United States Nuclear Regulatory Commission
Protecting People and the Environment

Technical Letter Report

ORNL/SPR-2020/1653

Oak Ridge National Laboratory Technical Input for the Nuclear Regulatory Commission Review of the 2017 Edition of the ASME Boiler and Pressure Vessel Code, Section III, Division 5, "High Temperature Reactors"

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PREPARED FOR:

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TABLE OF ACRONYMS

ADAMS	Agencywide Documents Access and Management System
AISI	American Iron and Steel Institute
ANLWR	advanced non-light-water reactor
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BPVC	Boiler and Pressure Vessel Code
BPVC-II	Boiler and Pressure Vessel Code Section II
C	Celsius
ECCC	European Creep Collaborative Committee
EPRI	Electric Power Research Institute
F	Fahrenheit
FN	Ferrite Number
GTAW	Gas Tungsten Arc Welding
HJP	Hollomon-Jaffee Parameter
III-5	(BPVC) Section III Division 5
JRC	Joint Research Centre (the European Union)
LMP	Larson-Miller Parameter
N&T	normalized & tempered
NIMS	National Institute for Materials Science (Japan)
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PAW	Plasma Arc Welding
RG	Regulatory Guide
SEE	standard error of the estimate
SERs	Permit Safety Evaluation Reports
STP	Selected Technical Paper
TTP	time-temperature parameter
U.S.	United States

EXECUTIVE SUMMARY

To assist the Nuclear Regulatory Commission in its decision making on endorsement of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code Section III, Division 5 (2017 Edition) for development of advanced non-light water reactors, the following Division 5 portions were reviewed.

- Article HBB-2000 Material
- Article HCB-2000 Material
- Article HGB-2000 Material
- Mandatory Appendix HBB-I-14 Tables and Figures
- Nonmandatory Appendix HBB-U Guidelines for Restricted Material Specifications to Improve Performance in Certain Service Applications

In addition to the 2017 Edition, the same parts of the 2019 Edition have also been reviewed as indicated in various sections of the report. This review was conducted by a collaboration of national laboratory and private sector participants with significant industrial experience, including some heavy lifting and deep diving from Clarus Consulting, LLC., all intended to achieve an objective, independent, and practical perspective. The report provides recommendations, descriptions of the evaluation methods, and the source references for the data used.

To build confidence required for endorsement of the Code, this review was conducted as a verification and validation of the above Code contents. The objective of verification is to ensure that the Code is free of error – direct or implied; contains the information needed for its use, including proper coverage of the Code-specified materials for the intended application, and completeness and adequacy of references to other portions of the Code. The objective of validation is to authenticate that the Code tabulations and graphs represent design inputs consistent with what are determined using rules and methods specified by the Code. The authentication process used data that were assembled and/or generated independent of Code development, while the methods of analysis followed Code-specified methods where appropriate.

The designated portions for this review cover the five alloys codified for high temperature reactor applications in Division 5, i.e. 316 SS, 304 SS, 800H, 2¼Cr-1Mo, and 9Cr-1Mo-V, regarding their general requirements, permitted specifications and design stress intensity values for pressure-retaining applications, deterioration in service, fatigue acceptance test, permissible weld materials, tensile and yield strength, expected minimum stress-to-rupture values (including for Alloy 718), weld stress rupture factors, permissible materials for bolting use, and restricted specifications in certain service applications. Additionally, stress intensity values for bolting materials including 316 SS, 304 SS and alloy 718 were reviewed. Analysis and discussion are also provided on contents outside of these designated Code portions where it was deemed relevant and necessary to develop a technically sound understanding of issues relating to the designated portions.

Due to unavailability of sufficient test data on welds during the review period, the weld stress rupture factors in Tables HBB-I-10.14A to E, which cover a total of ten tables for the five alloys welded with twenty-eight different weld metals (some with similar properties), have been deferred to a future review effort.

The review identified mainly two types of issues. The first type includes instances where the Code is found factually incomplete or incorrect, such as obsolete materials specifications listings and missing tabulation of stresses for bolting. Changes to the Code are recommended in these cases.

The second type of issue includes instances where the Code tabulations and graphs are found to be less conservative than the review analysis results. In these cases, recommendations are made for further review and consideration where the difference in conservatism exceeds 10%, which is our threshold for questioning technical adequacy, meriting a risk assessment by the Nuclear Regulatory Commission and/or reactor designers. It is noted that this effort has been executed using all available data and established methods of analysis, including methods and criteria specified and used by the Code. As such, the findings that are presented in quantitative detail, in a format for convenient comparison with the Code, and with identification of where further review is recommended, should provide a sound technical basis for quantifying the implications of the reduced design margins and technical adequacy/inadequacy in order to form a basis for conditioning specific Code tabulation values on endorsement. Recommendations for specific changes to the Code, however, entail design conservatism considerations beyond the scope of this review effort, and are not made in this report.

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1. INTRODUCTION

1.1. Background

The absence of a code of construction endorsed by the United States (U.S.) Nuclear Regulatory Commission (NRC) for nuclear reactors operating above 425°C (800°F) is a significant obstacle for advanced non-light water reactor (ANLWR) designs. Review and approval of an elevated temperature code of construction during a licensing review of a new nuclear power plant would result in substantial cost and a longer schedule.

In a letter dated June 21, 2018 (ADAMS Accession No. ML18184A065), American Society of Mechanical Engineering (ASME), based on letters from both industry consortia and individual companies interested in developing ANLWR designs, requested the NRC review and endorse the 2017 Edition of ASME Boiler and Pressure Vessel Code (BPVC) Section III, Division 5, "High Temperature Reactors." The NRC responded in a letter dated August 16, 2018 (ADAMS Accession No. ML18211A571) that the NRC is initiating efforts to endorse (with conditions, if necessary) the 2017 Edition of ASME Section III, Division 5 in a new Regulatory Guide (RG) as one way of meeting the NRC's regulatory requirements.

In order to support the review and endorsement effort, the NRC requested the technical support of Oak Ridge National Laboratory (ORNL). This report documents ORNL's technical input for the NRC's review of the 2017 Edition of ASME Section III, Division 5. This report will be used as part of the NRC's review and to support the NRC's findings in the associated RG as needed.

2. OVERVIEW

2.1. Review Approach

The NRC wants to ensure its licensing reviews are performed commensurate with its safety and security mission and requested ORNL to perform its technical review in accordance with the guidance in two recent NRC examples. One example is the NRC Transformation Team, which provided their findings in SECY-18-0060, "Achieving Modern Risk-Informed Regulation," dated June 8, 2018 (ADAMS Package Accession Number ML18110A186). Another example is an NRC memo from Frederick Brown, Director, Office of New Reactors, titled, "Expectations for New Reactor Reviews," dated August 29, 2018 (ADAMS Accession No. ML18240A410). This memo is further described below.

One of the expectations in the NRC memo is to base the NRC's regulatory findings upon the principle of "Reasonable Assurance of Adequate Protection" (of public health and safety), but not on absolute certainty or risk avoidance. This is the legal standard for the NRC's licensing decisions. The memo discusses considerations for the terms "reasonable" and "adequate."

The RG that will endorse the use of ASME Section III, Division 5 will be based on the finding that the rules in Division 5 provide "Reasonable Assurance of Adequate Protection." In accordance with the Memo, new or novel designs or design features may need additional review and/or requirements. Furthermore, any technical areas that are not addressed by ASME Section III, Division 5, and would lead to a demonstrably increased likelihood or consequence of failure, should be considered.

Another area of the memo is the consideration of margin. If the ASME Code is sufficiently conservative in a particular area such that it provides significant margin to relevant limits, and sufficient data exists to support the Code values, then the review in that area should be reduced. In contrast, where the Code includes lesser margin and less supporting data, then the review in that area should be increased to ensure that the staff has an adequate basis for endorsing the Code and any associated conditions. In any case, the review must either conclude that the Code provides reasonable assurance of adequate protection, or that the NRC cannot endorse that section of the Code and the basis for concluding so.

Similarly, the memo discusses making safety evaluations more succinct, and including only the information necessary to make the NRC staff's safety findings. Therefore, this report provides a concise basis for its conclusions, while also maintaining clarity and completeness. This report focuses on why and how ORNL reached its conclusions without unnecessary historical or tangential information.

The NRC performed research to establish the scope of the review. This research includes a historical review on previous high temperature design rules and NRC approvals. The NRC's specific historical findings will be fully documented in the final RG or another accompanying NRC document. The specific historical findings relevant to this report are discussed below.

This report considers the adequacy of the technical basis provided in the ASME Code, including the quality and quantity of the underlying data within the context of the selected safety margins. This report also considers the previous NRC historical findings, current operating experience, and international experience including similar design rules, as applicable.

The approach of this research was to help evaluate and build confidence required for endorsement of the ASME Code through verification and validation. In verification, efforts were focused on whether the reviewed Code portions were developed as intended, free of error, and whether information integrity was well maintained with proper coverage of the codified materials for the intended applications as well as completeness and adequacy of references to other portions of the Code. In validation, effort was made to authenticate, by garnering and using test datasets that were assembled and/or generated independently of Code development, that the Code curves and tables can function as intended with reasonable assurance. In the authentication analysis, the garnered datasets were analyzed in compliance with ASME rules and guidelines for Code design stress value development to examine relative margins on time, temperature, and design stress, with considerations of variations in material properties when applicable.

2.2. Historical Basis

The NRC researched previous high temperature design rules and NRC approvals to establish the scope of the review. These reviews included historical RGs, Code Cases, Construction Permit Safety Evaluation Reports (SERs), and pre-application SERs. The NRC found that the following ASME Code Cases were accepted for use, with conditions, in NRC Regulatory Guide 1.87, Guidance for Construction of Class 1 Components in Elevated-Temperature Reactors

(Supplement to ASME Section III Code Cases 1592, 1593, 1594, 1595, and 1596), Revision 1, dated June 1975.

- ASME Code Case 1592, Class 1 Components in Elevated Temperature Service Section III, Division 1, Revision 0, dated April 29, 1974.
- ASME Code Case 1593, Fabrication and Installation of Elevated Temperature Components Section III, Class 1, Revision 0, dated November 5, 1973
- ASME Code Case 1594, Examination of Elevated Temperature Nuclear Components Section III, Class 1, Revision 0, dated November 5, 1973
- ASME Code Case 1595, Testing of Elevated Temperature Nuclear Components Section III, Class 1, Revision 0, dated November 5, 1973
- ASME Code Case 1596, Protection Against Overpressure or Elevated Temperature Components Section III, Class 1, Revision 0, dated November 5, 1973

This technical report uses these Code Cases as a basis for the review of the 2017 Edition of ASME Section III, Division 5.

2.3. Review Scope

The specific portions of the Code (i.e. Subsection, Article, Code Case, etc.) that are reviewed, and the reviewing organization are listed in Table 1, "Review Assignments."

Some assignments have additional detail provided related to supporting another contractor's review. For example, the contractor listed for Class A Metallic Pressure Boundary Components, Elevated Temperature Service (HBB), Article 2000, Material is responsible for documenting the assessment for Article 2000. However, during their review they may need to support the contractor that is responsible for reviewing HBB, Article 3000, Design.

Similarly, contractors may need to review information within other portions of the Code to support the review of their assignments. For example, the contractor responsible for reviewing Article 3000 may need to review information in Article 2000. If the Article 3000 contractor has concerns with Article 2000, then the Article 3000 contractor should discuss with the Article 2000 contractor. The Article 3000 contractor is not responsible for any part of the documentation for Article 2000, although the Article 3000 review may impact the Article 2000 review and documentation.

Table 1, Review Assignments

Task B, General Requirements, Low Temperature Metallic Components, and Supports:

ASME Code Section	Reviewer
General Requirements, Metallic Materials (Subsection HAA)	NRC Staff
Class A Metallic Pressure Boundary Components, Low Temperature Service (HBA)	NRC Staff
Class B Metallic Pressure Boundary Components (HCA)	NRC Staff
Class A and Class B Metallic Supports, Low Temperature Service (HFA)	NRC Staff

ASME Code Section	Reviewer
Class A Metallic Core Support Structures, Low Temperature Service (HGA)	NRC Staff

Task C, Elevated Temperature Metallic Components:

ASME Code Section	Reviewer
Class A Metallic Pressure Boundary Components, Elevated Temperature Service (HBB)	
1000 Introduction	NRC Staff
2000 Material	ORNL
3000 Design	PNNL
4000 Fabrication and Installation	PNNL
5000 Examination	PNNL
6000 Testing	PNNL
7000 Overpressure Protection	NRC Staff
8000 Nameplates, Stamping with the Certification Mark, and Reports	NRC Staff
Mandatory Appendix HBB-I-14 Tables and Figures	ORNL
Mandatory Appendix HBB-II Use of SA-533 Type B, Class 1 Plate and SA-508 Grade 3, Class 1 Forgings and Their Weldments for Limited Elevated Temperature Service	NUMARK
Nonmandatory Appendix HBB-T Rules for Strain, Deformation, and Fatigue Limits at Elevated Temperatures	NUMARK
Nonmandatory Appendix HBB-U Guidelines for Restricted Material Specifications to Improve Performance in Certain Service Applications	ORNL
Nonmandatory Appendix HBB-Y Guidelines for Design Data Needs for New Materials	Not reviewed
Class B Metallic Pressure Boundary Components, Elevated Temperature Service (HCB)	
1000 Introduction	NRC Staff
2000 Material	ORNL
3000 Design	PNNL
4000 Fabrication and Installation	PNNL
5000 Examination	PNNL
6000 Testing	PNNL
7000 Overpressure Protection	NRC Staff
8000 Nameplates, Stamping with the Certification Mark, and Reports	NRC Staff
Mandatory Appendix HCB-I Stress Range Reduction Factor for Piping	NUMARK
Mandatory Appendix HCB-II Allowable Stress Values for Class B Components	NUMARK
Mandatory Appendix HCB-III Time-Temperature Limits for Creep and Stress-Rupture Effects	NUMARK
Class A Metallic Core Support Structures, Elevated Temperature Service (HGB)	
1000 Introduction	NRC Staff
2000 Material	ORNL
3000 Design	PNNL
4000 Fabrication and Installation	PNNL
5000 Examination	PNNL
8000 Nameplates, Stamping with the Certification Mark, and Reports	NRC Staff

ASME Code Section	Reviewer
Mandatory Appendix HGB-I Rules for Strain, Deformation, and Fatigue Limits at Elevated Temperatures	PNNL
Mandatory Appendix HGB-II Rules for Construction of Core Support Structures, Extended for Restricted Service at Elevated Temperature, Without Explicit Consideration of Creep and Stress-Rupture	PNNL
Mandatory Appendix HGB-III Buckling and Instability	PNNL
Mandatory Appendix HGB-IV Time–Temperature Limits	PNNL

Task D, Graphite and Composites:

ASME Code Section	Reviewer
General Requirements, Graphite and Composite Materials (HAB)	
1000 Introduction 2000 Classification of Graphite Core Components 3000 Responsibilities and Duties 4000 Quality Assurance 5000 Authorized Inspection 7000 Reference Standards 8000 Certificates and Data Reports 9000 Glossary	NRC Staff
Mandatory Appendix HAB-I Certificate Holder's Data Report Forms, Instructions, and Application Forms for Certificates of Authorization	NRC Staff
Class A Nonmetallic Core Components, Graphite Materials (HHA)	
1000 Introduction 2000 Material 3000 Design 4000 Fabrication and Installation 5000 Examination	NUMARK
8000 Nameplates, Stamping with the Certification Mark, and Reports	NRC Staff
Mandatory Appendix HHA-I Graphite Material Specifications	NUMARK
Mandatory Appendix HHA-II Requirements for Preparation of a Material Data Sheet	NUMARK
Mandatory Appendix HHA-III Requirements for Generation of Design Data for Graphite Grades	NUMARK

Task E, Code Cases

Code Case	Code Case Title	Reviewer
N-861	Satisfaction of Strain Limits for Division 5 Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis	NUMARK
N-862	Calculation of Creep-Fatigue for Division 5 Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis	NUMARK
N-822	Application of the ASME Certification Mark	NRC Staff
N-837	Alternative to the Registered Professional Engineer Requirements	NRC Staff
N-852	Application of the ASME NPT Stamp	NRC Staff

2.4. Report Organization

This technical report uses the same nomenclature as the ASME Boiler and Pressure Vessel Code. The organization of ASME Code Section III is summarized below.

ASME Code Section III consists of Divisions. Divisions are broken down into Subsections. Subsections may be divided into Subparts, or more generally into Articles, subarticles, paragraphs, and, where necessary, subparagraphs and subsubparagraphs.

Articles are designated by the applicable letters indicated above for the Subsections and Subparts where applicable, followed by Arabic numbers, such as NB-1000. Where possible, Articles dealing with the same topics are given the same number in each Subsection, except NCA.

Subarticles are numbered in units of 100, such as NB-1100.

Subsubarticles are numbered in units of 10, such as NB-2130, and may have no text.

Paragraphs are numbered in units of 1, such as NB-2121.

Subparagraphs, when they are major subdivisions of a paragraph, are designated by adding a decimal followed by one or more digits to the paragraph number, such as NB-1132.1. When they are minor subdivisions of a paragraph, subparagraphs may be designated by lowercase letters in parentheses, such as NB-2121(a).

Subsubparagraphs are designated by adding lowercase letters in parentheses to the major subparagraph numbers, such as NB-1132.1(a). When further subdivisions of minor subparagraphs are necessary, subsubparagraphs are designated by adding Arabic numerals in parentheses to the subparagraph designation, such as NB-2121(a)(1).

3. TECHNICAL REVIEW SYNOPSIS

3.1. Article HBB-2000 Material

HBB-2100

HBB-2120 PRESSURE-RETAINING MATERIALS

HBB-2121, Permitted Material Specifications
It is recommended that HBB-2121 be accepted as is because (a) and (d) are consistent with paragraph HBB-2121(a) and (c) of NRC approved precedent ASME Code Case 1592 (Ref. Case 1592) and (b), (c), (e), (f), (g), and (h) do not specify detailed requirements but provides a procedural statement referring to tables, rules, and requirements that are separately evaluated.

HBB-2123, Design Stress Intensity Values
It is recommended that HBB-2123 be accepted as is because it does not specify detailed requirements but provides a procedural statement referring to tables, rules, and requirements whose acceptance must be separately reviewed.

HBB-2160, DETERIORATION OF MATERIAL IN SERVICE
It is recommended that BPVC 2017 (and 2019) III-5 HBB-2160(a), (b), and (c) be accepted as is because they do not specify detailed requirements, but appropriately indicate the responsibility of the Owner in considering materials factors affecting in-service deterioration.

It is recommended that BPVC 2017 (and 2019) III-5 HBB-2160(d) be accepted after consideration is given to review the yield and tensile strength reduction factors for 2¼Cr-1Mo and 9Cr-1Mo-V, and those for 800H at temperatures > 1400°F (760°C) because they appear non-conservative relative to our analysis results.

Details on supporting data and evaluations are provided in Section 4 HBB-2160.

HBB-2400

HBB-2430

HBB-2433, Delta Ferrite Determination
It is recommended that BPVC 2017 (and 2019) III-5 HBB-2400, including Table HBB-I-14.1(b) that is referred to, be accepted with the condition that the alternative delta ferrite determination by the wire manufacturer chemical analysis without preparation of a weld pad in HBB-2433.1 Method is limited to filler metals used with Gas Tungsten Arc Welding (GTAW) and Plasma Arc Welding (PAW) as currently directed by NRC Regulatory Guide 1.31 Rev. 4 (Ref. NRC RG 1.31 R4). Details of the condition and rationale are given in Section 4 HBB-2400. For electronic searchability, individual major divisions of the subparagraph corresponding to the organization of BPVC Section III are listed as follows:

HBB-2433.1, Method

HBB-2433.2, Acceptance Standards

HBB-2500

HBB-2530

HBB-2539, Repair by Welding
It is recommended that BPVC 2017 (and 2019) III-5 HBB-2539 be accepted as is because it mainly provides a procedural statement referring to tables, rules, and requirements whose acceptance must be separately approved by NRC.

HBB-2800, FATIGUE ACCEPTANCE TEST
It is recommended that BPVC 2017 (and 2019) III-5 HBB-2800 be accepted as is because it ensures adequate creep-fatigue resistance of 304 SS and 316 SS. An editorial correction of "paras. 6.1.1 and 6.1.2" to "paras. 8.1.1 and 8.1.2" in HBB-2800 (b) is required. Inclusion of the other alloys is a moot point.

3.2. Mandatory Appendix HBB-I-14 Tables and Figures

Table HBB-I-14.1(a), Permissible Base Materials for Structures other than Bolting
It is recommended that Table HBB-I-14.1(a) be accepted with the following conditions. Explanations for the conditions are provided in Section 4 Table HBB-I-14.1(a).

Conditions

Types 304 SS and 316 SS**:**

1. SA-430 is deleted from the list of specifications.
2. Note (2) includes an added requirement, such as: "The heat treatment is to be separately performed, and in process heat treatment such as by direct quenching from hot forming is not permitted."

2¼Cr-1Mo**:**

3. Under Note (6) clause (c), "Note (4)" is changed to "Note (5)."
4. In the line for SA-234, "WP22, WP22W" is replaced with "WP22 CL1."
5. A note for minimum annealing temperature and a normalizing temperature of 1,650°F (900°C) that ensures meeting the strength requirements is added.

Table HBB-I-14.1(b) Permissible Weld Materials
It is recommended that BPVC 2017 (and 2019) III-5 Table HBB-I-14.1(b), which is referred to in HBB-2539 Repair by Welding, be held for further review before it is accepted as part of the accepted HBB-2400. The materials listed are standard weld materials. However, the weldment properties-related reviews have not been concluded (see review report on Tables HBB-I-14.10A~E), and possible restrictions on the use of this table are currently unknown.

Table HBB-I-14.2, S_o — Maximum Allowable Stress Intensity, ksi (MPa), for Design Condition Calculations
It is recommended that Table HBB-I-14.2 be considered for further review as appropriate before being accepted because the S_o values at the higher temperatures are generally non-conservative compared to our analysis results and are also inconsistent with the 100,000-hour S_r values in BPVC 2017 (and 2019) III-5 Table HBB-I-14.6 over a significant portion of the time-dependent stress-controlled range. Details of the analysis and the need for further review are given in Section 4 Table HBB-I-14.2.

Figures and Tables HBB-I-14.3A ~ E, S_{mt} — Allowable Stress Intensity Values
It is recommended that BPVC 2017 III-5 Figures and Tables HBB-I-14.3A ~ E be considered for further review as appropriate before being accepted because the S_{mt} values are non-conservative compared to our analysis results, particularly in the time-temperature range over which the S_{mt} values are controlled by the time-dependent stress. It is noted, however, that Figure and Table HBB-I-14.3E for 9Cr-1Mo-V have been updated in BPVC 2019 III-5 and the 2019 edition Figure and Table HBB-I-14.3E are not recommended for further review. Details of

the analysis and the need for further review are given in Section 4 Figures and Tables HBB-I-14.3A ~ E. For electronic searchability, individual figure and table names corresponding to the organization of BPVC Section III are listed as follows:

Figure HBB-I-14.3A, S_{mt} — Type 304 SS

Table HBB-I-14.3A, S_{mt} — Allowable Stress Intensity Values, 1,000 psi, Type 304 SS — 30-YS, 75-UTS (30-YS, 70-UTS)

Figure HBB-I-14.3B, S_{mt} — Type 316 SS

Table HBB-I-14.3B, S_{mt} — Allowable Stress Intensity Values, 1,000 psi, Type 316 SS — 30-YS, 75-UTS (30-YS, 70-UTS)

Figure HBB-I-14.3C, S_{mt} — Ni-Fe-Cr (Alloy 800H)

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

Figure HBB-I-14.3D, S_{mt} — 2¼Cr-1Mo

Table HBB-I-14.3D, S_{mt} — Allowable Stress Intensity Values, ksi (MPa), 2¼Cr-1Mo

Figure HBB-I-14.3E, S_{mt} — 9Cr-1Mo-V

Table HBB-I-14.3E, S_{mt} — Allowable Stress Intensity Values, ksi (MPa), 9Cr-1Mo-V.

Figures and Tables HBB-I-14.4A ~ E, S_t — Allowable Stress Intensity Values

It is recommended that BPVC 2017 III-5 Figures and Tables HBB-I-14.4A ~ E be considered for further review as appropriate before being accepted because the S_t values are non-conservative compared to our analysis results, particularly in the high temperature and long service life regime. It is noted, however, that Figure and Table HBB-I-14.4E for 9Cr-1Mo-V have been updated in BPVC 2019 III-5 and the 2019 edition Figure and Table HBB-I-14.4E are not recommended for further review. Details of the analysis and the need for further review are given in Section 4 Figures and Tables HBB-I-14.4A ~ E. For electronic searchability, individual figure and table names corresponding to the organization of BPVC Section III are listed as follows.

Figure HBB-I-14.4A, S_t — Type 304 SS

Table HBB-I-14.4A, S_t — Allowable Stress Intensity Values, 1,000 psi (MPa), Type 304 SS

Figure HBB-I-14.4B, S_t — Type 316 SS

Table HBB-I-14.4B, S_t — Allowable Stress Intensity Values, 1,000 psi (MPa), Type 316 SS

Figure HBB-I-14.4C, S_t — Ni-Fe-Cr (Alloy 800H)

Table HBB-I-14.4C, S_t — Allowable Stress Intensity Values, ksi (MPa), Ni-Fe-Cr (Alloy 800H)

Figure HBB-I-14.4D, S_t — 2¼Cr-1Mo

Table HBB-I-14.4D, S_t — Allowable Stress Intensity Values, ksi (MPa), 2¼Cr-1Mo

Figure HBB-I-14.4E, S_t — 9Cr-1Mo-V

Table HBB-I-14.4E, St — Allowable Stress Intensity Values, ksi (MPa), 9Cr-1Mo-V.

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

It is recommended that BPVC 2017 (and 2019) III-5 Table HBB-I-14.5 be accepted after consideration is given to review the S_Y values for 304 SS at the two highest temperatures that appear non-conservative relative to our analysis results. It is noted that for 2¼Cr-1Mo, while the tabulated S_Y are acceptable, the strength of annealed material and of normalized and tempered material differ, with application of the tabulation to normalized and tempered material being less conservative than application to annealed material.

Details on supporting data and evaluations are provided in Section 4 Table HBB-I-14.5.

Figures and Tables HBB-I-14.6A ~ F, Minimum Stress-to-Rupture

It is recommended that, among BPVC 2017 III-5 Figures and Tables HBB-I-14.6A to HBB-I-14.6F, HBB-I-14.6C and E be accepted, but the others be considered for further review as appropriate because their S_r values are non-conservative compared to our analysis results, particularly in the high temperature and long service life regime. It is noted, however, that Figure and Table HBB-I-14.4F for 9Cr-1Mo-V have been updated in BPVC 2019 III-5 and the 2019 edition Figure and Table HBB-I-14.4F are acceptable and not recommended for further review. Details of the analysis and the need for further review are given in Section 4 Figures and Tables HBB-I-14.6A ~ F. For electronic searchability, individual figure and table names corresponding to the organization of BPVC Section III are listed as follows.

Figure HBB-I-14.6A, Minimum Stress-to-Rupture

Table HBB-I-14.6A, Expected Minimum Stress-to-Rupture Values, 1,000 psi (MPa), Type 304 SS

Figure HBB-I-14.6B, Minimum Stress-to-Rupture

Table HBB-I-14.6B, Expected Minimum Stress-to-Rupture Values, 1,000 psi (MPa), Type 316 SS

Figure HBB-I-14.6C, Minimum Stress-to-Rupture — Ni-Fe-Cr (Alloy 800H)

Table HBB-I-14.6C, Expected Minimum Stress-to-Rupture Values, ksi (MPa), Ni-Fe-Cr (Alloy 800H)

Figure HBB-I-14.6D, 2¼Cr-1Mo — 100% of the Minimum Stress-to-Rupture

Table HBB-I-14.6D, 2¼Cr-1Mo — Expected Minimum Stress-to-Rupture Values, ksi (MPa)

Figure HBB-I-14.6E, Minimum Stress-to-Rupture, Alloy 718

Table HBB-I-14.6E, Expected Minimum Stress-to-Rupture Values, ksi (MPa), Ni-Cr-Fe-Mo-Cb (Alloy 718)

Figure HBB-I-14.6F, 9Cr-1Mo-V — Expected Minimum Stress-to-Rupture, ksi (MPa)

Table HBB-I-14.6F, 9Cr-1Mo-V, S_r — Expected Minimum Stress-to-Rupture Values, ksi (MPa)

Tables HBB-I-14.10A-1 ~ E-1, Stress Rupture Factors for X Alloy Welded With L; M; and N
A recommendation on the acceptability of these tables was not reached.

Table HBB-I-14.11, Permissible Materials for Bolting
It is recommended that BPVC 2017 (and 2019) III-5 Table HBB-I-14.11 be accepted with a minor editorial correction as shown in Section 4 Table HBB-I-14.11.

Table HBB-I-14.12, S_o Values for Design Conditions Calculation of Bolting Materials S_o Maximum Allowable Stress Intensity, ksi (MPa)
It is recommended that BPVC 2017 (and 2019) III-5 Table HBB-I-14.12 be considered for further review as appropriate before being accepted because of a potential non-conservatism compared to our analysis results in the time-dependent stress values at the highest temperature(s) in case of 304 SS and 316 SS. In addition, it is recommended that a criteria/definition for S_o be considered as a condition for acceptance.

Details of the analysis supporting the need for further review are given in Section 4 Table HBB-I-14.12.

Figures and Table HBB-I-14.13A ~ C. S_{mt} –Allowable Stress Intensity of Bolting Materials
It is recommended that BPVC 2017 (and 2019) III-5 Figures HBB-I-14.13A, B and C, and Table HBB-I-14.13C be accepted with the following conditions recommended for consideration:

1. Add corresponding stress Tables HBB-I-14.13A and B
2. Add criteria/definitions of S_t, S_m and S_{mt} for bolting materials.
3. Review of the 304 SS and 316 SS S_t values that appear non-conservative relative to our analysis results.

Explanation of the conditions and analysis supporting the recommendations are given in Section 4 Figures and Table HBB-I-14.13A ~ C.

For electronic searchability, individual figure and table names corresponding to the organization of BPVC Section III are listed as follows:

Figure HBB-I-14.13A, S_{mt} — Allowable Stress Intensity, Type 304 SS, Bolting

Figure HBB-I-14.13B S_{mt} — Allowable Stress Intensity, Type 316 SS, Bolting

Figure HBB-I-14.13C S_{mt} — Allowable Stress, Alloy 718, Bolting

Table HBB-I-14.13C S_{mt} — Allowable Stress Values, ksi (MPa), Alloy 718, Bolting

3.3. Nonmandatory Appendix HBB-U Guidelines for Restricted Material Specifications to Improve Performance in Certain Service Applications

It is recommended that Nonmandatory Appendix HBB-U, which includes the subarticles and subsubarticle listed below, be accepted as is because it contains no technical guidelines in conflict with materials specifications, does not impact other requirements, and is judged to help assure material performance in the temperature regime, 800-1100°F (425-595°C) as noted in HBB-U-1200.

HBB-U-1100, Scope

HBB-U-1110, Objectives

HBB-U-1200, Service Conditions

HBB-U-1300, Recommended Restrictions

Table HBB-U-1, Recommended Restrictions
It is recommended that Table HBB-U-1 be accepted as is since its application is expected to assure, and on average, improve material performance, as commented in Section 4 Table HBB-U-1.

3.4. Article HCB-2000 Material

HCB-2100, GENERAL REQUIREMENTS FOR MATERIAL
It is recommended that BPVC 2017 (and 2019) III-5 HCB-2100 be accepted as is because the general requirements are plain procedural statements, referring to Division 1, Article NC-2000 (with stated exceptions) and Mandatory Appendix HCB-II whose acceptance must be separately approved by NRC and is beyond the review scope for the present Subarticle.

HCB-2400

HCB-2430

HCB-2433

HCB-2433.2, Acceptance Standards
It is recommended that BPVC 2017 (and 2019) III-5 HCB-2433.2 be accepted with a clarification of applicability to material types because some alloys covered in Table HBB-I-14.1(a) can be dominantly ferritic and Mandatory Appendix HCB-II referred to in HCB-2100 causes further ambiguity.

HCB-2500

HCB-2570

HCB-2571, Required Examination
It is recommended that BPVC 2017 (and 2019) III-5 HCB-25710 be accepted as is because it provides plain procedural statements referring to other portions of the code whose acceptance must be separately approved by NRC and is beyond the review scope for the present Paragraph. A clarification of material type applicability should also be added as recommended in HCB-2433.2.

For electronic searchability, individual major divisions of the subparagraph corresponding to the organization of BPVC Section III are listed as follows:

HCB-2571.1, Method

HCB-2571.2, Acceptance Standards

3.5. Article HGB-2000 Material

HGB-2100, GENERAL REQUIREMENTS FOR MATERIAL
It is recommended that BPVC 2017 (and 2019) III-5 HGB-2100 be accepted as is because the general requirements are plain procedural statements, referring to Division 1, Article NG-2000 (with stated exceptions) whose acceptance must be separately approved by NRC and is beyond the review scope for the present Subarticle.

HGB-2120

HGB-2121, Permitted Material Specifications
It is recommended that BPVC 2017 (and 2019) III-5 HGB-2121 be accepted as is because the stipulations are clarification of Certificate Holder's responsibilities (b) and procedural statements (with stated exceptions) (a) (c) referring to tables, rules, and requirements whose acceptance must be separately approved by NRC and is beyond the review scope for the present Paragraph. Review recommendation on the referred Table HBB-I-14.1(a) for base materials, Table HBB-I-14.11 for threaded structural fasteners, Table HBB-I-14.1(b) for weld materials, and Nonmandatory Appendix HBB-U guidelines for restricted material specifications to improve performance in certain elevated temperature applications where creep effects are significant can be found in other sections of the present report.

HGB-2160, DETERIORATION OF MATERIAL IN SERVICE
It is recommended that BPVC 2017 (and 2019) III-5 HGB-2160 be accepted as is because the stipulations do not specify detailed requirements, but appropriately indicate the responsibility of the Owner in considering materials factors affecting in-service deterioration and refer to rules and requirements whose acceptance must be separately approved by NRC and is beyond the review scope for the present Subsubarticle. Please refer to the review findings regarding HBB-2160 for information relating to the handling of material strength deterioration in elevated

temperature service for materials covered in Subpart HBB. BPVC XI Division 2 also provides stipulations regarding in-service deterioration and degradation mechanisms.

HGB-2400

HGB-2430

HGB-2433

HGB-2433.2, Acceptance Standards
It is recommended that BPVC 2017 (and 2019) III-5 HGB-2433.2 be accepted with a clarification of applicability to material types because some alloys covered in Table HBB-I-14.1(a) can be dominantly ferritic.

4. TECHNICAL REVIEW DETAIL

4.1. Article HBB-2000 Material

HBB-2100

HBB-2160, DETERIORATION OF MATERIAL IN SERVICE

HBB-2160(d)(3)(-a) through (-e):
Observations Indicating Need for Review Consideration

The yield strength and tensile strength reduction factors for 2¼Cr-1Mo and 9Cr-1Mo-V in BPVC 2017 (and 2019) III-5 Table HBB-3225-2 are not verified. Specifically,

- The yield strength reduction factors for 2¼Cr-1Mo as listed in BPVC 2017 (and 2019) III-5 Table HBB-3225-3A by reference in Table HBB-3225-2 are judged to be non-conservative. The judgment is based on the preliminary analysis of published data on laboratory aging experiments of the alloy, as summarized in Table R.3225-3A.
- The tensile strength reduction factors for 2¼Cr-1Mo as listed in BPVC 2017 (and 2019) III-5 Table HBB-3225-3B by reference in Table HBB-3225-2 are judged to be non-conservative. The judgment is based on the preliminary analysis of published data on laboratory aging experiments of the alloy, as summarized in Table R.3225-3B.
- The yield strength reduction factor for 9Cr-1Mo-V of 1.0 for temperature and exposure duration conditions ≥ 900°F (480°C) as listed in Table HBB-3225-2 is judged to be non-conservative. The judgment is based on the published tempering response of the alloy and preliminary analysis of aging experiments, as summarized in Table R.3225-2a.
- The tensile strength reduction factors for 9Cr-1Mo-V as listed in BPVC 2017 (and 2019) III-5 Table HBB-3225-4 by reference in Table HBB-3225-2 are judged to be generally acceptable and in reasonable agreement with our analysis as summarized in Table R.3225-4. However, other reported values suggest a non-conservatism, meriting consideration of a review.

The yield strength and tensile strength reduction factor for 800H of 0.90 for exposure temperature ≥ 1350°F (730°C) in BPVC 2017 (and 2019) III-5 Table HBB-3225-2 is potentially non-conservative, meriting further review. Specifically,

- Limited data for exposure temperature ≥ 1425°F (775°C) indicates strength reduction factors < 0.90 as summarized in Table R.3225-2b.

Basic Methods of Analysis

In case of 304 SS and 316 SS, the data reviewed for aging behavior showed no significant effect and need for a quantitative analysis (see Analysis and Discussion of Results). In case of 800H, the data reviewed are insufficient for a detailed quantitative evaluation, although simplified factors have been derived for perspective (see Analysis and Discussion of Results).

For the ferritic materials, 2¼Cr-1-Mo and 9Cr-1Mo-V, the issue of the dependence of yield and tensile strength on elevated-temperature exposure time and temperature is more significant, and the available data appear sufficient to conduct a quantitative analysis for aging factors. The general analysis approach used a time-temperature parameter (TTP) – Hollomon-Jaffee Parameter (HJP) in this case – traditionally used for evaluating tempering of ferritic steels (Ref. Hollomon 1945).

Since the 1945 Hollomon-Jaffee paper, (the identical Larson-Miller Parameter (LMP) followed in 1952), there have been numerous published studies and reviews regarding use of the parameter in tempering, with just a few examples (Ref. Parker 2013, Ref. Thomas 2008, Ref. Canale 2008, and Ref. Klueh 1988).

Excluding the effect of in-service stress on the aging response, the extension of the application of the TTP for tempering to predicting material strength with long-term aging follows from the strength-controlling microstructure changes being the same. This very Subpart of Section III, Division 5 being discussed specifies an HJP-based method for computing equivalent time for aging at varying temperatures and times in order to use the ASME-tabulated factors for 2¼Cr-1-Mo and 9Cr-1Mo-V (HBB-2160(d)). A few examples of the published work on the aging application are (Ref. Kim 2009, Ref. Yang 2004, Ref. Cardoso 2015, and Ref. ECCC 2005).

The European Creep Collaborative Committee (ECCC) recommends the use of a normalized hardness (aged-to-unaged ratio) versus HJP or LMP curve (2nd order fit), developed by Gooch et al. (National Power, UK) for aged hardness predictions (Ref. ECCC 2005). The curve, although having a wide uncertainty range, represents a single collapsed “master” curve, independent of initial hardness. Our curve-fitting analysis method follows the collapsed curve target approach by using the reduction factor to replace the normalized hardness, as measured for each case of material heat-initial strength-aged strength combination data point. The HJP constant is curve-fit optimized to minimize the standard error of the fit estimate. Our preference is to use a 1st order fit if the fit appears acceptable (used for 2¼Cr-1Mo) and a 2nd order fit otherwise (used for 9Cr-1Mo-V). The collapsed reduction factor vs. TTP curve method has significant value in that it can be applied regardless of initial, unaged material strength; i.e., it can be applied to any initial strength, including a Code-specified minimum strength.

Analysis and Discussion of Results

2¼Cr-1Mo

For 2¼Cr-1Mo, the yield strength and tensile strength reduction factors in Tables HBB-3225-2, HBB-3225-3A, and HBB-3225-3B are reviewed with calculations for verification.

A comprehensive set of data on the aging response of 2¼Cr-1Mo from Klueh (Ref. Klueh 1997) was used for the review analysis. The dataset covered post-aging tensile tests at room and the aging temperatures on four heats of annealed material that was aged at 454°C (850°F), 510°C (950°F), and 566°C (1050°F) for up to 20,000 hours. Analysis was conducted for the yield strength and tensile strength reduction factor, f (aged-to-unaged ratio), as a function of aging time and temperature for each heat. By use of the reduction factor, data of all the heats are analyzed together. A best-fit HJP, a time-temperature parameter identical to the LMP used for creep, was first determined, followed by a re-plot of the average factor for each HJP versus the HJP, yielding a first-order curve of $f_{(average)}$ vs. HJP from which the tabulated values for the reduction factor are developed. The data exhibits significant scatter and the use of the $f_{(average)}$ facilitates the analysis. The best-fit HJP constant is ≈ 15. Tables R.3225-3A and -3B summarize the results of this analysis compared with BPVC 2017 (and 2019) III-5 Tables HBB-3225-3A and -B values, respectively.

A second, relatively limited set of data by Pizzo and Mandurrago (Ref. Pizzo 1981) was also reviewed. The data were from a single heat for short aging times up to 3,000 hours and for material with an initial isothermal anneal + stress relief + post-weld heat treatment, and are not separately analyzed.

The Electric Power Research Institute (EPRI) (Ref. EPRI 1993) has published aging curves for the material. For the tensile strength reduction factor, the aging reduction factor curve (strength versus LMP with constant C = 10) was reportedly developed by fitting a proposed ASME HBB-3225 tabulation referring to a method presented by Chopra (Ref. Chopra 1984). For the yield strength reduction factor, that report offers a curve identical to that for the tensile strength but with an adjusted (reduced) intercept. No data were reported to verify the curve. For reference and not reported here, that yield strength reduction factor curve provides what appear to be excessively conservative, low reduction factors by comparison with the BPVC table and our analysis.

Our reported values summarized in Tables R.3225-3A and R.3225-3B extend beyond the maximum use temperature of the material since the relevant BPVC HBB-3225 tabulations include values at such temperatures up to 1,000 hours.

Table R.3225-3A, Comparison of BPVC 2017 (and 2019) III-5 HBB-3225-3A and This Analysis

[Black Regular: BPVC 2017 (and 2019) III-5 HBB-3225-3A]

[*RED-Italics*: This Analysis of data from Klueh (Ref. Klueh 1997) - 124 digitized data points, 454-566°C aging to 20,000 hours, tests at room temperature and aging temperature]

2¼Cr-1Mo, Yield Strength Reduction Factors											
Temp., °F	**1.E+00**	**1.E+01**	**3.E+01**	**1.E+02**	**3.E+02**	**1.E+03**	**3.E+03**	**1.E+04**	**3.E+04**	**1.E+05**	**3.E+05**
700	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
700	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
750	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
750	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*
800	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
800	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.98*	*0.95*	*0.93*
850	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92
850	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.96*	*0.94*	*0.92*	*0.90*
900	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.93	0.86
900	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.98*	*0.96*	*0.93*	*0.91*	*0.88*	*0.86*
950	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.91	0.85	0.80
950	*1.00*	*1.00*	*1.00*	*1.00*	*0.97*	*0.95*	*0.93*	*0.90*	*0.88*	*0.85*	*0.83*
1000	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.91	0.85	0.79	0.74
1000	*1.00*	*1.00*	*1.00*	*0.97*	*0.94*	*0.92*	*0.89*	*0.87*	*0.84*	*0.82*	*0.79*
1050	1.00	1.00	1.00	1.00	1.00	0.96	0.90	0.84	0.78	0.72	0.67
1050	*1.00*	*0.99*	*0.97*	*0.94*	*0.92*	*0.89*	*0.86*	*0.83*	*0.81*	*0.78*	*0.76*
1100	1.00	1.00	1.00	1.00	1.00	0.91	0.85	0.79	0.73	0.68	0.63
1100	*1.00*	*0.97*	*0.94*	*0.91*	*0.89*	*0.86*	*0.83*	*0.80*	*0.78*	*0.75*	*0.72*
1150	1.00	1.00	1.00	1.00	0.94	0.86	…	…	…	…	…
1150	*0.99*	*0.94*	*0.91*	*0.88*	*0.86*	*0.83*	*0.80*	*0.77*	*0.74*	*0.71*	*0.69*
1200	1.00	1.00	1.00	0.96	0.89	0.82	…	…	…	…	…
1200	*0.97*	*0.91*	*0.88*	*0.85*	*0.83*	*0.80*	*0.77*	*0.74*	*0.71*	*0.68*	*0.65*

2¼Cr-1Mo, Yield Strength Reduction Factors											
Temp., °C	**1.E+00**	**1.E+01**	**3.E+01**	**1.E+02**	**3.E+02**	**1.E+03**	**3.E+03**	**1.E+04**	**3.E+04**	**1.E+05**	**3.E+05**
375	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
375	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
400	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
400	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*
425	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
425	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.98*	*0.96*	*0.93*
450	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93
450	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*	*0.95*	*0.92*	*0.90*
475	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.95	0.88
475	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*	*0.94*	*0.92*	*0.89*	*0.87*
500	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.94	0.89	0.82
500	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.96*	*0.94*	*0.91*	*0.89*	*0.86*	*0.84*
525	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.95	0.88	0.82	0.77
525	*1.00*	*1.00*	*1.00*	*0.98*	*0.96*	*0.93*	*0.91*	*0.88*	*0.86*	*0.83*	*0.81*
550	1.00	1.00	1.00	1.00	1.00	0.98	0.95	0.88	0.82	0.76	0.71
550	*1.00*	*1.00*	*0.98*	*0.96*	*0.93*	*0.91*	*0.88*	*0.85*	*0.83*	*0.80*	*0.78*
575	1.00	1.00	1.00	1.00	1.00	0.94	0.88	0.82	0.76	0.71	0.66
575	*1.00*	*0.98*	*0.96*	*0.93*	*0.91*	*0.88*	*0.85*	*0.82*	*0.80*	*0.77*	*0.75*
600	1.00	1.00	1.00	1.00	0.99	0.90	…	…	…	…	…
600	*1.00*	*0.96*	*0.93*	*0.90*	*0.88*	*0.85*	*0.82*	*0.80*	*0.77*	*0.74*	*0.71*
625	1.00	1.00	1.00	0.99	0.93	0.85	…	…	…	…	…
625	*0.99*	*0.94*	*0.91*	*0.88*	*0.85*	*0.82*	*0.80*	*0.77*	*0.74*	*0.71*	*0.68*
650	1.00	1.00	1.00	0.96	0.89	0.82	…	…	…	…	…
650	*0.97*	*0.91*	*0.88*	*0.85*	*0.82*	*0.79*	*0.77*	*0.74*	*0.71*	*0.68*	*0.65*

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = $5 < \delta \leq 10\%$

Non-conservative relative to this analysis - Difference, $\delta > 10\%$ | % of ASME value

Table R.3225-3B, Comparison of BPVC 2017 (and 2019) III-5 HBB-3225-3B and This Analysis

[Black Regular: BPVC 2017 (and 2019) III-5 HBB-3225-3B]

[*RED-Italics:* This Analysis of data from Klueh (Ref. Klueh 1997) - 124 digitized data points, 454-566°C aging to 20,000 hours, tests at room temperature and aging temperature]

2¼Cr-1Mo, Tensile Strength Reduction Factors											
Temp., °F	1.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05
700	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
700	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.98*	*0.97*
750	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
750	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*	*0.96*	*0.94*
800	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.94
800	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.98*	*0.96*	*0.95*	*0.93*	*0.91*
850	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.92	0.88
850	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*	*0.96*	*0.94*	*0.92*	*0.90*	*0.89*
900	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.92	0.86	0.82
900	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*	*0.95*	*0.93*	*0.91*	*0.90*	*0.88*	*0.86*
950	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.91	0.86	0.82	0.77
950	*1.00*	*1.00*	*0.98*	*0.96*	*0.95*	*0.93*	*0.91*	*0.89*	*0.87*	*0.85*	*0.84*
1000	1.00	1.00	1.00	1.00	1.00	0.97	0.92	0.86	0.82	0.76	0.72
1000	*1.00*	*0.98*	*0.96*	*0.94*	*0.92*	*0.90*	*0.89*	*0.87*	*0.85*	*0.83*	*0.81*
1050	1.00	1.00	1.00	1.00	1.00	0.92	0.88	0.82	0.77	0.71	0.67
1050	*1.00*	*0.96*	*0.94*	*0.92*	*0.90*	*0.88*	*0.86*	*0.84*	*0.82*	*0.80*	*0.78*
1100	1.00	1.00	1.00	1.00	0.94	0.88	0.83	0.77	0.72	0.67	0.62
1100	*0.98*	*0.94*	*0.92*	*0.90*	*0.88*	*0.86*	*0.84*	*0.82*	*0.80*	*0.78*	*0.76*
1150	1.00	1.00	1.00	0.95	0.89	0.83	...	...	...	...	...
1150	*0.96*	*0.92*	*0.90*	*0.88*	*0.86*	*0.84*	*0.82*	*0.79*	*0.77*	*0.75*	*0.73*
1200	1.00	1.00	1.00	0.90	0.84	0.78	...	...	...	...	...
1200	*0.94*	*0.90*	*0.88*	*0.86*	*0.83*	*0.81*	*0.79*	*0.77*	*0.75*	*0.72*	*0.70*

2¼Cr-1Mo, Tensile Strength Reduction Factors											
Temp., °C	1.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05
375	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
375	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.98*	*0.96*
400	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
400	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*	*0.96*	*0.94*
425	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
425	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.98*	*0.97*	*0.95*	*0.93*	*0.92*
450	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	0.89
450	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.98*	*0.96*	*0.94*	*0.93*	*0.91*	*0.89*
475	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.94	0.88	0.84
475	*1.00*	*1.00*	*1.00*	*0.99*	*0.98*	*0.96*	*0.94*	*0.92*	*0.90*	*0.89*	*0.87*
500	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.93	0.88	0.83	0.79
500	*1.00*	*1.00*	*0.99*	*0.97*	*0.96*	*0.94*	*0.92*	*0.90*	*0.88*	*0.86*	*0.85*
525	1.00	1.00	1.00	1.00	1.00	0.98	0.94	0.88	0.84	0.79	0.74
525	*1.00*	*0.99*	*0.97*	*0.95*	*0.94*	*0.92*	*0.90*	*0.88*	*0.86*	*0.84*	*0.82*
550	1.00	1.00	1.00	1.00	1.00	0.95	0.90	0.84	0.80	0.74	0.70
550	*1.00*	*0.97*	*0.95*	*0.93*	*0.91*	*0.89*	*0.88*	*0.86*	*0.84*	*0.82*	*0.80*
575	1.00	1.00	1.00	1.00	0.98	0.91	0.86	0.80	0.75	0.70	0.65
575	*0.99*	*0.95*	*0.93*	*0.91*	*0.89*	*0.87*	*0.85*	*0.83*	*0.81*	*0.79*	*0.77*
600	1.00	1.00	1.00	1.00	0.93	0.87	...	...	...	...	...
600	*0.98*	*0.94*	*0.92*	*0.89*	*0.87*	*0.85*	*0.83*	*0.81*	*0.79*	*0.77*	*0.75*
625	1.00	1.00	1.00	0.94	0.88	0.82	...	...	...	...	...
625	*0.96*	*0.92*	*0.90*	*0.87*	*0.85*	*0.83*	*0.81*	*0.79*	*0.77*	*0.75*	*0.73*
650	1.00	1.00	1.00	0.90	0.84	0.78	...	...	...	...	...
650	*0.94*	*0.90*	*0.88*	*0.86*	*0.83*	*0.81*	*0.79*	*0.77*	*0.75*	*0.72*	*0.70*

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%

Non-conservative relative to this analysis - Difference, δ > 10% | % of ASME value

It is noted that the non-conservatism associated with the 2¼Cr-1Mo yield and tensile strength reduction factors of Tables HBB-3225-3A and -3B appears less significant than that for the 9Cr-1Mo-V yield strength reduction factor (see analysis below). However, the disagreement of our results with the HBB-3225 tabulated values indicates a need for further review.

9Cr-1Mo-V

For 9Cr-1Mo-V, the yield strength and tensile strength reduction factors in Tables HBB-3225-2 and HBB-3225-4 are reviewed with calculations for verification.

Several datasets were considered in calculation for the verification. A comprehensive set of controlled experiment, aging data on 9Cr-1Mo-V was from Li et al. (Ref. Li 2018) where two heats of normalized and tempered material were aged at 550°C (1,022°F), 600°C (1,112°F) and 650°C (1,200°F) for up to ~ 64,000 hours. Post-aging tensile tests were conducted and data reported for tests at the aging temperature. In addition, unstressed portions of four heats of previously creep-tested material from ORNL with exposures of 427-538°C (1000°F) for up to ~133,000 hours were tensile tested. Finally, material from an ex-service boiler tube with an estimated exposure of 550°C (1,022°F) for 155,000 hours was also tensile tested. Following our attempt to use all of the reported data in analysis for the reduction factor, we discovered that the lack of unaged material data for the ORNL heats and the ex-service material produced a vastly increased scatter when assumptions had to be made for the unaged strength in these cases. As a result, our final analysis excludes these material cases (consisting of only 10 data points). The final analyzed data comprised a total of 42 data points digitized from the reported graphs. In addition to the results of our analysis, the as-reported reduction factors of Li et al. (Ref. Li 2018) based on a material model are reported here for added perspective.

Tempering response data developed by EPRI (Ref. Parker 2013) are also evaluated. The data, provided as a graph of room temperature hardness versus HJP with the HJP constant, C = 22, are digitized and analyzed for the tensile strength reduction factor. The hardness is converted to approximate tensile strength per ASTM A370 and the pre-service, initial tensile strength used for all calculations is 690 MPa (100 ksi).

The data from DiStefano et al. (Ref. DiStefano 1986) for aging of two heats to 25,000 hours may have been the basis for the HBB-3225-2 yield strength reduction factor of 1.0. They report that there is no significant effect of aging on strength (yield and tensile) up to an aging temperature of 1112°F (600°C). That data, however, do show a consistent decrease in yield strength with aging temperature (tensile strength details not reported), although the data for up to 1,112°F (600°C) aging indicate the strength is maintained above the BPVC minimum (BPVC II-D, Table Y-1). The limited yield strength data have not been used in our analysis.

Tables R. 3225-2a and R. 3225-4 summarize our preliminary analysis results in comparison with the BPVC III-5 Tables HBB-3225-2 and -4 reduction factor values, respectively, along with the as-reported values from Li et al. (Ref. Li 2018).

Table R.3225-2a, Comparison of BPVC 2017 (and 2019) III-5 HBB-3225-2 and This Analysis
[Black Regular: BPVC 2017 (and 2019) III-5 HBB-3225-2]
[**Black Bold**: As reported by Li et al. (Ref. Li 2018) for metric units; interpolated for US Customary units]
[*RED-Italics*: This Analysis of data from Li et al. (Ref. Li 2018) - 43 digitized data points from 2 heats, 550-650°C aging to ~64,000 hours, tests at aging temperature]

9Cr-1Mo-V, Yield Strength Reduction Factors											
Temp., °F	**1.E+00**	**1.E+01**	**3.E+01**	**1.E+02**	**3.E+02**	**1.E+03**	**3.E+03**	**1.E+04**	**3.E+04**	**1.E+05**	**3.E+05**
700	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
700											
700	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*
750	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
750											
750	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.99*	*0.99*
800	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
800											
800	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.99*	*0.98*	*0.97*
850	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
850											
850	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.99*	*0.98*	*0.97*	*0.96*
900	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
900											
900	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.99*	*0.98*	*0.97*	*0.96*	*0.94*
950	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
950	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.97**	**0.91**	**0.81**
950	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.99*	*0.98*	*0.97*	*0.95*	*0.94*	*0.92*
1000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1000	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.98**	**0.95**	**0.88**	**0.77**
1000	*1.00*	*1.00*	*1.00*	*0.99*	*0.99*	*0.98*	*0.97*	*0.95*	*0.93*	*0.91*	*0.89*
1050	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1050	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.97**	**0.93**	**0.85**	**0.74**
1050	*1.00*	*1.00*	*0.99*	*0.99*	*0.98*	*0.97*	*0.95*	*0.93*	*0.91*	*0.89*	*0.86*
1100	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1100	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.96**	**0.92**	**0.83**	**0.72**
1100	*1.00*	*0.99*	*0.99*	*0.98*	*0.97*	*0.95*	*0.93*	*0.91*	*0.89*	*0.86*	*0.83*
1150	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1150	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.98**	**0.94**	**0.88**	**0.78**	**0.69**
1150	*1.00*	*0.99*	*0.98*	*0.97*	*0.95*	*0.93*	*0.91*	*0.88*	*0.86*	*0.82*	*0.79*
1200	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1200	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.97**	**0.91**	**0.83**	**0.72**	**0.64**
1200	*1.00*	*0.98*	*0.97*	*0.95*	*0.94*	*0.91*	*0.89*	*0.86*	*0.82*	*0.79*	*0.75*

Table continues to next page

9Cr-1Mo-V, Yield Strength Reduction Factors											
Temp., °C	1.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05
375	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
375											
375	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
400	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
400											
400	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
425	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
425											
425	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.98
450	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
450											
450	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.97	0.96
475	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
475											
475	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.97	0.96	0.95
500	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
500	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.97	0.92	0.83
500	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.97	0.96	0.94	0.93
525	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
525	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.96	0.90	0.79
525	1.00	1.00	1.00	0.99	0.99	0.98	0.97	0.96	0.94	0.92	0.91
550	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
550	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.94	0.86	0.76
550	1.00	1.00	0.99	0.99	0.98	0.97	0.96	0.94	0.93	0.90	0.88
575	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
575	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.97	0.93	0.84	0.73
575	1.00	1.00	0.99	0.98	0.97	0.96	0.95	0.93	0.90	0.88	0.85
600	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
600	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.96	0.91	0.82	0.72
600	1.00	0.99	0.99	0.98	0.96	0.95	0.93	0.90	0.88	0.85	0.82
625	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
625	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.94	0.87	0.77	0.68
625	1.00	0.99	0.98	0.97	0.95	0.93	0.91	0.88	0.85	0.82	0.78
650	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
650	1.00	1.00	1.00	1.00	1.00	0.99	0.97	0.91	0.83	0.72	0.64
650	1.00	0.98	0.97	0.95	0.94	0.91	0.89	0.86	0.82	0.78	0.75

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%

Non-conservative relative to this analysis - Difference, δ > 10% | % of ASME value

Table R.3225-4, Comparison of BPVC 2017 (and 2019) III-5 HBB-3225-4 and This Analysis
[Black Regular: BPVC 2017 (and 2019) III-5 HBB-3225-4]
[**Black Bold**] As reported by Li et al. (Ref. Li 2018) for metric units; interpolated for US Customary units.
[*RED-Italics*: This Analysis of data from Li et al. (Ref. Li 2018) - 43 digitized data points from 2 heats, 550-650°C aging to ~64,000 hours, tests at aging temperature]
[***Blue-Bold Italics***: This Analysis of data digitized from EPRI database (Ref. Parker 2013); room temperature hardness vs HJP (C=22)]

9Cr-1Mo-V, Tensile Strength Reduction Factors											
Temp., °F	**1.E+00**	**1.E+01**	**3.E+01**	**1.E+02**	**3.E+02**	**1.E+03**	**3.E+03**	**1.E+04**	**3.E+04**	**1.E+05**	**3.E+05**
700	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
700											
700	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
700	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
750	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
750											
750	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
750	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
800	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
800											
800	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
800	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
850	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
850											
850	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
850	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
900	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97
900											
900	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*
900	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
950	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.93
950	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.97**	**0.92**	**0.83**
950	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.98*	*0.96*
950	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
1000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.93	0.90
1000	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.98**	**0.95**	**0.88**	**0.79**
1000	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.98*	*0.96*	*0.93*
1000	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
1050	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.93	0.89	0.84
1050	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.97**	**0.94**	**0.86**	**0.76**
1050	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.98*	*0.96*	*0.93*	*0.90*
1050	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
1100	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.93	0.90	0.86	0.84
1100	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.97**	**0.92**	**0.84**	**0.74**
1100	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.98*	*0.95*	*0.93*	*0.90*	*0.86*
1100	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***0.99***	***0.98***
1150	1.00	1.00	1.00	1.00	1.00	0.97	0.94	0.90	0.87	0.84	0.81
1150	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.98**	**0.95**	**0.89**	**0.80**	**0.71**
1150	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.98*	*0.96*	*0.93*	*0.90*	*0.86*	*0.82*
1150	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***0.99***	***0.98***	***0.95***	***0.92***
1200	1.00	1.00	1.00	1.00	0.98	0.94	0.91	0.87	0.84	0.81	0.78
1200	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.97**	**0.92**	**0.84**	**0.74**	**0.66**
1200	*1.00*	*1.00*	*1.00*	*1.00*	*0.98*	*0.96*	*0.93*	*0.89*	*0.86*	*0.81*	*0.76*
1200	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***0.99***	***0.99***	***0.96***	***0.93***	***0.89***	***0.85***

Table continues to next page

9Cr-1Mo-V, Tensile Strength Reduction Factors

Temp., °C	1.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05
375	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
375											
375	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
375	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
400	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
400											
400	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
400	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
425	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
425											
425	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
425	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
450	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
450											
450	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
450	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
475	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98
475											
475	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*
475	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
500	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.97
500	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.97**	**0.93**	**0.84**
500	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*
500	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
525	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.91
525	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.96**	**0.90**	**0.81**
525	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*	*0.95*
525	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
550	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.92	0.89
550	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.98**	**0.95**	**0.87**	**0.78**
550	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*	*0.95*	*0.92*
550	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***
575	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.95	0.92	0.88	0.83
575	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.97**	**0.93**	**0.85**	**0.75**
575	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*	*0.95*	*0.92*	*0.89*
575	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***0.99***
600	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.92	0.89	0.85	0.84
600	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.97**	**0.92**	**0.83**	**0.74**
600	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*	*0.95*	*0.92*	*0.89*	*0.85*
600	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***0.99***	***0.99***	***0.97***
625	1.00	1.00	1.00	1.00	1.00	0.97	0.94	0.90	0.87	0.83	0.81
625	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.98**	**0.95**	**0.88**	**0.79**	**0.70**
625	*1.00*	*1.00*	*1.00*	*1.00*	*0.99*	*0.97*	*0.95*	*0.92*	*0.89*	*0.85*	*0.81*
625	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***0.99***	***0.98***	***0.95***	***0.91***
650	1.00	1.00	1.00	1.00	0.98	0.94	0.91	0.87	0.84	0.81	0.78
650	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.99**	**0.97**	**0.92**	**0.84**	**0.74**	**0.66**
650	*1.00*	*1.00*	*1.00*	*1.00*	*0.98*	*0.96*	*0.93*	*0.89*	*0.86*	*0.81*	*0.76*
650	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***0.99***	***0.99***	***0.96***	***0.93***	***0.89***	***0.84***

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%

Non-conservative relative to this analysis - Difference, δ > 10% | % of ASME value

It is noted from above that:

- The Table HBB-3225-2 yield strength factor of 1.0 for 9Cr-1 Mo appears significantly non-conservative as seen in Table R. 3225-2a.
- As seen in Table R. 3225-4, the Table HBB-3225-4 tensile strength reduction factors for 9Cr- 1Mo appear non-conservative relative to the Li et al. (Ref. Li 2018) reported values, but in reasonable agreement with the values derived from our preliminary analysis of the Li et al. data. Given the Li's published reported factors indicate potential non-conservatism in the BPVC tabulation, the Table HBB-3225-4 values merit review.
- As seen in Table R. 3225-4, the values derived from the EPRI database (Ref. Parker 2013) that are based on the (short-term) tempering response of as-quenched material appear non-conservative relative to the BPVC tabulation and the other values shown in the table.
- The equivalent time calculation method for 2¼Cr-1Mo and 9Cr-1Mo-V formulated on the LMP or HJP is conservative since the LMP or HJP constant specified is 10, lower than typical and published values for the ferritic steels (closer to 20), and lower than the best-fit results of our preliminary analyses of published aging data for the materials (Constant ≈ 15 for 2¼Cr-1Mo and ≈ 12 for 9Cr-1Mo-V.

800H

This alloy exhibits age hardening at moderate temperatures, mainly due to precipitation of γ' as shown by Lai and Kimball (Ref. Lai 1978) with data for aging at 1,200°F (650°C) up to 4,000 hours. No evidence is found for a need for strength reduction factors below 1,350°F (730°C), consistent with the yield strength reduction factor currently in Table HBB-3225-2.

However, a review of data on ex-service material exposed to a range of temperatures up to 1,490°F (810°C) as reported by Swindeman et al. (Ref. Swindeman 2007) suggests strength reduction factors below 0.90 at the highest exposure temperatures exceeding 1,425°F (775°C). Table R.3225-2b shows our derived reduction factors from the reported data using both the BPVC III-5 tabulated yield and tensile strength values (minimum) and the Swindeman et al.-reported typical strength values for the material (digitized for our analysis). For reference, and as reported by Swindeman et al. (Ref. Swindeman 2007), the controlled laboratory aging experimental data of McCoy (Ref. McCoy 1993) for a single heat at 760°C (1,400°F) for 18,600 hours showed a tensile strength very similar to that obtained for Heat B by Swindeman et al. (Ref. Swindeman 2007), suggesting a saturation of strength changes in about 20,000 hours at this temperature.

304SS and 316SS

The HBB-3225-2 tabulation of the strength reduction factors for 304 SS and 316 SS appears conservative and acceptable. Our finding is based on a review of the extensive work at ORNL, e.g. (Ref. Sikka 1982a, Ref. Horak 1983, and Ref. Sikka 1983), published data by Steichen (Ref. Steichen 1974), and other published work, e.g. (Ref. Stoter 1981 and Ref. NiDI 1979).

Table R.3225-2b, Reduction Factors derived from Swindeman et al. (Ref. Swindeman 2007) test results on ex-service piping relative to the yield and tensile factors for ≥ 1,350°F (730°C) = 0.90 BPVC 2017 (and 2019) III-5 Table HBB-3225-2.
YS: Yield Strength. TS: Tensile Strength

Heat	Heat A	Heat A	Heat B	Heat B	Heat C	Heat C	Heat A	Heat A	Heat B	Heat B	Heat C	Heat C
Test Temperature	for Typical YS	for Minimum YS	for Typical YS	for Minimum YS	for Typical YS	for Minimum YS	for Typical TS	for Minimum TS	for Typical TS	for Minimum TS	for Typical TS	for Minimum TS
23°C (73°F)	1.21	1.70	0.94	1.32	0.71	1.00	1.14	1.23	1.05	1.13	0.93	1.01
593°C (1100°F)	1.34	2.00	1.01	1.50	0.61	0.91	0.97	1.06	0.89	0.97	0.46	0.51
704°C (1300°F)	1.41	1.93	1.04	1.42	0.63	0.86	0.92	1.00	0.84	0.91	0.76	0.83
816°C (1500°F)	1.43	1.91	1.17	1.57	0.91	1.22	0.97	1.07	0.90	0.99	0.85	0.94

Heat A: 621-635°C (1150-1175°F), 73,500 hours.
Heat B: 752-774°C (1385-1425°F), 73,500 hours.
Heat C: 774-810°C (1425-1490°F), 90,000 hours.

The references from which the tensile data analyzed are obtained are provided below for convenient review, in addition to the listing in Section 6 References.

- (Ref. DiStefano 1986)
- (Ref. EPRI 1993)
- (Ref. Horak 1983)
- (Ref. Klueh 1997)
- (Ref. Lai 1978)
- (Ref. Li 2018)
- (Ref. McCoy 1993)
- (Ref. NiDI 1979)
- (Ref. Parker 2013)
- (Ref. Pizzo 1981)
- (Ref. Sikka 1982a)
- (Ref. Sikka 1983)
- (Ref. Steichen 1974)
- (Ref. Stoter 1981)
- (Ref. Swindeman 2007)

HBB-2400

HBB-2430

HBB-2433, Delta Ferrite Determination

Explanations of the Condition

Welding deposits performed by GTAW and PAW methods generally have low base metal dilution of the filler metal while many other welding processes that may be used for fabrication can have widely varying amounts of base metal dilution depending on weld joint design and weld procedure heat input.

Rationale and Discussion

The need for austenitic stainless steel weld metal to contain a minimum amount of delta ferrite to prevent hot cracking was identified over fifty years ago. One of the first constitutional diagrams to estimate the amount of delta ferrite formed was published by Schaeffler with the WRC 1992 diagram being the presently accepted ferrite predictor in AWS and ASME standards and codes (Ref. Schaeffler 1949, Ref. Kotecki 1992). The formation of delta ferrite prevents hot cracking by the significantly higher solubility of the elements of phosphorous and sulfur compared to austenite. The amount of delta ferrite needed for cracking resistance is under some debate as the solidification mode is also important. A general rule of a Ferrite Number (FN) of 3 to 5 will prevent hot cracking under most conditions except perhaps joints under severe restraint during welding.

Delta ferrite is not thermodynamically stable during high temperature exposure and precipitates a combination of sigma phase and chromium carbides. The temperatures of concern vary with chemical composition but are generally between 797 and 1,652°F (425 and 900°C) with faster and more complete transformation occurring at higher temperatures. Higher temperature heat treatments or exposures in the range of 1,742 and 2,012°F (950 to 1,100°C) will prevent the formation of sigma phase and chromium carbides (Ref. Kotecki 1992). The effect of sigma formation is an increase in hardness and a lowering of ductility due to the high hardness and brittleness of sigma phase. The formation of sigma creates a lower volume of precipitate than the original delta phase and welds containing a FN of 8 produced a 4% by volume of sigma phase and are not embrittling (Ref. Lippold 2005). The precipitation of chromium carbides reduces local chromium content adjacent to the carbides and increases the susceptibility to stress corrosion cracking. Some research has been performed on 16-8-2 stainless weld metal on controlling the chemistry to prevent the formation of the sigma and chi phases and prevent material property degradation (Ref. Leitnaker 1982).

