TLR/RES/DE/CIB-2020-13

Technical Input for the U.S. Nuclear Regulatory Commission Review of the 2017 Edition of ASME Boiler and Pressure Vessel Code, Section III, Division 5, "High-Temperature Reactors"

HBB-T, HBB-II, HCB-I, HCB-II, and HCB-III for Metallic Components

December 2020

PREPARED FOR:

U.S. NUCLEAR REGULATORY COMMISSION
CONTRACT NO. NRC-HQ-25-14-E-0004
TASK ORDER NO. 31310018F019

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ADAMS	Agencywide Documents Access and Management System
ANLWR	advanced nonlight-water reactor
ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
C	Celsius
DDS	Demonstration Reactor Design Standard
DOE	U.S. Department of Energy
Emc^2	Engineering Mechanics Corporation of Columbus
F	Fahrenheit
HTGR	high-temperature gas-cooled reactor
HTR	high-temperature reactor
INL	Idaho National Laboratory
ksi	kilopound per square inch
L-M	Larson-Miller
mm	millimeter
MPa	megapascal
NIMS	Busshitsu-zairyō kenkyū kikō (National Institute of Materials Science)
NRC	U.S. Nuclear Regulatory Commission
NUMARK	NUMARK Associates, Inc.
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
RCC-MR	Regles de Conception et de Construction des Materiels Mecaniques des ilots nucleaires (Rules for Design and Construction of Fast-Breeder Liquid-Metal-Cooled Reactors)
RG	regulatory guide
SG	subgroup
SS	stainless steel
U.K.	United Kingdom
WRC	Welding Research Council

EXECUTIVE SUMMARY

This report reviews the following subsections of American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), Section III, “Rules for Construction of Nuclear Facility Components,” Division 5, “High-Temperature Reactors”:

- Nonmandatory Appendix HBB-T, “Rules for Strain, Deformation, and Fatigue Limits at Elevated Temperatures”
- Mandatory Appendix HBB-II, “Use of SA-533 Type B, Class 1 Plate and SA-508 Grade 3, Class I Forgings and Their Weldments for Limited Elevated Temperature Service”
- Mandatory Appendix HCB-I, “Stress Range Reduction Factor for Piping”
- Mandatory Appendix HCB-II, “Allowable Stress Values for Class B Components”
- Mandatory Appendix HCB-III, “Time-Temperature Limits for Creep and Stress-Rupture Effects”

A summary of the review of each of these subsections follows. Given that the last two documents are closely related, this report combines the reviews for Mandatory Appendices HCB-II and HCB-III.

Nonmandatory Appendix HBB-T, “Rules for Strain, Deformation, and Fatigue Limits at Elevated Temperatures”

The load-controlled stress limits of HBB are mandatory, while the deformation-controlled limits in Appendix HBB-T, which is the subject of this review, are not mandatory. HBB-T rules provide strain limits, creep-fatigue limits, and buckling and instability limits for high-temperature design. The rules permit elastic analysis methods to be used where the rules are very conservative. In addition, inelastic analyses are permitted using advanced numerical modeling methods. For the strain limits and creep-fatigue limits, the rules are meant to limit crack initiation. Since there is usually considerable life remaining during the crack growth phase, these rules are considered to produce designs that are quite conservative. Likewise, the buckling and instability limits are also set to be very conservative. HBB-T rules have been developed over the years and are based on mathematical bounding theorems, which ensure conservative predictions for the most part—especially with the required margins and safety factors. Moreover, an extensive experience database over the years clearly shows the reliability and conservatism of the rules in HBB-T. In addition, years of experience with high-temperature service have been used to modify the rules as appropriate.

This review finds that the limits of HBB-T are an acceptable approach for demonstrating compliance with the design requirements for Division 5, Class A, components, although the owner may use other methods as justified in the design report ASME BPVC Section III, Division Subsection NCA-3550. It is anticipated that advanced nonlight-water reactor (ANLWR) vendors will use a nonlinear finite-element-based solution to demonstrate compliance for some components because of the large computational facilities available to these vendors. This may reduce the conservativism inherent in the simple HBB-T design rules based on elastic or simplified inelastic analysis. The justification for many of the rules in Appendix HBB-T are discussed below in the report with reference to the publications used to develop the rules. For Division 5, precedence was established earlier by ASME BPVC, Section I Rules for Construction of Power Boilers, and Section VIII Rules for Construction of Pressure Vessels, based on many years of operating experience at elevated temperatures. Section 3 provides an endorsement recommendation, while Section 4 and Appendices A and B present detailed justification for many of the rules in HBB-T.

Almost all rules within HBB-T are recommended for endorsement. However, in a few areas the designer and owner must be careful:

- Stress-relaxation cracking. Residual stresses during metal forming and weld fabrication occur, and these stresses relax during service creep. The stress relaxation results in some amount of creep damage. For components with low creep ductility, this can lead to cracking. Moreover, even if cracking does not occur some amount of creep damage develops from stress relaxation. Several European code groups, particularly in the United Kingdom, are concerned with preventing stress-relaxation cracking, and it is reasonable to question why HBB-T does not explicitly consider this mechanism. Minimizing weld constraint and use of post-weld heat treatment to reduce residual stresses may aid the mitigation of stress-relaxation cracking. This report recommends that the vendor address the potential for stress-relaxation cracking in its design.

- The creep-fatigue rules of HBB-T-1400 are recommended for endorsement contingent on HBB-2000 endorsement. In the assessment of HBB, the creep-rupture constants were found to provide nonconservative data, especially at high temperatures and long times. However, it is noted that the creep-fatigue rules using the linear damage interaction approach had safety factors and margins developed to ensure that very conservative predictions are made using the design procedures currently within HBB-T even without the above noted corrections. Therefore, while the possibly nonconservative data in Tables HBB-I-14.6 for 304 and 316 stainless steel (SS) and 2.25 Cr-1Mo steel may need to be addressed, the creep-fatigue procedures for design are deemed adequate because of the margins introduced and the comparisons with extensive test databases.

This review recommends that HBB-T-1820 be endorsed subject to the following stipulations. It may be necessary to re-examine these data for high temperatures and long times, although this is difficult to do since extrapolation is necessary for estimates over long time periods.

- The isochronous for temperatures higher than 700 degrees Celsius (1292 degrees Fahrenheit) for 304 and 316 stainless steel appear to be slightly nonconservative for times greater than 100,000 hours.

- The isochronous curves for 2.25Cr-1Mo material may be nonconservative for temperatures above 600 degrees C (1112 degrees F) at times greater than 100,000 hours.
- The isochronous curves for Alloy 800H material may be nonconservative for temperatures at 700 degrees C (1292 degrees F) and above, at times of 100,000 hours and above.
- The isochronous curves for 9Cr Mo material are higher than new curves recently produced by ASME Standards Technology, LLC[1] based on new data and may be slightly nonconservative in general.

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"

Mandatory Appendix HBB-II was developed to provide rules for the use of SA-533 Type B, Class 1 plates and SA-508 Grade 3, Class 1 forgings and their weldments for a limited time above the normal temperature limit of 371.1 degrees C (700 degrees F). The metal temperatures are limited to 426.7 degrees C (800 degrees F) during Level B events and 537.8 degrees C (1,000 degrees F) during Level C and D events. Service life is limited to 3,000 hours in the temperature range of 371.1 to 426.7 degrees C (700 to 800 degrees F) and 1,000 hours in the range of 426.7 to 537.8 degrees C (800 to 1,000 degrees F). The number of events above 426.7 degrees C (800 degrees F) is limited to three. The specific articles reviewed are HBB-II-1000, "Scope," HBB-II-2000, "Materials," and HBB-II-3000, "Design," as the remaining articles (HBB-II-4000 through HBB-II-7000) are based on sections of the code other contractors involved in this effort are reviewing.

Article HBB-II-2000 provides values of yield strength, S_y, tensile strength, S_u, and design stress intensity (allowable) values, S_m, for both materials in ASME BPVC Section II for temperatures less than 371.1 degrees C (700 degrees F), and Table HBB-II-3000-3 for temperatures greater than 371.1 degrees C (700 degrees F). These values were reviewed in detail to establish that the margin of safety (S_u/S_m) for the entire range of temperatures for both materials is consistently 3.0. This confirms that the S_m values in Table HBB-II-3000-3 are conservative, and therefore, HBB-II-2000 is recommended for endorsement.

Article HBB-II-3000 involves design rules for temperatures exceeding 371.1 degrees C (700 degrees F) and was reviewed to confirm that the following three aspects of the design bases were conservative and, therefore, recommended for endorsement:

- Allowable stress intensity had an adequate margin of safety for the allowable stress S_{mt} since it is dependent on both temperature and time at the given temperature based on

[1] ASME established ASME Standards Technology, LLC in August 2004 as a separate 501(c)(3) not-for-profit organization to address in part the need for technical basis documents supporting standards actions, particularly in emerging technology areas.

Figures HBB-II-3000-1, -2, -3, -13, and -14, along with their underlying data in Tables HBB-II-3000-1, -2, -3, and -4.

- Isochronous stress-strain curves for temperatures 700 degrees F (371.1 degrees C) through 1,000 degrees F (537.8 degrees C) in Figures HBB-II-3000-4 through HBB-II-3000-10 were reviewed to confirm adequate conservatism in the strain to failure under creep at the various stress and temperature values.

- Design fatigue strain in Figure HBB-II-3000-11, along with Table HBB-II-3000-9 and the creep-fatigue damage envelope in Figure HBB-II-3000-12, were conservative.

Mandatory Appendix HCB-I, "Stress Range Reduction Factor for Piping"

The most significant modification for creep effects in HCB-3630 is the definition of the stress reduction factor, f, which is covered in Mandatory Appendix HCB-I. This is essentially an extension of the definition of the stress reduction factor in ASME BPVC Section III NC-3611.2 where the factor, r_1, has been modified for elevated temperatures to include a term to account for the higher of the peak stresses due to either the through-the-wall temperature gradients or the axial temperature difference. The second modification is to the stress reduction factor in Table HCB-I-2000-1 and Table HCB-I-2000-2 for the number of cycles, N_1.

The stress range reduction factor is recommended for endorsement as Table HCB-I-2000-1 is a direct extension of Table NC-3611.2(e)-1 in ASME BPVC, Section III, Division 1 Subsection NC-2017 for materials in the noncreep regime. These reduction factors, f, in Table HCB-I-2000-1 are significantly lower than those in NC (as low as 0.2 for the lower bound case instead of 0.5) to account for the effect of the combination of creep at elevated temperatures and to ensure conservative design limits. The maximum number of allowable cycles (N_1) over which f=1 and the range over which the factors apply vary with the material involved and are provided in Table HCB-I-2000-2. The approach to determining equivalent cycles in HCB-I-3000 for cases where the temperature varies with time, as described in this article, involves the same methodology described in ASME BPVC.III.1.NC-2017, Article NC-3611.2, "Stress Limits," which the U.S. Nuclear Regulatory Commission (NRC) has endorsed.

A significant effort was undertaken to obtain the underlying data used by ASME to develop Tables HCB-I-2000-1 and HCB-I-2000-2. Both ASME staff and members of Division 5 who participated directly in the development of these original tables as far back as 1977 were contacted. The discussions confirmed the conservative approach used to develop the tables, and, therefore, this review recommends Mandatory Appendix HCB-I for endorsement.

Mandatory Appendix HCB-II, "Allowable Stress Values for Class B Components," and Mandatory Appendix HCB-III, "Time-Temperature Limits for Creep and Stress-Rupture Effects"

As indicated above, Mandatory Appendices HCB-II and HCB-III (which has only a single article) are closely related and, therefore, are reviewed together. Both appendices address the allowable stresses that are applicable for Class B components when creep and stress rupture are either negligible or must be accounted for.

Appendix HCB-II contains the allowable stresses for materials for Class B components. The extensive list of materials covered in Appendix HCB-II corresponds generally to the materials used at lower temperatures in Subsection NC. In Appendix HCB-II, two sets of allowable stresses are provided for all the materials: one set in which creep effects are not significant (negligible creep), and the other set for the general case in which creep is significant. The allowable stresses in Appendix HCB-II are based on the same criteria as those used to develop the allowable stresses for pressure vessels constructed in accordance with the rules for ASME BPVC Section VIII, Division 1, Rules for Construction of Pressure Vessels, for nonnuclear applications. However, reduction factors are also provided to account for the reduced in creep-rupture strength of weld metal and weldments. Given the complexity of the procedure involved, a detailed flowchart is provided to determine the allowable stress and reduction factor for different conditions and service levels.

Appendices HCB-II and HCB-III address many material grades for each of the seven material categories covered by Curves A–G in Figure HCB-III-1000-1. For the purpose of this review, one example for each of the material sets was selected for further review. The allowable stress values for all service conditions were calculated as described in the flowchart as a function of time based on the recommendations for the four designators: creep (A1), with weldments (A2), creep-significant event less than 1 hour (A3), and negligible creep (A4). The analysis of these cases indicated the following:

- The values for allowable stresses for “all service conditions” (A1) and the respective “weldments” (A2) for these cases generally provide lower bound conservative values, and therefore, these options are recommended for endorsement, especially as they are based on values from ASME BPVC.II.D.C-2017, which the NRC has already endorsed. However, some inconsistencies were noted in cases where the Designators A1 and A4 were not the most conservative values.

- For those cases with inconsistencies in the values of the allowable stresses (which ASME may need to resolve), this review recommends using the most conservative value of the allowable stress in every case.

1. INTRODUCTION

The absence of a code of construction endorsed by the U.S. Nuclear Regulatory Commission (NRC) for nuclear reactors operating above 425 degrees Celsius (C) (800 degrees Fahrenheit (F)) is a significant obstacle for advanced nonlight-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 Agencywide Documents Access and Management System (ADAMS) (ASME 2018), the American Society of Mechanical Engineers (ASME), responding to letters from both industry consortia and individual companies interested in developing ANLWR designs, asked the NRC to review and endorse the 2017 Edition of the ASME Boiler and Pressure Vessel Code (BPVC), Section III, “Rules for Construction of Nuclear Facility Components,” Division 5, “High-Temperature Reactors” (BPVC-III-5) (ASME 2017). The NRC responded, in a letter dated August 16, 2018 (, NRC 2018a), that the agency was initiating efforts to endorse (with conditions, if necessary) the 2017 Edition of BPVC-III-5 in a new regulatory guide (RG) as one way of meeting the NRC’s regulatory requirements.

To support the review and endorsement effort, the NRC requested the technical support of NUMARK Associates, Inc. (NUMARK), and its subcontractor Engineering Mechanics Corporation of Columbus (Emc^2). This report documents the technical input of NUMARK and Emc^2 for the NRC’s review of the 2017 Edition of BPVC-III-5. This report will be used as part of the NRC’s review and will support the NRC’s findings in the associated RG.

2. OVERVIEW

2.1 Review Approach

The NRC wants to ensure it performs its licensing reviews commensurate with its safety and security mission and asked NUMARK to conduct its technical review in accordance with the guidance in two recent NRC examples:

(1) SECY-18-0060, “Achieving Modern Risk-Informed Regulation,” dated May 23, 2018 (NRC 2018b), which provided the findings of the NRC Transformation Team

(2) an NRC memorandum from Frederick Brown, Director, Office of New Reactors, titled “Expectations for New Reactor Reviews,” dated August 29, 2018 (NRC 2018c)

One of the memorandum’s expectations for new reactor reviews is to base the NRC’s regulatory findings on 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 memorandum discusses the basis for using the terms “reasonable” and “adequate.”

The RG that will endorse the use of BPVC-III-5 will be based on the finding that the rules in Division 5 provide “reasonable assurance of adequate protection.” In accordance with the memorandum, new or novel designs or design features may need additional review or requirements. Furthermore, any technical areas that are not addressed by BPVC-III-5 and would lead to a demonstrably increased likelihood or consequence of failure, should be considered.

The memorandum also considers the topic of margin. If the ASME BPVC is sufficiently conservative in a particular area such that it provides significant margin to relevant limits, and sufficient data exist 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 this conclusion.

Similarly, the memorandum 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 NUMARK 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 of previous high-temperature design rules and NRC approvals. The final RG or another accompanying NRC document will fully document the NRC's specific historical findings. The findings relevant to this report are discussed below.

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

As discussed with staff of the Office of New Reactors and the Office of Nuclear Regulatory Research at the NRC and NUMARK's Project Manager, Emc^2's effort on this project involved detailed review of the following portions of the 2017 BPVC-III-5 relating to metallic materials:

- Nonmandatory Appendix HBB-T, "Rules for Strain, Deformation, and Fatigue Limits at Elevated Temperatures," pp. 163–251

- 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," pp. 140–162

- Mandatory Appendix HCB-I, "Stress Range Reduction Factor for Piping," pp. 277–279

- Mandatory Appendix HCB-II, "Allowable Stress Values for Class B Components," pp. 280–308

- Mandatory Appendix HCB-III, “Time-Temperature Limits for Creep and Stress-Rupture Effects,” pp. 309–310

- Code Case N-861, “Satisfaction of Strain Limits for Division 5 Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis,” pp. 1(N-861)–4(N-861)

- Code Case N-862, “Calculation of Creep-Fatigue for Division 5 Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis,” pp. 1(N-862)–4(N-862)

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 and preapplication safety evaluation reports. The NRC found that the following ASME Code Cases were accepted for use, with conditions, in NRC RG 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, (NRC, 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 BPVC-III-5.

2.3 Review Scope

Table 2.3-1 lists the specific portions of the ASME BPVC (e.g., subsection, article, Code Case) that are reviewed and the reviewing organization.

Some assignments have additional details 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 its review, this contractor may need to support the contractor responsible for reviewing HBB, Article 3000, “Design.”

Similarly, contractors may need to examine information in other parts of the code to support the review of their assignments. For example, the contractor responsible for reviewing Article 3000 may need to view information in Article 2000. If the Article 3000 contractor has concerns with Article 2000, then the Article 3000 contractor should discuss them 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 2.3-1 Review Assignments

General Requirements, Low Temperature Metallic Components, and Supports:

ASME BPVC Section (Subsection)	Reviewer
General Requirements, Metallic Materials (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
Class A Metallic Core Support Structures, Low Temperature Service (HGA)	NRC Staff

Elevated Temperature Metallic Components:

ASME BPVC 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)	

ASME BPVC Section	Reviewer
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
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

Graphite and Composites:

ASME BPVC 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

ASME BPVC Section	Reviewer
Class A Nonmetallic Core Components, Graphite Materials (HBB-T)	
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 HBB-T-I, Graphite Material Specifications	NUMARK
Mandatory Appendix HBB-T-II, Requirements for Preparation of a Material Data Sheet	NUMARK
Mandatory Appendix HBB-T-III, Requirements for Generation of Design Data for Graphite Grades	NUMARK

Code Cases

Code Case	ASME 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

3. TECHNICAL REVIEW SYNOPSIS

3.1 Nonmandatory Appendix HBB-T, “Rules for Strain, Deformation, and Fatigue Limits at Elevated Temperatures”

The load-controlled stress limits of HBB are mandatory. In contrast, the deformation-controlled limits in Appendix HBB-T are not mandatory. These rules provide strain limits (also addressed with Code Case N-861), creep-fatigue limits (also addressed with Code Case N-862), and buckling and instability limits (Rao, 2017; Jawad and Jetter, 2009; and Griffin, 1980). This report’s technical recommendation finds that the limits of HBB-T are an acceptable approach for demonstrating compliance with the design requirements for Division 5 Class A components, although the owner may use other methods as justified in the design report ASME BPVC Section III, Subsection NCA-3550. It is anticipated that ANLWR vendors will use a nonlinear finite-element-based solution to demonstrate compliance for some components because of the large computational facilities available to these vendors. This may reduce the conservativism inherent in the simple HBB-T design rules based on elastic analysis. Jetter (1976), and references cited in that report in the context of Code Case 1592, contain the justification for many of the rules in Appendix HBB-T. These remain appropriate for the rules of Appendix HBB-

T. For ASME BPVC Division 5, Sections I and VIII, established precedence earlier based on many years of operating experience at elevated temperatures. Section 4 in this report provides detailed justification for many of the rules in Appendix HBB-T.

3.1.1 Article HBB-T-1000, “Introduction”

HBB-T-1100 Introduction
Introduction is left blank.

HBB-T-1110 Objective. This review recommends that HBB-T-1110 be accepted because, when used with the load-controlled stress requirements of Subsection HB, Subpart B, the objectives provide structural integrity and functionality of high-temperature components, and conservative margins are expected.

HBB-T-1120 General Requirements.
HBB-T-1121 Type of Analysis. This review recommends that the general rules specified in HBB-T-1121 be accepted because the rules include all pertinent damage mechanisms possible when creep effects are determined to be significant. The elastic rules will produce conservative results (in some cases, overly conservative). Likewise, full inelastic analysis, if used with proper constitutive laws and with the corresponding safety margins specified in HBB-T, will produce conservative results.

HBB-T-1122 Analysis Required. This review recommends that HBB-T-1122 be accepted because this article describes the general procedure consistent with high-temperature distortion design. Figure HBB-3221-1, which includes the rules for load-controlled HBB stress limits, illustrates the rules for design for distortion and fatigue.

HBB-T-1200 Deformation Limits for Functional Requirements
HBB-T-1210 Statement in Design Specification. This review recommends that HBB-T-1210 be accepted because this subarticle is general and provides requirements necessary for functional design.

HBB-T-1220 Elastic Analysis Method. This review recommends that HBB-T-1220 be accepted because this subarticle is general and refers to specific requirements in HBB-T-3200 for elastic analysis for compliance with distortion requirements. The 1-percent inelastic strain limit is considered very conservative and has been borne out by many years of successful elevated temperature operating history (Jetter, 1976, 2017). Moreover, the elastic analysis methods, as summarized in Section 4 of this report, have a good theoretical basis backed up with extensive test data and operating experience. The discussion of HBB-T-1320 in Section 4 provides details for this endorsement.

