14.1(a)
Permissible Base Materials for Structures Other Than Bolting

Base Material	Spec. No.	Product Form	Types, Grades or Classes
Alloy 617	SB-166	Bar, rod	UNS N06617
[Note (7)]	SB-167	Smls. pipe & tube	UNS N06617
	SB-168	Plate, sheet, strip	UNS N06617
	SB-564	Forgings	UNS N06617

NOTE:
(7) The minimum material thickness shall be 0.125 inches.

Table HBB-I-14.1(b)
Permissible Weld Materials

Base Material	Spec. No. [Note (1)]	Class
Alloy 617	SFA-5.14	ERNiCrCoMo-1

NOTE:
(1) Only Gas Tungsten Arc Welding (GTAW) is permitted.

Table HBB-I-14.2

S_o − **Maximum Allowable Stress Intensity, ksi (MPa), for Design Condition Calculations**

U.S. Customary Units	
For Metal Temperature Not Exceeding, °F	**N06617**
700	—
750	—
800	21.5
850	21.3
900	21.2
950	21.0
1,000	20.9
1,050	20.9
1,100	20.8
1,150	20.7
1,200	18.1
1,250	14.5
1,300	11.2
1,350	8.7
1,400	6.6
1,450	5.1
1,500	3.9
1,550	3.0
1,600	2.3
1,650	1.8
1,700	1.4
1,750	1.1

SI Units		
For Metal Temperature Not Exceeding, °C	**N06617**	
375	—	
400	—	
425	148	
450	147	
475	146	
500	145	
525	144	
550	144	
575	144	
600	143	
625	142	
650	124	
675	101	
700	81	
725	64	
750	50	
775	40	
800	31	
825	25	
850	19	
875	15	
900	12	
925	10	[Note (5)]
950	7.9	[Note (5)]

NOTE:
(5) Interpolated from values given in Note G29 of
  Section II, Part D, Subpart 1, Table 1B.

Figure HBB-I-14.3F
S_{mt} − Alloy 617
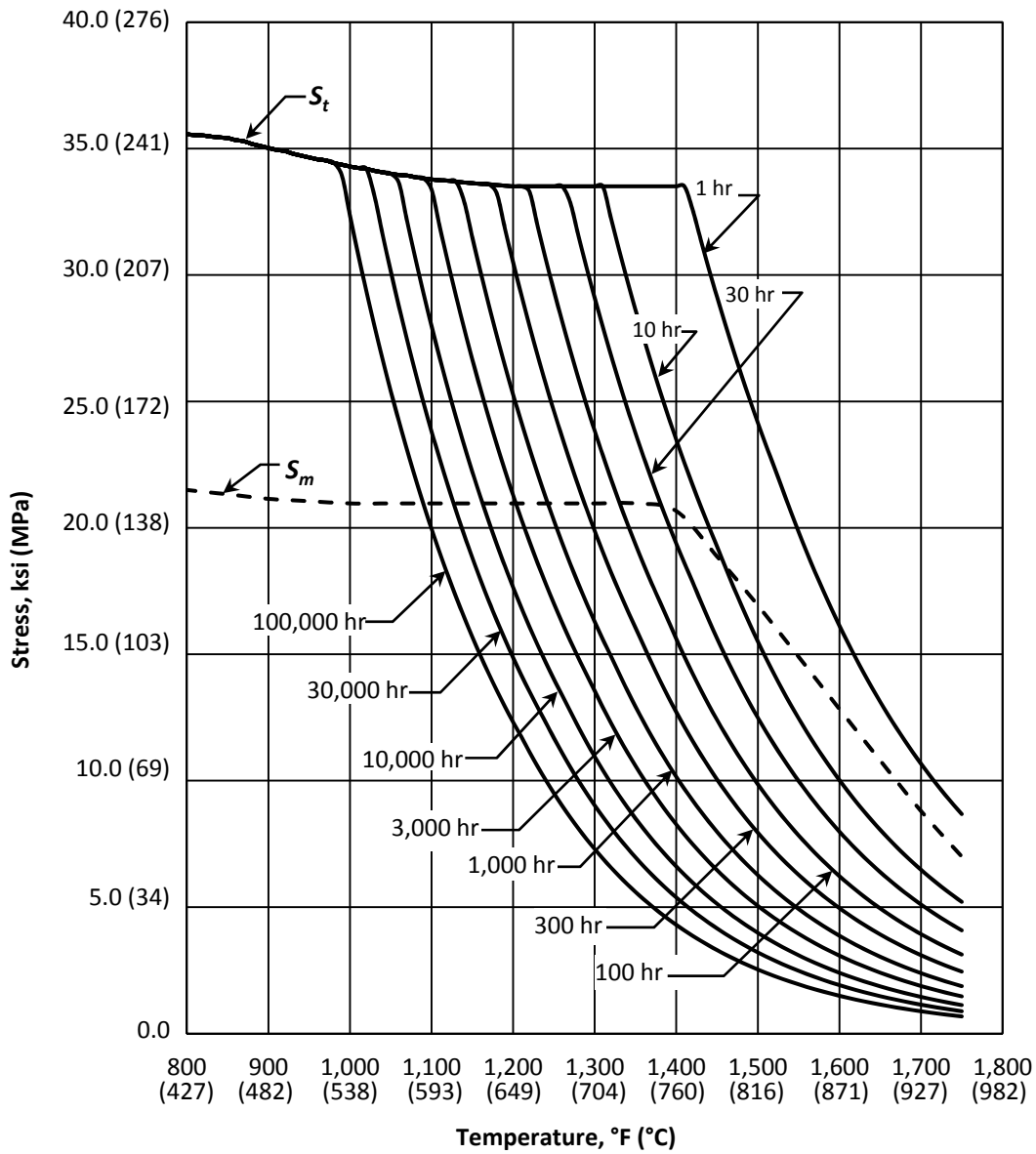
Table HBB-I-14.3F

S_{mt} – Allowable Stress Intensity Values, ksi (MPa), Alloy 617

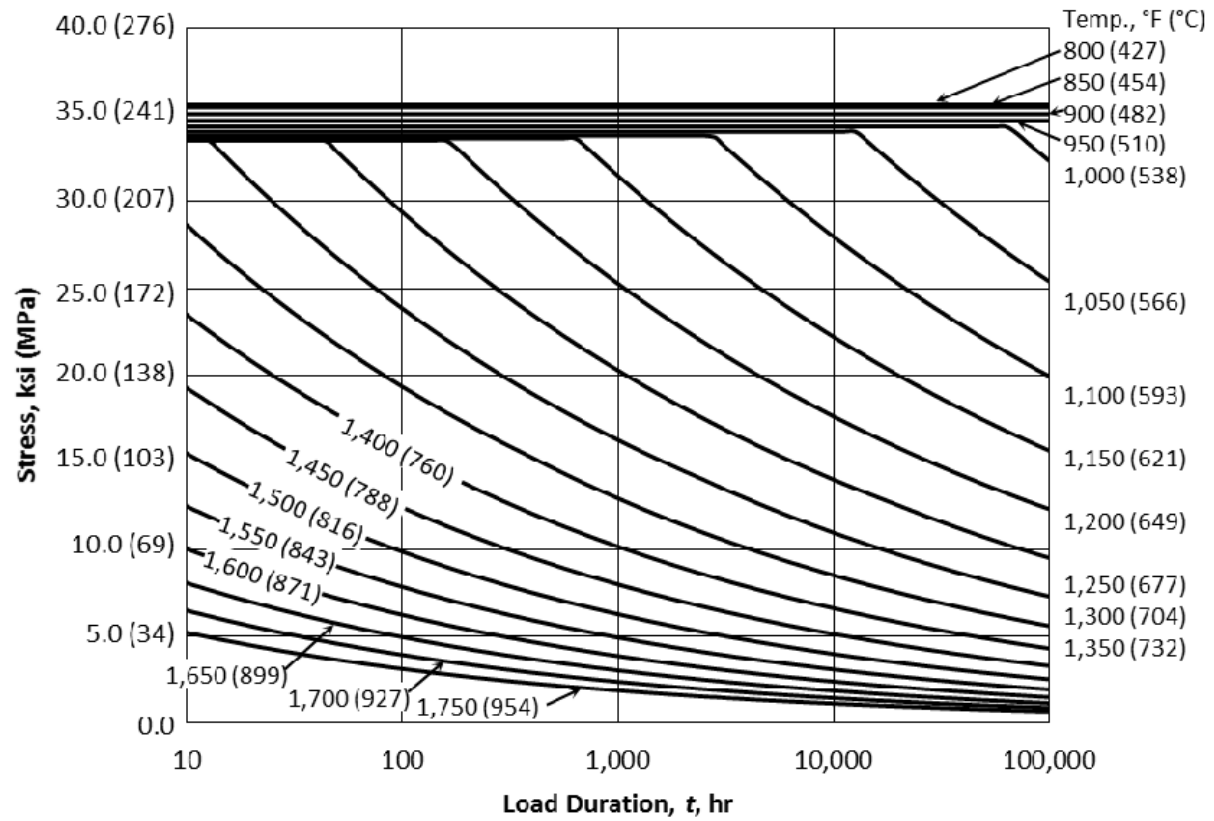| U.S. Customary Units									
Temp., °F	1 hr	10 hr	30 hr	100 hr	300 hr	1,000 hr	3,000 hr	10,000 hr	30,000 hr	100,000 hr
800	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5
850	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3
900	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2
950	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1
1,000	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
1,050	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
1,100	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	20.0
1,150	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	18.8	15.7
1,200	21.0	21.0	21.0	21.0	21.0	21.0	21.0	17.6	14.9	12.3
1,250	21.0	21.0	21.0	21.0	21.0	20.3	17.0	14.0	11.7	9.5
1,300	21.0	21.0	21.0	21.0	19.9	16.3	13.6	11.0	9.0	7.3
1,350	21.0	21.0	21.0	19.3	16.0	12.9	10.6	8.5	7.0	5.6
1,400	21.0	20.7	19.4	15.6	12.7	10.2	8.3	6.6	5.4	4.3
1,450	19.3	18.9	15.6	12.4	10.0	8.0	6.5	5.1	4.2	3.3
1,500	16.9	15.5	12.5	9.9	7.9	6.3	5.0	4.0	3.2	2.5
1,550	14.9	12.5	10.0	7.8	6.3	4.9	3.9	3.1	2.5	1.9
1,600	12.8	10.0	8.0	6.2	5.0	3.9	3.1	2.4	1.9	1.5
1,650	10.8	8.1	6.4	4.9	3.9	3.0	2.4	1.9	1.5	1.1
1,700	8.8	6.5	5.1	3.9	3.1	2.4	1.9	1.4	1.1	0.9
1,750	7.0	5.2	4.1	3.1	2.4	1.9	1.5	1.1	0.9	0.7
SI Units									
Temp., °C	1 h	10 h	30 h	100 h	300 h	1,000 h	3,000 h	10,000 h	30,000 h	100,000 h
425	148	148	148	148	148	148	148	148	148	148
450	148	148	148	148	148	148	148	148	148	148
475	146	146	146	146	146	146	146	146	146	146
500	146	146	146	146	146	146	146	146	146	146
525	145	145	145	145	145	145	145	145	145	145
550	145	145	145	145	145	145	145	145	145	145
575	145	145	145	145	145	145	145	145	145	145
600	145	145	145	145	145	145	145	145	145	130
625	145	145	145	145	145	145	145	145	125	105
650	145	145	145	145	145	145	145	121	102	84
675	145	145	145	145	145	142	119	98	82	67
700	145	145	145	145	142	116	97	79	65	52
725	145	145	145	141	117	95	78	63	51	41
750	145	145	144	117	95	76	62	50	41	33
775	145	136	119	95	77	61	50	40	32	26
800	124	121	98	77	62	49	40	32	26	20
825	112	99	80	63	51	40	32	25	20	16
850	99	82	65	51	41	32	26	20	16	13
875	87	67	53	42	33	26	21	16	13	10
900	74	55	44	34	27	21	16	13	10	8
925	62	45	36	27	22	17	13	10	8	6
950	50	37	29	22	18	13	11	8	6	5

GENERAL NOTE: As described in HBB-2160(d), it may be necessary to adjust the values of S_{mt} to account for the effects of long-time service at elevated temperature.

Figure HBB-I-14.4F
S_t — **Alloy 617**

Table HBB-I-14.4F
S_t – Allowable Stress Intensity Values, ksi (MPa), Alloy 617

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
800	35.6	35.6	35.6	35.6	35.6	35.6	35.6	35.6	35.6	35.6
850	35.4	35.4	35.4	35.4	35.4	35.4	35.4	35.4	35.4	35.4
900	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
950	34.6	34.6	34.6	34.6	34.6	34.6	34.6	34.6	34.6	34.6
1,000	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	32.3
1,050	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	30.1	25.4
1,100	33.8	33.8	33.8	33.8	33.8	33.8	33.4	28.0	23.8	20.0
1,150	33.6	33.6	33.6	33.6	33.6	31.5	26.7	22.2	18.8	15.7
1,200	33.5	33.5	33.5	33.5	30.5	25.3	21.3	17.6	14.9	12.3
1,250	33.5	33.5	33.5	29.4	24.6	20.3	17.0	14.0	11.7	9.5
1,300	33.5	33.5	29.1	23.8	19.9	16.3	13.6	11.0	9.0	7.3
1,350	33.5	28.6	23.7	19.3	16.0	12.9	10.6	8.5	7.0	5.6
1,400	33.5	23.5	19.4	15.6	12.7	10.2	8.3	6.6	5.4	4.3
1,450	29.1	19.3	15.6	12.4	10.0	8.0	6.5	5.1	4.2	3.3
1,500	24.2	15.5	12.5	9.9	7.9	6.3	5.0	4.0	3.2	2.5
1,550	19.8	12.5	10.0	7.8	6.3	4.9	3.9	3.1	2.5	1.9
1,600	16.1	10.0	8.0	6.2	5.0	3.9	3.1	2.4	1.9	1.5
1,650	13.1	8.1	6.4	4.9	3.9	3.0	2.4	1.9	1.5	1.1
1,700	10.7	6.5	5.1	3.9	3.1	2.4	1.9	1.4	1.1	0.9
1,750	8.7	5.2	4.1	3.1	2.4	1.9	1.5	1.1	0.9	0.7

SI Units									
Temp., °C	1 h	10 h	30 h	100 h	300 h	1,000 h	3,000 h	10,000 h	30,000 h	100,000 h
425	245	245	245	245	245	245	245	245	245	245
450	245	245	245	245	245	245	245	245	245	245
475	242	242	242	242	242	242	242	242	242	242
500	240	240	240	240	240	240	240	240	240	240
525	238	238	238	238	238	238	238	238	238	238
550	235	235	235	235	235	235	235	235	235	200
575	234	234	234	234	234	234	234	225	192	161
600	233	233	233	233	233	233	218	182	155	130
625	232	232	232	232	232	210	178	148	125	105
650	231	231	231	231	208	173	145	121	102	84
675	231	231	231	205	172	142	119	98	82	67
700	231	231	207	170	142	116	97	79	65	52
725	231	208	173	141	117	95	78	63	51	41
750	231	174	144	117	95	76	62	50	41	33
775	219	146	119	95	77	61	50	40	32	26
800	185	121	98	77	62	49	40	32	26	20
825	156	99	80	63	51	40	32	25	20	16
850	130	82	65	51	41	32	26	20	16	13
875	108	67	53	42	33	26	21	16	13	10
900	90	55	44	34	27	21	16	13	10	8
925	75	45	36	27	22	17	13	10	8	6
950	62	37	29	22	18	13	11	8	6	5

Table HBB-I-14.5
Yield Strength Values, S_y, Versus Temperature

U.S. Customary Units	
	Stresses, ksi
Temp., °F	**UNS N06617**
RT : 1,000	See Section II, Part D, Subpart 1, Table Y-1 for Values up to 1,000°F
1,050	23.3
1,100	23.3
1,150	23.3
1,200	23.3
1,250	23.3
1,300	23.3
1,350	23.3
1,400	23.3
1,450	23.3
1,500	22.6
1,550	21.6
1,600	20.4
1,650	19.0
1,700	17.4
1,750	15.7

SI Units	
	Stresses, MPa
Temp., °C	**UNS N06617**
RT : 525	See Section II, Part D, Subpart 1, Table Y-1 for Values up to 538°C
550	161
575	161
600	161
625	161
650	161
675	161
700	161
725	161
750	161
775	161
800	159
825	153
850	147
875	139
900	131
925	121
950	110