The amount of delta ferrite formed during welding operations effects the morphology and the extent of creating continuous networks. As the amount of delta ferrite approaches or exceeds approximately 13 FN, continuous networks may form and a change from vermicular ferrite to a more continuous lacy morphologies may take place, with a tendency to create greater property degradation (Ref. Kokawa 1989).

The weld deposits performed by GTAW and PAW generally have low base metal dilution of the filler metal and the calculation of FN will have little error as the chemistry is not significantly affected by base metal dilution. Many other welding processes that may be used for fabrication can have widely varying amounts of base metal dilution depending on weld joint design and weld procedure heat input which creates a problem of predicting delta ferrite content by calculation from filler metal chemistry.

The NRC Regulatory Guide 1.31 Rev. 4 (Ref. NRC RG 1.31 R4) states for welding consumables not for GTAW and PAW, the weld pad preparation as described by SFA-5.4 is acceptable for delta ferrite determination. The guide also states that that ferrite measurements from 5 to 20 FN are acceptable for production welding.

The minimum ferrite level of 5 FN stipulated in HBB-2433.2 Acceptance Standards for service temperatures below 797°F (425°C) is consistent with NRC guidance (Ref. NRC RG 1.31 R4) and relevant parts of BPVC III-1. Below 797°F (425°C) the transformation of delta ferrite to sigma phase and chromium carbides is limited or does not occur. For service temperatures above 797°F (425°C) where the transformation of delta ferrite will occur, limiting the filler metals to produce no more than 10 FN will limit the property degradation and is consistent with stipulations in other sections of the BPVC for high temperature service although currently they may not be endorsed by the NRC. The condition as described in Section 3 HBB-2400 to filler metals not using GTAW or PAW is also consistent with RG 1.31.

4.2. Mandatory Appendix HBB-I-14 Tables and Figures

Table HBB-I-14.1(a), Permissible Base Materials for Structures other than Bolting
Explanations of the Conditions

Types 304 SS and 316 SS**:**

1. SA-430 does not exist. ASTM A430 (last edition A430-1991) was superseded by ASTM A312 in 1995.
2. In-process heat treatment can adversely impact the elevated temperature properties of the material and is specifically prohibited for the H grades, but permitted for the non-H grades in several specifications (SA-182, SA-213, SA-376, SA-403), while other specifications are silent (SA-249, SA-240, SA-479). Only SA-965 prohibits in-process heat treatment for all grades.

2¼Cr-1Mo**:**

3. Under Note (6) clause (c), "Note (4)" is an obvious error, possibly a carry-over from a prior edition, and should be "Note (5)."
4. WP22, by itself, is not a listed material (excludes specified grade/class) and the "W" identifier is only for marking purposes.
5. Only SA-182 for Forgings specifies a minimum anneal temperature and a normalizing temperature of 1,650°F (900°C). While the strength requirements typically force an appropriate anneal or normalize + temper, the addition of a heat treatment temperature minimum note is recommended to ensure properties.

Comments

- For 304 SS and 316 SS, ASME has published a set of additional recommendations relating to ensuring a minimum amount of free nitrogen for improved and less scattered creep properties for use temperatures ≥ 1100°F (59°5°C) (Ref. Turek 2013). Independent verification of these recommendations is beyond the scope of this review, but we understand that ASME has been considering updating HBB-I-14.1(a) to include chemistry requirements to ensure a minimum amount of free nitrogen, and we support consideration for inclusion of such requirements.

- For 9Cr-1Mo-V, a recent BPVC Section I Code Case (2864) specifies a refined chemical composition (Type 2 material currently under action by ASTM for inclusion in several material product specifications), including control of tramp elements, all intended to help assure elevated temperature performance. It is noted, however, that the BPVC 2017 (and 2019) III-5 tabulated stresses and our analysis results have been generated from data on material without this restricted chemistry specification. Also, we have conducted no independent analysis of the properties of this Type 2 material. As such, no recommendation is made regarding use of the restricted chemistry in BPVC III-5. Nevertheless, the composition specifications of that Code Case are available for future consideration as an addition to BPVC III-5, possibly in the form of a nonmandatory guideline.

Table HBB-I-14.2, S_o — Maximum Allowable Stress Intensity, ksi (MPa), for Design Condition Calculations

Primary Findings

Types 304 SS and 316 SS:

- Table HBB-I-14.2 S_o values for both materials are judged to be non-conservative relative to our analysis for temperatures ≥ 650°C (1200°F).

- A comparison of our analysis results with S_o values calculated from curve-fit parameters in an ASME STP-NU-063 "Correct and Extend Allowable Stress Values for 304 and 316 Stainless Steel (Ref. Sengupta 2013)" indicates reasonably good agreement. However, the S_o values of ASME STP-NU-063 have not been incorporated into BPVC 2017 (and 2019) III-5. Such incorporation would largely eliminate the discrepancy between our results and the S_o values in BPVC 2017 (and 2019) III-5 Table HBB-I-14.2. The finding strongly supports that the S_o values in Table HBB-I-14.2 be further reviewed.

Ni-Fe-Cr (Alloy 800H):

- Only at the highest temperature(s) do the Table HBB-I-14.2 S_o values appear marginally non-conservative (by slightly over 10%) compared with our analysis results. These compared results do not support a detailed review. However, as part of an overall review of Table HBB-I-14.2 and given its inconsistency with the 100,000-hour S_r stresses in BPVC 2017 (and 2019) III-5 Table HBB-I-14.6C, we recommend that these S_o values be also examined.

2¼Cr-1Mo:

- Table HBB-I-14.2 S_o values are judged to be non-conservative relative to our analysis for temperatures ≥ 525°C (≥ 1000°F), meriting further review.

9Cr-1Mo-V:

- Table HBB-I-14.2 S_o values in the time-dependent regime are judged to be non-conservative relative to our analysis for temperatures ≥ 600°C (≥ 1150°F).
- A comparison of the results of our analysis with the current BPVC 2019 II-D Table 1A stresses (updated in the 2019 edition) and with the S_r values in the current BPVC 2019 III-5 (updated in the 2019 edition) indicate good agreement. The finding supports the recommendation that BPVC 2017 (and 2019) III-5 Table HBB-I-14.2 needs to be updated to be consistent with the current II-D Table 1A and the other III-5 updated stresses.

Analysis and Results

Table R.14.2-1 summarizes our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.2 S_o values. Values in the table that are S_{mt} (300khr or 500 khr)-controlled (see lower temperature stresses for 2¼Cr-1Mo and 9Cr-1Mo-V) are so identified.

Inconsistency was found in BPVC 2017 (and 2019) III-5 S_o and S_r Tabulated Stresses.

In the time-dependent stress-controlled region, S_o, per Section II, Part D, cannot exceed the lowest of the following: (1) 100% of the average stress to produce a creep rate of 0.01%/1,000 hr; (2) 100F_{avg}% of the average stress to cause rupture at the end of 100,000 hr; and (3) 80% of the minimum stress to cause rupture at the end of 100,000 hr. 80% of S_r at 100,000 hr thus represents criterion (3). Regardless of which criterion actually controls the S_o value, the S_o value can never exceed 80% S_r at 100,000 hr.

Table R.14.2-1. Comparison between S_o values of Table HBB-I-14.2 and This Analysis

°F ksi	304SS		316SS		Ni-Fe-Cr UNS N08810		2¼Cr-1Mo		9Cr-1Mo-1V	
	30-75 & 30-70ksi (YS-UTS)		30-75 & 30-70ksi (YS-UTS)						60-85 and 60-90ksi (YS-UTS)	
	ASME 2017 ASME 2019 III-5, Table HBB-I-14.2	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.2	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.2	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.2	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.2	This Analysis
700	.....	.....	.....	.....	…		17.9	17.2	26.7	25.4
750	.....	.....	.....	.....	…		17.9	16.9	25.9	24.9
800	15.2	15.9	15.9	16.7	15.3	15.1	16.6	16.5	24.9	24.2
850	14.8	15.7	15.7	16.4	15.1	14.9	16.6	16.1	23.7	23.3
900	14.6	15.5	15.6	16.1	14.8	14.8	13.6	13.4	21.9	21.1
950	14.2	15.3	15.5	15.9	14.6	14.7	10.8	9.8	17.8	18.1
1000	11.1	14.8	14.0	15.6	14.1	14.6	8.0	6.9	16.3	16.4
1050	10.1	11.7	11.2	15.2	11.2	13.6	5.7	4.5	12.9	12.1
1100	9.8	9.2	11.1	11.7	10.0	10.9	3.8	2.7	9.6	8.6
1150	7.7	7.2	9.8	8.9	9.3	8.7	.....		7.0	5.7
1200	6.1	5.5	7.4	6.7	7.4	6.9	.....		4.3	3.4
1250	4.7	4.2	5.5	4.9	5.9	5.5	.....		.....	
1300	3.7	3.1	4.1	3.5	4.7	4.3	.....		.....	
1350	2.9	2.3	3.1	2.4	3.8	3.4	.....		.....	
1400	2.3	1.6	2.3	1.9	3.0	2.7	.....		.....	
1450	1.8	1.1	1.7	1.3	…	2.1	.....		.....	
1500	1.4	0.77	1.3	0.90	…	1.6	.....		.....	

Table continues to next page

°C MPa	304SS 30-75 & 30-70ksi (YS-UTS)		316SS 30-75 & 30-70ksi (YS-UTS)		Ni-Fe-Cr UNS N08810		2¼Cr-1Mo		9Cr-1Mo-1V 60-85 and 60-90ksi (YS-UTS)	
	ASME 2017 ASME 2019 III-5, Table HBB-I-14.2	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.2	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.2	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.2	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.2	This Analysis
375	.....	.....	.....	.....	...		123	118	184	175
400	.....	.....	.....	.....	...		123	116	178	171
425	105	110	110	115	105	104	116	114	172	167
450	102	108	108	113	104	103	116	111	165	162
475	101	107	108	112	103	102	99	100	154	156
500	99	106	107	110	101	102	81	76	133	128
525	86	105	101	109	99	101	64	56	117	120
550	74	92	88	107	89	100	48	40	102	99
575	69	75	77	96	74	86.8	35	27	81	75
600	65	60	76	76	68	71.1	26[Note (1)]	19[Note (1)]	62	54
625	51	48	62	59	62	58.1			46	37
650	42	37	51	46	51	47.3			29	23
675	34	29	39	34	41	38.4	...		...	
700	27	22	30	25	34	31.0	...		...	
725	21	17	23	18	28.0	25.0	...		...	
750	17	13	18	15	23[Note (2)]	20.1	...		...	
775	14	9.3	13	11	.....	16.0	...		...	
800	11[Note (3)]	6.7[Note (3)]	11[Note (4)]	7.8[Note (4)]	.....	12.8	...		...	

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%
Non-conservative relative to this analysis - Difference, δ > 10%
% of ASME value
300 khr Smt (Yield Strength-controlled)
Sm (Yield Strength-Controlled)
Sm (Tensile Strength-Controlled (60-85 material for 9Cr-1Mo-V))
500 khr Smt (67% Minimum Stress to Rupture)
500 khr Smt (60-85 material for 9Cr-1Mo-V, tensile strength-controlled)

NOTES:	This Analysis
(1) This is the value of *So* for 2¼Cr-1Mo at 593°C.	19 MPa
(2) At 760°C the value of *So* for UNS N08810 is 21 MPa.	18 MPa
(3) At 816°C the value of *So* for 304 SS is 9.7 MPa.	5.3 MPa
(4) At 816°C the value of *So* for 316 SS is 9.0 MPa.	6.2 MPa

In comparing the BPVC 2017 (and 2019) III-5 Table HBB-I-14.2 listed S_o values in the creep-controlled regime (as identified in BPVC 2017 (and 2019) II-D) with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6 S_r at 100,000 hour values, it is found that S_o > 80% S_r for 304 SS from 1100-1500°F (575-800°C); for 316 SS from 1150-1400°F (600-750°C); for Alloy 800H from 1150-1400°F (600-750°C); for 2¼Cr-1Mo from 900-1050°F (500-575°C); and for 9Cr-1Mo-V from 1150-1200°F (625-650°C) of BPVC 2017 while from 1050-1200°F (525-650°C) of BPVC 2019 (S_r values of 9Cr-1Mo-V have been updated in BPVC 2019). Since S_o cannot exceed 80% S_r by its definition, the observations indicate an inconsistency between several time-dependent stresses in BPVC 2017 (and 2019) III-5, Table HBB-I-14.2 and Tables HBB-I-14.6.

The analysis for each of the tabulated materials is conducted using the ASME time-dependent software, version 2016-2-10, that is separately verified for accuracy in the regression of the data for the LMP-Logarithmic Stress polynomial curve. The software is downloaded from the ASME

Materials Properties Database. Given the constraints of the project, the analysis of multiple materials and selection of the optimal regression model, the need to execute the effort with a relatively automated computer program is essential. The ASME software provides one such option for execution and is used following its verification for accuracy.

Material: For all the alloys evaluated, care was taken to ensure that the data were from material that conformed to the specifications and additional ASME III-5 requirements (Table HBB-I-14.1(a)).

Data Censoring and Region Splitting: For 304 SS and 316 SS and for 2¼Cr-1Mo, due to the significant scatter in the very short rupture time frame, data with rupture time < 100 hours were excluded from the analysis, consistent with traditional ASME B&PV Code practice. For 9Cr-1Mo-V, the more recently established region splitting method per NIMS/Kimura is used (Ref. Kimura 2016). The data were split into two regimes – a high stress regime and a low stress regime, and the two sets were separately analyzed. The stress boundary is defined as 50% of the nominal 0.2% yield strength at temperature, a criterion developed by Kimura (see Ref. Kimura 2016) and one that is found to eliminate potential inaccuracies in the long-term extrapolations while enhancing the predictions for the short-term. The temperature-dependent boundary stresses selected were those reported by Kimura in the 550 to 700°C range and stresses estimated by a curve-fit to these values for temperatures outside of this range. In interpretation of the analysis results, care is taken to use the relevant curve-fit, depending on the computed average stress for rupture in 100,000 hours; i.e., an average stress in the low stress region would require use of the low stress region curve-fit for predicting S_o.

Rupture Strength Curve: The data are analyzed using the LMP-Logarithmic stress polynomial function - $LMP = T(C + \log t_R) = a_0 + a_1 * \log S + a_2 * (\log S)^2 + a_3 * (\log S)^3$ (t_R = rupture time in hours, S is the stress, and T, the temperature in absolute units). The regression method used is heat/lot-centered and the preferred polynomial order is 2 (a_3=0). The commonly encountered problem with the 2nd order is that the parabolic fit always has a vertex at which the logarithmic stress-time curve exhibits a turn-around; i.e., the rupture time begins to decrease with decreasing stress. This can produce excessively conservative predictions of rupture strength or as is also often the case, no feasible rupture strength solution. This is an ongoing issue with the preferred use of a 2nd order fit and the analyst must always need to be cautious regarding use of extrapolations that can be artificially over-conservative. Where relevant, additional analyses have been conducted to decide on acceptance of the 2nd order fit using the F-factor as described below.

In case of 304 SS, the 2nd order fit exhibited a tendency to potentially underpredict the behavior at the highest temperatures, partly a result of the constrained parabolic curve shape. On close review, it was seen that the 1st order fit is clearly non-conservative, and the 3rd order fit produces stresses slightly greater than does the 2nd order fit, but within about 0.7 MPa (0.1 ksi). No justification can be made for use of the 3rd order, particularly where the fit may be non-conservative if used for longer term extrapolations, such as for S_r and S_t.

The 316 SS dataset exhibited similar curve shape behavior as did 304 SS. In this case, the 3rd order fit exhibited an upturn that is clearly non-conservative. Since, at the highest temperatures

(≥ 750°C, ≥ 1400°F), the 2nd order is judged to be excessively conservative and the 1st order to be non-conservative, the final stress estimate is made using the average of the two predictions at these highest temperatures.

While the 2nd order curve-fit data analysis for 2¼Cr-1Mo also exhibited a striking parabolic vertex turn-around, the rupture strength curves are such that the shapes do not impact the stress predictions within the temperature range of interest.

In case of 9Cr-1Mo-V, the region splitting method for the dataset permits use of the 2nd order curve-fit for both the high and the low stress regions with no influencing turn-around and no indication that the predictions are excessively conservative.

The references from which the stress rupture data analyzed are obtained are provided below for convenient review, in addition to the listing in Section 6 References.

For 304SS

Data (after 100-hour censor): 90 Heats/Lots, 964 Data Points, Maximum rupture time ≈ 179,400 hours.

- (Ref. Ajaja 1979)
- (Ref. Bocek 1983)
- (Ref. BSCC 1974)
- (Ref. Bynum 1992)
- (Ref. Gold 1975)
- (Ref. Klueh 1976b)
- (Ref. Martin 1963)
- (Ref. McCoy 1974a)
- (Ref. McCoy 1974b)
- (Ref. MPC 1983)
- (Ref. NRIM 1986b)
- (Ref. NRIM 1995)
- (Ref. Sikka 1976)
- (Ref. Sikka 1981)
- (Ref. Simmons 1965)
- (Ref. Swindeman 1977)
- (Ref. Swindeman 1981)
- (Ref. Swindeman 1974)
- (Ref. Swindeman 1975)
- (Ref. Williams 1986)

For 316SS

Data (after 100-hour censor): 142 Heats/Lots, 1616 Data Points, Maximum rupture time ≈ 320,400 hours

- (Ref. BSCC 1974)

- (Ref. NIMS 2015)
- (Ref. NRIM 1979)
- (Ref. NRIM 1988)
- (Ref. NRIM 2000)
- (Ref. Sikka 1980)
- (Ref. Simmons 1965)

For Ni-Fe-Cr (Alloy 800H)

Data: 49 Heats/Lots, 960 Data Points, Maximum rupture time ≈ 136,100 hours.

- Data compiled by ORNL from various published and unpublished sources, including NIMS, JRC Petten, Huntington Alloys, General Atomics, etc.

For 2¼Cr-1Mo (Annealed and N&T material combined).

Data (after 100-hour censor): 93 Heats/Lots, 671 Data Points, Maximum rupture time ≈ 213,300 hours.

- (Ref. Klueh 1976a)
- (Ref. Klueh 1978)
- (Ref. NRIM 1986a)
- (Ref. NRIM 1997)
- (Ref. Smith 1971)

For 9Cr-1Mo-V

Data: 112 Heats/Lots, 2046 Data Points, Maximum rupture time ≈ 170,370 hours.

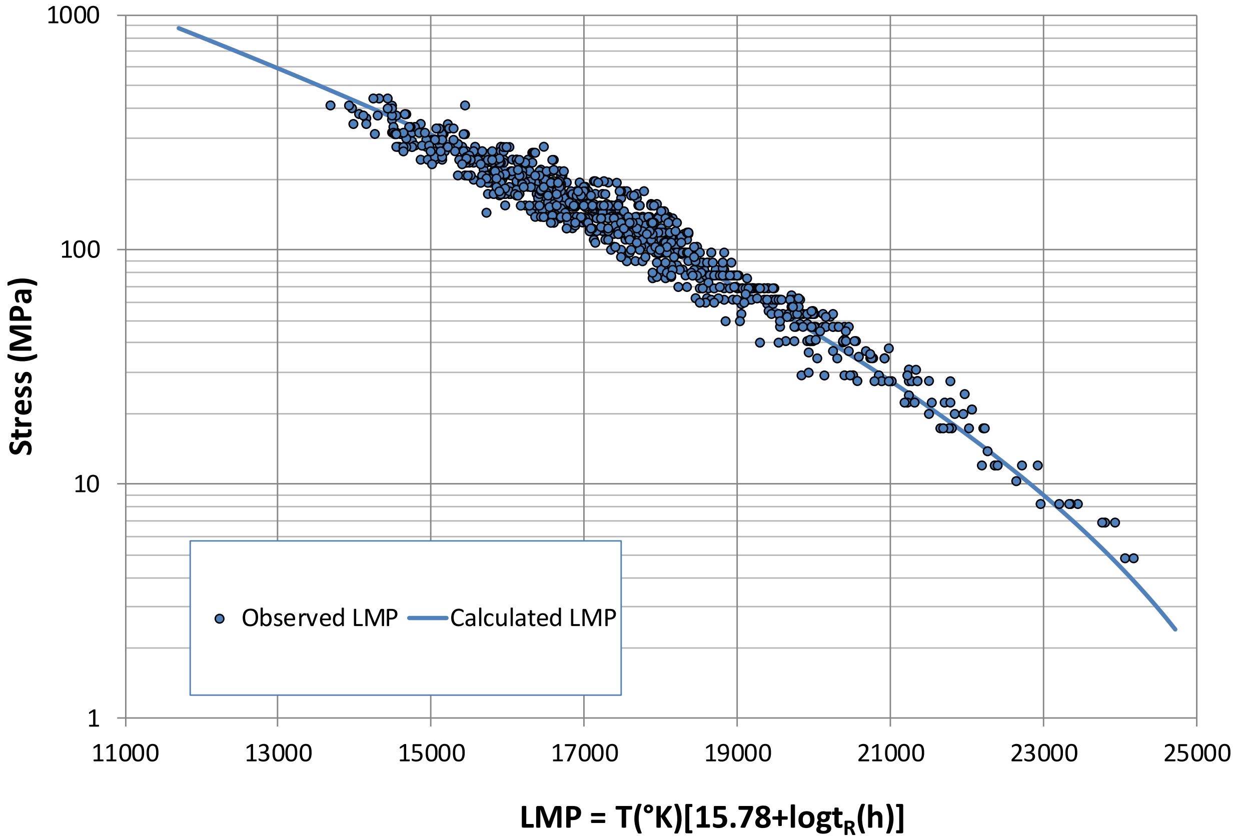
- All data from ASME Material Properties Database (ASME Record no. 16-2627).

Discussion of Analysis and Results

304SS

Figure R.14.2-1 summarizes the results of the analysis in the form of the rupture strength LMP curve and the coefficients and LMP constant for the best-fit, 2nd order curve.

An analysis of the F-factor value for the curve [10^(1/n) where n is the $\Delta \log t_R / \Delta \log S$ slope of the curve] at 50,000 hours shows it to be > 0.50 at all temperatures. The F-factor here is computed in a manner identical to that for F_{avg} as defined in Section II, Part D, Appendix 1 for use at 100,000 hours. Based on independently compiled data on numerous alloys and unpublished analysis of the datasets (Ref. Foulds 2019), the curve-fit is therefore judged to be acceptable with no cause for concern with excessive conservatism. The method for precluding excessive conservatism, developed using the F-factor, is currently part of a yet unpublished draft document produced by the Working Group on Data Analysis of ASME BPVC-II. The F-factor is a measure of the steepness of the rupture curve, i.e., how rapidly the rupture stress is decreasing with increasing time. This F-factor computation has value when deciding on the acceptability of stresses obtained from 2nd order polynomial fits where extrapolations may be too close in time to where the 2nd order parabola vertex (turn-around) exists, resulting in artificial over-conservatism.



C_{LP}=	15.77887
a_0 =	25483.48
a_1 =	-1611.22
a_2 =	-1040.6
SEE=	0.464138
R^2	0.67

$\log t_R = -C_{LP} + a_0/T + a_1/T*\log S + a_2/T*(\log S)^2$

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

Figure R.14.2-1. Summary of regression results for 304 SS

The significant non-conservatism of the BPVC 2017 (and 2019) III-5 Table HBB-I-14.2 S_o values relative to our analysis (see Table R.14.2-1) was further examined in light of the recent effort to analyze the data for this material in order to correct and extend the BPVC III-5 S_{mt} and S_r stresses to 500,000 hours (STP-NU-063) (Ref. Sengupta 2013). The results of that work are evidently not incorporated into the BPVC 2017 (and 2019) III-5 Table HBB-I-14.2 for S_o. Table R.14.2-2 summarizes the calculated S_o per the reported LMP-2nd order logarithmic stress regression coefficients, LMP constant, and standard error of estimate (SEE) from STP-NU-063 compared with the results of this analysis. The table illustrates reasonable agreement with the results of that effort.

Table R.14.2-2. This Analysis compared with calculated values for 304 SS per reported regression data from STP-NU-063 for S_o

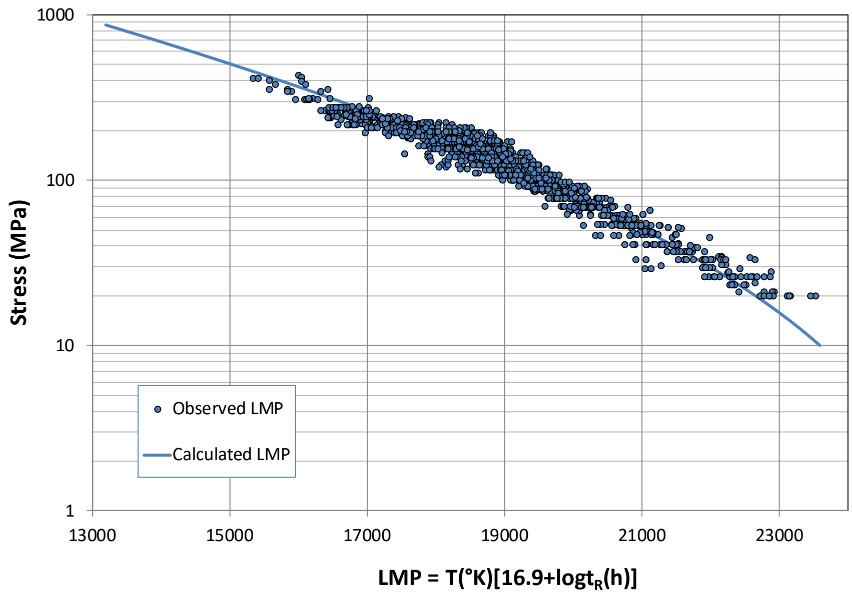
°C	S_o (MPa)	
	Calculated from STP-NU-063	This Analysis
525	103.5	113.6
550	83.9	92.4
575	67.7	74.6
600	54.2	59.8
625	43.2	47.5
650	34.1	37.4
675	26.7	29.2
700	20.7	22.5
725	15.9	17.1
750	12.0	12.7
775	9.0	9.3
800	6.6	6.7
825	4.8	4.6

316 SS

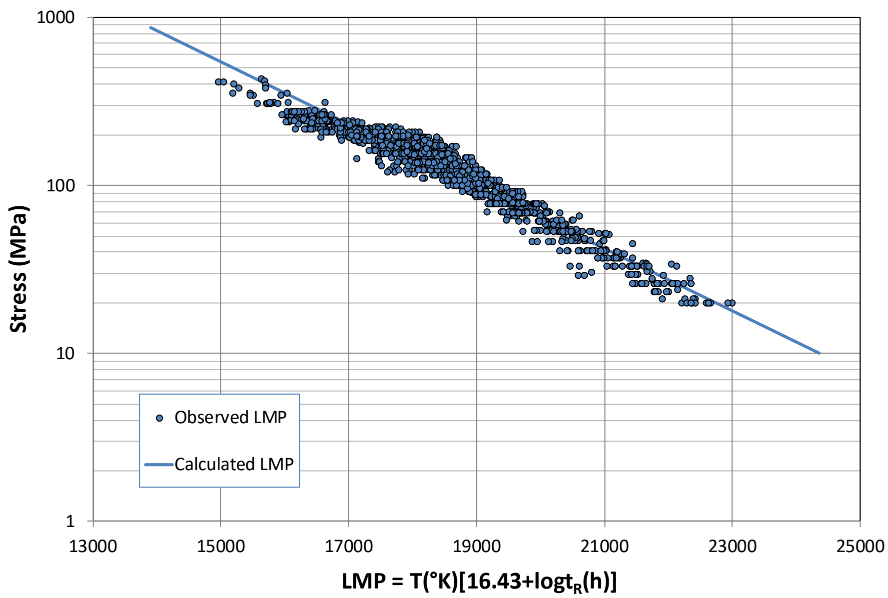
Figure R.14.2-2 summarizes the results of the analysis in the form of the rupture strength LMP curves for the 2nd order [used to 725°C (1350°F)] and the 1st order [average of 1st and 2nd order used for ≥ 750°C (≥ 1400°F)].

An analysis of the F-Factor value for the 2nd order fit curve [10^(1/n) where n is the $\Delta \log t_R / \Delta \log S$ slope of the curve] at 50,000 hours shows it to drop below 0.50 at the highest temperatures [>775°C, (> 1400°F)]. Based on independently compiled data on numerous alloys and unpublished analysis of the datasets (Ref. Foulds 2019), the curve-fit is judged to be excessively conservative at these temperatures. Based on examination of the isotherms in this temperature range, the choice was made to use an average stress of the two curve-fits in the temperatures range 750 to 816°C (1400-1500°F). The issue with attempting to use the 2nd order fit alone gets much worse when extrapolating to longer times (such as for S_r and S_t).

As in the case of 304 SS, the significant non-conservatism of the BPVC 2017 (and 2019) III-5 Table HBB-I-14.2 S_o values relative to our analysis (see Table R.14.2-1) was further examined in light of the relatively recent effort to analyze the data for this material in order to correct and extend the ASME III-5 S_{mt} and S_r stresses to 500,000 hours (STP-NU-063) (Ref. Sengupta 2013). The results of that work are evidently not incorporated into the BPVC 2017 (and 2019) III-5 Table HBB-I-14.2 for S_o. Table R.14.2-3 summarizes the calculated S_o per the reported LMP-2nd order logarithmic stress regression coefficients, LMP constant, and standard error of estimate (SEE) from STP-NU-063 compared with the results of this analysis. The table illustrates reasonable agreement with that effort, albeit not as good as for 304 SS.



2nd order fit



1st order fit

C_{LP}=	16.8983	16.43029
a_0 =	24932.78	29754.5
a_1 =	18.86962	-5393.79
a_2 =	-1367.04	0
SEE=	0.35016	0.370971
R^2=	0.79	0.77

$\log t_R = -C_{LP} + a_0/T + a_1/T*\log S + a_2/T*(\log S)^2$

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

Figure R.14.2-2. Summary of regression results for 316 SS

Table R.14.2-3. This Analysis compared with calculated values for 316 SS per reported regression data from STP-NU-063 for S_o

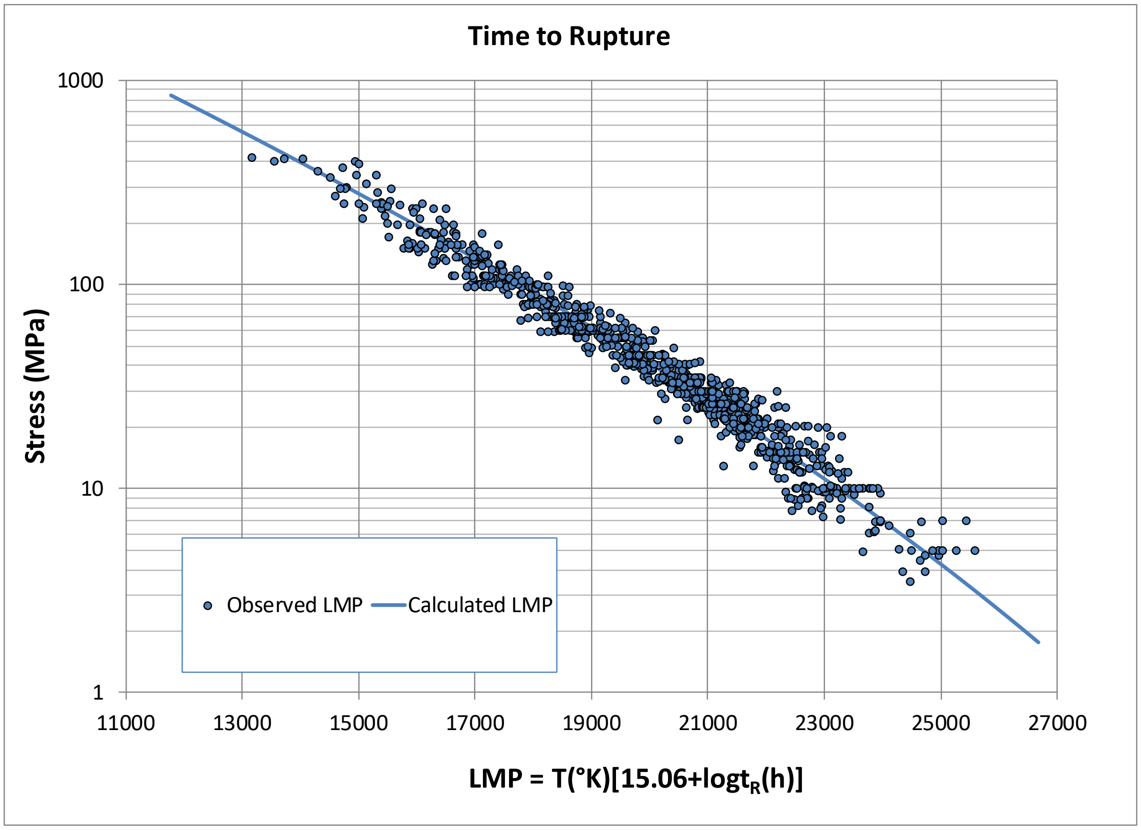
°C	So (MPa)	
	Calculated from STP-NU-063	This Analysis
525	147.1	147.3
550	118.5	120.0
575	94.9	96.0
600	75.5	75.9
625	59.6	59.3
650	46.6	45.7
675	36.1	34.5
700	27.7	25.5
725	21.0	18.3
750	15.7	15.0
775	11.6	10.9
800	8.4	7.8
825	5.9	5.4

Ni-Fe-Cr (Alloy 800H)

Figure R.14.2-3 summarizes the results of the analysis in the form of the rupture strength LMP curve for the 2nd order fit.

The data scatter at the higher stresses and shorter rupture was low enough to permit analysis without time-censoring the data. Overall, the fit is good with a relatively high regression coefficient (R^2) and low standard error of the estimate (SEE). The fit is also close to linear with the parabolic vertex turn-around not impacting the predictions and extrapolations.

A comparison of the analysis results with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.2 stresses indicates a potential non-conservatism only at the highest temperature(s), marginally greater than 10% (see Table R.14.2-1).



C_{LP}=	15.05545
a_0 =	27661.01
a_1 =	-3919.96
a_2 =	-516.121
SEE=	0.38245
R^2	0.85

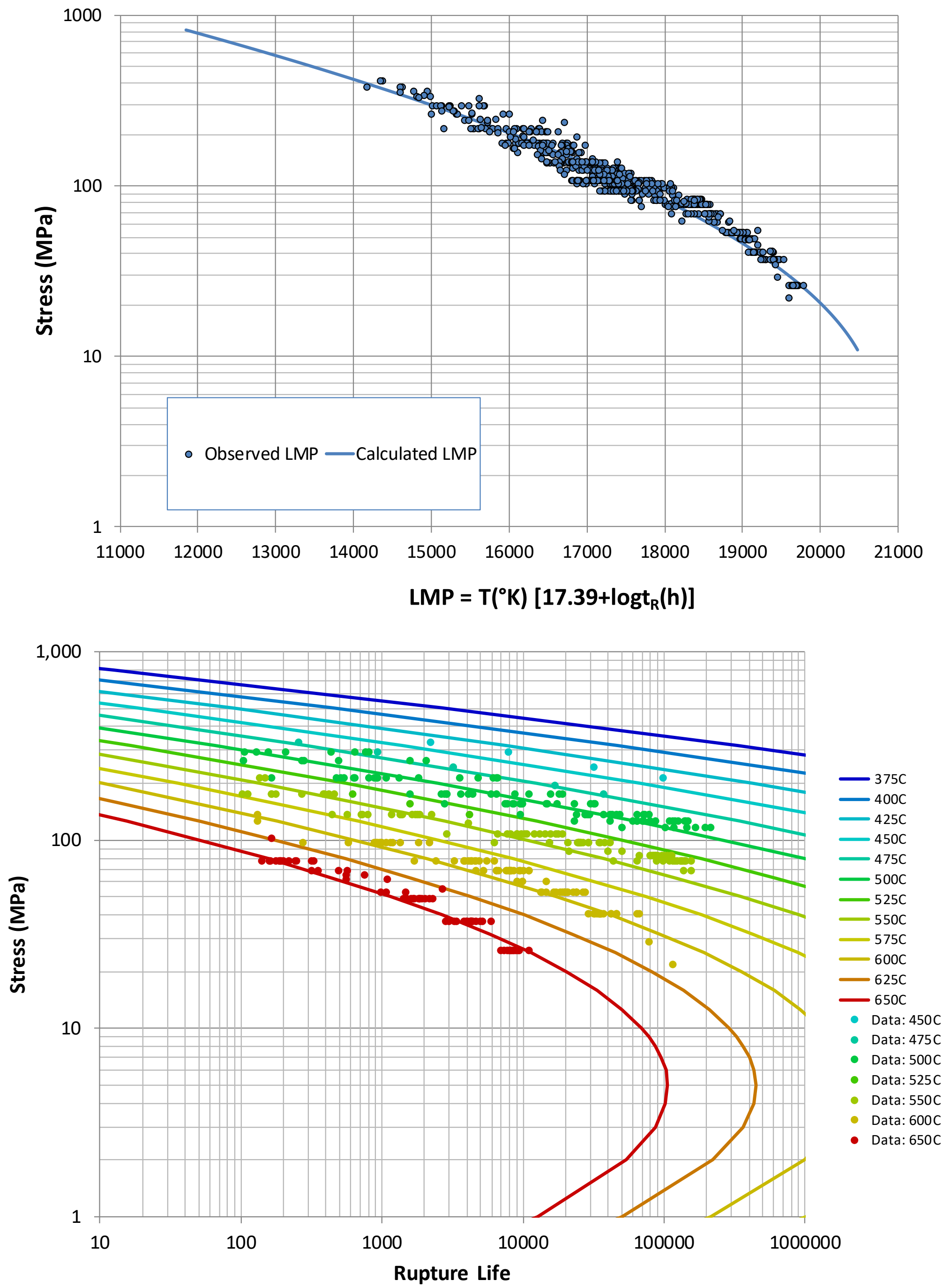
$$\log t_R = -C_{LP} + a_0/T + a_1/T*\log S + a_2/T*(\log S)^2$$

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

Figure R.14.2-3. Summary of regression results for Ni-Fe-Cr (Alloy 800H)

<u>2¼Cr-1Mo</u>

Figure R.14.2-4 summarizes the results of the analysis in the form of the rupture strength LMP curve for the 2nd order. Also shown in the figure are the isotherms with a striking turn-around at the highest temperature.



C_{LP}=	17.39036
a_0 =	19839.43
a_1 =	2470.977
a_2 =	-1786.47
SEE=	0.339601

$$\log t_R = -C_{LP} + a_0/T + a_1/T*\log S + a_2/T*(\log S)^2$$

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

Figure R.14.2-4. Summary of regression results for 2¼Cr-1Mo

A review of the F-factor at 50,000 hours for the temperature range of interest (to 593°C or 1100°F) shows that the F-factor exceeds 0.50, suggesting, as based on experience (Ref. Foulds 2019), no basis for judging the predictions to be excessively conservative, despite the parabolic vertex turn-around. The 2nd order curve-fit is therefore used.

Apparent from Table R.14.2-1 summarizing the findings in comparison with the BPVC 2017 (and 2019) III-5 S_o table is that for temperatures ≥ 525°C (≥ 1000°F), the ASME values are relatively non-conservative. The ASME II-D Table 1A values were last updated circa 1990 and the origins of the Table HBB-I-14.2 values are not known. Also, our analysis combined data for both annealed and normalized + tempered material (since both heat treatments are permitted) and it is unclear as to what data were used in development of the current ASME stresses.

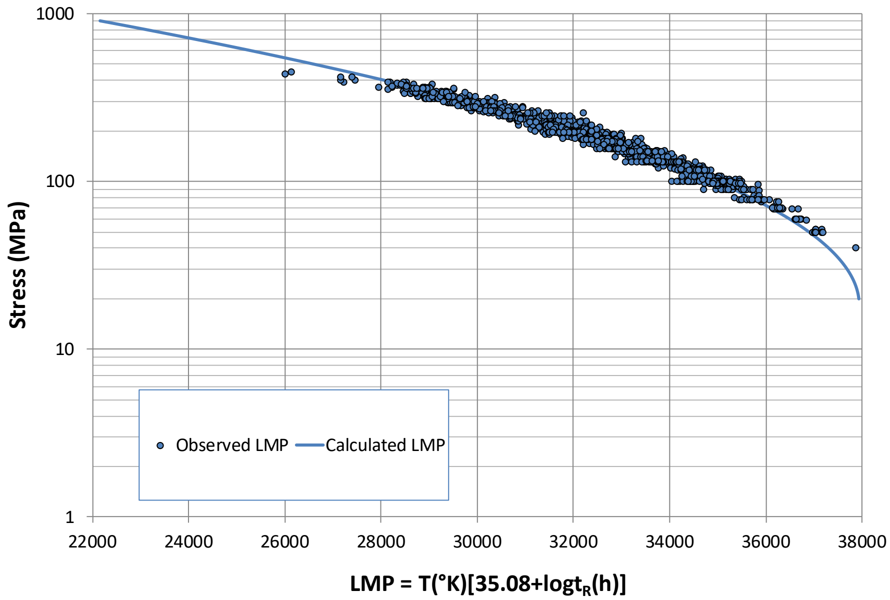
9Cr-1Mo-V

As noted earlier, a split region analysis was conducted for this material case. The curve-fits both exhibit acceptable LMP-2nd order logarithmic stress fits. The methodology is the same as one used in the recent correction and expansion of the S_r, S_t, S_t and S_{mt} tables in BPVC III-5, first appearing in the BPVC 2019 edition (Record No. 16-2627). However, that project did not include updating of the S_o table. Additionally, ASME II-D, Table 1A values have also been updated, again first appearing in BPVC 2019 edition.

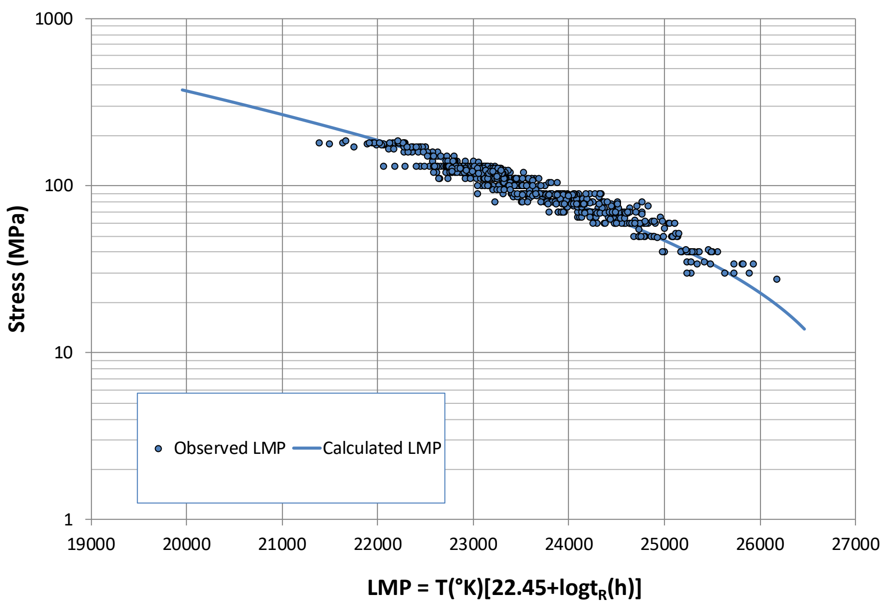
Our analysis results, although generally consistent with the current II-D Table 1A stresses and the current III-5 S_r (and S_t) values, differ significantly from the current S_o. The summary of results below provides some details on the analysis.

Figure R.14.2-5 graphically summarizes the best-fit rupture strength-LMP curves for the two split region analyses. The high stress region curve exhibited a turn-around at the highest temperature of interest (650°C or 1200°F). However, since at this temperature, the rupture strength is in the low stress region, the turn-around does not impact use of the 2nd order high stress region analysis.

For perspective on the need for updating ASME III-5 Table HBB-I-14.2 with regard to the 9Cr-1Mo-V S_o values, Table R.14.2-4 compares the results of this analysis with ASME 2019 II-D, Table 1A stresses in the temperature regime where the S_o is time-dependent (see Table R.14.2-1). Table R.14.2-5 provides a similar comparison for the stresses in the time-independent regime. The reasonable agreement with the ASME 2019 II-D Table 1A stresses (updated in this edition of the Code) supports the need to further review the ASME III-5, Table HBB-I-14.2 S_o table.



High Stress Region



Low Stress Region

	Hi Stress	Lo stress
C_{LP}=	35.08069	22.45217
a0 =	29108.19	25841.75
a1 =	13965.19	2809.952
a2 =	-5523.75	-1982.95
SEE=	0.377826	0.258595
R^2=	0.77	0.72

$$\log t_R = -C_{LP} + a_0/T + a_1/T^*\log S + a_2/T^*(\log S)^2$$

$$\log t_R = -C_{LP} + a_0/T + a_1/T^*\log S + a_2/T^*(\log S)^2$$

Figure R.14.2-5. Summary of regression results for 9Cr-1Mo-V

Table R.14.2-4. This Analysis compared with ASME 2019 II-D Table 1A time-dependent stresses for perspective on the need to update ASME III-5, Table HBB-I-14.2 for the 9Cr-1Mo-V stresses

°C/MPa	ASME 2019 II-D Table 1A	This Analysis
550	98.5	99.3
575	75.5	74.7
600	54.3	54.1
625	36.8	36.6
650	24.0	22.7

Table R.14.2-5. This Analysis compared with ASME 2019 II-D Table 1A time-independent stresses for perspective on the need to update ASME III-5, Table HBB-I-14.2 for the 9Cr-1Mo-V stresses

°C/MPa	ASME 2019 II-D Table 1A (60-85)	This Analysis
375	157	150
400	153	147
425	147	143
450	141	139
475	134	134
500	126	127

Figures and Tables HBB-I-14.3A ~ E, S_{mt} — Allowable Stress Intensity Values
Observations Indicating Need for Further Review

Types 304 SS and 316 SS**:**

For both alloys, BPVC 2017 (and 2019) III-5 Figures and Tables HBB-I-14.3A and 14.3B show S_{mt} values that are non-conservative relative to our analysis over a significant range of time and temperature encompassing the time-dependent stress-controlled regime. The figures and tables merit further review, particularly given that our analysis results are in good agreement with the reported analysis results on a relatively recent effort to "Correct and Extend Allowable Stress Values for 304 and 316 Stainless Steel," ASME STP-NU-063 (Ref. Sengupta 2013). The S_{mt} results of ASME STP-NU-063 have not been incorporated into BPVC 2017 (and 2019) III-5. Such incorporation would largely eliminate the discrepancy between our results and the S_{mt} results in the Figures and Tables HBB-I-14.3A and 14.3B.

Ni-Fe-Cr (Alloy 800H)**:**

BPVC 2017 (and 2019) III-5 Figure and Table HBB-I-14.3C show S_{mt} values that are non-conservative relative to our analysis over a significant range of time and temperature at the longer times and higher temperatures encompassing the time-dependent-controlled stress regime. The figure and table merit further review, particularly given that our analysis results are in good agreement with the reported analysis results on a relatively recent effort to "Extend Allowable Stress Values for Alloy 800H," ASME ST-LLC STP-NU-035 (Ref. Swindeman 2012). The S_{mt} results of ASME STP-NU-035 have not been incorporated into BPVC III-5. Such incorporation would largely eliminate the discrepancy between our results and the S_{mt} values in Figure and Table HBB-I-14.3C.

2¼Cr-1Mo:

BPVC 2017 (and 2019) III-5 Figure and Table HBB-I-14.3D are judged to be non-conservative relative to our analysis for the higher temperatures and extended times. It is not known when the stresses were last reviewed, but the BPVC II-D Table 1A time-dependent stresses were last reviewed and updated circa 1990. We recommend review of Table HBB-I-14.3D and the corresponding Figure HBB-I-14.3D.

9Cr-1Mo-V:

The BPVC 2017 III-5 Figure and Table HBB-I-14.3E are seen to be non-conservative relative to our analysis and would be recommended for further review. However, the table and figure have been updated in the BPVC 2019 edition. A further review of the 2019 edition figure and table is neither needed nor recommended because there is no observed non-conservatism relative to our analysis results. Since the 2019 edition figure and table are found to be acceptable, a review of the 2017 edition figure and table is moot. Meanwhile, it is noted there should be two sets of S_m values that are tensile strength-controlled in Figure and Table HBB-I-14.3E, given two tensile strength classes of material are permitted (60-85 and 60-90), consistent with the BPVC 2019 II-D Table 2A lines.

Comments

A major portion of the time-temperature range over which the BPVC III-5 S_{mt} values have been found to be non-conservative relative to our analysis is the range over which the S_{mt} values are controlled by the (time-dependent) stress to initiate tertiary creep. For perspective, the issues associated with implementation of the tertiary creep criterion and our limited research into its effect for 304 SS, by way of example, are described in Appendix TCOC: "Comments on the Tertiary Creep Criterion for S_t (and S_{mt})."

With regard to stress intensity values controlled by time-dependent creep properties, we note that for extended durations (> 100,000 hours) and for temperatures at the upper-end of the use temperature range, the materials may strain by a diffusion creep mechanism, more likely in case of 304 SS, 316 SS and Alloy 800H. The creep and rupture data used in development of the allowable stress intensity values, however, include, at best, a very small number of data points representing this mechanism, so that the computed, extrapolated design values can be somewhat non-conservative when diffusion creep is operative. Unfortunately, the paucity of such data makes analysis for diffusion creep-specific stress intensity values impractical. In any case, as is seen in our analysis for S_t and S_{mt}, the discrepancy between our results and the tabulations in BPVC 2017 (and 2019) for 304 SS, 316 SS and Alloy 800H occurs over a significant range of time and temperature judged to be well outside of the diffusion creep-controlled regime, meriting consideration for review.

Comparison of BPVC III-5 S_{mt} Values and Results of This Analysis

The figures and tables resulting from our analysis are first reported below, followed by key details on the analysis method, data used, and summary of analyses.

Figure R.14.3-1A is the resulting graphic, shown alongside BPVC 2017 (and 2019) III-5 Figure HBB-I-14.3A for 304 SS. The corresponding Table R.14.3-1A provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3A S_{mt} values.

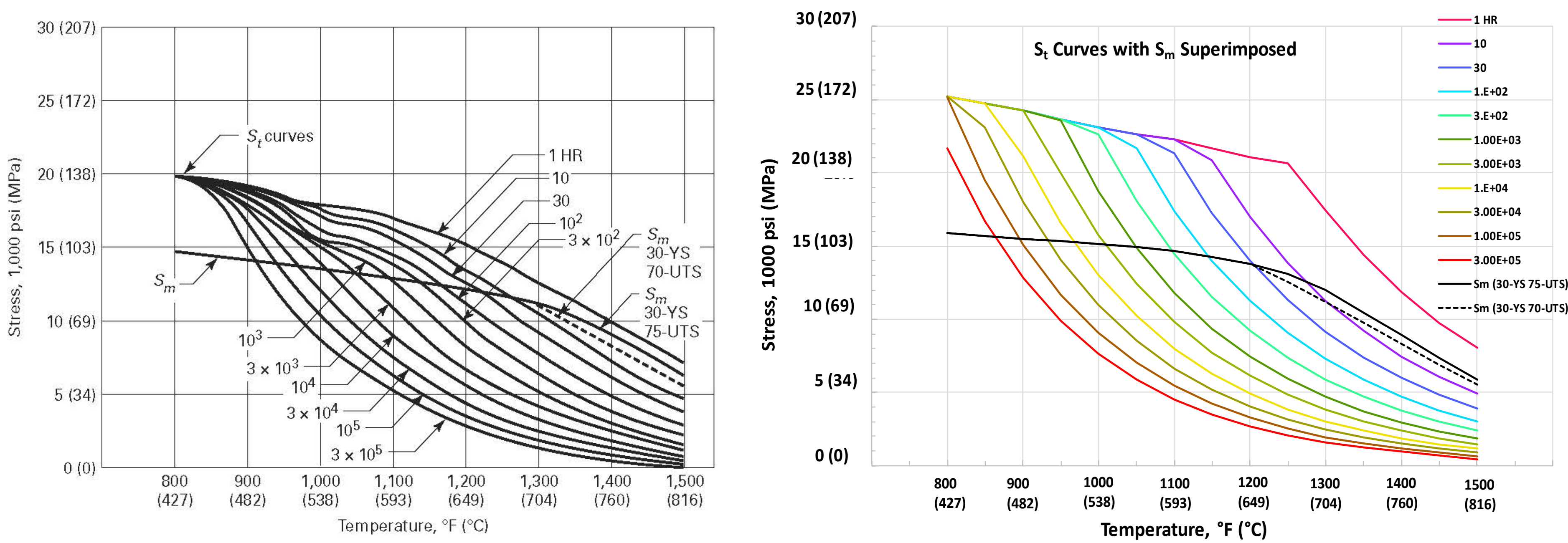
Figure R.14.3-1B is the resulting graphic, shown alongside BPVC 2017 (and 2019) III-5 Figure HBB-I-14.3B for 316 SS. The corresponding Table R.14.3-1B provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3B S_{mt} values.

Figure R.14.3-1C is the resulting graphic, shown alongside BPVC 2017 (and 2019) III-5 Figure HBB-I-14.3C for Ni-Fe-Cr (Alloy 800H). The corresponding Table R.14.3-1C provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3C S_{mt} values.

Figure R.14.3-1D is the resulting graphic, shown alongside BPVC 2017 (and 2019) III-5 Figure HBB-I-14.3D for 2¼Cr-1Mo. The corresponding Table R.14.3-1D provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3D S_{mt} values.

Figure R.14.3-1E is the resulting graphic, shown alongside BPVC 2017 III-5 Figure HBB-I-14.3E for 9Cr-1Mo-V. The corresponding Table R.14.3-1E provides our analysis results compared with the BPVC 2017 III-5 Table HBB-I-14.3E S_{mt} values.

Figure R.14.3-1E-2019 is the resulting graphic, shown alongside BPVC 2019 III-5 Figure HBB-I-14.3E for 9Cr-1Mo-V. The corresponding Table R.14.3-1E-2019 provides our analysis results compared with the BPVC 2019 III-5 Table HBB-I-14.3E S_{mt} values.



ASME 2017 (and 2019) III-5

This Analysis

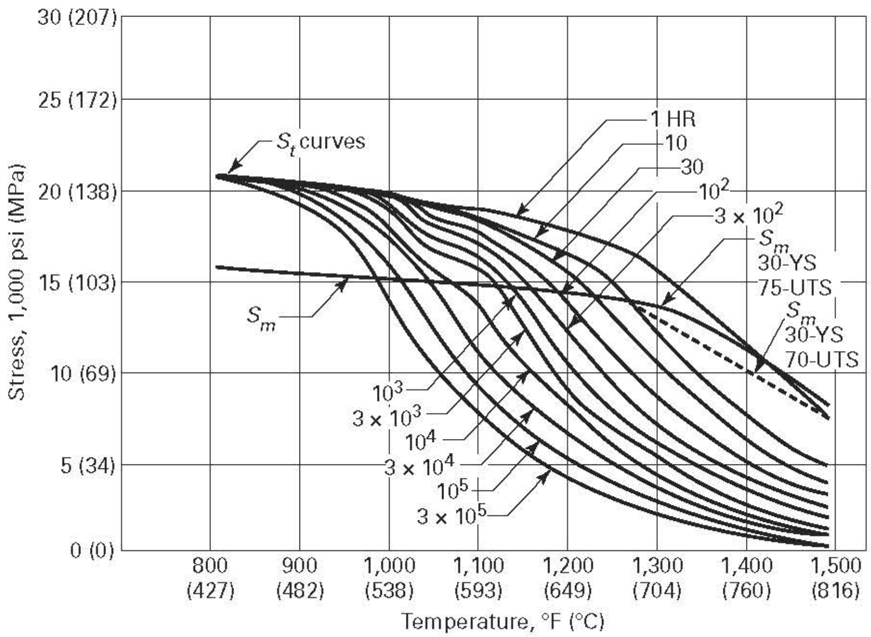
Figure R.14.3-1A. Summary of S_t-S_{mt} curves for 304 SS

Table R.14.3-1A. This Analysis for Type 304 SS S_{mt} (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.3A

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis
800	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9
850	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7
900	14.6	15.5	14.6	15.5	14.6	15.5	14.6	15.5	14.6	15.5	14.6	15.5	14.6	15.5	14.6	15.5	14.6	15.5	14.6	15.1	14.6	12.8
950	14.3	15.3	14.3	15.3	14.3	15.3	14.3	15.3	14.3	15.3	14.3	15.3	14.3	15.3	14.3	15.3	14.3	14.0	14.2	11.7	12.2	9.9
1000	14	15.1	14.0	15.1	14.0	15.1	14.0	15.1	14.0	15.1	14.0	15.1	14.0	15.1	14.0	13.0	13.1	11.0	11.1	9.1	9.3	7.6
1050	13.6	14.9	13.6	14.9	13.6	14.9	13.6	14.9	13.6	14.9	13.6	14.9	13.6	12.4	12.2	10.2	10.3	8.5	8.7	7.0	7.3	5.9
1100	13.2	14.6	13.2	14.6	13.2	14.6	13.2	14.6	13.2	14.5	13.2	11.8	11.5	9.8	9.7	8.0	8.2	6.7	6.8	5.4	5.7	4.5
1150	12.9	14.3	12.9	14.3	12.9	14.3	12.9	14.0	12.9	11.6	11.0	9.4	9.3	7.7	7.7	6.3	6.4	5.2	5.3	4.2	4.4	3.5
1200	12.7	13.8	12.7	13.8	12.7	13.8	12.2	11.3	10.6	9.2	8.9	7.5	7.4	6.1	6.1	4.9	5.1	4.0	4.1	3.3	3.4	2.7
1250	12.3	13.1 (12.6)	12.3	13.1 (12.6)	11.9	11.3	10.3	9.1	8.7	7.4	7.2	5.9	5.9	4.8	4.9	3.9	4.0	3.2	3.2	2.5	2.7	2.1
1300	11.9 (11.8)	12.0 (11.2)	11.4	11.3	10.0	9.2	8.5	7.3	7.0	5.9	5.9	4.7	4.8	3.8	3.9	3.0	3.2	2.5	2.5	2.0	2.1	1.6
1350	10.9 (10.5)	10.5 (9.8)	9.7	9.2	8.4	7.4	7.1	5.9	5.9	4.7	4.8	3.7	3.9	3.0	3.1	2.4	2.5	1.9	2.0	1.5	1.6	1.2
1400	9.5 (9.0)	8.9 (8.3)	8.1	7.5	6.9	6.0	5.9	4.7	4.8	3.8	3.9	3.0	3.1	2.4	2.5	1.9	2.0	1.5	1.6	1.2	1.2	0.9
1450	8.2 (7.5)	7.4 (6.9)	6.8	6.1	5.8	4.9	4.6	3.8	3.8	3.0	3.0	2.4	2.4	1.9	1.9	1.5	1.5	1.2	1.2	0.9	0.9	0.7
1500	7.0 (6.4)	5.9 (5.5)	5.3	5.0	4.4	3.9	3.5	3.0	2.8	2.4	2.2	1.9	1.7	1.5	1.3	1.1	1.0	0.9	0.8	0.6	0.6	0.4

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3A	This Analysis
425	105	110	105	110	105	110	105	110	105	110	105	110	105	110	105	110	105	110	105	110	105	110
450	102	108	102	108	102	108	102	108	102	108	102	108	102	108	102	108	102	108	102	108	102	108
475	101	107	101	107	101	107	101	107	101	107	101	107	101	107	101	107	101	107	101	107	101	95
500	99	106	99	106	99	106	99	106	99	106	99	106	99	106	99	106	99	106	99	88	93	75
525	98	105	98	105	98	105	98	105	98	105	98	105	98	105	98	100	98	85	87	70	73	59
550	96	104	96	104	96	104	96	104	96	104	96	104	96	98	94	81	82	68	70	56	58	47
575	93	102	93	102	93	102	93	102	93	102	93	95	91	79	78	65	66	54	56	44	46	37
600	91	100	91	100	91	100	91	100	91	95	89	77	75	64	63	52	54	43	44	35	37	29
625	89	98	89	98	89	98	89	94	87	77	74	63	62	52	51	42	43	35	36	28	29	23
650	88	95	88	95	88	95	84	77	73	63	61	51	51	42	42	34	35	28	28	22	23	18
675	85	91 (87)	85	91 (87)	83	79	77	63	61	52	51	41	42	34	35	27	28	22	22	18	19	14
700	82 (81)	84 (79)	80	80	69	65	61	52	50	42	42	34	34	27	28	22	23	18	18	14	15	11
725	77 (74)	75 (70)	70	67	61	54	52	43	43	35	35	27	29	22	22	17	18	14	15	11	12	9.0
750	69 (66)	65 (61)	60	56	52	45	44	35	36	28	29	22	23	18	18	14	15	11	12	8.9	9	7.1
775	61 (57)	56 (52)	51	46	44	37	36	29	29	23	24	18	19	14	15	11	12	9.0	9	7.1	7.0	5.6
800	53 (49)	46 (43)	43	38	37	30	29	24	23	19	18	15	15	12	11	9.1	9.0	7.2	7	5.6	5.0	3.9

S_m (Yield strength)-controlled	S_m (Tensile strength)-controlled	80% Minimum Stress to Initiate Tertiary Creep	Red entries are 30-70 S_m (tensile strength)-controlled
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%			67% Minimum Stress to Rupture
Non-conservative relative to this analysis - Difference, δ > 10%		(Used rounding for characterization of δ)	



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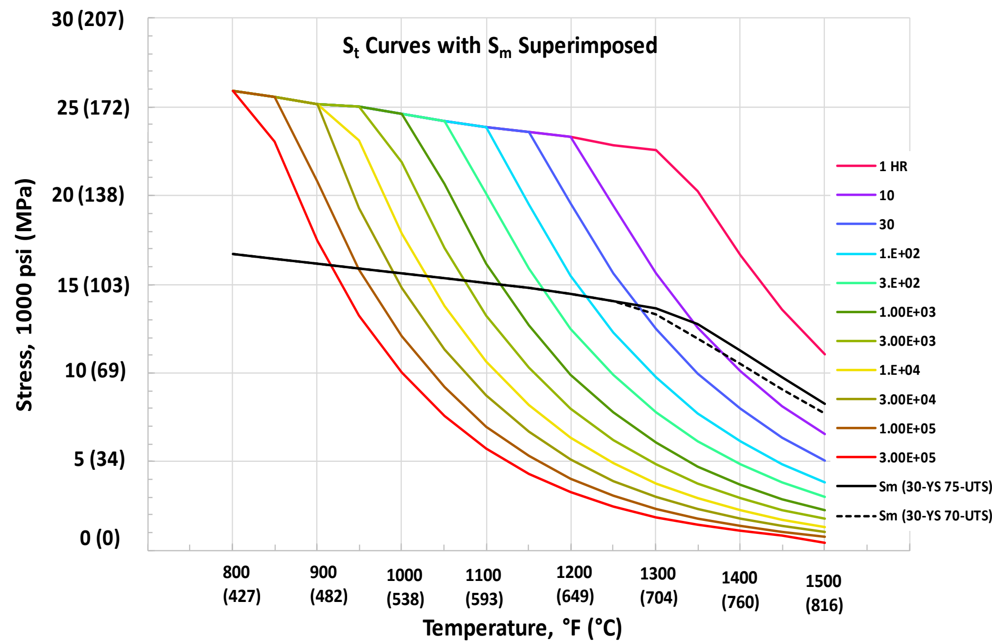


This Analysis

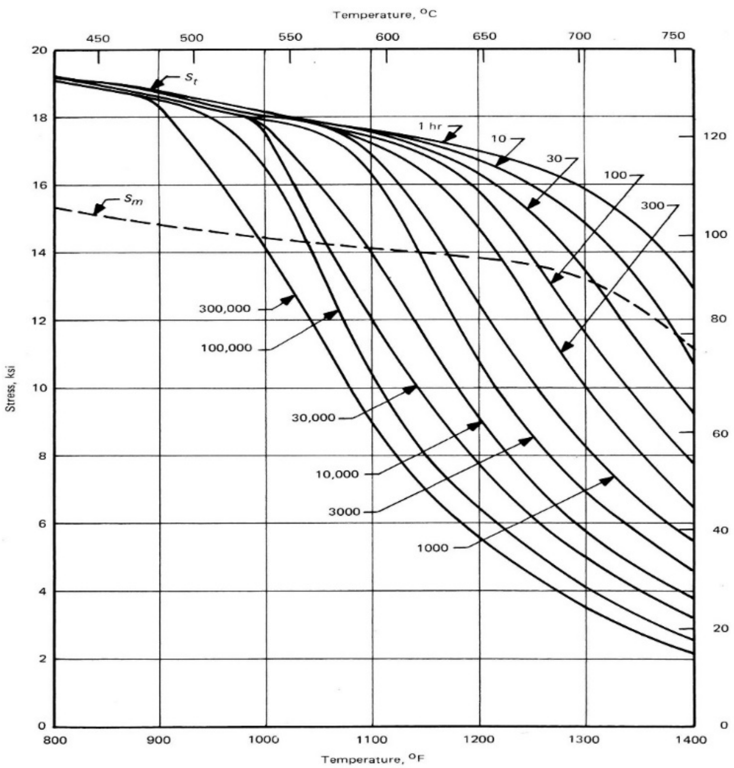
Figure R.14.3-1B. Summary of S_t-S_{mt} curves for 316 SS

Table R.14.3-1B. This Analysis for Type 316 SS S_{mt} (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.3B

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis
800	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7
850	15.7	16.4	15.7	16.4	15.7	16.4	15.7	16.4	15.7	16.4	15.7	16.4	15.7	16.4	15.7	16.4	15.7	16.4	15.7	16.4	15.7	16.4
900	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1
950	15.5	15.9	15.5	15.9	15.5	15.9	15.5	15.9	15.5	15.9	15.5	15.9	15.5	15.9	15.5	15.9	15.5	15.9	15.5	15.8	15.5	13.2
1000	15.4	15.6	15.4	15.6	15.4	15.6	15.4	15.6	15.4	15.6	15.4	15.6	15.4	15.6	15.4	15.6	15.4	14.8	15.4	12.1	14.0	10.0
1050	15.1	15.4	15.1	15.4	15.1	15.4	15.1	15.4	15.1	15.4	15.1	15.4	15.1	15.4	15.1	13.8	14.9	11.4	12.5	9.2	10.7	7.6
1100	14.8	15.1	14.8	15.1	14.8	15.1	14.8	15.1	14.8	15.1	14.8	15.1	14.8	13.2	13.9	10.6	11.5	8.7	9.5	7.0	7.8	5.7
1150	14.7	14.8	14.7	14.8	14.7	14.8	14.7	14.8	14.7	14.8	14.2	12.7	13.0	10.3	10.9	8.2	8.9	6.7	7.2	5.3	5.9	4.3
1200	14.6	14.4	14.6	14.4	14.6	14.4	14.2	14.4	12.4	12.5	10.6	9.9	9.4	8.0	8.3	6.3	6.9	5.1	5.5	4.1	4.5	3.3
1250	14.2	14.1	14.2	14.1	14.2	14.1	11.5	12.3	9.8	9.9	8.3	7.8	7.3	6.2	6.3	4.9	5.4	3.9	4.2	3.1	3.3	2.5
1300	13.8 (13.4)	13.7 (13.3)	12.8	13.7 (13.3)	10.9	12.5	9.1	9.7	7.5	7.8	6.4	6.1	5.6	4.8	4.7	3.8	3.9	3.0	3.1	2.4	2.5	1.9
1350	12.8 (11.9)	10.5 (9.8)	10.3	12.6 (11.9)	8.6	10.0	7.0	7.7	5.9	6.1	5.0	4.8	4.2	3.8	3.4	2.9	2.8	2.3	2.1	1.8	1.8	1.4
1400	11.3 (10.5)	12.8 (11.9)	8.2	10.1	6.7	8.0	5.4	6.1	4.5	4.8	3.8	3.7	3.1	2.9	2.5	2.3	2.0	1.8	1.5	1.4	1.2	1.1
1450	9.7 (9.0)	11.3 (10.5)	6.4	8.1	5.1	6.4	4.1	4.9	3.4	3.8	2.9	2.9	2.2	2.3	1.7	1.7	1.4	1.4	1.0	1.0	0.9	0.82
1500	7.8 (7.7)	8.3 (7.7)	4.9	6.5	3.9	5.1	3.2	3.9	2.6	3.0	2.1	2.3	1.6	1.8	1.2	1.3	0.9	1.0	0.65	0.76	0.5	0.45