HBB-T-1230 Use of Inelastic Analysis. This review recommends that HBB-T-1230 be accepted because this subarticle is general and stipulates that inelastic analysis rules are required if the elastic method does not comply. The 1-percent inelastic strain limit is considered very conservative. Section 4 includes detailed discussion of inelastic analysis. If inelastic analysis is used for design, the design report should demonstrate the validity of the material models.

<u>HBB-T-1300 Deformation and Strain Limits for Structural Integrity</u>

HBB-T-1310 Limits for Inelastic Strains. This review recommends that HBB-T-1310 be accepted with the caveat below. This is because the deformation-controlled inelastic strain limits are considered quite conservative (Jetter, 1976) and have been used with a large experience base for more than 50 years (see discussion in Section 4).

Experience with stress-relaxation cracking in a number of high-temperature components, especially for high carbon grades of stainless steel, suggests that weld residual stresses may cause damage even though these stresses relax with time. Hughes et al. (2019) discussed stress-relaxation cracking issues in the United Kingdom (U.K.) advanced gas reactors in stainless steel and American Petroleum Institute Report 942-A (2014) discusses this issue in stainless steel and Alloy 800 along with techniques to prevent it. This review recommends that vendors develop their own plan to address the potential for stress-relaxation cracking in their designs.

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

<u>HBB-T-1321 General Requirements</u>. Use of elastic methods to account for design in the creep regime is a legacy approach developed before the widespread use of computational modeling. At that time (the 1970s), it was felt that considerable expertise and experience were required to perform these complex analyses and "their reliability as design tools in the hands of inexperienced users may be questioned" (O'Donnell and Porowski, 1974). For this reason, ASME developed simple, if overly conservative and complex to apply, elastic and simplified inelastic analysis rules in the BPVC.

If any one of the three strain limit test cases described below are satisfied, then the strain limit requirements of HBB-T-1220 are considered to be addressed. This includes the procedure for defining loading cycles and stress intensities. This review recommends that this article be endorsed. Section 4 includes extensive discussion of the source, background, and validation of these rules.

<u>HBB-T-1322 Test No. A-1</u>. This review recommends that HBB-T-1322 be accepted because this test ensures that the maximum value of the load-controlled stresses throughout service life and maximum secondary stresses are limited to the elastic Bree regime where ratcheting may occur. This test is considered conservative, and Section 17.4.4.3.6.2 of the ASME BPVC companion guide (Rao, 2017), the example residual stress case of Jetter (1976), and arguments of O'Donnell and Porowski (1974) describe its rationale in detail. Section 4 provides a more detailed discussion of the rationale. This endorsement is contingent on the assessment of HBB-2000 at Oak Ridge National Laboratory by Ren et al. (2020) which suggests that yield stress values may not be conservative for some high temperatures.

<u>HBB-T-1323 Test No. A-2</u>. This review recommends that HBB-T-1323 be accepted because this test ensures that the maximum value of the load-controlled stresses throughout service life

and maximum secondary stresses are limited to the elastic Bree regime where ratcheting may occur. This is ensured if one end of the temperature cycle is below the creep range as discussed in Section 4. This endorsement is contingent on the assessment of HBB-2000 data by ORNL, which suggests that yield stress values may not be conservative for some high temperatures.

HBB-T-1324 Test No. A-3. This review recommends that HBB-T-1324 be accepted subject to the stipulation discussed below. This test ensures that the primary plus secondary stresses satisfy the rules of Subsection NB when creep effects are insignificant, with certain restrictions defined in this test. The restrictions ensure that ratcheting does not occur for limited creep damage. This additional test protects against any possible unaccounted-for creep effects using suitable safety factors and is considered conservative. The ORNL review of HBB-2000 identified some possible nonconservatism in the creep-rupture values for high temperatures and long times. Therefore, Test A-3 is endorsed subject to the review of HBB-1-14.6A, B, and D for 304 SS, 316 SS, and 2.25Cr-1Mo.

HBB-T-1325 Special Requirements for Piping Components. This review recommends that HBB-T-1325 be accepted because this subarticle includes provisions in the A-1, A-2, and A-3 tests to conservatively account for elastic followup in piping systems where stress relaxation due to creep may only partially occur. The elastic followup corrections are considered to be conservative as discussed in Section 4.

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

HBB-T-1331 General Requirements. Simplified inelastic analysis methods are based on elastic analysis that extends the Bree approach for ratcheting control. This procedure, developed by O'Donnell and Porowski (1974), is based on a mathematical bounding strategy (similar to methods used to validate Code Case N-861) to ensure an upper bound on the accumulated strains due to ratcheting. The enhancements by Sartory (1989) to account for peak thermal stress effects ensure conservative results for all possible conditions. Many authors, including Sartory (1976), have provided validation by using finite element methods to ensure accuracy. Section 4 presents details on the development of these rules and acceptance of the procedure.

Tests B-1 to B-3 are considered to produce conservative results for the following reasons: (1) the bounding theorems ensure that conservative results are predicted using the tests, (2) the strain limits of HBB-1310 are considered quite conservative, and (3) the methodology predicts only when crack initiation occurs rather than full failure. There is typically much more structural life in high-temperature structures beyond crack initiation.

This review recommends that HBB-T-1331 be accepted based on the foregoing summary and arguments in Section 4.

HBB-T-1332 Test No. B-1 and B-2. This review recommends that HBB-T-1332 be accepted based on the foregoing summary and arguments in Section 4. However, conservative estimates of ratcheting will be calculated using Tests B-1 and B-2 with the low-temperature end of the cycles below the creep range.

O'Donnell and Porowski (1974) discuss the effect of residual stresses due to welding and other fabrication processes. These could be added to the operating stresses and the bounds obtained using their method, but this may make the methods overly conservative. They note that the theorem of Frederick and Armstrong (1966) applies directly to this issue and implies that residual stresses will relax and have a second order effect on ratcheting. However, experience in some operating ANLWRs (Hughes et al., 2019) clearly shows that stress-relaxation cracking, from relaxation of weld residual stresses, can occur in some materials under some conditions. Other references documenting stress-relaxation cracking include the experience with the Prototype Fast Reactor in the United Kingdom (Cruikshank and Judd, 1998; Guidez, 2013) with regard to Phénix, a French prototype fast breeder reactor, along with a recent Ph.D. thesis from Imperial College (Kapadia, 2014). Recent work (Natesan et al., 2008) is addressing this issue but does not appear to have worked its way into the code. This review recommends that vendors develop their own plans to address the potential for stress-relaxation cracking in their designs rather than include it directly in this code.

In addition, the average isochronous stress-strain curves of HBB-T-1800, which are used to obtain upper bounds of the total inelastic strain including strains due to creep ratcheting with Tests B-1 and B-2, are discussed later in this report with regard to HBB-T-1800. For long times and high temperatures for some materials, the isochronous curves may need reevaluation.

HBB-T-1333 Test No. B-3. This review recommends that HBB-T-1333 be accepted based on the discussion in Section 4 and the enhancements to the method by Porowski and O'Donnell (1979). These enhancements permitted hardening and temperature-dependent yield stress to be accounted for, which reduces conservatism in Tests B-1 and B-2. This test permits a limited number of severe ratcheting excursions in the plastic range by allowing partial relaxation of the core stress. With the restriction to axisymmetric geometry and loading, and since the test can only be used away from structural discontinuities, conservative results are expected for all components. It is noted that Test B-3 was voted to be removed from the code in ASME BPVC Subgroup on High Temperature Reactors (SG-HTR) in April 2020 because the test is no longer considered useful and is too difficult to pass. This change may appear in the 2021 BPVC rules.

HBB-T-1400 Creep-Fatigue Evaluation

HBB-T-1410 General Requirements.

HBB-T-1411 Damage Equation. As discussed in Section 4, many possible approaches were considered before developing the HBB-T approach to creep-fatigue assessment in Division 5 and the precursor Code Cases. Ultimately, the simple linear creep-fatigue interaction approach was chosen because it is easy for designers to use and the material data requirements are the simplest among all approaches considered.

This approach accounts for creep damage on a time-fraction basis, and fatigue damage is accumulated using Miner's rules independent of strain rate (as done in Subsection NB). The combined damage is limited to an interaction damage value determined empirically for different materials. The use of this creep-fatigue damage assessment rule is nonconservative without application of safety factors (see discussion in Section 4 and Appendix B). However, with the use of safety factors, this approach has been repeatedly shown to be conservative over the years according to Jetter (2017). Moreover, the rules guard against crack initiation, and often, considerable life remains after crack initiation occurs at one point in the component. Section 4 and Appendix B present additional discussion of this rationale.

This review recommends that HBB-T-1411 be accepted for the reasons discussed above.

HBB-T-1412 Exemption from Fatigue Analysis. The exemption from fatigue rules does not apply to temperatures above Subsection NB temperature limits unless service loads can be qualified as not introducing significant time-dependent effects. This review recommends that HBB-T-1412 be accepted for this reason since the NRC has endorsed Subsection NB.

HBB-T-1413 Equivalent Strain Range. The methods for determining the equivalent strain range for use in fatigue design under multiaxial loading are basically the same as that used in Subsection NB as noted by Jetter (2017). Moreover, the BPVC fatigue design curves ignore the effect of mean stress (Jetter, 2017). In the same work, Jetter discussed how application of the modified Goodman diagram approach for Subsection NB resulted in no adjustment of the fatigue curves. Section 4 contains more discussion and detail.

This review recommends that HBB-T-1413 be accepted because Subsection NB uses this approach. A recent ORNL report studied the mean stress effect (Wang et al., 2019, 2020). This recent test work shows that the mean stress effect at elevated temperature is not important. This makes sense since, at elevated temperature, creep will tend to remove mean stress effects.

HBB-T-1414 Alternative Calculation Method—Equivalent Strain Range. This review recommends that HBB-T-1414, the alternative approach to defining multiaxial strain ranges for fatigue assessment when principal strains do not rotate during the service history, be accepted because Subsection NB uses this approach (see discussion in Section 4).

HBB-T-1420 Limits Using Inelastic Analysis. Full inelastic analysis involves performing a finite-element-based analysis of the creep-fatigue problem for the component of interest, with a proper constitutive law that handles combined creep and plasticity (all inelastic behavior) as functions of temperature throughout the service load history. The entire history of loading is modeled to perform the assessment. Performing such an analysis and fitting the material behavior and constants are challenging tasks.

This review recommends that HBB-T-1420 be accepted with the condition that the user show validation of the constitutive models used in assessments for cyclic creep loading. However, use of the limits should ensure conservative design. The validity of the inelastic constitutive models must be demonstrated. Section 4 provides more discussion of inelastic analysis.

HBB-T-1430 Limits Using Elastic Analysis.

HBB-T-1431 General Requirements. The most recent general rules in BPVC-III-5 were developed by Severud (1991) and references cited in that work, and the current rules for creep-fatigue assessment using elastic analysis methods are based on this work. Because the carefully developed arguments of Severud (1978, 1991), which are based on years of work and vetting by the code committee and operational experience, are considered conservative, this article is recommended for endorsement. For creep-fatigue the articles below are recommended for endorsement. Section 4 contains extensive discussion and references supporting this endorsement, and Appendix B further explores the conservative nature of these rules.

HBB-T-1432 Strain Range Determination. The increase in modified equivalent strain range for use is obtained from Figure HBB-T-1432 and is identical to Figure 2 of Severud (1991). The range is constructed from the appropriate isochronous curves of HBB-T-1800. The multiaxial adjustment factors (K), also described in detail in Severud (1991), are determined from Figure HBB-T-1432-2 (Figure 3 of Severud, 1991). Jetter (2017) describes in physical terms the other procedures for determining the strain range. These procedures are considered appropriate and are expected to provide conservative estimates of the fatigue damage portion. An extensive operational experience base supports them.

This review recommends that HBB-T-1432 be accepted because the procedure is expected to provide conservative predictions of the fatigue portion of the damage (perhaps too conservative in some cases).

HBB-T-1433 Creep Damage Evaluation. The creep damage evaluation procedure based on elastic analysis is likewise based on the procedure summarized by Severud (1991). The bounding theorems discussed in Section 4 are part of the rationale to ensure conservative estimations of creep damage. As noted by Severud (1991), experience has indicated that the creep damage, rather than the fatigue damage, usually controls the creep-fatigue damage prediction. Based on the assessment in Section 4 and Appendix A, there may be nonconservatism in some of the isochronous curves at high temperatures and long times. This affects the stress relaxation terms. Moreover, the assessment of HBB-2000 by ORNL has determined that some high-temperature, long-time creep-rupture curves in HBB-I-14.6 might need adjustment. However, because the margins and safety factors associated with the creep-fatigue rules have been developed to ensure conservatism based on test data over the years, it is unlikely that there is an issue with this rule. However, this review recommends that HBB-T-1433 be accepted contingent on further review of the figures and tables in HBB-I-14.6.

HBB-T-1434 Calculation of Strain Range for Piping. This review recommends that HBB-T-1434 be accepted. The procedures developed to account for elastic followup when using elastic analysis are considered appropriate and conservative (see Section 4).

HBB-T-1435 Alternative Creep-Fatigue Evaluation. This review recommends that HBB-T-1435 be accepted. At a high level, it is simple; if the negligible creep criteria are satisfied, one can use the ASME BPVC Section III Subsection NB procedures with the elevated temperature fatigue curves. T-1435(a) just converts the strain range from the Division 5 fatigue curves to stress amplitude for NB. T-1435(b) substitutes the primary plus secondary stress, S_n, with the peak stress, S_p. This is conservative. The use of S_p for S_n is very roughly the equivalent of the use of $3\bar{S}_m$ in HBB-T-1324(c). Finally, an allowable usage factor of 0.9 is an added conservatism.

HBB-T-1500 Buckling and Instability

HBB-T-1510 General Requirements. The design rules for buckling, along with the design factors for time-dependent buckling, have been significantly enhanced from the original rules from Code Case 1592. Some of the original guidance from RG 1.87 for buckling (Section C, Regulatory Position 2, Code Case 1592-d(1) and d(3)) is no longer needed because the new rules are more specific, especially with the temperature limits defined in Figures HBB-T-1522-1 to HBB-T-1522-3. Moreover, the current rules require use of the load-controlled buckling factors for conditions where strain and load-controlled buckling may interact or for conditions where significant elastic followup may occur. This review recommends that HBB-T-1510 be accepted because this article is general. Section 4 discusses these requirements. However, this report recommends that RG 1.87, Section C, Regulatory Position 2, Code Case 1592-d(2), remain, and the design must justify that a process is purely strain controlled or confirm that "significant elastic followup" is not occurring.

HBB-T-1520 Buckling Limits.

HBB-T-1521 Time-Independent Buckling. This review recommends that HBB-T-1521 be accepted because the load factors used for buckling assessment will produce conservative results and guard against instability. Moreover, for configurations considered in NB-3133, the NB rules are valid. Section 4 provides details of this endorsement.

HBB-T-1522 Time-Dependent Buckling. This review recommends that HBB-T-1522 be accepted because, as demonstrated by Griffin (1980) and references cited in that work showing validation with modeling and test data, conservative predictions are expected. Moreover, from service experience over the years, conservative creep-buckling predictions are expected when using these rules (see Section 4 for discussion and references).

HBB-T-1700 Special Requirements

HBB-T-1710 Special Strain Requirements at Welds. This review recommends that HBB-T-1710 be conditionally accepted because the rules should result in conservative designs and caution the designer to place welds in lower strain regions. However, stress-relaxation cracking has occurred in high-temperature applications from relaxation of weld residual stresses even in regions where the weld residual stresses were partially reduced from post-weld heat treatment (Hughes et al., 2019; Cruikshank and Judd, 1998; Guidez, 2013; and Kapadia, 2014). The reviewers suggest that the BPVC should state that it is up to the vendor to ensure that its design considers the potential for stress-relaxation cracking.

HBB-T-1711 Scope. This review recommends that HBB-T-1711 be accepted because code rules address limited ductility of weld metal at elevated temperatures based on test data discussed under HBB-T-1710 in Section 4.

HBB-T-1712 Material Properties. This review recommends that HBB-T-1712 be accepted because code rules address the limited ductility of weld metal at elevated temperatures based on test data discussed under HBB-T-1710 of Section 4 (see the discussion of this topic in Section 4 for details).

HBB-T-1713 Strain Limits. This review recommends that HBB-T-1713 be accepted because the one-half factor reduction in strain limits for weldments provides sufficient conservatism as described in the HBB-T-1710 discussion above.

HBB-T-1714 Analysis of Geometry. This review recommends that HBB-T-1714 be accepted because the worst surface geometry is to be used in the design.

HBB-T-1715 Creep-Fatigue Reduction Factors. This review recommends that HBB-T-1715 be accepted because the reduction factors for use in the fatigue evaluation procedures of HBB-T-1515 are expected to produce conservative designs. Corum (1989) provided conservative validation from extensive comparison of test data to code rules.

HBB-T-1720 Strain Requirements for Bolting.

HBB-T-1721 Strain Limits. This review recommends that HBB-T-1721 be accepted because the strain limits used in HBB-1300 should apply equally to bolts.

HBB-T-1722 Creep-Fatigue Damage Accumulation. This review recommends that HBB-T-1722 be accepted because the strain limits used in HBB-1400 should apply equally to bolts with the lower creep- and fatigue-reduction factors required.

HBB-T-1800 Isochronous Stress-Strain Relations

HBB-T-1810 Objective. This review recommends that HBB-T-1810 be conditionally accepted since the objective is to use isochronous stress-strain curves for high-temperature design elevated temperatures. Use of isochronous curves has been shown, in general, to produce conservative results, although a rigorous proof is not available. The ongoing activity at Argonne National Laboratory has validated the curves and found some minor errors that are expected to be corrected in the 2021 version of the code. This article is recommended for acceptance pending review of the curves for long times and high temperatures for 304 SS, 316 SS, 2.25Cr-1Mo, and 9Cr-Mo steels. However, see the discussion of HBB-T-1820 below, as differences arise from the extrapolation procedures used for long time periods.

HBB-T-1820 Materials and Temperature Limits. Figures HBB-T-1800-A-1 through HBB-T-1800-E-11 show the isochronous stress-strain curves for each Division 5 qualified material. These are used to provide the designer with information on the total strain from stress at elevated temperatures. These data were produced before 1985 from tests performed at the U.S. Department of Energy (DOE) National Laboratories.

Appendix A discusses a study of the isochronous curves compared to additional data. The isochronous curves are meant to be “average” data curves. The additional data used for comparison cannot be categorized as upper, lower, or average data. Therefore, the following stipulations are made without full pedigree of the new data or the older data.

With the above stipulation, based on the discussion in Appendix A, this review recommends that HBB-T-1820 be endorsed subject to the following stipulations:

- The isochronous for temperatures higher than 700 degrees Celsius (1292 degrees Fahrenheit) for 304 and 316 stainless steel appear to be slightly nonconservative for times greater than 100,000 hours.
- The isochronous curves for 2.25Cr-1Mo material may be nonconservative for temperatures above 600 degrees C (1112 degrees F) at times greater than 100,000 hours.
- The isochronous curves for Alloy 800H material may be nonconservative for temperatures at 700 degrees C (1292 degrees F) and above, at times of 100,000 hours and above.
- The isochronous curves for 9Cr Mo material are higher than new curves recently produced by ASME Standards Technology, LLC[1] based on new data and may be slightly nonconservative in general.

3.2 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"

Appendix HBB-II was developed to provide rules for the use of SA-533 Type B, Class 1 (previously designated as Grade B, Class 1) plates and SA-508 Grade 3, Class 1 (previously designated as Class 3) forgings and their weldments for a limited time above the normal temperature limit of 700 degrees F (371.1 degrees C) as detailed in Subsection NB. The metal temperatures are limited to 800 degrees F (426.7 degrees C) during Level B events and 1,000 degrees F (537.8 degrees C) during Level C and D events. Service life is limited to 3,000 hours in the temperature range of 700 to 800 degrees F (371.1 to 426.7 degrees C) and 1,000 hours in the range of 800 to 1,000 degrees F (426.7 to 537.8 degrees C). The number of events above 800 degrees F (426.7 degrees C) is limited to three. ASME used available supporting test data to develop the basis for these limitations. Appendix HBB-II provides the necessary data to implement the design evaluation in accordance with the rules of Appendix HBB-T.

3.2.1 Article HBB-II-1000, "Scope"

This article is recommended for endorsement as it only describes the scope of the materials and temperatures covered by Mandatory Appendix HBB-II.

[1] ASME established ASME Standards Technology, LLC in August 2004 as a separate 501(c)(3) not-for-profit organization to address in part the need for technical basis documents supporting standards actions, particularly in emerging technology areas.

3.2.2 Article HBB-II-2000, "Material"

This article confirms that the rules for Division 1, Article NB-2000, and HBB-2000 for Class A components in elevated temperatures apply to the two materials covered by this appendix. It also provides guidance on the allowable stress values (time independent) for these materials at temperatures above 700 degrees F (371.1 degrees C) as listed in Table HBB-II-3000-3 and is recommended for endorsement on the technical basis described in Section 4.2.2 below.

3.2.3 Article HBB-II-3000, "Design"

Sections (a) through (i) of this article present the rules for design. They are recommended for endorsement with the following items that need further review by the NRC from a regulatory perspective:

- Table HBB-II-3000-1 provides the values of S_{mt} (allowable stress intensity values) for SA-533 Type B, Class 1, and SA-508 Grade 3, Class 1, in Mandatory Appendix HBB-II for temperatures ranging from 700 to 1,000 degrees F (371.1 to 537.8 degrees C) for time at temperature values between 1 hour and 3,000 hours, as appropriate. As detailed in Section 4.2.3 below, the margins of safety relative to the creep-stress rupture values as presented in Table HBB-II-3000-4 for some of the conditions are below 2.0. Therefore, before endorsement, further regulatory review by the NRC staff is recommended to confirm that adequate conservatism exists.