Figure HBB-I-14.6G
Minimum Stress-to-Rupture - Alloy 617
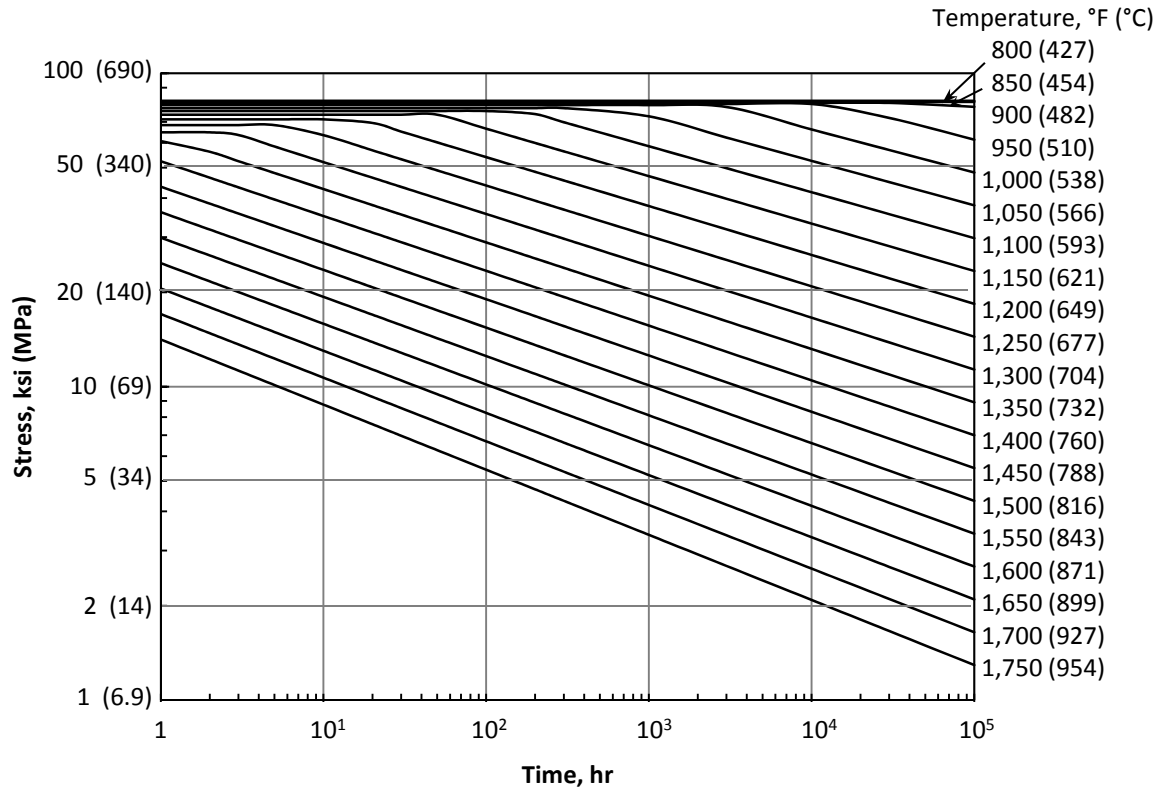
Table HBB-I-14.6G
Expected Minimum Stress-to-Rupture Values, ksi (MPa), Alloy 617

U.S. Customary Units										
Temp., °F	1 hr	3 hr	10 hr	30 hr	100 hr	300 hr	1,000 hr	3,000 hr	10,000 hr	30,000 hr	100,000 hr
800	81.7	81.7	81.7	81.7	81.7	81.7	81.7	81.7	81.7	81.7	81.7
850	81.1	81.1	81.1	81.1	81.1	81.1	81.1	81.1	81.1	81.1	81.1
900	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	78.2
950	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8	72.1	61.4
1,000	79.2	79.2	79.2	79.2	79.2	79.2	79.2	78.1	66.2	56.9	48.3
1,050	77.5	77.5	77.5	77.5	77.5	77.5	72.9	62.4	52.6	45.0	37.9
1,100	75.8	75.8	75.8	75.8	75.8	69.8	58.5	49.8	41.8	35.5	29.8
1,150	73.8	73.8	73.8	73.8	66.6	56.4	47.0	39.8	33.2	28.1	23.4
1,200	71.3	71.3	71.3	65.2	54.0	45.5	37.7	31.8	26.3	22.2	18.4
1,250	68.4	68.4	63.5	53.2	43.8	36.7	30.3	25.4	20.9	17.5	14.4
1,300	64.8	63.6	52.1	43.4	35.6	29.7	24.3	20.3	16.6	13.8	11.3
1,350	60.8	52.4	42.7	35.4	28.9	24.0	19.5	16.2	13.2	10.9	8.9
1,400	52.4	43.3	35.1	28.9	23.4	19.3	15.7	12.9	10.5	8.6	7.0
1,450	43.5	35.7	28.8	23.6	19.0	15.6	12.6	10.3	8.3	6.8	5.5
1,500	36.1	29.4	23.6	19.3	15.4	12.6	10.1	8.2	6.6	5.4	4.3
1,550	29.9	24.3	19.4	15.7	12.5	10.2	8.1	6.6	5.2	4.3	3.4
1,600	24.8	20.0	15.9	12.8	10.2	8.2	6.5	5.3	4.2	3.4	2.7
1,650	20.6	16.5	13.0	10.5	8.2	6.6	5.2	4.2	3.3	2.7	2.1
1,700	17.1	13.6	10.7	8.5	6.7	5.4	4.2	3.4	2.6	2.1	1.6
1,750	14.1	11.3	8.8	7.0	5.4	4.3	3.4	2.7	2.1	1.7	1.3

SI Units										
Temp., °C	1 h	3 h	10 h	30 h	100 h	300 h	1,000 h	3,000 h	10,000 h	30,000 h	100,000 h
425	564	564	564	564	564	564	564	564	564	564	564
450	560	560	560	560	560	560	560	560	560	560	560
475	555	555	555	555	555	555	555	555	555	555	555
500	552	552	552	552	552	552	552	552	552	541	462
525	548	548	548	548	548	548	548	548	508	438	372
550	539	539	539	539	539	539	539	488	412	354	299
575	531	531	531	531	531	531	466	398	335	286	241
600	520	520	520	520	520	457	383	325	272	232	194
625	506	506	506	506	446	377	314	266	221	187	156
650	491	491	491	446	369	311	258	217	180	152	126
675	473	473	443	371	306	257	212	177	146	123	101
700	451	451	371	309	254	212	174	145	119	99	81
725	427	380	310	258	210	175	142	118	97	80	65
750	387	320	260	215	174	144	117	97	78	65	53
775	327	269	217	179	144	119	96	79	64	52	42
800	276	226	182	149	120	98	79	64	52	42	34
825	233	190	152	124	99	81	65	53	42	34	27
850	197	160	127	103	82	67	53	43	34	28	22
875	167	135	106	86	68	55	44	35	28	22	18
900	141	113	89	72	56	45	36	29	23	18	14
925	119	95	75	60	47	37	29	23	18	15	12
950	100	80	62	50	39	31	24	19	15	12	9

Table HBB-I-14.10F-1
Stress Rupture Factors for Alloy 617 Welded with ERNiCrCoMo-1

U.S. Customary Units		SI Units	
Temp., °F	Ratio	Temp., °C	Ratio
800	1.0	425	1.0
850	1.0	450	1.0
900	1.0	475	1.0
950	1.0	500	1.0
1,000	1.0	525	1.0
1,050	1.0	550	1.0
1,100	1.0	575	1.0
1,150	1.0	600	1.0
1,200	1.0	625	1.0
1,250	1.0	650	1.0
1,300	1.0	675	1.0
1,350	1.0	700	1.0
1,400	1.0	725	1.0
1,450	1.0	750	1.0
1,500	1.0	775	1.0
1,550	1.0	800	1.0
1,600	0.85	825	1.0
1,650	0.85	850	0.85
1,700	0.85	875	0.85
1,750	0.85	900	0.85
		925	0.85
		950	0.85

Table HBB-I-14.11
Permissible Materials for Bolting

Not applicable for Alloy 617.

NONMANDATORY APPENDIX HBB-T
RULES FOR STRAIN, DEFORMATION, AND FATIGUE LIMITS AT ELEVATED TEMPERATURES

HBB-T-1300   Deformation and Strain Limits for Structural Integrity

HBB-T-1320 Satisfaction of Strain Limits Using Elastic Analysis

HBB-T-1321   General Requirements

(e) Paragraph HBB-T-1321, HBB-T-1322 and HBB-T-1323 are not applicable to Alloy 617 above 1200°F (650°C).

HBB-T-1323   Test No. A-2

The following data are added for Alloy 617 in Table HBB-T-1323 of this Code Case as indicated below.

Table HBB-T-1323
Temperatures at Which $S_m = S_t$ at 10^5 hr

Material	Temp., °F (°C)
Alloy 617	1090 (588)

HBB-T-1324   Test No. A-3

The following data are added for Alloy 617 in Table HBB-T-1324 of this Code Case as indicated below.

Table HBB-T-1324
Values of the *r* and *s* Parameters

Material	*r*	*s*
Alloy 617	1.0	1.5

The reference for determination of maximum allowable time, t_{id}, shall be revised to Figure HBB-I-14.6G of this Code Case for expected minimum stress-to-rupture.

HBB-T-1330 Satisfaction of Strain Limits Using Simplified Inelastic Analysis

HBB-T-1331   General Requirements

(i) Paragraph HBB-T-1331 is not applicable to Alloy 617 above 1200°F (650°C).

HBB-T-1332   Tests No. B-1 and B-2

(e) Paragraph HBB-T-1332 is not applicable to Alloy 617 above 1200°F (650°C).

HBB-T-1333   Test No. B-3

(d) Paragraph HBB-T-1333 is not applicable to Alloy 617 above 1200°F (650°C).

HBB-T-1340 Satisfaction of Strain Limits Using Elastic-Perfectly Plastic Analysis

HBB-T-1341   General Requirements

As an alternative to HBB-T-1320 and HBB-T-1330, the strain limits of HBB-T-1310 and HBB-T-1713 are considered satisfied if the requirements of this Subsubarticle are satisfied.

The design methodology employed for evaluation of strain limits is based on ratcheting analyses using a small strain theory elastic-perfectly plastic material model where the yield stress is adjusted based on a pseudo-yield stress selected to bound accumulated inelastic strain. Guidance on ratcheting analysis is provided in HBB-T-1346. The term "pseudo-yield stress" refers to a temperature-dependent isochronous stress based on the total time duration of elevated temperature service and a target inelastic strain, not to exceed the yield strength of the material at temperature and is explicitly defined in HBB-T-1344.2.

(a) This design methodology is not applicable to skeletal structures, e.g., a constant diameter bar with uniform axial load throughout, nor to structures where geometrical nonlinearities exist, e.g., canopy or omega seals.

HBB-T-1342   Load Definition

Define all applicable loads and load cases per Section III, Division 5, HBB-3113.2, Service Loadings.

HBB-T-1342.1   *Composite Cycle Definition.* For the purpose of performing an elastic-perfectly plastic ratcheting analysis, an overall cycle must be defined that includes all relevant features from the individual Level A, B and C Service Loadings identified in the Design Specification. Relevant features include, as a minimum, the time-dependent sequence of thermal, mechanical and pressure loading, including starting and ending conditions. Such an overall cycle is defined herein as a composite cycle subject to the following requirements.

(a) An individual cycle, as defined in the Design Specification, cannot be further subdivided into individual cycles to satisfy these requirements.

(b) Except as described in paragraph *(c)* below, a single cycle from each Level A, B and C Service Loading cycle type shall be included in the composite cycle for evaluation of strain limits.

(c) Level C Service Loadings may be combined with the applicable Level A and B Service Loadings to define an additional composite cycle(s) to be evaluated separately from the composite cycle defined in paragraph HBB-T-1342.1. Multiple composite cycles that include Level C Service Loadings may be defined for separate evaluation. The total number of Level C Service Loading cycles shall not exceed 25.

HBB-T-1343   Numerical Model

Develop a numerical model of the component, including all relevant geometry characteristics. The model used for the analysis shall be selected to accurately represent the component geometry, boundary conditions, and applied loads. The model must also be accurate for small details, such as small holes, fillets, corner radii, and other stress risers. The local temperature history shall be determined from a thermal transient analysis based on the thermal boundary conditions determined from the loading conditions defined in HBB-T-1342.

HBB-T-1344   Requirements for Satisfaction of Strain Limits

Perform a ratcheting analysis for each of the composite cyclic histories defined in HBB-T-1342.1. Each of these cyclic histories must be shown to be free from ratcheting based on the pseudo-yield stress, S_{xT}, as defined in HBB-T-1344.2. In the following steps, inelastic strain for a particular stress, time and temperature is obtained by subtracting the elastic strain from the total strain as given by the isochronous stress-strain curve at the same stress, time and temperature. Additional requirements for weldments are shown in HBB-T-1345.

HBB-T-1344.1   Step 1. Define t_{design} as the total time duration of elevated temperature service for all Level A, B, and C Service Loadings when the temperature is above 800°F (425°C).

HBB-T-1344.2 **Step 2.** Select a target inelastic strain, x, where $0 < x < \varepsilon_{avg}$ and ε_{avg} is equal to 0.01 for base metal or 0.005 for weldments. Define a pseudo-yield stress, S_{xT}, at each location,[a] using the temperature determined from the transient thermal analysis. This pseudo-yield stress is equal to the lesser of the quantities defined below in (a) and (b).

(a) The yield strength, S_y, given in Table HBB-I-14.5 of this Code Case;

(b) The stress to cause x inelastic strain in time t_{design}, as determined from the isochronous stress-strain curves in HBB-T-1800 of this Code Case.

HBB-T-1344.3 **Step 3.** Perform a cyclic elastic-perfectly plastic analysis for each composite cycle defined in HBB-T-1342.1 above with temperature-dependent pseudo-yield stress, S_{xT}. If ratcheting does not occur, obtain the plastic strain distribution throughout the component. The plastic strain, ε_p, is evaluated according to

$$\varepsilon_p = \sqrt{\frac{2}{3}\left[\left(\varepsilon_x^p\right)^2 + \left(\varepsilon_y^p\right)^2 + \left(\varepsilon_z^p\right)^2 + 2\left(\varepsilon_{xy}^p\right)^2 + 2\left(\varepsilon_{yz}^p\right)^2 + 2\left(\varepsilon_{zx}^p\right)^2\right]}$$

(1)

where the plastic strain components, ε_x^p, ε_y^p, ε_z^p, ε_{xy}^p, ε_{yz}^p and ε_{zx}^p, are those strains accumulated at the end of the composite cycle.

HBB-T-1344.4 **Step 4.** Assess acceptability in accordance with (a) and (b) below by using the plastic strains, ε_p, from Step 3. If the requirements of both (a) and (b) are satisfied, then the strain limits of HBB-T-1310 for base metal and HBB-T-1713 for weldments are also considered satisfied. This condition is illustrated in Figure HBB-T-1344, sketch (a).

(a) The requirement $x + \varepsilon_p \leq \varepsilon_{avg}$ must be satisfied at least at one point for all through-thickness locations. As defined in Step 2, ε_{avg} is equal to 0.01 for base metal or 0.005 for weldments. Failure of this requirement is illustrated in Figure HBB-T-1344, sketch (b).

(b) The requirement $x + \varepsilon_p \leq \varepsilon_{local}$ must be satisfied at all points. The local strain limit, *ε_{local}*, is equal to 0.05 for base metal and 0.025 for weldments. Failure of this requirement is illustrated in Figure HBB-T-1344, sketch (c).

(c) In order to proceed if either of the requirements of *(a)* or *(b)* above are not satisfied, return to Step 2 and select a smaller value of the target inelastic strain, *x*. If it is not possible to find a value of *x* that does not ratchet and also satisfies the requirements of Step 4, then the loading conditions of HBB-T-1342 applied to the component configuration defined in HBB-T-1343 do not meet the requirements of HBB-T-1340.

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a. "Each location" refers to nodal points or integration points in the finite element mesh where the calculations are performed.

Figure HBB-T-1344 Strain Limits Pass/Fail Criteria Illustrated

$x + \varepsilon_p \leq \varepsilon_{avg}$ $\qquad$ $\varepsilon_{avg} < x + \varepsilon_p \leq \varepsilon_{local}$ $\qquad$ $x + \varepsilon_p \geq \varepsilon_{local}$
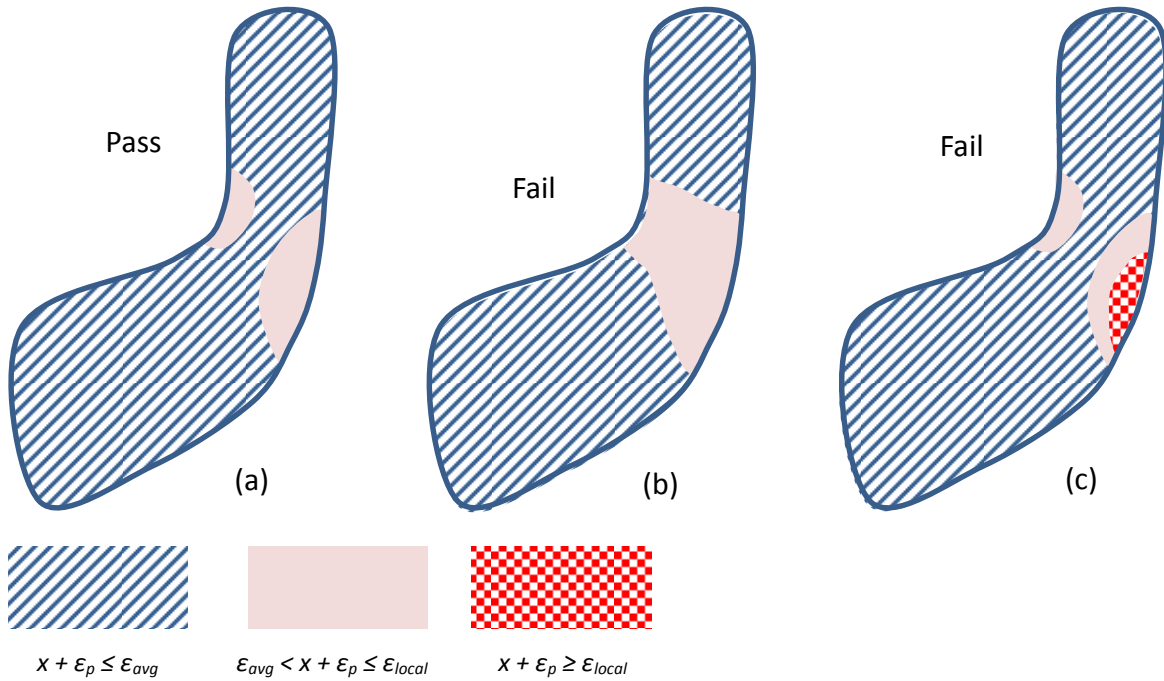
HBB-T-1345   Weldments

Implementation of the strain limits for weldments defined above in HBB-T-1344 requires additional consideration.