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3B	This Analysis
425	110	115	110	115	110	115	110	115	110	115	110	115	110	115	110	115	110	115	110	115	110	115
450	108	113	108	113	108	113	108	113	108	113	108	113	108	113	108	113	108	113	108	113	108	113
475	107	112	107	112	107	112	107	112	107	112	107	112	107	112	107	112	107	112	107	112	107	112
500	106	110	106	110	106	110	106	110	106	110	106	110	106	110	106	110	106	110	106	110	106	101
525	105	109	105	109	105	109	105	109	105	109	105	109	105	109	105	109	105	109	105	94	105	78
550	104	107	104	107	104	107	104	107	104	107	104	107	104	107	104	107	104	91	101	74	87	61
575	104	105	104	105	104	105	104	105	104	105	104	105	104	105	104	87	95	72	79	58	67	47
600	102	103	102	103	102	103	102	103	102	103	102	103	102	86	91	69	75	56	62	45	51	37
625	101	102	101	102	101	102	101	102	101	102	94	84	86	69	72	55	59	44	48	35	40	29
650	101	99	101	99	101	99	98	99	84	85	72	68	64	55	57	43	48	35	38	28	31	22
675	98	97	98	97	98	97	80	86	69	69	58	54	51	44	44	34	38	28	30	22	24	17
700	95 (92)	95 (93)	91	95 (93)	78	89	65	70	54	56	46	44	41	35	34	27	28	22	22	17	18	14
725	90 (85)	91 (85)	75	91 (85)	63	73	52	57	44	45	36	35	31	28	25	22	21	17	16	13	13	11
750	82 (76)	81 (76)	62	75	51	60	41	46	35	36	29	28	24	22	19	17	16	13	11	10	9	8.2
775	70 (65)	72 (67)	50	62	40	49	32	37	27	29	23	22	18	18	14	14	12	11	8	8.2	7	6.4
800	61 (58)	46 (43)	40	51	32	40	25	30	21	24	17	18	13	14	10	11	8	8.4	5	6.4	4	4.6

S_m (Yield strength)-controlled	S_m (Tensile strength)-controlled	80% Minimum Stress to Initiate Tertiary Creep	Red entries are 30-70 S_m (tensile strength)-controlled
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%		67% Minimum Stress to Rupture	
Non-conservative relative to this analysis - Difference, δ > 10%		(Used rounding for characterization of δ)	



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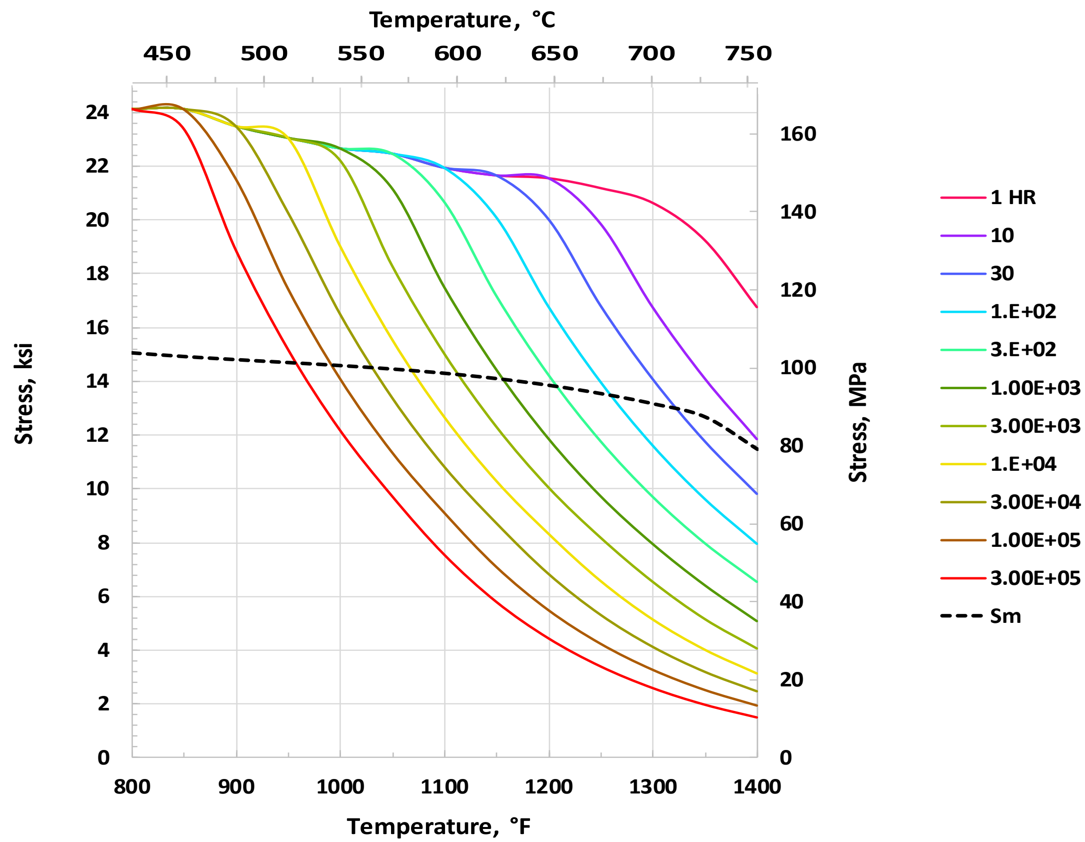


This Analysis

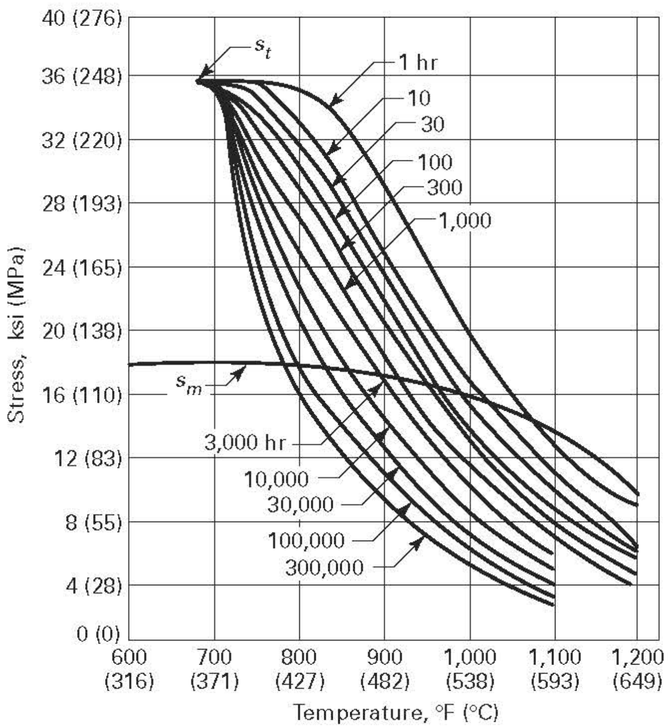
Figure R.14.3-1C. Summary of S_t-S_{mt} curves for Ni-Fe-Cr (Alloy 800H)

Table R.14.3-1C. This Analysis for Ni-Fe-Cr (Alloy 800H) S_{mt} (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.3C

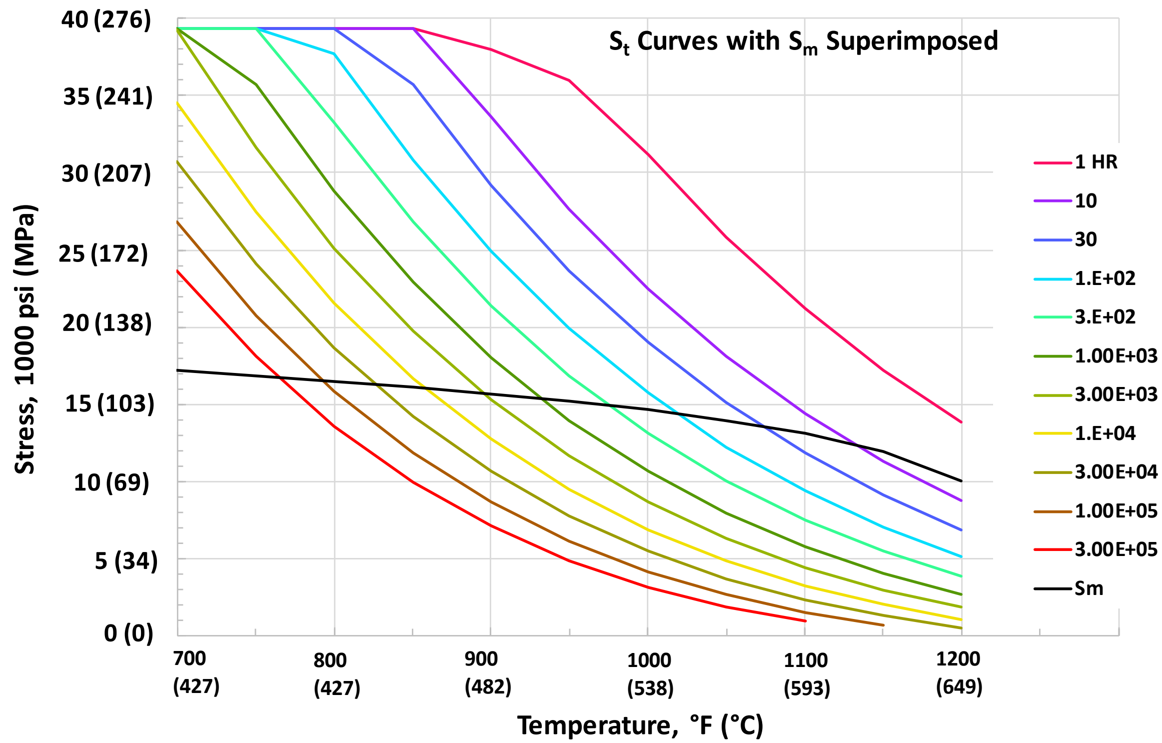
ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis
800	15.3	15.1	15.3	15.1	15.3	15.1	15.3	15.1	15.3	15.1	15.3	15.1	15.3	15.1	15.3	15.1	15.3	15.1	15.3	15.1	15.3	15.1
850	15.1	14.9	15.1	14.9	15.1	14.9	15.1	14.9	15.1	14.9	15.1	14.9	15.1	14.9	15.1	14.9	15.1	14.9	15.1	14.9	15.1	14.9
900	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	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	14.7	14.6	14.7	14.6	14.7	14.6	14.7	14.6	14.7	14.6	14.7	14.6	14.7	14.6	14.7	14.6	14.7	14.6	14.7	14.6	14.7
1000	14.4	14.6	14.4	14.6	14.4	14.6	14.4	14.6	14.4	14.6	14.4	14.6	14.4	14.6	14.4	14.6	14.4	14.6	14.4	14.1	14.1	12.2
1050	14.3	14.5	14.3	14.5	14.3	14.5	14.3	14.5	14.3	14.5	14.3	14.5	14.3	14.5	14.3	14.5	14.3	13.4	12.8	11.4	11.2	9.7
1100	14.1	14.3	14.1	14.3	14.1	14.3	14.1	14.3	14.1	14.3	14.1	14.3	14.1	14.3	13.9	12.7	12.0	10.8	10.2	9.1	8.9	7.6
1150	13.9	14.1	13.9	14.1	13.9	14.1	13.9	14.1	13.9	14.1	13.9	14.1	13.2	12.3	11.2	10.3	9.6	8.7	8.2	7.1	7.0	5.8
1200	13.8	13.9	13.8	13.9	13.8	13.9	13.8	13.9	13.8	13.9	12.4	11.9	10.7	10.0	9.0	8.3	7.7	6.9	6.5	5.5	5.6	4.5
1250	13.5	13.6	13.5	13.6	13.5	13.6	13.5	13.6	12.0	11.8	10.1	9.7	8.6	8.2	7.2	6.6	6.2	5.3	5.2	4.2	4.4	3.4
1300	13.2	13.2	13.2	13.2	13.2	13.2	11.6	11.6	9.8	9.7	8.2	8.0	7.0	6.5	5.8	5.2	5.0	4.1	4.1	3.3	3.5	2.6
1350	12.0	12.7	12.0	12.7	11.3	11.8	9.5	9.6	8.0	8.0	6.7	6.4	5.7	5.1	4.7	4.0	4.0	3.2	3.3	2.5	2.8	2.0
1400	11	11.5	10.8	11.5	9.3	9.8	7.8	8.0	6.5	6.6	5.4	5.1	4.6	4.1	3.8	3.1	3.2	2.5	2.6	1.9	2.2	1.5

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3C	This Analysis
425	105	104	105	104	105	104	105	104	105	104	105	104	105	104	105	104	105	104	105	104	105	104
450	104	103	104	103	104	103	104	103	104	103	104	103	104	103	104	103	104	103	104	103	104	103
475	103	102	103	102	103	102	103	102	103	102	103	102	103	102	103	102	103	102	103	102	103	102
500	101	102	101	102	101	102	101	102	101	102	101	102	101	102	101	102	101	102	101	102	101	102
525	100	101	100	101	100	101	100	101	100	101	100	101	100	101	100	101	100	101	100	101	98	93
550	99	100	99	100	99	100	99	100	99	100	99	100	99	100	99	100	99	100	94	88	88	76
575	98	99	98	99	98	99	98	99	98	99	98	99	98	99	98	99	94	86	82	73	72	62
600	97	98	97	98	97	98	97	98	97	98	97	98	96	98	91	83	79	71	67	59	58	49
625	96	97	96	97	96	97	96	97	96	97	96	97	92	82	80	69	68	58	59	47	50	39
650	95	95	95	95	95	95	95	95	95	95	84	81	73	69	62	57	53	47	45	37	39	30
675	93	94	93	94	93	94	93	94	84	82	71	68	60	57	51	46	44	37	37	30	31	24
700	91	91	91	91	91	91	82	82	70	69	59	57	50	47	41	37	35	30	29	23	25	19
725	85	89	85	89	81	85	69	70	58	58	49	47	41	38	34	30	30	24	24	18	20	15
750	78	82	77	82	69	72	58	59	49	49	40	38	34	30	28	24	24	19	20	15	16	12

S_m (Yield strength)-controlled	S_m (Tensile strength)-controlled	80% Minimum Stress to Initiate Tertiary Creep	Red entries are 30-70 S_m (tensile strength)-controlled
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%			67% Minimum Stress to Rupture
Non-conservative relative to this analysis - Difference, δ > 10%		(Used rounding for characterization of δ)	



ASME 2017 (and 2019) III-5



This Analysis

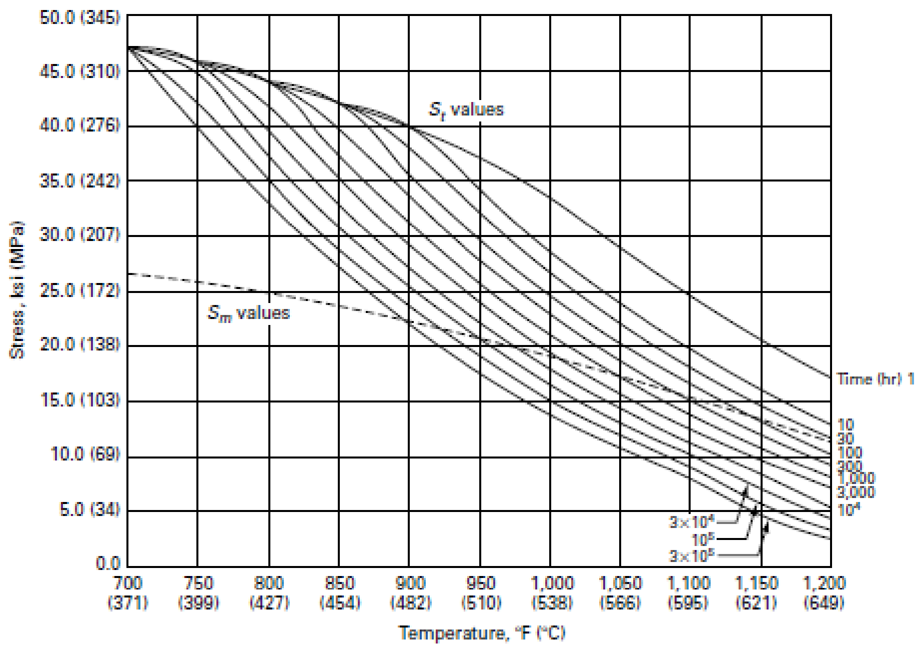
Figure R.14.3-1D. Summary of S_t-S_{mt} curves for 2¼Cr-1Mo

Table R.14.3-1D. This Analysis for 2¼Cr-1Mo S_{mt} (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.3D

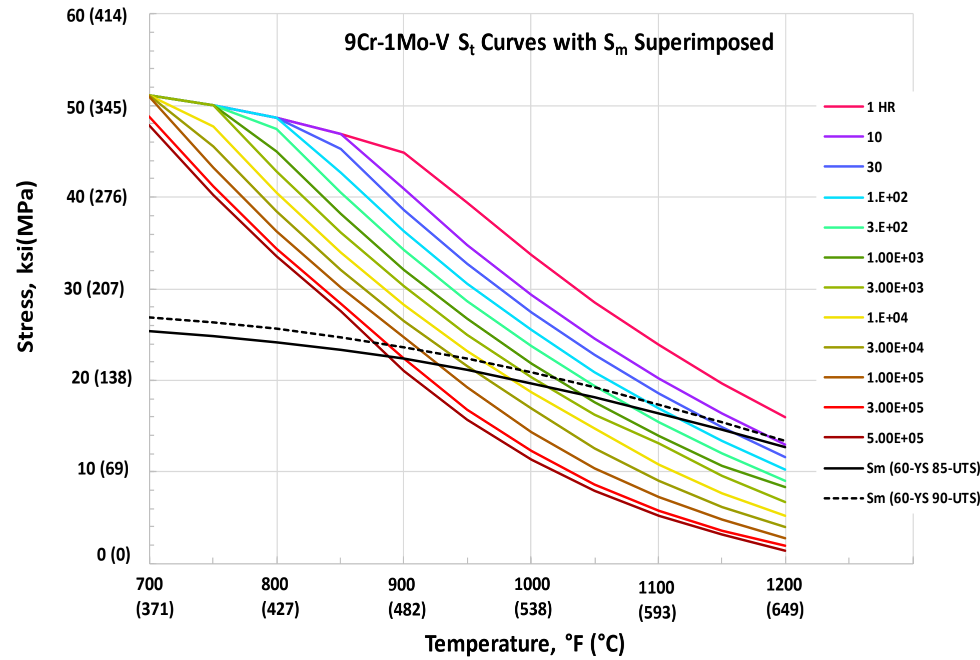
ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis
700	...	17.2	17.9	17.2	17.9	17.2	17.9	17.2	17.9	17.2	17.9	17.2	17.9	17.2	17.9	17.2	17.9	17.2	17.9	17.2	17.9	17.2
750	17.9	16.9	17.9	16.9	17.9	16.9	17.9	16.9	17.9	16.9	17.9	16.9	17.9	16.9	17.9	16.9	17.9	16.9	17.9	16.9	17.9	16.9
800	17.9	16.5	17.9	16.5	17.9	16.5	17.9	16.5	17.9	16.5	17.9	16.5	17.9	16.5	17.9	16.5	17.9	16.5	17.9	15.8	16.1	13.6
850	17.6	16.1	17.6	16.1	17.6	16.1	17.6	16.1	17.6	16.1	17.6	16.1	17.6	16.1	17.6	16.1	16.3	14.2	14.0	11.8	12.3	9.9
900	17.2	15.7	17.2	15.7	17.2	15.7	17.2	15.7	17.2	15.7	17.2	15.7	16.5	15.3	14.4	12.7	12.5	10.6	10.9	8.7	9.6	7.1
950	16.7	15.2	16.7	15.2	16.7	15.2	16.7	15.2	16.3	15.2	14.8	14.0	13.2	11.7	11.3	9.5	9.7	7.7	8.4	6.1	7.3	4.9
1000	15.9	14.6	15.9	14.6	15.5	14.6	14.2	14.6	13.1	13.1	11.9	10.6	10.4	8.7	8.7	6.9	7.5	5.5	6.3	4.2	5.2	3.2
1050	14.9	13.9	13.8	13.9	12.5	13.9	11.2	12.2	10.2	10.0	9.3	7.9	7.9	6.3	6.7	4.8	5.7	3.7	4.7	2.6	4.0	1.9
1100	13.6	13.1	11.0	13.1	10.0	11.8	9.0	9.4	8.2	7.5	7.2	5.8	6.2	4.4	5.0	3.2	4.1	2.3	3.3	1.5	2.7	0.9
1150	10.8	11.9	8.8	11.3	8.0	9.1	7.2	7.0	6.3	5.4	5.4	4.0	...	2.9	...	2.0	...	1.3	...	0.6	...	NS
1200	9	10.0	6.2	8.7	6.1	6.8	5.9	5.1	5.1	3.8	4.1	2.7	...	1.8	...	1.0	...	0.4	...	...	...	...

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.3D	This Analysis
375	...	118	123	118	123	118	123	118	123	118	123	118	123	118	123	118	123	118	123	118	123	118
400	123	116	123	116	123	116	123	116	123	116	123	116	123	116	123	116	123	116	123	116	123	116
425	123	114	123	114	123	114	123	114	123	114	123	114	123	114	123	114	123	114	123	111	112	95
450	122	111	122	111	122	111	122	111	122	111	122	111	122	111	122	111	116	103	101	86	89	72
475	119	109	119	109	119	109	119	109	119	109	119	109	114	109	106	94	92	79	80	65	71	54
500	116	106	116	106	116	106	116	106	116	106	111	106	99	89	85	73	74	60	64	48	56	39
525	112	103	112	103	112	103	106	103	97	102	89	83	78	69	66	55	57	44	48	34	41	27
550	107	99	107	99	98	99	89	97	81	80	74	65	64	52	54	41	46	32	38	24	33	17
575	100	94	89	94	80	94	72	77	66	63	59	49	50	39	42	29	35	22	29	15	25	10
600	89	89	72	89	66	76	59	60	53	48	47	37	...	28	...	20	...	14	...	8.8	...	4.8
625	72	80	58	75	53	60	49	46	42	36	36	26	...	19	...	13	...	7.9	...	3.5	...	...
650	62	68	45	59	42	47	41	35	35	26	28	18	...	12	...	7.0	...	2.8	...	...	...	...

S_m (Yield strength)-controlled	S_m (Tensile strength)-controlled	80% Minimum Stress to Initiate Tertiary Creep
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%		
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)	



ASME 2017 III-5



This Analysis

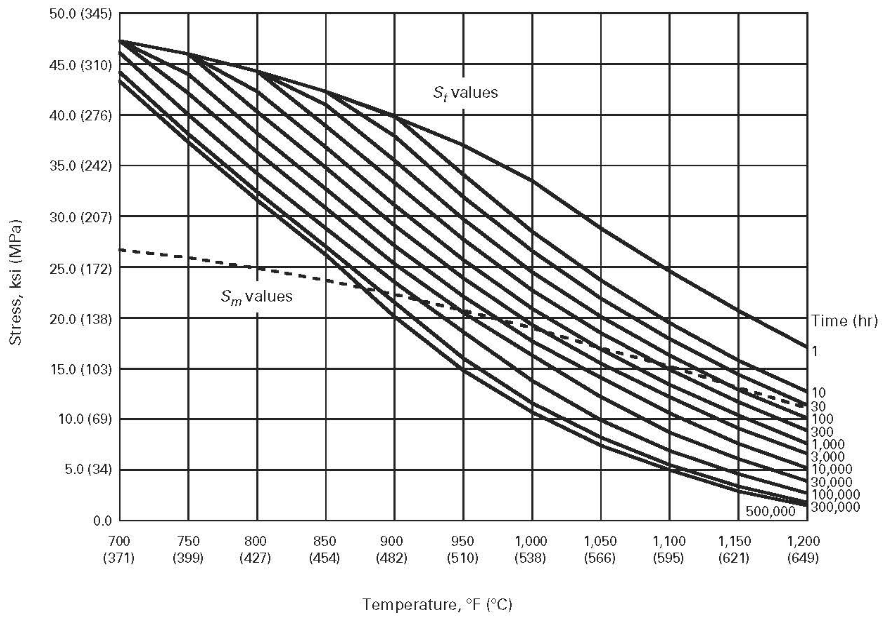
Figure R.14.3-1E. Summary of S_t-S_{mt} curves for 9Cr-1Mo-V

Table R.14.3-1E. This Analysis for 9Cr-1Mo-V S_{mt} (ksi and MPa) compared with BPVC 2017 III-5 Table HBB-I-14.3E

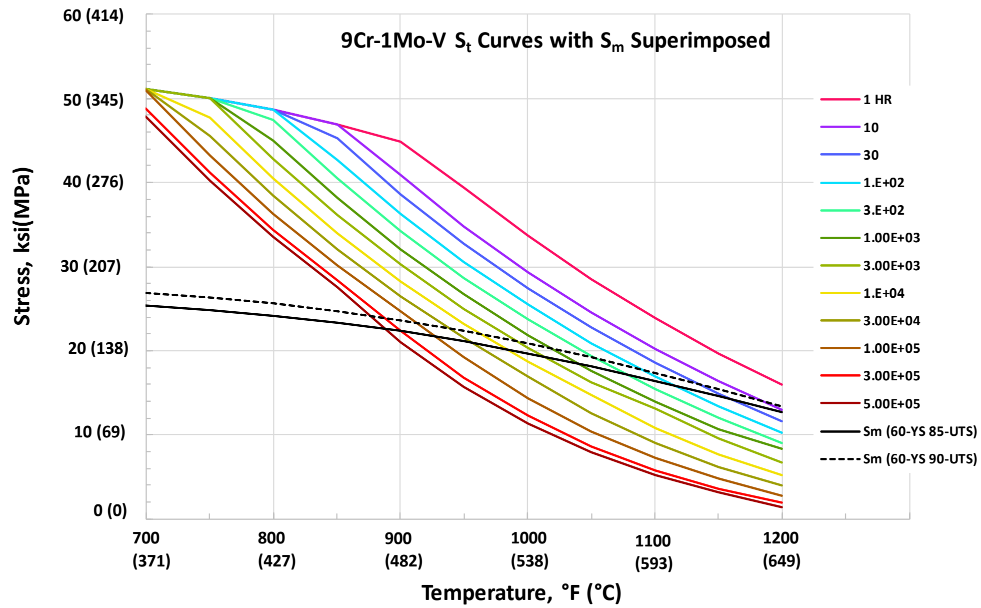
ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °F	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis
700	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)		25.4 (26.9)
750	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)		24.9 (26.3)
800	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)		24.2 (25.6)
850	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)		23.3 (24.7)
900	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	21.9	22.3 (23.6)		21.1
950	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.5	21.1 (22.4)	18.8	19.3	17.4	16.8		15.7
1000	19.0	19.7 (20.9)	19.0	19.7 (20.9)	19.0	19.7 (20.9)	19.0	19.7 (20.9)	19.0	19.7 (20.9)	19.0	19.7 (20.9)	19.0	19.7 (20.9)	17.7	18.7	16.3	16.9	14.9	14.3	13.7	12.3		11.4
1050	17.1	18.2 (19.2)	17.1	18.2 (19.2)	17.1	18.2 (19.2)	17.1	18.2 (19.2)	17.1	18.2 (19.2)	16.9	17.7	15.5	16.2	14.1	14.7	12.8	12.5	11.5	10.4	10.5	8.7		7.9
1100	15.2	16.4 (17.4)	15.2	16.4 (17.4)	15.2	16.4 (17.4)	15.2	16.4 (17.4)	14.9	15.4	13.4	13.9	12.3	13.1	10.9	10.8	9.9	9.0	8.7	7.2	7.8	5.8		5.2
1150	13.1	14.6 (15.4)	13.1	14.6 (15.4)	13.1	14.6 (15.4)	12.9	13.3	11.7	12.0	10.5	10.6	9.5	9.5	8.3	7.7	6.8	6.2	5.5	4.7	4.5	3.6		3.1
1200	11.1	12.7(13.4)	11.1	12.7(13.4)	11.1	11.6	10.1	10.2	9.1	9.0	7.9	8.3	6.5	6.7	5.3	5.2	4.3	4.0	3.3	2.8	2.5	1.9		1.5

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °C	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis	ASME 2017 III-5 Table HBB-I-14.3E	This Analysis
375	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)		175 (185)
400	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)		171 (181)
425	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)		167 (177)
450	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)		162 (171)
475	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	154	156 (165)		156
500	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	138	147	131	128		121
525	136	141 (149)	136	141 (149)	136	141 (149)	136	141 (149)	136	141 (149)	136	141 (149)	136	141 (149)	132	141 (149)	126	133	115	114	106	98		91
550	125	131 (139)	125	131 (139)	125	131 (139)	125	131 (139)	125	131 (139)	125	131 (139)	121	127	111	119	102	102	93	86	85	73		67
575	114	121 (128)	114	121 (128)	114	121 (128)	114	121 (128)	114	121 (128)	108	113	99	103	90	92	81	77	73	64	66	52		48
600	101	110 (117)	101	110 (117)	101	110 (117)	101	110 (117)	97	101	86	90	80	84	71	69	63	57	54	45	48	36		32
625	88	99 (105)	88	99 (105)	88	99 (105)	86	89	78	80	70	70	63	63	54	50	44	40	36	31	30	23		20
650	76	87 (92)	76	87 (92)	76	79	69	70	62	61	54	57	44	46	36	35	29	27	22	19	17	13		10

S_m (Tensile strength)-controlled. Stress values are for 60-85 (YS-TS) material with 60-90 (YS-TS) material in parentheses.	67% Minimum Stress to Rupture	80% Minimum Stress to Initiate Tertiary Creep
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%	Value as extrapolated at 650C/1200F using final table stresses from 30khr to 300 khr	
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)	



ASME 2019 III-5



This Analysis

Figure R.14.3-1E-2019. Summary of S_t-S_{mt} curves for 9Cr-1Mo-V

Table R.14.3-1E-2019. This Analysis for 9Cr-1Mo-V S_{mt} (ksi and MPa) compared with BPVC 2019 III-5 Table HBB-I-14.3E

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °F	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis
700	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)	26.7	25.4 (26.9)
750	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)	25.9	24.9 (26.3)
800	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)	24.9	24.2 (25.6)
850	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)	23.7	23.3 (24.7)
900	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	22.3	22.3 (23.6)	21.5	22.3 (23.6)	20.1	21.1
950	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.7	21.1 (22.4)	20.5	21.1 (22.4)	18.6	19.3	16.0	16.8	14.8	15.7
1000	19.0	19.7 (20.9)	19.0	19.7 (20.9)	19.0	19.7 (20.9)	19.0	19.7 (20.9)	19.0	19.7 (20.9)	19.0	19.7 (20.9)	19.0	19.7 (20.9)	17.7	18.7	16.3	16.9	13.8	14.3	11.6	12.3	10.7	11.4
1050	17.1	18.2 (19.2)	17.1	18.2 (19.2)	17.1	18.2 (19.2)	17.1	18.2 (19.2)	17.1	18.2 (19.2)	16.9	17.7	15.5	16.2	14.1	14.7	12.2	12.5	9.9	10.4	8.2	8.7	7.4	7.9
1100	15.2	16.4 (17.4)	15.2	16.4 (17.4)	15.2	16.4 (17.4)	15.2	16.4 (17.4)	14.9	15.4	13.4	13.9	12.2	13.1	10.6	10.8	8.7	9.0	6.9	7.2	5.5	5.8	5.0	5.2
1150	13.1	14.6 (15.4)	13.1	14.6 (15.4)	13.1	14.6 (15.4)	12.9	13.3	11.7	12.0	10.4	10.6	9.1	9.5	7.6	7.7	6.1	6.2	4.6	4.7	3.4	3.6	2.9	3.1
1200	11.1	12.7(13.4)	11.1	12.7(13.4)	11.1	11.6	10.1	10.2	8.9	9.0	7.6	8.3	6.5	6.7	5.2	5.2	3.9	4.0	2.7	2.8	1.8	1.9	1.5	1.5

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °C	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis	ASME 2019 III-5 Table HBB-I-14.3E	This Analysis
375	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)	183	175 (185)
400	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)	179	171 (181)
425	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)	172	167 (177)
450	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)	165	162 (171)
475	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	156	156 (165)	154	156 (165)	149	156
500	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	147	149 (157)	138	147	123	128	115	121
525	136	141 (149)	136	141 (149)	136	141 (149)	136	141 (149)	136	141 (149)	136	141 (149)	136	141 (149)	132	141 (149)	126	133	109	114	93	98	86	91
550	125	131 (139)	125	131 (139)	125	131 (139)	125	131 (139)	125	131 (139)	125	131 (139)	119	127	111	119	100	102	83	86	69	73	63	67
575	114	121 (128)	114	121 (128)	114	121 (128)	114	121 (128)	114	121 (128)	108	113	99	103	89	92	75	77	61	64	50	52	45	48
600	101	110 (117)	101	110 (117)	101	110 (117)	101	110 (117)	97	101	86	90	78	84	68	69	55	57	44	45	34	36	31	32
625	88	99 (105)	88	99 (105)	88	99 (105)	86	89	78	80	69	70	60	63	50	50	40	40	30	31	22	23	18	20
650	76	87 (92)	76	87 (92)	76	79	69	70	61	61	52	57	44	46	35	35	27	27	18	19	12	13	10	10

S_m (Tensile strength)-controlled. Stress values are for 60-85 (YS-TS) material with 60-90 (YS-TS) material in parentheses.	67% Minimum Stress to Rupture	80% Minimum Stress to Initiate Tertiary Creep
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%	Value as extrapolated at 650C/1200F using final table stresses from 30khr to 300 khr	
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)	

Basic Method of Analysis

For summary of the data analyzed for S_{mt}, please refer to Appendix SISm for S_m and the review of HBB-I-14.4 for S_t since the value of S_{mt} is derived from those of S_m and S_t.

The tabulated S_{mt} values represent the lower of S_m, the time-independent stress intensity as defined in BPVC II-D, and S_t, the temperature- and time-dependent stress intensity as defined per the criteria in BPVC III-5 HBB-3221. The graphics, on the other hand, separately show the S_m and S_t values as curves. Derivation of S_m values, along with tabulation, is described in Appendix SIS_m "Stress Intensity S_m" since it is not provided in BPVC III-5. Similarly, derivation of S_t is described where Tables and Figures HBB-I-14.4 are discussed in this report, and therefore is not repeated here.

A major portion of the time-temperature range over which the BPVC III-5 S_{mt} values have been found to be non-conservative relative to our analysis is the range over which the S_{mt} values are controlled by the (time-dependent) stress to initiate tertiary creep. The issues associated with implementation of the tertiary creep criterion and our limited research into its effect for 304 SS, by way of example, are described in Appendix TCOC: "Comments on the Tertiary Creep Criterion for S_t (and S_{mt})."

Discussion of Results

<u>304 SS (Table R.14.3-1A, Figure R.14.3-1A):</u>

The significant non-conservatism of the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3A values relative to our analysis for a large portion of the table (see Table R.14.3-1A) was further examined in light of the relatively recent effort to analyze the data for this alloy in order to correct and extend the BPVC III-5 S_{mt} and S_r stresses to 500,000 hours, published as ASME STP-NU-063 (Ref. Sengupta 2013). Figure R.14.3-2A and Table R.14.3-2A summarize the STP-NU-063-reported results compared with this analysis. The table illustrates our analysis results to be in good agreement with that effort. Additionally, STP-NU-063 indicates that the long time, high temperature values are all controlled by the time-to-tertiary creep values, similar to the results of our analysis. The findings support the need to further review and update the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3A and the corresponding Figure HBB-I-14.3A.

<u>316 SS (Table R.14.3-1B, Figure R.14.3-1B):</u>

The significant non-conservatism of the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3B values relative to our analysis for a significant portion of the table (see Table R.14.3-1B) was further examined in light of the relatively recent effort to analyze the data for this material in order to correct and extend the BPVC III-5 S_{mt} and S_r stresses to 500,000 hours, published as ASME STP-NU-063 (Ref. Sengupta 2013). Figure R.14.3-2B and Table R.14.3-2B below summarize the STP-NU-063-reported results compared with this analysis. The table illustrates our analysis results to be in good agreement with that effort. Additionally, STP-NU-063 indicates that the long time, high temperature values are all controlled by the time-to-tertiary creep values, similar to the results of our analysis. The findings support the need to further review and update the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3A and the corresponding Figure HBB-I-14.3A.

Ni-Fe-Cr/Alloy 800H (Table R.14.3-1C, Figure R.14.3-1C):

The significant non-conservatism of the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3C values relative to our analysis for a significant portion of the table (see Table R.14.3-1C) was further examined in light of a relatively recent effort to analyze the data for this alloy in order to extend the BPVC III-5 allowable stresses, published as ASME STP-NU-035 (Ref. Swindeman 2012). Figure R.14.3-2C and Table R.14.3-2C below summarize the STP-NU-035-reported results compared with this analysis. The table illustrates our analysis results to be in good agreement with that effort. STP-NU-035 indicates that the long time, high temperature values are all controlled by the time-to-tertiary creep values. Our analysis indicates a mix of controlling criteria in the long-term, high temperature regime – the expected minimum rupture strength for some of the intermediate time-temperature values and the time to initiate tertiary creep for the highest times and temperatures (see Table R.14.3-1C). The findings support the need to further review and update the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3C and corresponding Figure HBB-I-14.3C.

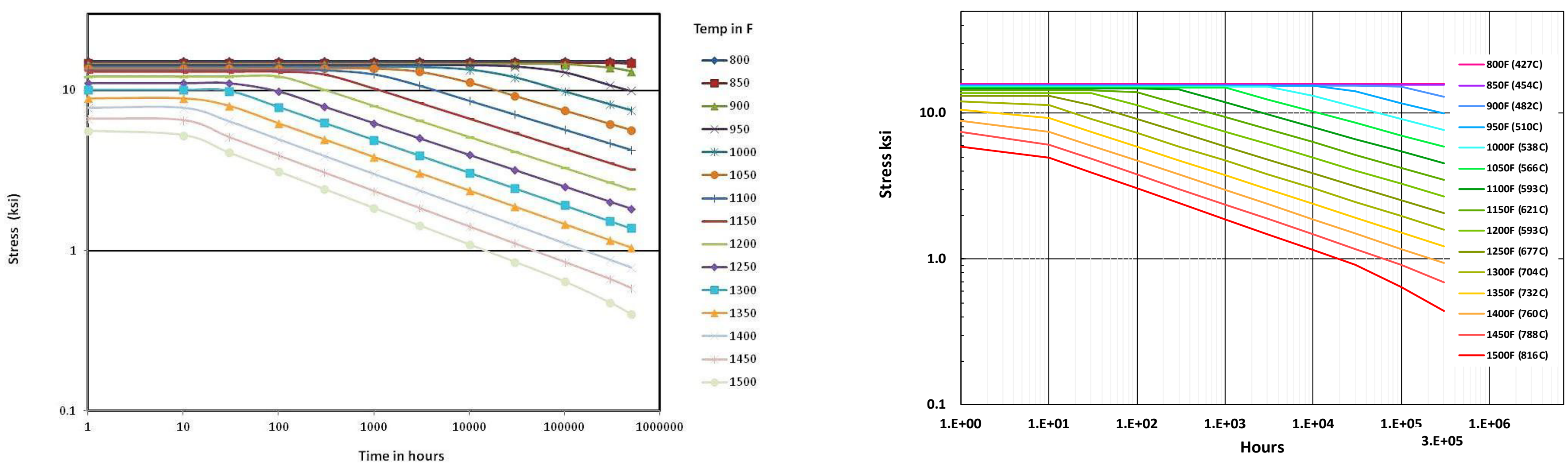
2¼Cr-1Mo (Table R.14.3-1D, Figure R.14.3-1D):

Apparent from Table R.14.3-1D summarizing the findings in comparison with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3D S_{mt} values is that for the higher temperatures and extended times, the BPVC values are relatively non-conservative. It is not known when the current HBB-I-14.3D table was developed. However, as discussed as part of the report for S_o, the last time the BPVC II-D Table 1A stresses were updated was circa 1990. Also, our analysis combined data for both annealed and normalized and tempered material (since both heat treatments are permitted) and it is unclear as to what data were used in development of the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3D S_{mt} values.

Table R.14.3-2A. This Analysis for 304 SS compared with values reported in STP-NU-063

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis
800	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9	15.2	15.9
850	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7	14.8	15.7
900	14.5	15.5	14.5	15.5	14.5	15.5	14.5	15.5	14.5	15.5	14.5	15.5	14.5	15.5	14.5	15.5	14.5	15.5	14.5	15.1	13.8	12.8
950	14.3	15.3	14.3	15.3	14.3	15.3	14.3	15.3	14.3	15.3	14.3	15.3	14.3	15.3	14.3	15.3	14.0	14.0	12.9	11.7	10.8	9.9
1000	14.0	15.1	14.0	15.1	14.0	15.1	14.0	15.1	14.0	15.1	14.0	15.1	14.0	15.1	13.5	13.0	12.1	11.0	9.8	9.1	8.2	7.6
1050	13.7	14.9	13.7	14.9	13.7	14.9	13.7	14.9	13.7	14.9	13.7	14.9	13.1	12.4	11.2	10.2	9.3	8.5	7.5	7.0	6.2	5.9
1100	13.4	14.6	13.4	14.6	13.4	14.6	13.4	14.6	13.4	14.5	12.6	11.8	10.8	9.8	8.7	8.0	7.1	6.7	5.7	5.4	4.7	4.5
1150	13.0	14.3	13.0	14.3	13.0	14.3	13.0	14.0	12.5	11.6	10.2	9.4	8.3	7.7	6.7	6.3	5.4	5.2	4.3	4.2	3.5	3.5
1200	12.2	13.8	12.2	13.8	12.2	13.8	12.2	11.3	10.1	9.2	8.0	7.5	6.5	6.1	5.1	4.9	4.2	4.0	3.3	3.3	2.7	2.7
1250	11.1	13.1 (12.6)	11.1	13.1 (12.6)	11.1	11.3	9.9	9.1	7.9	7.4	6.3	5.9	5.0	4.8	4.0	3.9	3.2	3.2	2.5	2.5	2.0	2.1
1300	10.0	12.0 (11.2)	10.0	11.3	9.9	9.2	7.8	7.3	6.3	5.9	4.9	4.7	3.9	3.8	3.1	3.0	2.5	2.5	1.9	2.0	1.5	1.6
1350	8.9	10.5 (9.8)	8.9	9.2	8.0	7.4	6.2	5.9	4.9	4.7	3.8	3.7	3.1	3.0	2.4	2.4	1.9	1.9	1.5	1.5	1.2	1.2
1400	7.8	8.9 (8.3)	7.8	7.5	6.4	6.0	4.9	4.7	3.9	3.8	3.0	3.0	2.4	2.4	1.8	1.9	1.4	1.5	1.1	1.2	0.9	0.9
1450	6.6	7.4 (6.9)	6.5	6.1	5.1	4.9	3.9	3.8	3.1	3.0	2.4	2.4	1.8	1.9	1.4	1.5	1.1	1.2	0.9	0.9	0.7	0.7
1500	5.6	5.9 (5.5)	5.2	5.0	4.1	3.9	3.1	3.0	2.4	2.4	1.8	1.9	1.4	1.5	1.1	1.1	0.9	0.9	0.6	0.6	0.5	0.4

S_m (Yield strength)-controlled	S_m (Tensile strength)-controlled	80% Minimum Stress to Initiate Tertiary Creep	Red entries are 30-70 S_m (tensile strength)-controlled
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%			67% Minimum Stress to Rupture
Non-conservative relative to this analysis - Difference, δ > 10%		(Used rounding for characterization of δ)	



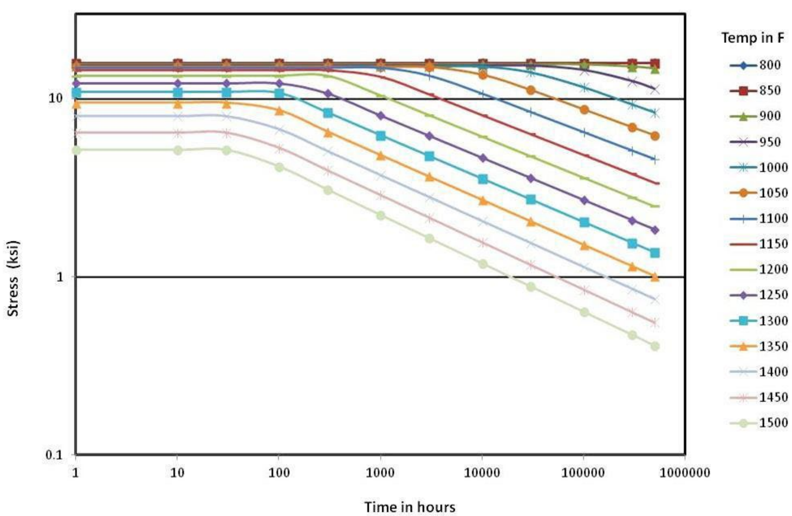
(a) (b)

Figure R.14.3-2A. Summary of S_{mt} curves for 304 SS: (a) From STP-NU-063 (30-70 or 30-75 material not reported); and (b) This Analysis for 30-75 material.

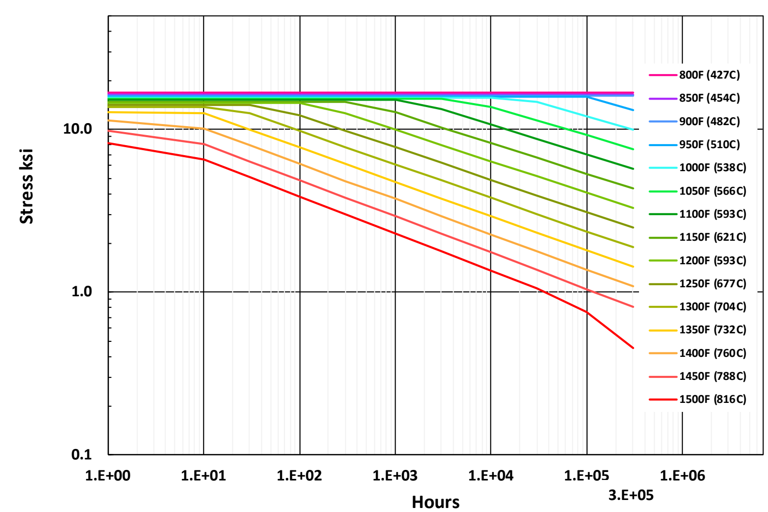
Table R.14.3-2B. This Analysis for 316 SS compared with values reported in STP-NU-063

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis
800	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7	15.9	16.7
850	15.8	16.4	15.8	16.4	15.8	16.4	15.8	16.4	15.8	16.4	15.8	16.4	15.8	16.4	15.8	16.4	15.8	16.4	15.8	16.4	15.8	16.4
900	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.6	16.1	15.1	16.1
950	15.4	15.9	15.4	15.9	15.4	15.9	15.4	15.9	15.4	15.9	15.4	15.9	15.4	15.9	15.4	15.9	15.4	15.9	14.5	15.8	12.6	13.2
1000	15.2	15.6	15.2	15.6	15.2	15.6	15.2	15.6	15.2	15.6	15.2	15.6	15.2	15.6	15.2	15.6	14.1	14.8	11.7	12.1	9.3	10.0
1050	15.1	15.4	15.1	15.4	15.1	15.4	15.1	15.4	15.1	15.4	15.1	15.4	15.1	15.4	13.7	13.8	11.2	11.4	8.7	9.2	6.9	7.6
1100	14.9	15.1	14.9	15.1	14.9	15.1	14.9	15.1	14.9	15.1	14.9	15.1	13.5	13.2	10.7	10.6	8.4	8.7	6.5	7.0	5.1	5.7
1150	14.5	14.8	14.5	14.8	14.5	14.8	14.5	14.8	14.5	14.8	13.3	12.7	10.6	10.3	8.1	8.2	6.4	6.7	4.9	5.3	3.8	4.3
1200	13.5	14.4	13.5	14.4	13.5	14.4	13.5	14.4	13.5	12.5	10.5	9.9	8.1	8.0	6.1	6.3	4.8	5.1	3.6	4.1	2.8	3.3
1250	12.2	14.1	12.2	14.1	12.2	14.1	12.2	12.3	10.7	9.9	8.1	7.8	6.2	6.2	4.7	4.9	3.6	3.9	2.7	3.1	2.1	2.5
1300	10.9	13.7 (13.3)	10.9	13.7 (13.3)	10.9	12.5	10.8	9.7	8.4	7.8	6.2	6.1	4.8	4.8	3.6	3.8	2.7	3.0	2.0	2.4	1.6	1.9
1350	9.5	10.5 (9.8)	9.5	12.6 (11.9)	9.5	10.0	8.6	7.7	6.5	6.1	4.8	4.8	3.7	3.8	2.7	2.9	2.1	2.3	1.5	1.8	1.2	1.4
1400	8.0	12.8 (11.9)	8.0	10.1	8.0	8.0	6.8	6.1	5.1	4.8	3.7	3.7	2.8	2.9	2.1	2.3	1.6	1.8	1.1	1.4	0.9	1.1
1450	6.4	11.3 (10.5)	6.4	8.1	6.4	6.4	5.3	4.9	4.0	3.8	2.9	2.9	2.2	2.3	1.6	1.7	1.2	1.4	0.9	1.0	0.6	0.82
1500	5.2	8.3 (7.7)	5.2	6.5	5.2	5.1	4.2	3.9	3.1	3.0	2.2	2.3	1.7	1.8	1.2	1.3	0.9	1.0	0.6	0.76	0.5	0.45

S_m (Yield strength)-controlled	S_m (Tensile strength)-controlled	80% Minimum Stress to Initiate Tertiary Creep	Red entries are 30-70 S_m (tensile strength)-controlled
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%			67% Minimum Stress to Rupture
Non-conservative relative to this analysis - Difference, δ > 10%		(Used rounding for characterization of δ)	



(a)



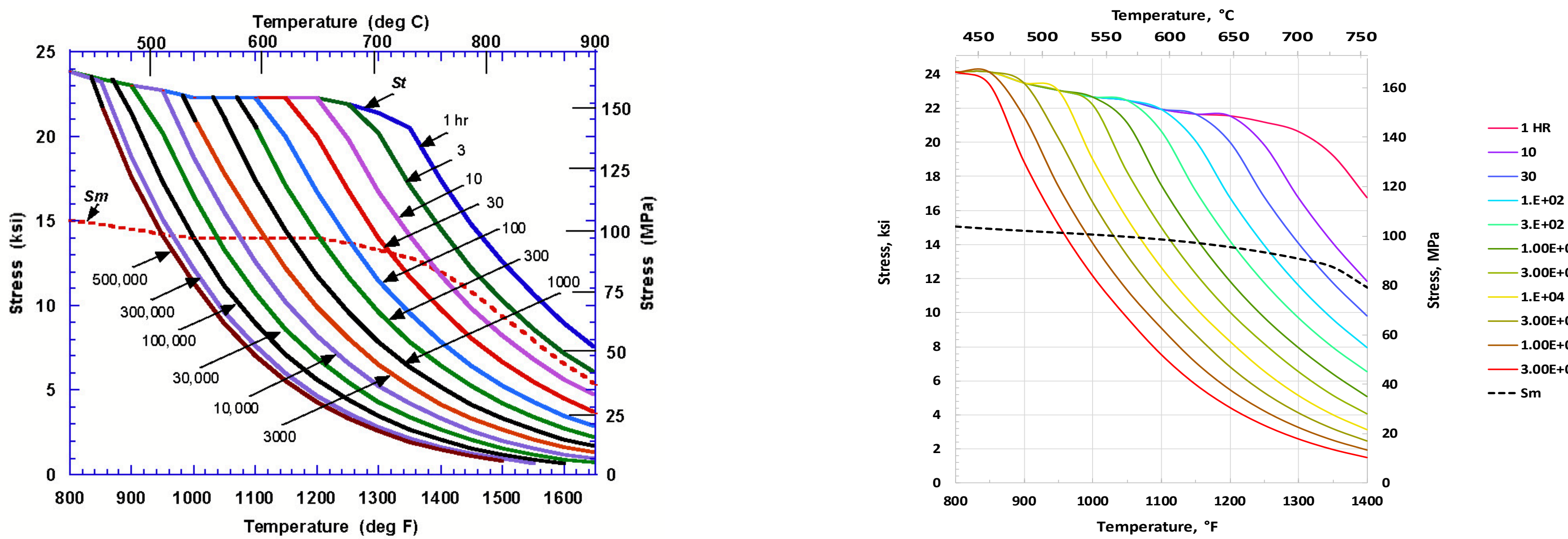
(b)

Figure R.14.3-2B. Summary of S_{mt} curves for 316 SS: (a) From STP-NU-063 (30-70 or 30-75 material not reported); and (b) This Analysis for 30-75 material.

Table R.14.3-2C. This Analysis for Ni-Fe-Cr (Alloy 800H) compared with values reported in STP-NU-035

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis
800	15.0	15.1	15.0	15.1	15.0	15.1	15.0	15.1	15.0	15.1	15.0	15.1	15.0	15.1	15.0	15.1	15.0	15.1	15.0	15.1	15.0	15.1
850	14.8	14.9	14.8	14.9	14.8	14.9	14.8	14.9	14.8	14.9	14.8	14.9	14.8	14.9	14.8	14.9	14.8	14.9	14.8	14.9	14.8	14.9
900	14.5	14.8	14.5	14.8	14.5	14.8	14.5	14.8	14.5	14.8	14.5	14.8	14.5	14.8	14.5	14.8	14.5	14.8	14.5	14.8	14.5	14.8
950	14.2	14.7	14.2	14.7	14.2	14.7	14.2	14.7	14.2	14.7	14.2	14.7	14.2	14.7	14.2	14.7	14.2	14.7	14.2	14.7	14.2	14.7
1000	14.0	14.6	14.0	14.6	14.0	14.6	14.0	14.6	14.0	14.6	14.0	14.6	14.0	14.6	14.0	14.6	14.0	14.6	14.0	14.1	12.1	12.2
1050	14.0	14.5	14.0	14.5	14.0	14.5	14.0	14.5	14.0	14.5	14.0	14.5	14.0	14.5	14.0	14.5	13.3	13.4	11.2	11.4	9.61	9.7
1100	14.0	14.3	14.0	14.3	14.0	14.3	14.0	14.3	14.0	14.3	14.0	14.3	14.0	14.3	12.6	12.7	10.7	10.8	8.98	9.1	7.61	7.6
1150	14.0	14.1	14.0	14.1	14.0	14.1	14.0	14.1	14.0	14.1	14.0	14.1	12.2	12.3	10.2	10.3	8.61	8.7	7.14	7.1	6.00	5.8
1200	14.0	13.9	14.0	13.9	14.0	13.9	14.0	13.9	13.9	13.9	11.8	11.9	9.94	10.0	8.21	8.3	6.88	6.9	5.65	5.5	4.70	4.5
1250	13.7	13.6	13.7	13.6	13.7	13.6	13.7	13.6	11.7	11.8	9.64	9.7	8.06	8.2	6.59	6.6	5.47	5.3	4.44	4.2	3.66	3.4
1300	13.3	13.2	13.3	13.2	13.3	13.2	11.5	11.6	9.62	9.7	7.85	8.0	6.50	6.5	5.27	5.2	4.33	4.1	3.47	3.3	2.83	2.6
1350	12.8	12.7	12.8	12.7	11.7	11.8	9.54	9.6	7.88	8.0	6.37	6.4	5.23	5.1	4.19	4.0	3.40	3.2	2.70	2.5	2.17	2.0
1400	12.0	11.5	11.8	11.5	9.73	9.8	7.85	8.0	6.43	6.6	5.15	5.1	4.18	4.1	3.31	3.1	2.66	2.5	2.08	1.9	1.66	1.5

S_m (Yield strength)-controlled	S_m (Tensile strength)-controlled	80% Minimum Stress to Initiate Tertiary Creep
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%		67% Minimum Stress to Rupture
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)	



(a) (b)

Figure R.14.3-2C. Summary of S_{mt} curves for Ni-Fe-Cr (Alloy 800H): (a) From STP-NU-035; and (b) This Analysis

9Cr-1Mo-V (Table R.14.3-1E-2019, Figure R.14.3-1E-2019):

Our results are in good agreement with the BPVC 2019 III-5 Figure HBB-I-14.3E and Table HBB-I-14.3E values (see Figure and Table R.14.3-1E-2019). The BPVC figure and table have been updated since the 2017 edition. However, there should be two sets of S_m values that are tensile strength-controlled in Figure and Table HBB-I-14.3E, as previously noted.

Figures and Tables HBB-I-14.4A ~ E, S_t — Allowable Stress Intensity Values
Observations Indicating Need for Review Consideration

Types 304 and 316SS**:**

For both alloys, the BPVC 2017 (and 2019) III-5 Figures and Tables HBB-I-14.4A and 14.4B show S_t values that are non-conservative relative to our analysis over a significant range of time and temperature encompassing the time-dependent stress-controlled regime. The figures and tables merit further review, particularly given that our analysis results are in good agreement with the reported analysis results on a relatively recent effort to "Correct and Extend Allowable Stress Values for 304 and 316 Stainless Steel," ASME STP-NU-063 (Ref. Sengupta 2013). The S_t results of ASME STP-NU-063 have not been incorporated into BPVC III-5. Such incorporation would largely eliminate the discrepancy between our analysis results and the S_t values in Figures and Tables HBB-I-14.4A and 14.4B.

Ni-Fe-Cr (Alloy 800H)**:**

The BPVC 2017 (and 2019) III-5 Figure and Table HBB-I-14.4C show S_t values that are non-conservative relative to our analysis over a significant range of time and temperature over the longer times and higher temperatures encompassing the time-dependent-controlled stress regime. The figure and table merit further review, particularly given that our analysis results are in good agreement with the reported analysis results on a relatively recent effort to analyze the data for this alloy in order to extend the BPVC III-5 allowable stresses as discussed in "Extend Allowable Stress Values for Alloy 800H," ASME ST-LLC STP-NU-035 (Ref. Swindeman 2012). The S_t results of ASME STP-NU-035 have not been incorporated into BPVC III-5. Such incorporation would largely eliminate the discrepancy between our analysis results and the S_t values in Figure and Table HBB-I-14.4C.

2¼Cr-1Mo**:**

The BPVC 2017 (and 2019) III-5 Figure and Table HBB-I-14.4D are judged to be non-conservative relative to our analysis for the higher temperatures and extended times. It is not known when the stresses were last reviewed, but the BPVC II-D Table 1A time-dependent stresses were last reviewed and updated circa 1990. We recommend further review of the Figure and Table HBB-I-14.4C.

9Cr-1Mo-V:

The BPVC 2017 III-5 Figure and Table HBB-I-14.4E are seen to be non-conservative relative to our analysis and would be recommended for further review. However, the table and figure have been updated in the BPVC 2019 edition. A further review of the 2019 edition figure and table is neither needed nor recommended since there is no observed non-conservatism relative to our analysis results. Since the 2019 edition figure and table are found to be acceptable, a review of the 2017 edition figure and table is moot.

Comments

A major portion of the time-temperature range over which the BPVC III-5 S_t values have been found to be non-conservative relative to our analysis results is the range over which the S_t values are controlled by the (time-dependent) stress to initiate tertiary creep. The issues associated with implementation of the tertiary creep criterion and our limited research into its effect for 304 SS, by way of example, are described in Appendix TCOC, "Comments on the Tertiary Creep Onset Criterion for S_t (and S_{mt})."

BPVC III does not appear to provide specific criteria for limiting the S_t values below the time-temperature regime where time-dependent stresses govern. In the absence of defined criteria, we have used the hot tensile 1% strain (also used in other prior work such as STP-NU-035 and -063 (Ref. Swindeman 2012, Ref. Sengupta 2013) and the 67% tensile strength (S_u) to limit the S_t below the time-dependent regime.

With regard to stress intensity values controlled by time-dependent creep properties, we note that for extended durations (> 100,000 hours) and for temperatures at the upper-end of the use temperature range, the materials may strain by a diffusion creep mechanism, more likely in case of 304 SS, 316 SS and Alloy 800H. The creep and rupture data used in development of the allowable stress intensity values, however, include, at best, a very small number of data points representing this mechanism, so that the computed, extrapolated design values can be somewhat non-conservative when diffusion creep is operative. Unfortunately, the paucity of such data makes analysis for diffusion creep-specific stress intensity values impractical. In any case, as is seen in our analysis for S_t and S_{mt}, the discrepancy between our results and the tabulations in BPVC 2017 (and 2019) for 304 SS, 316 SS and Alloy 800H occurs over a significant range of time and temperature judged to be well outside of the diffusion creep-controlled regime, meriting consideration for review.

Comparison of BPVC III-5 S_t Values and This Analysis Results

The figures and tables resulting from our analysis are first reported below in comparison with the BPVC III-5 S_t values, followed by key details on the analysis method, data used, and summary of analyses.

Figure R.14.4-1A is the resulting graphic, shown alongside BPVC 2017 (and 2019) III-5 Figure HBB-I-14.4A for 304 SS. The corresponding Table R.14.4-1A provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.4A S_t values.

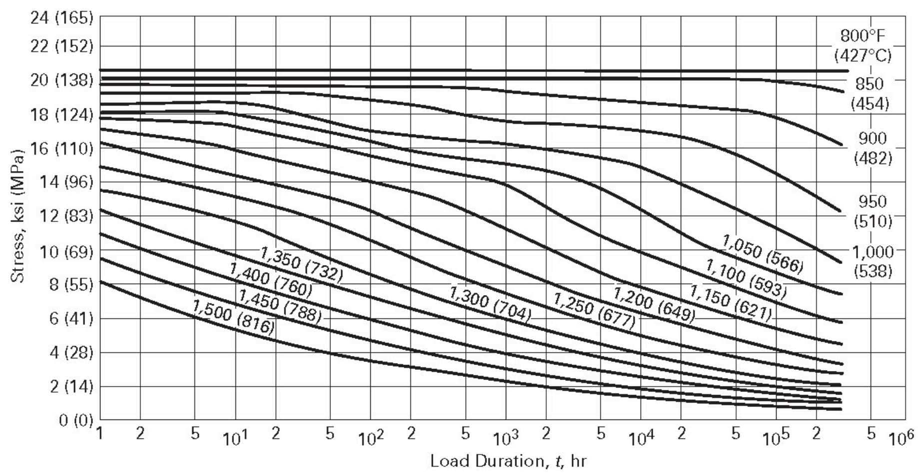
Figure R.14.4-1B is the resulting graphic, shown alongside BPVC 2017 (and 2019) III-5 Figure HBB-I-14.4B for 316 SS. The corresponding Table R.14.4-1B provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.4B S_t values.

Figure R.14.4-1C is the resulting graphic, shown alongside BPVC 2017 (and 2019) III-5 Figure HBB-I-14.4C for Ni-Fe-Cr (Alloy 800H). The corresponding Table R.14.4-1C provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.4C S_t values.

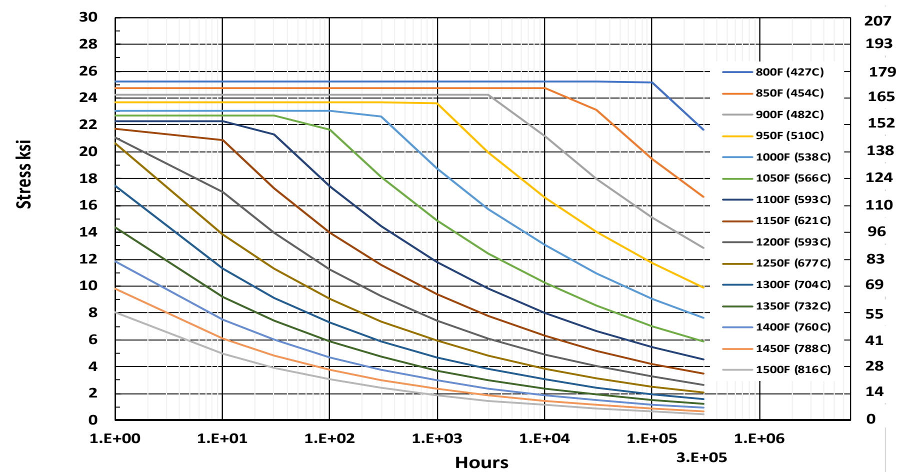
Figure R.14.4-1D is the resulting graphic, shown alongside BPVC 2017 (and 2019) III-5 Figure HBB-I-14.4D for 2¼Cr-1Mo. The corresponding Table R.14.4-1D provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.4D S_t values.

Figure R.14.4-1E is the resulting graphic, shown alongside BPVC 2017 III-5 Figure HBB-I-14.4E for 9Cr-1Mo-V. The corresponding Table R.14.4-1E provides our analysis results compared with the BPVC 2017 III-5 Table HBB-I-14.4E S_t values.

Figure R.14.4-1E-2019 is the resulting graphic, shown alongside BPVC 2019 III-5 Figure HBB-I-14.4E for 9Cr-1Mo-V. The corresponding Table R.14.4-1E-2019 provides our analysis results compared with the BPVC 2019 III-5 Table HBB-I-14.4E S_t values.