- Figure HBB-II-3000-11, and Figure HBB-II-3000-12, that describe the design fatigue strain range and creep-fatigue damage envelope respectively, for the two materials covered by this appendix may need further clarification. As discussed in Section 4.2.3 below, these figures appear to be based on the methodology described in HBB-T-1400 for the 2.25Cr-1Mo and Alloy 800H. HBB-II-3000(i) needs to reference HBB-T-1400 for the methodology adopted and state that the approach using the basis for 2.25Cr-1Mo and Alloy 800H provides a conservative lower bound for the analyses for the two materials in this appendix.

3.2.4 Article HBB-II-4000, "Fabrication and Installation"

Pacific Northwest National Laboratory (PNNL) is currently reviewing the rules of Article HBB-II-4000 for endorsement.

3.2.5 Article HBB-II-5000, "Examination"

PNNL is currently reviewing the rules of Article HBB-II-5000 for endorsement.

3.2.6 Article HBB-II-6000, "Testing"

PNNL is currently reviewing the rules of Article HBB-II-6000 for endorsement.

3.2.7 Article HBB-II-7000, "Overpressure Protection"

PNNL is currently reviewing the rules of Article HBB-II-7000 for endorsement.

3.3 Mandatory Appendix HCB-I, "Stress Range Reduction Factor for Piping"

As explained in Chapter 17 of Rao (2017), the most significant modification for creep effects in HCB-3630 is the definition of the stress reduction factor, f, which is covered in Appendix HCB-I. Conceptually, this is an extension of the definition of the stress reduction factor in NC-3611.2. However, for elevated temperature, the factor r_1 has been modified to include a term to account for the higher of the peak stresses due to either the through-the-wall temperature gradients or the axial temperature difference. The second modification is to the stress reduction factor in Table HCB-I-2000-1 and Table HCB-I-2000-2 for the number of cycles, N_1. These tables have been modified to account for the effects of creep on cyclic life. Depending on the material and service temperature, the effects can be quite significant.

3.3.1 Article HCB-I-1000, "Stress Range Reduction Factor"

This article is recommended for endorsement as Table HCB-I-2000-I is a direct extension of Table NC-3611.2(e)-1 in ASME BPVC Section III, Division 1, Subsection NC-2017 for materials outside the creep regime. Section 4.3.1 below describes this further.

3.3.2 Article HCB-I-2000, "Maximum Number of Allowable Cycles with f = 1"

This article is recommended for endorsement based on the response received from ASME BPVC members who were involved in the development of the technical basis of the Code Case that was subsequently incorporated into Appendix HCB-I, as described in Section 4.3.2 below.

3.3.3 Article HCB-I-3000, "Equivalent Cycle"

The rules for design, presented in Sections (a) through (i) of this article, describe the approach to determine equivalent cycles for cases where the temperature varies with time. This is the same methodology described in ASME BPVC.III.1.NC-2017, Article NC-3611.2, "Stress Limits," and since the NRC endorsed BPVC NC-2017 in June 2020, this article is recommended for endorsement also.

3.4 Mandatory Appendix HCB-II, "Allowable Stress Values for Class B Components," and Mandatory Appendix HCB-III, "Time-Temperature Limits for Creep and Stress-Rupture Effects"

Mandatory Appendices HCB-II and HCB-III (which has only a single article) are closely related and have many cross-references to address the allowable stresses that are applicable to Class B components when creep and stress rupture are either negligible or must be accounted for. Therefore, this report reviews these two mandatory appendices from BPVC-III-5 together in Sections 3.4 and 4.4.

Appendix HCB-II lists the allowable stresses for materials for Class B components. The extensive list of materials in the appendix corresponds generally with those used at lower temperatures in Subsection NC. Appendix HCB-II provides two sets of allowable stresses for all the materials: one set, in HCB-II-2000, is for the case where, because of the short time at temperature as defined by the criteria in Appendix HCB-III, creep effects are not significant (referred to as “negligible creep” in the code); the other, HCB-II-3000, is for the general case where creep is significant.

An important point noted by Rao (2017) is that the allowable stresses in Appendix HCB-II are based on the same criteria as those used to develop the allowable stresses for pressure vessels constructed in accordance with the rules for Section VIII, Division 1 (ASME, 2011), except that reduction factors are also provided to account for the reduction in creep rupture strength of weld metal and weldments. A detailed flowchart, Figure HCB-II-1000-1, shows the applicability of these factors for different conditions and service levels to determine the allowable stress values.

3.4.1 Article HCB-II-1000, “Scope”

This article describes the scope of the appendix and primarily covers the above-referenced flowchart in Figure HCB-II-1000-1, which describes how to determine the allowable stress, S, for Class B components for various service level conditions, depending on whether creep is significant. The various cases in the flowchart result in four possible values of allowable stresses, which are denoted by Designators A1 through A4.

For any or all service conditions, the user always has the explicit option of choosing the more conservative allowable stresses according to Designators A1 for base metals or Designator A2 for weldments. Because this article specifically provides this lower bound conservative option, described in Section 4.4.1 of this report, this review recommends for endorsement.

3.4.2 Article HCB-II-2000, “Service with Negligible Creep Effects”

This article is recommended for conditional endorsement as detailed in Section 4.4.2 below after review of the technical basis for Designator A3. While the Appendix HCB-III criteria that define when creep effects are negligible have been confirmed to be conservative, some of the example cases for materials selected for Curves A through G in Figure HCB-III-1000-1 appear to have inconsistent allowable stress values. Section 4.4.2 below discusses these in further detail. Therefore, this article is recommended for further review by ASME before NRC endorsement. However, as stated above, the more conservative values of allowable stresses under Designators A1 and A2 can still be used for design in negligible creep cases.

3.4.3 Article HCB-II-3000, “Service that May Include Creep Effects”

After review of the technical basis for Designator A4, this article is also recommended for conditional endorsement as detailed in Section 4.4.3 below. While the Appendix HCB-III criteria that define when creep effects are negligible have been confirmed to be conservative, some of the example cases for materials selected for Curves A through G in Figure HCB-III-1000-1 appear to have inconsistent allowable stress values. Section 4.4.3 below discusses these in further detail. Therefore, this article is recommended for further review by ASME before NRC endorsement. However, as noted in Section 3.4.1 above, the more conservative values of allowable stresses under Designators A1 and A2 can still be used for design for cases where creep is significant.

3.4.4 Article HCB-III-1000, "Introduction"

This article, and its Subarticles HCB-1100 and HCB-1200 which define criteria for negligible creep, are recommended for endorsement. The technical basis for Figure HCB-III-1000-1 and Table HCB-III-1000-1 has been reviewed and determined to be conservative based on the data and analysis in Nonmandatory Appendix HBB-T for each of the example cases of materials selected for evaluation, as discussed in Section 4.4.4 below.

4. Technical Review Detail

The load-controlled stress limits of HBB are mandatory. In contrast, the deformation-controlled limits in Appendix HBB-T are not mandatory. These rules provide strain limits (also addressed by Code Case N-861), creep-fatigue limits (also addressed by Code Case N-862), and buckling and instability limits (Rao, 2017; Jawad and Jetter, 2009; and Jetter, 1976). Compliance with the limits of HBB-T is an acceptable approach for demonstrating compliance with the design requirements for Division 5 Class A components. Load-controlled stresses are those that are necessary to satisfy equilibrium of the structure under externally applied loads and are covered in HBB. By contrast, deformations can relieve or reduce secondary stresses under many circumstances and are addressed within HBB-T.

As stated in HBB-3250, it is mandatory to evaluate deformation limits for design, and the owner may use methods of its choice and include such analyses in the design report. However, use of Appendix HBB-T is an acceptable method without further justification. Alternate rules to be applied for deformation-controlled stress limits must be included in the certified design specification for the component. This nonmandatory approach was taken in HBB-T to provide flexibility to address unique design situations and to take advantage of new technology, since the rules of Appendix HBB-T are considered to be quite conservative.

4.1 Nonmandatory Appendix HBB-T, "Rules for Strain, Deformation, and Fatigue Limits at Elevated Temperatures"

4.1.1 Article HBB-T-1000, "Introduction"

<u>**HBB-T-1000 Introduction**</u>

HBB-T-1110 Objective. This review recommends that HBB-T-1110 be accepted because, when used with the load-controlled stress requirements of Subsection HB, Subpart B, the objectives provide integrity and functionality of the high-temperature components. In general, the rules in HBB-T-1110 are quite conservative.

HBB-T-1120 General Requirements.

<u>*HBB-T-1121 Type of Analysis*</u>*.* This review recommends that HBB-T-1121 be accepted because the general rule aspects covered include all pertinent damage mechanisms when

creep effects are determined to be significant. Elastic and simplified analysis methods permitted here establish conservative bounding limit rules.

HBB-T-1122 Analysis Required. This review recommends that HBB-T-1122 be accepted because this article describes the general procedure consistent with high-temperature distortion design. Figure HBB-3221-1 illustrates the rules for design for distortion and fatigue, which include the rules for load control stress limits of HBB.

HBB-T-1200 Deformation Limits for Functional Requirements

HBB-T-1210 Statement in Design Specification. This review recommends that HBB-T-1210 be accepted because this subarticle is general and does not affect safety.

HBB-T-1220 Elastic Analysis Method. This review recommends that HBB-T-1220 be accepted because this subarticle is general and refers to requirements in Article HBB-T-3200 for specific requirements of elastic analysis for compliance with distortion requirements. The 1-percent inelastic strain limit is considered very conservative and is supported by many years of successful operating history at elevated temperatures (Jetter, 1976). The elastic analysis methods have a good theoretical basis as discussed below and are supported by extensive test data and operating experience.

HBB-T-1230 Use of Inelastic Analysis. This review recommends that HBB-T-1230 be accepted because this subarticle is general. Full inelastic analyses have been performed for many designs over the years. Datta et al. (1991) (in Welding Research Council (WRC) Bulletin 366) gives examples of this type of analysis performed in the 1970s and 1980s. If inelastic analysis is used for designing, the design report should demonstrate the validity of the material models. See more discussion of inelastic analysis below in the discussion of HBB-T-1420.

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

HBB-T-1310 Limits for Inelastic Strains. The deformation control inelastic strain limits are considered quite conservative (Jetter, 1976) and have been used with a large experience base for more than 50 years. The strain limits apply to principal tensile strains averaged through the thickness (1-percent limit over the life). The equivalent linear strain at the surface is limited to 2 percent and peak local strains to 5 percent. Jetter (1976) discusses the rationale for these values with regard to Code Case 1592. These limits have been used for many years and are considered applicable for displacement control stresses. They are consistent with ASME BPVC, Sections I and VIII, and the corresponding experience base. In addition, the limits are to prevent crack initiation. Since there is often considerable life remaining after crack initiation, the conservative nature of these limits should be apparent. A number of publications discuss the origin of these limits, including O’Donnell and Porowski (1974), Porowski and O’Donnell (1979), Severud (1991), Jetter (1976; 2017), and show them to be conservative.

For welds, the strain limits are half of the above values. Since welds often have associated weld residual stresses, creep damage and deformation may occur solely because of relaxation of these stresses due to creep. This has traditionally been the case in the BPVC. However, experience with stress-relaxation cracking in a number of high-temperature reactors, especially for certain grades of stainless steel, suggest that weld residual stresses may cause damage even though these stresses relax with time (Turk et al., 2019). Other references documenting stress-relaxation cracking include the experience with the U.K. Prototype Fast Reactor (Cruikshank and Judd, 1998; Guidez, 2013) with regard to Phénix, along with a recent Ph.D. thesis from Imperial College (Kapadia, 2014). The weld reduction factor apparently accounts for stress-relaxation cracking, but the half value appears to be arbitrary.

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

<u>HBB-T-1321 General Requirements</u>. When a full time-dependent inelastic analysis is performed using proper constitutive relations, phenomena such as elastic followup and ratcheting are automatically accounted for with deformation-controlled quantities. Alternatively, Division 5 permits deformation-controlled quantities to be evaluated using elastic analysis. Evaluation schemes have been developed to take account of the effects of time-dependent deformations, but these models are more conservative than full inelastic analysis. Under displacement control loading of a simple specimen, the initial stresses relax with time because of creep.

For more complex structures, such as a piping system, displacement control stresses may not fully relax under creep. This effect is automatically accounted for when performing a full inelastic analysis as the partial relaxation of stresses is a result of the solution process. The term “elastic followup” refers to a case where an elastic analysis is performed to make design assessments for displacement control load situations. This effect (along with ratcheting) is accounted for with elastic analysis by using development and results based on a Bree diagram (Bree, 1967, 1968 (also discussed below)). Enhancements by O’Donnell and Porowski (1974), Porowski and O’Donnell (1979), and O’Donnell, et al. (2008) extended the use to “simplified inelastic” analysis, which is discussed below. These rules are based on analyses of tests of cylinders with internal pressure subjected to thermal cycling gradients.

Use of elastic methods to account for design in the creep regime is a legacy approach developed before the widespread use of computational modeling. As noted by O’Donnell and Porowski (1974), the total accumulated strain and strain ranges could be calculated using a finite-element-based time history analysis. At the time of the study (the 1970s), considerable expertise and experience were required to perform these complex analyses and “their reliability as design tools in the hands of inexperienced users may be questioned” (O’Donnell and Porowski, 1974). Thus, simple, if overly conservative and complex, elastic and simplified inelastic analysis rules were developed in the code. However, vendors developing ANLWRs will likely use full inelastic analysis to augment design. This review recommends that HBB-T-1321 be accepted because this subarticle is general, and the results produced using this procedure are expected to be conservative under all design circumstances. The discussion of HBB-T-1331 below includes more about this work.

If the component being analyzed passes any one of the three strain-limit test cases described below, the component satisfies the strain limits established in HBB-T-1310, discussed above.

The four-step procedure defining the load and cycles to be considered, along with the stress intensity definitions, produces conservative test results.

HBB-T-1322 Test No. A-1. If any of the test cases (A-1 to A-3) are satisfied, the strain limits and ratcheting requirements are considered satisfied. The test cases were developed based on work by Bree (1967, 1968). Bree analyzed pressurized cylinders subjected to pressure loading and a cyclic thermal gradient through the cylinder wall. This work led to the original Bree diagram that identified six regions of thermal and pressure stress combinations. Three of these regimes resulted in ratcheting even without the presence of creep straining. Two of the regions resulted in shakedown to elastic action in the absence of creep. Finally, an elastic "safe" regime was identified where no ratcheting occurs under plastic and creep conditions. The loading conditions for the analysis based on the Bree diagram were extended to account for realistic load conditions: general primary and general secondary stress. Hence, the intent of the rules is to consider the maximum value of primary and secondary loads in the ratcheting assessment, which is quite conservative. Jetter summarizes the conservative nature of these tests with extensive discussion (Jetter, 1976, pages 224–225), and the reviewers agree that this test is indeed conservative. The yield stress used in normalizing the load stress intensities for comparison to the Bree elastic regime is the average value of the maximum and minimum wall average temperatures during the cycle under consideration. Choice of the higher temperature for yield stress would be too conservative, but the average is considered an inappropriate choice (Rao, 2017).

This review recommends that HBB-T-1322 be accepted because this test ensures that the cyclic loading remains in the elastic regime and ratcheting is therefore precluded. This endorsement is contingent on the assessment of HBB-2000 data by ORNL, which suggests that yield stress values may not be conservative for some high temperatures.

HBB-T-1323 Test No. A-2. For reasons discussed above, this test is valid. This review recommends that HBB-T-1323 be accepted because this test ensures that the maximum value of the load-controlled stresses throughout service life and maximum secondary stresses are limited to the elastic Bree regime where ratcheting may occur. This is ensured if one end of the temperature cycle is below the creep range. This endorsement is contingent on the assessment of HBB-2000 data by ORNL, which suggests that yield stress values may not be conservative for some high temperatures.

HBB-T-1324 Test No. A-3. For reasons discussed above, this is a conservative test and, if passed, the limits are ensured. This review recommends that this test be endorsed. The "r" and "s" values of Table HBB-T-1324 provide additional conservatism as discussed by Jetter et al. (2011). This endorsement is contingent on the assessment on HBB-2000 data by ORNL, which suggests that rupture stress at high temperatures may sometimes be nonconservative.

HBB-T-1325 Special Requirements for Piping Components. The procedures developed and validated (see above) ensure that elastic followup is conservatively addressed when using elastic analysis.

HBB-T-1330 Satisfaction of Strain Limits Using Simplified Inelastic Analysis.
HBB-T-1331 General Requirements. O'Donnell and Porowski (1974) and Porowski and O'Donnell (1979) originally developed simplified inelastic analysis methods and the corresponding tests. Sartory (1989) later enhanced these methods. The discussion of Tests A-1 to A-3 address this briefly; more detail is provided below where the "B" tests are established for simplified inelastic analysis.

The tests developed by O'Donnell, Porowski, and Sartory are termed "simplified" inelastic analyses, but they are based on elastic stress analysis methods that are adjusted to account for inelastic deformations, which must satisfy the strain limits summarized in HBB-T-1310. These tests extend the range of use of the Bree diagram approach (Tests A-1 to A-3), which is limited to an elastic response to prevent ratcheting. O'Donnell and Porowski (1974) recognized that the rules of elastic analysis methods could be extended to include other regions of the Bree diagram for compliance with the strain limits.

O'Donnell and Porowski (1974) developed simplified inelastic analysis methods using the Bree cylinder with pressure loading and cyclic thermal loading. They modified the Bree method to estimate creep ratcheting in regions of the Bree diagram where no plastic ratcheting occurs. The solution is obtained in a one-dimensional elastic-plastic creep analysis. Enforcing beam theory assumptions, plane sections are assumed to remain plane, which occurs, for practical purposes, even under inelastic straining. Bree discusses the accuracy of these assumptions in detail (Bree, 1967). The bounding theorems of Frederick and Armstrong (1966) and Leckie (1974) and others are used to place an upper bound on inelastic strains.[2] The bounding theorems permit extension of rules to regions of the Bree diagram beyond elastic limits. These are represented by regions S_1, S_2, and P of the Bree diagram (see Figure 2 of O'Donnell and Porowski (1974), for example), which are outside the range of applicability of Tests A-1 to A-3 (region E for elastic).

The concept of an "elastic core" near the middle of the wall thickness was introduced. In this core, only elastic and creep strains can occur, and bounds on creep ratcheting strains could be established under cyclic loading based on bounding theorems. This is the basis of the B series of tests in BPVC-III-5, Appendix T. Porowski and O'Donnell (1979) extended this concept to elastic-plastic hardening materials (instead of elastic perfect plastic materials), temperature-dependent yield stresses, and a limited number of severe cycles into the plastic ratcheting regime. Porowski and O'Donnell (1979) used energy concepts to extend the applicability of the bounds to include intermittent cycling in the plastic ratcheting (extending the applicability of the regions for ratcheting rules using Tests B-1 to B-3 in HBB-T). The procedures are developed for both isotropic and kinematic hardening and are therefore general. Most material response follows mixed hardening, which is bounded by isotropic and kinematic hardening.

[2] These bounding theorems were precursors to those used to establish the validity of Code Cases N-861 and N-862.

The code procedure consists of determining the core stress with a safety factor applied for each load block from Figures HBB-T-1332-1 and HBB-T-1332-2 for Tests B-1 and B-2, respectively. These curves were originally published by O'Donnell and Porowski (1974), where they were referred to as the "O'Donnell-Porowski iso-strains" and are used to obtain the creep ratcheting strain from isochronous stress-strain curves provided in HBB-T for different materials. Restrictions on the tests are clearly indicated in HBB-T for Tests B-1 and B-2. The original approach of O'Donnell and Porowski ignored peak thermal stress considerations as occur in a stepped-wall cylinder, for example.

Sartory (1989) modified Tests B-1 and B-2 to account for peak thermal stress. To this point, no geometries analyzed by Sartory using finite element analyses to examine the appropriateness of the O'Donnell and Porowski (1974) approach have resulted in nonconservative results. Ignoring peak stress can lead to nonconservatism in applying the rules. The revised technique was found to be conservative in all test cases and was consequently included in Code Case N-47 and now in HBB-T. Validation has been made using finite element methods and compared to the simplified "Bree-type" analytical solutions.

This review considers Tests B-1 to B-3 to produce conservative results for the following reasons:

- The bounding theorems ensure that conservative results are predicted.
- The strain limits of HBB-1310 are considered quite conservative.
- The methodology predicts only when crack initiation occurs. There is typically more structural life in high-temperature structures beyond crack initiation.

This review recommends that HBB-T-1331 be accepted based on the foregoing summary and arguments. This endorsement is contingent on the assessment of the isochronous stress-strain curves (see Appendix A), which may sometimes be nonconservative for high temperatures and long times.

HBB-T-1332 Test Nos. B-1 and B-2. For reasons discussed above, these are considered valid tests.

HBB-T-1333 Test No. B-3. For reasons discussed above, this is considered a valid test. It is noted that the ASME BPVC Section III, Division 5 Subgroup on High Temperature Reactors (SG-HTR) voted to remove Test B-3 from the BPVC in April 2020 because it is no longer considered useful and is too difficult to pass. This change may appear in the 2021 BPVC rules, but since it is so conservative, Test B-3 is recommended for endorsement in BPVC-III-5 (2017).

HBB-T-1400 Creep-Fatigue Evaluation

HBB-T-1410 General Requirements. Before the endorsement recommendations, an overview is provided of the HBB-T approach to creep-fatigue design, including some history. This information will help support the rationale for the recommendations. Please see supporting information in Appendix B for material parameters for creep-fatigue evaluation.