HBB-T-1345.1   Weld Region Model Boundaries. Figure HBB-T-1345 shows a full-penetration butt weld as an example of the definition of a weld region. As shown, w_1 and w_2 are needed to define the weld region for use in this Code Case and are approximations consistent with the specified weld configuration and parameters. The specified weld region must include applicable stress concentrations in accordance with the requirements for analysis of geometry, HBB-T-1714, unless ground flush.

The weld shown in Figure HBB-T-1345 represents a full-penetration butt weld in a shell. Other weld configurations may be needed for construction of an elevated temperature service component in accordance with Section III, Division 5, Subsection HB, Subpart B. Section III, Division 5, HBB-4200 refers to various Section III, Division 1, Article NB-4000 paragraphs for weld configurations and requirements. These NB-4000 weld configurations are represented by the shaded region.

Figure HBB-T-1345 Weld Region Model Boundaries
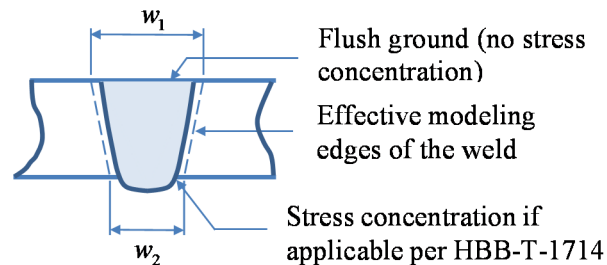
HBB-T-1345.2   *Geometry.* The requirements for analysis of geometry of Section III, Division 5, HBB-T-1714 are applicable for satisfaction of the requirements of this Code Case.

HBB-T-1345.3   *Physical Properties.* The thermal/physical properties of weldments shall be assumed to be the same as the corresponding base metal for the base metal-weld combinations listed in Table HBB-I-14.10F-1.

HBB-T-1345.4   *Dissimilar Metal Welds.* Requirements for dissimilar metal welds are in the course of preparation.

HBB-T-1346   Ratcheting Analysis

The steps to perform a ratcheting analysis to demonstrate compliance with strain limits are as follows:

(a) Define Composite Cycle Load Time-Histories and Analysis Step(s).

    (1) It may consist of histories of mechanical loads, pressure loads, displacements, temperatures and thermal boundary conditions.

    (2) Time-independent parts of the cycle may be truncated because the elastic-perfectly plastic analysis is not time-dependent.

    (3) The cycle should not have discontinuities. Discontinuities arising from the selection of the specified cycles to form a composite cycle should be eliminated by a simple and reasonable transition from one operating state to the next.

    (4) Subject to the requirements in *(b)* below, the composite cycle time does not affect the result of the ratcheting analysis.

    (5) Temperatures, thermal boundary conditions, boundary displacements and mechanical loads over a cycle should be cyclic; that is, begin and end at the same value.

    (6) A single analysis step may represent one cycle. Dividing a single cycle into more than one step to facilitate definition of the load cycle, and to ensure that maximum loads are analyzed, is often helpful.

(b) Define Analysis Types.

    (1) A sequentially coupled thermal-mechanical analysis of the composite cycle may be performed. First, a thermal analysis is performed to generate temperature histories. Next, the mechanical analyses are performed using these temperature histories as inputs. Care must be taken that times in the mechanical analysis step and in the previous thermal analysis are the same or do not conflict, depending on the requirements of the analysis software.

    (2) Alternatively, a coupled thermal-mechanical analysis may be performed. The composite temperature history to be used in the mechanical analysis should be cyclic; that is, the beginning and end temperature distributions should be the same.

(c) Define Material Properties.

    (1) For the thermal analyses, density and temperature-dependent specific heat and conductivity will generally be required.

    (2) For the mechanical analyses, the temperature-dependent properties required are elastic modulus, Poisson's ratio, and the mean expansion coefficient. Density may also be required.

    (3) In addition, the mechanical analyses temperature-dependent yield stress will need to be adjusted based on the selected pseudo-yield stress, S_{xT}, defined in HBB-T-1344.2.

(d) Perform Analyses.

(1) Perform an elastic-perfectly plastic cyclic mechanical and thermal stress analysis using the temperature-dependent pseudo-yield stress defined above. Enough cycles are required to demonstrate ratcheting or the absence of ratcheting.

(2) Care must be taken to ensure that the analysis deals with all the changes within a cycle. Elastic-plastic analysis routines increase increment size where possible, and may miss a detail in the loading. A conservative limit to maximum increment size can address this problem, as can division of the cycle into more than one step, as discussed in *(a)(6)* above.

(e) Detect Ratcheting.

(1) Ratcheting is defined as repeated non-cyclic deflections; that is, between the beginning and end of a cycle, a repeated finite displacement change occurs somewhere in the structure.

(2) Detecting ratcheting is most easily done by plotting nodal deflections over time. Cyclic (repeated) behavior indicates non-ratcheting. History plots of equivalent plastic strains will also identify ratcheting.

HBB-T-1400   Creep‑Fatigue Evaluation

HBB-T-1410 General Requirements

HBB-T-1411   Damage Equation

(d) The constant *C* for Alloy 617 that is used in determining the equivalent stress is under development.

The following Alloy 617 data are added in Table HBB-T-1411-1 of this Code Case.

Table HBB-T-1411-1

	K'	
Material	**Elastic Analysis**	**Inelastic Analysis**
Alloy 617	0.9	0.67

HBB-T-1420 Limits Using Inelastic Analysis

(b) The fatigue damage term of Equation HBB-T-1411(10) is evaluated by entering a design fatigue curve at the strain range ϵ_t. The strain range ϵ_t is defined as $\epsilon_t = \Delta\epsilon_{max}$; where $\Delta\epsilon_{max}$ is the value calculated in either HBB-T-1413 or HBB-T-1414. The appropriate design fatigue curve for Alloy 617 is Figure HBB-T-1420-1F and corresponds to the maximum metal temperature experienced during the cycle.

(c) The total damage, *D*, shall not exceed the creep-fatigue damage envelope in Figure HBB-T-1420-2 of this Code Case.

Figure HBB-T-1420-1F
Design Fatigue Strain Range, ϵ_t, for Alloy 617

Number of Cycles,	U.S. Customary Units				
	Strain Range, ε_t, in./in. at Temperature				
N_d	800°F	800°F	1,300°F	1,600°F	1,750°F
[Note (1)]	Zero Mean Stress	Maximum Mean Stress			
1.E+01	0.05007	0.05007	0.02354	0.02015	0.01868
2.E+01	0.03621	0.03621	0.01606	0.01303	0.01166
4.E+01	0.02681	0.02681	0.01156	0.00885	0.00760
1.E+02	0.01846	0.01846	0.00815	0.00582	0.00469
2.E+02	0.01421	0.01421	0.00661	0.00455	0.00350
4.E+02	0.01123	0.01123	0.00558	0.00375	0.00279
1.E+03	0.00842	0.00842	0.00466	0.00310	0.00223
2.E+03	0.00686	0.00686	0.00407	0.00278	0.00198
4.E+03	0.00570	0.00570	0.00331	0.00227	0.00175
1.E+04	0.00453	0.00453	0.00266	0.00178	0.00131
2.E+04	0.00396	0.00396	0.00233	0.00155	0.00112
4.E+04	0.00340	0.00340	0.00207	0.00139	0.00099
1.E+05	0.00289	0.00289	0.00181	0.00124	0.00088
2.E+05	0.00254	0.00254	0.00165	0.00115	0.00082
4.E+05	0.00227	0.00199	0.00151	0.00107	0.00077
1.E+06	0.00199	0.00146	0.00135	0.00098	0.00072

Number of Cycles,	SI Units				
	Strain Range, ε_t, m/m at Temperature				
N_d	425°C	425°C	704°C	871°C	950°C
[Note (1)]	Zero Mean Stress	Maximum Mean Stress			
1.E+01	0.05007	0.05007	0.02354	0.02015	0.01868
2.E+01	0.03621	0.03621	0.01606	0.01303	0.01166
4.E+01	0.02681	0.02681	0.01156	0.00885	0.00760
1.E+02	0.01846	0.01846	0.00815	0.00582	0.00469
2.E+02	0.01421	0.01421	0.00661	0.00455	0.00350
4.E+02	0.01123	0.01123	0.00558	0.00375	0.00279
1.E+03	0.00842	0.00842	0.00466	0.00310	0.00223
2.E+03	0.00686	0.00686	0.00407	0.00278	0.00198
4.E+03	0.00570	0.00570	0.00331	0.00227	0.00175

Figure HBB-T-1420-1F
Design Fatigue Strain Range, ϵ_t, for Alloy 617 (Cont'd)

Number of Cycles, N_d [Note (1)]	SI Units				
	Strain Range, ε, m/m at Temperature				
	425°C Zero Mean Stress	425°C Maximum Mean Stress	704°C	871°C	950°C
1.E+04	0.00453	0.00453	0.00266	0.00178	0.00131
2.E+04	0.00396	0.00396	0.00233	0.00155	0.00112
4.E+04	0.00340	0.00340	0.00207	0.00139	0.00099
1.E+05	0.00289	0.00289	0.00181	0.00124	0.00088
2.E+05	0.00254	0.00254	0.00165	0.00115	0.00082
4.E+05	0.00227	0.00199	0.00151	0.00107	0.00077
1.E+06	0.00199	0.00146	0.00135	0.00098	0.00072

NOTE:
(1) Cyclic strain rate: 1×10^{-3} and 4×10^{-3} in./in./sec (m/m/s)

Figure HBB-T-1420-2
Creep-Fatigue Damage Envelope for Alloy 617
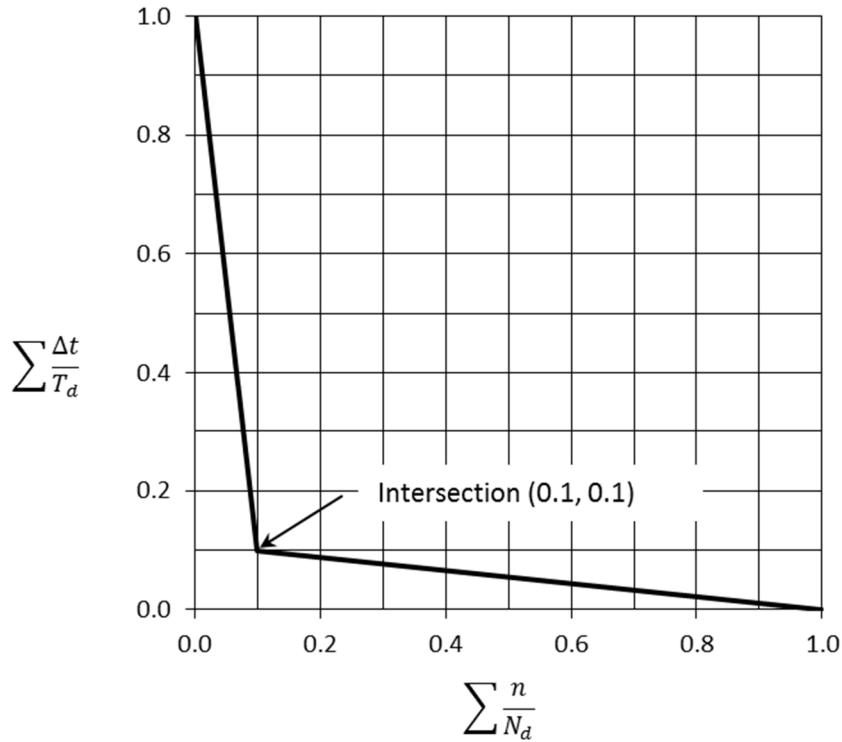
HBB-T-1430 Limits Using Elastic Analysis

HBB-T-1431   General Requirements

(b) Revise the reference to the appropriate design fatigue curve to HBB-T-1420-1F of this Code Case.

(d) The total damage, D, shall not exceed the creep- fatigue damage envelope of Figure HBB-T-1420-2 of this Code Case.

(e) Paragraph HBB-T-1431 is not applicable to Alloy 617 above 1200°F (650°C).

HBB-T-1432   Strain Range Determination

(c) Revise the references to the appropriate time -independent isochronous stress-strain curves to be Figures HBB-T-1800-F-1 through HBB-T-1800-F-20 of this Code Case.

(g) Revise the reference to the isochronous stress-strain curve to Figures HBB-T-1800-F-1 through HBB-T-1800-F-20 of this Code Case.

(h) Revise the reference to the design fatigue curves to HBB-T-1420-1F of this Code Case.

HBB-T-1433   Creep Damage Evaluation

(a) In Step 4, revise the references to the time-independent isochronous stress-strain curves to be Figures HBB-T-1800-F-1 through HBB-T-1800-F-20 of this Code Case. In Step 5(b), revise the references to the appropriate time-independent isochronous stress-strain curves to be Figures HBB-T-1800-F-1 through HBB-T-1800-F-20 of this Code Case. In Step 10, revise the reference to the expected minimum stress-to-rupture curve to Figure HBB-I-14.6G of this Code Case and K' is from Table HBB-T-1411-1 of this Code Case.

(b) Revise the reference to the expected minimum stress-to-rupture curve to Figure HBB-I-14.6G of this Code Case and K' is from Table HBB-T-1411-1 of this Code Case.

HBB-T-1435   Alternate Creep-Fatigue Evaluation

(a) The reference to Section III Appendices, Mandatory Appendix I is replaced by Figure HBB-T-1420-1F, where Sa is one-half the product of єt and Young's Modulus, E, is at the metal temperature of the cycle for the point under consideration.

HBB-T-1440 Limits Using Elastic-Perfectly Plastic Analysis

HBB-T-1441   General Requirements

Fatigue and cyclic creep damage may be evaluated using elastic-perfectly plastic material models instead of the procedures of HBB-T-1420, HBB-T-1430 and HBB-T-1715, when performed in accordance with the requirements of this Subsubarticle.

The design methodology employed for evaluation of creep damage is based on elastic shakedown analyses using an elastic-perfectly plastic material model, small strain theory, and a pseudo-yield stress selected to bound creep damage. In this Subsubarticle, "shakedown" refers to the achievement of cyclic elastic behavior throughout the part, based on real or pseudo-yield stress. In this Code Case, the term "pseudo-yield stress" refers to a temperature-dependent minimum stress-to-rupture value based on a selected trial time duration, not to exceed the yield strength of the material at temperature and is explicitly defined in HBB-T-1444.2. Guidance on shakedown analysis is provided in HBB-T-1447.

HBB-T-1441.1   Allowable Damage Accumulation. The combination of Levels A, B, and C Service Loadings shall be evaluated for accumulated creep and fatigue damage, including hold time and strain rate effects. For a design to be acceptable, the creep and fatigue damage at each point in the component shall satisfy the following relation:

$$D_c + D_f \leq D \tag{2}$$

where

> D = total creep-fatigue damage, as limited by Figure HBB-T-1420-2 of this Code Case

> D_c = creep damage, as determined in paragraph HBB-T-1444, below

> D_f = fatigue damage, as determined in paragraph HBB-T-1445, below

This design methodology is not applicable to structures where geometrical nonlinearities exist, e.g., canopy and omega seals.

HBB-T-1442   Load Definition

Define all applicable loads and load cases per Section III, Division 5, HBB-3113.2, Service Loadings.

HBB-T-1442.1   Composite Cycle Definition. For the purpose of performing an elastic-perfectly plastic shakedown analysis, an overall cycle must be defined that includes all relevant features from the individual Level A, B and C Service Loadings identified in the Design Specification. Relevant features include, as a minimum, the time-dependent sequence of thermal, mechanical and pressure loading, including starting and ending conditions. Such an overall cycle is defined herein as a composite cycle subject to the following requirements:

(a) An individual cycle as defined in the Design Specification cannot be further subdivided into individual cycles to satisfy these requirements.

(b) Except as described in *(c)* below, a single cycle from each Level A, B and C Service Loading cycle type shall be included in the composite cycle for evaluation of creep-fatigue.

(c) Level C Service Loadings may be combined with the applicable Level A and B Service Loadings to define a composite cycle(s) to be evaluated separately from the composite cycle defined in *(b)* above. Multiple composite cycles that include Level C Service Loadings may be defined for separate evaluation. The total number of Level C Service Loading cycles shall not exceed 25.

HBB-T-1443   Numerical Model

Develop a numerical model of the component, including all relevant geometry characteristics. The model used for the analysis shall be selected to accurately represent the component geometry, boundary conditions, and applied loads. The model must also be accurate for small details, such as small holes, fillets, corner radii, and other stress risers. The local temperature history shall be determined from a thermal transient analysis based on the thermal boundary conditions determined from the loading conditions defined in paragraph HBB-T-1442.

HBB-T-1444   Calculation of Creep Damage

Perform a shakedown analysis for each of the composite cyclic histories defined in HBB-T-1442.1. Each of these cyclic histories must be shown to shakedown based on the pseudo-yield stress, $S_{Td'}$, as defined in HBB-T-1444.2. Additional requirements for welds are found in HBB-T-1446.

HBB-T-1444.1   Step 1. Define t_{design} as the total time duration of elevated temperature service for all Level A, B, and C Service Loadings when the temperature is above 800°F (425°C).