ASME 2017 III-5 (and 2019) III-5



This Analysis

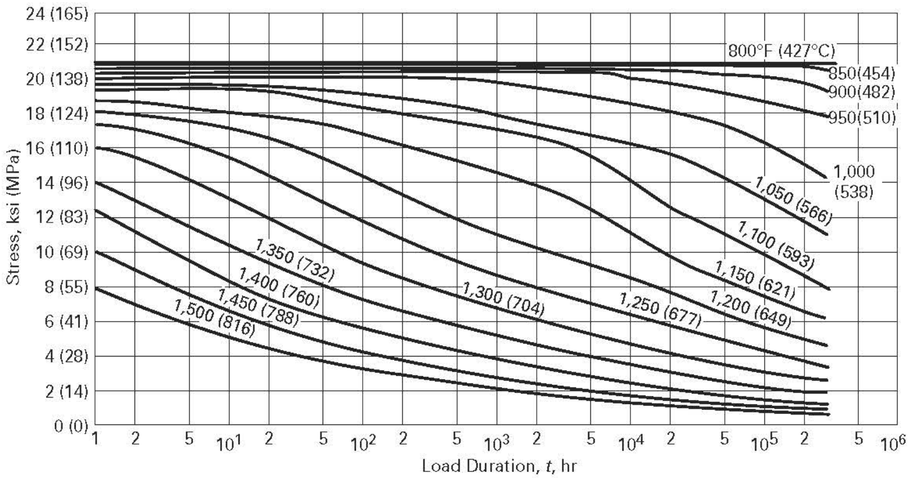
Figure R.14.4-1A. Summary of S_t curves for 304 SS

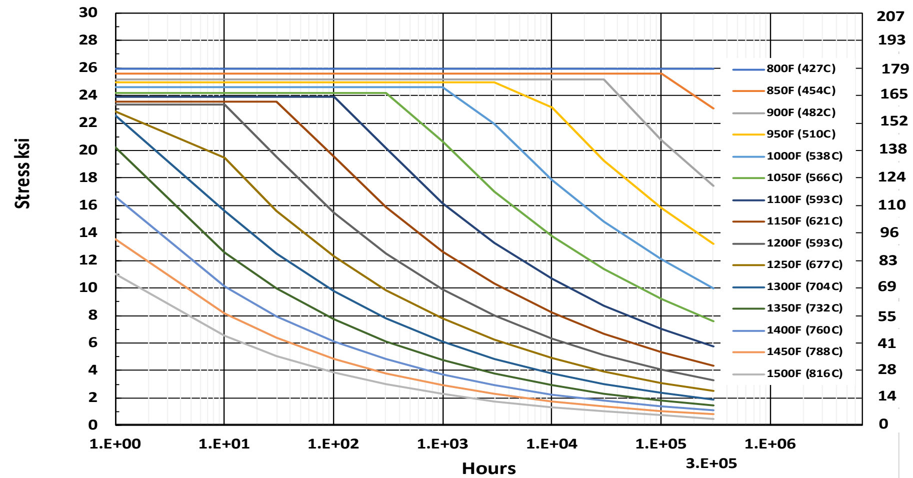
Table R.14.4-1A. This Analysis for 304 SS S_t (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.4B

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis
800	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.1	20.4	21.7
850	20.0	24.8	20.0	24.8	20.0	24.8	20.0	24.8	20.0	24.8	20.0	24.8	20.0	24.8	20.0	24.8	19.9	23.1	19.8	19.5	19.3	16.7
900	19.6	24.2	19.6	24.2	19.5	24.2	19.5	24.2	19.4	24.2	19.2	24.2	18.8	24.2	18.5	21.2	18.3	18.0	17.7	15.1	16.0	12.8
950	19.1	23.7	19.1	23.7	19.0	23.7	18.7	23.7	18.2	23.7	17.5	23.6	17.2	19.9	16.9	16.6	16.2	14.0	14.2	11.7	12.2	9.9
1000	18.5	23.1	18.4	23.1	17.8	23.1	16.9	23.1	16.2	22.6	15.9	18.7	15.5	15.7	14.7	13.0	13.1	11.0	11.1	9.1	9.3	7.6
1050	18.0	22.7	17.7	22.7	17.1	22.7	16.2	21.6	15.5	18.1	14.9	14.9	14.1	12.4	12.2	10.2	10.3	8.5	8.7	7.0	7.3	5.9
1100	17.6	22.3	17.1	22.3	16.3	21.3	15.3	17.4	14.5	14.5	13.5	11.8	11.5	9.8	9.7	8.0	8.2	6.7	6.8	5.4	5.7	4.5
1150	17.0	21.7	15.7	20.9	14.8	17.3	13.8	14.0	12.9	11.6	11.0	9.4	9.3	7.7	7.7	6.3	6.4	5.2	5.3	4.2	4.4	3.5
1200	16.0	21.1	14.2	17.0	13.3	14.0	12.2	11.3	10.6	9.2	8.9	7.5	7.4	6.1	6.1	4.9	5.1	4.0	4.1	3.3	3.4	2.7
1250	14.7	20.6	12.9	13.9	11.9	11.3	10.3	9.1	8.7	7.4	7.2	5.9	5.9	4.8	4.9	3.9	4.0	3.2	3.2	2.5	2.7	2.1
1300	13.4	17.5	11.4	11.3	10.0	9.2	8.5	7.3	7.0	5.9	5.9	4.7	4.8	3.8	3.9	3.0	3.2	2.5	2.5	2.0	2.1	1.6
1350	12.2	14.4	9.7	9.2	8.4	7.4	7.1	5.9	5.9	4.7	4.8	3.7	3.9	3.0	3.1	2.4	2.5	1.9	2.0	1.5	1.6	1.2
1400	10.8	11.9	8.1	7.5	6.9	6.0	5.9	4.7	4.8	3.8	3.9	3.0	3.1	2.4	2.5	1.9	2.0	1.5	1.6	1.2	1.2	0.94
1450	9.3	9.8	6.8	6.1	5.9	4.9	4.6	3.8	3.8	3.0	3.0	2.4	2.4	1.9	1.9	1.5	1.5	1.2	1.2	0.91	0.9	0.69
1500	7.9	8.1	5.3	5.0	4.4	3.9	3.5	3.0	2.8	2.4	2.2	1.9	1.7	1.5	1.3	1.1	1.0	0.91	0.8	0.65	0.6	0.44

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis
425	141	174	141	174	141	174	141	174	141	174	141	174	141	174	141	174	141	174	141	174	141	152
450	138	171	138	171	138	171	138	171	138	171	138	171	138	171	138	171	138	166	137	140	134	120
475	136	168	136	168	135	168	135	168	135	168	134	168	132	168	130	155	129	132	126	111	116	95
500	133	165	133	165	132	165	131	165	128	165	125	165	123	150	121	125	117	106	107	88	93	75
525	130	161	129	161	127	161	122	161	118	161	115	144	113	121	108	100	100	85	87	70	73	59
550	126	158	125	158	121	158	115	158	110	141	107	117	103	98	94	81	82	68	70	56	58	47
575	123	155	121	155	116	155	110	139	105	116	100	95	91	79	78	65	66	54	56	44	46	37
600	120	153	115	153	109	140	102	114	97	95	88	77	75	64	63	52	54	43	44	35	37	29
625	116	149	107	140	101	116	93	94	87	77	74	63	62	52	51	42	43	35	36	28	29	23
650	110	145	98	116	92	96	84	77	73	63	61	51	51	42	42	34	35	28	28	22	23	18
675	102	143	90	97	83	79	72	63	61	52	51	41	42	34	35	27	28	22	22	18	19	14
700	93	124	80	80	71	65	61	52	50	42	42	34	34	27	28	22	23	18	18	14	15	11
725	86	104	70	67	61	54	52	43	43	35	35	27	29	22	22	17	18	14	15	11.2	12	9.0
750	78	88	60	56	52	45	44	35	36	28	29	22	23	18	18	14	15	11.3	12	8.9	9	7.1
775	69	74	51	46	44	37	36	29	29	23	24	18	19	14	15	11.3	12	9.0	9	7.1	7	5.6
800	60	46	43	38	37	30	29	24	23	19	18	15	15	12	11	9.1	9	7.2	7	5.6	5	3.9

Hot Tensile Stress at 1% Strain, ASME HBB-T digitized	80% Minimum Stress to Initiate Tertiary Creep	67% Minimum Stress to Rupture
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%		
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)	





ASME 2017 (and 2019) III-5

This Analysis

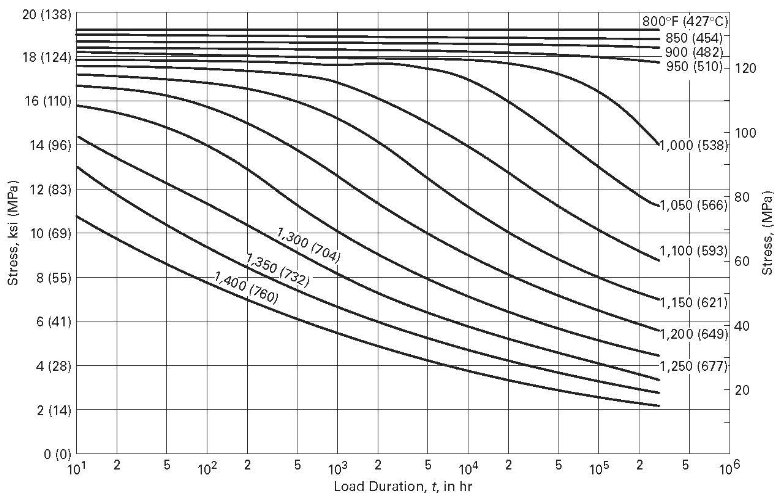
Figure R.14.4-1B. Summary of S_t curves for 316 SS

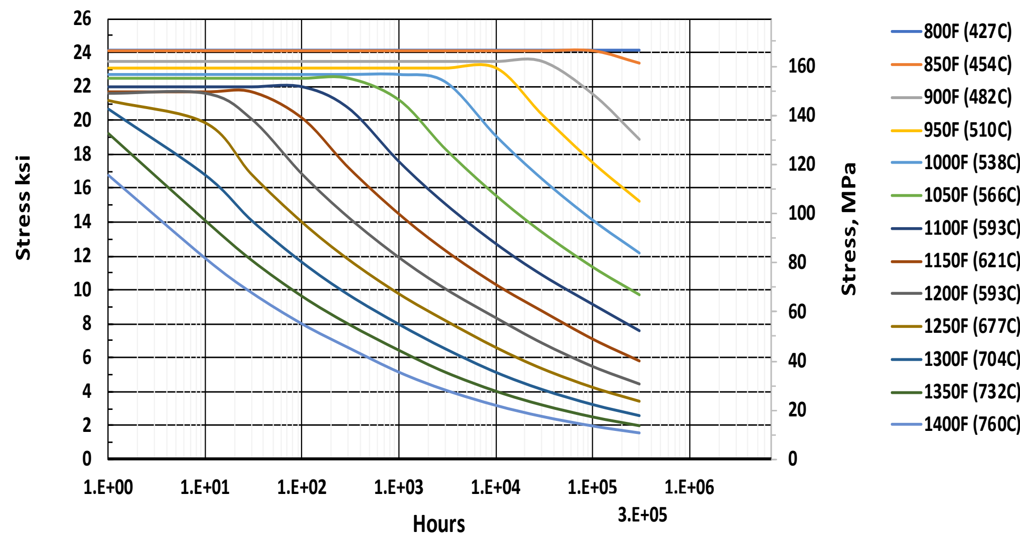
Table R.14.4-1B. This Analysis for 316 SS S_t (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.4B

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis
800	20.8	25.9	20.8	25.9	20.8	25.9	20.8	25.9	20.8	25.9	20.8	25.9	20.8	25.9	20.8	25.9	20.8	25.9	20.8	25.9	20.8	25.9
850	20.6	25.6	20.6	25.6	20.6	25.6	20.6	25.6	20.6	25.6	20.6	25.6	20.6	25.6	20.6	25.6	20.6	25.6	20.6	25.6	20.3	23.0
900	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.2	20.4	25.2	20.2	25.1	19.9	20.8	19.3	17.4
950	20.1	25.0	20.1	25.0	20.1	25.0	20.1	25.0	20.1	25.0	20.0	25.0	20.0	25.0	19.7	23.1	19.2	19.3	18.4	15.8	17.6	13.2
1000	19.8	24.6	19.8	24.6	19.8	24.6	19.8	24.6	19.8	24.6	19.5	24.6	19.0	21.9	18.2	17.8	17.5	14.8	16.2	12.1	14.0	10.0
1050	19.4	24.2	19.4	24.2	19.2	24.2	18.7	24.2	18.3	24.2	17.6	20.7	16.8	17.0	15.9	13.8	14.9	11.4	12.5	9.2	10.7	7.6
1100	19.1	23.9	19.0	23.9	18.5	23.9	17.8	23.9	17.3	20.1	16.6	16.2	15.9	13.2	13.9	10.6	11.5	8.7	9.5	7.0	7.8	5.7
1150	18.5	23.6	17.7	23.6	17.3	23.6	16.4	19.5	15.4	15.9	14.2	12.7	13.0	10.3	10.9	8.2	8.9	6.7	7.2	5.3	5.9	4.3
1200	17.8	23.3	16.8	23.3	15.8	19.5	14.2	15.5	12.4	12.5	10.6	9.9	9.4	8.0	8.3	6.3	6.9	5.1	5.5	4.1	4.5	3.3
1250	17.1	22.9	15.2	19.4	13.5	15.6	11.5	12.3	9.8	9.9	8.3	7.8	7.3	6.2	6.3	4.9	5.4	3.9	4.2	3.1	3.3	2.5
1300	16.1	22.6	12.8	15.6	10.9	12.5	9.1	9.7	7.5	7.8	6.4	6.1	5.6	4.8	4.7	3.8	3.9	3.0	3.1	2.4	2.5	1.9
1350	14.2	20.2	10.3	12.6	8.6	10.0	7.0	7.7	5.9	6.1	5.0	4.8	4.2	3.8	3.4	2.9	2.8	2.3	2.1	1.8	1.8	1.4
1400	12.0	16.7	8.2	10.1	6.7	8.0	5.4	6.1	4.5	4.8	3.8	3.7	3.1	2.9	2.5	2.3	2.0	1.8	1.5	1.4	1.2	1.1
1450	9.7	13.6	6.4	8.1	5.1	6.4	4.1	4.9	3.4	3.8	2.9	2.9	2.2	2.3	1.7	1.7	1.4	1.4	1.0	1.0	0.8	0.82
1500	7.8	11.1	4.9	6.5	3.9	5.1	3.2	3.9	2.6	3.0	2.1	2.3	1.6	1.8	1.2	1.3	0.9	1.0	0.65	0.76	0.5	0.45

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4B	This Analysis
425	143	179	143	179	143	179	143	179	143	179	143	179	143	179	143	179	143	179	143	179	143	179
450	142	177	142	177	142	177	142	177	142	177	142	177	142	177	142	177	142	177	142	177	140	166
475	141	174	141	174	141	174	141	174	141	174	141	174	141	174	141	174	140	174	138	154	135	129
500	140	173	140	173	140	173	140	173	140	173	139	173	139	173	138	173	134	146	131	120	125	101
525	138	171	138	171	138	171	138	171	138	171	136	171	134	170	130	139	126	115	118	94	108	78
550	136	168	136	168	135	168	134	168	132	168	128	164	125	135	119	110	113	91	101	74	87	61
575	133	166	133	166	131	166	127	166	124	163	119	131	114	108	105	87	95	72	79	58	67	47
600	131	164	129	164	126	164	121	160	116	131	110	105	105	86	91	69	75	56	62	45	51	37
625	127	162	121	162	118	162	111	130	103	106	94	84	86	69	72	55	59	44	48	35	40	29
650	123	161	116	161	108	134	97	106	84	85	72	68	64	55	57	43	48	35	38	28	31	22
675	118	158	106	136	94	109	80	86	69	69	58	54	51	44	44	34	38	28	30	22	24	17
700	112	156	91	112	78	89	65	70	54	56	46	44	41	35	34	27	28	22	22	17	18	14
725	101	146	75	92	63	73	52	57	44	45	36	35	31	28	25	22	21	17	16	13	13	11
750	88	124	62	75	51	60	41	46	35	36	29	28	24	22	19	17	16	13	11	10	9	8
775	74	103	50	62	40	49	32	37	27	29	23	22	18	18	14	14	12	11	8	8.2	7	6.4
800	61	86	40	51	32	40	25	30	21	24	17	18	13	14	10	11	8	8.4	5	6.4	4	4.6

Hot Tensile Stress at 1% Strain, ASME HBB-T digitized	80% Minimum Stress to Initiate Tertiary Creep	67% Minimum Stress to Rupture
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%		
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)	





ASME 2017 (and 2019) III-5

This Analysis

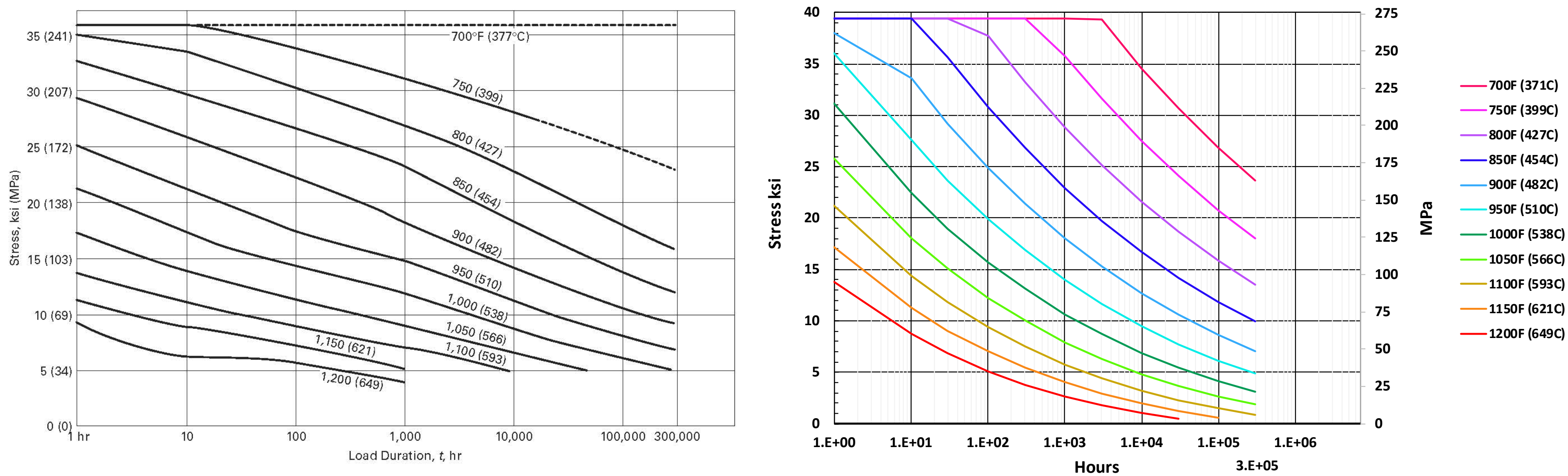
Figure R.14.4-1C. Summary of S_t curves for Ni-Fe-Cr (Alloy 800H)

Table R.14.4-1C. This Analysis for Ni-Fe-Cr (Alloy 800H) S_t (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.4C

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis
800	19.2	24.1	19.2	24.1	19.2	24.1	19.2	24.1	19.2	24.1	19.2	24.1	19.2	24.1	19.2	24.1	19.2	24.1	19.1	24.1	19.1	24.1
850	18.9	24.1	18.9	24.1	18.9	24.1	18.9	24.1	18.9	24.1	18.9	24.1	18.9	24.1	18.9	24.1	18.9	24.1	18.8	24.1	18.8	23.4
900	18.7	23.5	18.7	23.5	18.7	23.5	18.7	23.5	18.7	23.5	18.7	23.5	18.6	23.5	18.6	23.5	18.6	23.5	18.5	21.5	18.4	18.9
950	18.4	23.1	18.4	23.1	18.4	23.1	18.4	23.1	18.4	23.1	18.4	23.1	18.3	23.1	18.2	23.1	18.2	20.3	18.0	17.5	17.8	15.2
1000	18.2	22.7	18.1	22.7	18.1	22.7	18.1	22.7	18.1	22.7	18.0	22.7	17.9	22.2	17.8	19.0	17.6	16.5	16.5	14.1	14.1	12.2
1050	17.9	22.5	17.9	22.5	17.8	22.5	17.8	22.5	17.7	22.5	17.6	21.2	17.4	18.3	17.1	15.6	15.0	13.4	12.9	11.4	11.1	9.7
1100	17.6	21.9	17.6	21.9	17.5	21.9	17.4	21.9	17.2	20.7	16.9	17.5	16.3	15.0	13.9	12.7	12.0	10.8	10.3	9.1	8.9	7.6
1150	17.3	21.7	17.2	21.7	17.0	21.7	16.8	20.1	16.4	17.2	15.3	14.4	13.2	12.3	11.2	10.3	9.6	8.7	8.1	7.1	7.0	5.8
1200	17.0	21.6	16.7	21.6	16.3	20.0	15.8	16.8	14.7	14.2	12.4	11.9	10.7	10.0	9.0	8.3	7.7	6.9	6.5	5.5	5.6	4.5
1250	16.5	21.2	15.8	19.9	15.2	16.8	14.1	14.0	12.0	11.8	10.1	9.7	8.6	8.2	7.2	6.6	6.2	5.3	5.2	4.2	4.4	3.4
1300	15.8	20.6	14.4	16.8	13.4	14.1	11.5	11.6	9.8	9.7	8.2	8.0	7.0	6.5	5.8	5.2	5.0	4.1	4.1	3.3	3.5	2.6
1350	14.7	19.2	13.1	14.1	11.3	11.8	9.5	9.6	8.0	8.0	6.7	6.4	5.7	5.1	4.7	4.0	4.0	3.2	3.3	2.5	2.8	2.0
1400	13.0	16.8	10.8	11.8	9.3	9.8	7.8	8.0	6.5	6.6	5.4	5.1	4.6	4.1	3.8	3.1	3.2	2.5	2.6	1.9	2.2	1.5

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4C	This Analysis
425	132	166	132	166	132	166	132	166	132	166	132	166	132	166	132	166	132	166	132	166	132	166
450	130	166	130	166	130	166	130	166	130	166	130	166	130	166	130	166	130	166	130	166	130	166
475	129	163	129	163	129	163	129	163	129	163	129	163	128	163	128	163	128	163	127	157	126	138
500	128	160	128	160	128	160	128	160	128	160	128	160	127	160	126	160	126	151	125	130	124	113
525	126	158	126	158	126	158	126	158	126	158	125	158	124	158	124	144	122	125	119	107	109	93
550	124	156	124	156	124	156	124	156	124	156	123	156	122	141	121	120	113	104	103	88	88	76
575	123	154	123	154	123	154	122	154	121	154	120	137	117	118	111	100	96	86	83	73	72	62
600	121	151	121	151	120	151	119	151	117	136	114	115	107	99	91	83	79	71	67	59	58	49
625	119	149	118	149	116	149	115	135	109	115	102	97	89	82	75	69	64	58	55	47	47	39
650	117	149	115	149	112	137	109	115	101	98	85	81	74	69	62	57	53	47	45	37	39	30
675	114	146	109	138	105	117	98	97	85	82	72	68	61	57	52	46	44	37	37	30	31	24
700	110	155	100	119	94	100	82	82	70	69	59	57	50	47	41	37	35	30	29	23	25	19
725	99	137	88	102	82	85	70	70	58	58	49	47	41	38	34	30	29	24	24	18	20	15
750	94	121	80	87	69	72	58	59	49	49	40	38	34	30	28	24	24	19	20	15	16	12

Hot Tensile Stress at 1% Strain, ASME HBB-T digitized	80% Minimum Stress to Initiate Tertiary Creep	67% Minimum Stress to Rupture	1% Strain in Creep
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%			
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)		



ASME 2017 (and 2019) III-5 This Analysis

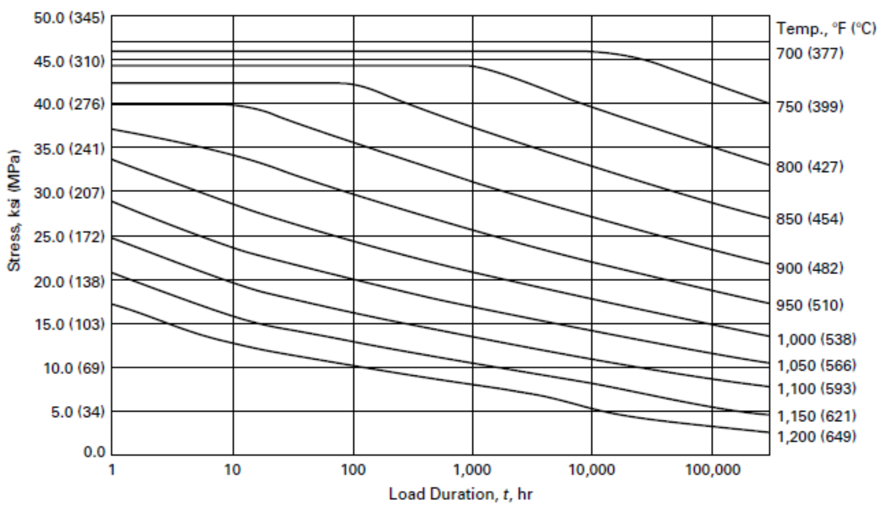
Figure R.14.4-1D. Summary of S_t curves for 2¼Cr-1Mo

Table R.14.4-1D. This Analysis for 2¼Cr-1Mo S_t (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.4D

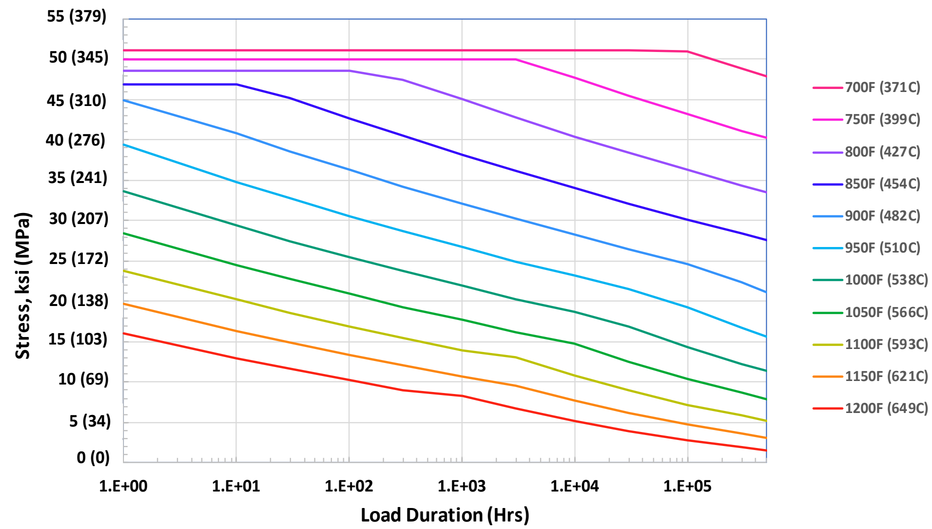
ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis
700	...	39.4	35.5	39.4	35.5	39.4	35.5	39.4	35.5	39.4	35.5	39.4	35.5	39.3	35.5	34.6	35.5	30.7	35.5	26.8	35.5	23.6
750	35.3	39.4	35.2	39.4	34.6	39.4	33.5	39.4	32.5	39.4	31.3	35.8	29.7	31.6	28.4	27.5	26.6	24.1	25.0	20.8	23.3	18.1
800	35.0	39.4	33.2	39.4	31.8	39.4	30.4	37.8	28.8	33.2	26.8	28.8	25.0	25.1	23.0	21.6	20.5	18.7	18.0	15.8	16.1	13.6
850	32.3	39.4	29.4	39.4	28.0	35.7	26.4	30.8	25.0	26.8	23.2	22.9	21.0	19.8	18.3	16.7	16.3	14.2	14.0	11.8	12.3	9.9
900	29.0	38.0	25.5	33.6	23.7	29.2	22.0	24.9	20.2	21.4	18.5	18.0	16.5	15.3	14.4	12.7	12.5	10.6	10.9	8.7	9.6	7.1
950	25.0	36.0	21.0	27.6	19.3	23.7	17.5	19.9	16.3	16.9	14.8	14.0	13.2	11.7	11.3	9.5	9.7	7.7	8.4	6.1	7.3	4.9
1000	20.7	31.2	17.1	22.4	15.5	19.0	14.2	15.7	13.1	13.1	11.9	10.6	10.4	8.7	8.7	6.9	7.5	5.5	6.3	4.2	5.2	3.2
1050	16.8	25.8	13.8	18.1	12.5	15.1	11.2	12.2	10.2	10.0	9.3	7.9	7.9	6.3	6.7	4.8	5.7	3.7	4.7	2.6	4.0	1.9
1100	13.6	21.2	11.0	14.4	10.0	11.8	9.0	9.4	8.2	7.5	7.2	5.8	6.2	4.4	5.0	3.2	4.1	2.3	3.3	1.5	2.7	0.9
1150	10.8	17.2	8.8	11.3	8.0	9.1	7.2	7.0	6.3	5.4	5.4	4.0	...	2.9	...	2.0	...	1.3	...	0.6	...	...
1200	9.0	13.8	6.2	8.7	6.1	6.8	5.9	5.1	5.1	3.8	4.1	2.7	...	1.8	...	1.0	...	0.4	...	...	...	...

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4D	This Analysis
375	...	271	245	271	245	271	245	271	245	271	245	271	245	263	245	231	245	205	245	179	245	157
400	243	271	243	271	239	271	231	271	224	271	216	244	205	216	196	188	183	164	172	142	161	123
425	241	271	230	271	220	271	211	263	200	232	186	201	173	176	160	151	142	131	125	111	112	95
450	226	265	207	265	197	254	186	219	176	191	164	164	149	142	130	120	116	103	101	86	89	72
475	206	265	183	244	170	212	159	181	147	157	136	132	122	113	106	94	92	79	80	65	71	54
500	182	253	156	204	144	176	132	149	122	127	111	106	99	89	85	73	74	60	64	48	56	39
525	153	234	127	170	116	145	106	121	97	102	89	83	78	69	66	55	57	44	48	34	41	27
550	131	198	108	141	98	119	89	97	81	80	74	65	64	52	54	41	46	32	38	24	33	17
575	109	167	89	115	80	96	72	77	66	63	59	49	50	39	42	29	35	22	29	15	25	10
600	89	139	72	94	66	76	59	60	53	48	47	37	...	28	...	20	...	14	...	8.8	...	4.8
625	72	115	58	75	53	60	49	46	42	36	36	26	...	19	...	13	...	7.9	...	3.5	...	...
650	62	95	43	59	42	47	41	35	35	26	28	18	...	12	...	7.0	...	2.8	...	...	...	...

80% Minimum Stress to Initiate Tertiary Creep	67% Su
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%	
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)



ASME 2017 III-5



This Analysis

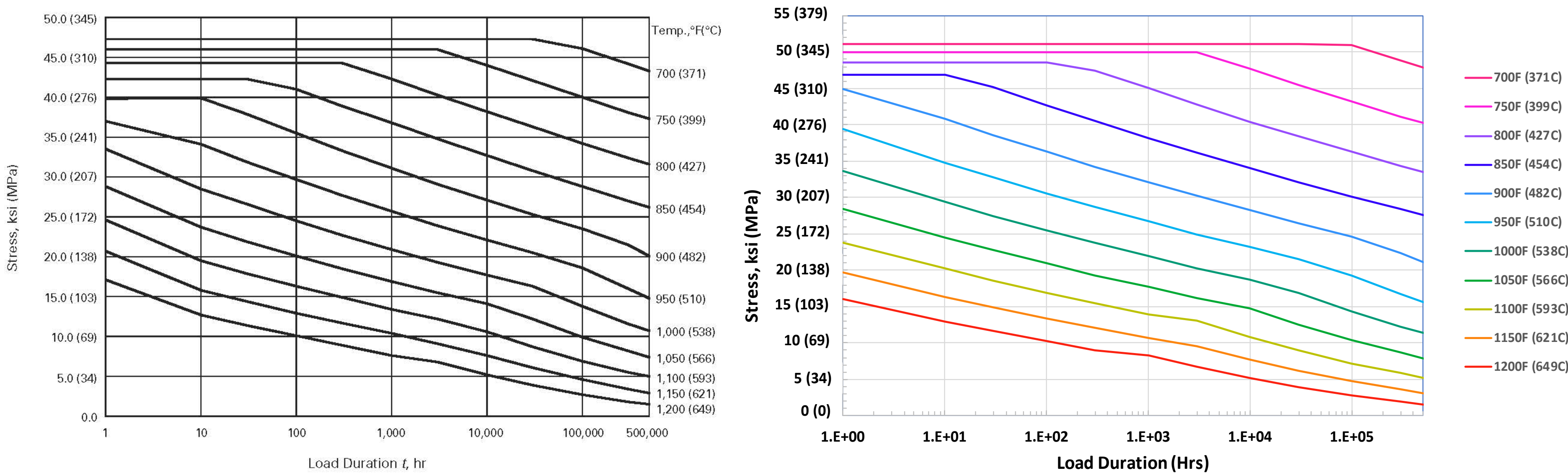
Figure R.14.4-1E. Summary of S_t curves for 9Cr-1Mo-V

Table R.14.4-1E. This Analysis for 9Cr-1Mo-V S_t (ksi and MPa) compared with BPVC 2017 III-5 Table HBB-I-14.4E

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °F	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis		
700	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.0	47.3	48.8		
750	46.0	50.0	46.0	50.0	46.0	50.0	46.0	50.0	46.0	50.0	46.0	50.0	46.0	50.0	46.0	47.7	44.9	45.5	42.3	43.2	40.1	41.2		
800	44.3	48.6	44.3	48.6	44.3	48.6	44.3	48.6	44.3	47.5	44.3	45.0	42.1	42.8	39.6	40.5	37.4	38.4	35.1	36.3	33.1	34.4		
850	42.3	46.9	42.3	46.9	42.3	45.2	42.3	42.7	39.8	40.5	37.3	38.2	35.1	36.1	32.9	34.0	30.9	32.1	28.9	30.1	27.1	28.4		
900	39.8	44.9	39.9	40.8	38.0	38.6	35.5	36.3	33.3	34.3	31.1	32.1	29.1	30.2	27.1	28.2	25.3	26.5	23.5	24.7	21.9	22.3		
950	37.0	39.4	34.1	34.8	31.9	32.7	29.7	30.6	27.7	28.7	25.7	26.7	23.9	25.0	22.1	23.1	20.5	21.6	18.8	19.3	17.4	16.8		
1000	33.5	33.6	28.5	29.4	26.6	27.5	24.5	25.5	22.7	23.7	20.9	21.9	19.3	20.3	17.7	18.7	16.3	16.9	14.9	14.3	13.7	12.3		
1050	28.8	28.5	23.7	24.5	21.9	22.8	20.1	20.9	18.5	19.3	16.9	17.7	15.5	16.2	14.1	14.7	12.8	12.5	11.5	10.4	10.5	8.7		
1100	24.6	23.8	19.5	20.2	17.9	18.6	16.3	16.9	14.9	15.4	13.4	13.9	12.2	13.1	10.9	10.8	9.9	9.0	8.7	7.2	7.8	5.8		
1150	20.7	19.7	15.8	16.4	14.4	14.9	12.9	13.3	11.7	12.0	10.5	10.6	9.4	9.5	8.3	7.7	6.8	6.2	5.5	4.7	4.5	3.6		
1200	17.1	16.0	12.7	13.0	11.4	11.6	10.1	10.2	9.1	9.0	7.9	8.3	7.0	6.7	5.3	5.2	4.3	4.0	3.3	2.8	2.5	1.9		

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °C	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis	ASME 2017 III-5 Table HBB-I-14.4E	This Analysis		
375	325	351	325	351	325	351	325	351	325	351	325	351	325	351	325	351	325	351	325	344	325	329		
400	317	344	317	344	317	344	317	344	317	344	317	344	316	344	316	327	307	312	290	296	275	282		
425	307	336	307	336	307	336	307	336	307	330	307	313	292	298	276	282	262	268	246	253	232	240		
450	294	325	294	325	294	319	294	302	279	287	264	270	249	256	234	241	220	228	206	214	193	202		
475	275	313	275	293	271	278	256	261	241	247	225	232	211	219	197	205	184	192	171	179	160	165		
500	262	287	249	254	235	240	219	225	205	211	191	197	178	185	165	172	153	160	141	147	131	128		
525	242	250	214	219	200	206	185	191	172	179	163	166	148	154	136	142	126	133	115	114	106	98		
550	217	216	182	187	170	175	156	161	144	150	132	138	119	127	111	119	102	102	93	86	85	73		
575	189	185	154	159	142	147	130	134	119	124	108	113	99	103	90	92	81	77	73	64	66	52		
600	164	157	126	133	115	122	107	110	97	101	86	90	79	84	71	69	63	57	54	45	48	36		
625	139	132	106	109	96	99	86	89	78	80	70	70	62	63	54	50	44	40	36	31	30	23		
650	117	109	87	88	78	79	69	70	62	61	54	57	47	46	36	35	29	27	22	19	17	13		

67% Minimum Stress to Rupture	80% Minimum Stress to Initiate Tertiary Creep	67% S_u (60-85 material)
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%		
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)	
Value as extrapolated at 650C/1200F using final table stresses from 30khr to 300 khr		



ASME 2019 III-5

This Analysis

Figure R.14.4-1E-2019. Summary of S_t curves for 9Cr-1Mo-V

Table R.14.4-1E-2019. This Analysis for 9Cr-1Mo-V S_t (ksi and MPa) compared with BPVC 2019 III-5 Table HBB-I-14.4E

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °F	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis
700	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	47.3	51.1	46.1	51.0	44.2	48.8	43.3	47.8
750	46.0	50.0	46.0	50.0	46.0	50.0	46.0	50.0	46.0	50.0	46.0	50.0	46.0	50.0	44.0	47.7	42.1	45.5	40.0	43.2	38.1	41.2	37.3	40.2
800	44.3	48.6	44.3	48.6	44.3	48.6	44.3	48.6	44.3	47.5	42.3	45.0	40.3	42.8	38.2	40.5	36.3	38.4	34.2	36.3	32.4	34.4	31.6	33.5
850	42.3	46.9	42.3	46.9	42.3	45.2	41.0	42.7	38.9	40.5	36.8	38.2	34.8	36.1	32.7	34.0	30.8	32.1	28.8	30.1	27.0	28.4	26.2	27.6
900	39.8	44.9	38.8	40.8	37.9	38.6	35.5	36.3	33.3	34.3	31.1	32.1	29.1	30.2	27.1	28.2	25.3	26.5	23.5	24.7	21.5	22.3	20.1	21.1
950	37.0	39.4	34.1	34.8	31.9	32.7	29.7	30.6	27.7	28.7	25.7	26.7	23.9	25.0	22.1	23.1	20.5	21.6	18.6	19.3	16.0	16.8	14.8	15.7
1000	33.5	33.6	28.5	29.4	26.6	27.5	24.5	25.5	22.7	23.7	20.9	21.9	19.3	20.3	17.7	18.7	16.3	16.9	13.8	14.3	11.6	12.3	10.7	11.4
1050	28.8	28.5	23.7	24.5	21.9	22.8	20.1	20.9	18.5	19.3	16.9	17.7	15.5	16.2	14.1	14.7	12.2	12.5	9.9	10.4	8.2	8.7	7.4	7.9
1100	24.6	23.8	19.5	20.2	17.9	18.6	16.3	16.9	14.9	15.4	13.4	13.9	12.2	13.1	10.6	10.8	8.7	9.0	6.9	7.2	5.5	5.8	5.0	5.2
1150	20.7	19.7	15.8	16.4	14.4	14.9	12.9	13.3	11.7	12.0	10.4	10.6	9.1	9.5	7.6	7.7	6.1	6.2	4.6	4.7	3.4	3.6	2.9	3.1
1200	17.1	16.0	12.7	13.0	11.4	11.6	10.1	10.2	8.9	9.0	7.6	8.3	6.6	6.7	5.2	5.2	3.9	4.0	2.7	2.8	1.8	1.9	1.5	1.5

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °C	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis	ASME 2019 III-5 Table HBB-I-14.4E	This Analysis
375	325	351	325	351	325	351	325	351	325	351	325	351	325	351	325	351	325	351	312	344	299	329	293	322
400	317	344	317	344	317	344	317	344	317	344	317	344	316	344	302	327	289	312	274	296	261	282	255	275
425	307	336	307	336	307	336	307	336	307	330	294	313	281	298	266	282	253	268	238	253	226	240	220	234
450	294	325	294	325	294	319	289	302	275	287	259	270	246	256	231	241	218	228	204	214	192	202	186	196
475	279	313	275	293	271	278	255	261	241	247	225	232	211	219	197	205	184	192	171	179	159	165	149	156
500	262	287	249	254	235	240	219	225	205	211	191	197	178	185	165	172	153	160	141	147	123	128	115	121
525	242	250	214	219	200	206	185	191	172	179	160	166	148	154	136	142	126	133	109	114	93	98	86	91
550	217	216	182	187	168	175	156	161	144	150	132	138	119	127	111	119	100	102	83	86	69	73	63	67
575	189	185	154	159	142	147	130	134	119	124	108	113	99	103	89	92	75	77	61	64	50	52	45	48
600	164	157	126	133	115	122	107	110	97	101	86	90	78	84	68	69	55	57	44	45	34	36	31	32
625	139	132	106	109	96	99	86	89	78	80	69	70	60	63	50	50	40	40	30	31	22	23	18	20
650	117	109	87	88	78	79	69	70	61	61	52	57	45	46	35	35	27	27	18	19	12	13	10	10

67% Minimum Stress to Rupture	80% Minimum Stress to Initiate Tertiary Creep	67% S_u (60-85 material)
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%		
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)	
Value as extrapolated at 650C/1200F using final table stresses from 30khr to 300 khr		

Basic Method of Analysis

S_t, the temperature- and time-dependent stress intensity, is derived as the lowest value from three criteria per BPVC III-5, HBB-3221: the average stress for a total strain of 1%, 80% of the minimum stress to cause initiation of tertiary creep, and 67% of the minimum stress to cause rupture. The method thus requires analysis of data for stresses per each of the criteria. In all cases, the curve-fitting method used is the LMP as a function of a polynomial in logarithmic stress.

The analysis for each of the tabulated materials and criteria is conducted using the ASME time-dependent software, version 2016-2-10, that is separately verified for accuracy in the regression of the data for the LMP-Logarithmic Stress polynomial curve, as discussed in Appendix VTDS. The software is downloaded from the ASME Materials Properties Database.

The data are analyzed using the LMP-Logarithmic stress polynomial function - $LMP = T(C + \log t) = a_0 + a_1*\log S + a_2*(\log S)^2 + a_3*(\log S)^3$ (t = time to 1% strain, time to initiate tertiary creep, or rupture time in hours, S is the stress, and T, the temperature in absolute units). The regression method used is heat/lot-centered and the preferred polynomial order is 2 (a_3=0). The minimum stress is computed using a lower-bound on log t by 1.65.SEE, where SEE is the standard error of the estimate on log t. A 2nd order fit is used in all cases, except the following where the 1st order provided a superior fit – 304 SS: 1%, tertiary; 316 SS: tertiary.

The 2nd order curve-fit is evaluated in each case, particularly with regard to the suitability of extrapolation as affected by the parabolic vertex turn-around effect that can produce excessively conservative stress values or, in some cases, no solution (where the turn-around vertex precedes the desired exposure duration). Also, in some cases for the 1% strain and tertiary creep data, the observed scatter is large enough to warrant exclusion of data that are clear outliers. In those cases, the data are culled to exclude data outside of the 10X factor bounds on an ideally perfect prediction line (predicted versus actual time) and the dataset re-analyzed. Data with time exceeding 10,000 hours are generally not excluded, even if outside of the 10X bounds. In case of 2¼Cr-1Mo with by and large the greatest scatter, the curve-fit was strikingly poor (based on the regression coefficient, R^2, and SEE), and a significant number of data points outside of the 10X bounds are excluded in the final analysis. The 1% strain and tertiary creep data for 2¼Cr-1Mo included a substantial amount of data generated in Helium. An evaluation of the analysis results with and without the Helium data showed little difference. As such, all of the data are used in this analysis.

Following the data censoring as above, there was no apparent need to further censor the data such as by time-censoring performed for the minimum rupture strength calculations (for Table HBB-I-14.6, S_r). In case of 9Cr-1Mo-V, the region splitting method used for the minimum rupture strength (see report on Table HBB-I-14.6), is also used for the 1% strain and tertiary creep initiation data analysis.

For the minimum rupture strength, results of the analyses conducted for S_r (Table HBB-I-14.6) are used, and the method of analysis in that case is described as part of the report on Table HBB-I-14.6.

A major portion of the time-temperature range over which the BPVC S_t values have been found to be non-conservative relative to our analysis is the range over which the S_t values are controlled by the (time-dependent) stress to initiate tertiary creep. For perspective, the issues associated with implementation of the tertiary creep criterion and our limited research into its effect for 304 SS, by way of example, are described in Appendix TCOC: "Comments on the Tertiary Creep Onset Criterion for S_t (and S_{mt})."

Finally, extrapolation of the computed S_t outside of the time-dependent (creep) regime, i.e., to lower temperatures and shorter durations, produces stress values that exceed known time-independent strength levels (tensile strength, stress at 1% strain in a hot tensile curve). BPVC III-5 does not call out specific upper limits on S_t values, although development of Table HBB-I-14.4 requires such a limit. For this review, we have used the stress at 1% strain in the hot tensile curve to limit the time-dependent 1% strain criterion stress, and 67% of the hot tensile strength defined by S_u (per BPVC III-5 HBB-3225-1) to limit the 67% minimum rupture strength criterion stress. Note that we have used the S_u, developed as part of this review, without a 1.1 divisor, in order to be consistent with the S_m values. For 304 SS and 316 SS and Alloy 800H, the 1% hot tensile strain applied, whereas for 2¼Cr-1Mo and 9Cr-1Mo-V, the 67% hot tensile strength applied. For the 1% hot tensile strain value of stress, we have used a stress digitized from the pertinent hot tensile stress-strain curve published in BPVC 2019 III-5, HBB-T.

Data and References

The analysis methods are the same as used for work described in STP-NU-035 and STP-NU-063 for 800H and for the stainless steels (304 and 316 SS), respectively. The datasets employed in the analysis for these materials were garnered independent of any Code-related work, including that of the STP publications.

For 304SS

- Rupture Data (after 100-hour censor): 90 Heats/Lots, 964 Data Points, Maximum rupture time ≈ 179,400 hours. Data from references as listed for the report on Table HBB-I-14.6 (S_r).
- 1% Strain (No Censor): 17 Heats/Lots, 351 Data Points, Maximum time = 97,000 hours. Data compiled by ORNL, including references as listed for the discussion of Table HBB-I-14.6.
- Tertiary Creep (11 data points censored): 8 Heats/Lots, 206 Data Points, Maximum time = 55,000 hours. Data compiled by ORNL, including references as listed for the discussion of Table HBB-I-14.6.

For 316SS

- Rupture Data (after 100-hour censor): 142 Heats/Lots, 1616 Data Points, Maximum rupture time ≈ 320,400 hours. Data from references as listed for the report on Table HBB-I-14.6 (S_r).
- 1% Strain (No Censor): 19 Heats/Lots, 183 Data Points, Maximum time = 174,000 hours. Data compiled by ORNL, including references as listed for the discussion of Table HBB-I-14.6.

- Tertiary Creep (No Censor): 22 Heats/Lots, 327 Data Points, Maximum time = 141,000 hours. Data compiled by ORNL, including references as listed for the discussion of Table HBB-I-14.6.

For Ni-Fe-Cr (Alloy 800H)

- Rupture Data (No Censor): 49 Heats/Lots, 960 Data Points, Maximum rupture time ≈ 136,100 hours. Data compiled by ORNL from various published and unpublished sources.
- 1% Strain (32 data points censored): 32 Heats/Lots, 418 Data Points, Maximum time = 69,900 hours. Data compiled by ORNL from various published and unpublished sources.
- Tertiary Creep (6 data points censored): 24 Heats/Lots, 324 Data Points, Maximum time = 94,800 hours. Data compiled by ORNL from various published and unpublished sources.

For 2¼Cr-1Mo (Annealed, Annealed and Tempered, and N&T material combined)

- Rupture Data (after 100-hour censor): 93 Heats/Lots, 671 Data Points, Maximum rupture time ≈ 213,300 hours. Data from references as listed for the discussion of Table HBB-I-14.6 (S_r).
- 1% Strain (52 data point censored): 21 Heats/Lots, 208 Data Points, Maximum time = 94,700 hours. Data compiled by ORNL, derived from various sources.
- Tertiary Creep (32 data point censored): 37 Heats/Lots, 310 Data Points, Maximum time = 94,900 hours. Data compiled by ORNL, derived from various sources.

For 9Cr-1Mo-V (All data imported from the ASME Materials Properties Database relating to ASME Record no. 16-2627)

- Rupture Data (No Censor): 112 Heats/Lots, 2046 Data Points, Maximum rupture time ≈ 170,370 hours
- 1% Strain (No Censor): 11 Heats/Lots, 388 Data Points, Maximum time = 68,800 hours.
- Tertiary Creep (No Censor): 22 Heats/Lots, 523 Data Points, Maximum time = 84,500 hours.

Analysis and Results

Figures R.14.4-2A through R.14.4-2E graphically summarize the curve-fitting results for each of the materials cases. Each figure provides the results of the curve-fit for each of the three criteria.

304 SS (Figure R.14.4-2A)

Note the 1st order fit used for the 1% and tertiary criteria. Also, note the generally higher SEE compared with the rupture case, for the 1% and tertiary analysis where the data have higher scatter.

316 SS (Figure R.14.4-2B)

Note the 1st order fit used for the tertiary criterion. As described in the discussion for S_r, the 2nd order fit for rupture data is used for temperature < 750°C and the 1st order otherwise. Again, although not as large as for 304 SS, the 1% and tertiary curve fit SEE > that for the rupture data analysis.

Ni-Fe-Cr/Alloy 800H (Figure R.14.4-2C)

Again, the somewhat higher SEE for the 1% strain and tertiary cases over the rupture data analysis reflects the scatter. Note the tertiary LMP curve appears near-linear and similar in shape to the rupture curve.

2¼Cr-1Mo (Figure R.14.4-2D)

Again, the somewhat higher SEE for the 1% strain and tertiary cases over the rupture data analysis reflects the scatter. In fact, the as-compiled 2¼Cr-1Mo 1% strain and tertiary data exhibited very large scatter (details not shown here), and a significant number of data points outside of the 10X bounds on the perfect prediction were excluded (censored); see the Data and References section above.

9Cr-1Mo-V (Figure R.14.4-2E)

For this alloy, the region splitting method is used (see details of splitting for S_o and S_r report sections). As such, the figures show both, the high and the low stress region curve-fits. The parabolic vertex turn-around seen for the high stress tertiary and rupture data does not impact the long-term, low stress predictions, so the 2nd order fit is used. Note that in the final analysis, the S_t value at the highest time and temperature could not be determined by the curve-fits, and in this case, as shown in Table R.14.4-1E, the stress value is determined by extrapolation from the values at the highest temperature.

The 9Cr-1Mo-V 1% strain and tertiary datasets are exceptionally well-behaved with regard to scatter, as reflected in the SEE values that are comparable to that seen for the rupture data.

Discussion of Results

304SS (Table R.14.4-1A, Figure R.14.4-1A):

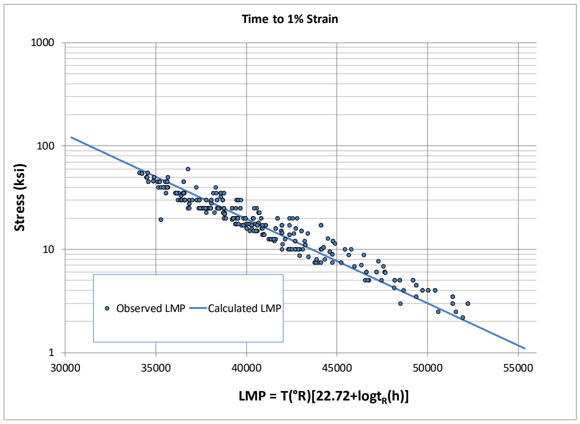
The significant non-conservatism of the BPVC 2017 (and 2019) III-5 Table HBB-I-14.4A values relative to our analysis for a large portion of the table (see Table R.14.4-1A) was further examined in light of the relatively recent effort to analyze the data for this material in order to correct and extend the BPVC III-5 S_{mt} and S_r values to 500,000 hours (STP-NU-063) (Ref. Sengupta 2013). The results of that work are evidently not incorporated into the BPVC 2017 (and 2019) III-5 Table HBB-I-14.4A. Figure R.14.4-3A and Table R.14.4-3A below summarize the STP-NU-063-reported results compared with this analysis. The table illustrates our analysis results to be in good agreement with that effort in the obvious time-dependent stress regime. Differences observed appear to be related to differences in extrapolated stresses below or at the lower time-temperature end of the time-dependent controlled stress regime. STP-NU-063 indicates that the long time, high temperature values are all controlled by the time-to-tertiary creep values, similar to the results of our analysis. The findings support the need to further review and update the BPVC III-5 Table HBB-I-14.4A and corresponding Figure HBB-I-14.4A.

316 SS (Table R.14.4-1B, Figure R.14.4-1B):

The significant non-conservatism of the BPVC 2017 (and 2019) III-5 Table HBB-I-14.4B values relative to our analysis for a large portion of the table (see Table R.14.4-1B) was further examined in light of the relatively recent effort to analyze the data for this material in order to correct and extend the BPVC III-5 S_{mt} and S_r stresses to 500,000 hours (STP-NU-063) (Ref. Sengupta 2013). The results of that work are evidently not incorporated into the BPVC 2017 (and 2019) III-5 Table HBB-I-14.4B. Figure R.14.4-3B and Table R.14.4-3B below summarize the STP-NU-063-reported results compared with this analysis. The table illustrates our analysis results to be in good agreement with that effort in the obvious time-dependent stress regime. Differences observed appear to be related to differences in extrapolated stresses below or at the lower time-temperature end of the time-dependent controlled stress regime. STP-NU-063 indicates that the long time, high temperature values are all controlled by the time-to-tertiary creep values, similar to the results of our analysis. The findings support the need to further review and update the BPVC III-5 Table HBB-I-14.4B and corresponding Figure HBB-I-14.4B.

Ni-Fe-Cr/Alloy 800H (Table R.14.4-1C, Figure R.14.4-1C):

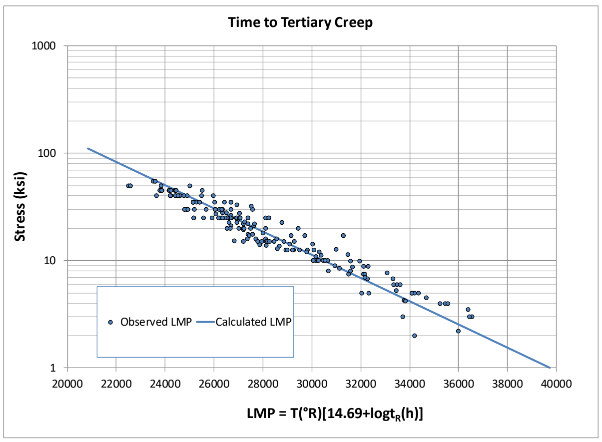
The significant non-conservatism of the BPVC 2017 (and 2019) III-5 Table HBB-I-14.4C values relative to our analysis for a significant portion of the table (see Table R.14.4-1C) was further examined in light of a relatively recent effort to analyze the data for this material in order to extend the BPVC III-5 allowable stresses (STP-NU-035) (Ref. Swindeman 2012). The results of that work are evidently not incorporated into the BPVC 2017 (and 2019) III-5 Table HBB-I-14.3C. Figure R.14.4-3C and Table R.14.4-3C below summarize the STP-NU-035-reported results compared with this analysis. The table illustrates our analysis results to be in good agreement with that effort. Additionally, STP-NU-035 indicates that the long time, high temperature values are all controlled by the time-to-tertiary creep values. Our analysis indicates a mix of controlling criteria in the long-term, high temperature regime – the expected minimum rupture strength for some of the intermediate time-temperature values and the time to initiate tertiary creep for the highest times and temperatures (see Table R.14.4-1C). The findings support the need to further review and update the BPVC III-5 Table HBB-I-14.4C and corresponding Figure HBB-I-14.4C.



LMP-1st order polynomial -	logt1 = -CLP + a0/T + a1/T*logS

S is stress in ksi, T is temperature in °R and t1 is time in hours to 1% strain

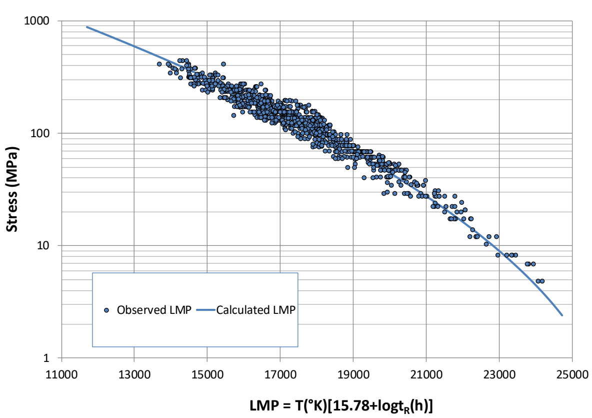
CLP=	22.72198
a0 =	55846.75
a1 =	-12272
SEE=	0.675307
R^2=	0.811152



LMP-1st order polynomial -	logt3 = -CLP + a0/T + a1/T*logS

S is stress in ksi, T is temperature in °R and t3 is time in hours to tertiary creep onset

CLP=	14.68774
a 0=	39735.05
a 1=	-9260.06
a 2=	0
SEE=	0.510928
R^2=	0.808216

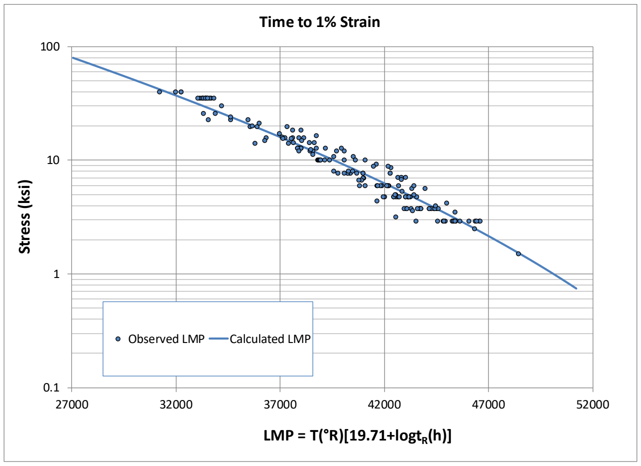


LMP-2nd order polynomial -	$\log t_R = -C_{LP} + a_0/T + a_1/T*\log S + a_2/T*(\log S)^2$

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

C_{LP}=	15.77887
a_0 =	25483.48
a_1 =	-1611.22
a_2 =	-1040.6
SEE=	0.464138
R^2	0.67

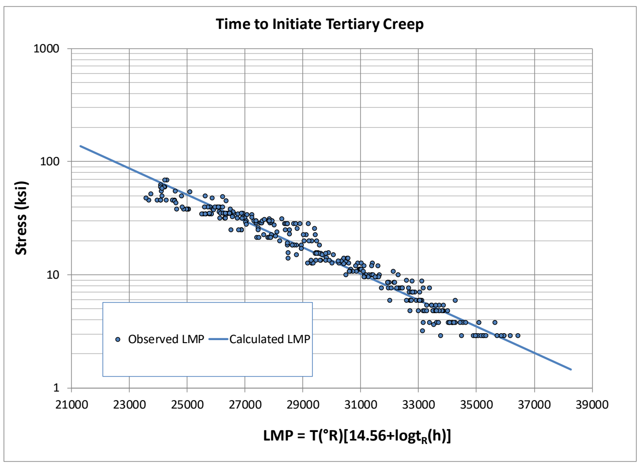
Figure R.14.4-2A. Summary of curve-fitting results for 304 SS – time to 1% strain, time to initiate tertiary creep, and time to rupture



LMP-2nd order polynomial -	logt1 = -CLP + a0/T + a1/T*logS + a2/T [logS]^2

LMP-1st order polynomial -	logt1 = -CLP + a0/T + a1/T*logS

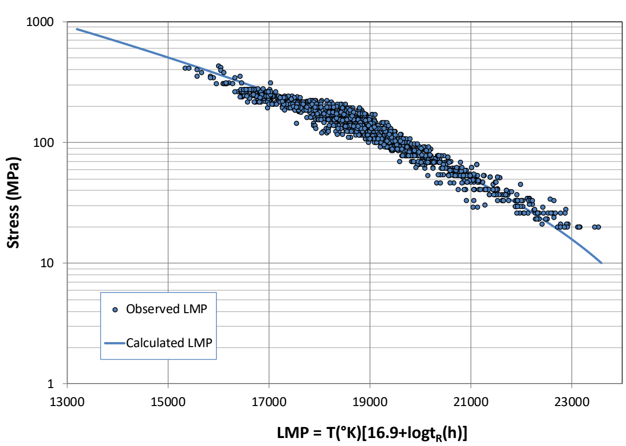
CLP=	19.71198
a0 =	50132.31
a1 =	-8754.19
a2=	-1769.34
SEE=	0.514194
R^2=	0.830272



LMP-2nd order polynomial -	logt3 = -CLP + a0/T + a1/T*logS + a2/T [logS]^2

S is stress in ksi, T is temperature in °R and t3 is time in hours to tertiary creep onset

CLP=	14.56247
a 0=	39656.29
a 1=	-8572.78
a 2=	0
SEE=	0.41307
R^2=	0.835397

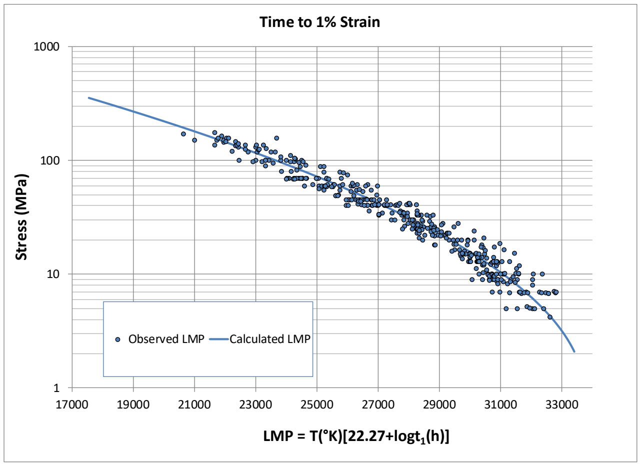


S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

C_{LP}=	16.8983
a_0 =	24932.78
a_1 =	18.86962
a_2 =	-1367.04
SEE=	0.35016
R^2	0.79

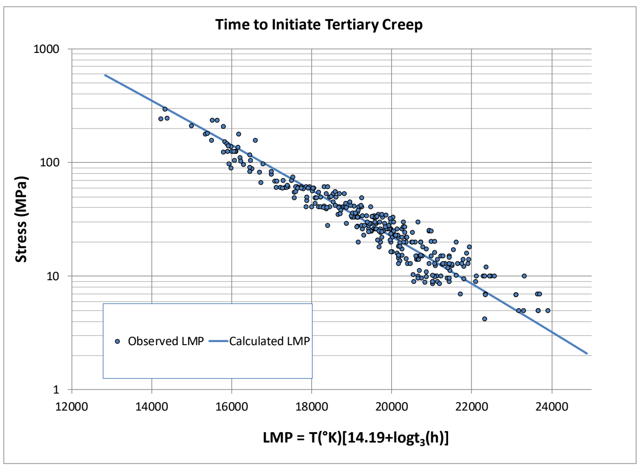
Figure R.14.4-2B. Summary of curve-fitting results for 316 SS – time to 1% strain, time to initiate tertiary creep, and time to rupture. The rupture data fit used is 2nd order for <750°C and 1st order otherwise (see S_r section of report)



LMP-2nd order polynomial - logt1 = -CLP + a0/T + a1/T*logS + a2/T [logS]^2

S is stress in MPa, T is temperature in °K and t1 is time in hours to 1% strain

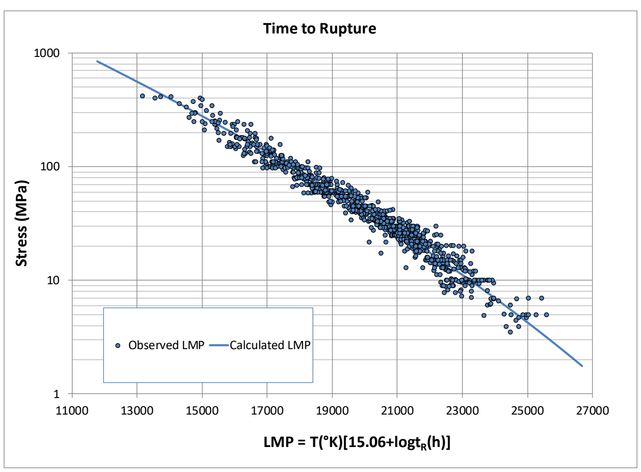
CLP=	22.2743
a0 =	33729.51
a1 =	-265.899
a2=	-2390.08
SEE=	0.51955
R^2=	0.839077



LMP-2nd order polynomial - logt3 = -CLP + a0/T + a1/T*logS + a2/T [logS]^2

S is stress in MPa, T is temperature in °K and t3 is time in hours to onset of tertiary creep

CLP=	14.18657
a 0=	26331.14
a 1=	-4518.32
a 2=	-126.302
SEE=	0.474782
R^2=	0.669958

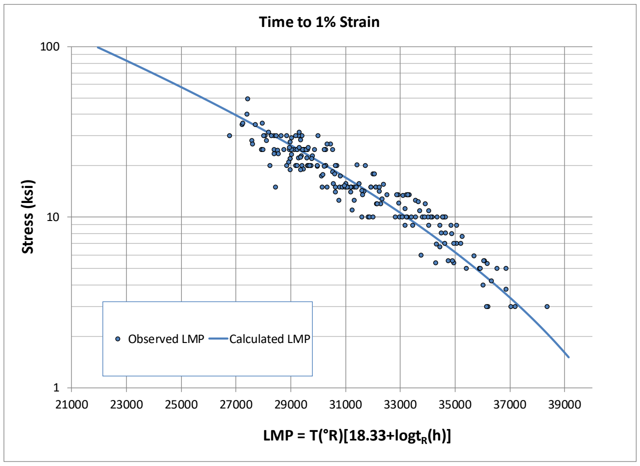


S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

C_{LP}=	15.05545
a_0 =	27661.01
a_1 =	-3919.96
a_2 =	-516.121
SEE=	0.38245
R^2	0.849958

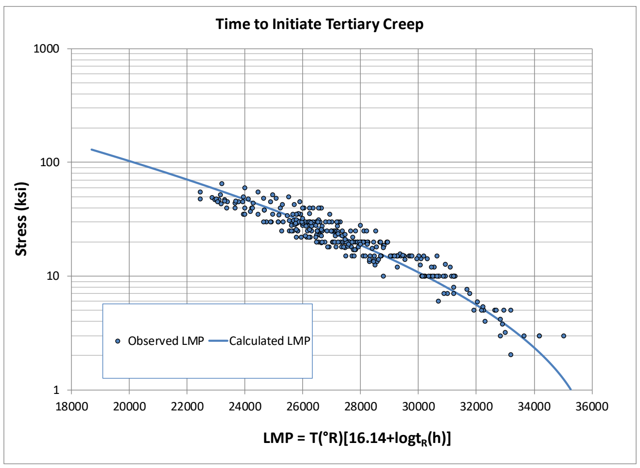
Figure R.14.4-2C. Summary of curve-fitting results for Ni-Fe-Cr (Alloy 800H) – time to 1% strain, time to initiate tertiary creep, and time to rupture



LMP-2nd order polynomial -	logt1 = -CLP + a0/T + a1/T*logS + a2/T [logS]^2

LMP-1st order polynomial -	logt1 = -CLP + a0/T + a1/T*logS

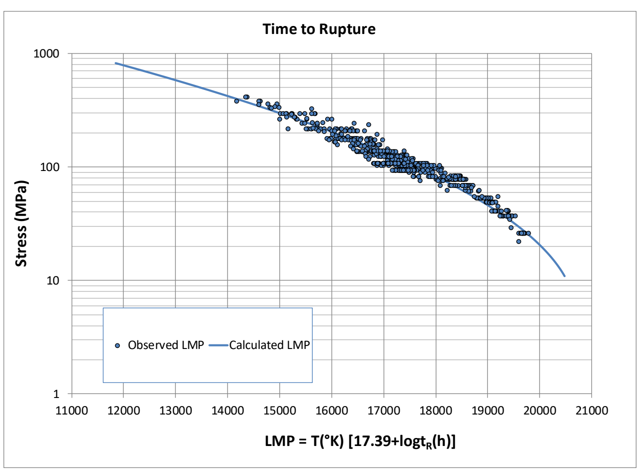
CLP=	18.32508
a0 =	40011.79
a1 =	-4532.16
a2=	-2268.25
SEE=	0.569913
R^2=	0.711398



LMP-2nd order polynomial -	logt3 = -CLP + a0/T + a1/T*logS + a2/T [logS]^2

S is stress in ksi, T is temperature in °R and t3 is time in hours to tertiary creep onset

CLP=	16.13634
a 0=	35269.46
a 1=	-2479.36
a 2=	-2538.85
SEE=	0.555194
R^2=	0.616271



LMP-2nd order polynomial -	$\log t_R = -C_{LP} + a_0/T + a_1/T*\log S + a_2/T*(\log S)^2$

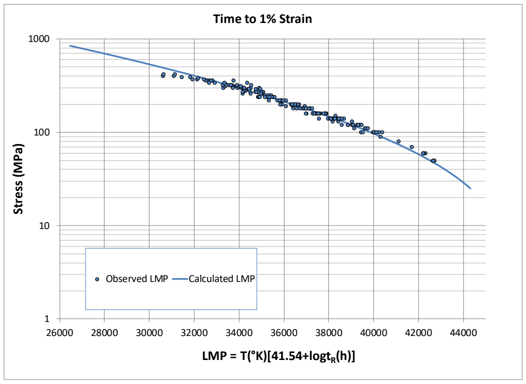
S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

C_{LP}=	17.39036
a_0 =	19839.43
a_1 =	2470.977
a_2 =	-1786.47
SEE=	0.339601
R^2	0.85

Figure R.14.4-2D. Summary of curve-fitting results for 2¼Cr-1Mo – time to 1% strain, time to initiate tertiary creep, and time to rupture

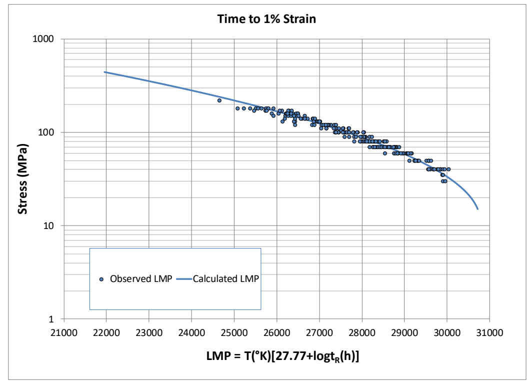
High Stress Region Data

Low Stress Region Data



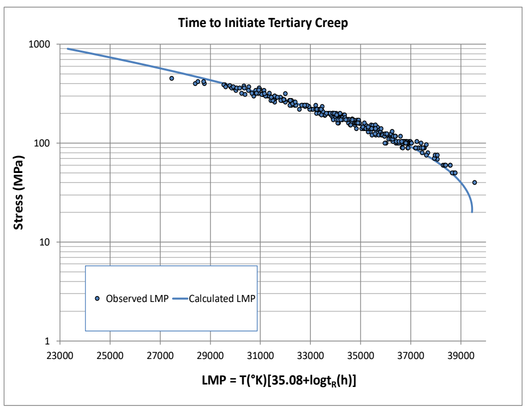
CLP=	41.54171
a0 =	41704.28
a1 =	8348.532
a2=	-4635.08
SEE=	0.44956
R^2=	0.765031

CLP=	27.77076
a0 =	26934.72
a1 =	7314.38
a2=	-3480.44
SEE=	0.247339
R^2=	0.851695



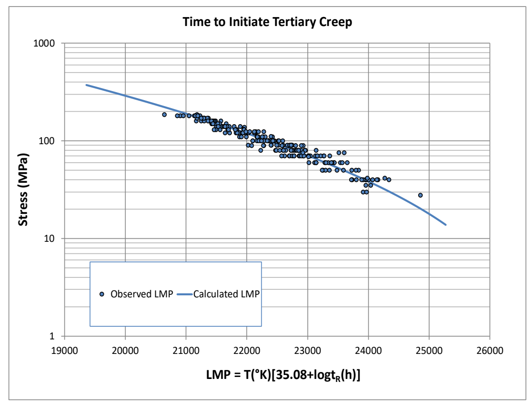
LMP-2nd order polynomial - $\log t1 = -CLP + a0/T + a1/T*\log S + a2/T\ [\log S]^2$

S is stress in MPa, T is temperature in °K and t1 is time in hours to 1% strain



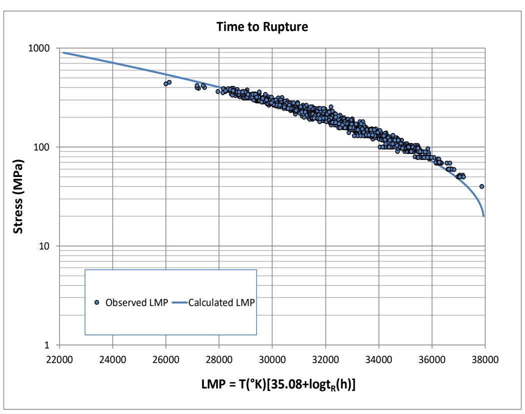
CLP=	37.17857
a 0=	28648.02
a 1=	16235.35
a 2=	-6107.21
SEE=	0.376306
R^2=	0.806272