Jetter (1976 and 2017) summarizes the philosophy of the development and implementation of the creep-fatigue design rules in HBB-T. In 1970, the linear creep-fatigue interaction approach was chosen. At the time, several different possible creep-fatigue approaches were considered for code implementation in Code Case 1592 (the precursor to NH and HBB-T), with some of the approaches seeming more accurate when compared with experimental data. For example, the creep-fatigue approach of Majumdar (Jetter, 2017) appears to be the most accurate but requires extensive testing needs compared with the linear damage rules. The material data requirements for the linear damage interaction rules in HBB-T were by far the simplest to achieve, and this ultimately led to this choice for the code. With this approach, creep damage is accounted for on a time-fraction basis, and fatigue damage is accumulated using Miner's rules independent of strain rate (as done in Subsection NB). The combined damage is limited to an interaction damage value, which is determined empirically and, for BPVC-III-5, is more conservative compared to the procedures in the Japanese code (DDS) and the French code (RCC-MR) for most materials. The use of this creep-fatigue damage assessment rule is nonconservative without applying safety factors and margins, and these are applied at almost every step of the design procedure in the code. Therefore, the choice of safety factors in this assessment procedure is critical, especially for long hold times between cycles. Appendix B discusses in more detail the conservative nature of the code rules for creep-fatigue damage evaluation. The BPVC-III-5 rules, with the Appendix T safety factors, provide conservative results, with the conservatism decreasing as strain range and rate decrease (i.e., where creep dominates). This is expected to be true despite the fact that the stress-rupture times examined in HBB-2000 may be nonconservative for high temperatures and long times and the isochronous stress-strain curves may also be slightly nonconservative for high temperatures and long times. This is because the safety factors were chosen to produce conservative results with the current BPVC-III-5 values for rupture times and isochronous stress-strain curves.

Creep-fatigue interaction strongly affects life for both crack initiation predictions (HBB-T) and for the creep-fatigue fracture procedures currently under development in Section XI and Division 5. This approach, however, has repeatedly been shown to be conservative over the years according to Jetter (2017). Moreover, the rules guard against crack initiation, and there is often considerable life remaining after crack initiation occurs in a component making this approach quite conservative. The extension to account for multiaxial effects for evaluating creep damage using the Huddleston (1984) approach has been sufficiently validated. Further discussion is provided for the articles below in Appendix B, which justify their endorsement.

<u>HBB-T-1411 Damage Equation</u>. As discussed in the previous article, many possible approaches were considered before development of the HBB-T approach to creep-fatigue assessment in Division 5 and the precursor Code Cases. Ultimately, the simple linear creep-fatigue interaction approach was chosen because it is easy for designers to use and the material data requirements are the simplest among all approaches considered.

With the creep-fatigue interaction approach, creep damage is accounted for on a time-fraction basis, and fatigue damage is accumulated using Miner's rules independent of strain rate (as done in Subsection NB). The combined damage is limited to a linear interaction damage value that is determined empirically. Multiaxial effects for the creep part of the damage equation are based on work by Huddleston (1984, 1993). The Huddleston equivalent stress accounts for compressive stresses, which are not as damaging as tensile stresses (for most materials), and it reduces overconservatism in the creep damage portion, especially for stainless steel. This is considered valid, since for multiaxial tension, the rupture contour is identical to Von Mises criteria, while for compression, it is larger than Von Mises. Huddleston (1993) validated these rules, which are considered conservative by the current reviewers.

These creep-fatigue damage assessment rules must be used with margins and safety factors. This approach, with safety factors, has been repeatedly shown to be conservative over the years according to Jetter (2017). Moreover, the rules guard against crack initiation, and there is often considerable life remaining after crack initiation occurs in the component. For these reasons, endorsement of HBB-T-1411 is recommended. (Please see the discussion in Appendix B.)

HBB-T-1412 Exemption from Fatigue Analysis. The exemption from fatigue does not apply to temperatures above those in Subsection NB unless service loads can be qualified as not introducing significant time-dependent effects. For service loadings that do not introduce time-dependent effects, the rules of Division 1, Subsection NB, apply, and this section is recommended for endorsement.

HBB-T-1413 Equivalent Strain Range. As discussed by Severud (1991) and related references in that report, the original creep-fatigue design rules of Code Case N-47 using elastic analysis were problematic and overly conservative resulting in only a few successful applications. Costly, detailed inelastic analyses were necessary to pass the code rules (HBB-T-1420). Such analyses have been performed before (Datta et al., 1991 (WRC Bulletin 365)). The current elastic analysis procedures in the code are based on the work of Severud (1991) and the ASME working group at the time. This work reduced the overly conservative nature of the elastic analysis methods.

The methods for determining the equivalent strain range for use in fatigue design under multiaxial loading is basically the same as that used in Subsection NB as noted by Jetter (2017). This procedure is to be used for both inelastic and elastic analysis. Moreover, the effect of mean stress is ignored in the code fatigue design curves (Jetter, 2017), where the application of the modified Goodman diagram approach for Subsection NB resulted in no adjustment of the fatigue curves. The intent is that mean stress effects are covered by the safety factors. A recent report by Oak Ridge National Laboratory (ORNL) studied the mean stress effect (Wang et al., 2019, 2020). This recent test work showed that the mean stress effect at an elevated temperature is not important. This makes sense, since at an elevated temperature, creep will tend to remove residual and mean stress effects.

This review recommends that HBB-T-1413 be accepted because the multiaxial strain range definitions used in Subsection NB are essentially the basis for the fatigue damage portion of the Division 5 rules. The rules have been shown to provide conservative results over years of application (Severud, 1978, 1991).

HBB-T-1414 Alternative Calculation Method—Equivalent Strain Range. This review recommends that HBB-T-1414, the alternative approach to define multiaxial strain ranges for fatigue assessment when principle strains do not rotate during the service history, be accepted because this approach is used in Subsection NB (see discussion in Section 4), and experience shows that it is valid (Rao, 2017).

HBB-T-1420 Limits Using Inelastic Analysis. Full inelastic analysis involves performing a full finite-element-based analysis of the creep-fatigue problem for the component of interest, with a proper constitutive law that handles combined creep and plasticity (all inelastic behavior) as functions of temperature throughout the service load history. The entire history of loading is included in order to perform the assessment. Performing such an analysis is a challenge as is fitting the material behavior and constants.

In this approach, one performs this complicated analysis and obtains the creep damage term via integration (HBB-T-1420 (a)) and similarly obtains the strain ranges for fatigue from the finite element analysis, as corrected for multiaxial effects of HBB-T-1413 or HBB-T-1414. This complicated analysis is difficult to apply to components subjected to real service loads. For this reason, the more conservative elastic analysis procedure of HBB-T-1430 was developed.

Currently, the Division 5 High-Temperature Reactors (HTR) Working Group—Inelastic Analysis Group is addressing this topic. This group is developing modern visco-plastic constitutive formulations for Division 5 materials instead of the elastic-plastic-creep formulations used in the past. Messner et al. (2018) and Phan et al. (2019) have summarized some of these ongoing developments.

It is anticipated that current vendors will use the inelastic approach for a number of their ANLWR component designs in the future because of the advances in computer technology and the use of high-performance computing. Discussions with some vendors during ASME BPVC meetings indicate that high-performance computers and software that performs well in a high-performance computing environment are available and will be used extensively for next-generation ANLWR design. The design of future ANLWRs is expected to involve inelastic analysis for a number of components.

Figure HBB-T-1420-1 for the different materials provides design fatigue curves for determining the fatigue damage fraction as a function of temperature. These data were obtained from fully reversed loading conditions at temperature, and safety factors were applied to the curves before implementation into the code. As is the case for lower temperatures covered by Subsection NB, the design curve is constructed by reducing the best-fit curve of continuous cycling fatigue data by a factor of 2 on total strain range or a factor of 20 on life, whichever results in a minimum value. This is considered quite conservative and is consistent with the lower temperature rules in Subsection NB. Note that the design allowable in Section HB, Subpart B, is presented as total strain range versus cycles compared to Subsection NB where the design allowable is stress amplitude versus cycles.

This review recommends that HBB-T-1420 be accepted for the reasons discussed above and because the choice of the interaction diagrams is very conservative. The creep-fatigue interaction curves in Figure HBB-T-1420-2 are considered quite conservative. The validity of the inelastic constitutive models must be demonstrated. The standards necessary to ensure that the model used is valid for the component being investigated are somewhat unclear. Jetter (2017), in Section 17.4.4.3.9.4, provides six goals for the constitutive relations used for inelastic assessment (see Appendix B).

HBB-T-1430 Limits Using Elastic Analysis.

HBB-T-1431 General Requirements. As discussed above under HBB-T-1410 and by Jetter (2017) and Severud (1991), the original elastic analysis rules were unduly conservative in the original creep-fatigue design procedure because of redundant counting of creep damage. Severud (1991) and the references cited in that work address this issue, and the current rules for creep-fatigue assessment using elastic analysis methods are based on this work. The carefully developed arguments of Severud (1978, 1991) are based on years of work and vetting by the ASME BPVC Section III Division 5 committee, are considered conservative, and are the reason the articles for creep-fatigue discussed below are recommended for endorsement.

Elastic analysis methods exist in the code because some designers do not have the background and experience to perform detailed inelastic analysis of the creep-fatigue component design process. A series of inelastic finite-element-based analyses performed by Becht (1989) examined the effect of stress relaxation at structural discontinuities (e.g., at a pipe reducer) subjected to mechanical and thermal load combinations. This work considered 10 different configurations in piping and vessels with different discontinuities that are typical of inservice components. The results led to important additions to HBB-T in which pressure-induced secondary stresses are now considered as primary stresses for creep-fatigue analysis purposes. Becht (1989) referred to this as “creep followup” rather than “elastic followup,” but the code was modified to classify secondary stresses for ratcheting and creep-fatigue.

WRC Bulletin 366 (Datta, 1991) summarizes the procedures for accounting for elastic followup, which are based on so-called “adjusted secant for piping” methods. In addition, Jawad and Jetter (2009) provide detailed examples along with discussion of the rationale behind the rules. Elastic followup must be included in the elastic analysis rules to account for stress relaxation due to creep, which is often only partial in complex components such as piping systems. The methods identify the fraction of stress necessary to be included as primary stress due to restrained thermal expansion for both strain limits (discussed above) and creep-fatigue damage.

The fatigue curves for 304H, 316H, Alloy 800H, and 2.25Cr were established long ago (before 1985 according to R. Jetter who was chair of the ASME BPVC, Section III Subsection NH (the precursor to Division 5 during that time). For Grade 91, there is a current action updating and extending the fatigue curves based on data from the Japanese. For Grade 91, there is only one temperature curve, 538 degrees C (1,000 degrees F), and the corresponding new curve at that temperature is in good agreement. The new Grade 91 curves go up to 649 degrees C (1,200 degrees F). The reviewers did examine the legacy data to the extent possible for the materials, and Appendix B discusses this review. This procedure has been used with success for many years and, therefore, is recommended for endorsement, contingent on fatigue curve accuracy.

Many of the isochronous stress-strain curves are also based on data developed before 1985. However, the code committee has examined these data carefully in recent years and has validated their accuracy (except for a few minor corrections), contingent on the material test data being accurate. The discussion of HBB-T-1800 below presents more information on this topic, and Appendix A provides a detailed comparison to new creep data.

This review recommends that HBB-T-1420 be accepted because of the careful arguments discussed in the above references and the conservative results expected. Moreover, additional conservatism is ensured because the elastic ratcheting rules of HBB-T-1320 must be satisfied before the approach in HBB-T-1430 can be used. Finally, elastic followup is addressed by classifying certain secondary stresses as primary for the assessment.

HBB-T-1432 Strain Range Determination. Based on work by Severud (1991), the modified equivalent strain range to use for the fatigue damage fraction calculation is somewhat complicated. Severud (1991) describes the use of modified Neuber-type equations to account for geometric inelastic concentration effects, which is supported by other references. In addition, rules for conservative classification of stresses, inclusion of shakedown, and ratcheting are included to mitigate elastic followup effects. This is necessary because of the elastic nature of the procedure. The increase in the modified equivalent strain range to use is obtained from Figure HBB-T-1432 and is identical to Figure 2 of Severud (1991). The strain range is constructed from the appropriate isochronous curves of HBB-T-1800. The multiaxial adjustment factors (K), also described in detail in Severud (1991), are determined from Figure HBB-T-1432-2 (Figure 3 of Severud (1991)). Jetter (2017) describes in physical terms the other procedures for determining the strain range.

Severud (1991) outlines several sources of conservatism in the determination of the strain range for evaluating the allowable cycles for each strain range in the assessment. As discussed in Appendix B, the use of the isochronous stress-strain curve procedure to account for stress relaxation during the hold cycles, as shown in Figure HNN-T-1432-1, results in less relaxation compared with other high-temperature codes. A factor of 1.25 must be applied to the core stress in this determination, along with the equivalent stress concentration factors applied in determining the strain range.

These procedures are considered appropriate and are expected to provide conservative estimates of the fatigue damage portion and technical justification for recommending endorsement of the rules. This review recommends that HBB-T-1432 be accepted because the procedures are expected to provide conservative predictions of the fatigue portion of the damage (perhaps too conservative in some cases).

HBB-T-1433 Creep Damage Evaluation. The creep damage evaluation procedure based on elastic analysis is also based on the method summarized by Severud (1991). The bounding theorems of Frederick and Armstrong (1966) and Leckie (1974), applied by O'Donnell and

Porowski (1974, 1979) (discussed above), are part of the rationale to ensure conservative estimations of creep damage. As noted by Severud, experience indicates that creep damage, rather than fatigue damage, usually controls the creep-fatigue damage prediction for nuclear plants because hold times are typically long.

HBB-T-1433 provides two alternatives for evaluating the creep damage using elastic analysis. Severud (1991) carefully explains the rationale for both these choices, and he provides numerous validation cases. The first method requires the designer to go through a 10-step procedure that requires an estimate of stress relaxation with correction factors to account for multiaxiality and elastic followup. Severud (1991) also explains the methods for accounting for relaxation using isochronous stress-strain curves (Figure HBB-T-1433-1) and the stress relaxation limits (Figures HBB-T-1433-2 and HBB-T-1433-3); the methods are conservative in that the relaxation is underestimated. The composite stress-time envelope of Figure HBB-T-1433-4 is also provided. Validation discussed by Severud (1991) and references cited in that study, along with experience, have shown that conservative predictions are expected. The second method is simpler to apply, but more conservative than the first method described in HBB-T-1433. These arguments provide technical justification for the rules.

The time fraction allowable for each accumulated hold time is calculated by using the isochronous stress-strain curves of HBB-T-1800. As discussed in this document for HBB-T-1800 and Appendix A, these curves are slightly nonconservative for higher temperatures and long hold times (typically greater than 100,000 hours). However, the hold times for evaluating the creep-fatigue time-fraction limits for each accumulated hold cycle are unlikely to be greater than 100,000 seconds. In addition, the allowable time duration is obtained from Figures HBB-I-14.6A through HBB-I-14.6F for the various materials. From the data analyses of HBB-2000, it was found that some of the creep-rupture curves are nonconservative, particularly for higher temperatures and long hold times (similar to the observations in Appendix A for the isochronous curves). Again, the hold times for each portion of the composite cycles may very well be for times shorter than 100,000 hours.

This review recommends that HBB-T-1433 be conditionally accepted because the isochronous curves and rupture curves may need adjustment for higher temperatures and longer times. However, the procedure is expected to provide conservative predictions of the creep portion of the damage and has consistently been shown to produce conservative results over the years.

HBB-T-1434 Calculation of Strain Range for Piping. This review recommends that HBB-T-1434 be accepted for the reasons discussed above regarding the corrections for elastic followup.

HBB-T-1435 Alternative Creep-Fatigue Evaluation. This review recommends that HBB-T-1435 be accepted. At a high level, the evaluation is simple; if the negligible creep criteria are satisfied, one can use the NB procedures with the elevated temperature fatigue curves. HBB-T-1435(a) just converts the strain range from the Division 5 fatigue curves to stress amplitude for NB. HBB-T-1435(b) substitutes the primary plus secondary stress, S_n, with the peak stress,

S_p. This is conservative. The use of S_p for S_n is very roughly the equivalent of the use of $3\bar{S}_m$ in HBB-T-1324(c). Finally, an allowable usage factor of 0.9 is just an added conservatism.

HBB-T-1500 Buckling and Instability

HBB-T-1510 General Requirements. HBB-T requires consideration of both time-independent buckling and creep buckling and requires that buckling loads or strains be calculated for all cases where compressive loads may lead to instability. Subsection NB may be used for cylindrical and spherical shells for instantaneous buckling and to include the effects of initial imperfections and temperature effects on properties but not creep. Time-independent load factors are defined to provide margin for load or strain that may occur instantaneously at any time with time-independent material properties at the time of loading. The rules permit use of NB buckling rules when creep buckling is not a concern. Griffin (1996) developed a rationale and temperature limit charts (Figure HBB-T-1522), which when satisfied, permit use of Subsection NB. Jawad and Jetter (2009) provide examples of the use of the HBB-T rules for buckling assessment, and Carter and Marriott (2008) updated the validation of these rules.

HBB-T distinguishes between load-control and strain-control creep buckling. Load-control buckling is more severe because instability will occur into the post-buckling regime, while strain-control buckling occurs as the load is reduced. Examples of load-control buckling are spheres and cylinders under external pressure, and examples of strain-control buckling include compressive stresses in spheres and cylinders induced by thermal expansion, because stresses can relax under these conditions.

As noted above, Griffin (1980) and his colleagues established the buckling rules in HBB-T. In the original Code Case 11592, the rules required the designer to ensure that buckling would not occur for a period of 10 times the design life. One of the main problems with this design philosophy is that creep properties would be needed for 300 years for a 30-year life of a nuclear component. In HBB-T, the design specifies load factors for load-controlled creep buckling (Table HBB-T-1522-1) to be applied to service loads. The load factors were meant to produce results comparable to a factor of 10 on time to buckle in the original Code Case. As pointed out by Griffin (1980), service loads are typically low, so that the load factor (1.5 for load levels A, B, and C) is also low, resulting in small creep strains.

Time-dependent buckling rules are meant to account for uncertainties in initial deformation and material creep uncertainty. The load factor of 10 on buckling time in the original rule is difficult to verify. However, as noted by Griffin (1980), this factor (replaced by a load factor of 1.5) is generally accepted and borne out by inelastic finite element solutions and avoidance of creep buckling failures over the years.

For strain-controlled buckling, no safety factors are imposed. Griffin (1980) showed that strain-controlled buckling limits can be handled from time-independent limits as long as the isochronous stress-strain curves are used for the design time. In distinguishing between load-controlled and strain-controlled buckling, care must be taken to ensure that the designer properly interprets the situation, and if there is doubt, load control should be assumed. For combined load- and strain-controlled buckling, if there is interaction, the load control factors must be applied to ensure conservative results if the distinction between loads is not clear. This is required because, although strain-controlled buckling is self-limiting, it can result in a shape change that affects load-controlled buckling. Griffin (1980) discusses this in some detail. Berman and Gupta (1976) also discuss inelastic modeling and test results that validate the conservative nature of these rules. These arguments appear valid and are a key reason for the endorsement provided below.

The design rules for buckling, along with the design factors for time-dependent buckling, have been significantly enhanced from the original rules in Code Case 1592. Some of the original guidance from RG 1.87 for buckling (Section C, Regulatory Position 2, Code Case 1592-d(1) and d(3)) is no longer needed because the new rules are more specific, especially with the temperature limits defined in Figures HBB-T-1522-1 to HBB-T-1522-3. Moreover, the current rules require the use of load-controlled buckling factors for conditions where strain and load-controlled buckling may interact or for conditions where significant elastic followup may occur. This review recommends that HBB-T-1510 be accepted because this article is general. However, RG 1.87, Section C, Regulatory Position 2, Code Case 1592-d(2), remains, and the design must justify that a process is purely strain controlled or justify that "significant elastic followup" is not occurring.

HBB-T-1520 Buckling Limits.
HBB-T-1521 Time-Independent Buckling. This review recommends that HBB-T-1521 be accepted because the load factors used for buckling assessment will produce conservative results and guard against instability. Moreover, for configurations considered in NB-3133, the NB rules are valid.

HBB-T-1522 Time-Dependent Buckling. This review recommends that HBB-T-1522 be accepted because, as shown by Griffin (1980) and references cited in that work, conservative creep buckling predictions are expected when using the rules. In addition, more recent validation work by BPVC-III-5 further supports the conservative nature of the rules. Jawad and Jetter (2009) provide numerous examples as well.

HBB-T-1700 Special Requirements
HBB-T-1710 Special Strain Requirements at Welds. Jetter (2017) discusses the special requirements and rationale for welds. The general philosophy for the reduced strain limits for welds is to ensure that the designer locates welds in regions of relatively low strain. Three concerns for welds are (1) the creep rupture strengths of welds are often lower than those of base metal, (2) long-term creep ductility is often lower than that of base metal, and (3) long-term exposure at an elevated temperature could lead to diffusion, which may change material properties with time (Corum, 1989, includes some data showing these concerns).

Corum (1989) substantiated the overall adequacy of the HBB-T primary stress limits for weldments from a compilation of weld test data developed at ORNL and a number of U.S. and international organizations. Code rules for weldments were clearly shown to be conservative for all test sets considered. The arguments for using base metal properties for the weld for analysis appear valid since welds can be made at least as strong as base metal and verified via tests.

This review recommends that HBB-T-1710 be endorsed because the rules should result in conservative designs and caution the designer to place welds in lower strain regions with the stipulation below. However, stress-relaxation cracking has occurred in high-temperature applications from relaxation of weld residual stresses even in regions where the weld residual stresses were partially reduced by post-weld heat treatment (Turk et al., 2019). Since Division 5 does not explicitly mention stress-relaxation cracking, this review recommends that the vendor consider the potential for stress-relaxation cracking in its design.

HBB-T-1711 Scope. This review recommends that HBB-T-1711 be accepted because code rules address limited ductility of weld metal at elevated temperatures.