HBB-T-1444.2   Step 2. Select a trial time duration, T_d', in order to define a pseudo-yield stress, $S_{Td'}$, at each location, using the temperature determined from the transient thermal analysis. This pseudo-yield stress is equal to the lesser of the quantities defined in *(a)* and *(b)* below.

(a) The yield strength, S_y, given in Table HBB-I-14.5 of this Code Case;

(b) S_r, where S_r is the minimum stress to rupture in time, $T_d{'}$, from Figure HBB-I-14.6G multiplied by the factor, $K{'}$, from Table HBB-T-1411-1 of this Code Case, using the tabulated values for elastic analysis.

HBB-T-1444.3 **Step 3.** Perform a cyclic elastic-perfectly plastic analysis for each composite cycle defined in HBB-T-1442 above with temperature-dependent pseudo-yield stress, $\boldsymbol{S_{Td'}}$. The assessment temperature shall be taken as the local instantaneous temperature at every location in the numerical model of the component. If shakedown occurs, that is, cycles with eventual elastic behavior everywhere, proceed to HBB-T-1444.4.

HBB-T-1444.4 **Step 4.** The maximum creep damage over the structure for the composite cycle under consideration is:

$$D_c = \frac{t_{design}}{T_d{'}}$$ (3)

The above value of D_c is used to evaluate total damage in Equation (2). If the pseudo-yield stress in HBB-T-1444.2 Step 2 is governed by the yield strength as defined in HBB-T-1444.2(a), then the trial time duration for use in Equation (2) is given by the time at which the minimum stress to rupture is equal to the yield strength; $S_r = S_y$. Linear extrapolation of S_r values corresponding to the two longest tabulated times can be used to obtained the trial time duration, when necessary.

(a) Steps 2, 3 and 4 may be repeated to revise the value of D_c by selecting alternative values of the trial time duration, $T_d{'}$. Longer values of $T_d{'}$ will reduce the calculated creep damage. However, these longer values will lead to lower values of the pseudo-yield stress, $S_{Td'}$, which will make shakedown more difficult to achieve. If it is not possible to achieve shakedown, then the loading conditions of HBB-T-1442 applied to the component configuration defined in HBB-T-1443 do not meet the requirements of HBB-T-1440.

HBB-T-1445   Calculation of Fatigue Damage

The fatigue damage summation, D_f, in Equation (2) is determined in accordance with Steps 1 through 3 below. Additional requirements for welds are found in HBB-T-1446.

HBB-T-1445.1 **Step 1.** Determine all of the total (elastic plus plastic) strain components for the composite cycle at each point of interest from the shakedown analysis performed in Step 3 of HBB-T-1444.3 above.

HBB-T-1445.2 **Step 2.** Calculate the equivalent strain range in accordance with HBB-T-1413, or HBB-T-1414 when applicable, with Poisson's ratio $v* = 0.3$.

HBB-T-1445.3 **Step 3.** Determine the fatigue damage for each composite cycle from the expression:

$$D_f = \sum_j \frac{n_j}{(N_d)_j}$$ (4)

where

n_j =   number of applied repetitions of cycle type, j

$(N_d)_j$ =   number of design allowable cycles for cycle type, j, determined from Figure HBB-T-1420-1F, corresponding to the maximum metal temperature occurring during the cycle.

The value of D_f used to evaluate total damage in Equation (2) is the maximum value at any location in the numerical model.

HBB-T-1446   Weldments

Implementation of the evaluation of creep-fatigue damage in HBB-T-1444 and HBB-T-1445 above for weldments requires additional consideration.

HBB-T-1446.1   Pseudo-Yield Stress. In the weld region, the pseudo-yield stress value, $S_{Td'}$, defined by T_d' in HBB-1444.2 is reduced further by multiplying the value of S_r for the base metal by the applicable weld strength reduction factor from Table HBB-I-14.10F-1.

HBB-T-1446.2   Allowable Cycles. The number of allowable cycles, $(N_d)_j$, in the weld region is one-half the number of allowable cycles from Figure HBB-T-1420-1F for base metal.

HBB-T-1446.3   Geometry. The requirements for analysis of geometry of HBB-T-1714 are applicable for satisfaction of the requirements of this Code Case.

HBB-T-1446.4   Physical Properties. The thermal/physical properties of weldments shall be assumed to be the same as the corresponding base metal for the base metal-weld combinations listed in Table HBB-I-14.10F-1.

HBB-T-1446.5   Weld Region Model Boundaries. Figure HBB-T-1345 shows a full-penetration butt weld as an example of the definition of a weld region. As shown, w_1 and w_2 are needed to define the weld region for use in this Code Case and are approximations consistent with the specified weld configuration and parameters. The specified weld region must include applicable stress concentrations in accordance with the requirements for analysis of geometry, HBB-T-1714, unless ground flush.

The weld shown in Figure HBB-T-1345 represents a full-penetration butt weld in a shell. Other weld configurations may be needed for construction of an elevated temperature service component in accordance with Section III, Division 5, Subsection HB, Subpart B. Section III, Division 5, HBB-4200 refers to various Section III, Division 1, Article NB-4000 paragraphs for weld configurations and requirements. These NB-4000 weld configurations are represented by the shaded region.

Figure HBB-T-1446 Weld Region Model Boundaries
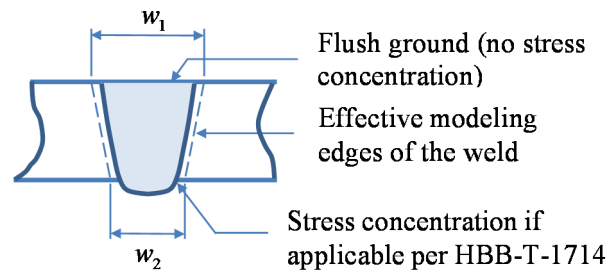
HBB-T-1446.6   Dissimilar metal welds. The requirements for dissimilar metal welds are in the course of preparation.

HBB-T-1447   Shakedown Analysis

The steps to perform a shakedown analysis to calculate bounding cyclic creep damage are as follows:

(a) Define Composite Cycle Load Time-Histories and Analysis Step(s).

   (1) It may consist of histories of mechanical loads, pressure loads, displacements, temperatures and thermal boundary conditions.

   (2) Time-independent parts of the cycle may be truncated because the elastic-perfectly plastic analysis is not time-dependent.

(3) The cycle should not have discontinuities. Discontinuities arising from the selection of the specified cycles to form a composite cycle should be eliminated by a simple and reasonable transition from one operating state to the next.

(4) Subject to the requirements in *(b)* below, the composite cycle time does not affect the result of the shakedown analysis.

(5) Temperatures, thermal boundary conditions, boundary displacements and mechanical loads over a cycle should be cyclic; that is, begin and end at the same value.

(6) A single analysis step may represent one cycle. Dividing a single cycle into more than one step to facilitate definition of the load cycle, and to ensure that maximum loads are analyzed, is often helpful.

(b) Define Analysis Types.

(1) A sequentially coupled thermal-mechanical analysis of the composite cycle may be performed. First, a thermal analysis is performed to generate temperature histories. Next, the mechanical analyses are performed using these temperature histories as inputs. Care must be taken that times in the mechanical analysis step and in the previous thermal analysis are the same or do not conflict, depending on the requirements of the analysis software.

(2) Alternatively, a coupled thermal-mechanical analysis may be performed. The composite temperature history to be used in the mechanical analysis should be cyclic; that is, the beginning and end temperature distributions should be the same.

(c) Define Material Properties.

(1) For thermal analyses, density, temperature-dependent specific heat and conductivity will generally be required.

(2) For the mechanical analyses, the temperature-dependent properties required are elastic modulus, Poisson's ratio, and mean expansion coefficient. Density may also be required.

(d) Perform Analyses.

(1) Perform an elastic-perfectly plastic cyclic mechanical and thermal stress analysis using the temperature-dependent pseudo-yield stress defined above. Enough cycles are required to demonstrate shakedown or otherwise.

(2) Care must be taken to ensure that the analysis deals with all the changes within a cycle. Elastic-plastic analysis routines increase increment size where possible, and may miss a detail in the loading. A conservative limit to maximum increment size can address this problem, as can division of the cycle into more than one step, as discussed in *(a)(6)* above.

(e) Shakedown.

(1) Shakedown is defined in this Code Case as eventual elastic behavior everywhere in the model. Failure to achieve shakedown may be identified by plotting history plots of equivalent plastic strain.

HBB-T-1500   BUCKLING AND INSTABILITY

HBB-T-1520 Buckling Limits

HBB-T-1522   *Time-Dependent Buckling*

The following curves for Alloy 617 are added to Figures HBB-T-1522-1, HBB-T-1522-2, and HBB-T-1522-3.

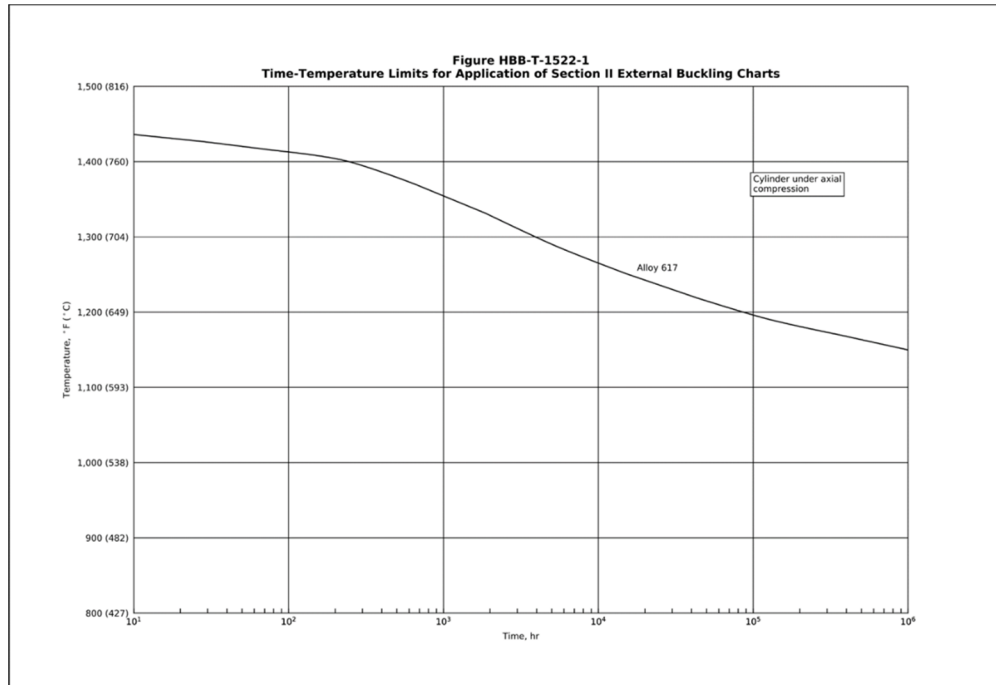**Figure HBB-T-1522-1 Buckling Chart for Cylinder Under Axial Load**

Figure HBB-T-1522-1
Time-Temperature Limits for Application of Section II External Buckling Charts

Figure HBB-1522-2 Buckling Chart for Sphere Under External Pressure

Figure HBB-T-1522-2
Time-Temperature Limits for Application of Section II External Buckling Charts
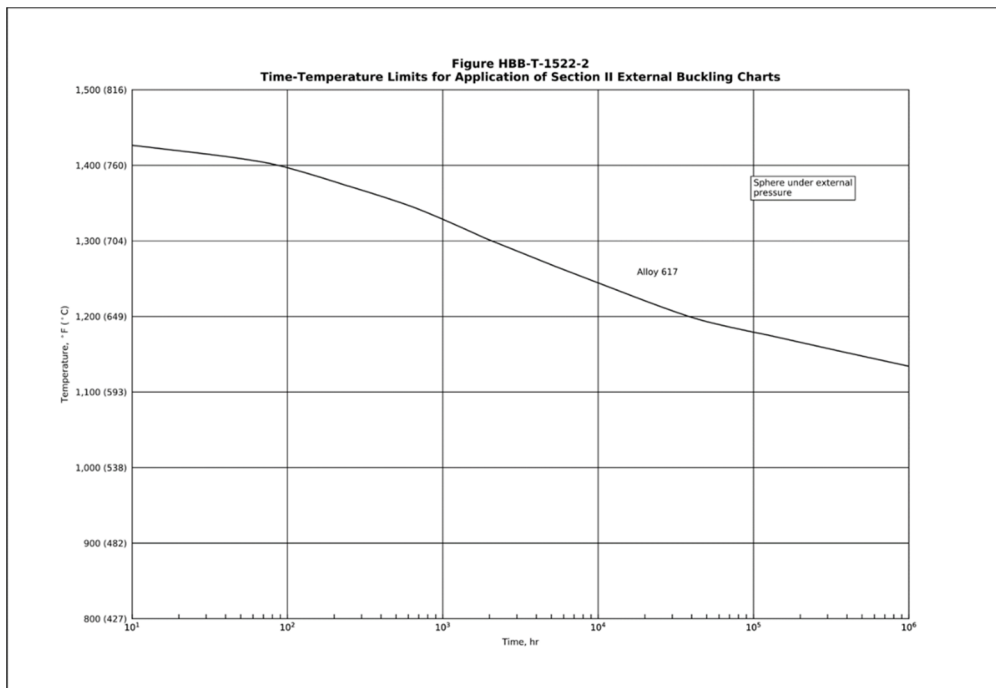
Figure HBB-T-1522-3 Buckling Chart for Cylinder Under External Pressure

Figure HBB-T-1522-3
Time-Temperature Limits for Application of Section II External Buckling Charts
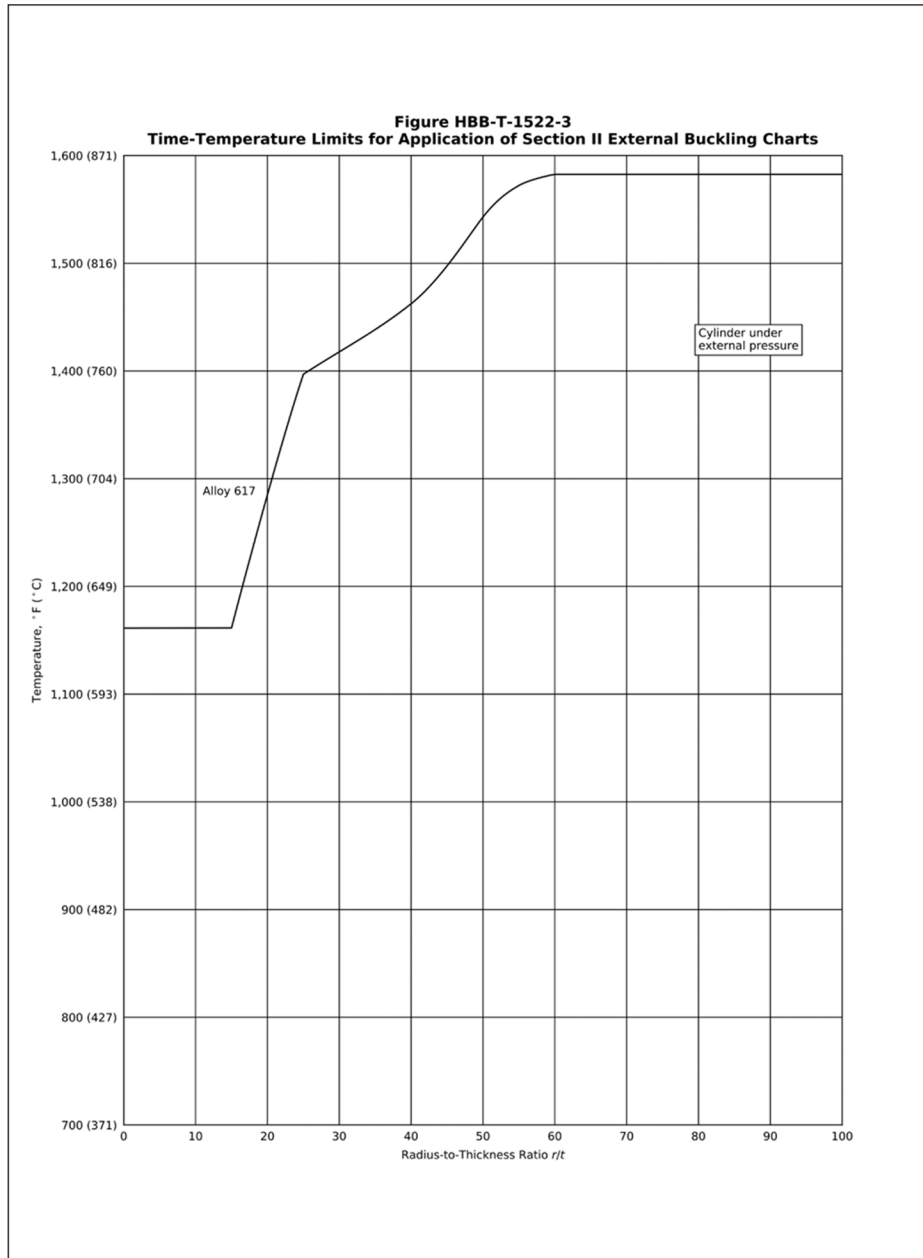
ARTICLE HBB-T-1800 ISOCHRONOUS STRESS-STRAIN RELATIONS
HBB-T-1820 MATERIALS AND TEMPERATURE LIMITS

Table HBB-T-1820-1

Material	Maximum Temp., °F (°C)	Temperature Increment, °F (°C)
Alloy 617	1750 (950)	50 (28)

The following figures are appended to the isochronous stress-strain curves listed in HBB-T-1800.