CLP=	21.3406
a 0=	26215.61
a 1=	632.874
a 2=	-1283.52
SEE=	0.217271
R^2=	0.8404



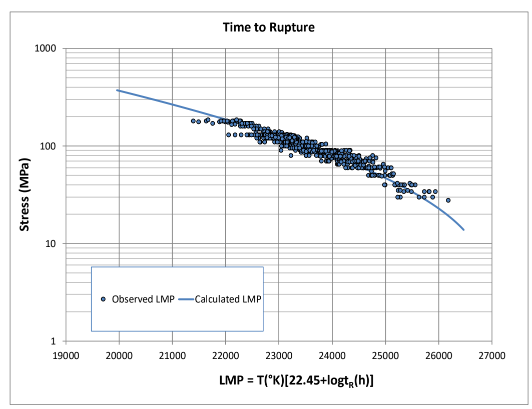
LMP-2nd order polynomial - $\log t3 = -CLP + a0/T + a1/T*\log S + a2/T\ [\log S]^2$

S is stress in MPa, T is temperature in °K and t3 is time in hours to tertiary creep onset



CLP=	35.08069
a 0=	29108.19
a 1=	13965.19
a 2=	-5523.75
SEE=	0.377826
R^2=	0.765552

CLP=	22.45217
a 0=	25841.75
a 1=	2809.952
a 2=	-1982.95
SEE=	0.258595
R^2=	0.717088



LMP-2nd order polynomial - $\log t_R = -C_{LP} + a_0/T + a_1/T*\log S + a_2/T*(\log S)^2$

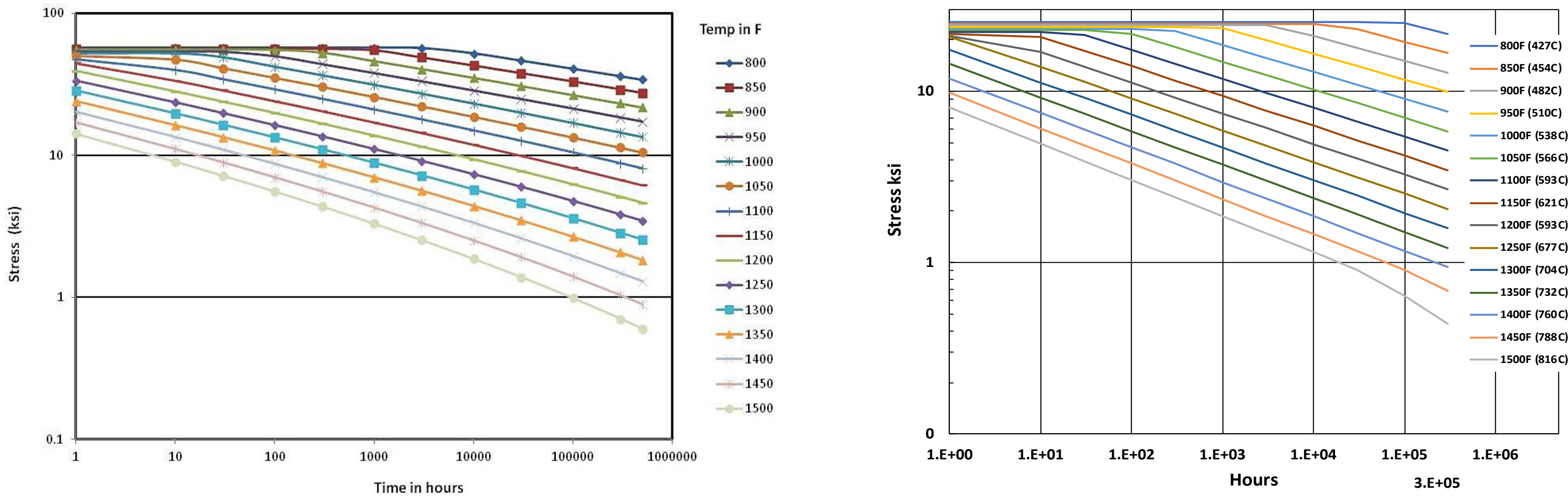
S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

Figure R.14.4-2E. Summary of curve-fitting results for 9Cr-1Mo-V – time to 1% strain, time to initiate tertiary creep, and time to rupture

Table R.14.4-3A. This Analysis for 304 SS compared with values reported in STP-NU-063

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis
800	26.0	25.2	26.0	25.2	26.0	25.2	26.0	25.2	26.0	25.2	26.0	25.2	26.0	25.2	26.0	25.2	26.0	25.2	25.8	25.1	24.2	21.7
850	25.4	24.8	25.4	24.8	25.4	24.8	25.4	24.8	25.4	24.8	25.4	24.8	25.4	24.8	25.4	24.8	24.8	23.1	22.0	19.5	18.8	16.7
900	24.9	24.2	24.9	24.2	24.9	24.2	24.9	24.2	24.9	24.2	24.9	24.2	24.7	24.2	23.5	21.2	20.4	18.0	16.9	15.1	14.3	12.8
950	24.4	23.7	24.4	23.7	24.4	23.7	24.4	23.7	24.4	23.7	23.9	23.6	22.3	19.9	18.8	16.6	15.7	14.0	12.9	11.7	10.8	9.9
1000	23.8	23.1	23.8	23.1	23.8	23.1	23.8	23.1	23.3	22.6	21.0	18.7	17.8	15.7	14.5	13.0	12.1	11.0	9.8	9.1	8.2	7.6
1050	23.3	22.7	23.3	22.7	23.3	22.7	22.6	21.6	20.3	18.1	16.8	14.9	13.8	12.4	11.2	10.2	9.3	8.5	7.5	7.0	6.2	5.9
1100	22.8	22.3	22.8	22.3	22.3	21.3	19.5	17.4	16.3	14.5	13.1	11.8	10.8	9.8	8.7	8.0	7.1	6.7	5.7	5.4	4.7	4.5
1150	22.3	21.7	22.1	20.9	19.3	17.3	15.7	14.0	12.8	11.6	10.2	9.4	8.3	7.7	6.7	6.3	5.4	5.2	4.3	4.2	3.5	3.5
1200	21.8	21.1	18.9	17.0	15.7	14.0	12.5	11.3	10.1	9.2	8.0	7.5	6.5	6.1	5.1	4.9	4.2	4.0	3.3	3.3	2.7	2.7
1250	21.2	20.6	15.6	13.9	12.5	11.3	9.9	9.1	7.9	7.4	6.3	5.9	5.0	4.8	4.0	3.9	3.2	3.2	2.5	2.5	2.0	2.1
1300	19.1	17.5	12.5	11.3	10.0	9.2	7.8	7.3	6.3	5.9	4.9	4.7	3.9	3.8	3.1	3.0	2.5	2.5	1.9	2.0	1.5	1.6
1350	16.1	14.4	10.1	9.2	8.0	7.4	6.2	5.9	4.9	4.7	3.8	3.7	3.1	3.0	2.4	2.4	1.9	1.9	1.5	1.5	1.2	1.2
1400	13.3	11.9	8.1	7.5	6.4	6.0	4.9	4.7	3.9	3.8	3.0	3.0	2.4	2.4	1.8	1.9	1.4	1.5	1.1	1.2	0.9	0.94
1450	10.9	9.8	6.5	6.1	5.1	4.9	3.9	3.8	3.1	3.0	2.4	2.4	1.8	1.9	1.4	1.5	1.1	1.2	0.9	0.91	0.7	0.69
1500	8.8	8.1	5.2	5.0	4.1	3.9	3.1	3.0	2.4	2.4	1.8	1.9	1.4	1.5	1.1	1.1	0.9	0.91	0.6	0.65	0.5	0.44

Hot Tensile Stress at 1% Strain, ASME HBB-T digitized	80% Minimum Stress to Initiate Tertiary Creep	67% Minimum Stress to Rupture
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%		
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)	



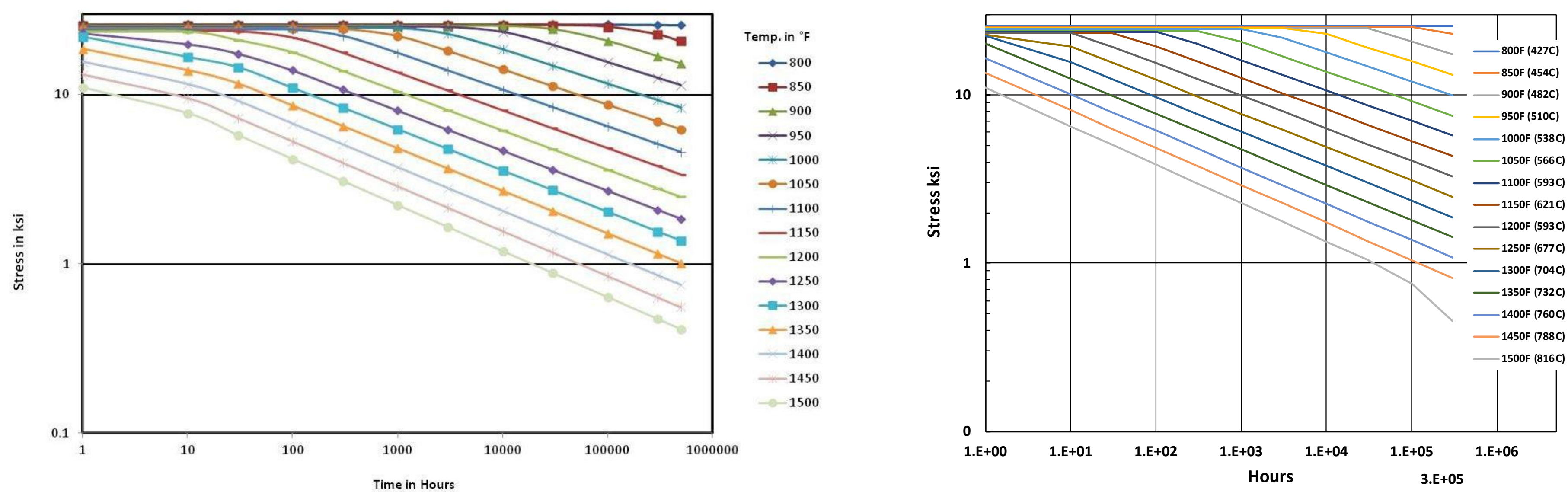
(a) (b)

Figure R.14.4-3A. Summary of S_t curves for 304 SS: (a) From STP-NU-063; and (b) This analysis

Table R.14.4-3B. This Analysis for 316 SS compared with values reported in STP-NU-063

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis	STP-NU-063	This Analysis
800	26.1	25.9	26.1	25.9	26.1	25.9	26.1	25.9	26.1	25.9	26.1	25.9	26.1	25.9	26.1	25.9	26.1	25.9	26.1	25.9	25.9	25.9
850	25.7	25.6	25.7	25.6	25.7	25.6	25.7	25.6	25.7	25.6	25.7	25.6	25.7	25.6	25.7	25.6	25.7	25.6	25.2	25.6	22.7	23.0
900	25.4	25.2	25.4	25.2	25.4	25.2	25.4	25.2	25.4	25.2	25.4	25.2	25.4	25.2	25.4	25.2	24.4	25.1	20.8	20.8	16.9	17.4
950	25.1	25.0	25.1	25.0	25.1	25.0	25.1	25.0	25.1	25.0	25.1	25.0	25.1	25.0	23.5	23.1	19.7	19.3	15.6	15.8	12.6	13.2
1000	24.8	24.6	24.8	24.6	24.8	24.6	24.8	24.6	24.8	24.6	24.8	24.6	22.9	21.9	18.6	17.8	14.9	14.8	11.7	12.1	9.3	10.0
1050	24.4	24.2	24.4	24.2	24.4	24.2	24.4	24.2	24.4	24.2	22.2	20.7	18.1	17.0	14.1	13.8	11.2	11.4	8.7	9.2	6.9	7.6
1100	24.1	23.9	24.1	23.9	24.1	23.9	24.1	23.9	22.2	20.1	17.6	16.2	13.9	13.2	10.7	10.6	8.4	8.7	6.5	7.0	5.1	5.7
1150	23.8	23.6	23.8	23.6	23.8	23.6	21.8	19.5	17.8	15.9	13.6	12.7	10.6	10.3	8.1	8.2	6.4	6.7	4.9	5.3	3.8	4.3
1200	23.5	23.3	23.5	23.3	20.9	19.5	17.7	15.5	13.8	12.5	10.5	9.9	8.1	8.0	6.1	6.3	4.8	5.1	3.6	4.1	2.8	3.3
1250	23.1	22.9	19.9	19.4	17.5	15.6	13.9	12.3	10.7	9.9	8.1	7.8	6.2	6.2	4.7	4.9	3.6	3.9	2.7	3.1	2.1	2.5
1300	22.0	22.6	16.7	15.6	14.5	12.5	11.0	9.7	8.4	7.8	6.2	6.1	4.8	4.8	3.6	3.8	2.7	3.0	2.0	2.4	1.6	1.9
1350	18.6	20.2	13.9	12.6	11.6	10.0	8.6	7.7	6.5	6.1	4.8	4.8	3.7	3.8	2.7	2.9	2.1	2.3	1.5	1.8	1.2	1.4
1400	15.7	16.7	11.6	10.1	9.2	8.0	6.8	6.1	5.1	4.8	3.7	3.7	2.8	2.9	2.1	2.3	1.6	1.8	1.1	1.4	0.9	1.1
1450	13.2	13.6	9.5	8.1	7.3	6.4	5.3	4.9	4.0	3.8	2.9	2.9	2.2	2.3	1.6	1.7	1.2	1.4	0.9	1.0	0.6	0.82
1500	11.0	11.1	7.8	6.5	5.8	5.1	4.2	3.9	3.1	3.0	2.2	2.3	1.7	1.8	1.2	1.3	0.9	1.0	0.6	0.76	0.5	0.45

Hot Tensile Stress at 1% Strain, ASME HBB-T digitized	80% Minimum Stress to Initiate Tertiary Creep	67% Minimum Stress to Rupture
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%		
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)	



(a) (b)

Figure R.14.4-3B. Summary of S_t curves for 316 SS: (a) From STP-NU-063; and (b) This analysis

Table R.14.4-3C. This Analysis for Ni-Fe-Cr (Alloy 800H) compared with values reported in STP-NU-035

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis	STP-NU-035	This Analysis
800	23.8	24.1	23.8	24.1	23.8	24.1	23.8	24.1	23.8	24.1	23.8	24.1	23.8	24.1	23.8	24.1	23.8	24.1	23.8	24.1	23.8	24.1
850	23.4	24.1	23.4	24.1	23.4	24.1	23.4	24.1	23.4	24.1	23.4	24.1	23.4	24.1	23.4	24.1	23.4	24.1	23.4	24.1	23.2	23.4
900	23.0	23.5	23.0	23.5	23.0	23.5	23.0	23.5	23.0	23.5	23.0	23.5	23.0	23.5	23.0	23.5	23.0	23.5	21.4	21.5	18.8	18.9
950	22.7	23.1	22.7	23.1	22.7	23.1	22.7	23.1	22.7	23.1	22.7	23.1	22.7	23.1	22.7	23.1	21.8	20.3	17.3	17.5	15.1	15.2
1000	22.3	22.7	22.3	22.7	22.3	22.7	22.3	22.7	22.3	22.7	22.3	22.7	22.1	22.2	18.7	19.0	16.4	16.5	14.0	14.1	12.1	12.2
1050	22.3	22.5	22.3	22.5	22.3	22.5	22.3	22.5	22.3	22.5	21.1	21.2	17.8	18.3	15.5	15.6	13.3	13.4	11.2	11.4	9.61	9.7
1100	23.3	21.9	22.3	21.9	22.3	21.9	22.3	21.9	20.6	20.7	17.4	17.5	14.9	15.0	12.6	12.7	10.7	10.8	8.98	9.1	7.61	7.6
1150	22.3	21.7	22.3	21.7	22.3	21.7	20.0	20.1	17.1	17.2	14.4	14.4	12.2	12.3	10.2	10.3	8.61	8.7	7.14	7.1	6.00	5.8
1200	22.3	21.6	22.3	21.6	19.4	20.0	16.7	16.8	14.2	14.2	11.8	11.9	9.94	10.0	8.21	8.3	6.88	6.9	5.65	5.5	4.70	4.5
1250	21.9	21.2	19.8	19.9	16.8	16.8	13.9	14.0	11.7	11.8	9.64	9.7	8.06	8.2	6.59	6.6	5.47	5.3	4.44	4.2	3.66	3.4
1300	21.4	20.6	16.7	16.8	14.0	14.1	11.5	11.6	9.62	9.7	7.85	8.0	6.50	6.5	5.27	5.2	4.33	4.1	3.47	3.3	2.83	2.6
1350	20.5	19.2	14.1	14.1	11.7	11.8	9.54	9.6	7.88	8.0	6.37	6.4	5.23	5.1	4.19	4.0	3.40	3.2	2.70	2.5	2.17	2.0
1400	16.7	16.8	11.8	11.8	9.73	9.8	7.85	8.0	6.43	6.6	5.15	5.1	4.18	4.1	3.31	3.1	2.66	2.5	2.08	1.9	1.66	1.5

Hot Tensile Stress at 1% Strain, ASME HBB-T digitized	80% Minimum Stress to Initiate Tertiary Creep	67% Minimum Stress to Rupture	1% Strain in Creep
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%			
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)		

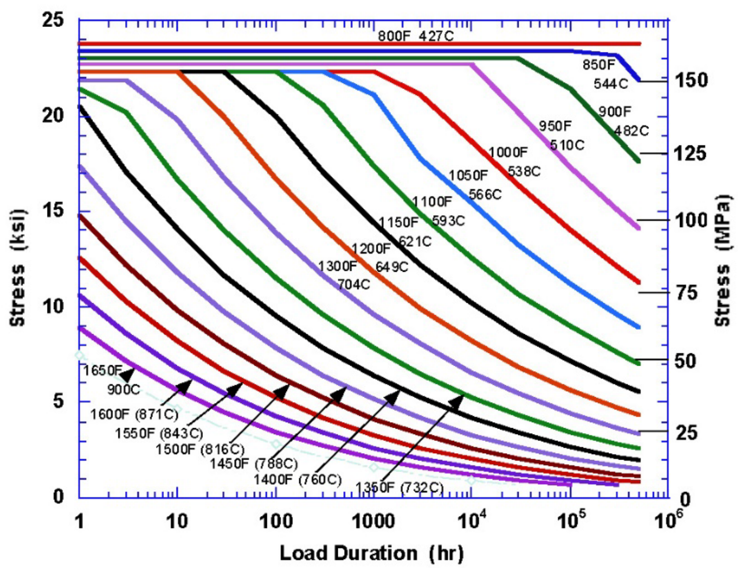
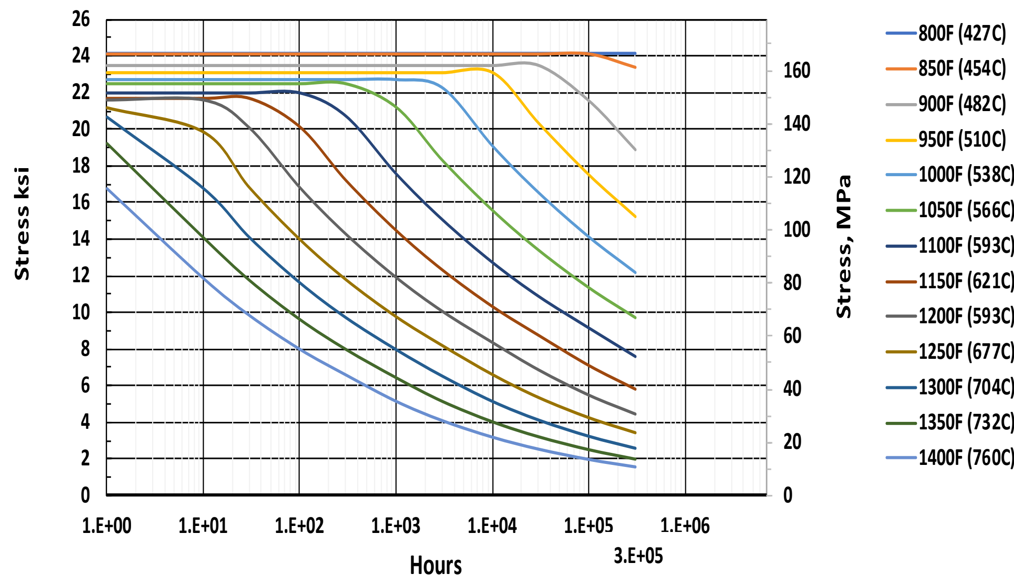


Figure 31 - S_t Versus Temperature

(a)



(b)

Figure R.14.4-3C. Summary of S_t curves for Ni-Fe-Cr (Alloy 800H): (a) From STP-NU-035; and (b) This analysis

2¼Cr-1Mo (Table R.14.4-1D, Figure R.14.4-1D):

Apparent from Table R.14.4-1D summarizing the findings in comparison with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.4D S_t values is that for the higher temperatures and extended times, the BPVC values are relatively non-conservative. It is not known when the current HBB-I-14.4D table was developed. However, as discussed as part of the report for S_o, the last time the BPVC II-D Table 1A stresses were updated was circa 1990. Also, our analysis combined data for annealed, annealed and tempered (for 1% strain and tertiary creep) and normalized and tempered material (since these heat treatments are permitted) and it is unclear as to what data were used in development of the current BPVC stresses.

9Cr-1Mo-V (Table R.14.4-1E, Figure R.14.4-1E):

Our results are in good agreement with the BPVC 2019 III-5 Table HBB-I-14.4E values. This BPVC table has been updated since the 2017 edition. A comparison of the S_t values in BPVC 2017 and 2019 III-5 Table HBB-I-14.4E is presented in Table R.14.4-4E.

Table R.14.4-4E. A comparison of the S_t values in BPVC 2017 and 2019 III-5 Table HBB-I-14.4E for 9Cr-1Mo-V

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °F	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E
700	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	46.1	47.3	44.2	-	43.3
750	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	44.0	44.9	42.1	42.3	40.0	40.1	38.1	-	37.3
800	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	42.3	42.1	40.3	39.6	38.2	37.4	36.3	35.1	34.2	33.1	32.4	-	31.6
850	42.3	42.3	42.3	42.3	42.3	42.3	42.3	41.0	39.8	38.9	37.3	36.8	35.1	34.8	32.9	32.7	30.9	30.8	28.9	28.8	27.1	27.0	-	26.2
900	39.8	39.8	39.9	38.8	38.0	37.9	35.5	35.5	33.3	33.3	31.1	31.1	29.1	29.1	27.1	27.1	25.3	25.3	23.5	23.5	21.9	21.5	-	20.1
950	37.0	37.0	34.1	34.1	31.9	31.9	29.7	29.7	27.7	27.7	25.7	25.7	23.9	23.9	22.1	22.1	20.5	20.5	18.8	18.6	17.4	16.0	-	14.8
1,000	33.5	33.5	28.5	28.5	26.6	26.6	24.5	24.5	22.7	22.7	20.9	20.9	19.3	19.3	17.7	17.7	16.3	16.3	14.9	13.8	13.7	11.6	-	10.7
1,050	28.8	28.8	23.7	23.7	21.9	21.9	20.1	20.1	18.5	18.5	16.9	16.9	15.5	15.5	14.1	14.1	12.8	12.2	11.5	9.9	10.5	8.2	-	7.4
1,100	24.6	24.6	19.5	19.5	17.9	17.9	16.3	16.3	14.9	14.9	13.4	13.4	12.2	12.2	10.9	10.6	9.9	8.7	8.7	6.9	7.8	5.5	-	5.0
1,150	20.7	20.7	15.8	15.8	14.4	14.4	12.9	12.9	11.7	11.7	10.5	10.4	9.4	9.1	8.3	7.6	6.8	6.1	5.5	4.6	4.5	3.4	-	2.9
1,200	17.1	17.1	12.7	12.7	11.4	11.4	10.1	10.1	9.1	8.9	7.9	7.6	7.0	6.6	5.3	5.2	4.3	3.9	3.3	2.7	2.5	1.8	-	1.5

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °C	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E	BPVC 2017 III-5 Table HBB-I-14.4E	BPVC 2019 III-5 Table HBB-I-14.4E
375	325	325	325	325	325	325	325	325	325	325	325	325	325	325	325	325	325	325	325	312	325	299	-	293
400	317	317	317	317	317	317	317	317	317	317	317	317	316	316	316	302	307	289	290	274	275	261	-	255
425	307	307	307	307	307	307	307	307	307	307	307	294	292	281	276	266	262	253	246	238	232	226	-	220
450	294	294	294	294	294	294	294	289	279	275	264	259	249	246	234	231	220	218	206	204	193	192	-	186
475	275	279	275	275	271	271	256	255	241	241	225	225	211	211	197	197	184	184	171	171	160	159	-	149
500	262	262	249	249	235	235	219	219	205	205	191	191	178	178	165	165	153	153	141	141	131	123	-	115
525	242	242	214	214	200	200	185	185	172	172	163	160	148	148	136	136	126	126	115	109	106	93	-	86
550	217	217	182	182	170	168	156	156	144	144	132	132	119	119	111	111	102	100	93	83	85	69	-	63
575	189	189	154	154	142	142	130	130	119	119	108	108	99	99	90	89	81	75	73	61	66	50	-	45
600	164	164	126	126	115	115	107	107	97	97	86	86	79	78	71	68	63	55	54	44	48	34	-	31
625	139	139	106	106	96	96	86	86	78	78	70	69	62	60	54	50	44	40	36	30	30	22	-	18
650	117	117	87	87	78	78	69	69	62	61	54	52	47	45	36	35	29	27	22	18	17	12	-	10

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

Comparison of Table HBB-I-14.5 in BPVC 2017 and BPVC 2019 showed no difference. Therefore, the analysis results apply to both editions.

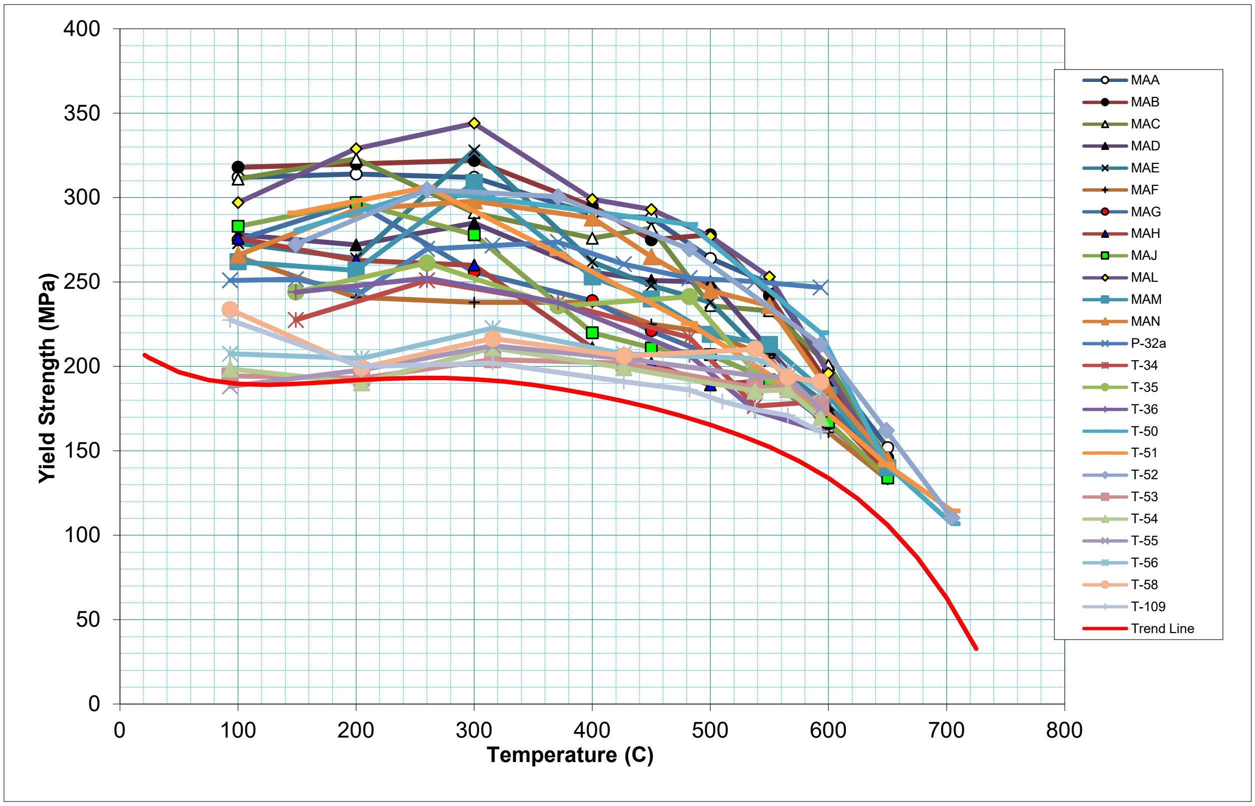
Observations Indicating Need for Review Consideration

304 SS

For 304 SS, our analysis for S_Y indicates that the trend curve shape is such that the Table HBB-I-14.5 values appear relatively non-conservative at temperature ≥ 1400°F (≥ 750°C), the relative non-conservatism increasing with temperature, and significant (> 10%) at the highest temperatures (1450 and 1500°F, and 775 and 800°C). The tabulation in Section 4 Table HBB-I-14.5 provides details on the specific calculated values compared with the BPVC Table HBB-I-14.5 values. A review of the tabulation, specifically the trend curve shape at and near the highest use temperature is recommended. A similar trend is also observed in S_u behavior for 304 SS in Table HBB-3225-1, further supporting the need for a review. The analysis of Table HBB-3225-1 for S_u is provided in Appendix HBB-3225-1.

2¼Cr-1Mo

For 2¼Cr-1Mo, BPVC 2017 (and 2019) II-D and III-5 do not distinguish between annealed material and normalized & tempered (N&T) material. Our analysis, as presented in Figure R. 14.5, shows distinctly different trend curves for material with the two heat treatments, and such difference was also noted in the 1971 ASTM Data Series DS 6S2 (Ref. Smith 1971), with the N&T material having lower strength. The use of data for both heat treatments is a compromise, but producing potentially less conservative strength parameters for the N&T material. Our analysis results indicate the differences in yield strength vary from being insignificant to about 12.5%. We do not have a specific recommendation regarding treatment of this alloy, but the findings beg the question as to whether separate classes of material merit definition for Code use.



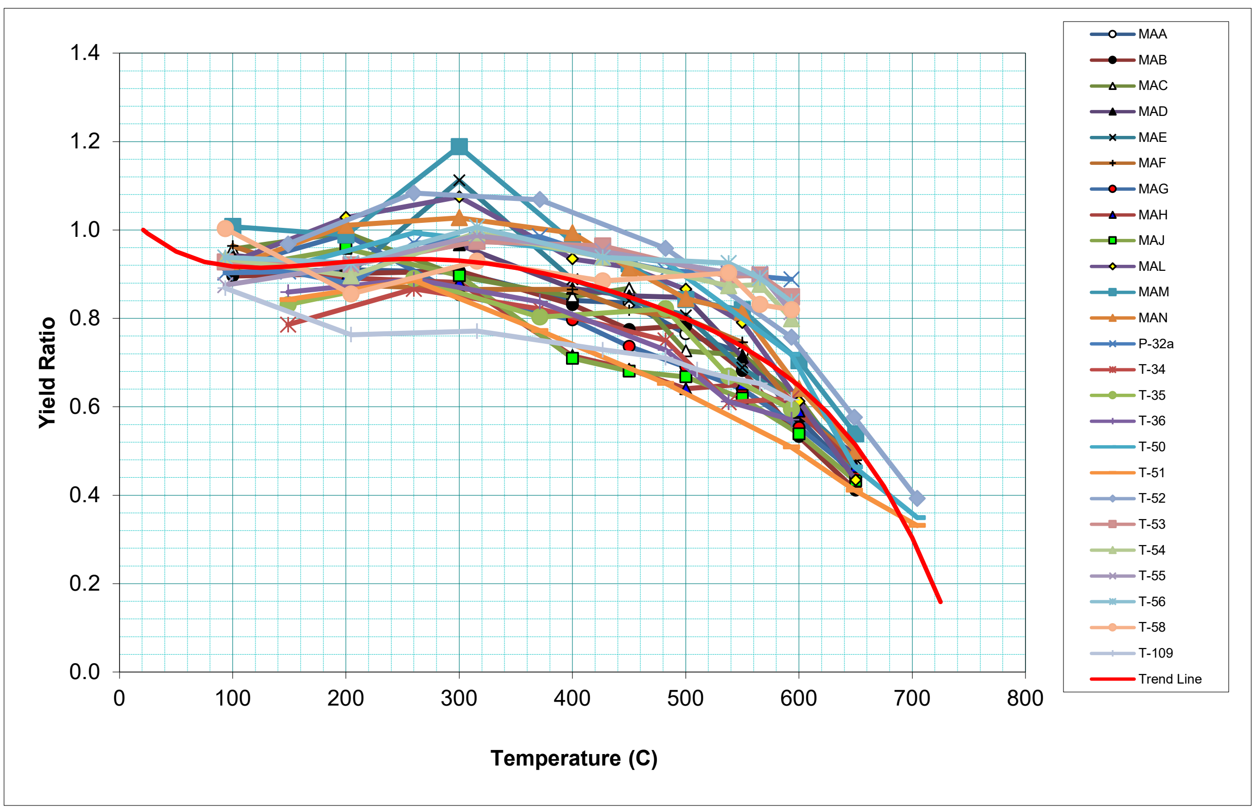
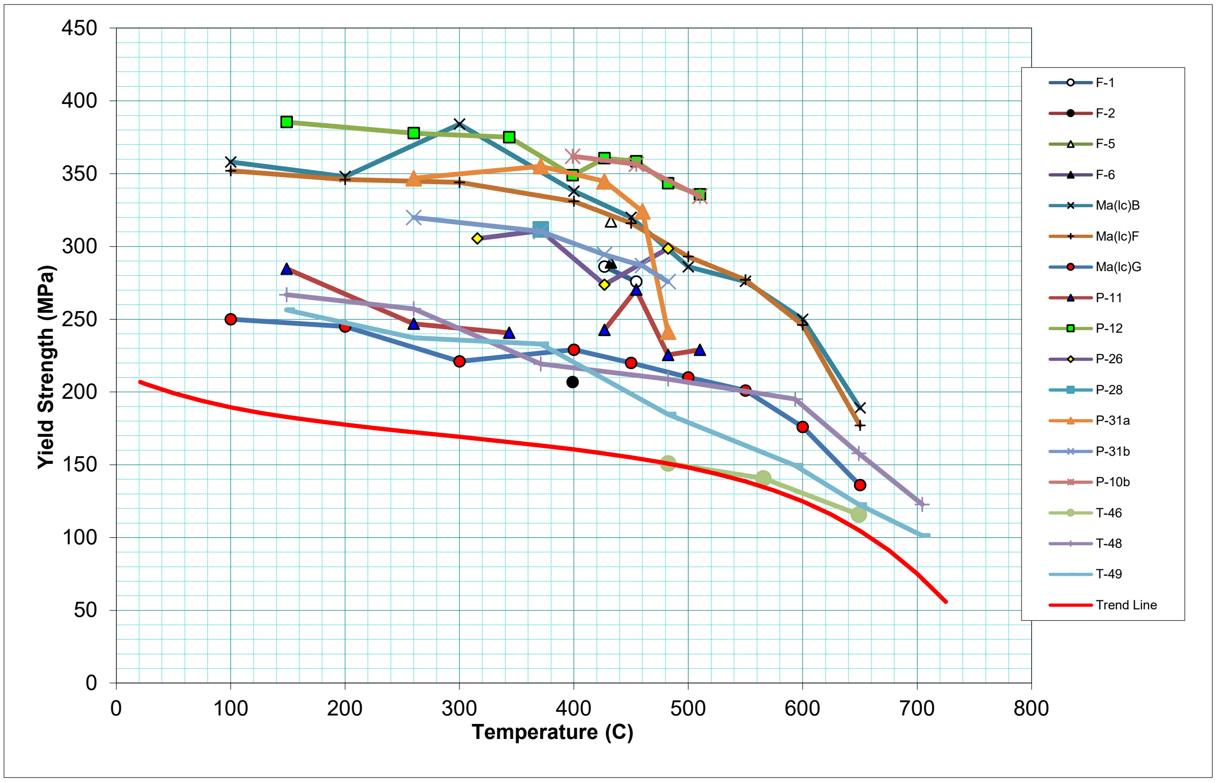


Figure R. 14.5a. Yield strength trend curves for annealed 2¼Cr-1Mo steel



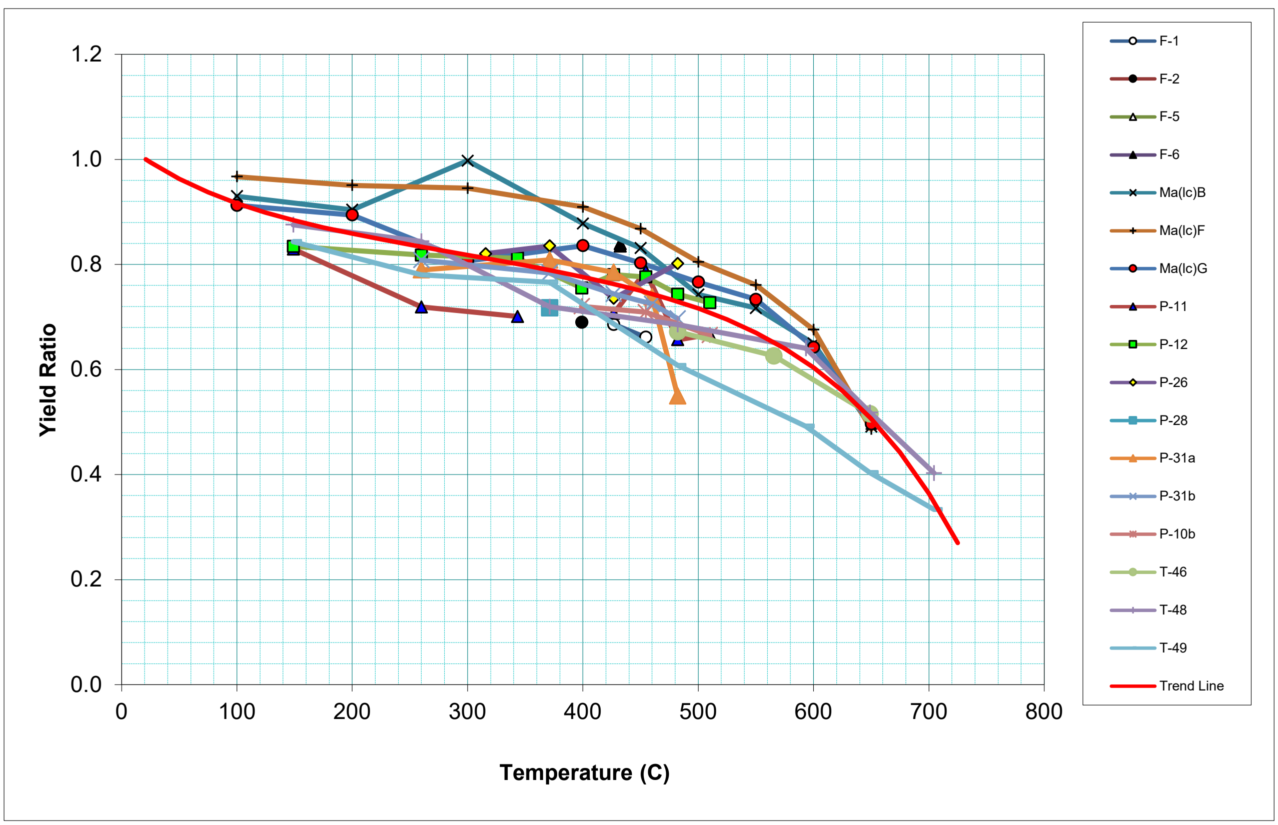


Figure R. 14.5b. Yield strength trend curves for normalized and tempered 2¼Cr-1Mo steel

Analysis and Results

An analysis was conducted using the ASME time-independent software, version 2015-DEC-27 that is separately verified for accuracy in the regression of the data for the trend curve polynomial, as discussed in Appendix VTIS. The results are compared with the BPVC tabulations as shown in Table R.14.5, which suggests acceptable differences with the exceptions and conditions discussed in corresponding part of Section 3.

The references from which the tensile data analyzed are obtained are provided by their ID below for convenient review, with details listed in Section 6 References.

<u>For 304 SS</u>

21 heats/lots and 218 data points

- (Ref. NRIM 1986b)
- (Ref. NRIM 1995)
- (Ref. Simmons 1965)

<u>For 316 SS</u>

26 heats/lots, 253 data points

- (Ref. NIMS 2015)
- (Ref. NRIM 1979)
- (Ref. NRIM 1988)
- (Ref. NRIM 2000)
- (Ref. Sikka 1980)
- (Ref. Simmons 1965)

<u>For 800H (N08810)</u>

28 heats/lots, 321 data points

- Data compiled by ORNL from various published and unpublished sources.

<u>For 2¼Cr-1Mo</u>

42 heats/lots, 326 data points- annealed and N&T material combined

- (Ref. NRIM 1986a)
- (Ref. NRIM 1997)
- (Ref. Smith 1971)

<u>For 9Cr-1Mo-V</u>

27 heats/lots, 299 data points

- (Ref. Caminada 2015)
- (Ref. DiStefano 1986)
- (Ref. NIMS 2014)

- (Ref. Ruggles 2015)
- (Ref. Sikka 1982b)
- (Ref. Sikka 1986a)
- (Ref. Sikka 1986b)

<u>For Alloy 718</u>

16 heats/lots, 171 data points

- (Ref. Korth 1978)
- (Ref. Smolik 1978)
- (Ref. Mills 1979)
- (Ref. Steichen 1976)

Table R.14.5. Comparison between S_Y values of This Analysis and BPVC Table HBB-I-14.5.

ksi	°F	304SS		316SS		Ni-Fe-Cr UNS N08810		2¼Cr-1Mo		9Cr-1Mo-1V		Ni-Cr-Fe-Mo-Cb UNS N07718	
		30-75 & 30-70ksi (YS-UTS)		30-75 & 30-70ksi (YS-UTS)						60-85 and 60-90ksi (YS-UTS)			
		ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis
ASME 2017 ASME 2019 II-D Table Y-1	RT	30.0	30.0	30.0	30.0	25.0	25.0	30.0	30.0	60.0	60.0	150.0	150.0
	100	30.0	30.0	30.0	30.0	25.0	25.0	30.0	30.0	60.0	60.0	148.4	150.0
	200	25.0	26.8	25.9	26.2	23.0	23.0	28.0	27.6	55.9	57.1	143.9	139.9
	300	22.4	24.4	23.4	24.0	21.7	21.3	27.2	27.3	54.8	54.9	140.7	138.4
	400	20.7	22.4	21.4	22.3	20.4	19.9	26.9	27.3	54.7	53.4	138.3	138.4
	500	19.4	20.6	20.0	21.0	19.3	18.7	26.9	27.2	54.7	52.6	136.7	138.2
	600	18.4	19.3	18.9	20.0	18.3	17.8	26.9	26.6	54.5	52.2	135.4	136.9
	700	17.6	18.3	18.2	19.2	17.4	17.2	26.9	25.8	53.2	51.6	134.3	134.9
	750	17.2	17.9	17.9	18.9	17.1	16.9	26.8	25.3	52.0	51.0	133.7	133.7
	800	16.9	17.7	17.7	18.5	16.7	16.7	26.6	24.7	50.4	50.1	133.1	132.5
	850	16.5	17.4	17.5	18.2	16.4	16.6	26.2	24.1	48.5	48.8	132.4	131.4
	900	16.2	17.2	17.3	17.9	16.1	16.5	25.6	23.5	46.1	47.1	131.5	130.5
	950	15.9	17.0	17.1	17.7	15.8	16.3	24.8	22.8	43.4	44.8	130.5	129.6
	1000	15.5	16.8	17.0	17.4	15.5	16.2	23.7	21.9	40.2	42.0	129.4	128.8
ASME 2017 ASME 2019 III-Div. 5 Table HBB-I-14.5	1050	15.2	16.6	16.8	17.1	15.5	16.1	22.4	20.9	36.6	38.7	128.0	128.0
	1100	14.9	16.3	16.6	16.7	15.5	15.9	20.7	19.6	32.7	34.9	...	
	1150	14.5	15.8	16.3	16.4	15.5	15.7	18.6	17.9	28.6	30.6	...	
	1200	14.1	15.3	16.0	16.0	15.5	15.4	16.1	15.7	24.2	26.0	...	
	1250	13.6	14.6	15.5	15.6	15.2	15.1	...		...		...	
	1300	13.1	13.6	14.9	15.2	14.8	14.6	...		...		...	
	1350	12.4	12.4	14.2	14.7	14.2	14.1	...		...		...	
	1400	11.6	10.8	13.3	14.1	13.6	13.5	...		...		...	
	1450	10.6	8.9	12.3	13.5	12.9	12.9	...		...		...	
	1500	9.3	6.5	10.9	12.8	12.2	12.1	...		...		...	
	1550	...		...		11.3	11.3	...		...		...	
	1600	...		...		10.3	10.3	...		...		...	
	1650	...		...		9.3	9.3	...		...		...	

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%	
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)

Table continues to next page

MPa	°C	304SS		316SS		Ni-Fe-Cr UNS N08810		2¼Cr-1Mo		9Cr-1Mo-1V		Ni-Cr-Fe-Mo-Cb UNS N07718	
		30-75 & 30-70ksi (YS-UTS)		30-75 & 30-70ksi (YS-UTS)						60-85 & 60-90ksi (YS-UTS)			
		ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis
ASME 2017 ASME 2019 II-D Table Y-1	RT	207	207	207	207	172	172	207	207	414	414	1034	1034
	50	207	207	207	207	164	172	207	207	414	414	1016	1013
	100	170	183	176	179	157	157	192	190	384	392	989	962
	150	154	168	161	165	149	147	187	188	378	378	970	954
	200	144	155	148	155	141	138	185	188	377	369	955	954
	250	135	144	139	147	134	130	185	188	377	363	945	953
	300	129	135	132	140	128	124	185	185	377	361	937	947
	350	123	128	127	135	123	120	185	180	371	358	929	936
	375	121	126	125	132	120	118	185	177	366	355	925	929
	400	118	124	123	130	118	117	185	174	358	352	922	922
	425	117	122	122	128	115	115	184	171	348	346	918	914
	450	114	120	121	126	113	115	181	167	337	338	914	907
	475	112	119	120	124	112	114	178	163	322	328	909	901
	500	110	118	118	122	110	113	173	159	306	315	902	896
	525	108	117	117	121	108	112	167	154	288	299	896	891
ASME 2017 ASME 2019 III-Div. 5 Table HBB-I-14.5	550	106	115	116	119	108	111	160	148	269	280	888	886
	575	104	114	115	117	108	110	151	141	243	258	883 [Note (1)]	880
	600	102	112	114	115	108	109	139	133	218	234		
	625	100	109	112	113	108	108	126	122	193	207		
	650	97	105	110	111	107	106	110	108	165	178		
	675	94	101	107	108	105	104	...		...			
	700	91	95	103	105	102	101	...		...			
	725	87	88	99	102	99.1	98.4	...		...			
	750	82	79	94	99	95.6	95.0	...					
	775	76	68	88	95	91.5	91.0	...					
	800	69 [Note (2)]	55	81 [Note (3)]	91	86.9	86.5	...					
	825	...		...		81.8	81.5	...					
	850	...		...		76.3	76.1	...					
	875	...		...		70.3	70.3	...					
	900	...		...		64.0	64.1	...					

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%

Non-conservative relative to this analysis - Difference, δ > 10% (Used rounding for characterization of δ)

NOTES:	This Analysis	
(1) At 566°C the yield strength, Sy, is 883 MPa for UNS N07718.	883	MPa
(2) At 816°C the yield strength, Sy, is 64 MPa for 304 SS.	45	MPa
(3) At 816°C the yield strength, Sy, is 75 MPa for 316 SS.	88	MPa

Figures and Tables HBB-I-14.6A ~ F, Minimum Stress-to-Rupture

Observations and the Need for Review Consideration

Types 304 and 316SS

For both alloys, the S_r values in BPVC 2017 (and 2019) III-5 Tables HBB-I-14.6A and 14.6B are non-conservative relative to our analysis in the higher temperature range. Both tables and the corresponding figures merit further review, particularly given that our analysis results are in good agreement with the reported analysis results on a relatively recent effort to “Correct and Extend Allowable Stress Values for 304 and 316 Stainless Steel,” ASME STP-NU-063 (Ref. Sengupta 2013). The results of ASME STP-NU-063 have not been incorporated into BPVC III-5. Such incorporation would largely eliminate the discrepancy between our results and the S_t values in Table HBB-I-14.6A and 6B.

800H

The S_r values in Table HBB-I-14.6C appear marginally (by slightly > 10%) non-conservative at the highest temperatures and longest durations, but the table is, overall, judged to be acceptable.

2¼Cr-1Mo

The S_r values in Table HBB-I-14.6D are non-conservative relative to our analysis for temperatures ≥ 525°C (≥ 1000°F) and extended times. It is not known when the values were last reviewed, but the BPVC II-D Table 1A stresses were last reviewed and updated circa 1990. We recommend further review of Table HBB-I-14.6D and Figure HBB-I-14.6D.

9Cr-1Mo-V

The BPVC 2017 III-5 Figure and Table HBB-I-14.6F have been updated in the BPVC 2019 edition. A further review of the 2019 edition figure and table is neither needed nor recommended since there is no observed non-conservatism relative to our analysis results. The 2017 edition figure and table, on the other hand, is seen to be non-conservative relative to our analysis and would be recommended for further review. However, since the 2019 edition figure and table are found to be acceptable, a review of the 2017 edition figure and table is moot.

Comparison of BPVC III-5 S_r Values and This Analysis Results

The figures and tables resulting from our analysis are first reported below in comparison with the BPVC III-5 S_r values, followed by key details on the analysis method, data used, and summary of results.

Figure R.14.6-1A is the resulting graphic, shown alongside the BPVC 2017 (and 2019) III-5 Figure HBB-I-14.6A for 304 SS. The corresponding Table R.14.6-1A provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6A S_r values.

Figure R.14.6-1B is the resulting graphic, shown alongside the BPVC 2017 (and 2019) III-5 Figure HBB-I-14.6B for 316 SS. The corresponding Table R.14.6-1B provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6A S_r values.

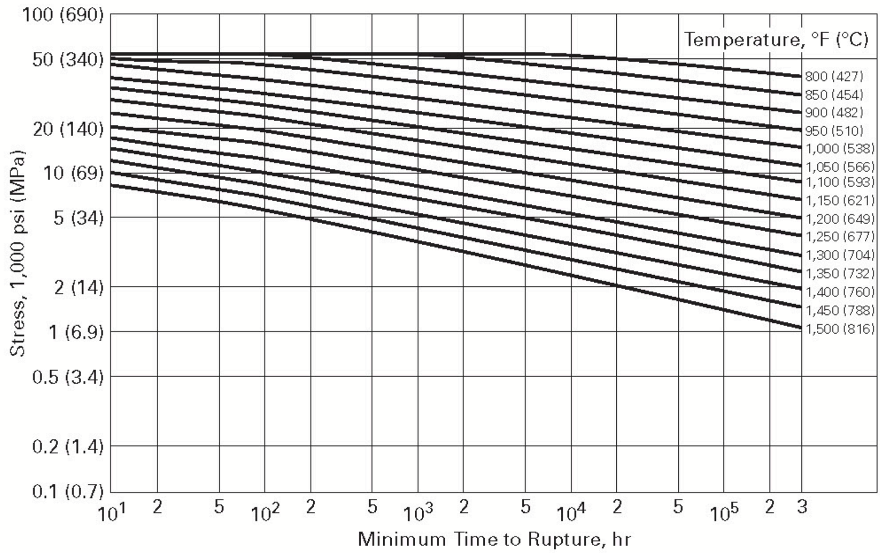
Figure R.14.6-1C is the resulting graphic, shown alongside the BPVC 2017 (and 2019) III-5 Figure HBB-I-14.6C for Ni-Fe-Cr (Alloy 800H). The corresponding Table R.14.6-1C provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6C S_r values.

Figure R.14.6-1D is the resulting graphic, shown alongside the BPVC 2017 (and 2019) III-5 Figure HBB-I-14.6D for 2¼Cr-1Mo. The corresponding Table R.14.6-1D provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6A S_r values.

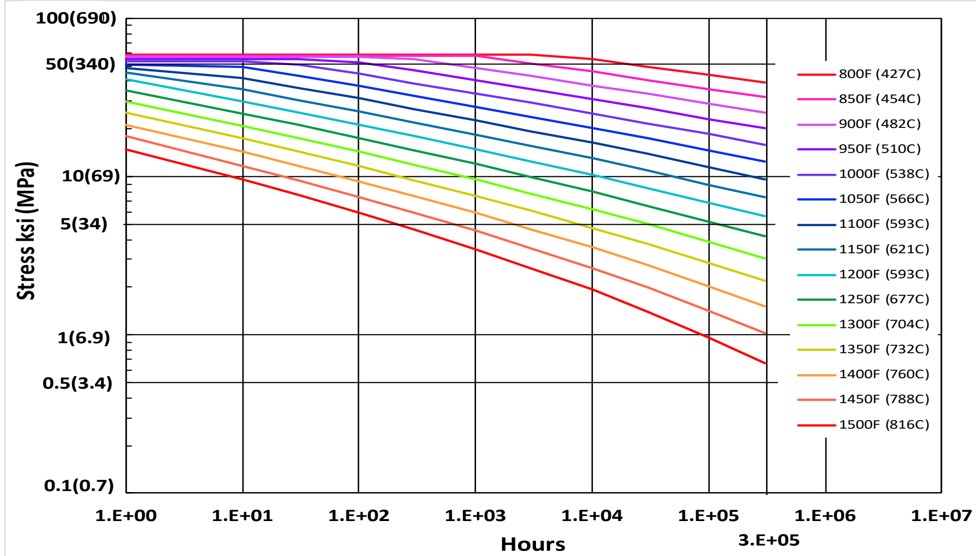
Figure R.14.6-1E is the resulting graphic, shown alongside the BPVC 2017 (and 2019) III-5 Figure HBB-I-14.6E for Alloy 718. The corresponding Table R.14.6-1E provides our analysis results compared with the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6E S_r values.

Figure R.14.6-1F is the resulting graphic, shown alongside the BPVC 2017 III-5 Figure HBB-I-14.6F for 9Cr-1Mo-V. The corresponding Table R.14.6-1F provides our analysis results compared with the BPVC 2017 III-5 Table HBB-I-14.6F S_r values.

Figure R.14.6-1F-2019 is the resulting graphic, shown alongside the BPVC 2019 III-5 Figure HBB-I-14.6F for 9Cr-1Mo-V. The corresponding Table R.14.6-1F-2019 provides our analysis results compared with the BPVC 2019 III-5 Table HBB-I-14.6F S_r values.



ASME 2017 III-5 (and 2019) III-5



This Analysis

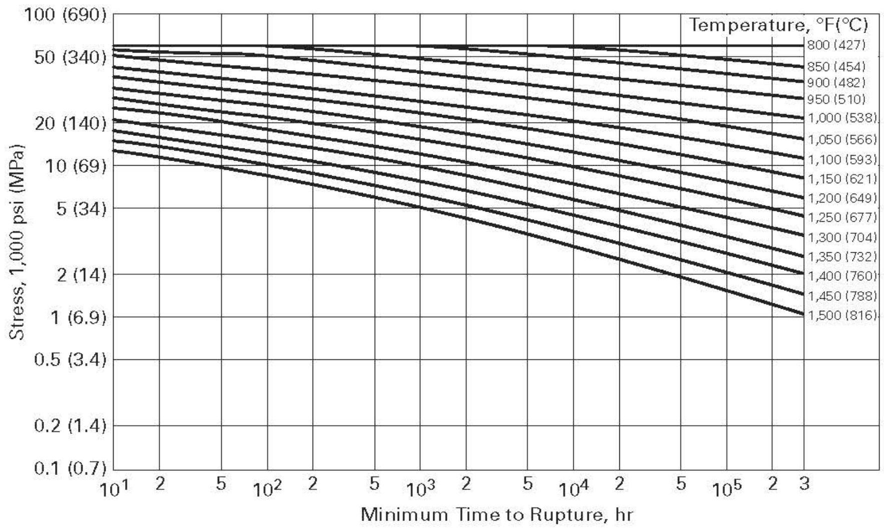
Figure R.14.6-1A. Summary of S_r curves for 304 SS

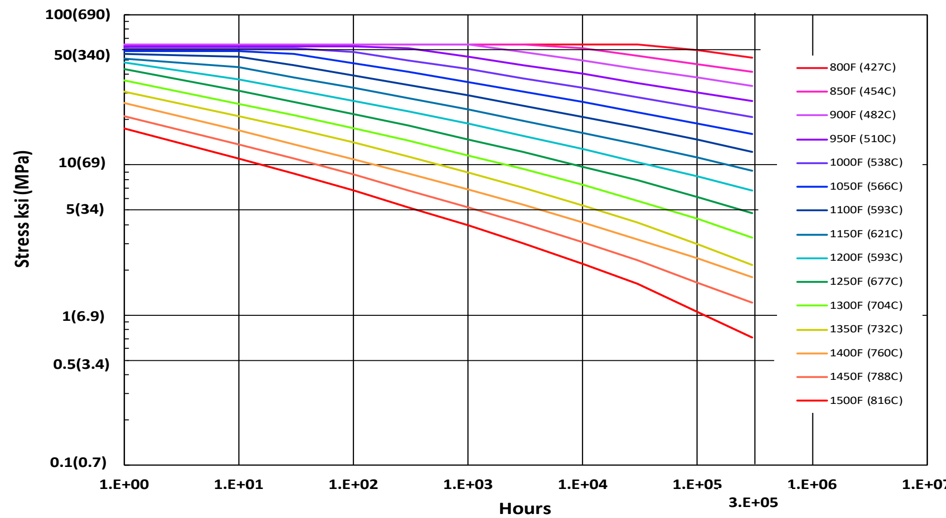
Table R.14.6-1A. This Analysis for 304 SS S_r (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.6A

ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis
800	57	58.8	57	58.8	57	58.8	57	58.8	57	58.8	57	58.8	57	58.8	57	55.5	51	49.7	44.3	44.0	39	39.2
850	56.5	58.4	56.5	58.4	56.5	58.4	56.5	58.4	56.5	58.4	56.5	58.4	50.2	52.2	45.4	45.9	40	40.8	34.7	35.8	30.5	31.6
900	55.5	57.3	55.5	57.3	55.5	57.3	55.5	57.3	51.5	55.7	46.9	48.9	41.2	43.3	36.1	37.8	31.5	33.3	27.2	28.9	24	25.4
950	54.2	55.7	54.2	55.7	51	55.7	48.1	52.9	43	46.7	38.0	40.6	33.5	35.7	28.8	30.9	24.9	27.0	21.2	23.2	18.3	20.2
1000	52.5	53.8	50	53.8	44.5	51.4	39.8	44.5	35	39.0	30.9	33.6	26.5	29.3	22.9	25.1	19.7	21.8	16.6	18.5	14.9	16.0
1050	50	51.3	41.9	49.7	37	43.4	32.9	37.3	28.9	32.4	25.0	27.7	21.6	23.9	18.2	20.3	15.5	17.4	13.0	14.7	11.0	12.5
1100	45	48.5	35.2	42.1	31	36.5	27.2	31.1	23.9	26.8	20.3	22.7	17.3	19.4	14.5	16.3	12.3	13.8	10.2	11.5	8.6	9.7
1150	38	45.3	29.5	35.6	26	30.6	22.5	25.9	19.3	22.1	16.5	18.5	13.9	15.7	11.6	13.0	9.6	10.9	8.0	8.9	6.6	7.4
1200	32	41.4	24.7	30.0	21.5	25.5	18.6	21.4	15.9	18.1	13.4	15.0	11.1	12.5	9.2	10.3	7.6	8.5	6.2	6.9	5.0	5.6
1250	27	35.3	20.7	25.1	17.9	21.2	15.4	17.5	13	14.7	10.8	12.0	8.9	9.9	7.3	8.0	6.0	6.6	4.9	5.2	4.0	4.2
1300	23	30.0	17.4	20.9	15	17.5	12.7	14.3	10.5	11.9	8.8	9.6	7.2	7.8	5.8	6.2	4.8	5.0	3.8	3.9	3.1	3.1
1350	19.5	25.4	14.6	17.4	12.6	14.4	10.6	11.6	8.8	9.5	7.2	7.6	5.8	6.1	4.6	4.7	3.8	3.7	3.0	2.8	2.4	2.2
1400	16.5	21.4	12.1	14.3	10.3	11.7	8.8	9.4	7.2	7.5	5.8	5.9	4.7	4.7	3.7	3.6	3.0	2.8	2.3	2.0	1.9	1.5
1450	14.0	18.0	10.2	11.8	8.8	9.5	7.3	7.5	5.8	5.9	4.6	4.6	3.8	3.5	2.9	2.6	2.3	2.0	1.8	1.4	1.4	1.0
1500	12.0	15.0	8.6	9.6	7.2	7.7	6.0	5.9	4.9	4.6	3.8	3.5	3.0	2.6	2.4	1.9	1.8	1.4	1.4	1.0	1.1	0.7

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6A	This Analysis
425	393	425	393	405	393	405	393	405	393	405	393	405	393	405	393	387	354	347	308	307	272	274
450	390	450	390	450	390	450	390	450	390	450	390	450	353	370	325	326	287	290	249	255	219	226
475	385	475	385	397	385	397	385	397	364	397	340	353	300	313	265	274	232	242	201	211	176	185
500	377	500	377	388	363	388	350	388	317	343	284	300	250	264	217	229	188	201	161	174	140	151
525	368	525	358	377	328	377	301	333	267	292	236	253	205	222	177	191	153	166	129	142	114	123
550	355	550	321	364	285	329	254	284	223	248	195	213	168	185	144	158	124	136	104	115	91	99
575	333	575	274	324	241	282	214	242	188	210	161	179	139	154	113	130	100	111	83	93	59	79
600	298	600	233	279	205	241	180	205	157	177	134	149	113	127	95	107	80	90	66	75	56	63
625	256	625	198	240	175	206	151	174	130	148	111	124	93	105	78	87	64	73	53	59	44	49
650	220	283	169	205	147	175	127	146	110	124	92	102	77	86	63	70	52	58	43	47	34	38
675	189	246	145	175	125	148	108	122	91	103	75	84	62	70	51	56	42	46	35	36	28	29
700	162	212	123	149	106	125	91	102	75	85	63	68	52	56	41	45	34	36	27	28	22	22
725	140	183	106	126	91	104	77	85	64	69	53	55	43	45	34	35	28	28	22	21	18	16
750	121	157	89	106	77	87	67	70	54	57	44	45	35	35	28	27	23	21	18	16	14	12
775	105	134	76	89	66	72	55	57	45	46	36	35	29	28	23	21	18	16	14	12	11	9
800	91	115	65	74	56	60	46	47	37	37	29	28	24	22	19	16	14	12	10	8.3	9	5.9

Tensile Strength (U) for 30-70ksi (YS-UTS) Material	
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = $5 < \delta \le 10\%$	
Non-conservative relative to this analysis - Difference, $\delta > 10\%$	(Used rounding for characterization of δ)





ASME 2017 III-5 (and 2019) III-5

This Analysis

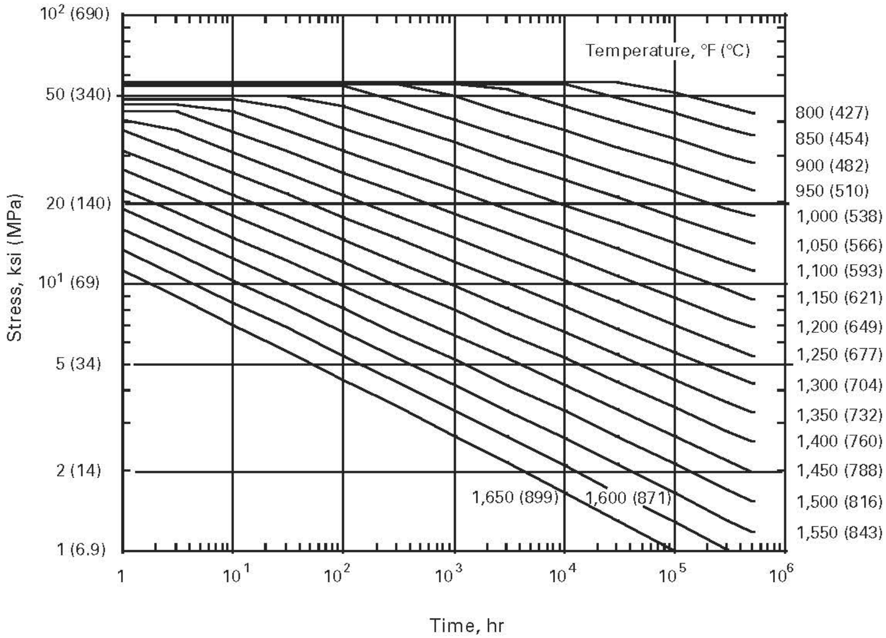
Figure R.14.6-1B. Summary of S_r curves for 316 SS

Table R.14.6-1B. This Analysis for 316 SS S_r (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.6B

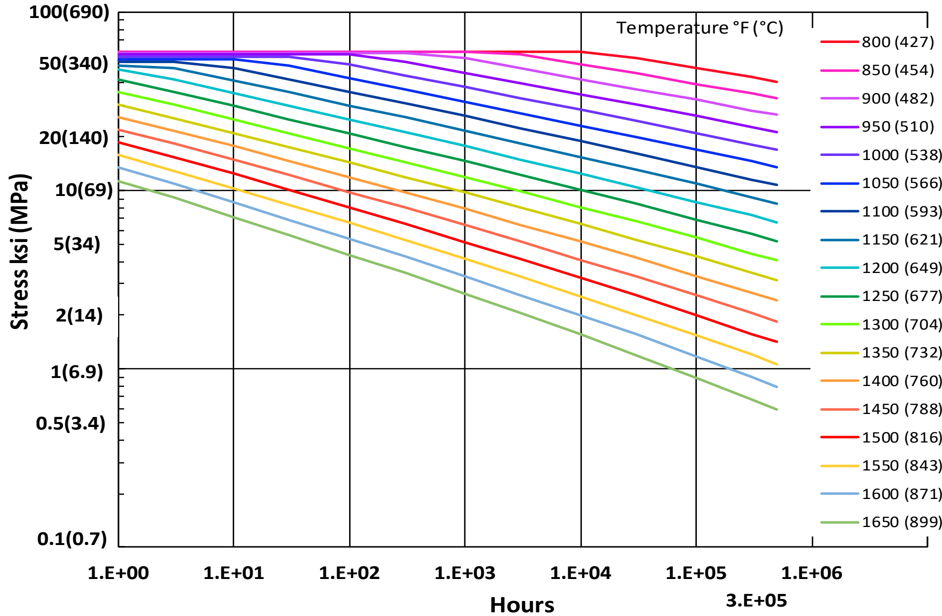
ksi hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis
800	64.5	63.6	64.5	63.6	64.5	63.6	64.5	63.6	64.5	63.6	64.5	63.6	64.5	63.6	64.5	63.6	64.5	63.6	64.5	58.0	64.5	52.0
850	63.3	63.6	63.3	63.6	63.3	63.6	63.3	63.6	63.3	63.6	63.3	63.6	63.3	63.6	63.3	59.9	60	53.5	56	47.2	52	41.9
900	62.2	63.5	62.2	63.5	62.2	63.5	62.2	63.5	62.1	63.5	62	63.1	58	56.1	54.1	49.3	48	43.6	42.6	38.1	38	33.5
950	60	61.9	60	61.9	60	61.9	60	61.9	56	59.9	51.6	52.4	46.5	46.3	42.6	40.2	37.5	35.3	32.4	30.5	28.3	26.6
1000	58.5	59.9	58.5	59.9	55	59.9	51.7	56.8	47	50.0	42.1	43.3	37.5	37.9	33.6	32.6	28.8	28.3	24.6	24.2	21	20.8
1050	56	57.5	52.9	57.5	47.5	54.9	43.4	47.5	38.2	41.4	34.4	35.5	30.2	30.8	26.4	26.2	22.3	22.5	18.8	19.0	16	16.1
1100	53.5	54.6	45.1	52.9	40	46.1	36.4	39.5	32.2	34.1	28.1	29.0	24.2	24.8	20.8	20.9	17.3	17.7	14.3	14.7	11.7	12.3
1150	46.5	51.4	38.4	44.5	34	38.5	30.5	32.6	26.6	27.9	23.0	23.4	19.5	19.8	16.4	16.4	13.4	13.7	10.9	11.2	8.8	9.2
1200	40	47.9	32.7	37.3	29	31.9	25.6	26.7	22	22.6	18.8	18.7	15.6	15.7	12.9	12.8	10.3	10.5	8.3	8.4	6.7	6.7
1250	35	43.4	27.8	31.1	24.3	26.3	21.4	21.8	18.1	18.2	15.4	14.8	12.7	12.2	10.2	9.8	8.1	7.9	6.3	6.1	4.9	4.8
1300	30	36.7	23.7	25.7	20.8	21.5	18.0	17.6	15	14.5	12.5	11.6	10.0	9.4	8.0	7.3	6.2	5.8	4.8	4.4	3.7	3.3
1350	26	30.8	20.0	21.1	17.5	17.5	15.0	14.0	12.7	11.4	10.4	8.9	8.2	7.1	6.4	5.4	4.9	4.1	3.6	3.0	2.7	2.2
1400	22.5	25.8	17.1	16.9	14.8	13.8	12.4	10.9	10.2	8.8	8.4	6.8	6.6	5.4	5.0	4.1	3.8	3.2	2.8	2.4	2.1	1.8
1450	19.5	21.3	14.6	13.7	12.6	11.0	10.5	8.6	8.6	6.8	6.8	5.2	5.2	4.1	3.9	3.1	2.9	2.3	2.1	1.7	1.5	1.2
1500	17	17.5	12.5	11.0	10.6	8.7	8.8	6.7	7.2	5.2	5.6	4.0	4.2	3.0	3.1	2.2	2.3	1.6	1.6	1.1	1.2	0.7