HBB-T-1712 Material Properties. The BPVC requires use of base metal properties for calculating strain deformations in the weld region. Jetter (2017) notes that, with the required controls on weld fabrication, base metal properties within the weldment are conservative. Jetter (2017) provides an excellent summary of the reduction factors required for welds. These reduction factors are based on four considerations: (1) the creep-rupture strengths of welds are typically lower than base metal, (2) creep ductility (or strain to failure) is typically lower in welds operating at high temperature, (3) long-time exposure of welds at high temperature can lead to diffusion processes and time-dependent changes to mechanical properties, and (4) local variations in stress-strain and creep response in the various weld regions (weld, heat affected zone) could redistribute stresses and strains and reduce life. The considerably conservative reduction factors used for welds were introduced to ensure that designers locate welds in regions of low strain.

Corum (1989) examined in detail the reduction factors for welds by studying extensive domestic and foreign test data on weldments. This study found that reduction factors for tests performed transverse to the welds are necessary with a reduction equivalent to at most a 50-percent reduction in life.

This review recommends that the satisfaction of strain limits for weldments for creep-fatigue damage and shakedown assessment be accepted as the rules for weldments are consistent with HBB-T rules (half the base metal limits). This is not considered to be a safety-related issue.

This review recommends that HBB-T-1712 be accepted because code rules address limited ductility of weld metal at elevated temperatures based on test data discussed in HBB-T-1710.

HBB-T-1713 Strain Limits. This review recommends that HBB-T-1713 be accepted because the one-half factor reduction in strain limits imposed with this rule for weldments provides a conservative design as discussed for HBB-T-1710.

HBB-T-1714 Analysis of Geometry. This review recommends that HBB-T-1714 be accepted because the worst surface geometry is to be used in the design. The code requires the designer to choose the worst geometry.

HBB-T-1715 Creep-Fatigue Reduction Factors. This review recommends that HBB-T-1715 be accepted because the reduction factors for use in the fatigue evaluation procedures of HBB-T-1515 are expected to produce conservative designs. Corum (1989) provided conservative validation through extensive test data comparison to code rules.

HBB-T-1720 Strain Requirements for Bolting.

HBB-T-1721 Strain Limits. This review recommends that HBB-T-1721 be accepted because the strain limits used in HBB-1300 should apply equally well to bolts.

HBB-T-1722 Creep-Fatigue Damage Accumulation. This review recommends that HBB-T-1722 be accepted because the strain limits used in HBB-1400 should apply equally well to bolts with the lower creep and fatigue reduction factors required.

HBB-T-1800 Isochronous Stress-Strain Relations

HBB-T-1810 Objective. This review recommends that HBB-T-1810 be accepted since the objective is to use isochronous stress-strain curves for high-temperature design strain from stress at elevated temperature. The accuracy of the curves is considered to be reasonable based on the discussion in HBB-T-1820.

HBB-T-1820 Materials and Temperature Limits. The isochronous stress-strain shown in Figures HBB-T-1800-A-1 through HBB-T-1800-E-11 for each material are based on average material properties. These are used to provide the designer with information on the total strain from stress at elevated temperatures. These data were produced before 1985 from tests performed at the DOE National Laboratories, and no apparent effort has been made to develop new data.

This report addresses the 2017 version of Division 5, but it is useful to discuss ongoing activities that will be used to validate the isochronous curves in HBB-T-1800. There is currently an effort to provide equations describing the isochronous stress-strain curves that will be present in the 2021 BPVC Edition. The models are not new as they were used to plot the curves in the 2017 BPVC Edition. The equations will allow the designer to easily calculate values at arbitrary combinations of time, stress, and temperature rather than interpolating values from the plots. Identifying the correct model and data required, in some cases, extensive historical research. As part of this effort, all of the isochronous stress-strain curves in HBB-T-1800 were checked and validated. This effort did identify minor errors in a few of the curves. Appendix A provides more detailed assessment of the validity of the material data used to produce the isochronous stress-strain curves.

Therefore, while the current reviewers did not examine the test data to determine the accuracy of the isochronous stress-strain curves in HBB-T-1800, previous work has scrutinized the curves for accuracy. This is the reason for the recommendation below.

As discussed in Appendix A, a study compared the isochronous curves with additional data. The isochronous curves are meant to be “average” data curves. The additional data that were compared to the code curves cannot be categorized as upper, lower, or average data.

Therefore, the following stipulations are made without full pedigree of the new data or the older data.

With the above caveat, based on the discussion in Appendix A, this review recommends that HBB-T-1820 be endorsed subject to the following stipulations:

- The isochronous for temperatures higher than 700 degrees Celsius (1292 degrees Fahrenheit) for 304 and 316 stainless steel appear to be slightly nonconservative for times greater than 100,000 hours.
- The isochronous curves for 2.25Cr-1Mo material may be nonconservative for temperatures above 600 degrees C (1112 degrees F) at times greater than 100,000 hours.
- The isochronous curves for Alloy 800H material may be nonconservative for temperatures at 700 degrees C (1292 degrees F) and above, at times of 100,000 hours and above.
- The isochronous curves for 9Cr Mo material are higher than new curves recently produced by ASME Standards Technology, LLC based on new data and may be slightly nonconservative in general.

4.2 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"

4.2.1 Article HBB-II-1000, "Scope"

This article describes the scope of Mandatory Appendix HBB-II, which provides guidance on the use of SA-533 Type B, Class 1 plates and SA-508 Grade 3, Class 1 forgings and their weldments when used above 700 degrees F (371.1 degrees C) for Level B, C, and D Service Limits. The article is recommended for endorsement.

4.2.2 Article HBB-II-2000, "Materials"

This article specifies the two materials covered by the appendix in the "Scope" and states that the allowable stress intensities are an extension of Section II, Part D, Subpart 1, Table 2A, of the ASME BPVC 2017 for temperatures greater than 700 degrees F (371.1 degrees C). A detailed review was conducted of the yield strength, S_y, tensile strength, S_u, and design stress intensity (allowable) values, S_m, for both materials in ASME BPVC Section II for temperatures less than 700 degrees F (371.1 degrees C) and Table HBB-II-3000-3 for temperatures greater than 700 degrees F (371.1 degrees C). Table 4.2.2-1 below shows these values along with the margin of safety (S_u/S_m) for the entire range of temperatures.

Table 4.2.2-1 Yield strength, S_y, ultimate strength, S_u, design allowable stress values, S_m, and margin of safety for SA-533 Type B, Class 1 plates and SA-508 Grade 3, Class 1 forgings for temperatures 100 to 1,000 degrees F (37.8 to 537.8 degrees C)

Basis for Allowable	temperature, °F	temperature, °C	Yield Strength, S-y, ksi *		Tensile Strength, S-u, ksi **		Design Stress Intensity, ksi S-m***		Margin, S-u/S-m	
Stresses, Sm			SA-533	SA-508	SA-533	SA-508	SA-533	SA-508	SA-533	SA-508
Section II, Part D	100	38	50.0	50.0	80.0	80.0	26.7	26.7	**3.0**	**3.0**
Subpart 1 (T < 700 F)	150	66	48.1	48.1	80.0	80.0	26.7	26.7	**3.0**	**3.0**
	200	93	47.0	47.0	80.0	80.0	26.7	26.7	**3.0**	**3.0**
	250	121	46.2	46.2	80.0	80.0	26.7	26.7	**3.0**	**3.0**
	300	149	45.5	45.5	80.0	80.0	26.7	26.7	**3.0**	**3.0**
	400	204	44.2	44.2	80.0	80.0	26.7	26.7	**3.0**	**3.0**
	500	260	43.2	43.2	80.0	80.0	26.7	26.7	**3.0**	**3.0**
	600	316	42.1	42.1	80.0	80.0	26.7	26.7	**3.0**	**3.0**
	650	343	41.5	41.5	80.0	80.0	26.7	26.7	**3.0**	**3.0**
	700	371	40.7	40.7	80.0	80.0	26.7	26.7	**3.0**	**3.0**
Mandatory App HBB-II	700	371	40.7	40.7	80.0	80.0	26.7	26.7	**3.0**	**3.0**
(700 F < T < 1000 F)	750	399	39.8	39.8	80.0	80.0	26.7	26.7	**3.0**	**3.0**
	800	427	38.6	38.6	80.0	80.0	26.7	26.7	**3.0**	**3.0**
	850	454	37.0	37.0	77.3	77.3	25.5	25.5	**3.0**	**3.0**
	900	482	34.9	34.9	73.1	73.1	24.3	24.3	**3.0**	**3.0**
	950	510	32.1	32.1	68.0	68.0	22.5	22.5	**3.0**	**3.0**
	1000	538	28.4	28.4	61.7	61.7	20.7	20.7	**3.0**	**3.0**

Note: The values provided in Table 4.2.2-1 were obtained from ASME BPVC-2017

* - ASME BPVC-2017 Section II, Part D, Subpart 1, Table Y-1: p 660, Line No. 42 for SA-533 & p 664, Line No. 29 for SA-508

** - ASME BPVC-2017 Section II, Part D, Subpart 1, Table U: p 538, Line No. 33 for SA-533 & p 540, Line No. 19 for SA-508

*** - ASME BPVC-2017 Section II, Part D, Subpart 1, Table 2A: p 302, Line No. 23 for SA-533 & p 306, Line No. 1 for SA-508 for Temp up to 700 F; Mandatory Appendix HBB-II Table HBB-II-3000-3 for Temperatures > 700 F

Figure 4.2.2-1 shows the values of S_m, S_y, and S_u for the two materials (which are identical) as seen in Table 4.2.2-1. *As may be noted in Table 4.2.2-1, the margin of safety (S_u/S_m) for both materials for the entire range of temperatures is consistently 3.0,* thereby confirming that the S_m values in Table HBB-II-3000-3 are both conservative and an extension of those values provided in ASME BPVC Section II, Part D, Subpart 1, as stated in Mandatory Appendix HBB-II-2000. Article HBB-II-2000 is therefore recommended for endorsement.

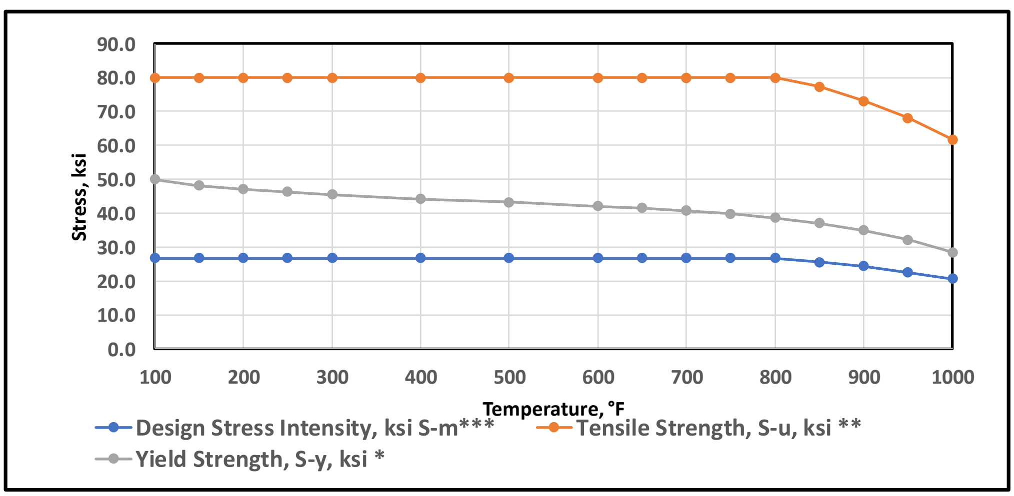

Figure 4.2.2-1 Values of S_y, S_u, and S_m for SA-533 and SA-508 materials confirming that the S_m values for T > 700 degrees F (371.1 degrees C) are an extension of those for T < 700 degrees F (371.1 degrees C) and are conservative

4.2.3 Article HBB-II-3000, "Design"

This article provides the rules for design for the two materials covered by this appendix: (1) SA-533 Type B, Class 1 plates and (2) SA-508 Grade 3, Class 1 forgings, along with the respective tables and figures needed. For temperatures below 700 degrees F (371.1 degrees C), the design conditions and rules are the same as those in Division 1, Article NB-3000. For temperatures exceeding 700 degrees F (371.1 degrees C), only loadings associated with Level B, C, and D Service Limits are permitted where rules from Article HBB-3000 apply. Metal temperatures cannot exceed 800 degrees F (426.7 degrees C) for Level B Service Limits, and 1,000 degrees F (537.8 degrees C) for Level C or Level D Service Limits.

Independent review of the above design rules for temperatures exceeding 700 degrees F (371.1 degrees C) focused on confirming that the following three aspects of the design bases were conservative:

(1) *Allowable Stress Intensity:* There was adequate margin of safety for the allowable stress, S_{mt}, which is dependent on both temperature and time at the given temperature based on Figures HBB-II-3000-1, HBB-II-3000-2, HBB-II-3000-3, and HBB-II-3000-13, and HBB-II-3000-14, along with their respective underlying data in Tables HBB-II-3000-1, HBB-II-3000-2, HBB-II-3000-3, and HBB-II-3000-4.

(2) *Isochronous Stress-Strain Curves:* The recommended isochronous stress-strain curves for temperatures 700 degrees F (371.1 degrees C) through 1,000 degrees F (537.8 degrees C) in Figures HBB-II-3000-4 through HBB-II-3000-10 provide adequate conservatism relative to the strain to failure under creep at the various stress and temperature values.

(3) *Fatigue Strain Range and Creep-Fatigue Interaction:* The proposed range for design fatigue strain in Figure HBB-II-3000-11, along with Table HBB-II-3000-9 and the creep-fatigue damage envelope in Figure HBB-II-3000-12, is conservative and consistent.

A detailed discussion of these three aspects follows.

Allowable Stress Intensity, S_{mt}: Since the allowable stress intensity values (S_{mt}) in Table HBB-II-3000-1 are both time and temperature dependent based on the creep characteristics of the two materials, the first step is to confirm the basis of the underlying creep data used to determine the minimum stress-to-rupture values (S_r) in Table HBB-II-3000-4 at which failure occurs and to establish the time-temperature limits. The creep data for the materials used to develop the technical basis for this appendix were originally developed at ORNL by McCoy (1989) and later confirmed with additional experiments at Idaho National

Laboratory (INL) by Wright (2014). While the final reports from these two studies were not available, the interim reports were available and were reviewed in detail. Figure 4.2.3-1 shows these data compared with the minimum stress-to-rupture values (S_r) from Table HBB-II-3000-4 on a standard Larson-Miller (L-M) parameter plot (see Wright, 2014), which is frequently used to normalize creep-rupture data for time, temperature, and stress as explained below.

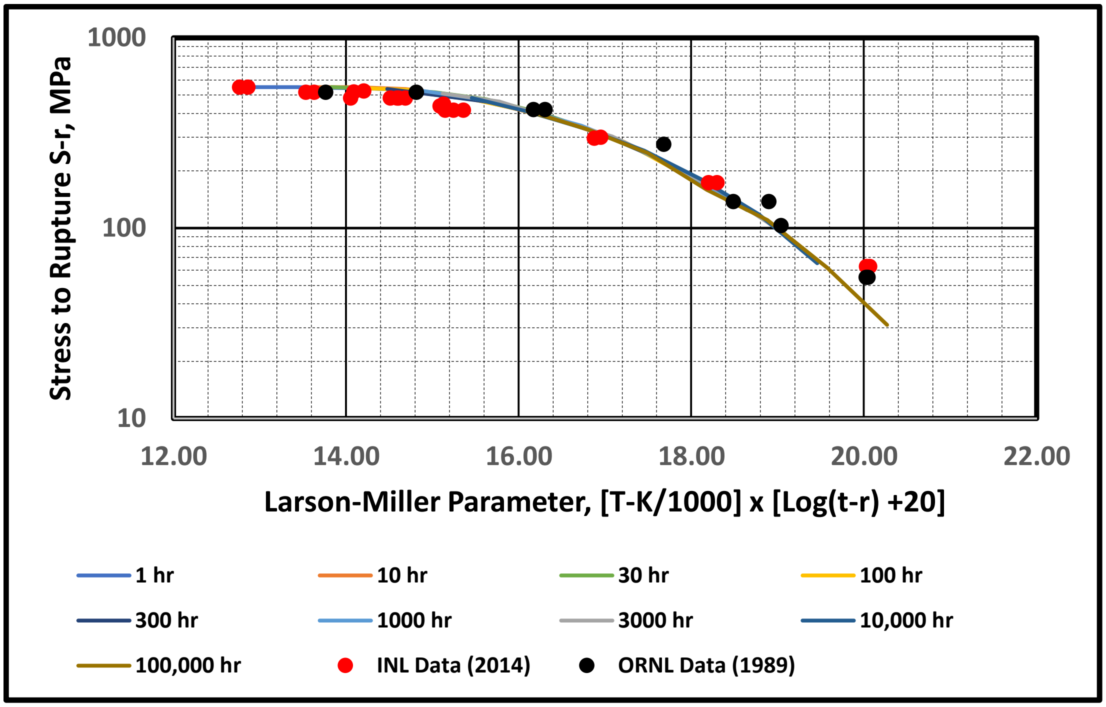

Figure 4.2.3-1 Creep-rupture data from ORNL (1989) and INL (2014) compared with values in Table HBB-II-3000-4 (Note: The stress values in the original reports were reported in MPa and are therefore shown in these units.)

Creep rupture generally involves temperature (T), stress to rupture (S_r), and time to rupture (t-r), which are combined in graphs of log (stress) versus the L-M parameter defined as follows:

$$L\text{-}M = [T/1000] \times [\text{Log}(t\text{-}r) + 20]$$

where T is the temperature in Kelvin, t-r is the rupture time in hours, and 20 is the original L-M coefficient. The curves on the L-M plots are then fit to a second-order polynomial such as those used by McCoy (1989) and are used to predict the creep-rupture times at other temperatures and stress levels. Since both the ORNL data and INL work have used the L-M approach to present the results, for this confirmatory work, the values from Table HBB-II-3000-4 were also converted using the L-M approach. As may be noted in Figure 4.2.3-1, the ORNL data from McCoy (1989) used to develop the original ASME Code Case N-499-2 (which was later incorporated into the current Division 5 as Appendix HBB-II) match the values from Table HBB-II-3000-4 very closely and confirm the basis for this table. (Note that values from Table HBB-II-3000-4 for all times from 1 hour to 100,000 hours collapse to a single curve on the L-M plot.)

Wright (2014) indicated that the original ORNL data from McCoy (1989) may be slightly nonconservative for some cases; for example, at 700 degrees F (371.1 degrees C) and for a time to rupture of 1,000 hours, Table HBB-II-3000-4 provides a value of 77 kilopounds per square inch (ksi) (530.9 MPA), while the statistical reanalysis of the original data results in a value of 62 ksi (427.5 MPA) for this rupture stress. Also, the INL work by Wright (2014) uses a more accurate third-order polynomial fit of the L-M plot, which has an L-M coefficient of 19.11 (instead of 20.0), to provide a more accurate and conservative basis for any revision of Table HBB-II-3000-4 for both SA-533 and SA-508 base and weld metals that could be considered by the ASME BPVC in the future.

Based on the minimum stress-to-rupture values (S_r) in Table HBB-II-3000-4 obtained from creep data as described above, the allowable stress intensity values, S_t, shown in Table HBB-II-3000-2, have been calculated using a margin of 1.5 or greater for all cases up to 3,000 hours and 1,000 degrees F (537.8 degrees C) (i.e., S_r/S_t > 1.5). As indicated in this Mandatory Appendix HBB-II, the final values for the allowable stress intensity, S_{mt}, in Table HBB-II-3000-1 (and Figure HBB-II-3000-1) involve selecting the lower of the values for S_t (time-dependent) and S_m (time-independent) for the given temperature and time from Tables HBB-II-3000-2 and HBB-II-3000-3, respectively. *The margin of safety for S_m is 3.0 (S_u/S_m) as shown in Table 4.2.2-1 above, while the margin for S_t is >1.5 (S_r/S_t), which has been deemed to be conservative by ASME Division 5*.

Table 4.2.3-1 shows the ratio of the minimum stress-to-rupture values (S_r) in Table HBB-II-3000-4 to the values of S_{mt} in Table HBB-II-3000-1, which provides a measure of overall margin of safety on stress for the given temperature and time at that temperature. Some cases highlighted in Table 4.2.3-1 reflect a margin of safety of stress rupture values (S_r) to S_{mt} less than 2.0.

Table 4.2.3-1 Ratio of stress-to-rupture S_r to S_{mt} for SA-533 Type B, Class 1 and SA508 Grade 3, Class 1 materials (margin of safety) based on Tables HBB-II-3000-4 and HBB-II-3000-1

Temperature		Time at Temp, hr						
°F	°C	1	10	30	100	300	1000	3000
700	371.1	3.0	3.0	3.0	3.0	2.9	2.9	2.8
750	398.9	3.0	3.0	2.9	2.9	2.7	2.6	2.5
800	426.7	3.0	2.9	2.8	2.6	2.5	2.2	2.0
850	454.4	3.1	2.8	2.7	2.4	2.2	2.0	
900	482.2	3.0	2.6	2.4	2.1	1.9	1.6	
950	510.0	3.0	2.4	2.1	1.8	1.5	1.7	
1,000	537.8	2.8	2.1	1.8	1.6	1.6	1.9	

Based on experience discussing ASME BPVC, Section III and Section XI, the NRC staff frequently requires additional justification before accepting a margin of safety below 2.0. It is therefore recommended that this issue be raised at meetings on BPVC-III-5 and clarification be sought as to whether these margins of safety are adequate for regulatory decisions.

One possible approach to resolving this issue is for the NRC to require that ASME review the reports and data and adopt the INL recommendations in Wright (2014), which are more conservative. As indicated above, the INL work included new creep data on SA-533 and SA-508, along with a reanalysis of the original ORNL creep data by McCoy (1989), to resolve some nonconservatisms, which were carried over from the original Code Case N-499-2 to Division 5, Appendix HBB-II. This approach may result in margins (S_r/S_{mt}) closer to 2.0 for all cases above.