Figure HBB-T-1800-F-1 Isochronous Stress Strain Curve for 800ºF

Figure HBB-T-1800-F-1
Average Isochronous Stress-Strain Curves
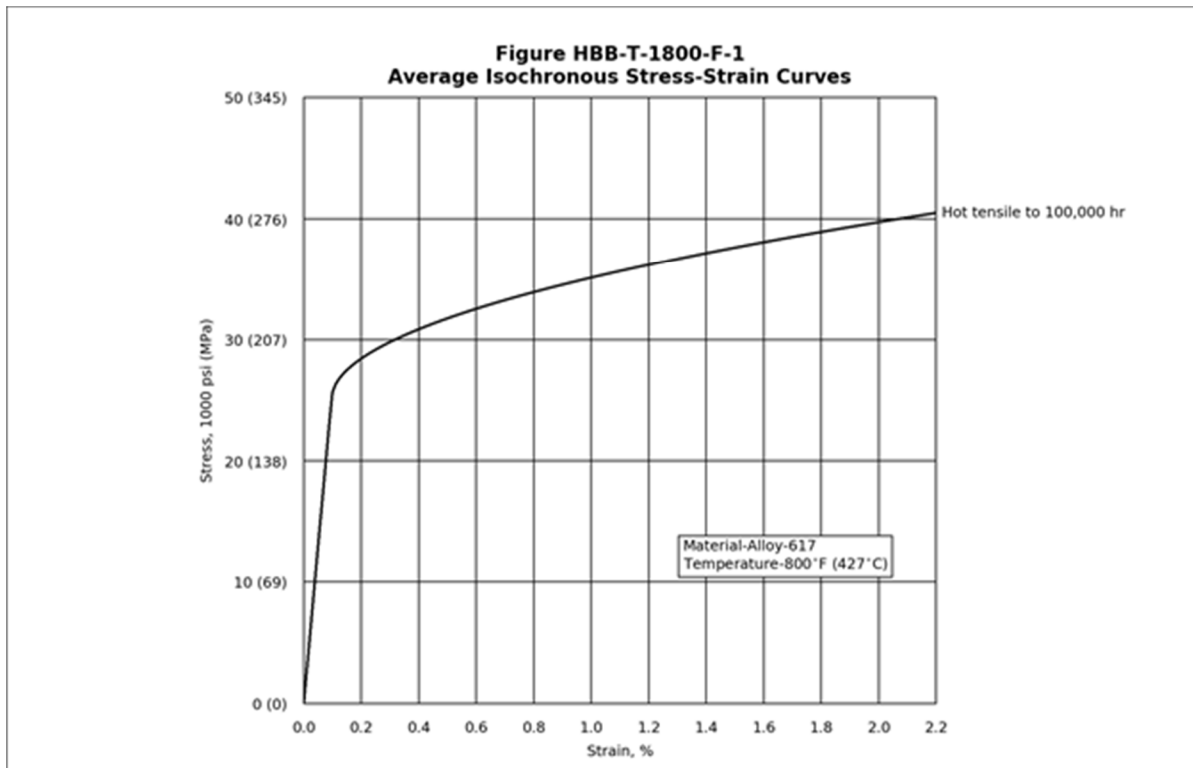
Figure HBB-T-1800-F-2 Isochronous Stress Strain Curve for 850ºF
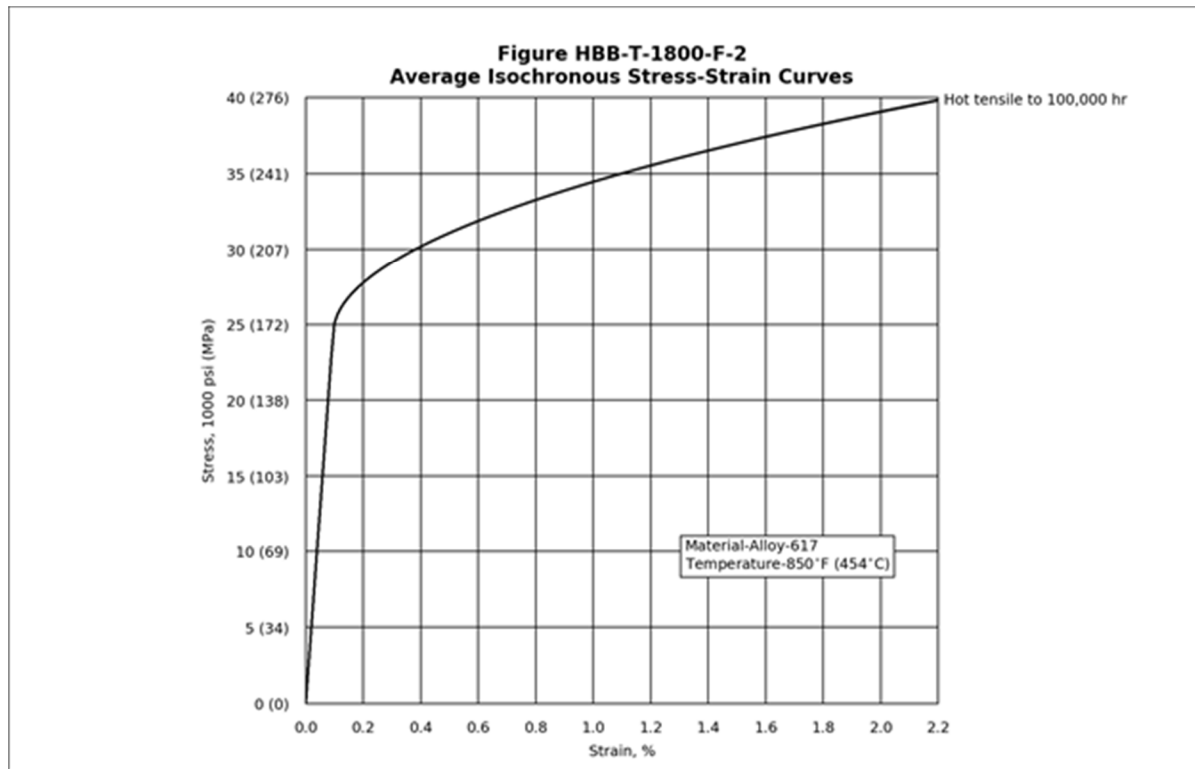
Figure HBB-T-1800-F-3 Isochronous Stress Strain Curve for 900ºF
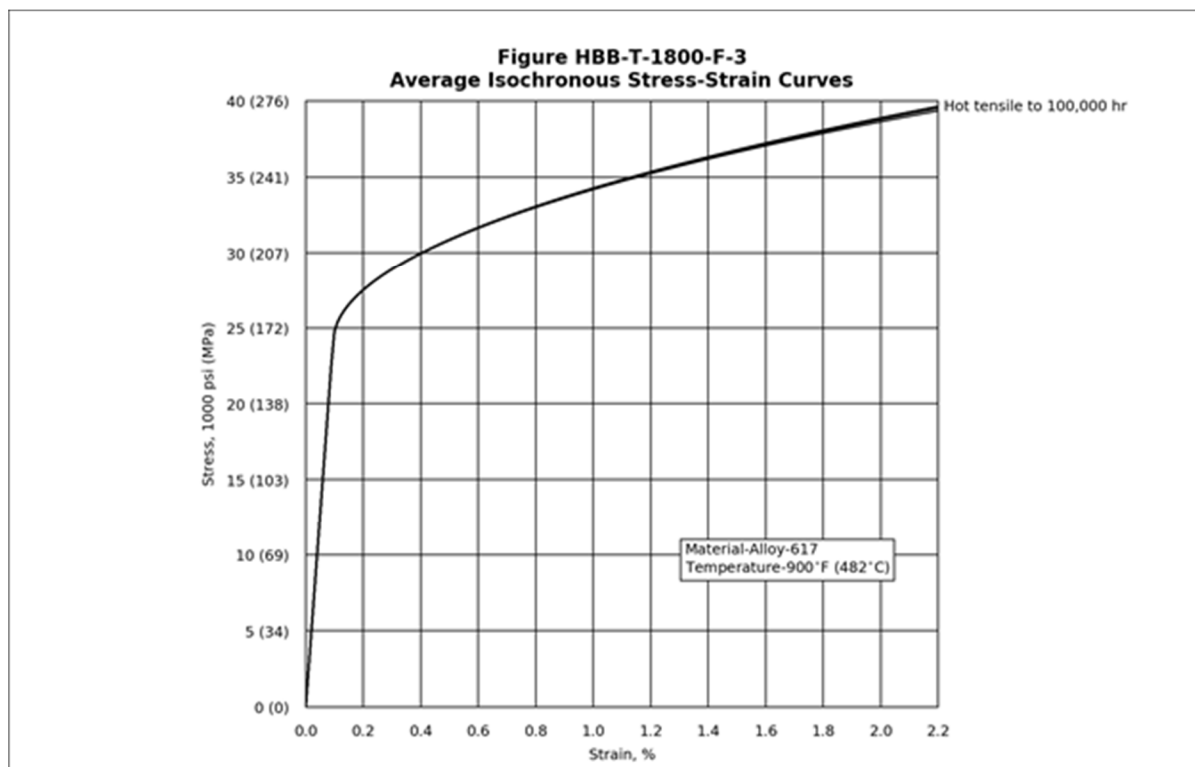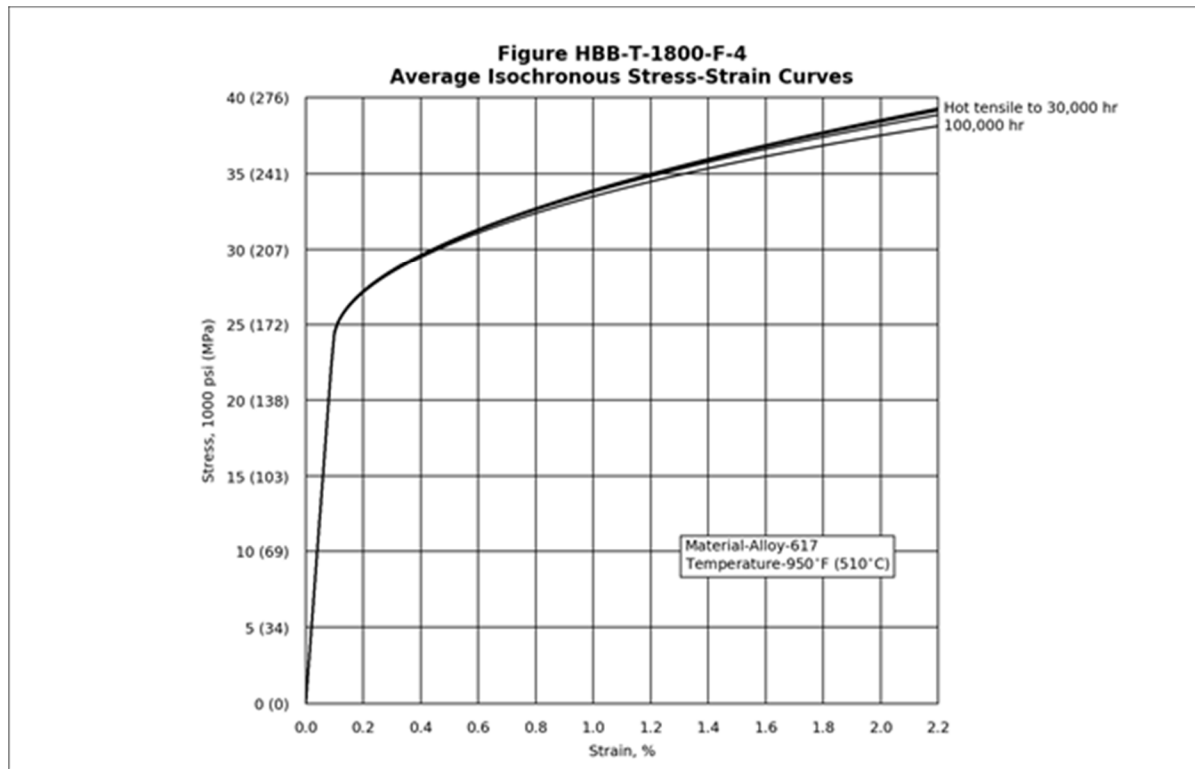
Figure HBB-T-1800-F-4 Isochronous Stress Strain Curve for 950ºF

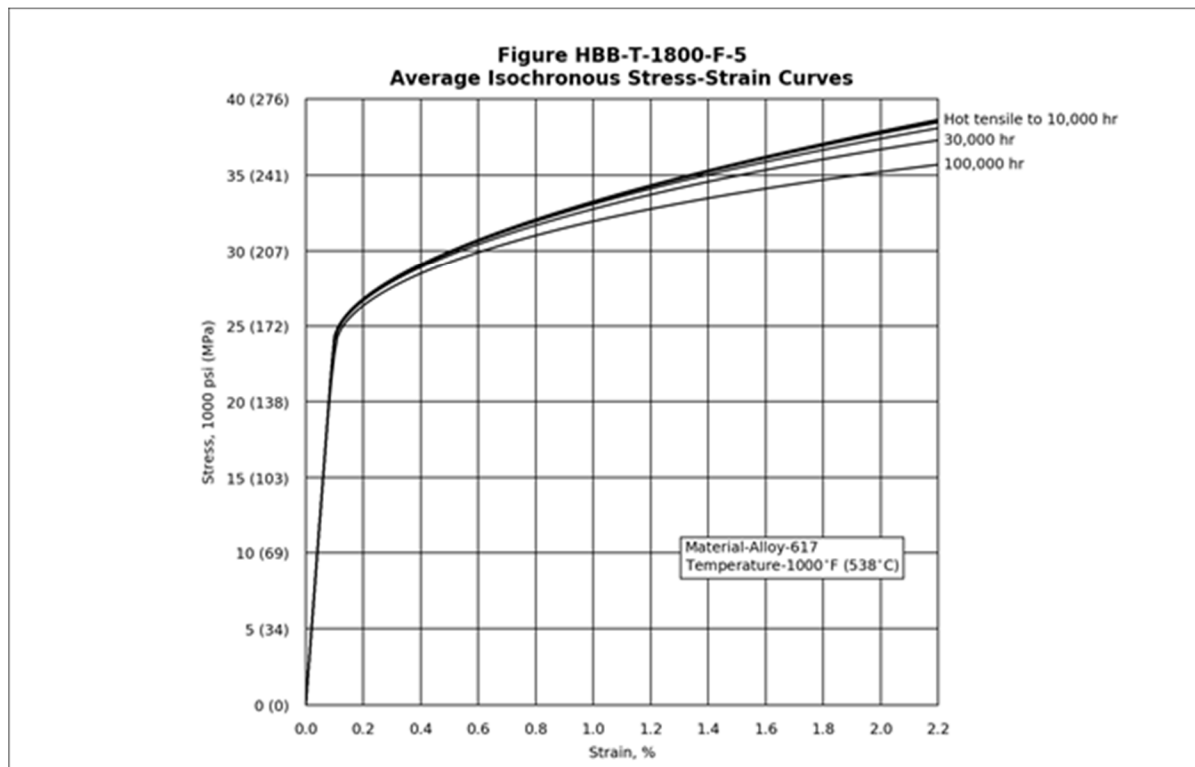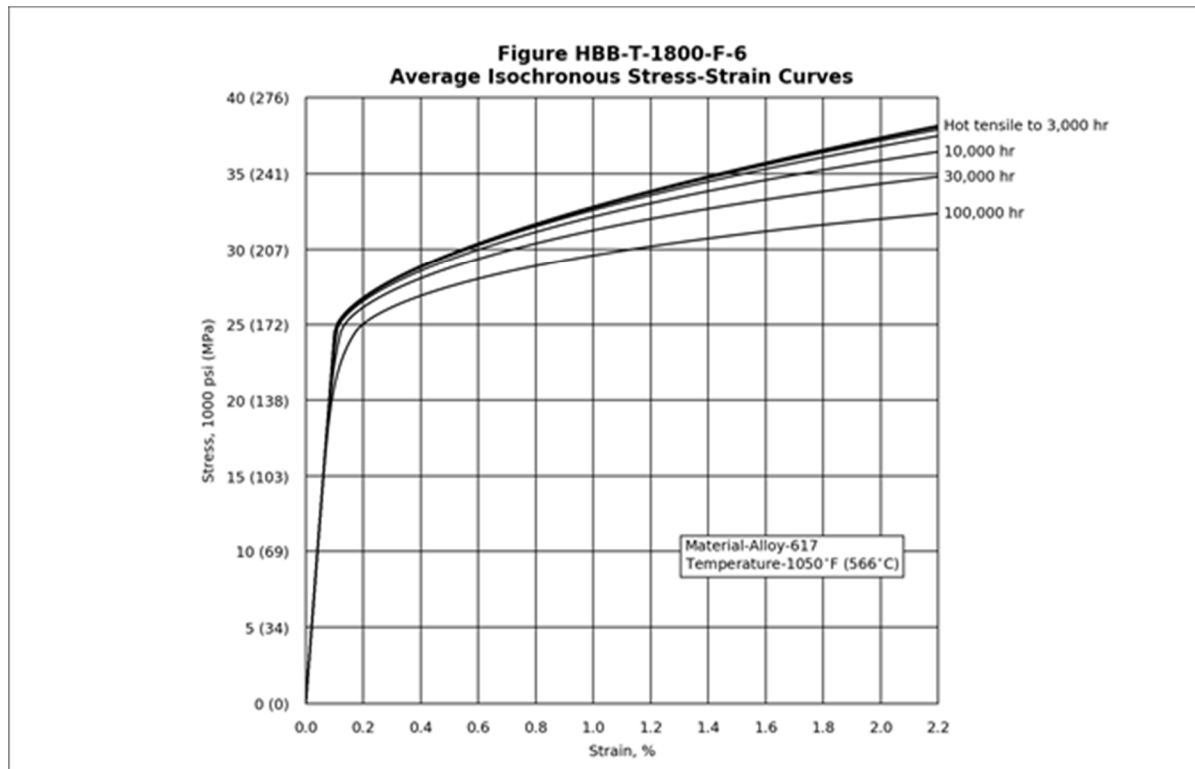**Figure HBB-T-1800-F-5 Isochronous Stress Strain Curve for 1000ºF**