MPa hours	1		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6B	This Analysis
425	445	439	445	439	445	439	445	439	445	439	445	439	445	439	445	439	445	439	445	404	445	363
450	437	439	437	439	437	439	437	439	437	439	437	439	437	439	437	426	419	381	395	336	372	299
475	431	439	431	439	431	439	431	439	430	439	429	439	409	407	389	358	352	317	317	278	286	245
500	419	431	419	431	419	431	419	431	401	431	381	387	349	342	322	299	285	263	248	228	219	199
525	406	420	406	420	388	420	371	420	340	375	307	326	275	287	248	248	226	216	183	186	158	161
550	393	406	381	406	350	406	323	362	289	317	268	274	230	239	203	204	173	177	147	150	125	128
575	380	390	347	390	311	357	283	307	249	268	223	229	194	198	169	167	142	143	120	120	100	101
600	357	372	300	350	266	304	241	260	212	224	185	190	159	162	136	136	112	115	94	95	79	79
625	315	351	259	300	229	258	205	219	179	187	155	157	130	132	110	109	89	91	72	74	59	61
650	275	329	224	255	199	218	176	183	151	155	129	128	107	107	88	87	70	72	57	57	46	46
675	244	302	194	217	170	184	150	152	127	127	108	104	89	85	71	68	57	55	44	43	35	34
700	212	260	167	183	147	153	128	125	106	104	89	83	72	68	57	53	45	42	34	32	27	24
725	186	223	144	153	127	127	108	103	92	84	76	66	60	53	47	40	36	31	27	23	21	17
750	163	191	125	126	109	103	91	82	76	66	63	52	50	41	38	32	29	25	21	19	16	14
775	144	161	109	104	94	84	78	66	64	53	52	41	41	32	30	24	23	19	16	14	12	10
800	124	135	92	86	79	69	65	53	54	42	42	32	32	25	24	18	18	14	12	9.6	9	6.9

Tensile Strength (U) for 30-70ksi (YS-UTS) Material	
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%	
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)



ASME 2017 III-5 (and 2019) III-5



This Analysis

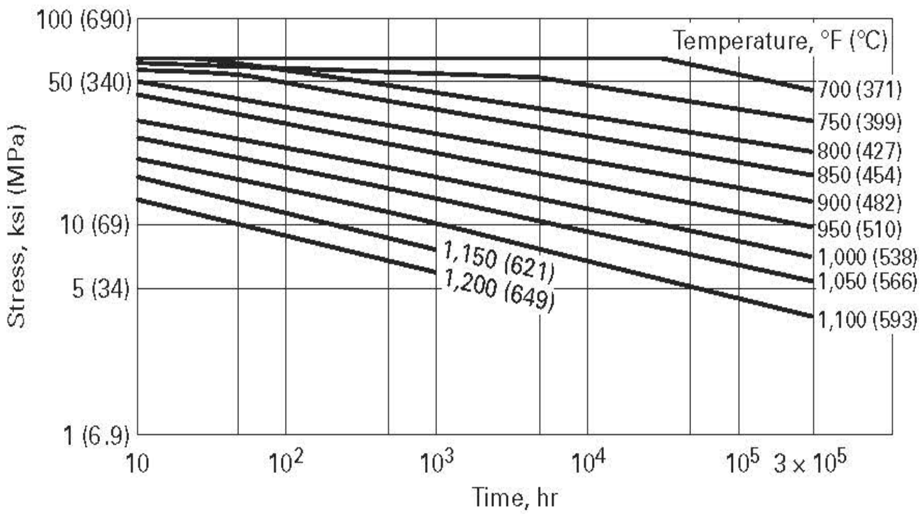
Figure R.14.6-1C. Summary of S_r curves for Ni-Fe-Cr (Alloy 800H)

Table R.14.6-1C. This Analysis for Ni-Fe-Cr (Alloy 800H) S_r (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.6C

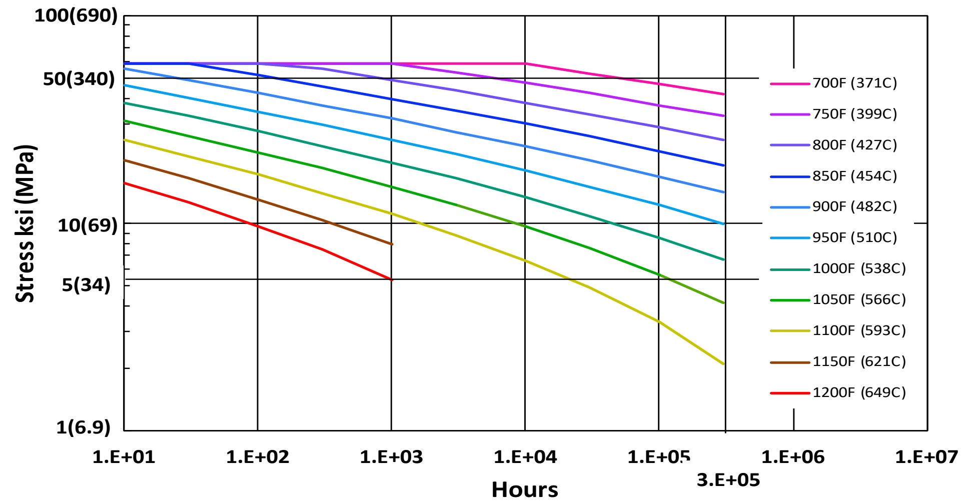
ksi hours	1		3		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis
800	56.2	60.4	56.2	60.4	56.2	60.4	56.2	60.4	56.2	60.4	56.2	60.4	56.2	60.4	56.2	60.4	56.2	60.4	56.2	55.2	51.9	48.5	45.9	43.1	43.3	40.8
850	55.9	59.8	55.9	59.8	55.9	59.8	55.9	59.8	55.9	59.8	55.9	59.8	55.9	59.8	55.9	58.5	55.9	51.2	49.6	45.3	43.0	39.6	37.8	34.9	35.6	32.9
900	55.6	58.9	55.6	58.9	55.6	58.9	55.6	58.9	55.6	58.9	55.6	58.9	55.6	55.1	53.0	48.5	45.8	42.2	40.1	37.1	34.5	32.2	30.2	28.2	28.3	26.5
950	55.3	57.7	55.3	57.7	55.3	57.7	55.3	57.7	55.3	57.7	55.3	53.0	49.8	45.9	43.4	40.2	37.2	34.7	32.3	30.3	27.7	26.1	24.0	22.7	22.5	21.3
1000	54.7	56.3	54.7	56.3	54.7	56.3	54.7	56.3	54.7	50.9	47.9	44.4	40.9	38.1	35.4	33.2	30.1	28.4	26.0	24.6	22.1	21.0	19.1	18.2	17.8	17.0
1050	50.2	54.5	50.2	54.5	50.2	54.5	50.2	49.9	45.9	42.7	39.5	37.0	33.5	31.6	28.8	27.3	24.4	23.2	20.9	20.0	17.7	16.9	15.1	14.5	14.1	13.5
1100	48.4	52.5	48.4	52.5	48.4	48.8	45.0	42.2	38.0	35.8	32.5	30.9	27.4	26.1	23.4	22.4	19.7	18.9	16.8	16.2	14.1	13.6	12.0	11.6	11.1	10.7
1150	46.3	50.2	46.3	48.9	44.0	41.4	37.5	35.5	31.5	30.0	26.8	25.7	22.4	21.6	19.0	18.4	15.9	15.4	13.4	13.0	11.2	10.9	9.5	9.2	8.7	8.5
1200	43.9	47.5	43.9	41.7	36.8	35.1	31.2	29.9	26.0	25.0	22.0	21.3	18.3	17.7	15.4	15.0	12.8	12.4	10.7	10.5	8.9	8.7	7.5	7.2	6.9	6.7
1250	41.1	41.8	37.1	35.5	30.8	29.6	25.9	25.1	21.5	20.9	18.0	17.6	14.9	14.5	12.5	12.2	10.3	10.0	8.6	8.4	7.0	6.9	5.9	5.7	5.4	5.2
1300	37.2	35.7	31.2	30.2	25.7	25.0	21.5	21.0	17.7	17.3	14.8	14.5	12.1	11.9	10.1	9.9	8.2	8.1	6.8	6.7	5.6	5.4	4.6	4.5	4.2	4.1
1350	31.4	30.5	26.2	25.6	21.5	21.0	17.8	17.6	14.6	14.4	12.1	11.9	9.8	9.7	8.1	8.0	6.6	6.5	5.4	5.3	4.4	4.3	3.6	3.5	3.3	3.1
1400	26.5	26.0	22.0	21.7	17.9	17.7	14.8	14.6	12.0	11.9	9.9	9.8	8.0	7.9	6.5	6.4	5.3	5.2	4.3	4.2	3.4	3.3	2.8	2.7	2.6	2.4
1450	22.4	22.1	18.4	18.3	14.9	14.8	12.2	12.2	9.8	9.8	8.0	8.0	6.4	6.4	5.2	5.2	4.2	4.1	3.4	3.3	2.7	2.6	2.2	2.1	2	1.9
1500	18.9	18.8	15.4	15.4	12.4	12.4	10.1	10.1	8.0	8.0	6.5	6.5	5.2	5.1	4.2	4.1	3.3	3.2	2.7	2.6	2.1	2.0	1.7	1.6	1.5	1.4
1550	15.9	15.9	12.9	13.0	10.3	10.3	8.3	8.3	6.6	6.6	5.3	5.3	4.2	4.1	3.4	3.3	2.6	2.6	2.1	2.0	1.6	1.5	1.3	1.2	1.2	1.1
1600	13.3	13.5	10.8	10.9	8.5	8.6	6.8	6.9	5.4	5.4	4.3	4.3	3.4	3.3	2.7	2.6	2.1	2.0	1.7	1.6	1.3	1.2	1.0	0.91	0.91	0.80
1650	11.2	11.4	9.0	9.1	7.0	7.1	5.6	5.7	4.4	4.4	3.5	3.4	2.7	2.6	2.1	2.1	1.6	1.6	1.3	1.2	1.0	0.89	0.78	0.68	0.70	0.59

MPa hours	1		3		10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6C	This Analysis
425	387	417	387	417	387	417	387	417	387	417	387	417	387	417	387	417	387	417	387	385	374	339	330	301	312	285
450	385	413	385	413	385	413	385	413	385	413	385	413	385	413	385	413	385	364	354	322	307	282	270	249	254	235
475	384	408	384	408	384	408	384	408	384	408	384	408	384	398	384	351	333	306	292	269	252	234	220	206	207	193
500	382	401	382	401	382	401	382	401	382	401	382	389	369	338	321	297	276	257	241	225	207	194	180	169	168	159
525	379	393	379	393	379	393	379	393	379	380	361	332	309	286	268	250	229	215	198	187	169	160	146	139	137	130
550	352	383	352	383	352	383	352	378	351	325	303	283	258	242	223	210	189	179	163	155	138	132	119	114	111	106
575	342	372	342	372	342	372	342	325	297	278	255	240	216	204	185	176	156	149	134	128	113	108	96	93	90	86
600	331	358	331	358	331	324	297	279	250	237	214	204	180	172	154	147	129	124	110	106	92	89	78	76	72	70
625	317	344	317	330	296	279	252	239	211	202	180	172	150	145	127	123	106	103	90	87	75	73	63	61	58	57
650	302	327	302	286	252	240	214	205	178	171	150	146	125	121	105	103	87	85	73	72	61	59	51	49	47	46
675	285	291	259	247	215	206	181	175	150	145	126	123	104	102	87	85	72	70	60	59	49	48	41	40	38	37
700	264	253	221	213	183	177	153	149	126	123	105	103	86	85	72	71	59	58	49	48	40	39	33	32	30	29
725	227	219	189	184	155	152	129	127	106	104	88	87	71	71	59	58	48	47	40	39	32	31	26	26	24	23
750	195	190	162	159	132	130	109	108	89	88	73	72	59	59	49	48	39	39	32	31	26	25	21	20	19	18
775	167	164	138	136	112	111	92	91	74	74	61	60	49	49	40	40	32	31	26	25	21	20	17	16	15	14
800	143	142	118	117	95	94	77	77	62	62	51	50	40	40	33	32	26	25	21	20	17	15.9	13	12.7	12	11.4
825	123	122	100	100	80	80	65	65	52	52	42	42	33	33	27	26	21	21	17	16	13	12.6	11	9.9	9.7	8.9
850	105	105	85	86	68	68	55	55	43	43	35	35	27	27	22	21	17	17	14	13	11	10.0	8.5	7.7	7.6	6.9
875	90	91	72	73	57	58	46	46	36	36	29	29	23	22	18	17	14	13	11	10	8.5	7.8	6.7	6.0	6.0	5.3
900	77	78	61	62	48	49	38	39	30	30	24	24	18	18	15	14	11	11	8.9	8.2	6.8	6.1	5.3	4.6	4.7	4.1

Tensile Strength (U)	
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%	
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)



ASME 2017 III-5 (and 2019) III-5



This Analysis

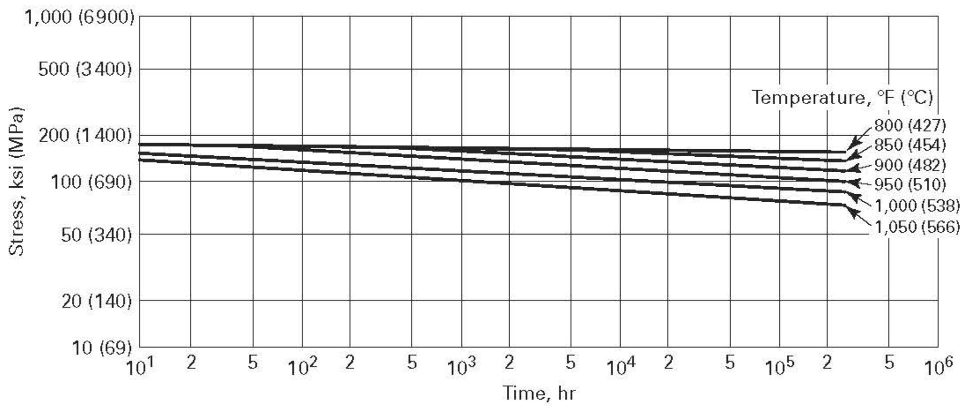
Figure R.14.6-1D. Summary of S_r curves for 2¼Cr-1Mo

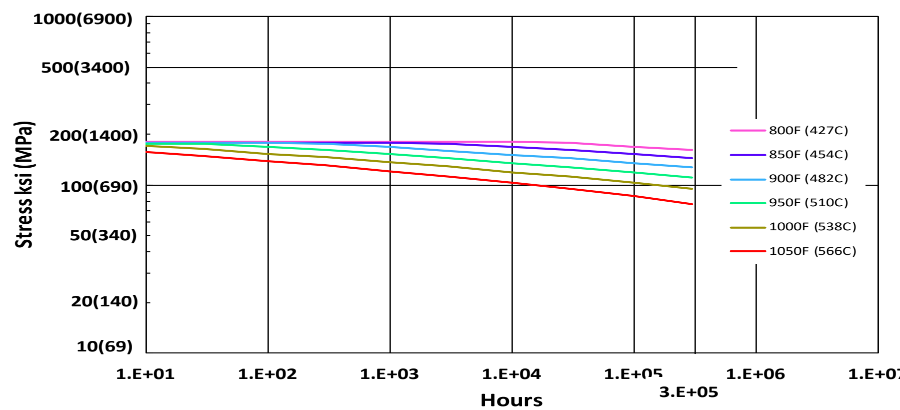
Table R.14.6-1D. This Analysis for 2¼Cr-1Mo S_r (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.6D

ksi hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis
700	59.0	58.8	59.0	58.8	59.0	58.8	59.0	58.8	59.0	58.8	59.0	58.8	59.0	58.6	59.0	52.8	54.0	46.9	49.0	42.0
750	58.0	58.8	57.0	58.8	56.0	58.8	54.6	58.8	53.0	58.8	51.2	53.7	48.0	47.5	43.3	42.4	37.5	37.2	34.1	32.9
800	56.0	58.8	55.5	58.8	54.0	58.8	48.5	55.7	43.0	49.0	37.5	43.6	34.5	38.1	30.5	33.6	27.0	29.1	24.0	25.4
850	52.0	58.8	50.5	58.8	46.0	51.6	40.5	45.7	35.0	39.8	31.0	34.9	27.5	30.1	24.0	26.2	21.0	22.3	18.5	19.1
900	46.0	55.3	41.0	48.8	36.0	42.4	32.0	37.1	28.0	31.9	25.0	27.6	21.6	23.5	19.0	20.1	16.4	16.7	14.1	14.1
950	40.0	46.0	35.0	40.2	30.0	34.5	26.0	29.8	22.2	25.2	19.5	21.5	17.0	17.9	14.6	15.0	12.6	12.2	11.0	10.0
1000	31.5	38.0	27.5	32.8	24.0	27.7	21.0	23.6	17.9	19.6	15.2	16.4	13.1	13.4	11.0	10.9	9.4	8.6	7.9	6.7
1050	26.0	31.1	22.5	26.4	19.0	22.0	16.5	18.4	14.0	15.0	12.0	12.2	10.0	9.6	8.3	7.6	7.0	5.7	5.8	4.1
1100	21.0	25.1	18.0	21.0	15.1	17.1	13.0	14.0	10.8	11.1	9.1	8.8	7.5	6.6	6.2	4.9	5.0	3.4	4.1	2.1
1150	17.0	20.0	14.1	16.5	11.8	13.1	9.8	10.4	8.0	7.9	...	...	...	...	...	...	...	...	...	...
1200	13.5	15.7	11.1	12.6	9.2	9.7	7.6	7.5	6.2	5.4	...	...	...	...	...	...	...	...	...	...

MPa hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6D	This Analysis
375	406	405	405	405	404	405	403	405	401	405	399	405	396	393	392	353	356	314	323	280
400	400	405	393	405	386	405	375	405	363	405	350	367	328	325	296	289	256	254	233	225
425	387	405	384	405	373	405	337	388	301	342	266	304	245	266	216	235	191	203	170	178
450	363	405	353	405	325	367	287	325	249	284	221	250	197	216	172	188	151	161	133	138
475	328	395	299	353	265	308	236	270	205	233	183	203	159	173	140	149	121	125	105	105
500	291	339	256	298	222	256	194	223	167	190	148	163	128	136	112	115	96	95	83	78
525	244	286	214	249	184	212	161	182	137	152	118	129	103	106	88	87	71	70	70	56
550	196	240	175	206	150	173	132	146	112	120	96	100	81	80	68	64	58	50	48	38
575	168	199	145	169	122	140	106	116	89	94	76	76	63	59	52	46	43	33	36	23
600	138	164	117	137	98	111	85	90	69	71	...	...	...	...	...	...	...	...	...	...
625	114	134	94	109	77	87	65	69	52	52	...	...	...	...	...	...	...	...	...	...
650	92	107	76	86	62	66	51	51	43	36	...	...	...	...	...	...	...	...	...	...

Tensile Strength (U) for 30-70ksi (YS-UTS) Material	
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%	
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)





ASME 2017 III-5 (and 2019) III-5

This Analysis

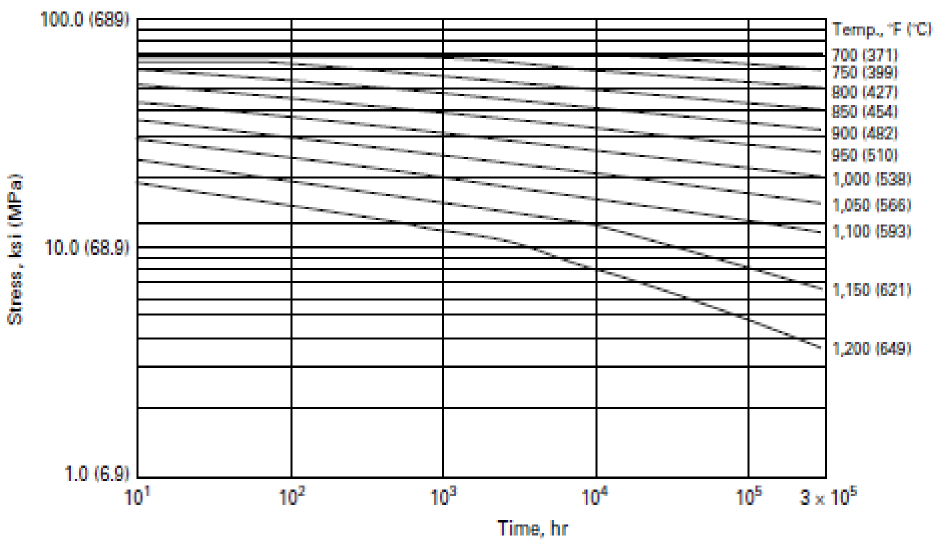
Figure R.14.6-1E. Summary of S_r curves for Alloy 718

Table R.14.6-1E. This Analysis for Alloy 718 S_r (ksi and MPa) compared with BPVC 2017 (and 2019) III-5 Table HBB-I-14.6E

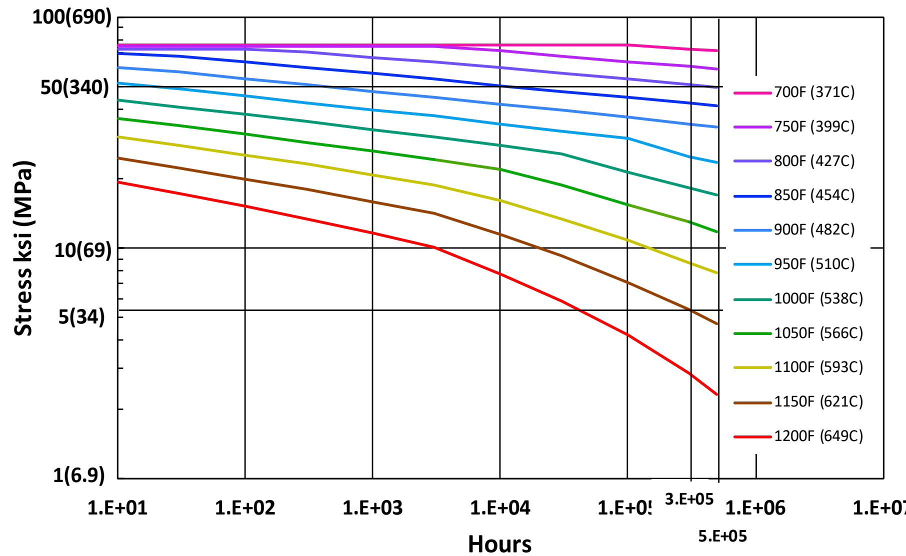
ksi hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis
800	168	180	168	180	168	180	168	180	168	180	168	180	168	180	168	177	160	169	154	162
850	172	179	172	179	172	179	172	179	172	179	166	179	159	168	151	160	146	152	140	145
900	170	178	170	178	170	178	166	176	158	168	151	168	144	151	138	144	130	135	124	128
950	170	176	166	176	158	169	150	161	144	152	136	152	129	135	122	127	114	119	106	111
1000	160	171	150	171	144	153	136	145	130	136	122	136	114	119	106	111	98	102	90	94
1050	146	156	138	156	130	138	124	130	114	121	106	121	98	104	91	95	81	86	74	77

MPa hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.6E	This Analysis
425	1160	1239	1160	1239	1160	1239	1160	1239	1160	1239	1160	1239	1160	1239	1160	1230	1100	1174	1060	1123
450	1180	1234	1180	1234	1180	1234	1180	1234	1180	1234	1150	1234	1110	1176	1060	1123	1020	1067	985	1016
475	1180	1228	1180	1228	1180	1228	1150	1228	1110	1185	1070	1131	1020	1073	974	1020	924	963	883	911
500	1170	1220	1150	1220	1120	1203	1070	1146	1030	1086	975	1031	926	972	881	918	825	860	775	807
525	1123	1210	1060	1169	1020	1106	962	1050	920	988	865	933	812	873	759	818	704	759	649	704
550	1050	1135	987	1076	938	1012	891	955	833	893	778	836	723	775	672	719	609	656	558	599

Tensile Strength (U) for 30-70ksi (YS-UTS) Material	
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%	
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)



ASME 2017 III-5



This Analysis

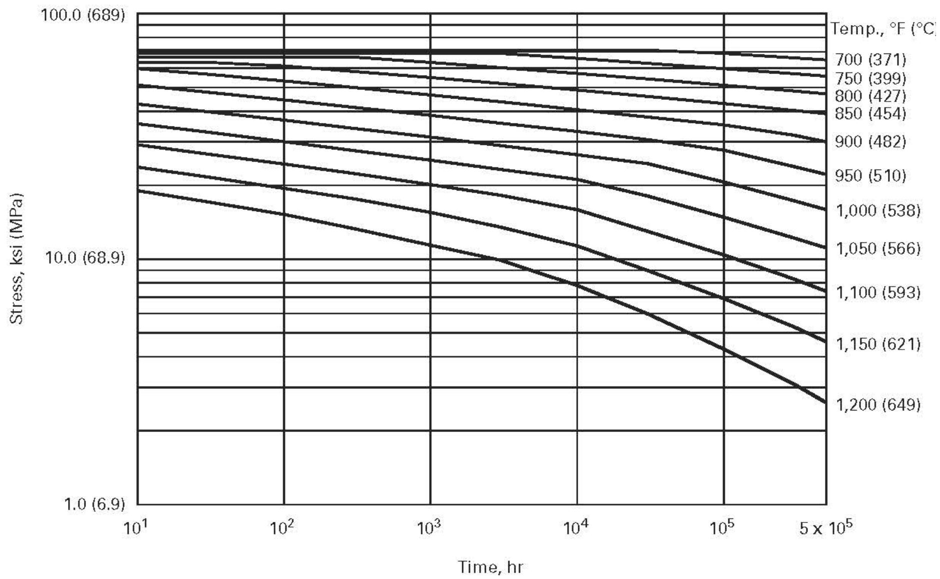
Figure R.14.6-1F. Summary of S_r curves for 9Cr-1Mo-V

Table R.14.6-1F. This Analysis for 9Cr-1Mo-V S_r (ksi and MPa) compared with BPVC 2017 III-5 Table HBB-I-14.6F

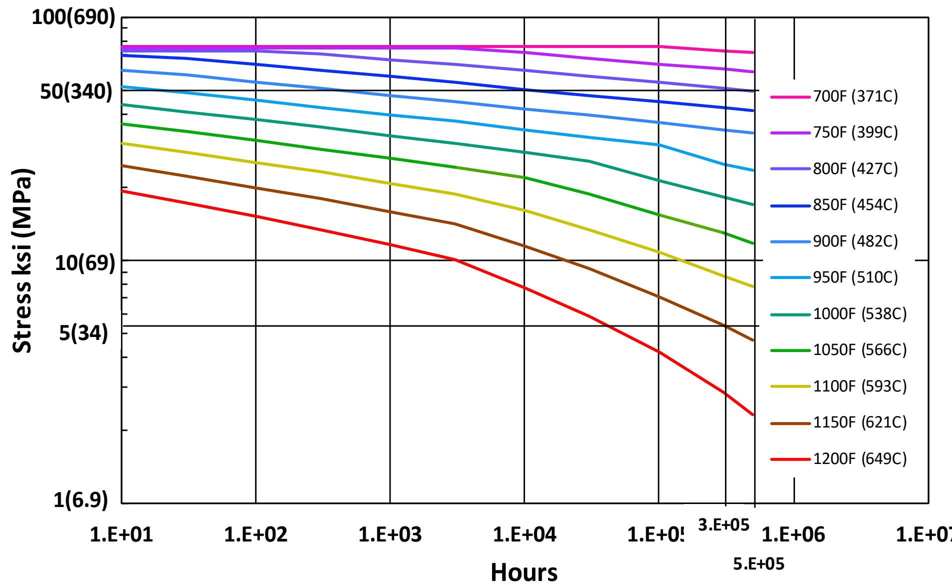
ksi hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °F	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis
700	71.0	76.3	71.0	76.3	71.0	76.3	71.0	76.3	71.0	76.3	71.0	76.3	71.0	76.3	71.0	76.3	71.0	76.1	71.0	72.8		71.3
750	69.0	74.6	69.0	74.6	69.0	74.6	69.0	74.6	69.0	74.6	69.0	74.6	69.0	71.3	67.3	68.0	63.5	64.5	60.2	61.4		60.0
800	66.5	72.6	66.5	72.6	66.5	72.6	66.5	70.9	66.5	67.2	63.1	63.9	59.4	60.4	56.1	57.4	52.7	54.1	49.6	51.3		50.0
850	63.4	70.0	63.4	67.5	63.4	63.7	59.7	60.5	56.0	57.0	52.7	53.9	49.3	50.7	46.3	47.9	43.3	45.0	40.6	42.4		41.2
900	59.8	61.0	57.0	57.7	53.3	54.2	50.0	51.1	46.6	47.9	43.7	45.1	40.6	42.1	37.9	39.6	35.2	36.8	32.8	34.5		33.4
950	51.2	51.9	47.9	48.9	44.5	45.6	41.5	42.8	38.5	39.8	35.8	37.3	33.1	34.5	30.7	32.2	28.2	29.7	26.1	25.0		23.4
1000	42.8	43.8	39.9	41.0	36.8	38.0	34.1	35.4	31.4	32.7	29.0	30.3	26.6	27.8	24.5	25.7	22.3	21.4	20.5	18.3		16.9
1050	35.6	36.6	32.9	34.0	30.1	31.2	27.7	28.8	25.3	26.4	23.2	24.2	21.1	22.0	19.2	18.7	17.3	15.5	15.7	12.9		11.8
1100	29.2	30.1	26.8	27.7	24.4	25.2	22.3	23.1	20.1	20.8	18.3	18.8	16.4	16.1	14.8	13.4	13.1	10.8	11.7	8.7		7.8
1150	23.7	24.4	21.6	22.2	19.4	19.9	17.6	17.9	15.7	15.9	14.1	14.2	12.4	11.4	10.2	9.2	8.2	7.1	6.7	5.4		4.7
1200	19.0	19.3	17.1	17.3	15.2	15.2	13.6	13.4	11.9	11.6	10.5	10.0	8.0	7.7	6.5	5.9	4.9	4.2	3.7	2.9		2.3

MPa hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °C	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis	ASME 2017 III-5 Table HBB-I-14.6F	This Analysis
375	487	525	487	525	487	525	487	525	487	525	487	525	487	525	487	525	487	513	487	491		480
400	475	514	475	514	475	514	475	514	475	514	475	514	475	488	461	466	435	442	412	421		438
425	459	501	459	501	459	501	459	493	459	467	436	445	412	421	390	400	366	377	345	358		374
450	440	486	440	477	440	451	418	428	396	404	374	382	350	360	329	340	308	320	289	301		317
475	419	438	404	414	385	390	361	369	338	346	317	326	295	305	276	287	257	268	240	251		265
500	374	380	353	358	329	335	307	315	285	294	266	276	247	256	229	239	212	222	196	192		180
525	322	327	301	307	278	285	259	267	239	247	222	230	204	213	189	197	173	170	159	146		136
550	274	280	251	261	234	241	216	224	198	206	178	190	166	173	153	153	139	129	127	109		100
575	231	237	213	219	194	201	179	185	163	168	149	154	135	139	122	115	110	95	99	78		71
600	192	198	176	182	160	165	146	150	132	135	118	122	106	103	94	85	82	68	72	54		48
625	159	163	145	148	130	133	117	119	105	105	94	94	81	75	67	60	53	46	42	35		30
650	130	132	117	118	104	104	93	92	81	79	72	68	54	52	44	40	33	28	25	19		15

Tensile Strength (U) for 60-85ksi (YS-UTS) Material	Stress values from low stress split region analysis
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%	
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)



ASME 2019 III-5



This Analysis

Figure R.14.6-1F-2019. Summary of S_r curves for 9Cr-1Mo-V

Table R.14.6-1F-2019. This Analysis for 9Cr-1Mo-V S_r (ksi and MPa) compared with BPVC 2019 III-5 Table HBB-I-14.6F

ksi hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °F	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis
700	71.0	76.3	71.0	76.3	71.0	76.3	71.0	76.3	71.0	76.3	71.0	76.3	71.0	76.3	71.0	76.3	68.8	76.1	66.0	72.8	64.7	71.3
750	69.0	74.6	69.0	74.6	69.0	74.6	69.0	74.6	69.0	74.6	68.9	74.6	65.7	71.3	62.8	68.0	59.7	64.5	56.9	61.4	55.6	60.0
800	66.5	72.6	66.5	72.6	66.5	72.6	66.5	70.9	63.2	67.2	60.2	63.9	57.0	60.4	54.2	57.4	51.1	54.1	48.4	51.3	47.1	50.0
850	63.4	70.0	63.4	67.5	61.2	63.7	58.1	60.5	54.9	57.0	51.9	53.9	48.8	50.7	46.0	47.9	43.0	45.0	40.3	42.4	39.1	41.2
900	59.7	61.0	56.6	57.7	53.2	54.2	50.0	51.1	46.6	47.9	43.7	45.1	40.6	42.1	37.9	39.6	35.2	36.8	32.0	34.5	30.0	33.4
950	51.2	51.9	47.9	48.9	44.5	45.6	41.5	42.8	38.5	39.8	35.8	37.3	33.1	34.5	30.7	32.2	27.8	29.7	23.8	25.0	22.1	23.4
1000	42.8	43.8	39.9	41.0	36.8	38.0	34.1	35.4	31.4	32.7	29.0	30.3	26.6	27.8	24.5	25.7	20.6	21.4	17.3	18.3	15.9	16.9
1050	35.6	36.6	32.9	34.0	30.1	31.2	27.7	28.8	25.3	26.4	23.2	24.2	21.1	22.0	18.1	18.7	14.8	15.5	12.2	12.9	11.1	11.8
1100	29.2	30.1	26.8	27.7	24.4	25.2	22.3	23.1	20.1	20.8	18.2	18.8	15.9	16.1	13.0	13.4	10.4	10.8	8.3	8.7	7.4	7.8
1150	23.7	24.4	21.6	22.2	19.4	19.9	17.6	17.9	15.5	15.9	13.5	14.2	11.3	11.4	9.0	9.2	6.9	7.1	5.3	5.4	4.6	4.7
1200	19.0	19.3	17.1	17.3	15.2	15.2	13.3	13.4	11.4	11.6	9.9	10.0	7.8	7.7	6.0	5.9	4.3	4.2	3.1	2.9	2.6	2.3

MPa hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °C	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis	ASME 2019 III-5 Table HBB-I-14.6F	This Analysis
375	487	525	487	525	487	525	487	525	487	525	487	525	487	525	487	525	465	513	446	491	437	480
400	475	514	475	514	475	514	475	514	475	514	473	514	451	488	431	466	409	442	390	421	381	438
425	459	501	459	501	459	501	459	493	439	467	419	445	397	421	377	400	356	377	337	358	328	374
450	440	486	440	477	431	451	410	428	387	404	367	382	345	360	326	340	305	320	287	301	278	317
475	419	438	404	414	381	390	360	369	338	346	317	326	295	305	276	287	257	268	238	251	223	265
500	374	380	353	358	329	335	307	315	285	294	266	276	247	256	229	239	212	222	183	192	171	180
525	322	327	301	307	278	285	259	267	239	247	222	230	204	213	189	197	163	170	139	146	128	136
550	274	280	251	261	234	241	216	224	198	206	178	190	166	173	149	153	123	129	103	109	94	100
575	231	237	213	219	194	201	179	185	163	168	149	154	133	139	112	115	91	95	74	78	67	71
600	192	198	176	182	160	165	146	150	132	135	117	122	101	103	83	85	65	68	51	54	46	48
625	159	163	145	148	130	133	117	119	102	105	89	94	74	75	59	60	45	46	34	35	30	30
650	130	132	117	118	104	104	91	92	78	79	67	68	53	52	40	40	29	28	21	19	17	15

Tensile Strength (U) for 60-85ksi (YS-UTS) Material	Stress values from low stress split region analysis
Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%	
Non-conservative relative to this analysis - Difference, δ > 10%	(Used rounding for characterization of δ)

The analysis for each of the alloys is conducted using the ASME time-dependent software, version 2016-2-10, that is separately verified for accuracy in the regression of the data for the LMP-Logarithmic Stress polynomial curve, as discussed in Appendix VTDS. Given the constraints of the project, the analysis of multiple alloys and selection of the optimal regression model, the need to execute the effort with a relatively automated computer program is essential. The ASME software provides one such option for execution and is used following its verification for accuracy.

Material:

For all the alloys evaluated, care was taken to ensure that the data were from material that conformed to the specifications and additional BPVC III-5 requirements (Table HBB-I-14.1(a)).

Data Censoring and Region Splitting:

For 304 SS and 316 SS and for 2¼Cr-1Mo, due to the significant scatter in the very short rupture time frame, data with rupture time < 100 hours were excluded from the analysis, consistent with traditional BPVC practice. For Alloy 718, the database consisted of data well above the temperature range of interest (425-550°C or 800 to 1050°F), including data at 760°C (1400°F). Given the restricted use temperature range, the data are censored to exclude data above 650°C (1200°F). For 9Cr-1Mo-V, the more recently established region splitting method per NIMS is used (Ref. Kimura 2016). The data were split into two regimes – a high stress regime and a low stress regime, and the two sets were separately analyzed. The temperature-dependent boundary stresses selected were those reported by NIMS in the 550 to 700°C range and stresses estimated by a curve-fit to these values for temperatures outside of this range. In interpretation of the analysis results, care is taken to use the relevant curve-fit, depending on the computed average stress for rupture in 100,000 hours; i.e., an average stress in the low stress region would require use of the low stress region curve-fit for predicting S_o.

Rupture Strength Curve:

The data are analyzed using the LMP-Logarithmic stress polynomial function - $LMP = T(C + \log t_R) = a_0 + a_1 * \log S + a_2 * (\log S)^2 + a_3 * (\log S)^3$ (t_R = rupture time in hours, S = stress, and T = temperature in absolute units). The regression method used is heat/lot-centered and the preferred polynomial order is 2 ($a_3=0$). The commonly encountered problem with the 2nd order is that the parabolic fit always has a vertex at which the logarithmic stress-time curve exhibits a turn-around; i.e., the rupture time begins to decrease with decreasing stress. This can produce excessively conservative predictions of rupture strength or as is also often the case, no feasible rupture strength solution.

For 304 SS, the 2nd order fit exhibited a tendency to potentially underpredict the behavior at the highest temperatures, partly a result of the constrained parabolic curve shape. On close review, it was seen that the 1st order fit is clearly non-conservative, and the 3rd order fit produces stresses slightly greater than does the 2nd order fit, but within about 0.7 MPa (0.1 ksi). No justification can be made for use of the 3rd order, particularly where the fit may be non-conservative if used for longer term extrapolations, such as for S_r and S_t.

The 316 SS dataset exhibited similar curve shape behavior as did 304 SS. In this case, the 3rd order fit exhibited an upturn that is clearly non-conservative. Since, at the highest temperatures (≥ 750°C, ≥ 1400°F), the 2nd order is judged to be excessively conservative and the 1st order to be non-conservative, the final stress estimate is made using the average of the two predictions at these highest temperatures.

For Ni-Fe-Cr (Alloy 800H), the scatter in the short-term data was not significant, so time-censoring was not needed. The 2nd order curve-fit produces acceptable results with no indication of the parabolic vertex turn-around affecting the results.

While the 2nd order curve-fit data analysis for 2¼Cr-1Mo also exhibited a striking parabolic vertex turn-around, the rupture strength curves are such that the shapes do not impact the stress predictions within the temperature range of interest.

For Alloy 718, similarly, the 2nd order data analysis showed a striking turn-around in the rupture strength curve, but with no impact on the stress estimates in the temperature range of interest.

For 9Cr-1Mo-V, the region splitting method for the dataset permits use of the 2nd order curve-fit for both the high and the low stress regions with no influencing turn-around and no indication that the predictions are excessively conservative.

The references from which the stress rupture data analyzed are obtained are provided by their ID below for convenient review, with details listed in Section 6 References.

For 304 SS

Data (after 100-hour censor): 90 Heats/Lots, 964 Data Points, Maximum rupture time ≈ 179,400 hours.

- (Ref. Ajaja 1979)
- (Ref. Bocek 1983)
- (Ref. BSCC 1974)
- (Ref. Bynum 1992)
- (Ref. Gold 1975)
- (Ref. Klueh 1976b)
- (Ref. Martin 1963)
- (Ref. McCoy 1974a)
- (Ref. McCoy 1974b)
- (Ref. MPC 1983)
- (Ref. NRIM 1986b)
- (Ref. NRIM 1995)
- (Ref. Sikka 1976)
- (Ref. Sikka 1981)
- (Ref. Simmons 1965)
- (Ref. Swindeman 1974)
- (Ref. Swindeman 1975)

- (Ref. Swindeman 1977)
- (Ref. Swindeman 1981)
- (Ref. Williams 1986)

<u>For 316 SS</u>

Data (after 100-hour censor): 142 Heats/Lots, 1616 Data Points, Maximum rupture time ≈ 320,400 hours.

- (Ref. BSCC 1974)
- (Ref. NIMS 2015)
- (Ref. NRIM 1979)
- (Ref. NRIM 1988)
- (Ref. NRIM 2000)
- (Ref. Sikka 1980)
- (Ref. Simmons 1965)

<u>For Ni-Fe-Cr (Alloy 800H)</u>

Data: 49 Heats/Lots, 960 Data Points, Maximum rupture time ≈ 136,100 hours.

- Data compiled by ORNL from various published and unpublished sources.

<u>For Alloy 718</u>

Data: 23 Heats/Lots, 210 Data Points, Maximum rupture time ≈ 86,800 hours.

- (Ref. Booker 1984)
- (Ref. Klueh 1976a)
- (Ref. Korth 1978)

<u>For 2¼Cr-1Mo (Annealed and N&T material combined).</u>

Data (after 100-hour censor): 93 Heats/Lots, 671 Data Points, Maximum rupture time ≈ 213,300 hours.

- (Ref. Klueh 1976a)
- (Ref. Klueh 1978)
- (Ref. NRIM 1986a)
- (Ref. NRIM 1997)
- (Ref. Smith 1971).

<u>For 9Cr-1Mo-V (112 Heats/Lots, 2046 Data Points):</u>

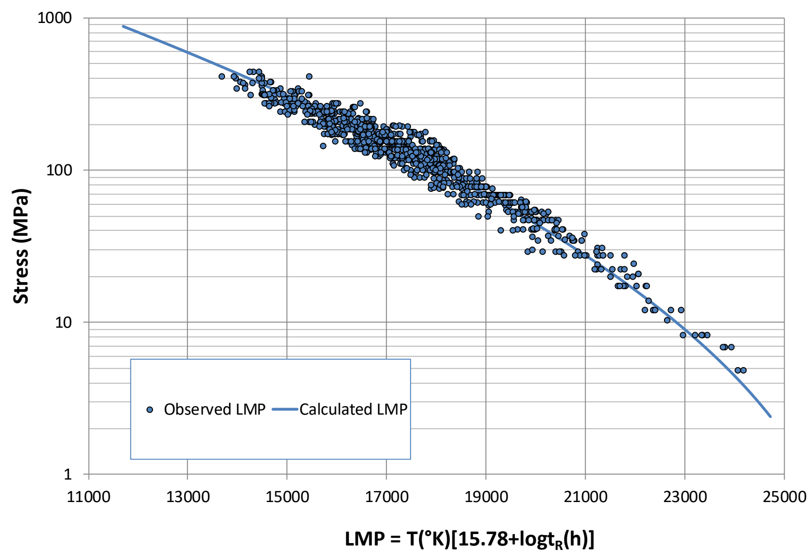
- All Data from ASME Material Properties Database (ASME Record no. 16-2627).

Analysis and Results

304SS:

Figure R.14.6-2A summarizes the results of the analysis in the form of the rupture strength LMP curve and the coefficients and LMP constant for the best-fit, 2nd order curve.

An analysis of the F-factor value for the curve [10^(1/n) where n is the $\Delta logt_R/\Delta logS$ slope of the curve] at 50,000 hours shows it to be > 0.50 at all temperatures. The F-factor here is computed in a manner identical to that for F_{avg} as defined in Section II, Part D, Appendix 1 for use at 100,000 hours. Based on independently compiled data on numerous alloys and unpublished analysis of the datasets (Ref. Foulds 2019), the curve-fit is therefore judged to be acceptable with no cause for concern with excessive conservatism. The method for precluding excessive conservatism, developed using the F-factor, is currently part of a yet unpublished draft document produced by the Working Group on Data Analysis of ASME BPVC-II. The F-factor is a measure of the steepness of the rupture curve, i.e., how rapidly the rupture stress is decreasing with increasing time. This F-factor computation has value when deciding on the acceptability of stresses obtained from 2 nd order polynomial fits where extrapolations may be too close in time to where the 2 nd order parabola vertex (turn-around) exists, resulting in artificial over-conservatism.



C_{LP}=	15.77887
a_0 =	25483.48
a_1 =	-1611.22
a_2 =	-1040.6
SEE=	0.464138
R^2	0.67

$logt_R = -C_{LP} + a_0/T + a_1/T*logS + a_2/T*(logS)^2$

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

Figure R.14.6-2A. Summary of regression results for 304 SS

The significant non-conservatism of the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6A S_r values relative to our analysis for the highest temperatures and extended times (see Table R.14.6-1A) was further examined in light of the relatively recent effort to analyze the data for this material in order to correct and extend the BPVC III-5 S_{mt} and S_r stresses to 500,000 hours (STP-NU-063) (Ref. Sengupta 2013). The results of that work are evidently not incorporated into the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6A for S_r. Table R.14.6-2A below summarizes the STP-NU-063-reported S_r compared with the results of this analysis shown for the higher temperatures and extended times. The table illustrates our analysis results to be in good agreement with that effort. The findings support the need to further review and update the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6A and Figure HBB-I-14.6A.

Table R.14.6-2A. This Analysis for 304 SS compared with values reported in STP-NU-063 for S_r

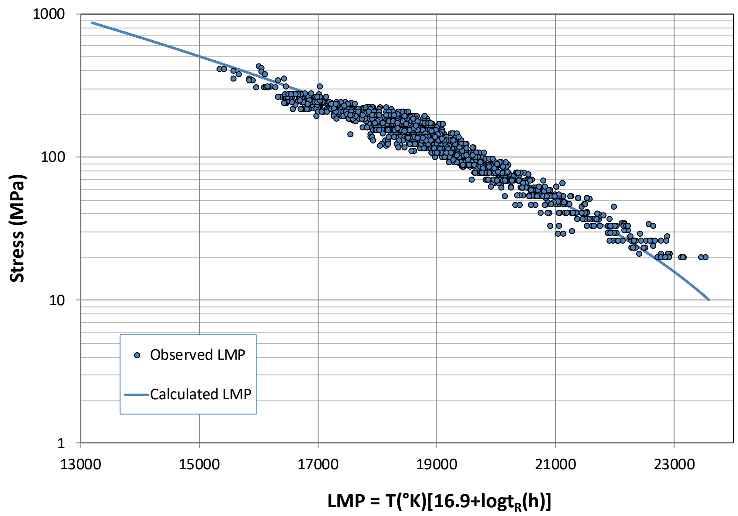
	Hours	3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
	MPa	ASME ST-LLC STP-NU-063	This Analysis	ASME ST-LLC STP-NU-063	This Analysis	ASME ST-LLC STP-NU-063	This Analysis	ASME ST-LLC STP-NU-063	This Analysis	ASME ST-LLC STP-NU-063	This Analysis
°C	725	41	45	32	35	26	28	20	21	15	16
	750	33	35	25	27	20	21	15	16	12	12
	775	26	28	20	21	15	16	11	12	8	8.5
	800	20	22	15	16	11	12	8	8.3	6	5.9
	ksi	3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
°F	1350	5.6	6.1	4.4	4.7	3.5	3.7	2.7	2.8	2.1	2.2
	1400	4.4	4.7	3.4	3.6	2.6	2.8	2.0	2.0	1.5	1.5
	1450	3.4	3.5	2.5	2.6	1.9	2.0	1.4	1.4	1.0	1.0
	1500	2.5	2.6	1.9	1.9	1.4	1.4	1.0	1.0	0.7	0.7

<u>316 SS</u>:

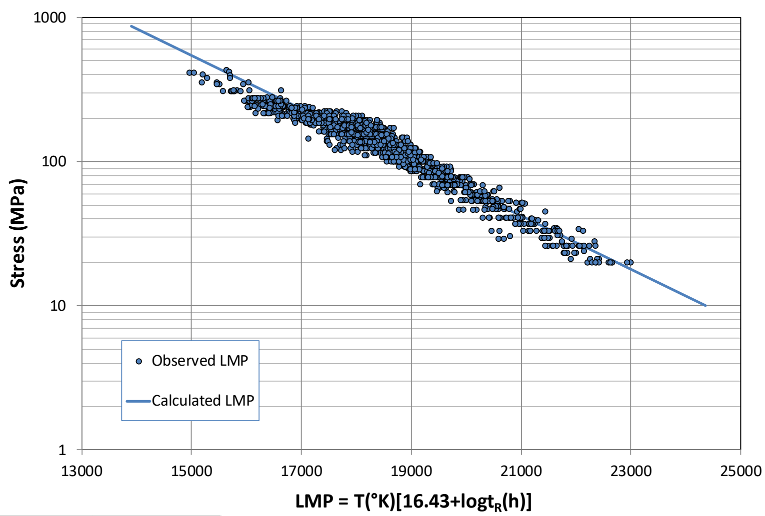
Figure R.14.6-2B summarizes the results of the analysis in the form of the rupture strength LMP curves for the 2nd order (used to 725°C (1350°F) and the 1st order (average of 1st and 2nd order used for ≥ 750°C (≥ 1400°F).

An analysis of the F-factor value for the 2nd order fit curve [10^(1/n) where n is the $\Delta \log t_R/\Delta \log S$ slope of the curve] at 50,000 hours shows it to drop below 0.50 at the highest temperatures (>775°C, > 1400°F). Based on independently compiled data on numerous alloys and unpublished analysis of the datasets (Ref. Foulds 2019), the curve-fit is judged to be excessively conservative at these temperatures. Based on examination of the isotherms in this temperature range, the choice was made to use an average stress of the two curve-fits in the temperatures range 750 to 816°C (1400-1500°F). The issue with attempting to use the 2nd order fit alone gets much worse when extrapolating to longer times.

As in the case of 304 SS, the significant non-conservatism of the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6B S_r values relative to our analysis (see Table R.14.6-1B) was further examined in light of the relatively recent effort to analyze the data for this material in order to correct and extend the BPVC III-5 S_{mt} and S_r stresses to 500,000 hours (STP-NU-063) (Ref. Sengupta 2013). The results of that work are evidently not incorporated into the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6B for S_r. Table R.14.6-2B below summarizes the STP-NU-063-reported S_r compared with the results of this analysis shown for the higher temperatures. The table illustrates our analysis results to be in good agreement with that effort. The findings support the need to review and update the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6B and Figure HBB-I-14.6B.



2nd order fit



1st order fit

C_{LP}=	16.8983	16.43029
a_0 =	24932.78	29754.5
a_1 =	18.86962	-5393.79
a_2 =	-1367.04	0
SEE=	0.35016	0.370971
R^2=	0.79	0.77

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

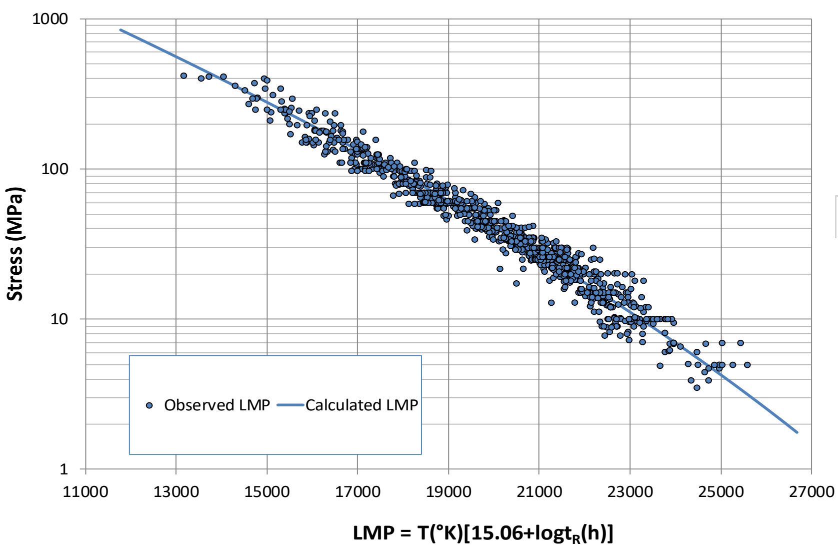
Figure R.14.6-2B. Summary of regression results for 316 SS

Table R.14.6-2B. This Analysis for 316 SS compared with values reported in STP-NU-063 for S_r

	Hours	1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
	MPa	ASME ST-LLC STP-NU-063	This Analysis	ASME ST-LLC STP-NU-063	This Analysis	ASME ST-LLC STP-NU-063	This Analysis	ASME ST-LLC STP-NU-063	This Analysis	ASME ST-LLC STP-NU-063	This Analysis	ASME ST-LLC STP-NU-063	This Analysis	ASME ST-LLC STP-NU-063	This Analysis	ASME ST-LLC STP-NU-063	This Analysis
°C	725	105	103	86	84	68	66	55	53	43	40	34	31	26	23	20	17
	750	86	82	70	66	55	52	44	41	34	32	26	25	20	19	15	14
	775	70	66	56	53	43	41	34	32	26	24	20	19	14	14	11	10
	800	57	53	45	42	34	32	26	25	19	18	15	14	10	9.6	8	6.9
	ksi	1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
°F	1350	14.5	14.0	11.8	11.4	9.4	8.9	7.5	7.1	5.9	5.4	4.6	4.1	3.5	3.0	2.7	2.2
	1400	11.6	10.9	9.3	8.8	7.3	6.8	5.8	5.4	4.4	4.1	3.4	3.2	2.6	2.4	1.9	1.8
	1450	9.2	8.6	7.3	6.8	5.6	5.2	4.4	4.1	3.3	3.1	2.5	2.3	1.8	1.7	1.3	1.2
	1500	7.2	6.7	5.6	5.2	4.3	4.0	3.2	3.0	2.4	2.2	1.8	1.6	1.2	1.1	0.9	0.7

Ni-Fe-Cr (Alloy 800H):

Figure R.14.6-2C summarizes the results of the analysis in the form of the rupture strength LMP curve and the coefficients and LMP constant for the best-fit, 2nd order curve.



$\log t_R = -C_{LP} + a_0/T + a_1/T*\log S + a_2/T*(\log S)^2$

C_{LP}=	15.05545
a_0 =	27661.01
a_1 =	-3919.96
a_2 =	-516.121
SEE=	0.38245
R^2	0.85

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

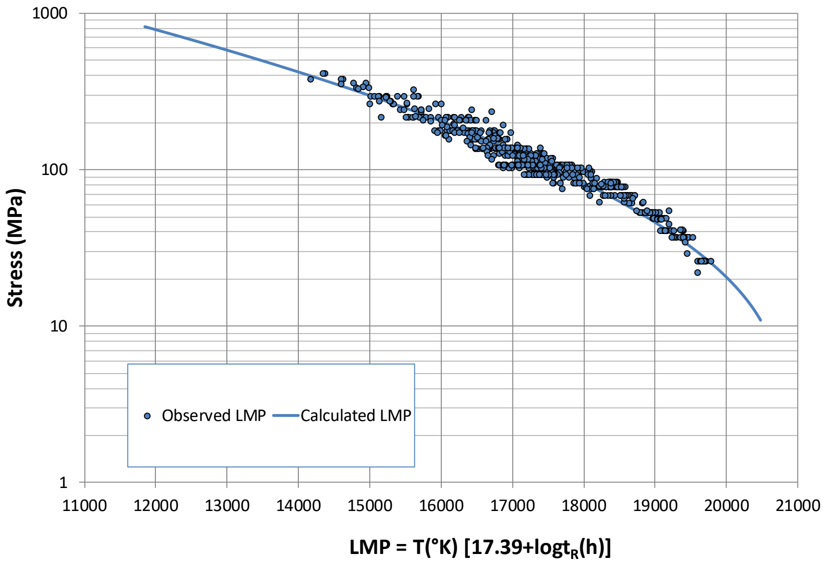
Figure R.14.6-2C. Summary of regression results for Ni-Fe-Cr (Alloy 800H)

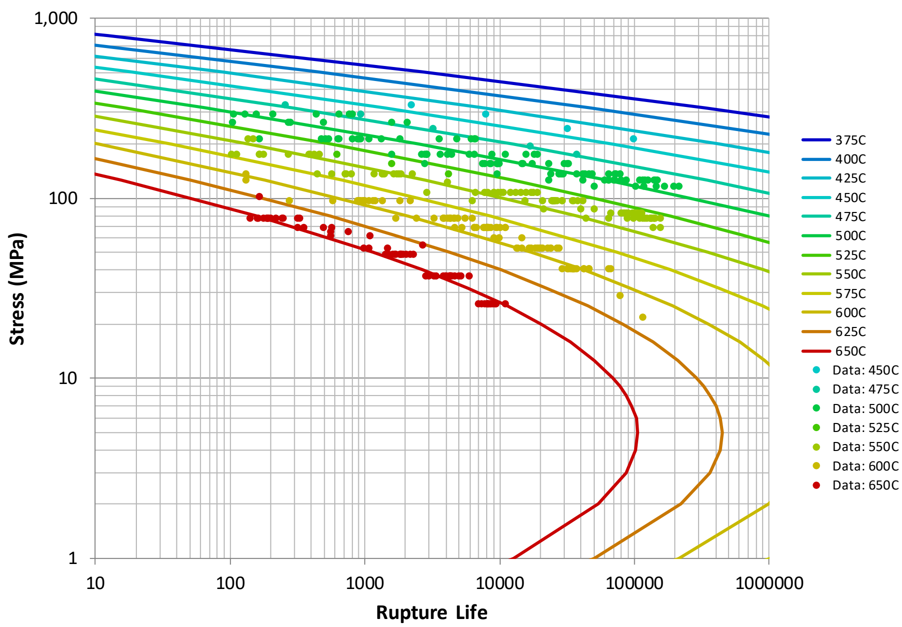
As seen in the final analysis in Table R.14.6-1C, our results are in generally good agreement with the current BPVC 2017 (and 2019) III-5 Table HBB-I-14.6C. A few stress values at the highest temperatures and exposure durations is marginally non-conservative (by slightly greater than 10%), but the table is overall, judged to be acceptable.

2¼Cr-1Mo:

Figure R.14.6-2D summarizes the results of the analysis in the form of the rupture strength LMP curve for the 2nd order. Also shown in the figure are the isotherms with a striking turn-around at the highest temperature.

A review of the F-factor at 50,000 hours for the temperature range of interest (to 593°C or 1100°F) shows that the F-factor exceeds 0.50, suggesting, as based on independently compiled data on numerous alloys and unpublished analysis of the datasets (Ref. Foulds 2019), no basis for judging the predictions to be excessively conservative, despite the parabolic vertex turn-around.





C_{LP}=	17.39036
a_0 =	19839.43
a_1 =	2470.977
a_2 =	-1786.47
SEE=	0.339601

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

Figure R.14.6-2D. Summary of regression results for 2¼Cr-1Mo

Apparent from Table R.14.6-1D summarizing the findings in comparison with the BPVC 2017 (and 2019) III-5 S_r table is that for the higher temperatures and extended times, the BPVC values are relatively non-conservative. It is not known when the current HBB-I-14.6D table was developed. However, as discussed as part of the Table HBB-I-14.2 report for S_o, the last time the BPVC II-D, Table 1A stresses were updated was circa 1990. Also, our analysis combined data for both annealed and normalized and tempered material (since both heat treatments are permitted) and it is unclear as to what data were used in development of the BPVC 2017 (and 2019) S_r values.

Alloy 718:

Figure R.14.6-2E graphically summarizes the rupture strength-LMP curve for the analysis and the isotherms. Further review of the isotherms shows the turn-around to be significant at temperatures ≥ 565°C (1050°F). Given the use temperature range (425-550°C or 800 to 1050°F) and review of isotherms and data in this range, there appears to be little effect of the turn-around. Thus, the 2nd order fit is used for all predictions.

As seen in Table R.14.6-1E, the BPVC 2017 (and 2019) III-5 Table HBB-I-14.6E S_r values are consistently conservative relative to our analysis results.

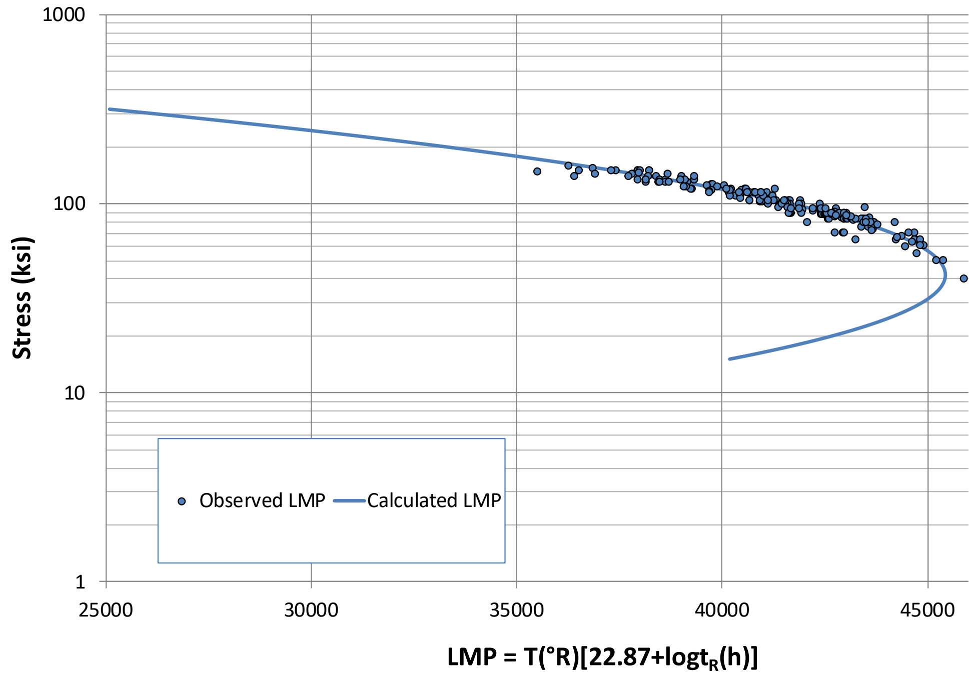
9Cr-1Mo-V:

As seen in Figure and Table R.14.6-1F, the BPVC 2017 III-5 Table HBB-I-14.6F S_r values are non-conservative relative to our analysis results at the higher temperatures and exposure durations, and the figure and table do not include S_r values for the 500,000-hour duration. However, this table and corresponding figure have been updated in BPVC 2019 III-5 with the addition of 500,000-hour S_r values. The updated Table and Figure HBB-I-14.6F in BPVC 2019 III-5 are found acceptable, and a recommendation for review of the 2017 edition is moot.

In our analysis, as noted earlier, a split region analysis was conducted for this material case. The curve-fits both exhibited acceptable LMP-2nd order logarithmic stress fits. The methodology is the same as one used in the recent correction and expansion of the S_r, S_t, S_t and S_{mt} tables in BPVC III-5, first appearing in the 2019 edition (ASME Record No. 16-2627). Additionally, BPVC II-D, Table 1A values have also been updated, again first appearing in the BPVC 2019 edition.

Figure R.14.6-2F graphically summarizes the best-fit rupture strength-LMP curves for the two split region analyses. The high stress region curve exhibited a turn-around at the highest temperature of interest (650°C or 1200°F). However, since at this temperature, the rupture strength is in the low stress region, the turn-around does not impact use of the 2nd order high stress region analysis.

As seen in the final analysis in Table R.14.6-1F-2019, our results are in generally good agreement with the current BPVC 2019 III-5 Table HBB-I-14.6F. The single stress value at 500,000 hours and the highest temperature is marginally non-conservative, but the table is judged to be acceptable. A comparison of the S_r values in BPVC 2017 and 2019 III-5 Table HBB-I-14.6F is presented in Table R.14.6-3F.



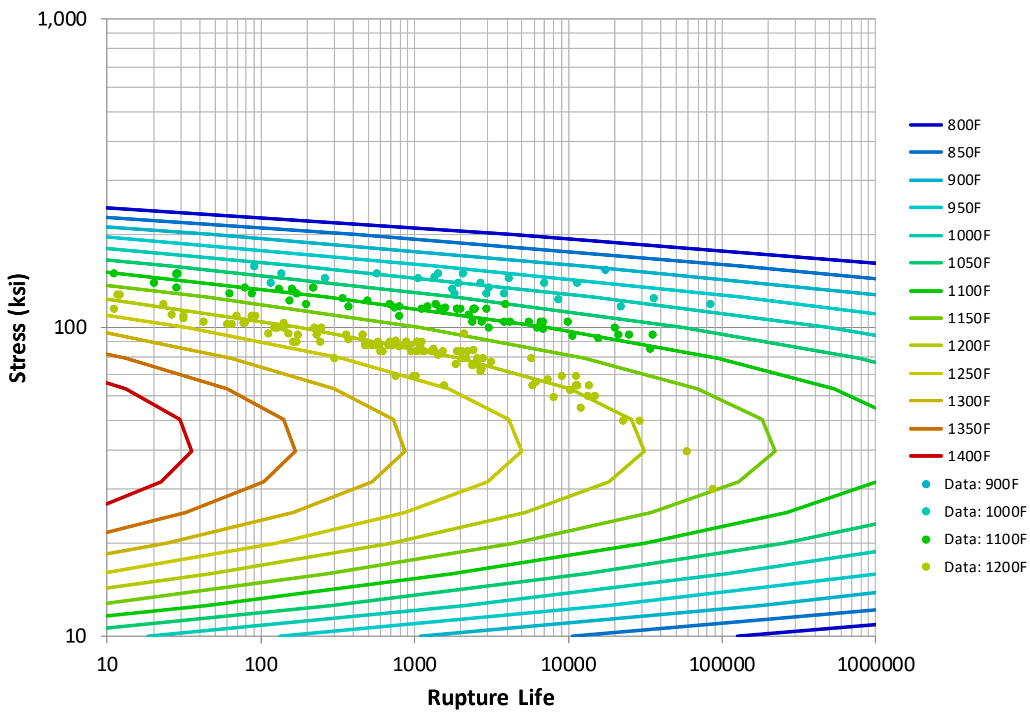
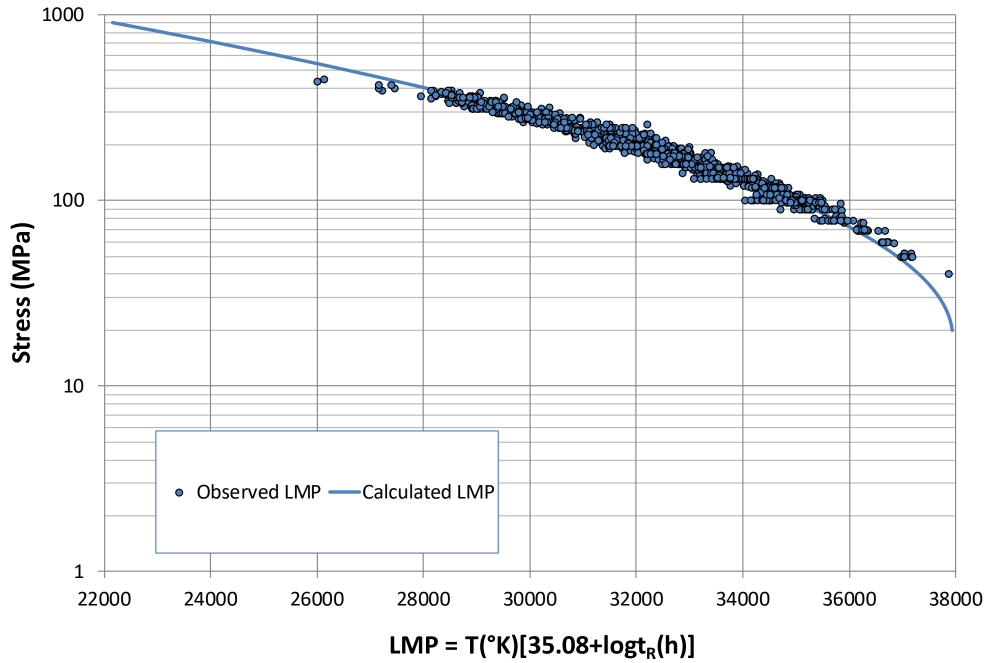
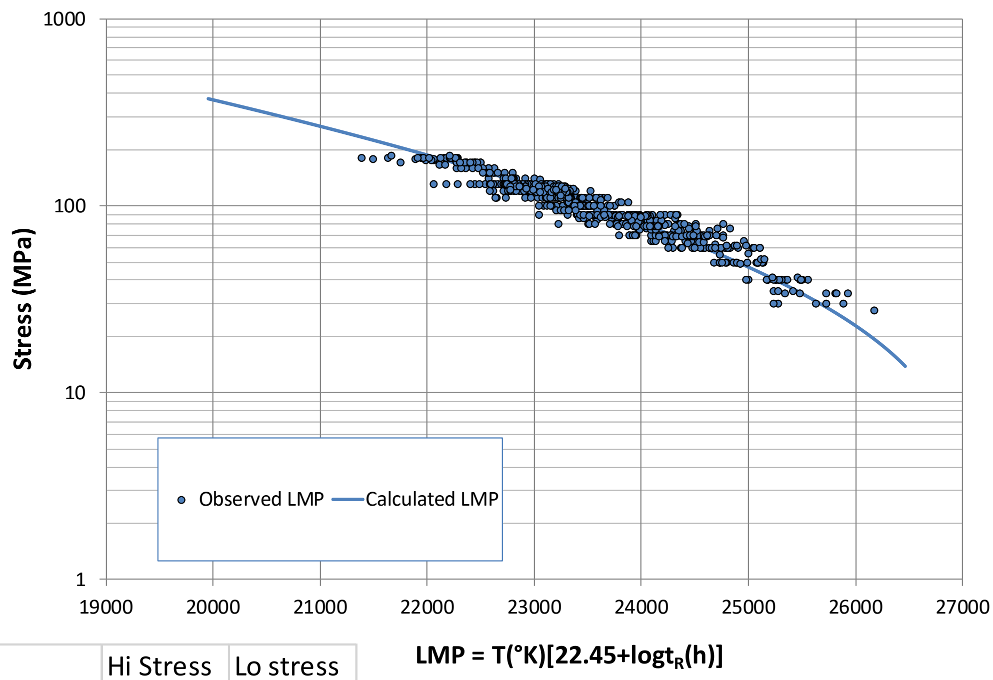


Figure R.14.6-2E. Summary of regression results for Alloy 718 – LMP plot and isotherms. The parabolic vertex turn-around does not impact the predictions for the use temperatures.