Isochronous Stress-Strain Curves: Figures HBB-II-3000-4 through HBB-II-3000-10 provide isochronous stress-strain curves for SA-533 Type B, Class 1 plates, and SA-508 Grade 3, Class 1 materials from 700 degrees F (371.1 degrees C) through 1,000 degrees F (537.8 degrees C) in increments of 50 degrees F (27.8 degrees C). Neither one of the references for the creep data for these two materials from ORNL (McCoy, 1989) or INL (Wright, 2014) has the complete creep curves or equations provided to reproduce and validate these isochronous curves as were provided for the five high-temperature metallic materials (304 SS, 316 SS, Alloy 800H, 2.25Cr-1Mo, and Grade 91) reviewed under HBB-T. However, to determine whether these isochronous curves are conservative, two related assessments were conducted to (1) determine if the total strains at the allowable stress levels S_{mt} (per Table HBB-II-3000-1) per the isochronous curves in Figures HBB-II-3000-4 through HBB-II-3000-10 were under the failure strains under creep loading at the given temperatures and (2) whether the time to reach 1-percent creep strain that is listed in McCoy (1989) is conservative compared to the times from the isochronous curves.

Table 4.2.3-2 shows the values of the maximum strain at the allowable stress levels S_{mt} and the respective time duration from the above isochronous curves.

Table 4.2.3-2 Maximum strain at allowable stress and time per isochronous stress-strain curves at temperatures from 700 degrees F (371.1 degrees C) through 1,000 degrees F (537.8 degrees C)

Temp	Temp	Allowable Stress	Time	Max Strain at Allowable stress	Reference
°F	°C	S_{mt}, ksi	hours	%	
700	371.1	26.7	All	0.11%	Figure HBB-II-3000-4
750	398.9	26.7	All	0.11%	Figure HBB-II-3000-5
800	426.7	26.7	All	0.11%	Figure HBB-II-3000-6
850	454.4	25.5	1000	0.10%	Figure HBB-II-3000-7
900	482.2	24.0	1000	0.21%	Figure HBB-II-3000-8
950	510.0	22.0	300	0.30%	Figure HBB-II-3000-9
1000	537.8	18.0	100	0.32%	Figure HBB-II-3000-10

The maximum value of strain in the above table is only 0.32 percent at 1,000 degrees F (537.8 degrees C)—which is well below the value of 18 percent, the minimum value of fracture strain under creep for SA-533 materials shown in the ORNL work by McCoy (1989).

The next step was to do some very limited comparisons between the creep data from ORNL (McCoy, 1989) with the isochronous curves above, since the data are presented in tabular format with only the time to reach 0.1 percent, 1.0 percent, and 2.0 percent strain at four temperatures (700 degrees F, 800 degrees F, 900 degrees F, and 1,000 degrees F (371.1 degrees C, 426.7 degrees C, 482.2 degrees C, and 537.8 degrees C)) at only two stress levels for each case for only one lot (Lot 3) of the materials. These limited ORNL data were used to interpolate and obtain values for the isochronous stress-strain curves at three temperatures—800 degrees F (426.7 degrees C) at 100 hours, 900 degrees F (482.2 degrees C) at 300 hours, and 1,000 degrees F (537.8 degrees C) at 300 hours—for comparisons to HBB-II curves above. Figure 4.2.3-2 below shows that the comparison between HBB-II and the ORNL data are reasonable. Given this confirmation and the fact that the minimum fracture strain to failure under creep rupture was 18 percent as discussed above, the proposed isochronous curves in HBB-II are recommended for endorsement.

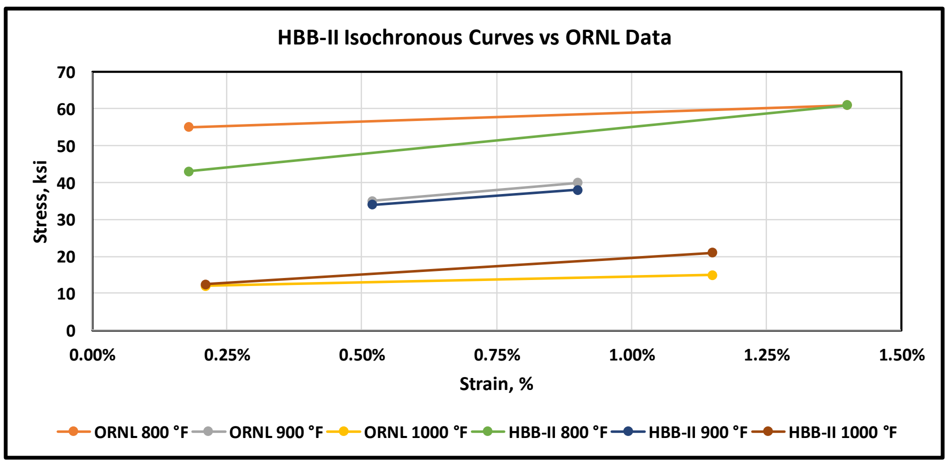

Figure 4.2.3-2 Comparison of HBB-II isochronous curves with ORNL data (1989) at 800 degrees F (426.7 degrees C) at 100 hours; 900 degrees F (482.2 degrees C) at 300 hours; and 1,000 degrees F (537.8 degrees C) at 300 hours

<u>Design Fatigue Strain Range and Creep-Fatigue Interaction</u>: In the basis for Figures HBB-II-3000-11 and HBB-II-3000-12 in the *Companion Guide to the ASME Boiler and Pressure Vessel Codes,* Section III (Rao, 2017)*,* the design fatigue strain range and the creep-fatigue damage envelope in these two figures are directly based on Nonmandatory Appendix HBB-T. This review recommends that HBB-II specifically reference HBB-T Section 1400, which describes the methodology used to develop the basis for fatigue and creep-fatigue design.

The ORNL interim report by McCoy (1989) that formed the basis for Code Case N-499-2 (later converted to Appendix HBB-II) does not include any fatigue and creep-fatigue interaction data.

There is a discussion of creep rupture of cyclic damaged specimens and limited data in the INL report by Wright (2014), but that cannot be used to validate Figures HBB-II-3000-11 and HBB-II-3000-12. However, on close examination, these two figures appear to be derived from HBB-T-1400 for the 2.25Cr-1Mo and Alloy 800H steels (perhaps this is because they are most similar to the SA-533 and SA-508 materials). Figure 4.2.3-3 shows a comparison of HBB-II-3000-11 design fatigue strain range curves with those presented in Figures HBB-T-1420-1C and HBB-T-1420-1D.

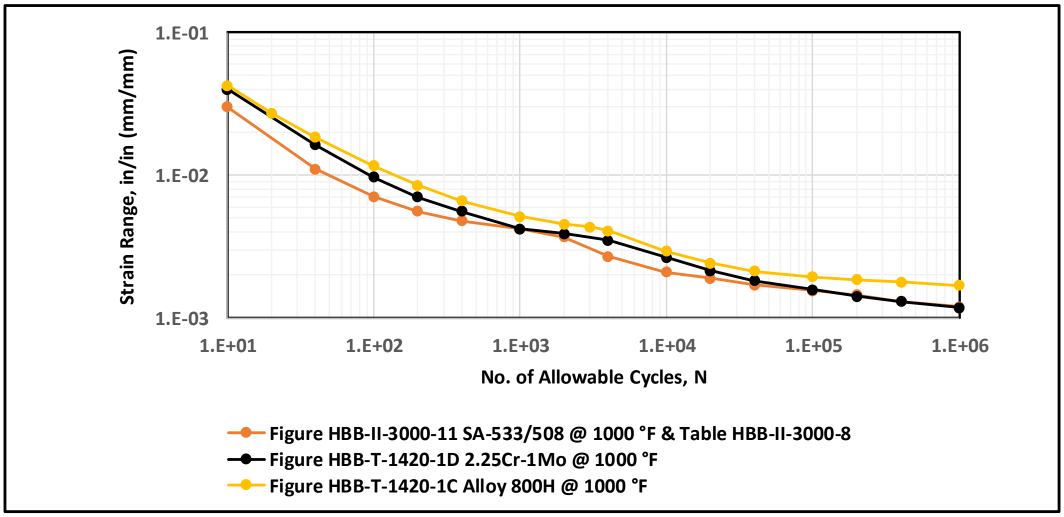

Figure 4.2.3-3 Design fatigue strain range for SA-533 and SA-508 from Figure HBB-II-3000-11 compared to those for 2.25Cr-1 Mo and Alloy 800H steels from HBB-T

As detailed in the review of HBB-T, the fatigue strain range curves for Alloy 800H and 2.25Cr-1Mo materials were shown to be conservative, and given that the materials are similar, the values presented in Figure HBB-II-3000-11 may be accepted for endorsement.

Separately, an earlier review for the NRC by Argonne National Laboratory (ANL) of Code Case N-499-1, the precursor to HBB-II (Shah et al., 2003), confirmed that the allowable fatigue cycles shown in Figure HBB-II-3000-11 were based on smooth specimens tested to determine crack initiation. The design curve for fatigue was developed by applying a factor of 2 to strain range and 20 to cycles, whichever is lower, to the mean failure curve for small polished specimens tested in air at 1,000 degrees F (537.8 degrees C). These factors account for size effect, surface finish, statistical scatter of the data, and differences between laboratory and industry environments. Miner's rule (i.e., the linear cumulative damage rule) is used to estimate total fatigue damage. There is no explicit allowance for crack growth from pre-existing flaws.

As discussed in the review of Appendix HBB-T, the linear damage creep-fatigue procedure rules were chosen for convenience compared to other candidate methods. This convenience lies in simple data requirements compared to other methods such as ductility exhaustion used in British R5 design code procedure (Hughes et al, 2019). If one compares actual creep-fatigue raw failure test data to the BPVC-III-5 interaction diagram, nonconservative results are predicted. As discussed in Appendix HBB-T, numerous margins and safety factors are applied at almost every step to ensure that code predictions of creep fatigue are conservative compared to the data. These margins and safety factors have been modified over the years as more data became available—including plant failure data. In fact, for many cases, creep-fatigue design procedures have safety factors of greater than 25. Since HBB-II permits only limited high-temperature excursions for these materials, the design rules are deemed sufficiently conservative.

Similarly, the creep-fatigue damage envelope diagram using the bilinear damage summation rule in Figure HBB-II-3000-12 is identical to the curves for Alloy 800H and 2.25Cr-1Mo materials in Figure HBB-T-1420-2. Shah (2003) has also confirmed this fact. Thus, Figure HBB-II-3000-12 may be accepted for endorsement.

4.2.4 Article HBB-II-4000, "Fabrication and Installation"

This article references the rules of Article HBB-II-4000, which is currently being reviewed by PNNL for endorsement.

4.2.5 Article HBB-II-5000, "Examination"

This article references the rules of Article HBB-II-5000, which is currently being reviewed by PNNL for endorsement.

4.2.6 Article HBB-II-6000, "Testing"

This article references the rules of Article HBB-II-6000, which is currently being reviewed by PNNL for endorsement.

4.2.7 Article HBB-II-7000, "Overpressure Protection"

This article references the rules of Article HBB-II-7000, which is currently being reviewed by PNNL for endorsement.

4.3 Mandatory Appendix HCB-I, "Stress Range Reduction Factor for Piping"

4.3.1 Article HCB-I-1000, "Stress Range Reduction Factor"

This article is recommended for endorsement as Table HCB-I-2000-I is a direct extension of Table NC-3611.2(e)-1 in ASME BPVC.III.1.NC-2017 for materials outside the creep regime. As stated above, the stress range reduction factors, f, in Table HCB-I-2000-1 are significantly lower than those in NC (as low as 0.2 for the lower bound case instead of 0.5) to account for the effect of the combination of creep at elevated temperatures and to ensure conservative design limits. However, the basis and the derivation of the coefficients for N_1 for various ranges, and the values of "f" in Table HCB-I-2000-1 are not available from ASME, nor is the source data used to calculate these values. Based on the response from ASME,[3] this article is recommended for endorsement, since the methodology used is consistent with that in ASME BPVC, Section III, NC-2017, which the NRC endorsed in June 2020 (*Federal Register*, 2020).

4.3.2 Article HCB-I-2000, "Maximum Number of Allowable Cycles with f = 1"

The maximum number of allowable cycles (N_1) over which f=1 and the range over which the factors apply vary with the material involved and are provided in Table HCB-I-2000-2. Based on the response from ASME members,[3] this article is recommended for endorsement.

4.3.3 Article HCB-I-3000, "Equivalent Cycle"

The approach to determining equivalent cycles for cases where the temperature varies with time as described in this article involves the same methodology described in ASME BPVC.III.1.NC-2017, Article NC-3611.2, "Stress Limits." Since BPVC NC-2017 has been endorsed by the NRC, this article is also recommended for endorsement.

A detailed review of the proposed Code Case and its Appendix B from ASME BPVC (1977) confirmed that the values used in Tables HCB-I-2000-1 and HCB-I-2000-2 were identical to and therefore derived directly from this document. However, there was no reference to the data or the analysis involved in the derivation of the stress range reduction factors or the maximum number of cycles for each of the materials. Further inquiry confirmed that the ASME member who developed these tables has since retired and is not available to provide further information. This review recommends that Appendix HCB-I be endorsed based on the feedback received by ASME BPVC members[3] that the values in the two tables in this appendix are conservative.

4.4 Mandatory Appendix HCB-II, "Allowable Stress Values for Class B Components," and Mandatory Appendix HCB-III, "Time-Temperature Limits for Creep and Stress-Rupture Effects"

4.4.1 Article HCB-II-1000, "Scope"

This article is recommended for endorsement as it describes the scope covered by the appendix. Given the complexity of when certain factors apply and to which allowable stress value they apply, Mandatory Appendix HCB-II provides a detailed flowchart (Figure HCB-II-1000-1).

[3] The NRC requested information from ASME regarding the source of data supporting Appendix HCB-I. A proposed Code Case for Class 2 or 3 components for elevated temperature service was recently located in the files of the Working Group on Piping Design dating to 1977, found in the archives of a member of this working group. The subject stress range reduction factors are included in Appendix B of this proposed Code Case from 1977. No additional information has been located in the ASME files, but there is general agreement that the stress range reduction factors are quite conservative. The entire communication with ASME on Mandatory Appendix HCB-I has been provided to the NRC staff. The communication includes the October 1977 ASME Boiler and Pressure Vessel Code meeting minutes. These minutes contain the document titled "Appendix B from the 1977 Proposed Code Case," which is the basis for Tables HCB-I-2000-1 and HCB-I-2000-2.

The various cases in the flowchart in Figure HCB-II-1000-1 result in four possible values of allowable stresses denoted as Designators A1 through A4 as follows:

- A1—allowable stress *for base metal* given in Tables HCB-II-3000-1 through HCB-II-3000-4 *applicable to all cases and service conditions (including creep) providing the most conservative lower bound values*

- A2—allowable stress *for welds* from Tables HCB-II-3000-1 through HCB-II-3000-4 multiplied by weld reduction factor from Tables HCB-II-3000-5 through HCB-II-3000-9 *applicable to all cases and service conditions (including creep) for the most conservative lower bound values*

- A3—allowable stress for cases involving *creep-significant events less than 1 hour* using the values in Tables HCB-II-2000-1 through HCB-II-2000-4 multiplied by an "aging factor" for various temperatures and materials provided in Table HCB-II-2000-5

- A4—allowable stress from Tables HCB-II-2000-1 through HCB-II-2000-4 for *negligible creep cases*

As indicated above, *for any or all service conditions, the user always has the option of choosing the more conservative allowable stresses (Designator A1 for base metals or Designator A2 for weldments)*. Because this article specifically provides this conservative option based on the allowable stress values from 2017 ASME BPVC, Section II, Part D, Subpart 1 (which has been endorsed by the NRC), for cases and for materials where supporting data for negligible creep may not be available or consistent (as detailed below in Sections 4.4.2 and 4.4.3), it is therefore recommended for endorsement.

4.4.2 Article HCB-II-2000, "Service with Negligible Creep Effects"

The first step in the procedure to review the proposed allowable stresses for "Service with Negligible Creep Effects" in HCB-II-2000 and for "Service that May Include Creep Effects" in HCB-II-3000 involved selecting one grade for each of the material set shown in Figure HCB-III-1000-1:

- Curve A—Carbon Steel
- Curve B—Low-Alloy Steel (1.25Cr-1Mo)
- Curve B—Grade 91 (9Cr-1Mo)
- Curve C—Cast 304 SS
- Curve D—Cast 316 SS
- Curve E—304 SS
- Curve F—316 SS
- Curve G—Alloy 800H

Curve B in Figure HCB-III-1000-1 covers both low-alloy steel and Grade 91, and therefore, example cases for both materials were reviewed for Curve B.

HCB-II and HCB-III cover many material grades in each of the material categories covered by Curves A–G in Figure HCB-III-1000-1. For the purpose of this review, after discussion with the NRC staff, one example case for each of the material sets listed above was selected for further study. For consistency, the “Plate” product form was selected for the example’s cases, if available on the lists in Figures HCB-II-2000-1 through HCB-II-2000-4. The allowable stress values for all service conditions, including creep (A1), with weldments (A2), creep-significant event less than 1 hour (A3), and negligible creep (A4), were selected or calculated as a function of time based on the recommendations for these four designators.

Tables HCB-II-3000-5 through HCB-II-3000-9 provide the weld factors for the materials. These factors are applied to derive the allowable stress values for A2 using the corresponding values for condition A1. Jetter (2017) provides an excellent summary of the basis of these weld reduction factors. As discussed in the review of Code Cases N-861 and N-862, these reduction factors are based on four considerations: (1) creep-rupture strengths of welds are typically lower than those of base metal, (2) creep ductility (or strain to failure) is typically lower in welds operating at high temperature, (3) long exposure of welds at high temperature can lead to diffusion processes and time-dependent changes to mechanical properties, and (4) local variations in stress-strain and creep response in the various weld regions (weld, heat affected zone) could redistribute stresses and strains and reduce life. The quite conservative reduction factors used for welds were introduced to ensure that designers locate welds in regions of low strain. Corum (1989) examined these reduction factors for welds in detail by reviewing extensive domestic and foreign test data on weldments. He found that reduction factors for tests performed transverse to the welds are necessary with a reduction equivalent to at most a 50-percent reduction in life. Moreover, the reduction factors in HBB-1-14-10 are considered to add margin in weld assessments. For negligible creep cases, because the time spent in the creep regime is managed much better, these reductions are less but still considered quite conservative.

Similarly, the “aging factors” in Table HCB-II-2000-5 are used to multiply the values for negligible creep (A4) to obtain the allowable stress factors for creep-significant events less than 1 hour (A3). Figures 4.4.2-1 through 4.4.2-8 show the allowable stresses versus temperature for each of the eight example cases selected for the four service levels and conditions described in Designators A1 through A4 in Section 4.4.1 above. Appendix C summarizes the procedure for determining these allowable stress values.

The following points are noted for the example cases reviewed in Figures 4.4.2-1 through 4.4.2-8 below:

- The values for allowable stresses for “all service conditions” (A1) and their respective “weldments” (A2) for these cases do provide lower bound conservative values, and therefore, these options are recommended for endorsement, especially as they are based on values from ASME BPVC.II.D.C-2017 Section II, which has already been endorsed by the NRC.

- As expected, the allowable stress values for “creep-significant events that are less than 1 hour” (A3) are lower than those for “negligible creep” (A4) in all cases.

- The values of allowable stresses at temperatures above which creep effects need to be considered (i.e., 700 degrees F (371.1 degrees C) for carbon steels, 2.25Cr-Mo, and Grade 91, and 800 degrees F (426.7 degrees C) for 304 SS, 316 SS, and Alloy 800H) would be expected to converge to the same values; however, this was not so for all the example material cases examined.

- The relative values of the two sets of curves for allowable stresses for A1 and A2 versus A3 and A4 appear to be inconsistent for several of the cases as noted above. For the example case selected for carbon steel (Figure 4.4.2-1), low-alloy steel (Figure 4.4.2-2), and Grade 91 (Figure 4.4.2-3), the allowable stress curves for cases A3 and A4 are lower than those for A1 and A2 at 700 degrees F (371.1 degrees C). For 304 SS (Figure 4.4.2-6) and 316 SS (Figure 4.4.2-7), the A3 and A4 stresses are higher than those for A1 and A2 at 800 degrees F (426.7 degrees C) and, therefore, could be nonconservative. For the remaining cases, Cast 304 SS (Figure 4.4.2-4), Cast 316 SS (Figure 4.4.2-5), and Alloy 800H (Figure 4.4.2-8), the curves appear to be consistent at 800 degrees F (426.7 degrees C); that is, the values for allowable stresses for A3 and A4 are in line with those for cases A1 and A2.

- Since only one case for each of the curves in Figure HCB-III-1000-1 was used as an example, and there are many grades for each of the seven material sets (Curves A-G) covered by Appendices HCB-II and HCB-III, it is important that ASME BPVC, Division 5, clarifies that the allowable stresses for negligible creep are both consistent and conservative before their endorsement.

- As described above, there are cases where the allowable stresses as determined for Designator A4 are lower than those for Designators A1 and A2. If users decide to follow the path in Figure HCB-II-1000-1 to determine and apply the allowable stresses for Designators A1 and A2, they may not actually be using the most conservative value of the allowable stress and would not be in compliance with the BPVC. In light of the above inconsistencies, which ASME will need to resolve, this review recommends that the most conservative value of the allowable stress be used in every case.