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Figure HBB-T-1800-F-6 Isochronous Stress Strain Curve for 1050ºF

Figure HBB-T-1800-F-6
Average Isochronous Stress-Strain Curves

Figure HBB-T-1800-F-7 Isochronous Stress Strain Curve for 1100ºF

Figure HBB-T-1800-F-7
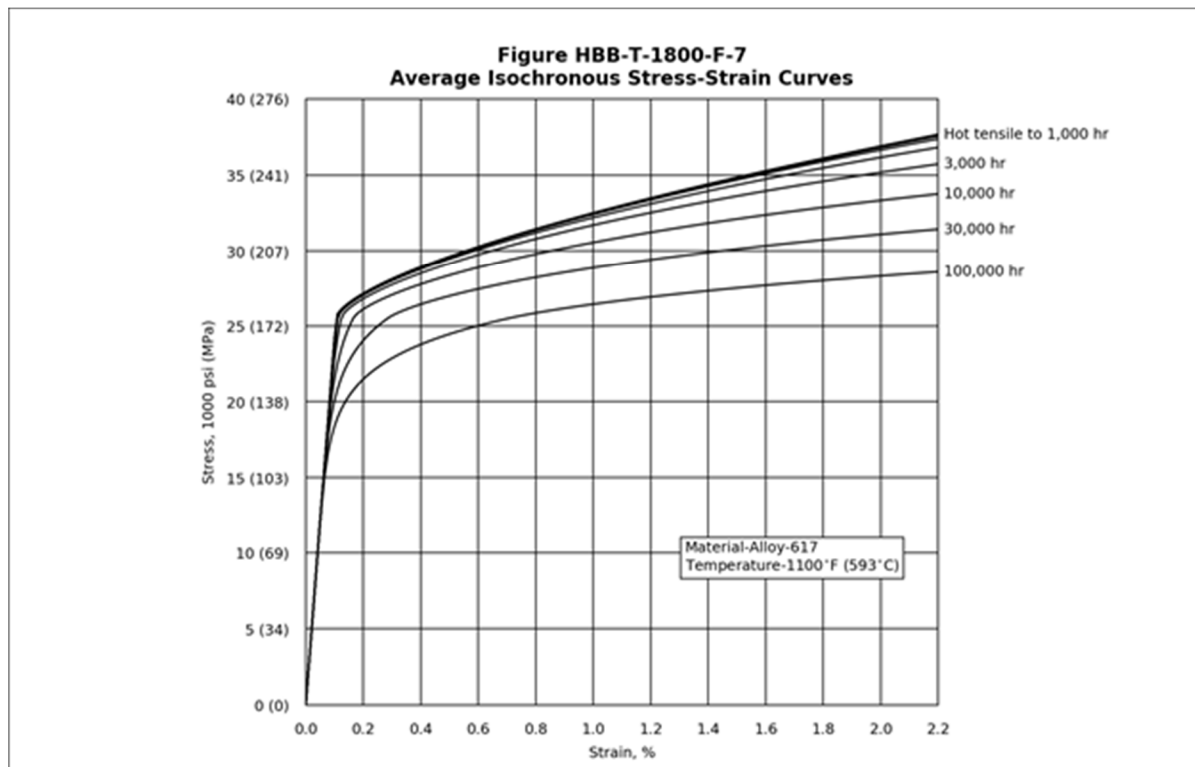Average Isochronous Stress-Strain Curves

Figure HBB-T-1800-F-8 Isochronous Stress Strain Curve for 1150⁰F
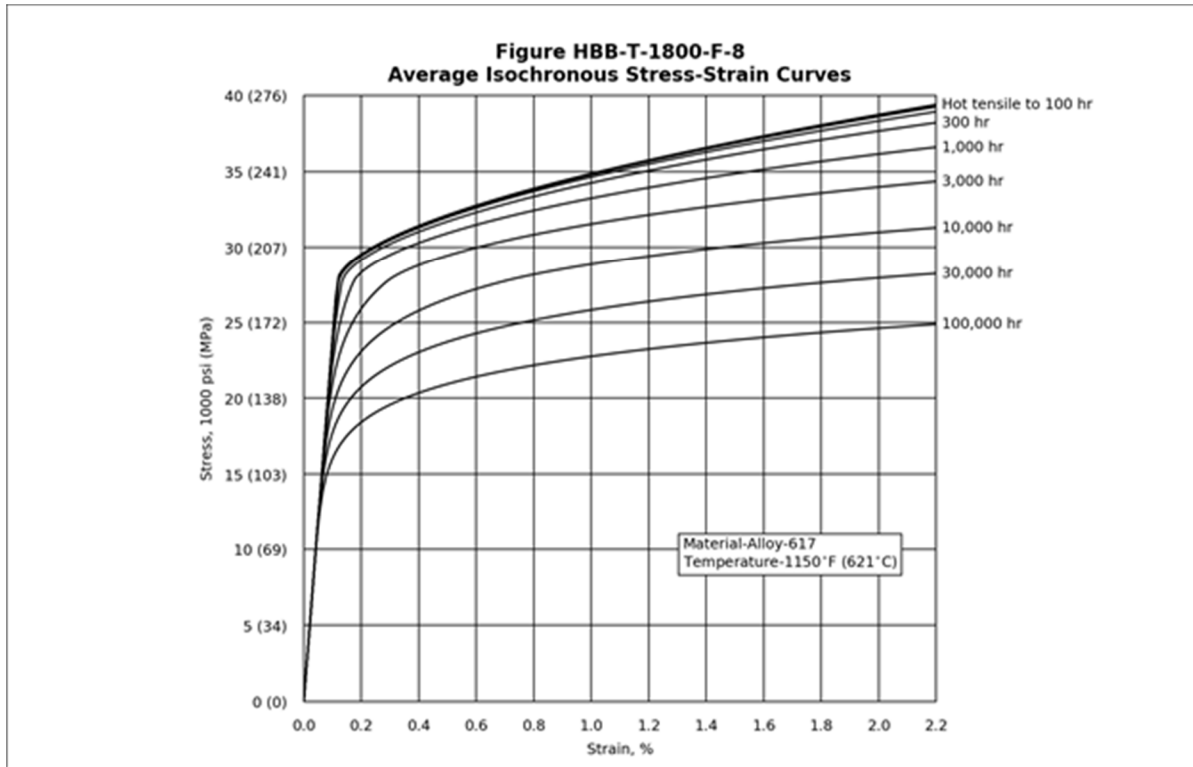

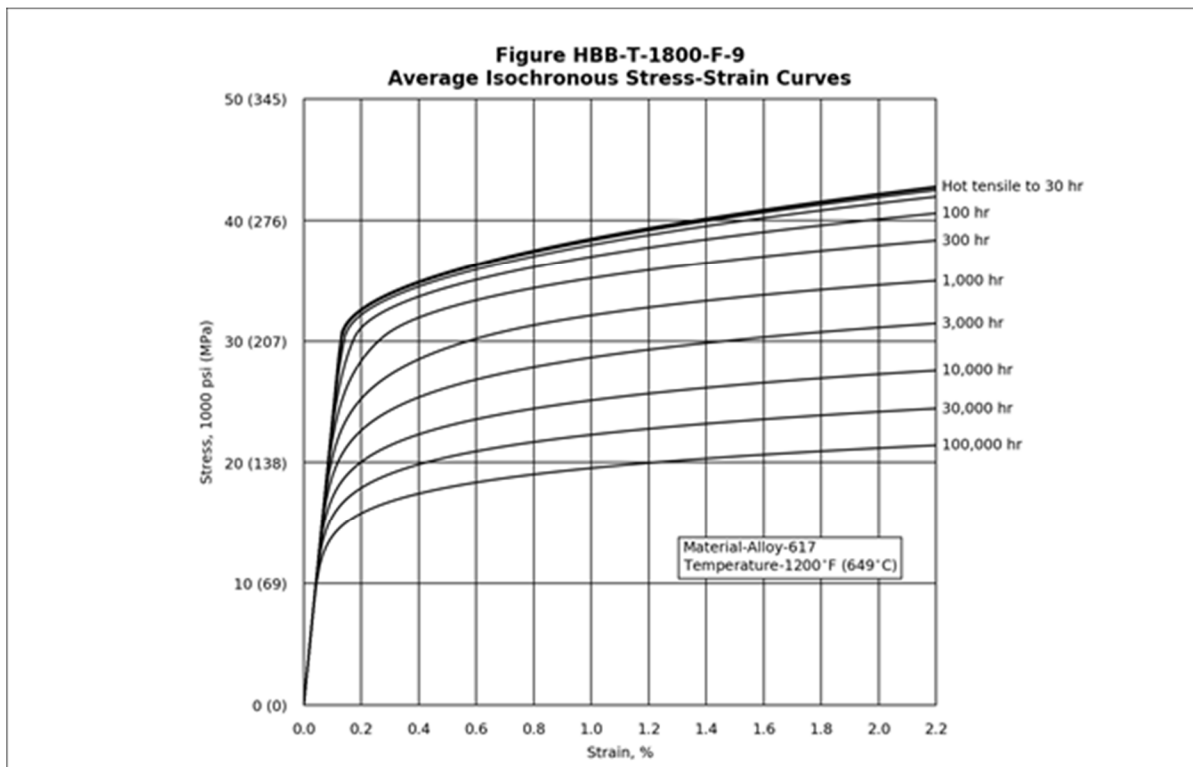**Figure HBB-T-1800-F-9 Isochronous Stress Strain Curve for 1200⁰F**

Figure HBB-T-1800-F-10 Isochronous Stress Strain Curve for 1250ºF
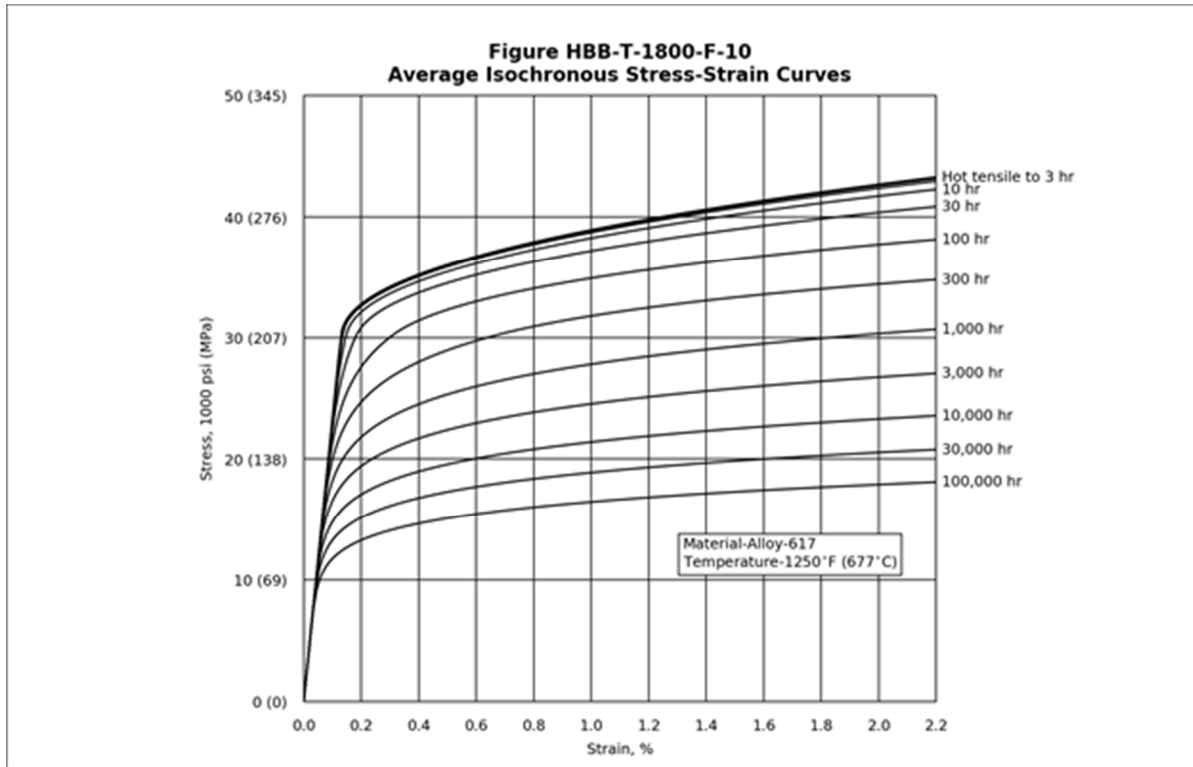

Figure HBB-T-1800-F-11 Isochronous Stress Strain Curve for 1300ºF

Figure HBB-T-1800-F-12 Isochronous Stress Strain Curve for 1350ºF

Figure HBB-T-1800-F-12
Average Isochronous Stress-Strain Curves

Figure HBB-T-1800-F-13 Isochronous Stress Strain Curve for 1400ºF

Figure HBB-T-1800-F-13
Average Isochronous Stress-Strain Curves

Figure HBB-T-1800-F-14 Isochronous Stress Strain Curve for 1450°F

Figure HBB-T-1800-F-14
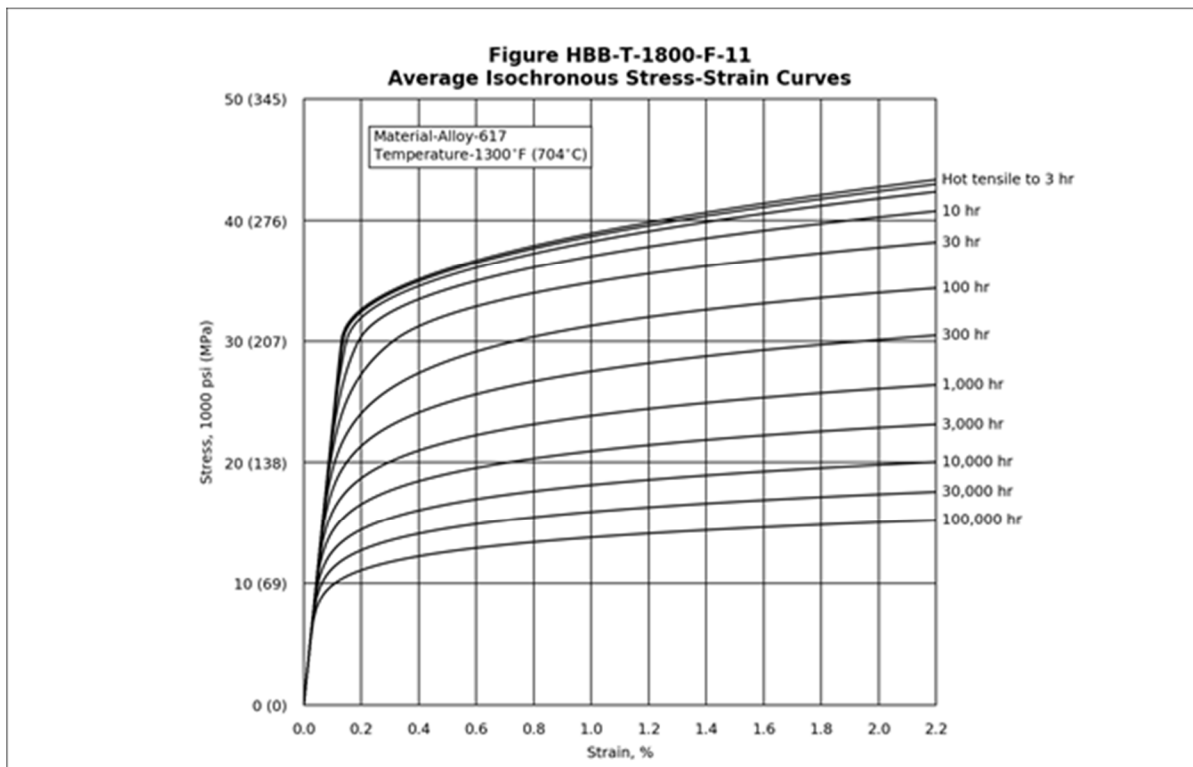Average Isochronous Stress-Strain Curves
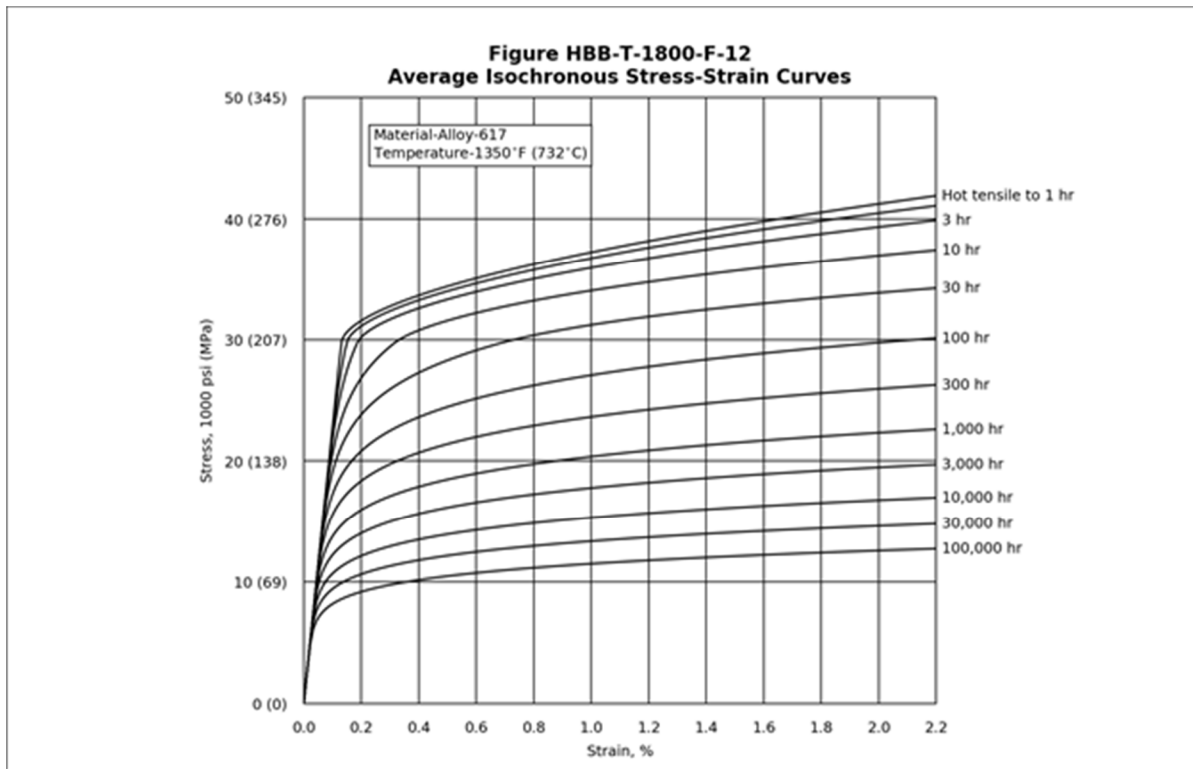
Figure HBB-T-1800-F-15 Isochronous Stress Strain Curve for 1500°F