High Stress Region



Low Stress Region

	Hi Stress	Lo stress
C_{LP}=	35.08069	22.45217
a0 =	29108.19	25841.75
a1 =	13965.19	2809.952
a2 =	-5523.75	-1982.95
SEE=	0.377826	0.258595
R^2=	0.77	0.72

$\log t_R = -C_{LP} + a_0/T + a_1/T*\log S + a_2/T*(\log S)^2$

S is stress in MPa, T is temperature in °K and t_R is rupture time in hours

Figure R.14.6-2F. Summary of regression results for 9Cr-1Mo-V

Table R.14.6-3F. A comparison of the S_r values in BPVC 2017 and 2019 III-5 Table HBB-I-14.6F for 9Cr-1Mo-V

ksi hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F
700	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	68.8	71.0	66.0		64.7
750	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	68.9	69.0	65.7	67.3	62.8	63.5	59.7	60.2	56.9		55.6
800	66.5	66.5	66.5	66.5	66.5	66.5	66.5	66.5	66.5	63.2	63.1	60.2	59.4	57.0	56.1	54.2	52.7	51.1	49.6	48.4		47.1
850	63.4	63.4	63.4	63.4	63.4	61.2	59.7	58.1	56.0	54.9	52.7	51.9	49.3	48.8	46.3	46.0	43.3	43.0	40.6	40.3		39.1
900	59.8	59.7	57.0	56.6	53.3	53.2	50.0	50.0	46.6	46.6	43.7	43.7	40.6	40.6	37.9	37.9	35.2	35.2	32.8	32.0		30.0
950	51.2	51.2	47.9	47.9	44.5	44.5	41.5	41.5	38.5	38.5	35.8	35.8	33.1	33.1	30.7	30.7	28.2	27.8	26.1	23.8		22.1
1,000	42.8	42.8	39.9	39.9	36.8	36.8	34.1	34.1	31.4	31.4	29.0	29.0	26.6	26.6	24.5	24.5	22.3	20.6	20.5	17.3		15.9
1,050	35.6	35.6	32.9	32.9	30.1	30.1	27.7	27.7	25.3	25.3	23.2	23.2	21.1	21.1	19.2	18.1	17.3	14.8	15.7	12.2		11.1
1,100	29.2	29.2	26.8	26.8	24.4	24.4	22.3	22.3	20.1	20.1	18.3	18.2	16.4	15.9	14.8	13.0	13.1	10.4	11.7	8.3		7.4
1,150	23.7	23.7	21.6	21.6	19.4	19.4	17.6	17.6	15.7	15.5	14.1	13.5	12.4	11.3	10.2	9.0	8.2	6.9	6.7	5.3		4.6
1,200	19.0	19.0	17.1	17.1	15.2	15.2	13.6	13.3	11.9	11.4	10.5	9.9	8.0	7.8	6.5	6.0	4.9	4.3	3.7	3.1		2.6

MPa hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05		5.00E+05	
Temp., °C	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F	BPVC 2017 III-5 Table HBB-I-14.6F	BPVC 2019 III-5 Table HBB-I-14.6F
375	487	487	487	487	487	487	487	487	487	487	487	487	487	487	487	487	487	465	487	446		437
400	475	475	475	475	475	475	475	475	475	475	475	473	475	451	461	431	435	409	412	390		381
425	459	459	459	459	459	459	459	459	459	439	436	419	412	397	390	377	366	356	345	337		328
450	440	440	440	440	440	431	418	410	396	387	374	367	350	345	329	326	308	305	289	287		278
475	419	419	404	404	385	381	361	360	338	338	317	317	295	295	276	276	257	257	240	238		223
500	374	374	353	353	329	329	307	307	285	285	266	266	247	247	229	229	212	212	196	183		171
525	322	322	301	301	278	278	259	259	239	239	222	222	204	204	189	189	173	163	159	139		128
550	274	274	251	251	234	234	216	216	198	198	178	178	166	166	153	149	139	123	127	103		94
575	231	231	213	213	194	194	179	179	163	163	149	149	135	133	122	112	110	91	99	74		67
600	192	192	176	176	160	160	146	146	132	132	118	117	106	101	94	83	82	65	72	51		46
625	159	159	145	145	130	130	117	117	105	102	94	89	81	74	67	59	53	45	42	34		30
650	130	130	117	117	104	104	93	91	81	78	72	67	54	53	44	40	33	29	25	21		17

Table HBB-I-14.11, Permissible Materials for Bolting

- For Alloy 718, a minor typographical error is found: NO 7718 needs to be changed to N07718.
- For 304 SS and 316 SS, the table does not specify a minimum Carbon content (0.04% as for non-bolting base material per Table HBB-I-14.1a). The minimum carbon content specified in Section III, Division 5 for base metal except for bolting in Table HBB-I-14.1(a) is 0.04% for service above 1000°F; i.e., to help ensure adequate creep (time-dependent) strength. Our review and analysis of the bolting material stresses in Table HBB-I-14.12 (for S_o) and in the Figures HBB-I-14.13A and B (for S_{mt}), separately reported, indicate that the BPVC III-5 stresses are generally controlled by time-independent strength properties and are conservative, except for the two highest temperatures in Table HBB-I-14.12 for S_o where the controlling stress is time-dependent and the current BPVC stress potentially non-conservative. Based on the BPVC II-D Tables 3 and 4 stresses and the BPVC III-5 stresses, we do not think a minimum Carbon content specification is required, but it may be considered.
- The tabulated bolting materials specifications represent material consistent with the Code parent, non-bolting material product, and we recommend acceptance of the listed materials.

Table HBB-I-14.12, S_o Values for Design Conditions Calculation of Bolting Materials S_o Maximum Allowable Stress Intensity, ksi (MPa)

Observations Indicating Need for Review Consideration

Table R.14.12 summarizes our analysis results compared with the ASME 2017 (and 2019) III-5 Table HBB-I-14.12 S_o values, followed by a brief description of the analysis method, data used, and summary of results.

Basic Method of Analysis

The method of analysis for the creep data is the same as used for the base materials analysis; refer to the report section on Table HBB-I-14.2 (S_o). In the time-independent regime, the analysis methods used for each of the three materials is as summarized below.

304SS and 316SS

An examination of the ASME 2017 (and 2019) III-5 Table HBB-I-14.12 S_o values at the lower temperatures indicate that these values have been computed using the criteria applicable to BPVC II-D, Table 4 for material that has been strength-enhanced by heat treatment or strain hardening, limited by 1/3rd the yield strength at temperature. This is verified by application of the criteria using the BPVC II-D tabulated Y-1 (yield strength) values. The criteria have also been applied in BPVC II-D, Table 4 to Class 1A (post-finish solution treated material). The table lists S_o values that have evidently not been developed using the BPVC II-D, Tables 3 or 4 criteria applicable to non-strength-enhanced material. It should be noted that the BPVC II-D, Table 4 stress intensity values in the time-independent stress-controlled regime are also one-half the values that would be obtained using the non-strength-enhanced bolt material yield strength-calculated criteria of Table 4. The one-half representation appears to be a consequence of the design rules limiting pressure loading stresses to one-half, but permitting pressure + preload + thermal expansion stresses to the nominal non-bolting material stress intensity value (HBB-3233.1 and HBB-3233.2). Indeed, the Companion Guide to the ASME Boiler & Pressure Vessel Code (Ref. ASME 2002) confirms both the 1/3rd yield strength criterion and the one-half representation to accommodate preload and thermal expansion loads by stating as follows: "The intent of the Design Limits for bolting is to keep primary stresses below the lessor of 1/3 the yield strength or the allowables established for bolting in Section VIII, Div. 1. The combination of 1/3 the yield strength and the Section VIII properties provides a smooth transition of design allowables between Subsection NB and Subsection NH. The intent of the paragraph on the maximum average stress across the bolt due to pressure loading is to carry forward the additional safety factor used in Subsection NB bolting rules. Thus, the S_{mt} values for approved bolting materials are one-half of the values given for the corresponding structural material in Subsection NH." The representation of allowable stress intensity evidently applies to the BPVC III-5 tabulated S_o when controlled by the time-independent stress intensity values per the BPVC II-D, Table 4, 1/3rd yield strength criterion (or one-half that for corresponding non-bolting material in BPVC III-5). Review of the highest temperature tabulation of Table HBB-I-14.12 indicates that the one-half representation is not extended to the time-dependent stress intensity.

Table R.14.12. This Analysis compared with ASME 2017 (and 2019) III-5 Table HBB-I-14.12 S_o

ksi	°F	304SS		316SS		Alloy 718	
		ASME 2017 ASME 2019 III-5, Table HBB-I-14.12	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.12	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.12	This Analysis
	800	5.5	5.9	5.8	6.2	33.3	35.9
	850	5.5	5.8	5.8	6.1	33.1	35.8
	900	5.4	5.7	5.7	6.0	32.9	35.6
	950	5.3	5.7	5.7	5.9	32.6	35.3
	1000	5.2	5.6	5.6	5.8	32.3	34.9
	1050	5.1	5.5	5.6	5.7	32.0	34.4
	1100	4.9	5.4	5.5	5.6	....	
	1150	4.8	5.3	5.4	5.5	....	
	1200	4.7	5.1	5.4	5.3	....	
	1250	4.7	4.2	5.3	4.9	....	
	1300	3.7	3.1	4.1	3.5	....	

Table continues on the next page

MPa	°C	304SS		316SS		Alloy 718	
		ASME 2017 ASME 2019 III-5, Table HBB-I-14.12	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.12	This Analysis	ASME 2017 ASME 2019 III-5, Table HBB-I-14.12	This Analysis
	425	38	41	40	43	230	248
	450	38	40	40	42	228	247
	475	37	40	39	41	227	246
	500	37	39	39	41	226	244
	525	36	39	39	40	224	242
	550	35	38	39	40	222	239
	575	35	38	39	39	....	
	600	34	37	38	38	....	
	625	33	36	37	38	....	
	650	32	35	37	37	....	
	675	32	29	37	34	....	
	700	27	22	29	25	....	

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%	
Non-conservative relative to this analysis - Difference, δ > 10%	% of ASME value
Yield Strength-Controlled	Tensile Strength-Controlled

For consistency and relevant comparison, we use the criteria that BPVC 2017 (and 2019) III-5 Table HBB-I-14.12 have apparently used.

The data and analysis method for the temperature-dependent yield and tensile strength are the same as used for the review of ASME III-5, Tables HBB-I-14.5 (yield strength) and HBB-3225-1 (tensile strength); refer to the report sections for those tables and details.

<u>Alloy 718</u>

In reviewing the BPVC 2017 (and 2019) III- 5 Table HBB-I-14.12 S_o values for Alloy 718, we infer that the values have been developed using a 'tensile strength divided by 5' criterion for all temperatures. In case of Alloy 718 with less strain hardening in contrast with the austenitic stainless steels, the BPVC II-D, Table 3 criteria for material strength-enhanced by heat treatment or strain hardening produce more conservative stresses than do the corresponding Table 4 criteria. The Table 3 criteria include the lower of 1/5th the room temperature tensile strength and 1/4th the S_u ($1.1S_TR_T$) tensile strength value at temperatures above room temperature. Based on the available tensile data reviewed, application of the criteria would yield a constant S_o value equal to 1/5th the room temperature tensile strength over the Table HBB-I-14.12 temperature range of relevance. The Table HBB-I-14.12 S_o values are monotonically decreasing, and indeed, appear to have been developed using a 1/5tth S_u (tensile strength at temperature) criterion. These S_o values are conservative relative to values that would be developed with strict application of the BPVC II-D Table 3 criterion. For consistency and comparison, we have used the 1/5th criterion that we infer has been used for Table HBB-I-14.12.

The data and analysis method for the temperature-dependent yield and tensile strength are the same as used for the review of BPVC 2017 (and 2019) III-5 Tables HBB-I-14.5 (yield strength) and HBB-3225-1 (tensile strength); refer to the report sections for those tables and details.

Discussion of Results

As seen with prior analyses in review of the base metal S_o, S_r and S_t tables (HBB-I-14.2, HBB-I-14.6, HBB-I-14.4, respectively), we again observe a potential non-conservatism in the time-dependent S_o values at the highest temperature(s) in case of 304 SS and 316 SS.

In case of Alloy 718, there is no evidence of the current BPVC 2017 (and 2019) III-5 Table HBB-I-14.12 S_o values being non-conservative. In the absence of specific Code criteria/definitions for S_o in case of these bolting materials, the analysis for comparisons with the Code-tabulated stress intensity values required inferring the criteria used for the Code values in each material case. The inferred criteria do not always appear self-consistent, such as the criteria apparently used for Alloy 718. The observations support the need for Code definitions of S_o.

Figures and Table HBB-I-14.13A ~ C, S_{mt} –Allowable Stress Intensity of Bolting Materials

Explanation of the Conditions

1) BPVC 2017 (and 2019) III-5, HBB-I-14.13A and B contain graphics illustrating S_{mt} (S_m and S_t) versus temperature up to 2. E+05 hours for 304 SS and 316 SS. In the absence of any tabulated S_{mt} values for these two alloys, the only option available to the user is to estimate the S_{mt} values from the HBB-I-14.13 A and B graphics, which is imprecise and subject to significant error.
2) The criteria used in establishing the S_t and S_m stresses for bolting material are not defined in BPVC III-5. Our review indicates that in some cases, the S_m values appear to be based on criteria different than those that would be used for BPVC II-D, Tables 3 and 4. Further, the S_t values inferred from the graphs for 304 SS and 316 SS and the tabulated stresses for Alloy 718 appear to be well below S_t values one would expect using the BPVC III-5 criteria for non-bolting material (HBB-3221).
3) Research into the unexpectedly low S_t values for the three materials indicates that the graphed and listed stresses are not consistent with those that would be computed using the definition of S_t in BPVC III-5 for non-bolting material. Rather, these values appear to be one-half the expected (by definition) values, consistent with an endnote appended to the time-dependent creep use-fraction rule for bolt design (explanation below under Basic Method of Analysis). This inconsistency in the presentation of S_t, including its apparent variance from the criteria for the time-dependent S_o for 304 and 316 SS (the one-half non-

bolting material representation not used for S_o - see discussion on Table HBB-I-14.12), merits review.

4) The graphed S_t values for 304 SS and 316 SS appear non-conservative relative to our analysis results, more so at the higher temperatures and longer exposure durations. In the absence of tabulated values, however, the extent of the relative non-conservatism cannot be determined.

Analysis and Results

Figure R14.13-1A summarizes the S_{mt} analysis results presented graphically along with the BPVC 2017 (and 2019) III-5 Figure HBB-I-14.3A for 304 SS.

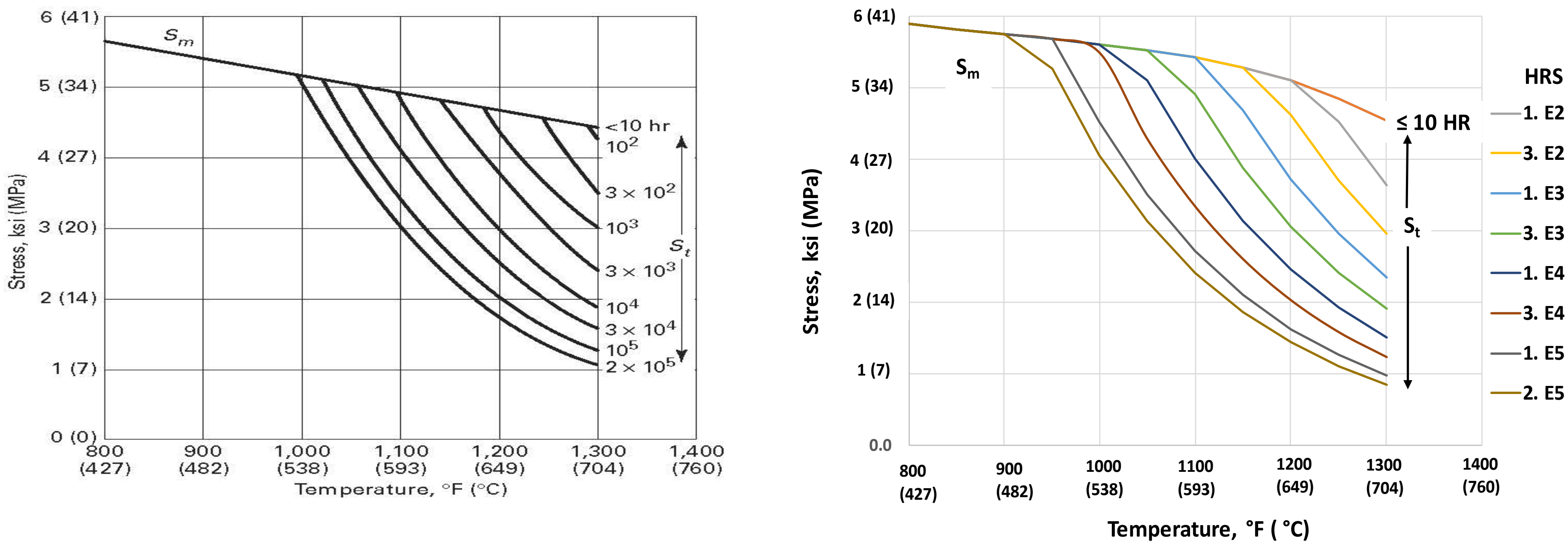
Figure R14.13-1B summarizes the S_{mt} analysis results presented graphically along with the BPVC 2017 (and 2019) III-5 Figure HBB-I-14.3B for 316 SS.

Figure R14.13-1C summarizes the S_{mt} analysis results presented graphically along with the BPVC 2017 (and 2019) III-5 Figure HBB-I-14.3C for Alloy 718.

Table R14.13-1A is a summary of the analysis results for 304 SS. No comparison can be made with the BPVC III-5 stresses since there is no tabulation associated with Figure HBB-I-14.13A.

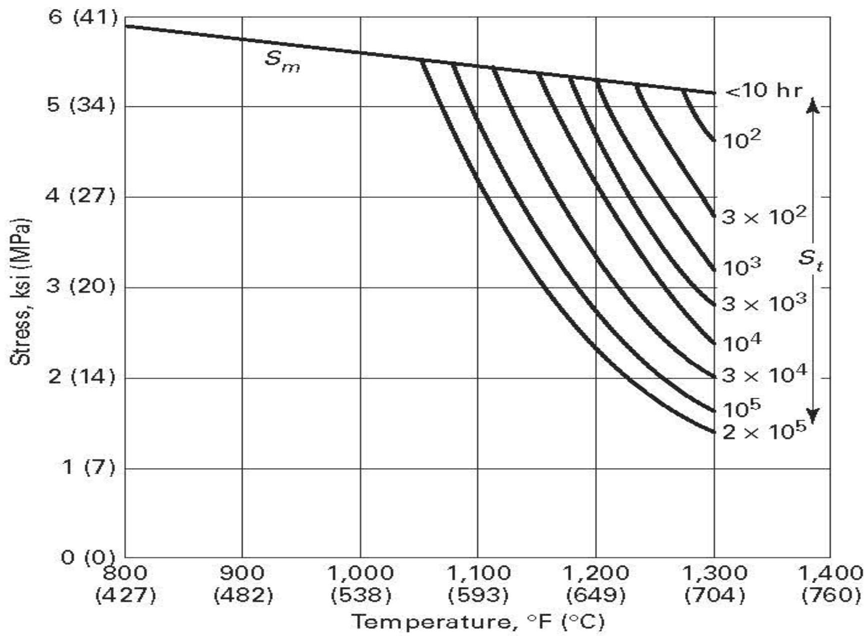
Table R14.13-1B is a summary of the analysis results for 316 SS. No comparison can be made with the BPVC III-5 stresses since there is no tabulation associated with Figure HBB-I-14.13B.

Table R14.13-1C is a tabulated summary of this analysis compared with the BPVC 2017 (and 2019) III-5, Table HBB-I-14.13C S_{mt} values.

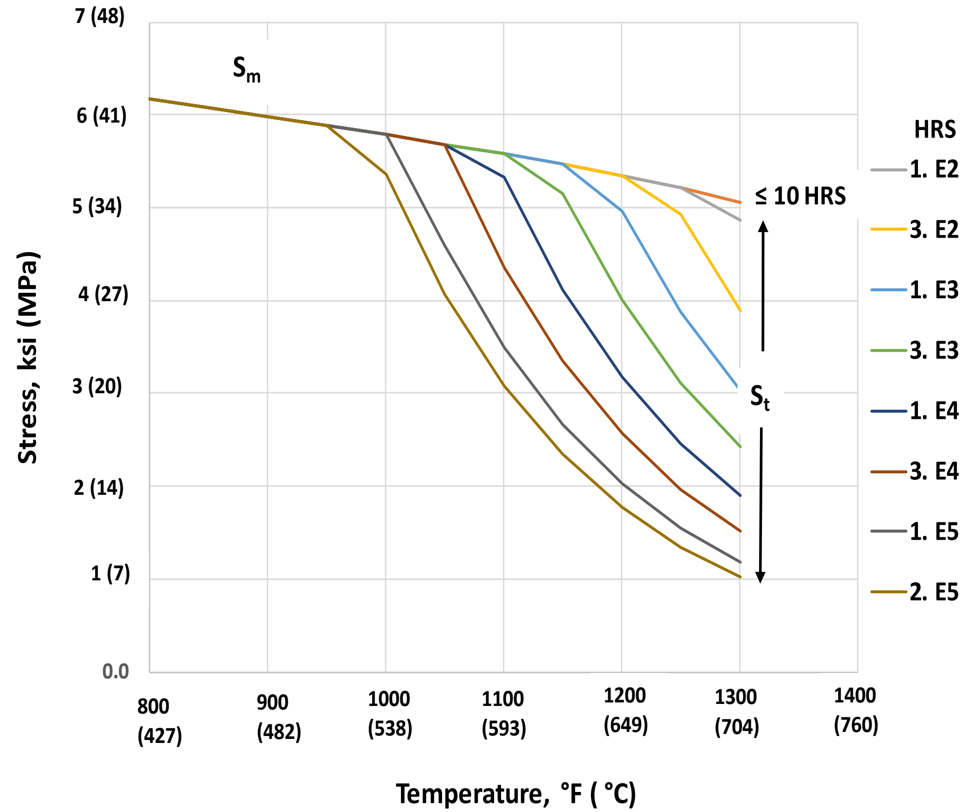


BPVC 2017 (and 2019) III-5 | This Analysis

Figure R14.13-1A. Graphical summary of the S_{mt} results of This Analysis compared with BPVC 2017 (and 2019) III-5, Figure HBB-I-14.13A for 304 SS

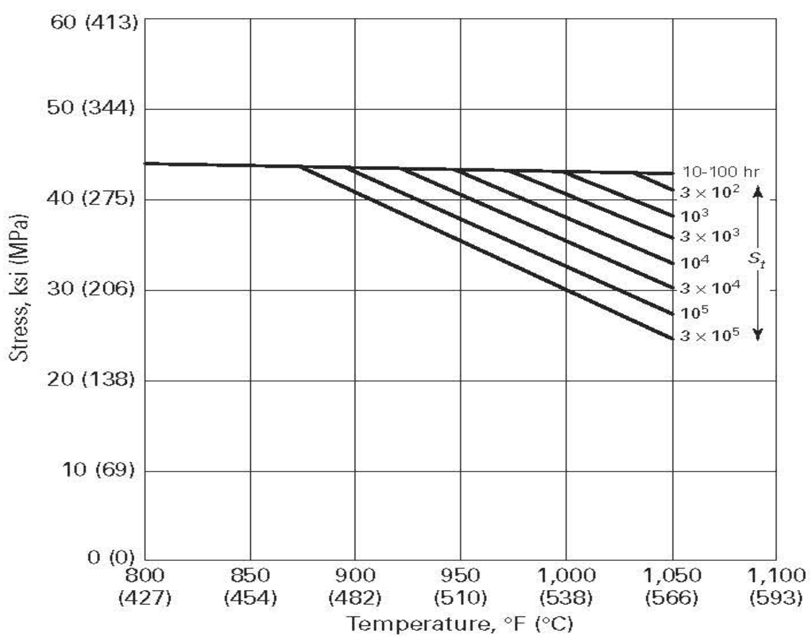


BPVC 2017 (and 2019) III-5

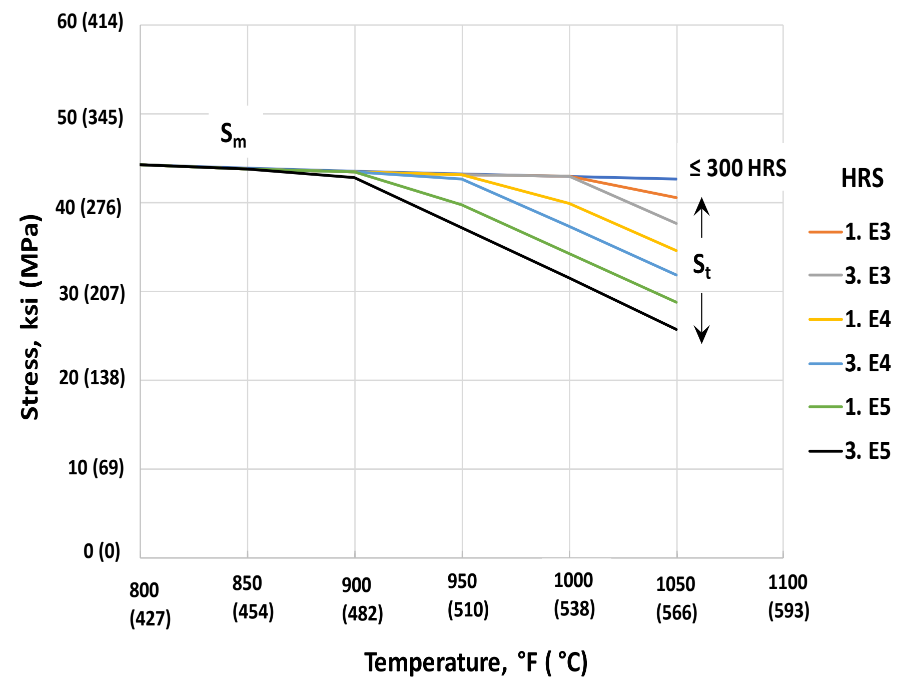


This Analysis

Figure R14.13-1B. Graphical summary of the S_{mt} results of This Analysis compared with BPVC 2017 (and 2019) III-5, Figure HBB-I-14.13B for 316 SS



BPVC 2017 (and 2019) III-5



This Analysis

Figure R14.13-1C. Graphical summary of the S_{mt} results of this analysis compared with BPVC 2017 (and 2019) III-5, Figure HBB-I-14.13C for Alloy 718

Table R14.13-1A. Tabulation of the results of This Analysis for S_{mt} for 304 SS, using the criteria inferred to have been used in development of the BPVC III-5, HBB-I-14.13A graphic

ksi hours	1	10	30	1.00E+02	3.00E+02	1.00E+03	3.00E+03	1.00E+04	3.00E+04	1.00E+05	2.00E+05
Temp., °F	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis
800	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9
850	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
900	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
950	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.3
1000	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.5	4.5	4.1
1050	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.1	4.3	3.5	3.1
1100	5.4	5.4	5.4	5.4	5.4	5.4	4.9	4.0	3.3	2.7	2.4
1150	5.3	5.3	5.3	5.3	5.3	4.7	3.9	3.1	2.6	2.1	1.9
1200	5.1	5.1	5.1	5.1	4.6	3.7	3.1	2.5	2.0	1.6	1.4
1250	4.9	4.9	4.9	4.5	3.7	3.0	2.4	1.9	1.6	1.3	1.1
1300	4.5	4.5	4.5	3.6	3.0	2.3	1.9	1.5	1.2	1.0	0.86

MPa hours	1	10	30	1.00E+02	3.00E+02	1.00E+03	3.00E+03	1.00E+04	3.00E+04	1.00E+05	2.00E+05
Temp., °C	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis
425	41	41	41	41	41	41	41	41	41	41	41
450	40	40	40	40	40	40	40	40	40	40	40
475	40	40	40	40	40	40	40	40	40	40	40
500	39	39	39	39	39	39	39	39	39	39	39
525	39	39	39	39	39	39	39	39	39	35	32
550	38	38	38	38	38	38	38	38	34	28	25
575	38	38	38	38	38	38	38	32	27	22	20
600	37	37	37	37	37	37	32	26	22	18	16
625	36	36	36	36	36	31	26	21	17	14	12
650	35	35	35	35	32	25	21	17	14	11	9.8
675	34	34	34	32	26	21	17	14	11	8.9	7.8
700	32	32	32	26	21	17	14	11	8.8	7.0	6.2

S_m ($1/3S_yR_y$) Yield strength-controlled	80% Minimum Stress to Initiate Tertiary Creep

Table R14.13-1B. Tabulation of the results of This Analysis for S_{mt} for 316 SS, using the criteria inferred to have been used in development of the BPVC III-5, HBB-I-14.13B graphic.

ksi hours	1	10	30	1.00E+02	3.00E+02	1.00E+03	3.00E+03	1.00E+04	3.00E+04	1.00E+05	2.00E+05
Temp., °F	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis
800	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
850	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
900	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
950	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9
1000	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.4
1050	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	4.6	4.1
1100	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.3	4.4	3.5	3.1
1150	5.5	5.5	5.5	5.5	5.5	5.5	5.2	4.1	3.3	2.7	2.3
1200	5.3	5.3	5.3	5.3	5.3	5.0	4.0	3.2	2.6	2.0	1.8
1250	5.2	5.2	5.2	5.2	4.9	3.9	3.1	2.5	2.0	1.5	1.3
1300	5.1	5.1	5.1	4.9	3.9	3.0	2.4	1.9	1.5	1.2	1.0

MPa hours	1	10	30	1.00E+02	3.00E+02	1.00E+03	3.00E+03	1.00E+04	3.00E+04	1.00E+05	2.00E+05
Temp., °C	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis	This Analysis
425	43	43	43	43	43	43	43	43	43	43	43
450	42	42	42	42	42	42	42	42	42	42	42
475	41	41	41	41	41	41	41	41	41	41	41
500	41	41	41	41	41	41	41	41	41	41	41
525	40	40	40	40	40	40	40	40	40	40	40
550	40	40	40	40	40	40	40	40	40	37	33
575	39	39	39	39	39	39	39	39	36	29	26
600	38	38	38	38	38	38	38	34	28	23	20
625	38	38	38	38	38	38	34	27	22	18	16
650	37	37	37	37	37	34	27	22	18	14	12
675	36	36	36	36	34	27	22	17	14	11	9.5
700	35	35	35	35	28	22	17	14	11	8.5	7.4

S_m ($1/3S_yR_y$) Yield strength-controlled	80% Minimum Stress to Initiate Tertiary Creep

Table R14.13-1C. Tabulation of the results of this analysis for S_{mt} for Alloy 718 using criteria inferred to have been used for the BPVC table, compared with BPVC 2017 (and 2019) III-5, Table HBB-I-14.13C stresses.

ksi hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis
800	44.4	44.2	44.4	44.2	44.4	44.2	44.4	44.2	44.4	44.2	44.4	44.2	44.4	44.2	44.4	44.2	44.4	44.2	44.4	44.2
850	44.1	43.8	44.1	43.8	44.1	43.8	44.1	43.8	44.1	43.8	44.1	43.8	44.1	43.8	44.1	43.8	44.1	43.8	44.1	43.8
900	43.8	43.5	43.8	43.5	43.8	43.5	43.8	43.5	43.8	43.5	43.8	43.5	43.8	43.5	43.8	43.5	43.3	43.5	43.3	42.8
950	43.5	43.2	43.5	43.2	43.5	43.2	43.5	43.2	43.5	43.2	43.5	43.2	43.0	43.2	40.7	42.7	38.0	39.8	35.3	37.2
1000	43.1	42.9	43.1	42.9	43.1	42.9	43.1	42.9	43.1	42.9	40.7	42.9	38.0	40.0	35.3	37.3	32.7	34.3	30.0	31.6
1050	42.7	42.7	42.7	42.7	42.7	42.7	41.3	42.7	38.0	40.5	35.3	37.7	32.7	34.7	30.3	31.9	27.0	28.7	24.7	25.7

MPa hours	10		30		1.00E+02		3.00E+02		1.00E+03		3.00E+03		1.00E+04		3.00E+04		1.00E+05		3.00E+05	
Temp., °C	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis	ASME 2017 ASME 2019 III-5 Table HBB-I-14.13C	This Analysis
425	306	305	306	305	306	305	306	305	306	305	306	305	306	305	306	305	306	305	306	305
450	304	302	304	302	304	302	304	302	304	302	304	302	304	302	304	302	304	302	304	302
475	303	300	303	300	303	300	303	300	303	300	303	300	303	300	303	300	300	300	300	300
500	301	299	301	299	301	299	301	299	301	299	301	299	298	299	288	299	275	288	263	270
525	298	297	298	297	298	297	298	297	298	297	290	297	282	292	261	274	242	254	224	236
550	296	295	296	295	296	295	296	295	282	295	265	280	250	260	228	241	208	220	191	201

S_m ($1/3 S_y R_y$) Yield strength-controlled	Unshaded: 67% Minimum Stress to Rupture

Basic Method of Analysis

Criteria and Method for Time-Dependent Stresses, S_t

The method of analysis for the creep data is the same as used for the review of S_t in Tables HBB-I-14.4A ~ E. However, in determining S_t for Alloy 718, we have only used rupture data and the 67% of the minimum rupture stress criterion without consideration of the 1% strain and tertiary creep onset criteria.

In the absence of BPVC III-5-defined criteria for non-bolting material, we initially applied the three BPVC III-5 criteria for S_t as defined for non-bolting material (HBB-3221), except for Alloy 718 as noted above, where only one criterion is applied. The results of this analysis indicated that the BPVC III-5 S_t stresses (same for both the 2017 and 2019 editions) are far below our computed values in all cases (results not reported here). In case of Alloy 718, the computed time-dependent S_t did not control S_{mt} that was governed by a single time-independent stress intensity, S_m, curve for the entire time-temperature range of relevance, in contrast to BPVC III-5 Figure and Table HBB-I-14.13C. The findings on stainless steels are also contrary to all of the other time-dependent analysis results on non-bolting material where in many cases the BPVC III-5 stresses were found to be relatively non-conservative (higher than our results).

In reviewing the BPVC III-5 Code design limits for bolts at elevated temperature (BPVC III-5 HBB-3233), we find that determination of bolt limit stresses in the time-dependent creep regime requires the designer to apply a use-fraction rule; i.e., a limit to time at stress divided by lifetime at stress computed using S_t (per HBB-3224 (b) or (d) for average cross section or periphery stress, respectively). Further, and of major relevance, the reference to implementation of the rule carries with it, an endnote (# 15) that states: "S_t values to be used are twice those given in Figures HBB-I-14.13A through HBB-I-14.13C." It is inferred then that the S_t values in the figures do not represent the time-dependent stress limit, S_t, as would be determined using the defined non-bolting material criteria (HBB-3221), but that the values reflected in the graphs (and in the Table HBB-I-14.13C for Alloy 718) are one-half the value computed per the HBB-3221 definition. Evidently, in case of S_t, the one-half representation used for time-independent strength-controlled bolting design (see discussion on Table HBB-I-14.12 for S_o) is extended to the time-dependent strength-controlled region (apparently not the case for S_o in Table HBB-I-14.12). This presentation of the design rules can be confusing and lead to errors, particularly since the mechanical design and the basis for setting the allowable stresses are often compartmentalized. Indeed, the use of the term, S_t, to mean two different stresses, whether for non-bolting or for bolting material, is, in itself, a significant issue. We therefore recommend requiring that the criteria/definition of S_t for bolting material be clearly indicated.

Based on our inference regarding how S_t has been determined for bolting in BPVC III-5, and for a more appropriate comparison with the BPVC III-5 figures and table, we re-executed our analysis using a one-half factor on the conventionally (for non-bolting material) computed S_t.

Time-Independent Stress Intensity, S_m

In the time-independent regime, the analysis methods used for each of the three materials are as summarized below.

304 SS and 316 SS

An examination of the BPVC 2017 (and 2019) III-5 graphics at the lower temperatures indicate that these stresses have been computed using the criteria applicable to BPVC II-D, Table 4 for material that has been strength-enhanced by heat treatment or strain hardening, also evidently used in development of the S_o table, HBB-I-14.12. This is verified by application of the criteria using the BPVC II-D tabulated Y-1 (yield strength) values. The criteria have also been applied in BPVC II-D, Table 4 to Class 1A (post-finish solution treated material), although for Class 1 material (a permitted material for BPVC III, Div. 5, per Table HBB-I-14.11), the Table 4 stress intensity values are evidently based on criteria for non-strength-enhanced material. This inconsistency highlights the importance of identifying the specific criteria used in development of the S_{mt} figures, HBB-I-14.13A and HBB-I-14.13B.

As discussed for Table HBB-I-14.12 for S_o, it is noted that the BPVC II-D, Table 4 stress intensity values in the time-independent stress-controlled regime are one-half the values that would be obtained using the non-strength-enhanced bolt material yield strength-calculated criteria of Table 4. This one-half factor is consistent with that inferred to have been used in the time-dependent S_t values; i.e., this one-half factor is extended into the time-dependent region, unlike in case of S_o of Table HBB-I-14.12. The one-half representation appears to be a consequence of the design rules limiting pressure loading stresses to one-half, but permitting pressure + preload + thermal expansion stresses to the nominal non-bolting material stress intensity value (HBB-3233.1 and HBB-3233.2). The discussion on Table HBB-I-14.12 provides further detail on the inferencing and on ASME background material confirming the inferences (Ref. ASME 2002). For consistency and relevant comparison, we use the criteria that have apparently been used in development of the graphics.

The data and analysis method for the temperature-dependent yield and tensile strength are the same as used for the review of BPVC III-5 Tables HBB-I-14.5 and HBB-3225-1, respectively.

Alloy 718

In reviewing the BPVC 2017 (and 2019) III- 5 Table HBB-I-14.13C S_{mt} values for Alloy 718, we infer that the stresses have been developed using the BPVC II-D, Table 4 criteria for materials with strength enhanced by heat treatment or precipitation hardening.

We have used the same criteria for the time-independent stresses (BPVC II-D, Table 4 for precipitation hardened material) as we infer ASME to have used in development of Figure HBB-I-14.13C and Table HBB-I-14.13C.

Discussion of Results

304 SS and 316 SS

Since there is no tabulation of the S_{mt} values given in Figures HBB-I-14.13A and B, no quantitative judgment can be made regarding the conservatism associated with the BPVC III-5 S_{mt} values. Simple visual comparison (see Figures R14.13-1A and B above) indicates that the BPVC stresses are non-conservative relative to our analysis in the time-dependent, S_t-controlled regime, more so at the higher temperatures and longer exposure durations. As is the case for the non-bolting material (report on HBB-I-14.4), the time-dependent S_t stresses are governed by the initiation of tertiary creep criterion. For perspective, the issues associated with implementation of the tertiary creep criterion and our limited research into its effect for 304 SS, by way of example, are described in Appendix TCOC: "Comments on the Tertiary Creep Onset Criterion for S_t (and S_{mt})."

Alloy 718

In case of Alloy 718, the BPVC III-5 HBB-I-14.13C tabulated stresses are either in good agreement with, or conservative relative to our analysis results.

4.3. Nonmandatory Appendix HBB-U Guidelines for Restricted Material Specifications to Improve Performance in Certain Service Applications

Table HBB-U-1, Recommended Restrictions
Comments

- It was found that the 100,000-hour expected creep rupture strength values derived from three NIMS datasets of 316 SS (Ref. NRIM 2011) fell on or below the BPVC 2017 (and 2019) S_o (Table HBB-I-14.2) design curve, as shown in Figure R.U-1 (Ref. Hoffelner 2013). It is believed that the low creep rupture strength can be improved by restricting the chemical composition, which is consistent with the ASME-published set of additional recommendations relating to ensuring a minimum amount of free nitrogen for improved and less scattered creep properties for use temperatures ≥ 1100°F (59°5°C) (Ref. Turek 2013) (also, see report Table HBB-I-14.1(a) Sec 4).
- The restrictions on the chemical composition and grain size of 304 SS and 316 SS as embodied in Table HBB-U-1 are not verified with regard to the optimal range of characteristics for improved performance. However, the tabulated restricted range of characteristics is expected to assure performance and, on average, provide improved performance over the materials produced without adherence to the guidelines of Table HBB-U-1.
- The restricted grain size range of ASTM No. 3-6 helps assure creep performance by maintaining a coarse grain structure of ASTM No. ≤ 6 that is not assured in many of the

permitted specifications listed in mandatory Appendix HBB-I-14, Table HBB-I-14.1(a). These include:

- for 304SS and 316SS, all except SA-479 that specifies ASTM No. ≤ 6 for ASME Code service at > 1000°F (540°C);
- for 304H and 316H SS, SA-213, SA-240, SA-376 that have a specified ASTM No. ≤ 7, and SA-403 without a specified grain size.

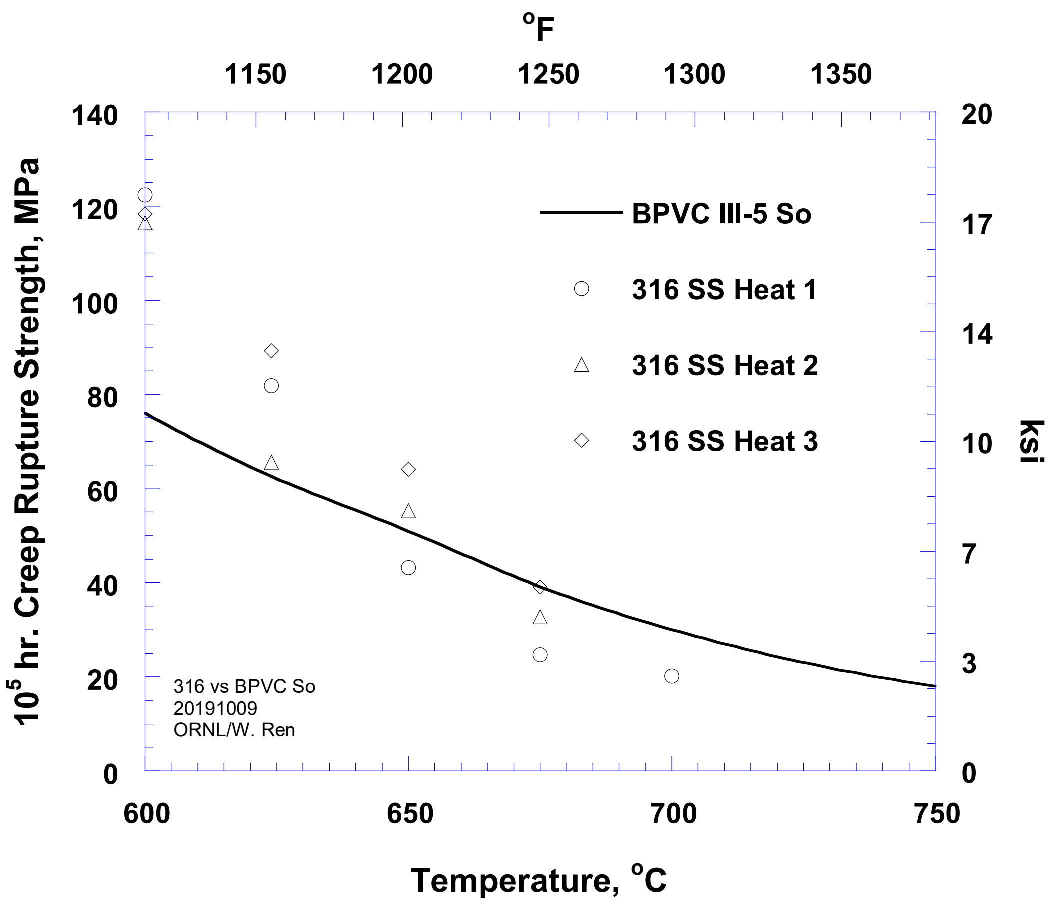


Figure R.U-1. Comparison of 100,000 hours expected creep rupture strength of 3 different Japan NIMS heats of 316 SS with the 2017 (and 2019) BPVC III-5 Table HBB-I-14.2 S_o design curve

- The upper limit grain size of ASTM No. 3 helps limit loss of toughness, while maintaining creep performance.
- The chemical composition of the guidelines embodied in Table HBB-U-1:
  - includes refined ranges of elements in the materials specifications to help creep performance (minimum C, specified N as in SA-182, SA-213, restricted Si, restricted Ni, increased Cr lower limit);
  - includes added restrictions on tramp and other elements not controlled by the specifications to minimize a deleterious effect of these on creep performance and toughness (Al, Sb, Pb, Se, Sn, Zn);

- includes addition of minor elements for creep performance (B in 316SS, Cb/Nb in 304SS).
- The Table HBB-U-1-tabulated melt practice of AOD or AOD/ESR, i.e. argon oxygen decarburization/electro-slag melting, helps maximize cleanliness, enhancing creep and toughness.

5. SUMMARY

This review covers some core portions of 2017 and 2019 Editions of ASME Section III, Division 5, "High Temperature Reactors," mostly presented in the form of tables and plots for reactor structural design use, as summarized in the following:

Code Item	Title
Article HBB-2000	Material [Title Only, for Class A Metallic Pressure Boundary Components, Elevated Temperature Service]
HBB-2100	[No Title]
HBB-2120	PRESSURE-RETAINING MATERIALS [Title Only]
HBB-2121	Permitted Material Specifications
HBB-2123	Design Stress Intensity Values
HBB-2160	DETERIORATION OF MATERIAL IN SERVICE
HBB-2400	[No Title]
HBB-2430	[No Title]
HBB-2433	Delta Ferrite Determination
HBB-2433.1	Method
HBB-2433.2	Acceptance Standards
HBB-2500	[No Title]
HBB-2530	[No Title]
HBB-2539	Repair by Welding
HBB-2800	FATIGUE ACCEPTANCE TEST
MANDATORY APPENDIX HBB-I-14	TABLES AND FIGURES [Title Only]
Table HBB-I-14.1(a)	Permissible Base Materials for Structures Other Than Bolting
Table HBB-I-14.1(b)	Permissible Weld Materials
Table HBB-I-14.2	S_o — Maximum Allowable Stress Intensity, ksi (MPa), for Design Condition Calculations
Figure HBB-I-14.3A	S_{mt} — Type 304 SS
Table HBB-I-14.3A	S_{mt} — Allowable Stress Intensity Values, 1,000 psi, Type 304 SS
Figure HBB-I-14.3B	S_{mt} — Type 316 SS
Table HBB-I-14.3B	S_{mt} — Allowable Stress Intensity Values, 1,000 psi, Type 316 SS
Figure HBB-I-14.3C	S_{mt} — Ni-Fe-Cr (Alloy 800H)
Table HBB-I-14.3C	S_{mt} — Allowable Stress Intensity Values, ksi (MPa), Ni-Fe-Cr (Alloy 800H)
Figure HBB-I-14.3D	S_{mt} — 2¼Cr-1Mo
Table HBB-I-14.3D	S_{mt} — Allowable Stress Intensity Values, ksi (MPa), 2¼Cr-1Mo

Code Item	Title
Figure HBB-I-14.3E	S_{mt} — 9Cr-1Mo-V
Table HBB-I-14.3E	S_{mt} — Allowable Stress Intensity Values, ksi (MPa), 9Cr-1Mo-V
Figure HBB-I-14.4A	S_t — Type 304 SS
Table HBB-I-14.4A	S_t — Allowable Stress Intensity Values, 1,000 psi (MPa), Type 304 SS
Figure HBB-I-14.4B	S_t — Type 316 SS
Table HBB-I-14.4B	S_t — Allowable Stress Intensity Values, 1,000 psi (MPa), Type 316 SS
Figure HBB-I-14.4C	S_t — Ni-Fe-Cr (Alloy 800H)
Table HBB-I-14.4C	S_t — Allowable Stress Intensity Values, ksi (MPa), Ni-Fe-Cr (Alloy 800H)
Figure HBB-I-14.4D	S_t — 2¼Cr-1Mo
Table HBB-I-14.4D	S_t — Allowable Stress Intensity Values, ksi (MPa), 2¼Cr-1Mo
Figure HBB-I-14.4E	S_t — 9Cr-1Mo-V
Table HBB-I-14.4E	S_t — Allowable Stress Intensity Values, ksi (MPa), 9Cr-1Mo-V
Table HBB-I-14.5	Yield Strength Values, Sy, Versus Temperature
Table HBB-I-14.5	Yield Strength Values, Sy, Versus Temperature (Cont'd)
Figure HBB-I-14.6A	Minimum Stress-to-Rupture
Table HBB-I-14.6A	Expected Minimum Stress-to-Rupture Values, 1,000 psi (MPa), Type 304 SS
Figure HBB-I-14.6B	Minimum Stress-to-Rupture
Table HBB-I-14.6B	Expected Minimum Stress-to-Rupture Values, 1,000 psi (MPa), Type 316 SS
Figure HBB-I-14.6C	Minimum Stress-to-Rupture — Ni-Fe-Cr (Alloy 800H)
Table HBB-I-14.6C	Expected Minimum Stress-to-Rupture Values, ksi (MPa), Ni-Fe-Cr (Alloy 800H)
Figure HBB-I-14.6D	2¼Cr-1Mo — 100% of the Minimum Stress-to-Rupture
Table HBB-I-14.6D	2¼Cr-1Mo — Expected Minimum Stress-to-Rupture Values, ksi (MPa)
Figure HBB-I-14.6E	Minimum Stress-to-Rupture, Alloy 718
Table HBB-I-14.6E	Expected Minimum Stress-to-Rupture Values, ksi (MPa), Ni-Cr-Fe-Mo-Cb (Alloy 718)
Figure HBB-I-14.6F	9Cr-1Mo-V — Expected Minimum Stress-to-Rupture, ksi (MPa)
Table HBB-I-14.6F	9Cr-1Mo-V, Sr — Expected Minimum Stress-to-Rupture Values, ksi (MPa)
Table HBB-I-14.11	Permissible Materials for Bolting
Table HBB-I-14.12	S_o Values for Design Conditions Calculation of Bolting Materials So Maximum Allowable Stress Intensity, ksi (MPa)
Figure HBB-I-14.13A	S_{mt} — Allowable Stress Intensity, Type 304 SS, Bolting
Figure HBB-I-14.13B	S_{mt} — Allowable Stress Intensity, Type 316 SS, Bolting
Figure HBB-I-14.13C	S_{mt} — Allowable Stress, Alloy 718, Bolting
Table HBB-I-14.13C	S_{mt} — Allowable Stress Values, ksi (MPa), Alloy 718, Bolting

Code Item	Title
NONMANDATORY APPENDIX HBB-U	GUIDELINES FOR RESTRICTED MATERIAL SPECIFICATIONS TO IMPROVE PERFORMANCE IN CERTAIN SERVICE APPLICATIONS
HBB-U-1100	SCOPE
HBB-U-1110	OBJECTIVES
HBB-U-1200	SERVICE CONDITIONS
HBB-U-1300	RECOMMEDED RESTRICTIONS
Table HBB-U-1	Recommended Restrictions
Article HCB-2000	Material [Title Only, for Class B Metallic Pressure Boundary Components, Elevated Temperature Service]
HCB-2100	GENERAL REQUIREMENTS FOR MATERIAL
HCB-2400	[No Title]
HCB-2430	[No Title]
HCB-2433	[No Title]
HCB-2433.2	Acceptance Standards
HCB-2500	[No Title]
HCB-2570	[No Title]
HCB-2571	Required Examination
HCB-2571.1	Method
HCB-2571.2	Acceptance Standards
Article HGB-2000	Material [Title Only, for Class A Metallic Core Support Structures, Elevated Temperature Service]
HGB-2100	GENERAL REQUIREMENTS FOR MATERIAL
HGB-2120	[No Title]
HGB-2121	Permitted Material Specifications
HGB-2160	DETERIORATION OF MATERIAL IN SERVICE
HGB-2400	[No Title]
HGB-2430	[No Title]
HGB-2433	[No Title]
HGB-2433.2	Acceptance Standards

Due to unavailability of sufficient test data on welds required for a quality assessment during the review period, the following portions, which cover a total of ten tables for the five alloys welded with twenty-eight different weld metals (some with similar properties), have been deferred to a future review effort.

Code Item	Title
Table HBB-I-14.10A-1	Stress Rupture Factors for Type 304 Stainless Steel Welded With SFA-5.22 E 308T and E 308LT; SFA-5.4 E 308 and E 308L; and SFA-5.9 ER 308 and ER 308L

Code Item	Title
Table HBB-I-14.10A-2	Stress Rupture Factors for Type 304 Stainless Steel Welded With SFA-5.22 EXXXT-G (16-8-2 Chemistry); SFA-5.4 E 16-8-2; and SFA-5.9 ER 16-8-2
Table HBB-I-14.10A-3	Stress Rupture Factors for Type 304 Stainless Steel Welded With SFA-5.22 E 316T and E 316LT-1, -2, and -3; SFA-5.4 E 316 and E 316L; and SFA-5.9 ER 316 and ER 316L
Table HBB-I-14.10B-1	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
Table HBB-I-14.10B-2	Stress Rupture Factors for Type 316 Stainless Steel Welded With SFA-5.22 EXXXT-G (16-8-2 Chemistry); SFA-5.4 E 16-8-2; and SFA-5.9 ER 16-8-2
Table HBB-I-14.10B-3	Stress Rupture Factors for Type 316 Stainless Steel Welded With SFA-5.22 E 316T and E 316LT-1 and -2; SFA-5.4 E 316 and E 316L; and SFA-5.9 ER 316 and ER 316L
Table HBB-I-14.10C-1	Stress Rupture Factors for Alloy 800H Welded With SFA-5.11 ENiCrFe-2 (INCO A)
Table HBB-I-14.10C-2	Stress Rupture Factors for Alloy 800H Welded With SFA-5.14 ERNiCr-3 (INCO 82)
Table HBB-I-14.10D-1	Stress Rupture Factors for 2¼Cr-1Mo (60/30) Welded With SFA-5.28 E 90C-B3; SFA-5.28 ER 90S-B3; SFA-5.5 E 90XX-B3 (> 0.05C); SFA-5.23 EB 3; SFA-5.23 ECB 3 (> 0.05C); SFA-5.29 E 90T1-B3 (> 0.05C)
Table HBB-I-14.10E-1	Stress Rupture Factors for 9Cr-1Mo-V Welded With SFA-5.28 ER 90S-B9; SFA-5.5 E90XX-B9; SFA-5.23 EB9

To facilitate understanding of the review comments and recommendations, the following appendices are provided.

Appendix ID	Title
Appendix TCOC	Comments on the Tertiary Creep Criterion for S_t (and S_{mt})
Appendix VTDS	Verification of ASME Time-Dependent Software
Appendix VTIS	Verification of ASME Time-Independent Software
Appendix HBB-3225-1	Tensile Strength Values, S_u
Appendix SIS_m	Updated Stress Intensity, S_m Report

In this review, some Code tabulations and graphs are found to be obviously less conservative than the results of our analysis and therefore a recommendation of further review is made. We have shown the fact of relative non-conservatism and indicated where the difference in conservatism exceeds 10%, which is our threshold for questioning technical adequacy, meriting a risk assessment by NRC and/or reactor designers. The recommended further review, not necessarily by ASME Code Committees, would require evaluating those tabulations not simply by comparison with our results, but by quantifying the implications of the reduced design margins and technical adequacy/inadequacy to form a basis for conditioning specific Code tabulation values on endorsement. Such evaluations and decision making on design margin acceptability is beyond the scope of this project.

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APPENDICES

Appendix TCOC, Comments on the Tertiary Creep Onset Criterion for S_t (and S_{mt})

S_t, the temperature- and time-dependent stress intensity limit, is derived as the lowest stress intensity from three criteria per ASME III-5, HBB-3221: the average stress for a total strain of 1%, 80% of the minimum stress to cause initiation of tertiary creep, and 67% of the minimum stress to cause rupture. Thus, any estimation of the allowable stress intensity, S_t, and consequently, the primary membrane stress intensity limit, S_{mt} derived therefrom, requires the compilation and analysis of data to examine each of the three criteria. The 1% total strain and the initiation of tertiary creep criteria are unique to the ASME III construction code. In contrast, the rupture strength is a commonly used basis for elevated temperature design in many pressure equipment ASME construction codes[1]. Historically, perhaps as a result of application demands and ease of generation, data on elevated temperature rupture strength are relatively voluminous and easy to compile. On the other hand, 1% strain and tertiary onset data are relatively sparse, and the availability of creep strain-time curves to derive these parameters, similarly relatively soft. For this review, within the constraints of the scope, we have made every effort to research and compile available data. Even so, as described below, the 1% strain and tertiary creep data compiled are a fraction of the rupture data in every case. In addition, the consistency with which data have been generated is questionable, particularly in case of the tertiary creep data where identification of the tertiary onset can vary, depending on the characteristics of the creep strain-time curve and the potentially subjective data derivation.

In analyses of the compiled data, we have found that in all of the materials cases, except for 9Cr-1Mo-V, computed S_t values over a very large portion of the time-temperature regime are controlled by the as-derived 80% minimum stress to initiate tertiary creep. These results are consistent with those previously reported for the stainless steels and 800H as part of ASME ST-LLC project reports (Ref. Sengupta 2013) (Ref. Swindeman 2012). Given the apparent import of the tertiary onset criterion, we offer a few observations in this section to help perspective.

It is beyond the scope of this review to comment on the appropriateness of the criteria, and one may refer, as an example, to a paper by Jetter et al. for historical perspective on the tertiary creep criterion (Ref. Jetter 2015). Our focus is only on the difficulty with implementing certain criteria. For perspective, we highlight the contrast between the tertiary and rupture datasets, the possible relationship in these cases of the tertiary onset data with the rupture data, such as proposed by Leyda and Rowe (Ref. Leyda 1969), and the sensitivity of the use of this criterion examined via a limited set of analyses on the 304 SS database. A tertiary-rupture strength relation can substantially expand the database by use of rupture data, possibly making the implementation of the criterion more robust and better balanced.

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[1] The strain rate criterion of 0.01% in 1000 hours, that may be considered similar to the ASME III-5, 1% strain criterion, is used in Sections I (Boilers) and VIII (Pressure Vessels) construction, but is based on a strain rate measurement and is also very rarely a controlling design stress criterion for those applications.

Contrasting Datasets

Table TCOC-1 summarizes the number of data points available for each of the materials examined, pertaining to each of the three criteria.

Table TCOC-1: Size and longest duration test data of datasets compiled for each of the three S_t criteria

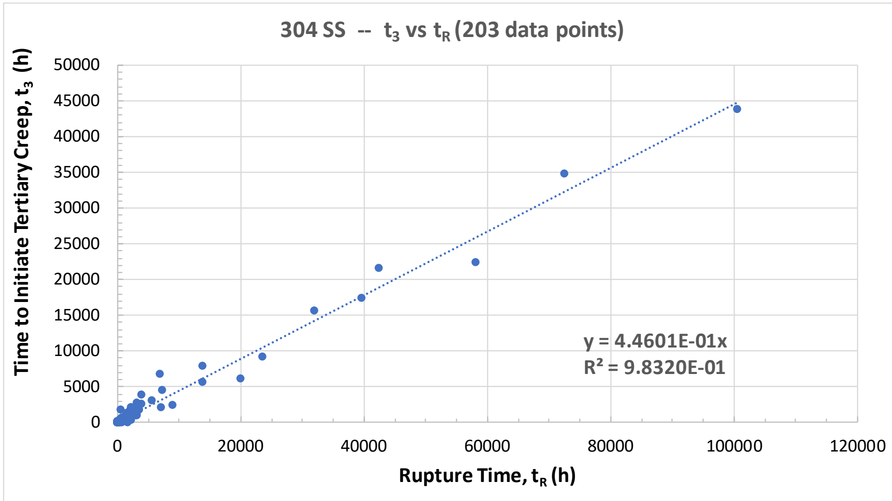
Material	Rupture Data		1% Strain Data		Tertiary Onset Data	
	# Lots/Data Points	Longest Test (h)	# Lots/Data Points	Longest Test (h)	# Lots/Data Points	Longest Test (h)
304 SS	90/964	179,368	17/351	97,000	8/206	55,000
316 SS	142/1616	320,421	19/183	174,000	22/327	141,000
800H	49/960	136,100	32/418	69,900	24/324	94,800
2¼Cr-1Mo	93/671	213,300	21/208	94,700	37/310	94,900
9Cr-1Mo-V	112/2046	170,370	11/388	68,800	22/523	84,500

Clearly, the size of the rupture strength database significantly exceeds that of the other two criteria. In some cases (304 SS, 316 SS, 9Cr-1Mo1V), the tertiary criterion dataset is a small fraction of the rupture dataset, both in the number of heats/lots and the number of data points. Although the tertiary criterion datasets do include long-term data, the data are not generally as well distributed over time and temperature as are the rupture data. The obvious differences in the size and nature of the datasets contrast with the criteria implementation that inherently assumes comparable confidence in, and robustness of the data. This unbalanced aspect of criteria implementation makes it difficult to accept the results of an implementation.

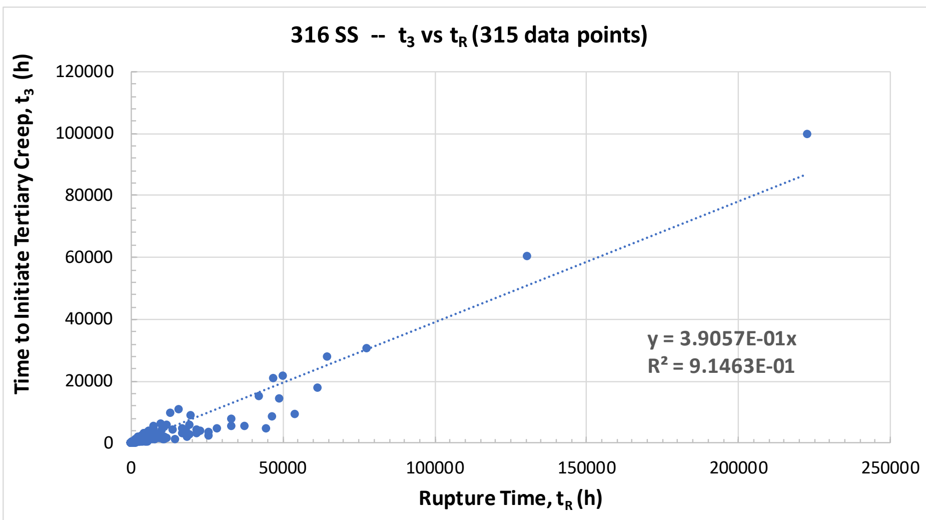
Tertiary-Rupture Data Correlation

A simple empirical exercise is conducted to examine a possible correlation between the compiled tertiary onset and rupture data for each of the materials. Figures TCOC-1(a) through (e) graphically show the correlations for data points where both rupture and tertiary onset time are available.

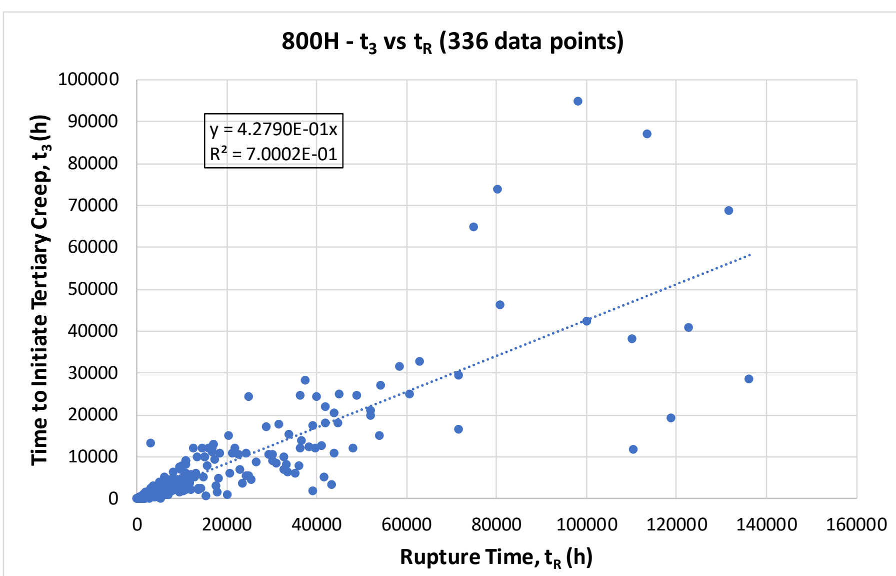
It is seen from Figure TCOC-1, that the 304 SS and 9Cr-1Mo-V data show potential for a usable correlation that appears to be temperature-independent, despite the scatter in the short-term data. The slope is roughly in the mid-range of the values reported by Leyda and Rowe for a variety of materials. 800H and 2¼Cr-1Mo, on the other hand, show large scatter and no apparent potential for a correlation. 316 SS shows marginal potential for a correlation, although Sengupta and Nestell have reported wide scatter and no correlation for this material (Ref. Sengupta 2015), possibly due to non-classic creep curve behavior. As described below, the data and correlation for 304 SS is used in a limited series of analyses to examine the effect of using the correlation to expand the database, as well the effect of entirely excluding the tertiary criterion.