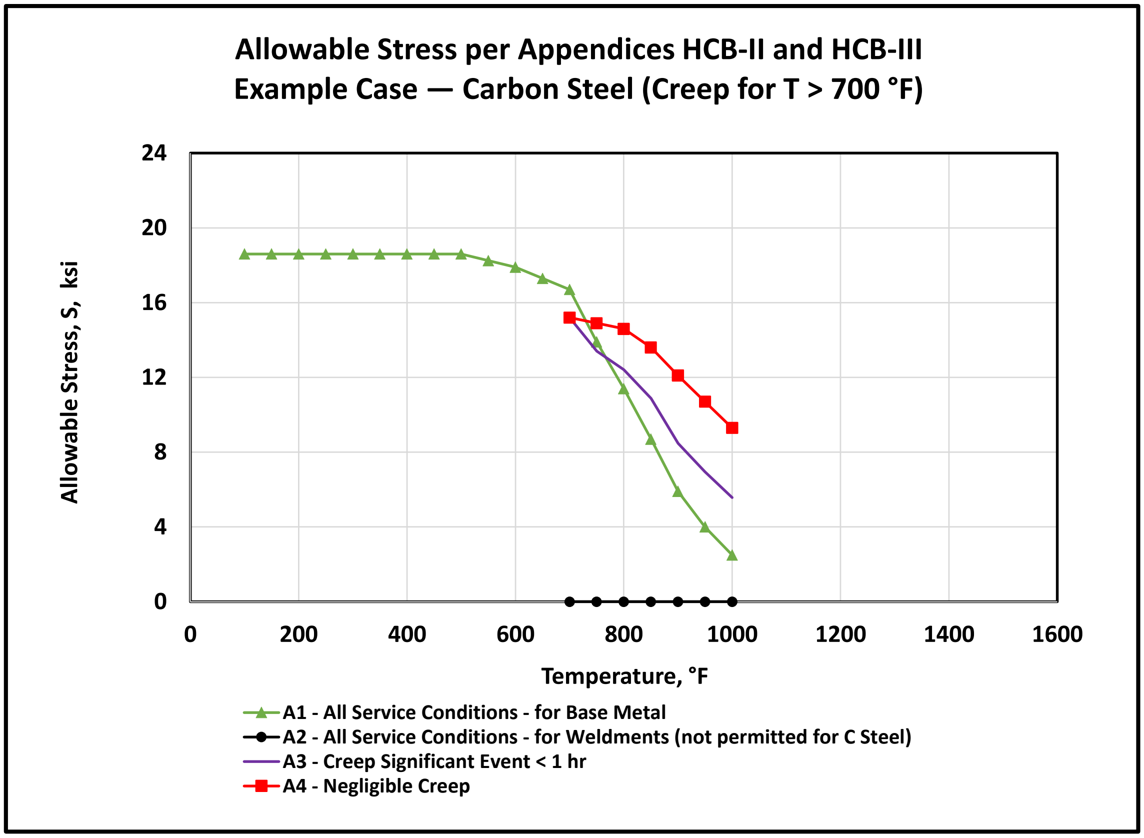

Figure 4.4.2-1 Allowable stresses for *carbon steel* per Appendices HCB-II and HCB-III for various service conditions using an example case for Curve A (SA-516 Plate, Grade 65, Part No. 1, Group 1 with S_y = 35 ksi, S_u = 65 ksi in Table HCB-2000-1 and Table HCB-II-3000-1 and per ASME BPVC.II.D.C-2017, Subpart 1, Table 1A, p. 14, Line 38)

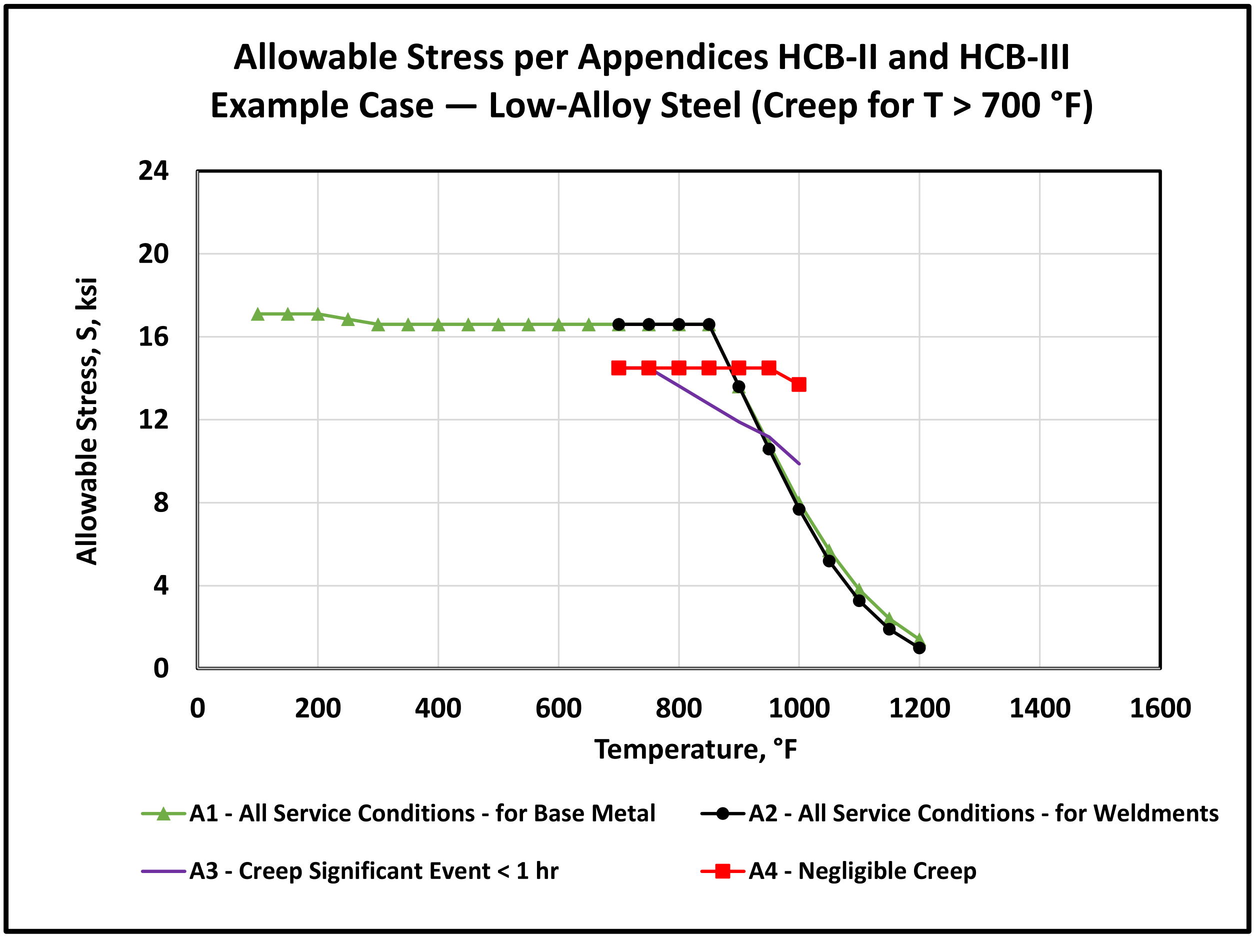

Figure 4.4.2-2 Allowable stresses for *low-alloy steel (2.25Cr-1Mo)* per Appendices HCB-II and HCB-III for various service conditions using an example case for Curve B (2.25Cr-1Mo, Part No. 5A, Group 1, Plate, SA-387, Grade 22 with S_y = 30 ksi, S_u = 60 ksi in Table HCB-II-2000-1 and Table HCB-II-3000-1 and per ASME BPVC.II.D.C-2017, Subpart 1, Table 1A, p. 38, Line 26)

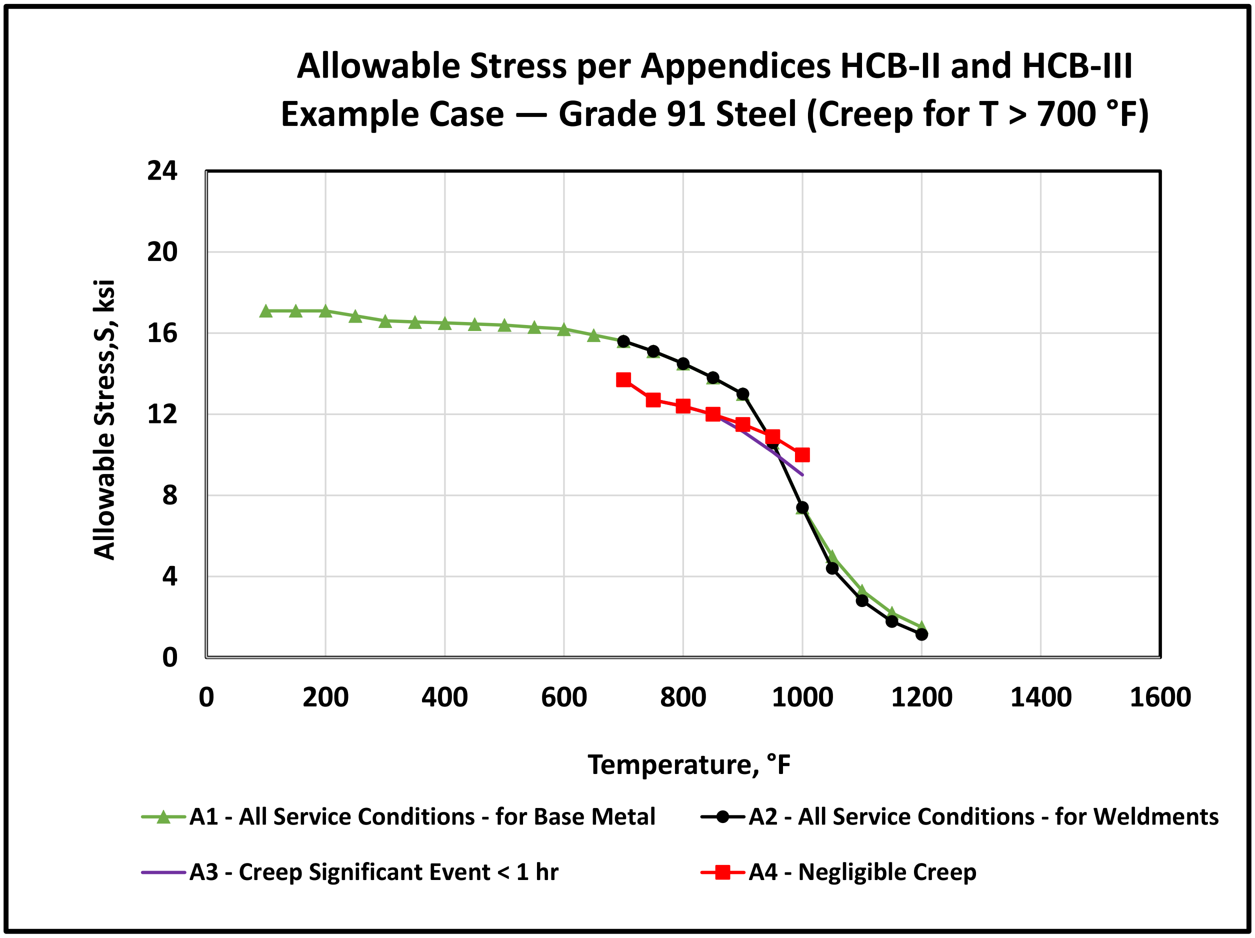

Figure 4.4.2-3 Allowable stresses for *Grade 91* steel per Appendices HCB-II and HCB-III for various service conditions using an example case for Curve B (9 Cr-1Mo, Part No. 5B, Group 1, Seamless Pipe, SA335, Grade P9; S_y = 30 ksi; S_u = 60 ksi in Table HCB-II-2000-1 and Table HCB-II-3000-1 and per ASME BPVC.II.D.C-2017, Subpart 1, Table 1A, p. 46, Line 3)

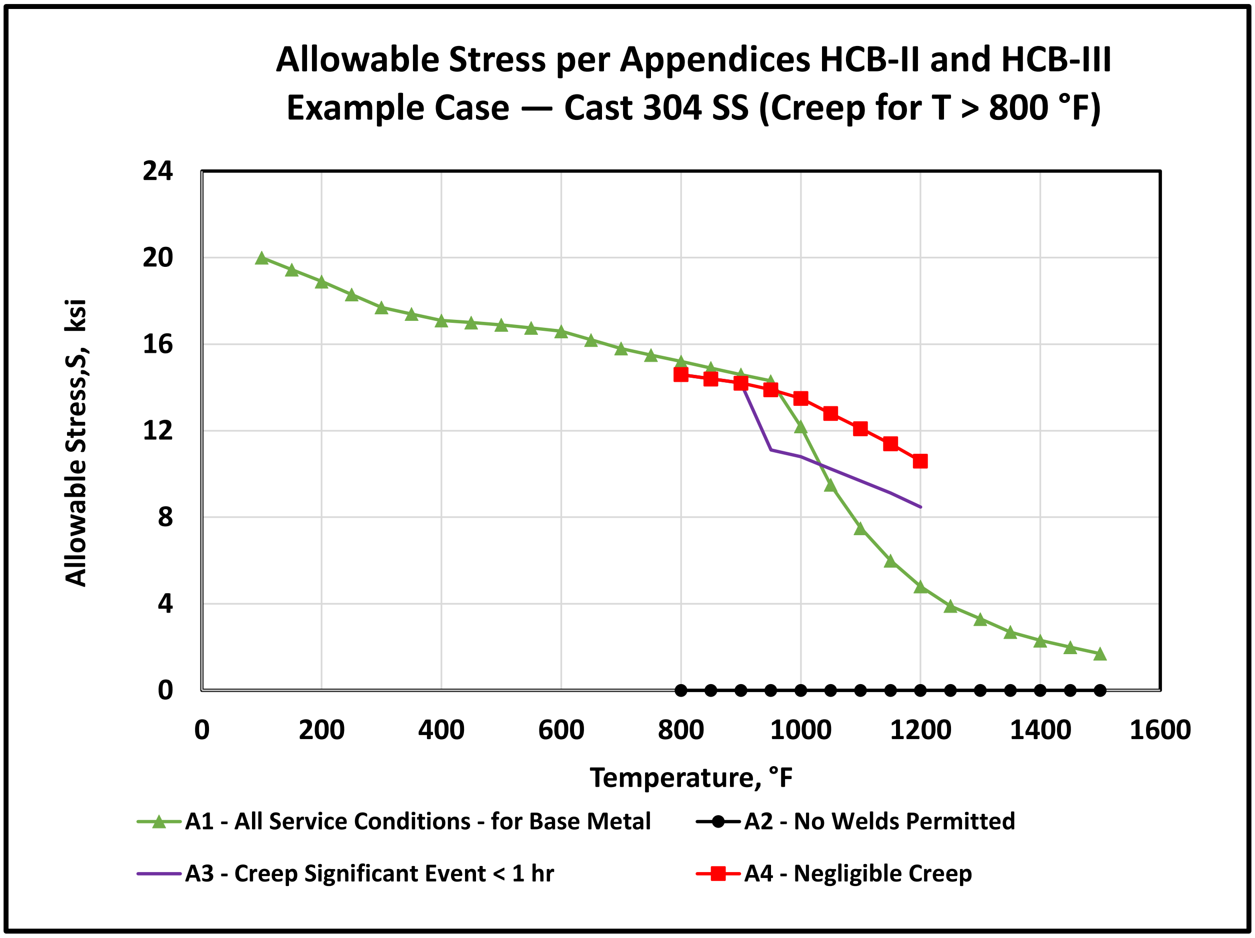

Figure 4.4.2-4 Allowable stresses for *Cast 304 SS* per Appendices HCB-II and HCB-III for various service conditions using an example case for Curve C (18Cr-8Ni, Part No. 8, Group 1 Casting, SA-351 CF8 with S_y = 30 ksi, S_u = 70 ksi in Table HCB-II-2000-3 and Table HCB-II-3000-3 and per ASME BPVC.II.D.C-2017, Subpart 1, Table 1A, p. 86, Line 1)

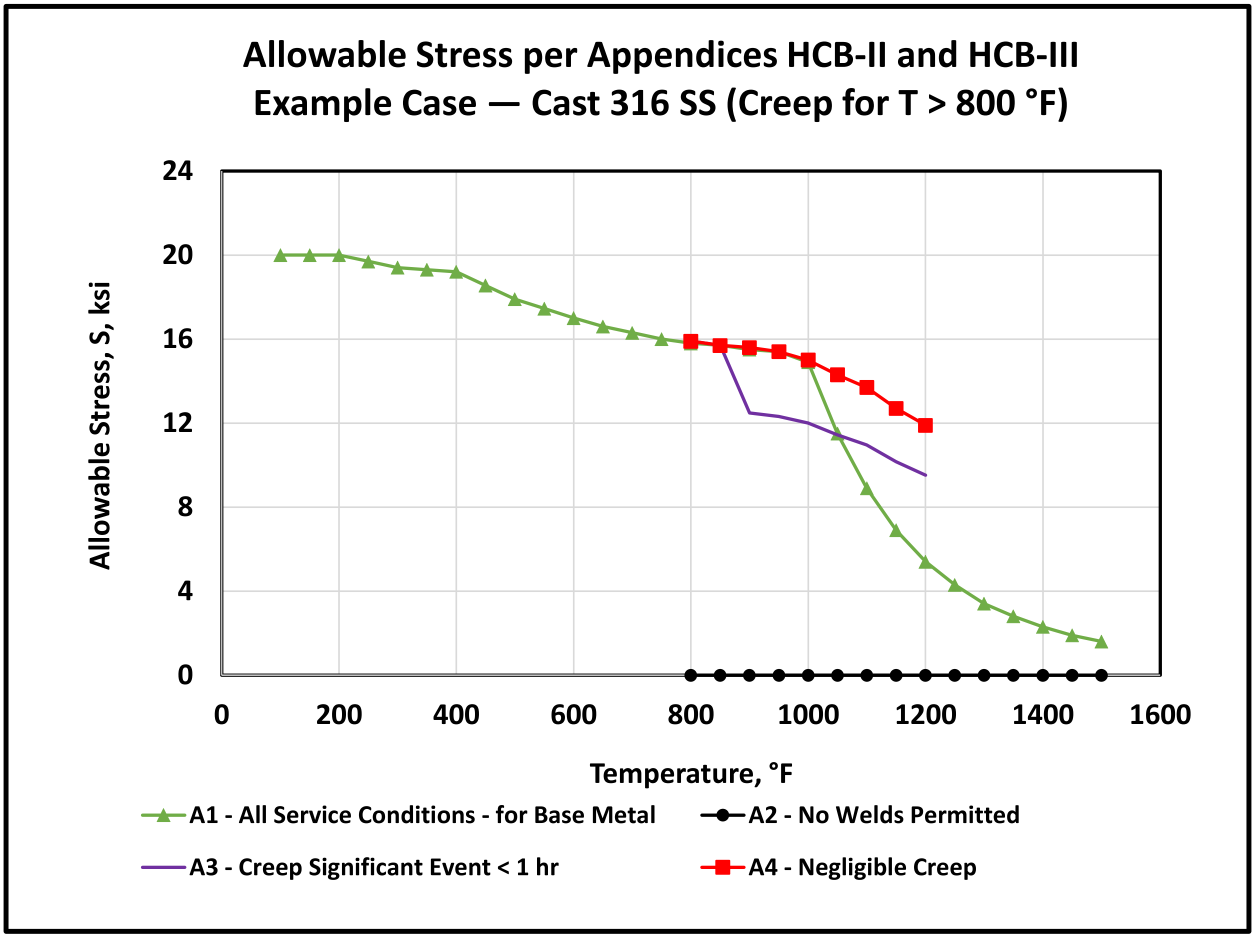

Figure 4.4.2-5 Allowable stresses for *Cast 316 SS* per Appendices HCB-II and HCB-III for various service conditions using an example case for Curve D (16Cr-12Ni-2Mo, Part No. 8, Group 1 Casting, SA-351 CF8M with S_y = 30 ksi, S_u = 70 ksi in Table HCB-II-2000-3 and Table HCB-II-3000-3 and per ASME BPVC.II.D.C-2017, Subpart 1, Table 1A, p. 70, Line 24)