Figure HBB-T-1800-F-15
Average Isochronous Stress-Strain Curves

Figure HBB-T-1800-F-16 Isochronous Stress Strain Curve for 1550ºF

Figure HBB-T-1800-F-16
Average Isochronous Stress-Strain Curves

Figure HBB-T-1800-F-17 Isochronous Stress Strain Curve for 1600ºF

Figure HBB-T-1800-F-17
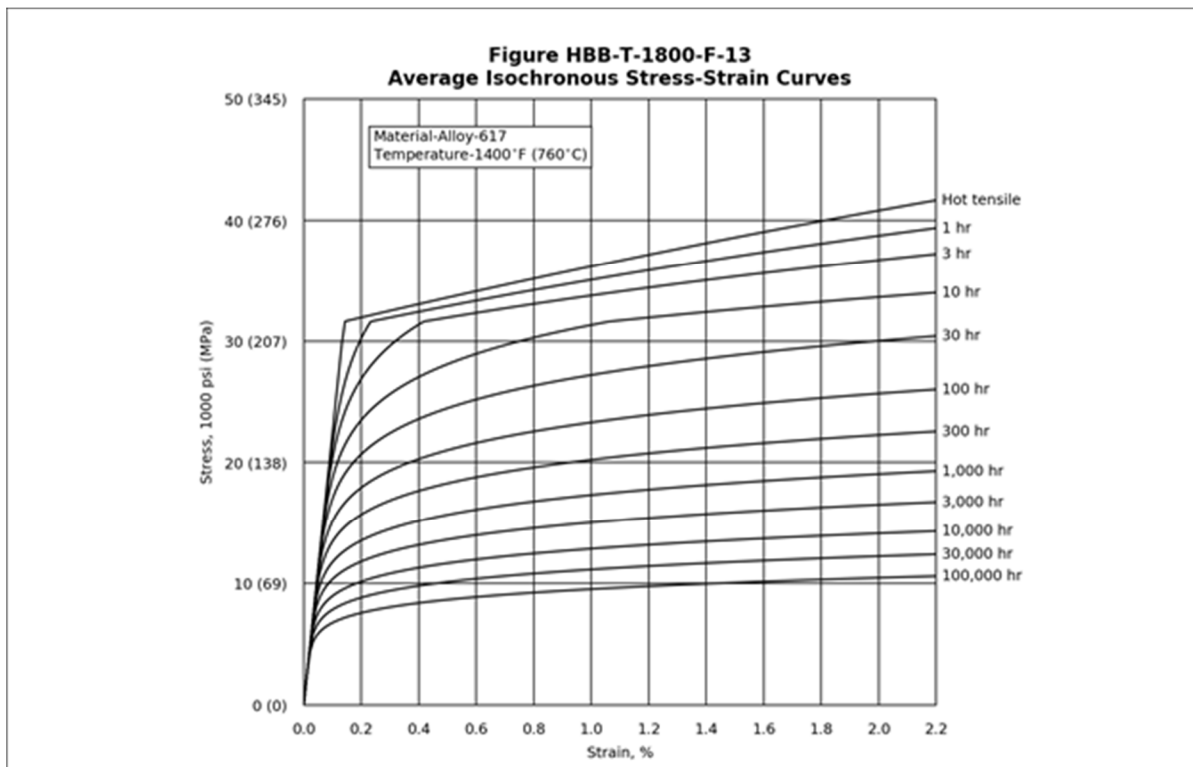Average Isochronous Stress-Strain Curves

Figure HBB-T-1800-F-18 Isochronous Stress Strain Curve for 1650⁰F
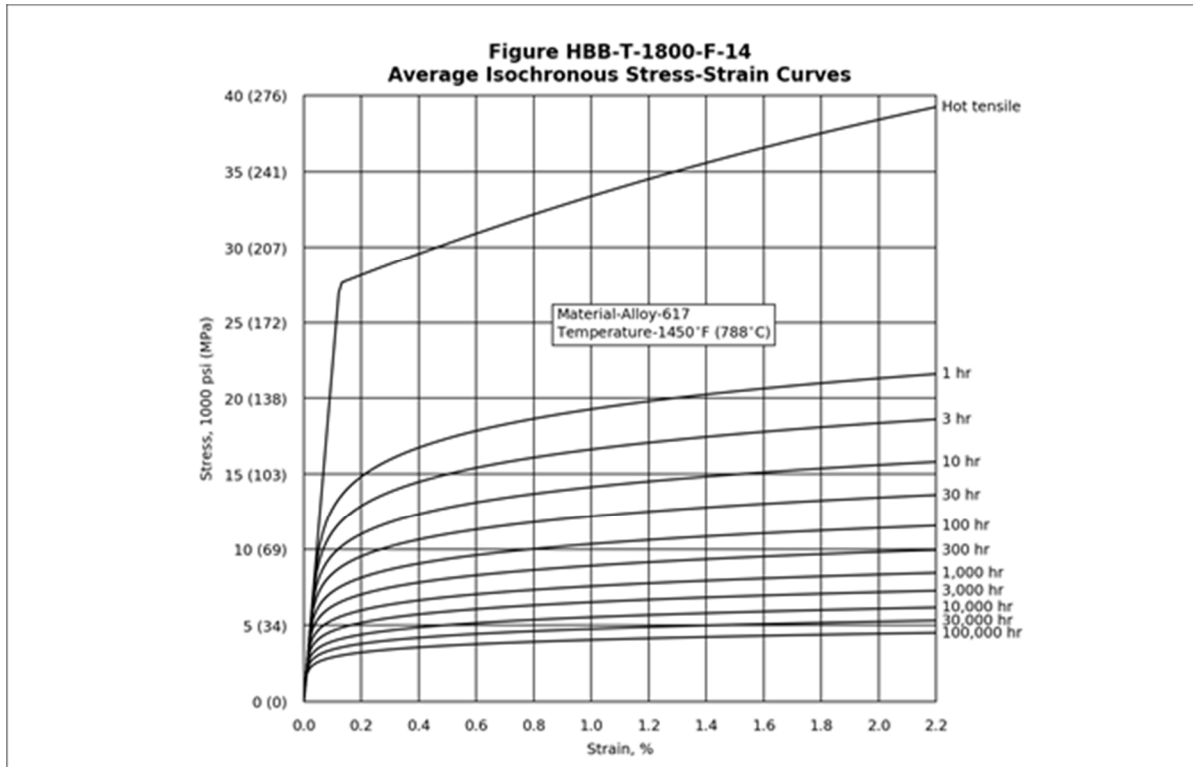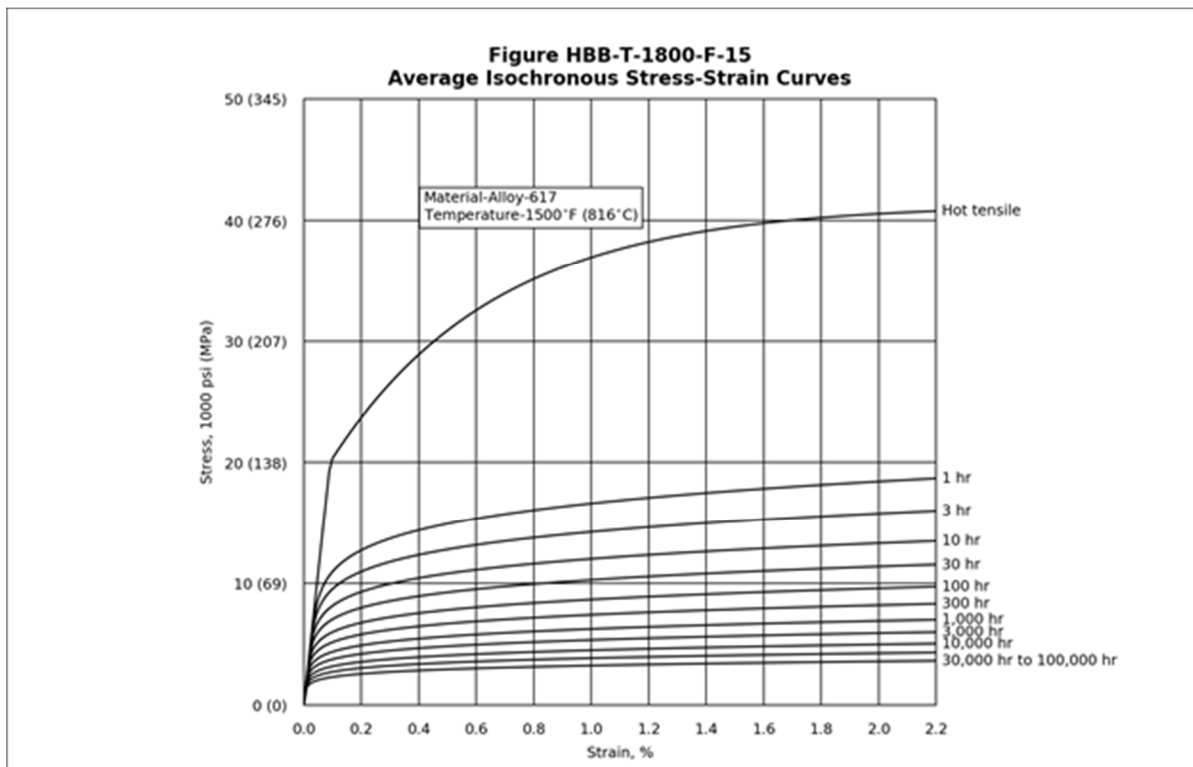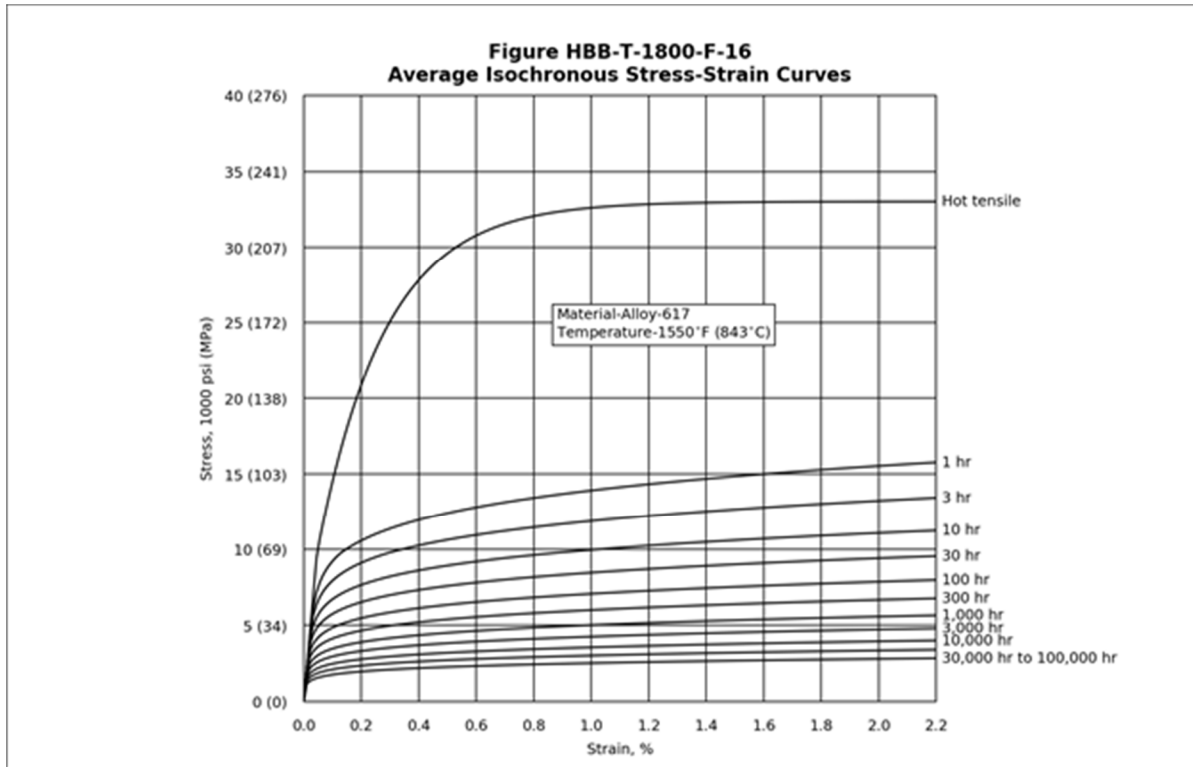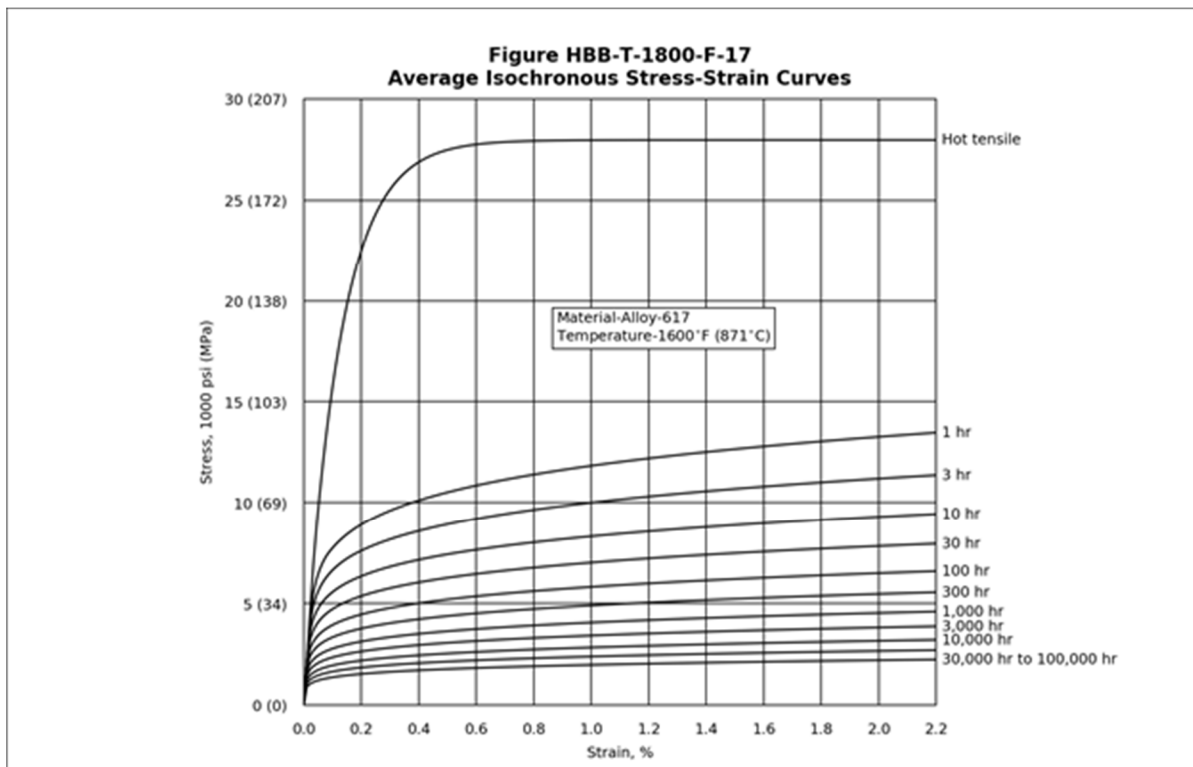