304 SS -- t_3 vs t_R (203 data points)
Time to Initiate Tertiary Creep, t_3 (h)
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
20000
40000
60000
80000
100000
120000
Rupture Time, t_R (h)
y = 4.4601E-01x
R^2 = 9.8320E-01

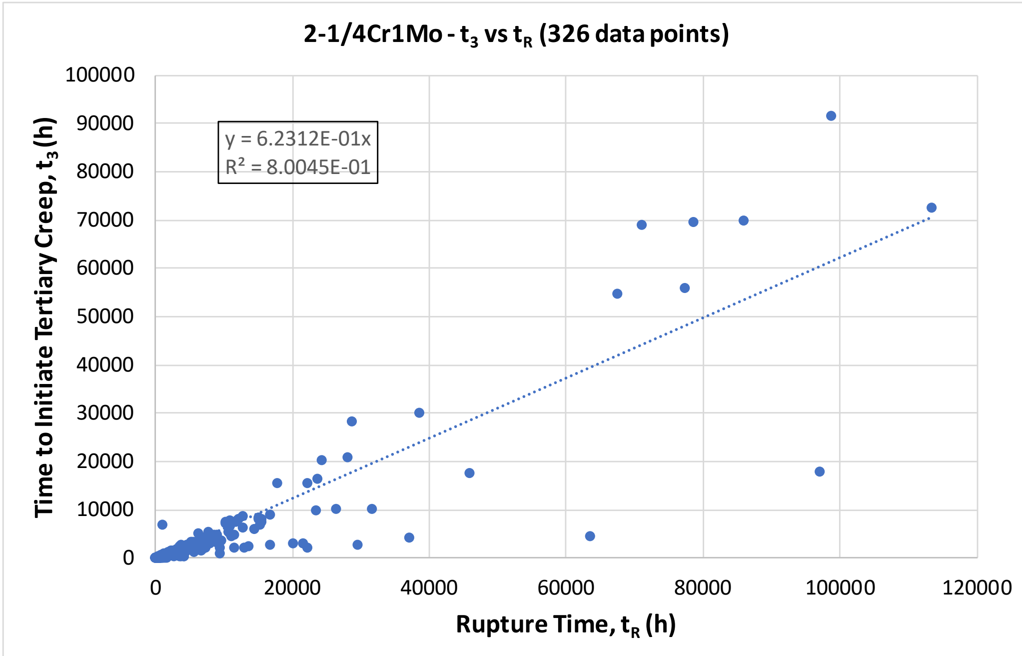
(a)


316 SS -- t_3 vs t_R (315 data points)
Time to Initiate Tertiary Creep, t_3 (h)
120000
100000
80000
60000
40000
20000
0
0
50000
100000
150000
200000
250000
Rupture Time, t_R (h)
y = 3.9057E-01x
R^2 = 9.1463E-01

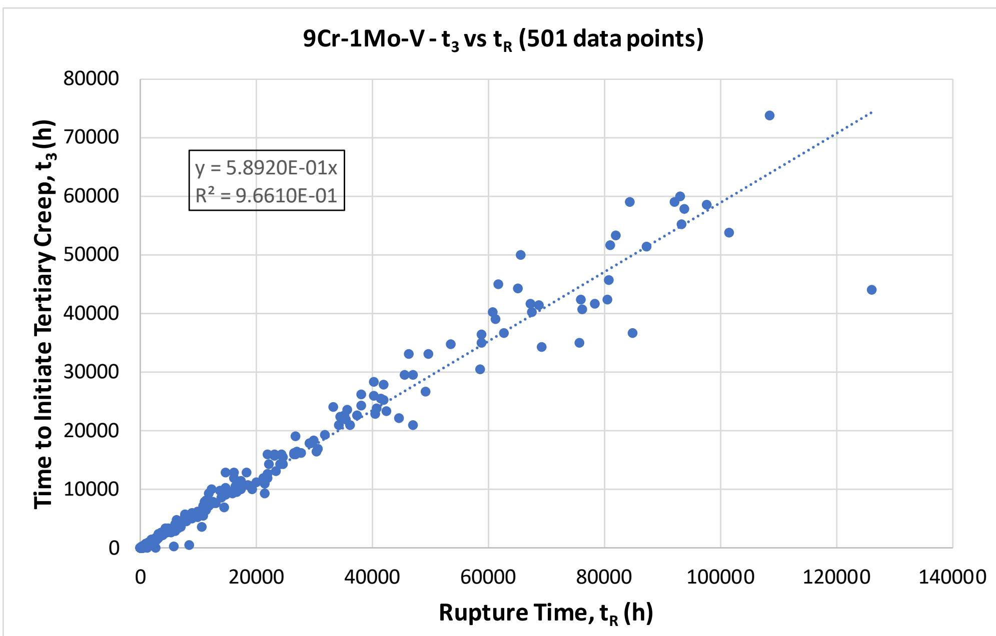
(b)


800H - t_3 vs t_R (336 data points)
Time to Initiate Tertiary Creep, t_3 (h)
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
0
20000
40000
60000
80000
100000
120000
140000
160000
Rupture Time, t_R (h)
y = 4.2790E-01x
R^2 = 7.0002E-01

(c)



(d)



(e)

Figure TCOC-1. Graphical summary of the compiled tertiary creep initiation (t_3) vs rupture (t_R) data for (a) 304 SS, (b) 316 SS, (c) 800H, (d) 2¼Cr-1Mo, and (e) 9Cr-1Mo-V

Quality of Data

The challenge associated with consistently characterizing the onset of tertiary creep in the face of various creep strain-time curve shapes has been noted by Swindeman et al. for 800H (Ref. Swindeman 2012) (Ref. Swindeman 2019). They observe that by using data derived only from classic creep strain-time curves (curves with the classic primary, secondary and tertiary creep regions), the computed tertiary onset strength is increased. The conventional procedure of using the +0.2% parallel (to the minimum rate region slope) offset intersection with the curve helps consistency. However, even with the convention, curve shapes can hinder consistency and make elusive a definition of the tertiary creep onset that can be used in practice.

The raw creep curve data used in developing the tertiary creep onset data compiled by ORNL used in this review have not been retrieved. As such, no insight can be provided regarding the data, its quality, whether it comes from a classic creep curve, etc.

Analyses of 304 SS Data

In addition to the primary analysis conducted for S_t using the criteria as defined in BPVC III-5 and the compiled data, two additional analyses were conducted: One where the tertiary criterion is excluded from consideration, and a second where the tertiary data used are calculated from each of the rupture data points using the Leyda-Rowe type of correlation empirically given in Figure TCOC-1(a) above (Tertiary=x.Rupture).

Table TCOC-2 is a tabulated summary of the analyses results. The following observations are made:

- Excluding the tertiary criterion results in all of the long duration, time-dependent stresses being governed by 67% of the minimum rupture strength, a change from the domination of the 80% minimum stress to initiate tertiary creep controlling when the criterion is included.
- Using a Leyda-Rowe multiplier on the rupture data developed empirically, as shown in Figure TCOC-1(a), to represent the tertiary creep onset data, it is seen that the 67% minimum rupture strength criterion continues to control over much of the longer term, except that the 80% minimum stress to initiate tertiary creep now controls stresses at the higher temperatures, and durations.
- What is particularly striking is that the 80% minimum tertiary onset criterion-controlling stresses are very close to the 67% minimum rupture strength values (compare columns 3 and 4 for each duration). It is naturally expected that the Leyda-Rowe proportionality factor produces estimates of tertiary onset data that reflect the rupture strength, but the closeness in stress values suggests a competition between the minimum rupture strength and the Leyda-Rowe-inferred tertiary criterion.
- The findings, overall, support application of the Leyda-Rowe approach to developing the S_t tabulation for 304 SS.

Table TCOC-2. S_t for 304 SS using various methods as identified

ksi hours	1				10				30				1.00E+02				3.00E+02				1.00E+03			
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis (All Criteria)	This Analysis (Excluding Tertiary)	This Analysis (Tertiary = x.Rupture)	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis (All Criteria)	This Analysis (Excluding Tertiary)	This Analysis (Tertiary = x.Rupture)	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis (All Criteria)	This Analysis (Excluding Tertiary)	This Analysis (Tertiary = x.Rupture)	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis (All Criteria)	This Analysis (Excluding Tertiary)	This Analysis (Tertiary = x.Rupture)	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis (All Criteria)	This Analysis (Excluding Tertiary)	This Analysis (Tertiary = x.Rupture)	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis (All Criteria)	This Analysis (Excluding Tertiary)	This Analysis (Tertiary = x.Rupture)
800	20.4	25.2	25.2	25.2	20.4	25.2	25.2	25.2	20.4	25.2	25.2	25.2	20.4	25.2	25.2	25.2	20.4	25.2	25.2	25.2	20.4	25.2	25.2	25.2
850	20.0	24.8	24.8	24.8	20.0	24.8	24.8	24.8	20.0	24.8	24.8	24.8	20.0	24.8	24.8	24.8	20.0	24.8	24.8	24.8	20.0	24.8	24.8	24.8
900	19.6	24.2	24.2	24.2	19.6	24.2	24.2	24.2	19.5	24.2	24.2	24.2	19.5	24.2	24.2	24.2	19.4	24.2	24.2	24.2	19.2	24.2	24.2	24.2
950	19.1	23.7	23.7	23.7	19.1	23.7	23.7	23.7	19.0	23.7	23.7	23.7	18.7	23.7	23.7	23.7	18.2	23.7	23.7	23.7	17.5	23.6	23.7	23.7
1000	18.5	23.1	23.1	23.1	18.4	23.1	23.1	23.1	17.8	23.1	23.1	23.1	16.9	23.1	23.1	23.1	16.2	22.6	23.1	23.1	15.9	18.7	22.5	22.5
1050	18.0	22.7	22.7	22.7	17.7	22.7	22.7	22.7	17.1	22.7	22.7	22.7	16.2	21.6	22.7	22.7	15.5	18.1	21.7	21.7	14.9	14.9	18.6	18.6
1100	17.6	22.3	22.3	22.3	17.1	22.3	22.3	22.3	16.3	21.3	22.3	22.3	15.3	17.4	20.9	20.9	14.5	14.5	18.0	18.0	13.5	11.8	15.2	15.2
1150	17.0	21.7	21.7	21.7	15.7	20.9	21.7	21.7	14.8	17.3	20.5	20.5	13.8	14.0	17.3	17.3	12.9	11.6	14.8	14.8	11.0	9.4	12.4	12.4
1200	16.0	21.1	21.1	21.1	14.2	17.0	20.1	20.1	13.3	14.0	17.1	17.1	12.2	11.3	14.3	14.3	10.6	9.2	12.1	12.1	8.9	7.5	10.0	10.0
1250	14.7	20.6	20.6	20.6	12.9	13.9	16.8	16.8	11.9	11.3	14.2	14.2	10.3	9.1	11.8	11.8	8.7	7.4	9.8	9.8	7.2	5.9	8.0	8.0
1300	13.4	17.5	19.6	19.6	11.4	11.3	14.0	14.0	10.0	9.2	11.7	11.7	8.5	7.3	9.6	9.6	7.0	5.9	7.9	7.9	5.9	4.7	6.4	6.4
1350	12.2	14.4	15.8	15.8	9.7	9.2	11.3	11.3	8.4	7.4	9.6	9.6	7.1	5.9	7.8	7.8	5.9	4.7	6.4	6.4	4.8	3.7	5.1	5.1
1400	10.8	11.9	12.8	12.8	8.1	7.5	9.0	9.0	6.9	6.0	7.6	7.6	5.9	4.7	6.3	6.3	4.8	3.8	5.1	5.1	3.9	3.0	4.0	4.0
1450	9.3	9.8	10.3	10.3	6.8	6.1	7.2	7.2	5.9	4.9	6.1	6.1	4.6	3.8	5.0	5.0	3.8	3.0	4.0	4.0	3.0	2.4	3.1	3.0
1500	7.9	8.1	8.4	8.4	5.3	5.0	5.8	5.8	4.4	3.9	4.9	4.9	3.5	3.0	4.0	4.0	2.8	2.4	3.1	3.1	2.2	1.9	2.3	2.3

ksi hours	3.00E+03				1.00E+04				3.00E+04				1.00E+05				3.00E+05			
Temp., °F	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis (All Criteria)	This Analysis (Excluding Tertiary)	This Analysis (Tertiary = x.Rupture)	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis (All Criteria)	This Analysis (Excluding Tertiary)	This Analysis (Tertiary = x.Rupture)	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis (All Criteria)	This Analysis (Excluding Tertiary)	This Analysis (Tertiary = x.Rupture)	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis (All Criteria)	This Analysis (Excluding Tertiary)	This Analysis (Tertiary = x.Rupture)	ASME 2017 ASME 2019 III-5 Table HBB-I-14.4A	This Analysis (All Criteria)	This Analysis (Excluding Tertiary)	This Analysis (Tertiary = x.Rupture)
800	20.4	25.2	25.2	25.2	20.4	25.2	25.2	25.2	20.4	25.2	25.2	25.2	20.4	25.1	25.2	25.2	20.4	21.7	25.2	25.2
850	20.0	24.8	24.8	24.8	20.0	24.8	24.8	24.8	19.9	23.1	24.8	24.8	19.8	19.5	24.0	24.0	19.3	16.7	21.2	21.2
900	18.8	24.2	24.2	24.2	18.5	21.2	24.2	24.2	18.3	18.0	22.3	22.3	17.7	15.1	19.4	19.4	16.0	12.8	17.0	17.0
950	17.2	19.9	23.7	23.7	16.9	16.6	20.7	20.7	16.2	14.0	18.1	18.1	14.2	11.7	15.6	15.6	12.2	9.9	13.5	13.5
1000	15.5	15.7	19.6	19.6	14.7	13.0	16.8	16.8	13.1	11.0	14.6	14.6	11.1	9.1	12.4	12.4	9.3	7.6	10.7	10.7
1050	14.1	12.4	16.0	16.0	12.2	10.2	13.6	13.6	10.3	8.5	11.7	11.7	8.7	7.0	9.8	9.8	7.3	5.9	8.4	8.4
1100	11.5	9.8	13.0	13.0	9.7	8.0	10.9	10.9	8.2	6.7	9.3	9.3	6.8	5.4	7.7	7.7	5.7	4.5	6.5	6.5
1150	9.3	7.7	10.5	10.5	7.7	6.3	8.7	8.7	6.4	5.2	7.3	7.3	5.3	4.2	6.0	6.0	4.4	3.5	5.0	5.0
1200	7.4	6.1	8.4	8.4	6.1	4.9	6.9	6.9	5.1	4.0	5.7	5.7	4.1	3.3	4.6	4.6	3.4	2.7	3.8	3.8
1250	5.9	4.8	6.7	6.7	4.9	3.9	5.4	5.4	4.0	3.2	4.4	4.4	3.2	2.5	3.5	3.5	2.7	2.1	2.8	2.8
1300	4.8	3.8	5.2	5.2	3.9	3.0	4.2	4.2	3.2	2.5	3.3	3.3	2.5	2.0	2.6	2.6	2.1	1.6	2.0	2.0
1350	3.9	3.0	4.1	4.1	3.1	2.4	3.2	3.2	2.5	1.9	2.5	2.5	2.0	1.5	1.9	1.9	1.6	1.2	1.5	1.4
1400	3.1	2.4	3.1	3.1	2.5	1.9	2.4	2.4	2.0	1.5	1.8	1.8	1.6	1.2	1.4	1.3	1.2	0.94	1.0	1.0
1450	2.4	1.9	2.4	2.3	1.9	1.5	1.8	1.7	1.5	1.2	1.3	1.3	1.2	0.91	1.0	0.90	0.9	0.69	0.69	0.63
1500	1.7	1.5	1.8	1.7	1.3	1.1	1.3	1.2	1.0	0.91	0.94	0.88	0.8	0.65	0.65	0.59	0.6	0.44	0.44	0.39

Hot Tensile Stress at 1% Strain, ASME HBB-T digitized	80% Minimum Stress to Initiate Tertiary Creep	1% Strain in Creep	67% Minimum Stress to Rupture

Summary Observations

Conducting a more detailed evaluation of the tertiary creep criterion implementation issue is beyond the scope of this review. A few preliminary observations are nevertheless made for perspective.

- In general, the number of 1% strain and tertiary data points are a fraction of the number of rupture data points, implying an imbalance in implementation of the ASME III-5 criteria in development of S_t.
- Accompanying the relatively low quantity, the 1% and tertiary data also appear to exhibit significantly more scatter than do the rupture data (see the standard error resulting from the curve-fits in the report section on S_t), a reflection of the overall quality.
- In the case of 304 SS, the Leyda-Rowe exercise to expand the tertiary creep onset database appeared feasible and resulted in the rupture strength and tertiary creep onset criteria being competitive.
- This suggests that, at least for this material, the direct application of the compiled tertiary creep data produces stresses that may be excessively conservative, and that the Leyda-Rowe approach may be feasible and preferred.
- It is unclear as to why there is as much difference between the results from the Leyda-Rowe data analysis method and the direct tertiary data analysis. The larger database resulting from application of the Leyda-Rowe approach, including an increased number of data points with longer duration may well have enhanced the long-term predictions, otherwise uncertain with use of the as-compiled tertiary creep data alone.
- The results for 304 SS and the calculated S_t values for the other materials, except for 9Cr-1Mo-V, suggest that implementation of the tertiary creep criterion by direct analysis of available tertiary data is unbalanced in comparison with the minimum rupture strength criterion. The effect of this imbalance depends on the quality and amount of data.

We are aware of ASME's continued interest in the application of the tertiary creep criterion. Unfortunately, evaluating the effect of the criteria imbalance and defining a suitable threshold for tertiary data (amount and quality) is beyond the scope of this review, limiting the constructiveness of our comments

Appendix VTDS, Verification of ASME Time-Dependent Software

The ASME Time-Dependent Data Analysis Software, Version 2016-2-10, as downloaded from the ASME Materials Properties Database, is verified for accuracy in the LMP-Log stress Polynomial curve-fit, evaluated for the curve-fit constants and the predicted 100,000-hour average rupture strength.

The software is used to develop various time-dependent stress values directly or indirectly related to S_o, S_r and S_t.

Rationale for the Use and Verification of the Software

To execute the project review objectives within the constraints of cost and schedule, use of an efficient computational method is critical. In this case, the ASME Time-Dependent Software provides one such vehicle for execution of the data analyses.

To ensure that computations of time-dependent stress values affecting S_o, S_r and S_t made with the software are accurate, curve-fitting predictions of the software are verified by comparing a set of manual computations with the software output.

Tables VTDS-1, -2 and -3 below compare the results of the manual and software analyses for the case of the 2¼Cr-1Mo dataset analyzed. The results are shown for an LMP-1st, 2nd and 3rd order polynomial fit in Tables VTDS-1, -2 and -3, respectively.

It can be seen from the tabulated results, that while the software output is not reproduced exactly by the manual analysis (likely a result of differing regression numerical methods), (a) the curve constants a_0, a_1, a_2 and a_3 (the logarithmic stress polynomial coefficients) and the LMP, C, are in very close agreement; and (b) the 100,000-hour average strength predictions are all well within 1% of each other, except for an outlier case at the highest temperature for the 2nd order polynomial fit (difference is 1.8%) where the steepness of the curve (approaching the parabolic turn-around) produces large variations in strength predictions for small differences in the curve-fit. The ASME software predictions for this database are consistently conservative, albeit by a very small amount, relative to the manual analysis results.

Table VTDS-1. Manual Analysis vs. ASME Time-Dependent Software (Version 2016-2-10) outputs for the 2¼Cr-1Mo dataset – LMP-1st Order Polynomial Curve-Fit

$\log t_R = - C + a_0/T + a_1{*}\log S/T + a_2{*}(\log S)^2/T + a_3{*}(\log S)^3/T$ (results for S in MPa and T in °K)

	This Manual Analysis	ASME Time-Dependent Software
a_0	27032.0979	26887.8731
a_1	-4671.923594	-4653.3575
a_2	0	0
a_3	0	0
C	17.5678	17.4408812
Variance	0.11959	0.12013797
SEE	0.346853	0.34660925
S_{yy}	507.13894	
R^2	0.84201	0.84175507

LMP-1st Order Polynomial		S_{avg}, 100 khr		Difference
Temperature		This Manual Analysis	ASME Software	
°C	°K	MPa	MPa	%
375	648.15	452.0	449.2	-0.63
400	673.15	342.3	340.3	-0.58
425	698.15	259.2	257.8	-0.53

LMP-1st Order Polynomial		S_{avg}, 100 khr		Difference
Temperature		This Manual Analysis	ASME Software	
°C	°K	MPa	MPa	%
450	723.15	196.3	195.3	-0.49
475	748.15	148.6	148.0	-0.44
500	773.15	112.6	112.1	-0.40
525	798.15	85.2	84.9	-0.35
550	823.15	64.5	64.3	-0.30
575	848.15	48.9	48.7	-0.26
600	873.15	37.0	36.9	-0.21
625	898.15	28.0	28.0	-0.16
650	923.15	21.2	21.2	-0.12

Table VTDS-2. Manual Analysis vs. ASME Time-Dependent Software (Version 2016-2-10) outputs for the 2¼Cr-1Mo dataset – LMP-2nd Order Polynomial Curve-Fit

$\log t_R = -C + a_0/T + a_1 * \log S/T + a_2 * (\log S)^2/T + a_3 * (\log S)^3/T$ (results for S in MPa and T in °K)

	This Manual Analysis	ASME Time-Dependent Software
a_0	19908.58675	19839.4345
a_1	2468.548054	2470.97658
a_2	-1788.1918	-1786.4718
a_3	0	0
C	17.4583	17.3903572
Variance	0.11454	0.11532873
SEE	0.339449	0.33960084
S_{yy}	507.13894	
R^2	0.84868	0.85928245

LMP-2nd Order Polynomial		S_{avg}, 100 khr		Difference
Temperature	Temperature	This Manual Analysis	ASME Software	
°C	°K	MPa	MPa	%
375	648.15	357.2	356.2	-0.27
400	673.15	292.8	292.1	-0.25
425	698.15	237.6	237.1	-0.24
450	723.15	190.6	190.2	-0.22
475	748.15	150.7	150.4	-0.21
500	773.15	117.1	116.9	-0.20
525	798.15	89.0	88.8	-0.19
550	823.15	65.8	65.6	-0.18
575	848.15	46.6	46.6	-0.18
600	873.15	31.1	31.0	-0.19
625	898.15	18.4	18.3	-0.26

LMP-2nd Order Polynomial		S_{avg}, 100 khr		Difference
Temperature	Temperature	This Manual Analysis	ASME Software	
°C	°K	MPa	MPa	%
650	923.15	6.5	6.4	-1.77

Table VTDS-3. Manual Analysis vs. ASME Time-Dependent Software (Version 2016-2-10) outputs for the 2¼Cr-1Mo dataset – LMP-3rd Order Polynomial Curve-Fit

$\log t_R = -C + a_0/T + a_1*\log S/T + a_2*(\log S)^2/T + a_3*(\log S)^3/T$ (results for S in MPa and T in °K)

	This Manual Analysis	ASME Time-Dependent Software
a_0	-5755.754241	-5425.1814
a_1	43359.66094	42758.375
a_2	-22662.29596	-22359.829
a_3	3490.760183	3441.51671
C	18.0981	18.0322248
Variance	0.10645	0.10715218
SEE	0.327241	0.32734107
S_{yy}	507.13894	
R^2	0.85937	0.85928245

LMP-3rd Order Polynomial		S_{avg}, 100 khr		Difference
Temperature		This Manual Analysis	ASME Software	
°C	°K	MPa	MPa	%
375	648.15	444	440	-0.87
400	673.15	316	315	-0.37
425	698.15	241	240	-0.23
450	723.15	188	188	-0.17
475	748.15	148	148	-0.16
500	773.15	117	117	-0.16
525	798.15	92	92	-0.18
550	823.15	70	70	-0.21
575	848.15	51	51	-0.23
600	873.15	NS	NS	NS
625	898.15	NS	NS	NS
650	923.15	NS	NS	NS

Appendix VTIS, Verification of ASME Time-Independent Software

The ASME Time-Independent Data Analysis Software, Version 2015-DEC-27 is verified for accuracy in the calculated yield strength ratio, R_Y (average [yield strength at temperature/yield strength at room temperature]) and the tensile strength ratio, R_T (average [tensile strength at temperature/tensile strength at room temperature]) trend curves (R_Y and R_T vs. temperature).

The trend curves are used in the determination of the BPVC yield strength (II-D, Table Y-1 and III-5 Table HBB-I-14.5), tensile strength (II-D, Table U and III-5 Table HBB-3225-1), and stress intensity, S_m (II-D Table 2A/2B and used in development of the tables and figures in III-5, HBB-I-14.3A through HBB-I-14.3E).

Rationale for the Use and Verification of the Software

To execute the project review objectives within the constraints of cost and schedule, use of an efficient computational method is critical. In this case, the ASME Time-Independent Software provides one such vehicle for execution of the data analyses.

To ensure that computations of yield strength, tensile strength and stress intensity made with the software are accurate, the trend curve-fitting accuracy of the software is verified by comparing a set of manual computations with the software output. Since all of the output stresses are simple multipliers of the yield strength ratio, R_Y, and the tensile strength ratio, R_T, as a function of temperature (trend curve), the polynomial best-fit curve constants obtained from the manual computations are compared against the constants output by the software. In addition, the calculated R_Y and R_T for the manual and the software cases are compared.

Table VTIS-1 below compares the results of the manual and software analyses for the case of the 2¼Cr-1Mo dataset analyzed. The results are shown for a 4^{th} and 5^{th} order polynomial trend curve since these are the possible curve shapes for the relevant materials as evidenced by decades of experience with trend curves.

It can be seen from the tabulated results, that while the software output is not reproduced exactly by the manual analysis, the difference in predictions for the trend curve R_Y and R_T values is, on average, < 0.5%. The reason(s) for the difference in results, such as the regression analysis method, has not been investigated.

Table VTIS-1. Manual Analysis vs. ASME Time-Independent Software (Version 2015-DEC-27) outputs for the 2¼Cr-1Mo dataset

Polynomial Order	$R_Y - 1 = a_1(T-21) + a_2(T-21)^2 + a_3(T-21)^3 + a_4(T-21)^4 + a_5(T-21)^5$, T in °C						% Difference in predicted R_y*		
		a_1	a_2	a_3	a_4	a_5	Max	Min	Ave
4	ASME Software	-0.00089	2.23E-06	-1.3E-09	-3E-12	0	0.83	-0.35	0.28
	Manual	-0.00078	1.21E-06	1.16E-09	-4.9E-12	0			
5	ASME Software	-0.00204	1.72E-05	-6.4E-08	1.05E-10	-6.4E-14	0.83	-0.35	0.28
	Manual	-0.00201	1.72E-05	-6.6E-08	1.1E-10	-6.9E-14			
	$R_T - 1 = b_1(T-21) + b_2(T-21)^2 + b_3(T-21)^3 + b_4(T-21)^4 + b_5(T-21)^5$, T in °C						% Difference in predicted R_y*		
		b_1	b_2	b_3	b_4	b_5	Max	Min	Ave
4	ASME Software	-0.00216	1.31E-05	-2.6E-08	1.28E-11	0	0.94	-0.48	0.35
	Manual	-0.00203	1.19E-05	-2.3E-08	1.1E-11	0			
5	ASME Software	-0.00171	7.24E-06	-9.9E-10	-2.9E-11	2.51E-14	2.66	-0.78	0.38
	Manual	-0.00179	8.76E-06	-9.6E-09	-1.2E-11	1.36E-14			

* Calculated as 100(ASME-Manual)/ASME for each data point

Appendix Table HBB-3225-1, Tensile Strength Values, S_u

Because the tensile strength as listed in Table HBB-3225-1 is the time-independent stress value that is a consideration in the derivation of stress intensity S_m and related S_{mt} (Figures and Tables, HBB-I-14.3), can control the limiting value for stress intensity, S_t (Figures and Tables, HBB-I-14.4), can control the stress intensity for bolting material (Figures HBB-I-14.13A ~ C, and Table HBB-I-14.13C), and is also referenced in Appendix SISm and Appendix VTIS, the table is reviewed and commented on in this Appendix, although its review is not a specific project requirement.

Review Recommendation

It is recommended that BPVC 2017 (and 2019) III-5 Table HBB-3225-1 be accepted with the following conditions.

Conditions

- For both 304 SS and 316 SS, a separate line for the 30-70 ksi (YS-TS) material is recommended, as is provided in BPVC II-D, Table U up to 1000°F and 525°C.
- For 304 SS, a further review is recommended, specifically the trend curve shape and resulting tabulated strength at and near the highest use temperature.

Explanations for the Conditions

1. For temperature > 1000°F (538°C), Table HBB-3225-1 does not provide a separate line for the lower specified tensile strength, 30-70 ksi (YS-TS) SA-965 forged product material. The lower strength material, although only for one product form (all other product forms are 30-75 material), is recognized by BPVC 2017 (and 2019) III-5 in tabulation and plotting of the stress intensity, S_{mt} (controlled by S_m).

2. Our analysis on S_u for the 30-75 material indicates that the trend curve shape is such that the Table HBB-3225-1 values appear relatively non-conservative at temperature ≥ 1300°F (700°C), the relative non-conservatism increasing with temperature, and significant (> 10%) at the highest temperatures (1450°F, 1500°F and 800°C). The relative non-conservatism is naturally amplified for the 30-70 material (Table HBB-3225-1 does not have a separate line for the 30-70 material), and in this case, the relative non-conservatism is significant (>10%) for temperature ≥ 1300°F and ≥ 725°C. Table R.3225-1 provides details on the specific calculated values in this analysis compared with the HBB-3225-1 tabulations. A similar trend is observed for the HBB-I-14.5 yield strength, S_Y behavior for 304 SS, supporting need for a review.

Analysis and Results

The analysis is conducted using the ASME time-independent software, version 2015-DEC-27 that is separately verified for accuracy in the regression of the data for the trend curve polynomial, as discussed in Appendix VTIS.

The references from which the analysed tensile data are obtained are provided below for convenient review, in addition to the listing in Section 6 References.

For 304SS

21 heats/lots and 218 data points

- (Ref. NRIM 1986b)
- (Ref. NRIM 1995)
- (Ref. Simmons 1965)

For 316SS

26 heats/lots, 253 data points

- (Ref. NIMS 2015)
- (Ref. NRIM 1979)
- (Ref. NRIM 1988)
- (Ref. NRIM 2000)
- (Ref. Sikka 1980)
- (Ref. Simmons 1965)

For 800H(N08810)

28 Heats/Lots, 321 Data Points

- Data compiled by ORNL from various published and unpublished sources.

For 2¼Cr-1Mo

42 heats/lots, 326 data points - annealed and N&T material combined

- (Ref. NRIM 1986a)
- (Ref. NRIM 1997)
- (Ref. Smith 1971)

For 9Cr-1Mo-V

27 heats/lots, 299 data points

- (Ref. Caminada 2015)
- (Ref. DiStefano 1986)
- (Ref. NIMS 2014)
- (Ref. Ruggles 2015)
- (Ref. Sikka 1982b)
- (Ref. Sikka 1986a)
- (Ref. Sikka 1986b)

Table R.3225-1. This Analysis compared with ASME 2017 (and 2019) III-5 Tensile Strength Values, S_u

ksi	°F	304SS				316SS				Ni-Fe-Cr UNS N08810		2-1/4Cr-1Mo		9Cr-1Mo-1V			
		30-75ksi (YS-UTS)		30-70ksi (YS-UTS)[a]		30-75ksi (YS-UTS)		30-70ksi (YS-UTS)[a]						60-85ksi (YS-UTS)		60-90ksi (YS-UTS)[b]	
		ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2019	This Analysis
BPVC II-D Table U	RT	75.0	75.0	70.0	70.0	75.0	75.0	70.0	70.0	65.0	65.0	60.0	60.0	85.0	85.0	90.0	90.0
	100	75.0	75.0	70.0	70.0	75.0	75.0	70.0	70.0	65.0	65.0	60.0	60.0	85.0	85.0	90.0	90.0
	200	71.0	69.7	66.3	65.0	75.0	72.0	70.0	67.2	65.0	65.0	59.9	60.0	85.0	85.0	90.0	90.0
	300	66.2	64.9	61.8	60.6	72.9	68.8	68.0	64.2	65.0	63.7	58.2	58.8	85.0	84.4	90.0	89.4
	400	64.0	63.1	59.7	58.9	71.9	68.2	67.1	63.6	64.6	62.4	58.2	58.8	84.7	82.1	89.7	86.9
	500	63.4	63.0	59.2	58.8	71.8	68.2	67.0	63.6	64.0	61.9	58.2	58.8	84.4	80.4	89.4	85.1
	600	63.4	63.0	59.2	58.8	71.8	68.2	67.0	63.6	63.8	61.6	58.2	58.8	83.1	78.7	88.0	83.3
	650	63.4	63.0	59.2	58.8	71.8	68.2	67.0	63.6	63.8	61.5	58.2	58.8	81.8	77.6	86.6	82.2
	700	63.4	63.0	59.2	58.8	71.8	68.2	67.0	63.6	63.8	61.2	58.2	58.8	80.0	76.3	84.7	80.8
	750	63.3	63.0	59.0	58.8	71.5	68.2	66.7	63.6	63.8	60.9	58.2	58.8	77.6	74.6	82.2	79.0
	800	62.8	63.0	58.6	58.8	70.8	68.2	66.1	63.6	63.8	60.4	58.2	58.8	74.7	72.6	79.1	76.8
	850	62.0	62.6	57.9	58.4	69.7	68.2	65.1	63.6	63.8	59.8	58.2	58.8	71.1	70.0	75.3	74.1
	900	60.8	61.4	56.8	57.3	68.3	68.0	63.8	63.5	63.6	58.9	58.2	56.7	66.9	66.9	70.8	70.9
	950	59.3	59.7	55.4	55.7	66.5	66.3	62.1	61.9	63.1	57.7	57.5	53.7	62.2	63.3	65.9	67.1
	1000	57.4	57.6	53.6	53.8	64.3	64.2	60.0	59.9	62.3	56.3	53.9	50.1	57.0	59.2	60.4	62.6
BPVC III-5 Table HBB-3225-1	1050	55.0	55.0	55.0	51.3	61.5	61.6	61.5	57.5	57.4	54.5	49.2	45.8	51.4	54.5	51.4	57.7
	1100	52.3	52.0	52.3	48.5	58.3	58.5	58.3	54.6	55.3	52.5	43.7	41.0	45.5	49.3	45.5	52.2
	1150	49.1	48.5	49.1	45.3	54.7	55.1	54.7	51.4	52.9	50.2	37.1	35.6	39.4	43.7	39.4	46.3
	1200	45.6	44.6	45.6	41.7	50.6	51.3	50.6	47.9	50.2	47.5	29.6	30.0	33.2	38.0	33.2	40.2
	1250	41.8	40.5	41.8	37.8	46.0	47.2	46.0	44.1	47.0	44.6	...		...		...	
	1300	37.7	36.0	37.7	33.6	41.0	42.9	41.0	40.0	43.6	41.5	...		...		...	
	1350	33.4	31.4	33.4	29.3	35.7	38.4	35.7	35.8	39.9	38.0	...		...		...	
	1400	29.1	26.7	29.1	25.0	30.0	33.8	30.0	31.5	36.0	34.5	...		...		...	
	1450	24.8	22.2	24.8	20.7	24.2	29.2	24.2	27.3	32.0	30.7	...		...		...	
	1500	20.6	17.8	20.6	16.6	18.2	24.8	18.2	23.2	27.8	27.0	...		...		...	
	1550	...		...		...		...		23.7	23.2	...		...		...	
	1600	...		...		...		...		19.7	19.6	...		...		...	
	1650	...		...		...		...		16.0	16.1	...		...		...	

a: ASME III-5 HBB-3225-1 does not provide a separate set of lines for the 30-70ksi (YS-UTS) material.

b: ASME III-5 HBB-3225-1 does not provide a separate set of lines for the 60-90ksi (YS-UTS) material.

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%

Non-conservative relative to this analysis - Difference, δ > 10% (Used rounding for characterization of δ)

MPa	°C	304SS				316SS				Ni-Fe-Cr UNS N08810		2-1/4Cr-1Mo		9Cr-1Mo-1V			
		30-75ksi (YS-UTS)		30-70ksi (YS-UTS)[a]		30-75ksi (YS-UTS)		30-70ksi (YS-UTS)[a]						60-85ksi (YS-UTS)		60-90ksi (YS-UTS)[b]	
		ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2019	This Analysis
BPVC II-D Table U	RT	517	517	483	483	517	517	483	483	448	448	414	414	586	586	621	621
	40	517	517	483	483	517	517	483	483	448	448	414	414	586	586	621	621
	100	485	475	453	417	516	493	482	460	448	448	412	413	586	586	621	621
	150	456	447	426	406	502	474	469	442	448	439	401	405	586	582	621	616
	200	442	435	412	405	496	470	463	439	446	431	401	405	584	567	618	600
	250	437	434	408	405	495	470	462	439	442	427	401	405	582	556	616	589
	300	437	434	408	405	495	470	462	439	440	425	401	405	577	546	611	578
	325	437	434	408	405	495	470	462	439	440	424	401	405	570	540	604	572
	350	437	434	408	405	495	470	462	439	440	423	401	405	561	533	594	564
	375	437	434	408	405	495	470	462	439	440	422	401	405	549	525	581	555
	400	436	434	407	405	493	470	460	439	440	420	401	405	534	514	565	544
	425	433	434	404	405	489	470	456	439	440	417	401	405	516	501	546	531
	450	429	432	400	404	482	470	450	439	440	413	401	405	494	486	523	514
	475	422	426	394	397	474	470	442	439	439	408	401	395	469	467	497	495
	500	413	416	386	388	463	462	433	431	437	401	400	378	441	446	467	472
	525	402	404	375	377	450	450	421	420	432	393	384	357	410	422	434	446
BPVC III-5 Table HBB-3225-1	550	388	390	388	364	435	435	435	406	402	383	358	333	379	394	379	417
	575	373	373	373	348	417	418	417	390	391	372	327	305	341	364	341	385
	600	355	353	355	329	396	398	396	372	378	358	290	274	303	331	303	350
	625	335	331	335	309	373	376	373	351	362	344	248	240	265	296	265	314
	650	314	307	314	286	347	353	347	329	345	327	202	205	228	260	228	275
	675	289	281	289	262	318	327	318	305	326	309	...		...		...	
	700	264	253	264	236	288	300	288	280	305	289	...		...		...	
	725	238	225	238	210	255	273	255	254	282	269	...		...		...	
	750	211	196	211	183	221	244	221	228	258	247	...		...		...	
	775	185	167	185	156	185	216	185	201	233	224	...		...		...	
	800	159	139	159	130	149	188	149	176	208	201	...		...		...	
	825	...		...		...		...		182	177	...		...		...	
	850	...		...		...		...		157	154	...		...		...	
	875	...		...		...		...		132	131	...		...		...	
	900	...		...		...		...		109	110	...		...		...	

a: ASME III-5 HBB-3225-1 does not provide a separate set of lines for the 30-70ksi (YS-UTS) material.

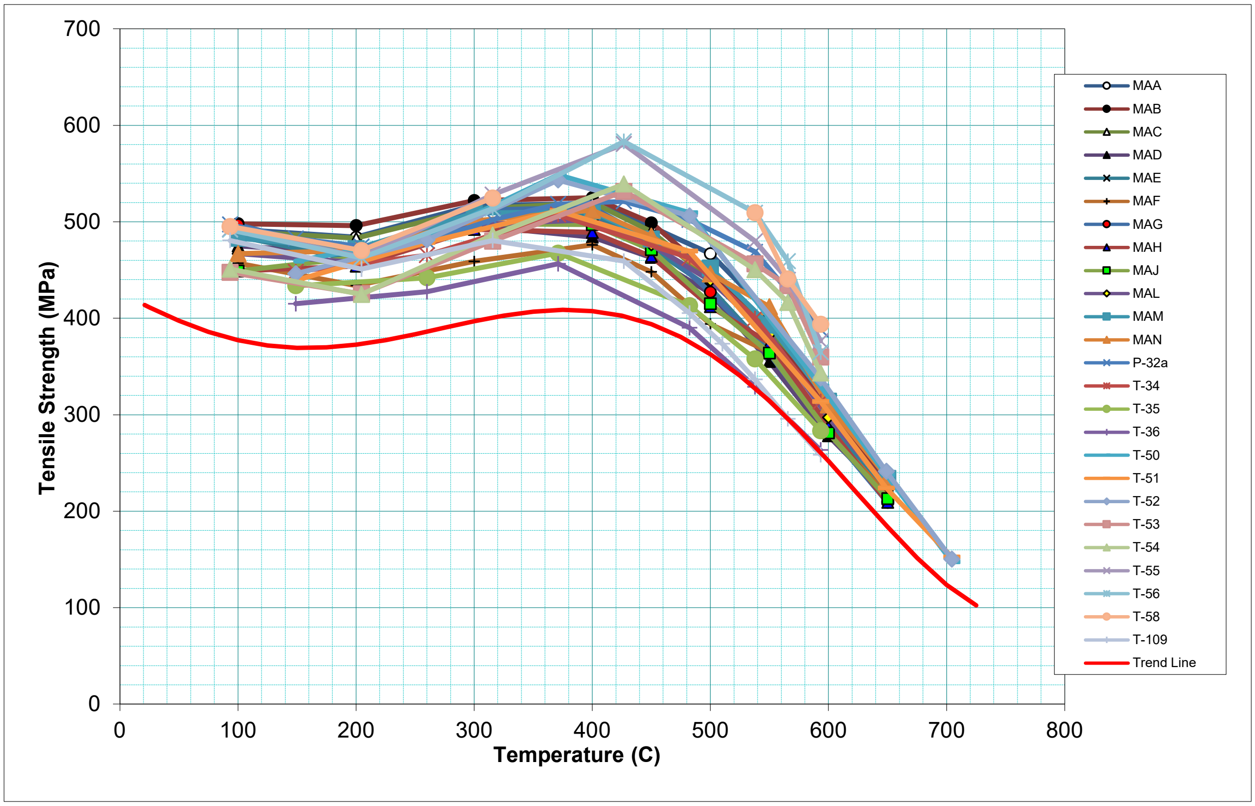
b: ASME III-5 HBB-3225-1 does not provide a separate set of lines for the 60-90ksi (YS-UTS) material.

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%

Non-conservative relative to this analysis - Difference, δ > 10% (Used rounding for characterization of δ)

Comments

- For 9Cr-1Mo-V, the 2019 edition of the Code includes a separate set of lines in II-D, Tables 2A and U for the higher specified tensile strength (90 ksi or 620 MPa) SA-182 forged product material (not in the 2017 edition). Table HBB-3225-1 does not recognize the higher strength material (other product specifications have a minimum tensile strength of 85 ksi or 585 MPa). However, use of the existing stress line in Table HBB-3225-1 when applied to the higher strength material, increases the conservatism. It is nevertheless recommended that a higher strength line be developed to avail of the high strength advantage and equally importantly, since it is likely that the minimum tensile strength for all product forms will increase to 90 ksi (620 MPa) in the future.
- For 2¼Cr-1Mo, BPVC 2017 (and 2019) II-D and III-5 do not distinguish between annealed material and normalized and tempered (N&T) material. Our analysis, as presented in Figure R.HBB-3225-1, showed distinctly different trend curves for material with the heat treatments (also noted in the 1971 ASTM Data Series DS 6S2 (Ref. Smith 1971), with the N&T material having lower strength. The use of data for both heat treatments is a compromise, but producing potentially less conservative strength parameters for the N&T material. Our analysis results indicate the differences in tensile strength vary from being insignificant to about 14%. We do not have a specific recommendation regarding treatment of this material, but the findings raise the question as to whether separate classes of material merit definition for Code use.



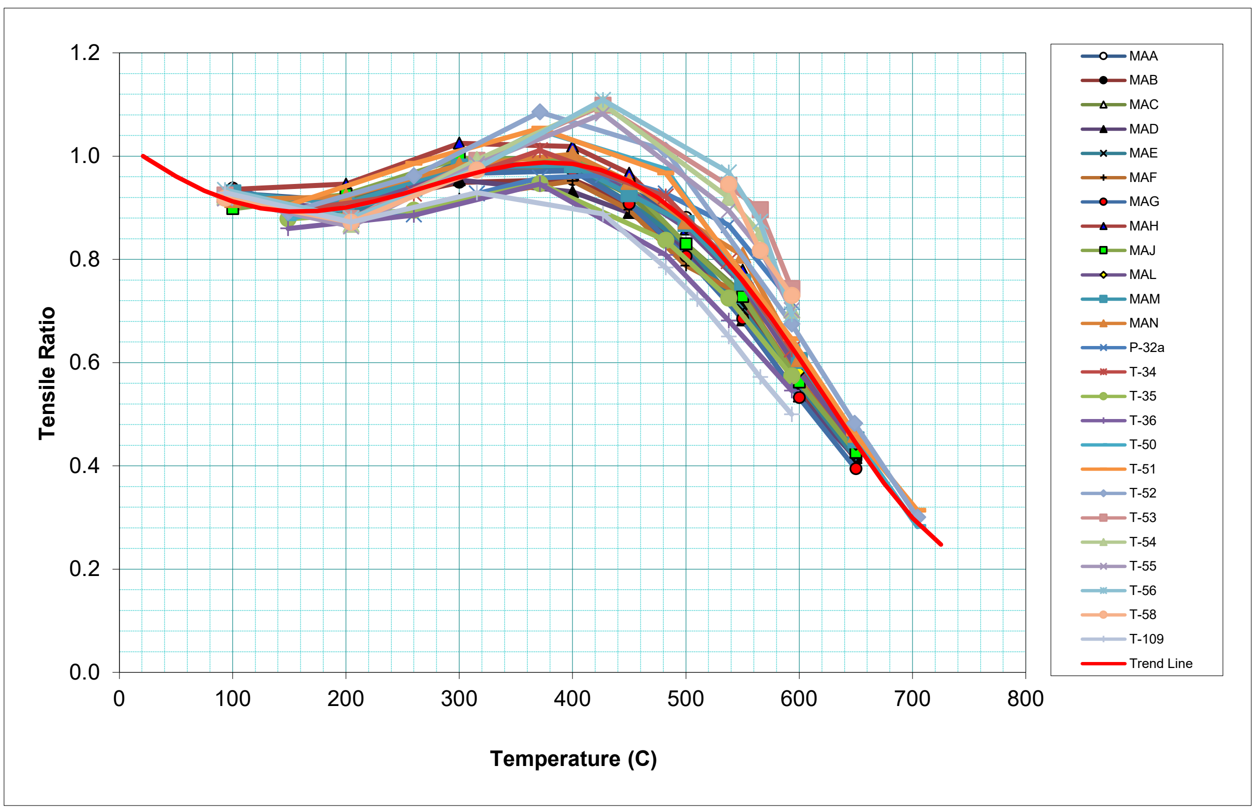
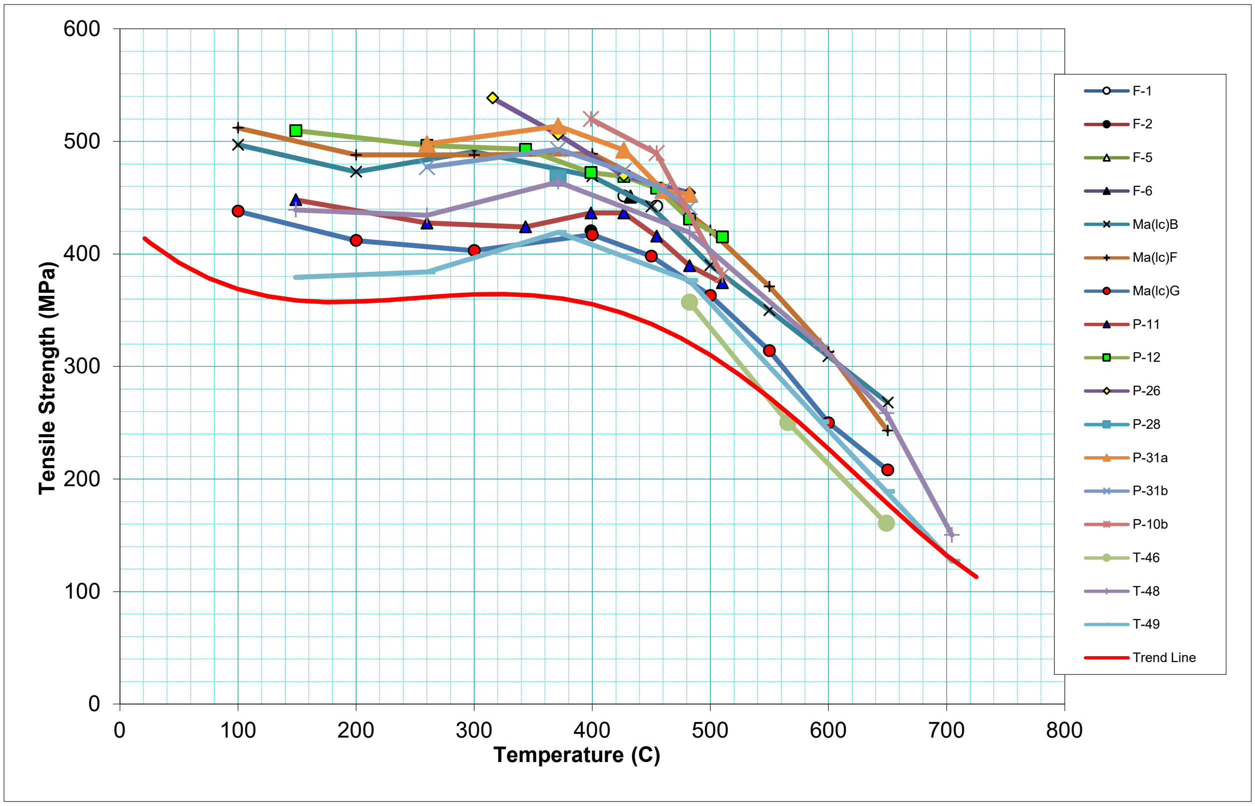


Figure R.HBB-3225-1a. Tensile strength trend curves for annealed 2¼Cr-1Mo steel



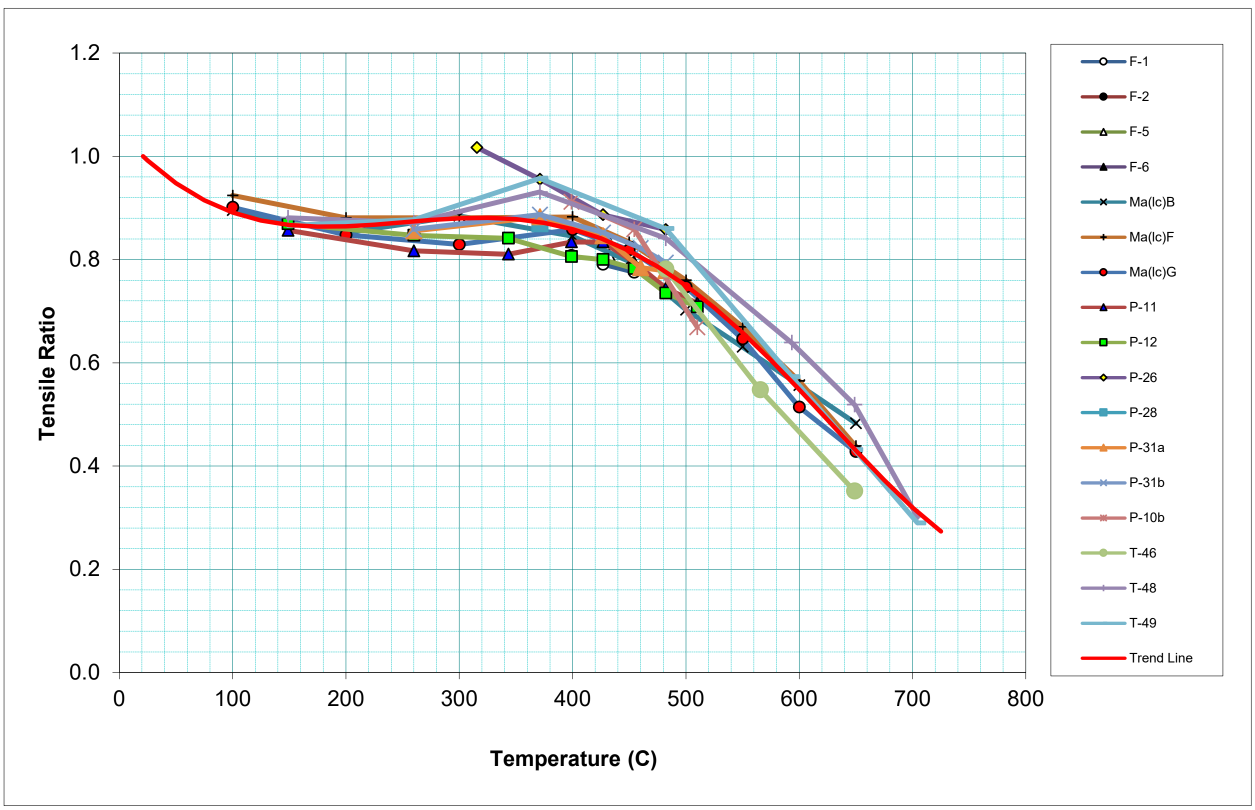


Figure R.HBB-3225-1b. Tensile strength trend curves for normalized and tempered 2¼Cr-1Mo steel

Appendix SISm, Stress Intensity, S_m

BPVC 2017 (and 2019) III-5 does not provide a tabulation of the stress intensity, S_m, values, only stating in HBB-3221: "S_m = the lowest stress intensity value at a given temperature among the time-independent strength quantities that are defined in Section II, Part D as criteria for determining S_m; in Subsection HB, Subpart B, the S_m values are extended to elevated temperatures by using the same criteria. As described in HBB-2160(d), it may be necessary to adjust the values of S_m to account for the effects of long-time service at elevated temperature."

Since S_m is a criterion for determining the allowable stress intensity limit, S_{mt}, its calculation and documentation, including with the appropriate strength reduction factors for a given time and temperature, are requisites for the present review. In this regard and for completeness, this appendix documents the results of our analysis for S_m, determined using the criteria defined in Section II, Part D, Appendix 2. The documentation includes a comparison of our analysis results with the BPVC 2017 (and 2019) II-D values and the baseline S_m inferred from the tables and figures of BPVC 2017 (and 2019) III-5 HBB-I-14.3 (1 h column of tables or digitized from the figure in two cases – 316 SS and 2¼Cr-1Mo – where the S_m value is not the value in the tabulated 1 h column).

Our analysis results are summarized in tabulation with self-explanatory footnotes below. The analysis is conducted using the ASME time-independent software, version 2015-DEC-27 that is separately verified for accuracy in the regression of the data for the trend curve polynomial, as discussed in Appendix VTIS.

The comparison of our results with the BPVC 2017 (and 2019) II-D, Table 2A/2B and III-5 Tables and Figures HBB-I-14.3-inferred values indicate a non-conservatism of the BPVC values relative to our analysis for 304 SS at the highest temperature (see Table SISm-1). This finding is consistent with the results of our analysis for yield strength and for tensile strength (see review of HBB-I-14.5 and Appendix HBB-3225-1).

For 2¼Cr-1Mo, BPVC 2017 (and 2019) II-D and III-5 do not distinguish between annealed material and normalized & tempered (N&T) material. Our analysis showed distinctly different trend curves for material with the heat treatments, which was also noted in the 1971 ASTM Data Series DS 6S2 (Ref. Smith 1971), with the N&T material having lower strength. The use of data for both heat treatments is a compromise, but producing potentially less conservative strength parameters for the N&T material. Our analysis results indicate the differences in S_m vary from being insignificant to about 12.5%. We do not have a specific recommendation regarding treatment of this material, but the findings raise the question as to whether separate classes of material merit definition for Code use.

Finally, for completeness, Table SISm-2 shows a comparison between the S_m values for the 2017 and 2019 BPVC editions. The only significant difference noted is that Table 2A of BPVC 2019 II-D has an added stress line for the higher specified tensile strength, SA-182 9Cr-1Mo-V forging material (90 ksi), and this is reflected in the last column of the table. Note, however, that BPVC III-5, including the 2019 edition, does not provide a separate set of stress intensity values for this higher tensile strength material.

The references from which the tensile data have been obtained and analyzed are provided below for convenient review, in addition to the listing in Section 6 References.

For 304 SS

Data: 21 heats/lots and 218 data points

- (Ref. NRIM 1986b)
- (Ref. NRIM 1995)
- (Ref. Simmons 1965)

For 316 SS

Data: 26 heats/lots, 253 data points

- (Ref. NIMS 2015)
- (Ref. NRIM 1979)
- (Ref. NRIM 1988)
- (Ref. NRIM 2000)
- (Ref. Sikka 1980)
- (Ref. Simmons 1965)

For 800H (N08810)

Data: 28 heats/lots, 321 data points

- Data compiled by ORNL from various published and unpublished sources.

For 2¼Cr-1Mo

Data: 42 heats/lots, 326 data points- annealed and N&T material combined

- (Ref. NRIM 1986a)
- (Ref. NRIM 1997)
- (Ref. Smith 1971)

For 9Cr-1Mo-V

Data: 27 heats/lots, 299 data points

- (Ref. Caminada 2015)
- (Ref. DiStefano 1986)
- (Ref. NIMS 2014)
- (Ref. Ruggles 2015)
- (Ref. Sikka 1982b)
- (Ref. Sikka 1986a)
- (Ref. Sikka 1986b)

Table SISm-1. Baseline S_m for All Materials

ksi	°F	304SS				316SS				Ni-Fe-Cr UNS N08810		2-1/4Cr-1Mo		9Cr-1Mo-1V			
		30-75ksi (YS-UTS)		30-70ksi (YS-UTS)[a]		30-75ksi (YS-UTS)		30-70ksi (YS-UTS)[a]						60-85ksi (YS-UTS)		60-90ksi (YS-UTS)[b]	
		ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2019	This Analysis
PBVC II-D Table 2A/2B	RT	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	16.7	16.7	20.0	20.0	28.3	28.3	30.0	30.0
	100	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	16.7	16.7	20.0	20.0	28.3	28.3	30.0	30.0
	200	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	16.7	16.7	18.7	18.4	28.3	28.3	30.0	30.0
	300	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	16.7	16.7	18.2	18.2	28.3	28.1	30.0	29.8
	400	18.6	20.0	18.6	19.6	19.3	20.0	19.3	20.0	16.7	16.7	18.0	18.2	28.2	27.4	29.9	29.0
	500	17.5	18.6	17.5	18.6	18.0	18.9	18.0	18.9	16.7	16.7	17.9	18.1	28.1	26.8	29.8	28.4
	600	16.6	17.3	16.6	17.3	17.0	18.0	17.0	18.0	16.5	16.0	17.9	17.8	27.7	26.2	29.3	27.8
	650	16.2	16.9	16.2	16.9	16.6	17.6	16.6	17.6	16.1	15.7	17.9	17.5	27.3	25.9	28.9	27.4
	700	15.8	16.5	15.8	16.5	16.3	17.3	16.3	17.3	15.7	15.4	17.9	17.2	26.7 (26.7)	25.4	28.2 (26.7)	26.9
	750	15.5	16.2	15.5	16.2	16.1	17.0	16.1	17.0	15.3	15.2	17.9 (17.9)	16.9	25.9 (25.9)	24.9	27.4 (25.9)	26.3
	800	15.2 (15.2)	15.9	15.2 (15.2)	15.9	15.9 (15.9)	16.7	15.9 (15.9)	16.7	15.0 (15.3)	15.1	17.7 (17.9)	16.5	24.9 (24.9)	24.2	26.4 (24.9)	25.6
	850	14.8	15.7	14.8	15.7	15.7	16.4	15.7	16.4	15.1	14.9	17.1 (17.6)	16.1	23.7 (23.7)	23.3	25.1 (23.7)	24.7
	900	14.6	15.5	14.6	15.5	15.6	16.1	15.6	16.1	14.8	14.8	13.6 (17.2)	15.7	22.3 (22.3)	22.3	23.6 (22.3)	23.6
BPVC III-5 Table HBB-I-14.3 1h Column*	950	14.3	15.3	14.3	15.3	15.5	15.9	15.5	15.9	14.6	14.7	16.7	15.2	20.7	21.1	20.7	22.4
	1000	14.0	15.1	14.0	15.1	15.4	15.6	15.4	15.6	14.4	14.6	15.9	14.6	19.0	19.7	19.0	20.9
	1050	13.6	14.9	13.6	14.9	15.1	15.4	15.1	15.4	14.3	14.5	14.9	13.9	17.1	18.2	17.1	19.2
	1100	13.2	14.6	13.2	14.6	14.8	15.1	14.8	15.1	14.1	14.3	13.4	13.1	15.2	16.4	15.2	17.4
	1150	12.9	14.3	12.9	14.3	14.7	14.8	14.7	14.8	13.9	14.1	11.7	11.9	13.1	14.6	13.1	15.4
	1200	12.7	13.8	12.7	13.8	14.6	14.4	14.6	14.4	13.8	13.9	9.3	10.0	11.1	12.7	11.1	13.4
	1250	12.3	13.1	12.3	12.6	14.2	14.1	14.2	14.1	13.5	13.6	...		...		...	
	1300	11.9	12.0	11.8	11.2	13.8	13.7	13.4	13.3	13.2	13.2	...		...		...	
	1350	10.9	10.5	10.5	9.8	12.8	12.8	11.9	11.9	12.0	12.7	...		...		...	
	1400	9.5	8.9	9.0	8.3	11.3	11.3	10.5	10.5	11.0	11.5	...		...		...	
	1450	8.2	7.4	7.5	6.9	9.4	9.7	9.0	9.1		10.2	...		...		...	
	1500	7.0	5.9	6.4	5.5	7.8	8.3	7.7	7.7		9.0	...		...		...	
	1550	...		...		...		...			7.7	...		...		...	
	1600	...		...		...		...			6.5	...		...		...	
	1650	...		...		...		...			5.4	...		...		...	

a: ASME II-D Table 2A does not provide a separate set of values for the 30-70ksi (YS-UTS) material (since the values are yield strength-controlled)

b: ASME III-5 HBB-I-14.3E does not provide a separate set of lines for the 60-90ksi (YS-UTS) material

_____ Red border line indicates limit of II-D Table 2A/2B values. (....) Numbers in parentheses are from Table HBB-I-14.3

* The first 1h column of ASME III-5, Table HBB-I-14.3 represents the S_m value (no reduction factor)

Yield Strength-Controlled | Tensile Strength-Controlled | Digitized from Figure HBB-I-14.3

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%

Non-conservative relative to this analysis - Difference, δ > 10% | (Used rounding for characterization of δ)

MPa	°C	304SS				316SS				Ni-Fe-Cr UNS N08810		2-1/4Cr-1Mo		9Cr-1Mo-1V			
		30-75ksi (YS-UTS)		30-70ksi (YS-UTS)[a]		30-75ksi (YS-UTS)		30-70ksi (YS-UTS)[a]						60-85ksi (YS-UTS)		60-90ksi (YS-UTS)[b]	
		ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2017 ASME 2019	This Analysis	ASME 2019	This Analysis
	RT	138	138	138	138	138	138	138	138	115	115	138	138	195	195	207	207
	40	138	138	138	138	138	138	138	138	115	115	138	138	195	195	207	207
	100	138	138	138	138	138	138	138	138	115	115	128	127	195	195	207	207
	150	138	138	138	138	138	138	138	138	115	115	125	126	195	194	207	205
PBVC II-D Table 2A/2B	200	129	138	129	135	134	138	134	138	115	115	124	126	194	189	206	200
	250	122	130	122	130	126	132	126	132	115	115	120	125	194	185	205	196
	300	116	122	116	122	119	126	119	126	115	112	123	123	192	182	204	193
	325	114	118	114	118	116	123	116	123	113	110	123	122	190	180	201	191
	350	111	116	111	116	114	121	114	121	110	108	123	120	187	178	198	188
	375	109	113	109	113	112	119	112	119	108	106	123	118	183 (183)	175	194 (183)	185
	400	107	111	107	111	111	117	111	117	105	105	123 (123)	116	179	171	179	181
	425	105 (105)	110	105 (105)	110	110 (110)	115	110 (110)	115	104 (105)	104	122 (123)	114	172	167	172	177
	450	103 (102)	108	103 (102)	108	108 (108)	113	108 (108)	113	104	103	119 (122)	111	165	162	165	171
	475	101	107	101	107	107	112	107	112	103	102	101 (119)	109	156	156	156	165
	500	99	106	99	106	106	110	106	110	101	102	116	106	147	149	147	157
	525	98	105	98	105	105	109	105	109	100	101	112	103	136	141	136	149
	550	96	104	96	104	104	107	104	107	99	100	107	99	125	131	125	139
	575	93	102	93	102	104	105	104	105	98	99	100	94	114	121	114	128
	600	91	100	91	100	102	103	102	103	97	98	90	89	101	110	101	117
	625	89	98	89	98	101	102	101	102	96	97	78	80	88	99	88	105
	650	88	95	88	95	101	99	101	99	95	95	64	68	76	87	76	92
	675	85	91	85	87	98	97	98	97	93	94	...		...		...	
BPVC III-5 Table HBB-I-14.3 1h Column*	700	82	84	81	79	95	95	92	93	91	91	...		...		...	
	725	77	75	74	70	90	91	85	85	85	89	...		...		...	
	750	69	65	66	61	82	81	76	76	78	82	...		...		...	
	775	61	56	57	52	71	72	65	67		75	...		...		...	
	800	53	46	49	43	61	63	58	59		67	...		...		...	
	825	...		...		...		...			59	...		...		...	
	850	...		...		...		...			51	...		...		...	
	875	...		...		...		...			44	...		...		...	
	900	...		...		...		...			37	...		...		...	

a: ASME II-D Table 2A does not provide a separate set of values for the 30-70ksi (YS-UTS) material (since the values are yield strength-controlled)

b: ASME III-5 HBB-I-14.3E does not provide a separate set of lines for the 60-90ksi (YS-UTS) material

_____ Red border line indicates limit of II-D Table 2A/2B values. (....) Numbers in parentheses are from Table HBB-I-14.3

* The first 1h column of ASME III-5, Table HBB-I-14.3 represents the S_m value (no reduction factor)

Yield Strength-Controlled | Tensile Strength-Controlled | Digitized from Figure HBB-I-14.3

Slightly non-conservative relative to this analysis - Difference, δ (calculated as % of ASME value) = 5 < δ ≤ 10%

Non-conservative relative to this analysis - Difference, δ > 10% | (Used rounding for characterization of δ)

Table SISm-2. Comparison of S_m values from tables of BPVC 2017 and 2019 editions

	Temp., °F	304 SS		304 SS		316 SS		316 SS		800H		2.25Cr-1Mo		9Cr-1Mo-V		9Cr-1Mo-V	
		30-75ksi (YS-UTS)		30-70ksi (YS-UTS)		30-75ksi (YS-UTS)		30-70ksi (YS-UTS)						60-85ksi (YS-UTS)		60-90ksi (YS-UTS)	
		BPVC 2017	BPVC 2019	BPVC 2017	BPVC 2019	BPVC 2017	BPVC 2019	BPVC 2017	BPVC 2019	BPVC 2017	BPVC 2019	BPVC 2017	BPVC 2019	BPVC 2017	BPVC 2019	BPVC 2017	BPVC 2019*
BPVC II-D Table 2A/2B	100	20.0	20.0			20.0	20.0			16.7	16.7	20.0	20.0	28.3	28.3	...	30.0
	150	...	...			...	...			16.7	16.7	...	...	...	...	...	...
	200	20.0	20.0			20.0	20.0			16.7	16.7	18.7	18.7	28.3	28.3	...	30.0
	250	...	...			...	...			16.7	16.7	...	...	...	...	...	...
	300	20.0	20.0			20.0	20.0			16.7	16.7	18.2	18.2	28.3	28.3	...	30.0
	350	...	...							16.7	16.7					...	...
	400	18.6	18.6			19.3	19.3			16.7	16.7	18.0	18.0	28.2	28.2	...	29.9
	450	...	...							16.7	16.7					...	...
	500	17.5	17.5			18.0	18.0			16.7	16.7	17.9	17.9	28.1	28.1	...	29.8
	550	...	...							16.7	16.7					...	...
	600	16.6	16.6			17.0	17.0			16.5	16.5	17.9	17.9	27.7	27.7	...	29.3
	650	16.2	16.2			16.6	16.6			16.1	16.1	17.9	17.9	27.3	27.3	...	28.9
	700	15.8	15.8			16.3	16.3			15.7	15.7	17.9	17.9	26.7 (26.7)	26.7 (26.7)	...	28.2
	750	15.5	15.5			16.1	16.1			15.3	15.3	17.9 (17.9)	17.9 (17.9)	25.9 (25.9)	25.9 (25.9)	...	27.4
	800	15.2 (15.2)	15.2 (15.2)	15.2 (15.2)	15.2 (15.2)	15.9 (15.9)	15.9 (15.9)	15.9 (15.9)	15.9 (15.9)	15.0 (15.3)	15.0 (15.3)	17.7 (17.9)	17.7 (17.9)	24.9 (24.9)	24.9 (24.9)	...	26.4
	850	14.8	14.8	14.8	14.8	15.7	15.7	15.7	15.7	15.1	15.1	17.1 (17.6)	17.1 (17.6)	23.7 (23.7)	23.7 (23.7)	...	25.1
	900	14.6	14.6	14.6	14.6	15.6	15.6	15.6	15.6	14.8	14.8	13.6 (17.2)	13.6 (17.2)	22.3 (22.3)	22.3 (22.3)	...	23.6
BPVC III-5 Table HBB-I-14.3 1h Column	950	14.3	14.3	14.3	14.3	15.5	15.5	15.5	15.5	14.6	14.6	16.7	16.7	20.7	20.7	...	...
	1,000	14.0	14.0	14.0	14.0	15.4	15.4	15.4	15.4	14.4	14.4	15.9	15.9	19.0	19.0	...	...
	1,050	13.6	13.6	13.6	13.6	15.1	15.1	15.1	15.1	14.3	14.3	14.9	14.9	17.1	17.1	...	...
	1,100	13.2	13.2	13.2	13.2	14.8	14.8	14.8	14.8	14.1	14.1	13.6	13.6	15.2	15.2	...	...
	1,150	12.9	12.9	12.9	12.9	14.7	14.7	14.7	14.7	13.9	13.9	10.8	10.8	13.1	13.1	...	...
	1,200	12.7	12.7	12.7	12.7	14.6	14.6	14.6	14.6	13.8	13.8	9.0	9.0	11.1	11.1	...	...
	1,250	12.3	12.3	12.3	12.3	14.2	14.2	14.2	14.2	13.5	13.5	...	...	...	...	...	...
	1,300	11.9	11.9	11.8	11.8	13.8	13.8	13.4	13.4	13.2	13.2	...	...	...	...	...	...
	1,350	10.9	10.9	10.5	10.5	12.8	12.8	11.9	11.9	12.0	12.0	...	...	...	...	...	...
	1,400	9.5	9.5	9.0	9.0	11.3	11.3	10.5	10.5	11.0	11.0	...	...	...	...	...	...
	1,450	8.2	8.2	7.5	7.5	9.7	9.7	9.0	9.0	...	...	...	...	...	...	...	...
	1,500	7.0	7.0	6.4	6.4	7.8	7.8	7.7	7.7	...	...	...	...	...	...	...	...

* The BPVC 2019 edition has an added stress line for forgings with a higher specified tensile strength (90 ksi), not in BPVC 2017, hence the additional column.

The values in parentheses are from BPVC III-5 Table HBB-I-14.3

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