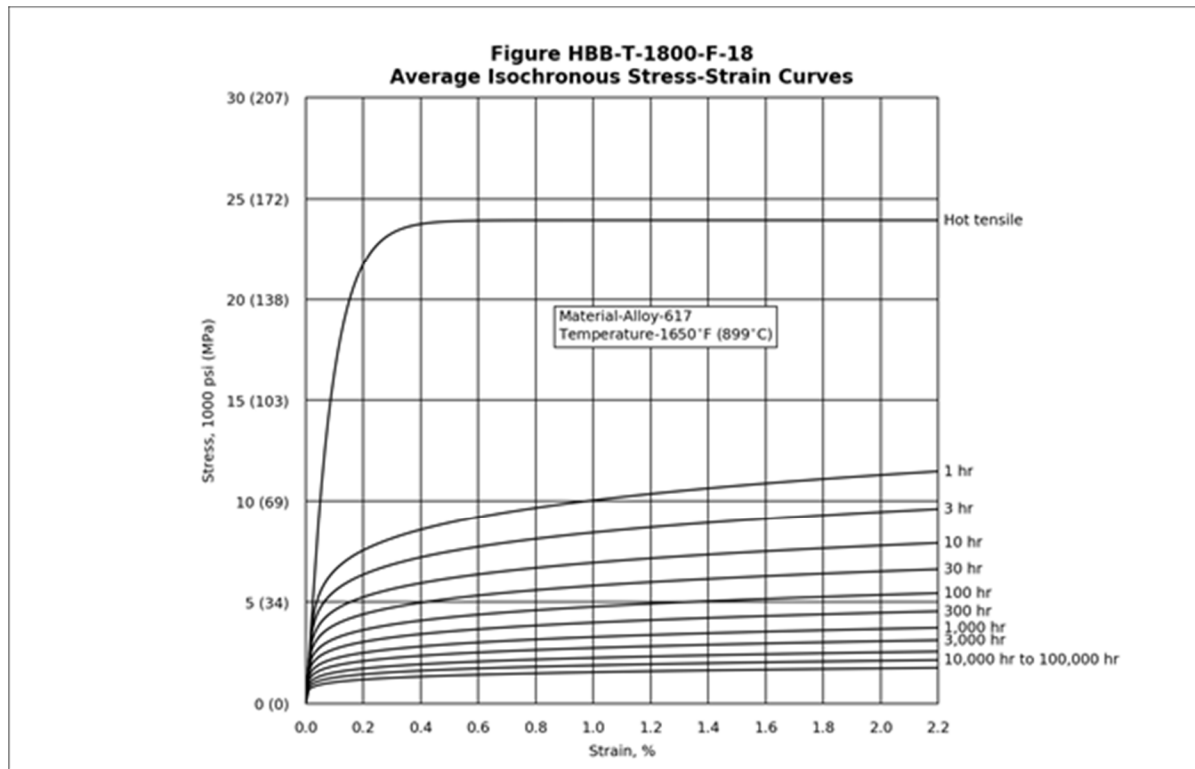**Figure HBB-T-1800-F-19 Isochronous Stress Strain Curve for 1700⁰F**
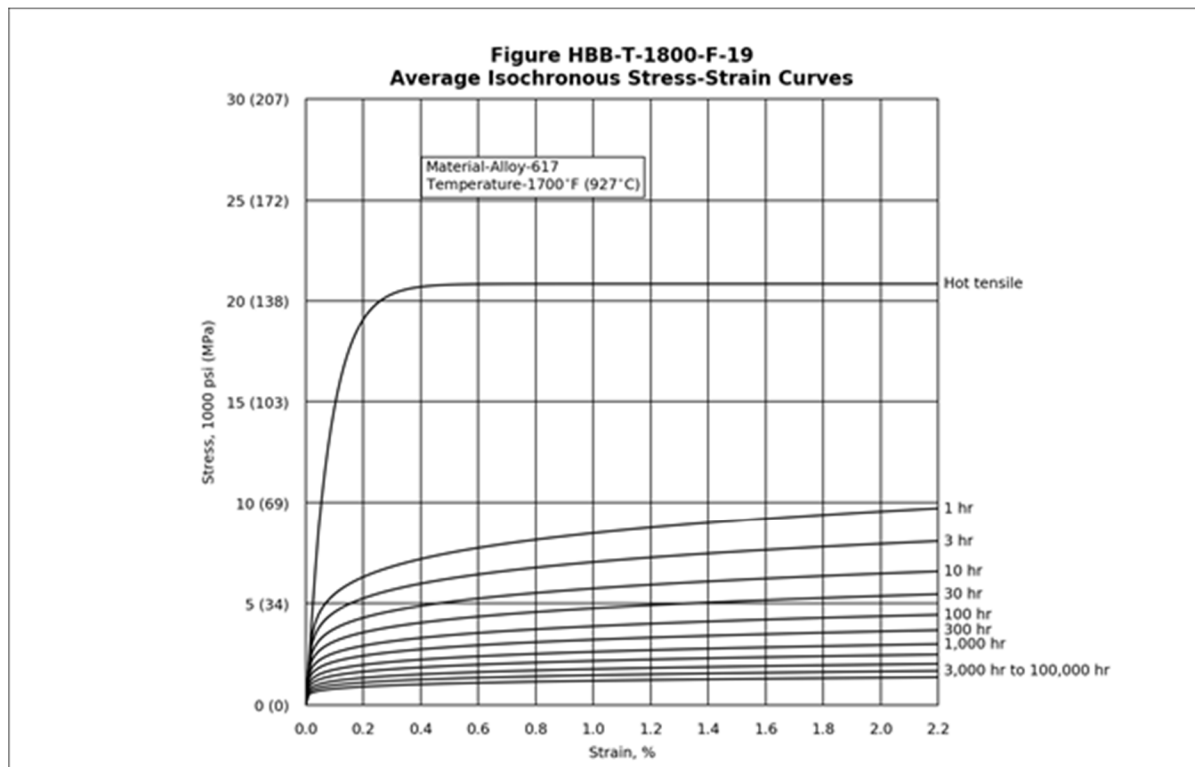
Figure HBB-T-1800-F-20 Isochronous Stress Strain Curve for 1750ºF

Figure HBB-T-1800-F-20
Average Isochronous Stress-Strain Curves
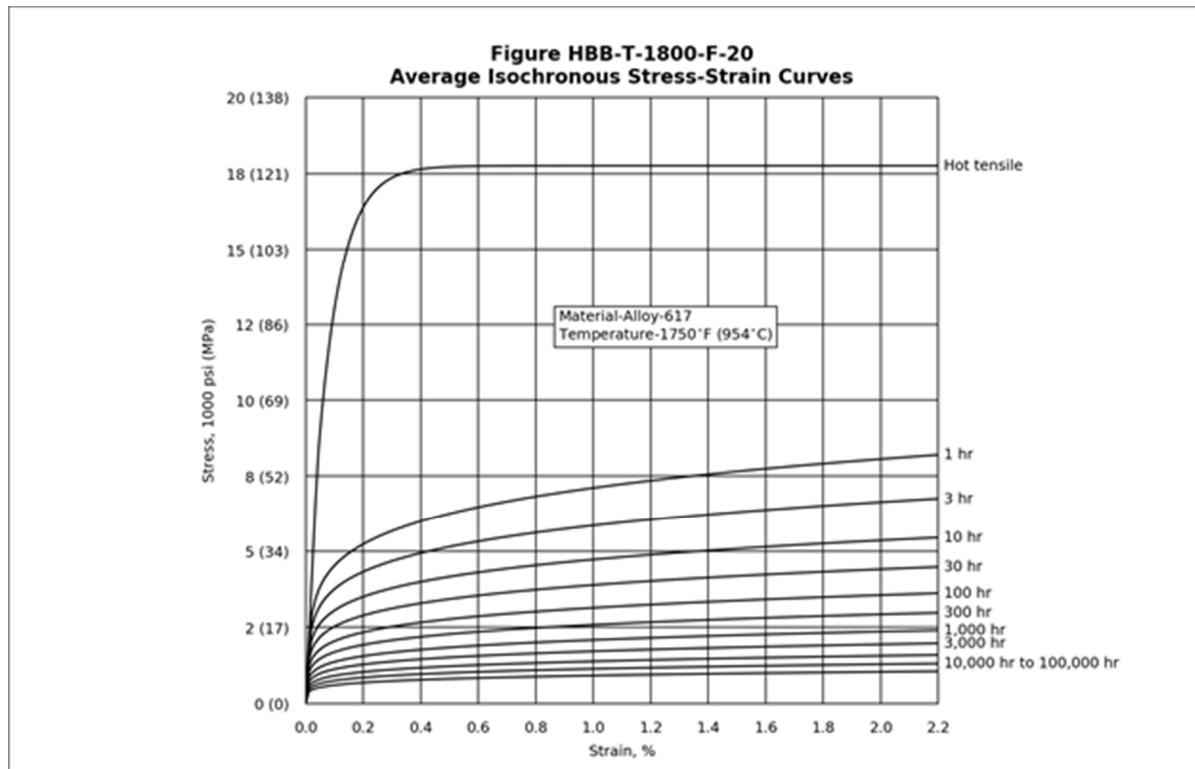
HBB-T-1700   Special Requirements

HBB-T-1710 Special Strain Requirements at Welds

HBB-T-1715   Creep-Fatigue Reduction Factors

Revise the reference for allowable number of design cycles, N_d, for parent material to Figure HBB-T-1420-1F of this Code Case. Revise the reference for the allowable time duration, T_d, based on parent material stress-to-rupture to HBB-I-14.6G of this Code Case and the reference for weld strength reduction factor to Table HBB-I-14.10F-1 of this Code Case. The factor K' is from Table HBB-T-1411-1 of this Code Case.

HBB-T-1800   Isochronous Stress‐Strain Relations

HBB-T-1810 Objective

Figures HBB-T-1800-F-1 through HBB-T-1800-F-20 of this Code Case provide graphs giving isochronous stress-strain curves, each graph being for Alloy 617 at a specific temperature. These graphs are currently under preparation.

HBB-T-1820 Materials and Temperature Limits

Data for Alloy 617 is added in Table HBB-T-1820-1 of this Code Case as indicated below.

Table HBB-T-1820-1

	Material	Maximum Temp., °F (°C)	Temperature Increment, °F (°C)
F	Alloy 617	1,750 (950)	50 (28)

Appendix B

PHYSICAL PROPERTIES TABLES

THERMAL EXPANSION

Table TE-4

Thermal Expansion for Alloy 617

Temperature, °F	Coefficients for N06617		
	A	B	C
70	7.0	7.0	0.0
100	7.1	7.0	0.3
150	7.1	7.1	0.7
200	7.2	7.1	1.1
250	7.3	7.1	1.6
300	7.4	7.2	2.0
350	7.5	7.2	2.4
400	7.6	7.3	2.9
450	7.7	7.3	3.4
500	7.8	7.4	3.8
550	7.9	7.4	4.3
600	8.0	7.5	4.8
650	8.2	7.5	5.3
700	8.3	7.6	5.8
750	8.4	7.6	6.3
800	8.6	7.7	6.8
850	8.7	7.8	7.3
900	8.9	7.8	7.8
950	9.0	7.9	8.4
1,000	9.2	8.0	8.9
1,050	9.4	8.0	9.5
1,100	9.5	8.1	10.0
1,150	9.7	8.2	10.6
1,200	9.9	8.2	11.2
1,250	10.1	8.3	11.8
1,300	10.3	8.4	12.4
1,350	10.5	8.5	13.0
1,400	10.7	8.5	13.7
1,450	10.9	8.6	14.3
1,500	11.1	8.7	15.0
1,550	11.3	8.8	15.6
1,600	11.5	8.9	16.3
1,650	11.8	9.0	17.0
1,700	12.0	9.1	17.7
1,750	12.2	9.1	18.5

GENERAL NOTE: Coefficient A is the instantaneous coefficient of thermal expansion x 10^{-6} (in./in./°F). Coefficient B is the mean coefficient of thermal expansion x 10^{-6} (in./in./°F) in going from 70°F to indicated temperature. Coefficient C is the linear thermal expansion (in./100 ft) in going from 70°F to indicated temperature.

Table TE-4 (M)
Thermal Expansion for Alloy 617

Temperature, °C	Coefficients for N06617		
	A	B	C
20	12.6	12.6	0.0
50	12.8	12.7	0.4
75	12.9	12.7	0.7
100	13.0	12.8	1.0
125	13.2	12.9	1.4
150	13.3	12.9	1.7
175	13.5	13.0	2.0
200	13.6	13.1	2.4
225	13.8	13.2	2.7
250	14.0	13.2	3.0
275	14.2	13.3	3.4
300	14.4	13.4	3.8
325	14.6	13.5	4.1
350	14.8	13.6	4.5
375	15.0	13.7	4.9
400	15.2	13.8	5.2
425	15.4	13.9	5.6
450	15.7	14.0	6.0
475	15.9	14.1	6.4
500	16.2	14.2	6.8
525	16.4	14.3	7.2
550	16.7	14.4	7.6
575	17.0	14.5	8.0
600	17.2	14.6	8.5
625	17.5	14.7	8.9
650	17.8	14.8	9.3
675	18.1	15.0	9.8
700	18.4	15.1	10.3
725	18.8	15.2	10.7
750	19.1	15.3	11.2
775	19.4	15.5	11.7
800	19.8	15.6	12.2
825	20.1	15.7	12.7
850	20.5	15.9	13.2
875	20.8	16.0	13.7
900	21.2	16.1	14.2
925	21.6	16.3	14.7
950	21.9	16.4	15.3

GENERAL NOTE: Coefficient A is the instantaneous coefficient of thermal expansion x 10^{-6} (mm/mm/°C). Coefficient B is the mean coefficient of thermal expansion x 10^{-6} (mm/mm/°C) in going from 20°C to indicated temperature. Coefficient C is the linear thermal expansion (mm/m) in going from 20°C to indicated temperature.

Thermal Conductivity and Thermal Diffusivity

Table TCD
Nominal Coefficients of Thermal Conductivity (TC) and Thermal Diffusivity (TD)
for Alloy 617

Temp., °F	N06617	
	TC	TD
70	6.1	0.112
100	6.3	0.114
150	6.6	0.118
200	6.9	0.122
250	7.2	0.125
300	7.5	0.129
350	7.8	0.132
400	8.1	0.136
450	8.4	0.139
500	8.7	0.142
550	9.0	0.145
600	9.3	0.149
650	9.5	0.152
700	9.8	0.155
750	10.0	0.158
800	10.3	0.161
850	10.5	0.164
900	10.8	0.167
950	11.0	0.171
1,000	11.3	0.174
1,050	12.1	0.177
1,100	13.2	0.181
1,150	14.1	0.184
1,200	14.6	0.188
1,250	14.9	0.192
1,300	14.8	0.194
1,350	14.7	0.191
1,400	14.6	0.189
1,450	14.5	0.188
1,500	14.6	0.189
1,550	14.7	0.191
1,600	14.9	0.193
1,650	15.1	0.196
1,700	15.5	0.199
1,750	15.9	0.203

GENERAL NOTES:

(a) TC is the thermal conductivity, Btu/(hr-ft-°F), and TD is the thermal diffusivity, ft²/hr:

$$TD = \frac{TC[Btu/hr \cdot ft - °F]}{density\ (lb/ft^3) \times specific\ heat\ (Btu/lb - °F)}$$

(b) Values of thermal expansion and thermal diffusivity should be used with the understanding that there is an associated ±10% uncertainty. This uncertainty results from compositional variations and variables associated with original data acquisition and analysis.

Table TCD (M)
Nominal Coefficients of Thermal Conductivity (TC) and Thermal Diffusivity (TD)
for Alloy 617

Temp., °C	N06617	
	TC	TD
20	10.5	2.88
50	11.1	2.99
75	11.6	3.08
100	12.1	3.17
125	12.6	3.25
150	13.0	3.33
175	13.5	3.41
200	14.0	3.49
225	14.4	3.57
250	14.9	3.64
275	15.3	3.71
300	15.8	3.79
325	16.2	3.86
350	16.6	3.93
375	17.0	4.01
400	17.4	4.08
425	17.8	4.15
450	18.2	4.22
475	18.6	4.30
500	18.9	4.37
525	19.3	4.45
550	19.6	4.53
575	21.7	4.60
600	23.3	4.69
625	24.5	4.77
650	25.3	4.85
675	25.7	4.94
700	25.7	5.03
725	25.4	4.94
750	25.3	4.89
775	25.2	4.86
800	25.2	4.87
825	25.3	4.90
850	25.5	4.94
875	25.8	5.00
900	26.2	5.07
925	26.7	5.14
950	27.4	5.22

GENERAL NOTES:
(a) TC is the thermal conductivity, W/(m·°C), and TD is the thermal diffusivity, 10^{-6} m^2/sec:

$$TD = \frac{TC[W/(m\cdot°C)]}{\text{density (kg/m}^3) \times \text{specific heat [J/(kg}\cdot°C)]}}$$

(b) Values of thermal expansion and thermal diffusivity should be used with the understanding that there is an associated ±10% uncertainty. This uncertainty results from compositional variations and variables associated with original data acquisition and analysis.

Modulus of Elasticity

Table TM-4

Moduli of Elasticity *E* of Alloy 617 for Given Temperatures

Material	Modulus of Elasticity E = Value Given × 10⁶ psi, for Temperature, °F, of

Material	-325	-200	-100	70	200	300	400	500	600	700	800	900	1,000	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800
N06617	-	-	-	29.2	28.4	28.0	27.7	27.4	27.0	26.5	26.0	25.5	24.9	24.3	23.8	23.2	22.5	21.8	21.0	20.2	19.3

Table TM-4 (M)

Moduli of Elasticity *E* of Alloy 617 for Given Temperatures

Material	-200	-125	-75	25	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950
N06617	-	-	-	201	196	193	191	189	187	184	181	178	174	171	167	164	160	156	152	146	141	136

Header for Table TM-4 (M): Modulus of Elasticity E = Value Given × 10³ MPa, for Temperature, °C, of