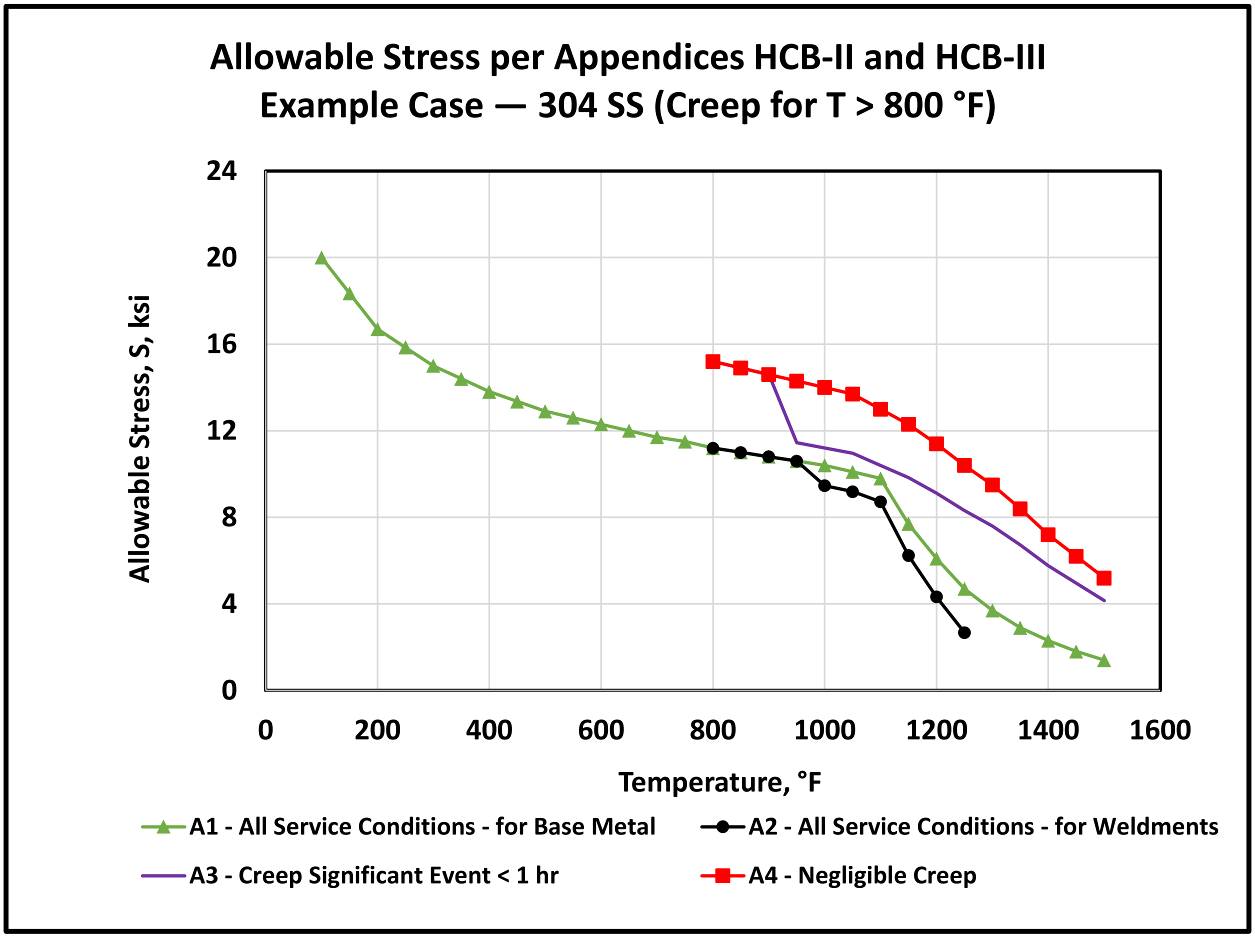

Figure 4.4.2-6 Allowable stresses for *304 SS* per Appendices HCB-II and HCB-III for various service conditions using an example case for Curve E (18Cr-8Ni, Part No. 8, Group 1 Plate, SA-240, Grade 304 with S_y = 30 ksi, S_u = 75 ksi in Table HCB-II-2000-3 and Table HCB-II-3000-3 and per ASME BPVC.II.D.C-2017, Subpart 1, Table 1A, p. 86, Line 30)

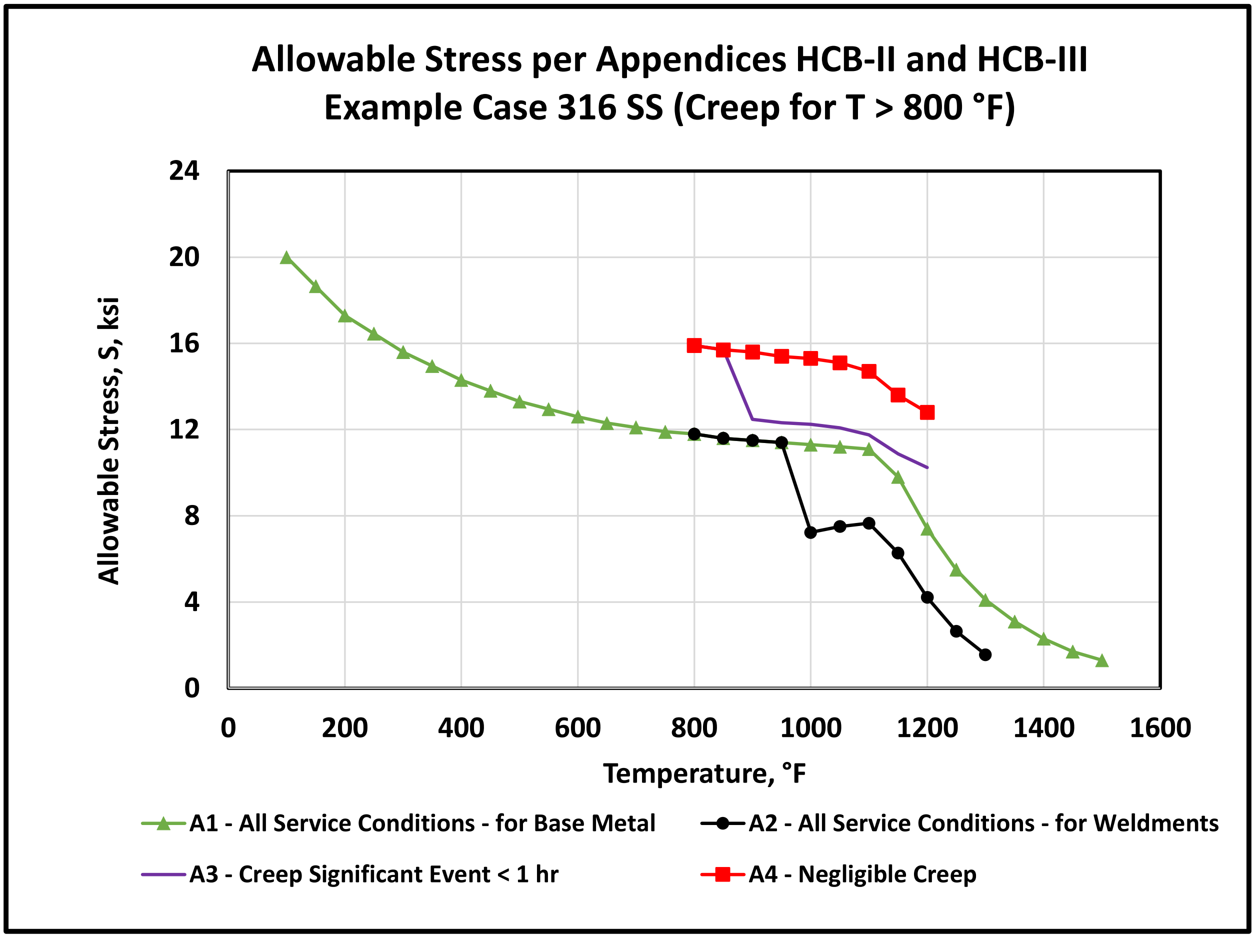

Figure 4.4.2-7 Allowable stresses for *316 SS* per Appendices HCB-II and HCB-III for various service conditions using an example case for Curve F (16Cr-12Ni-2Mo, Part No. 8, Group 1 Plate, SA-240 with S_y = 30 ksi, S_u = 75 ksi in Table HCB-II-2000-3 and Table HCB-II-3000-3 and per ASME BPVC.II.D.C-2017, Subpart 1, Table 1A, p. 70, Line 40)

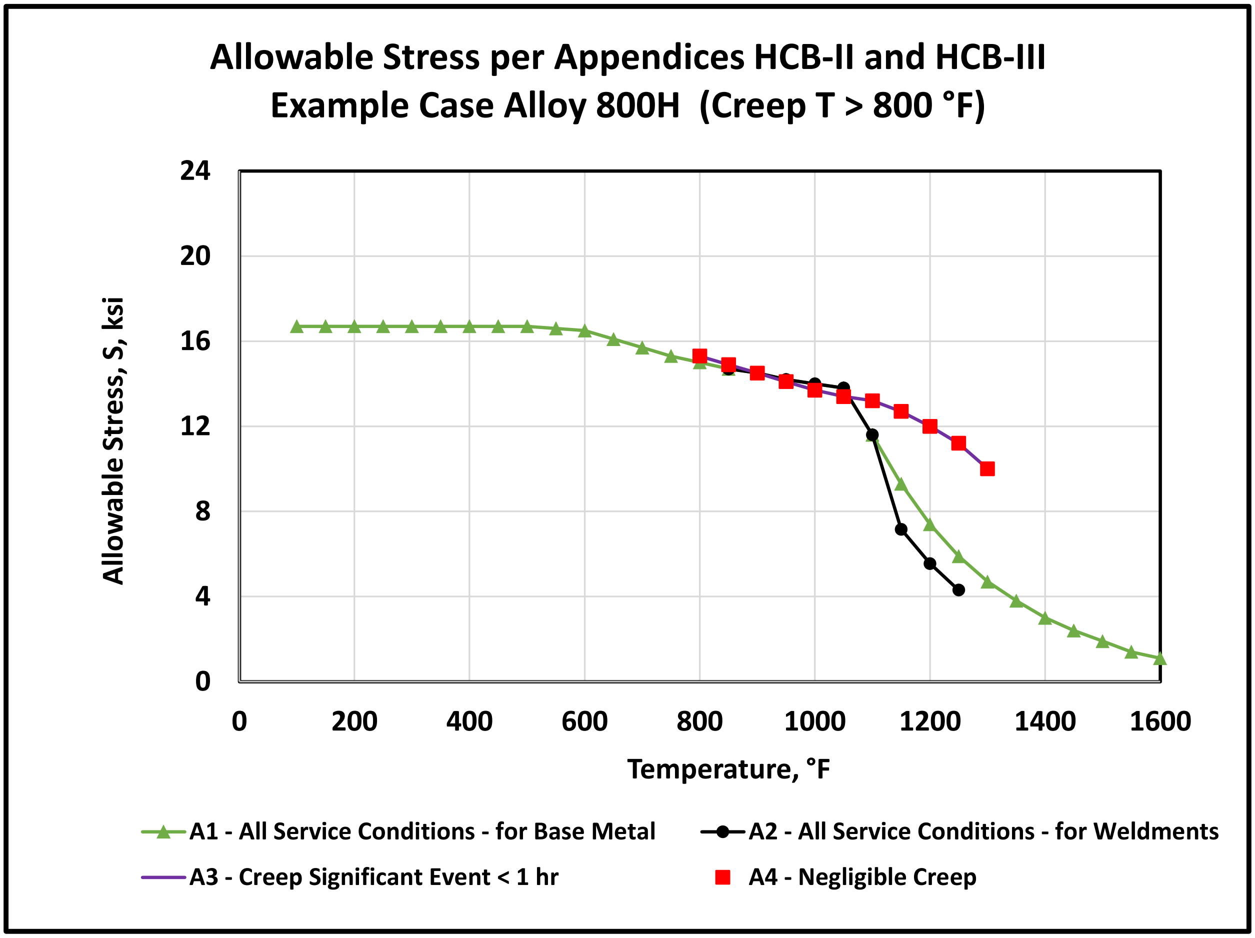

Figure 4.4.2-8 Allowable stresses for *Alloy 800H* per Appendices HCB-II and HCB-III for various service conditions using an example case for Curve G (33Ni-42Fe-21Cr, Part No. 45, Plate, SB-409 with S_y = 25 ksi, S_u = 65 ksi in Table HCB-II-2000-4 and Table HCB-II-3000-4 and per ASME BPVC.II.D.C-2017, Subpart 1, Table 1B, p. 234, Line 31)

4.4.3 Article HCB-II-3000, "Service that May Include Creep Effects"

For service that may include creep effects, based on the example cases described above in Figures 4.4.2-1 through 4.4.2-8, the values of allowable stresses A1 apply for base metal and A2 for weldments. These base values are directly obtained from ASME BPVC.II.D.C-2017 Section II, Part D, Subpart 1, which the NRC recently endorsed. As discussed above, the allowable stress values for A1 (and A2 for welds) are lower bound conservative values that apply to all service conditions and, therefore, may be recommended for endorsement.

4.4.4 Article HCB-III-1000, "Introduction"

As indicated above, this article and its Subarticles HCB-III-1100 and HCB-III-1200 define the criteria when creep and stress-rupture effects are negligible and need not be considered during the evaluation of elevated temperature failure modes (ratcheting, buckling, and creep-fatigue). Subarticle HCB-III-1100 provides Figure HCB-III-1000-1, which shows metal temperature versus allowable time at temperature for the seven material classes listed in Section 4.4.2 above and designated as Curves A through G. To confirm that these curves are conservative, the isochronous curves for the material classes, reviewed under Nonmandatory Appendix HBB-T, were used to determine the total strain level at two values of metal temperatures for each curve, as shown in Table 4.4.4-1.

Table 4.4.4-1 Confirmation of "negligible creep" criteria for Level A and B conditions covered in Figure HCB-III-1000-1

Material	Case	Temperature*	Allowable Time *	Allowable Stress for Negligble Creep**	Approx Total Strain at Allowable Stress	Reference for Total Strain at Allowable Stress (Isochronous Curve)	Notes/ Comments***
	Curve*	F	hours	ksi	%	Figure No.	
Alloy 800 H	G	1200	20	7.40	0.05	Figure HBB-T-1800-C-8	Confirms negligible creep strain limits; < 0.2%
		1000	30000	14.10	0.08	Figure HBB-T-1800-C-4	Confirms negligible creep strain limits; < 0.2%
316 SS	F	1100	20	11.80	0.10	Figure HBB-T-1800-B-7	Confirms negligible creep strain limits; < 0.2%
		900	200000	12.50	0.07	Figure HBB-T-1800-B-3	Confirms negligible creep strain limits; < 0.2%
304 SS	E	1000	50	11.20	0.08	Figure HBB-T-1800-A-5	Confirms negligible creep strain limits; < 0.2%
		850	100000	14.90	0.07	Figure HBB-T-1800-A-2	Confirms negligible creep strain limits; < 0.2%
Low Alloy Steel	B	850	40	12.80	0.10	Figure HBB-T-1800-D-4	Confirms negligible creep strain limits; < 0.2%
(2 1/4 Cr-1 Mo)		750	6000	14.50	0.15	Figure HBB-T-1800-D-2	Confirms negligible creep strain limits; < 0.2%
Grade 91	B	850	40	12.00	0.05	Figure HBB-T-1800-E-4	Confirms negligible creep strain limits; < 0.2%
		750	6000	12.70	0.04	Figure HBB-T-1800-E-2	Confirms negligible creep strain limits; < 0.2%

*- per Figure HCB-III-1000-1 curve designations
** - see Figure 4.4.2-X below for the given material
*** - Negligible creep is defined as <0.2% strain (inelastic strain at yield stress) and also referenced in HBB-T-1324

For each case analyzed in Table 4.4.4-1, the values of total strain from the isochronous stress-strain curves are less than 0.2 percent—which is the criteria commonly used for negligible creep as it equals the inelastic strain at yield stress. Subarticle HCB-III-1100 is therefore recommended for endorsement.

Subarticle HCB-III-1200 and Table HCB-III-100-1 define the criteria when creep and stress-rupture effects need not be considered for Level C events. Again, the isochronous stress-strain curves from the analyses in HBB-T were used to determine the approximate total strain for the allowable stress values at the peak temperatures listed in the above table. Again, these values of total strain at 25 hours (maximum limit allowable) are less than 0.2 percent, confirming that creep is negligible and the criteria listed are conservative.
Subarticle HCB-III-1200 is therefore recommended for endorsement.

Table 4.4.4-2 Confirmation of "negligible creep" criteria for Level C conditions covered in Table HCB-III-1000-1

Material	Peak Temp, °F	Peak Temp, °C	Allowable Stress, ksi	Approx Total Strain at 25hrs, %	Notes/Comments
Low-Alloy Steel	950	510.0	10.60	0.08	Figure HBB-T-1800-D-6
304 SS	1150	621.1	6.00	0.05	Figure HBB-T-1800-A-8
316 SS	1250	676.7	4.3	0.03	Figure HBB-T-1800-B-10
Alloy 800 H	1250	676.7	5.9	0.04	Figure HBB-T-1800-C-9

The reviewers, along with the NRC staff, had requested ASME confirmation that the criteria in Mandatory Appendices HCB-II and HCB-III are conservative. ASME Division 5 staff who were responsible for the original work on this appendix confirmed that negligible creep curves are smoothed versions of the criteria for negligible creep in Test A-3 in HBB-T-1324. Also, the negligible creep criteria permit the use of allowable stress values based on tensile properties for short-term loads like seismic instead of values based on long-term creep properties at elevated temperature. Even though they were approved in ASME BPVC Section III, Division 5 Subgroup Elevated Temperature Design (SGD-ETD), the details of their development have not been identified in the relevant ASME files, but they were independently confirmed as described above.

5. SUMMARY

Nonmandatory Appendix HBB-T, "Rules for Strain, Deformation, and Fatigue Limits at Elevated Temperatures"

The technical recommendation of this report finds that the limits of Appendix HBB-T are an acceptable approach for demonstrating compliance with the design requirements for Division 5, Class A, components, although the owner may use other methods as justified in the design report ASME BPVC, Section III, Subsection NCA-3550. It is anticipated that ANLWR vendors will use a nonlinear finite-element-based solution to demonstrate compliance for some components because the vendors now have access to large computational facilities. This may reduce the conservativism inherent in the simple HBB-T design rules based on elastic or simplified inelastic analysis.

The justification for many of the rules in Appendix HBB-T is discussed below with reference to the publications used to develop the rules. For Division 5, precedence was established earlier by Sections I and VIII based on many years of operating experience at elevated temperatures. Section 3 of this report provides endorsement recommendations, while Section 4 of this report presents detailed justifications for many of the rules in HBB-T.

Almost all rules within HBB-T are recommended for endorsement. However, the designer and owner must be careful in the following areas:

- Residual stresses during metal forming and weld fabrication occur, and these stresses relax during service creep. The stress relaxation results in some creep damage. If post-weld heat treatment is performed, the residual stresses can be partially relieved. For components with low creep ductility, this can lead to cracking. Moreover, even if cracking does not occur, some creep damage develops from stress relaxation. Several European code groups, particularly in the United Kingdom, are concerned with preventing stress-relaxation cracking and it is natural to question why HBB-T does not explicitly consider this mechanism. This report recommends that vendors address the potential for stress-relaxation cracking in their designs.

- The creep-fatigue rules of HBB-T-1400 are recommended for endorsement contingent on HBB-2000 endorsement. Some materials' creep-rupture constants in the assessment of HBB were found to provide nonconservative data, especially at high temperatures and long times. However, the creep-fatigue rules using the linear damage interaction approach had safety factors and margins developed to ensure that very conservative predictions are made using the design procedures currently within HBB-T even without the corrections noted above. Therefore, while the possibly nonconservative data in Table HBB-I-14.6 for 304 and 316 SS and 2.25Cr-1Mo steel may need to be addressed, the creep-fatigue procedures for design are deemed adequate because of the margins introduced and the comparisons with extensive test databases.

This report recommends that HBB-T-1820 be endorsed subject to the following stipulations. It may be necessary to re-examine these data for high temperatures and long times, although this is difficult to do since extrapolation is necessary for long time estimates.

- The isochronous for temperatures higher than 700 degrees Celsius (1292 degrees Fahrenheit) for 304 and 316 stainless steel appear to be slightly nonconservative for times greater than 100,000 hours.

- The isochronous curves for 2.25Cr-1Mo material may be nonconservative for temperatures above 600 degrees C (1112 degrees F) at times greater than 100,000 hours.

- The isochronous curves for Alloy 800H material may be nonconservative for temperatures at 700 degrees C (1292 degrees F) and above, at times of 100,000 hours and above.

- The isochronous curves for 9Cr Mo material are higher than new curves recently produced by ASME Standards Technology, LLC based on new data and may be slightly nonconservative in general.

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"

Mandatory Appendix HBB-II was developed to provide rules for the use of SA-533 Type B, Class 1 plates and SA-508 Grade 3, Class 1 forgings and their weldments for a limited time above the normal temperature limit of 700 degrees F (371.1 degrees C). The appendix is recommended for endorsement. Article HBB-II-2000 provides values of yield strength, S_y, tensile strength, S_u, and design stress intensity (allowable) values, S_m, for both materials in ASME BPVC Section II for temperatures less than 371.1 degrees C (700 degrees F) and Table HBB-II-3000-3 for temperatures greater than 371.1 degrees C (700 degrees F). These values were reviewed in detail to establish that the margin of safety (S_u/S_m) for the entire range of temperatures for both materials is consistently 3.0. This confirms that the S_m values in Table HBB-II-3000-3 are conservative, and therefore, HBB-II-2000 is recommended for endorsement.

Article HBB-II-3000 involves design rules for temperatures exceeding 371.1 degrees C (700 degrees F) and was reviewed to confirm that the following three aspects of the design bases were conservative and, therefore, recommended for endorsement:

(1) Allowable stress intensity had an adequate margin of safety for the allowable stress S_{mt} since it is dependent on both temperature and time at the given temperature based on Figures HBB-II-3000-1, -2, -3, -13, and -14, along with their respective underlying data in Tables HBB-II-3000-1, -2, -3, and -4.

(2) Isochronous stress-strain curves for temperatures 371.1 degrees C through 537.8 degrees C (700 through 1,000 degrees F) in Figures HBB-II-3000-4 through HBB-II-3000-10 were reviewed to confirm adequate conservatism in the strain to failure under creep at the various stress and temperature values.

(3) Design fatigue strain in Figure HBB-II-3000-11, along with Table HBB-II-3000-9 and the creep-fatigue damage envelope in Figure HBB-II-3000-12, were conservative.

Mandatory Appendix HCB-I, "Stress Range Reduction Factor for Piping"

Mandatory Appendix HCB-I is recommended for endorsement. The most significant modification for creep effects in HCB-3630 is the definition of the stress reduction factor, f, covered in this appendix. The definition is essentially an extension of the definition of the stress reduction factor in NC-3611.2 where the factor, r_1, has been modified for elevated temperatures to include a term to account for the higher of the peak stresses due to either the through-the-wall temperature gradients or the axial temperature difference. The second modification is to the stress reduction factor in Tables HCB-I-2000-1 and HCB-I-2000-2 for the number of cycles, N_1.

The stress range reduction factor is recommended for endorsement as Table HCB-I-2000-I is a direct extension of Table NC-3611.2(e)-1 in ASME BPVC.III.1.NC-2017 for materials in the noncreep regime. These reduction factors, f, in Table HCB-I-2000-1 are significantly lower than those in NC (as low as 0.2 for the lower bound case instead of 0.5) to account for the effect of the combination of creep at elevated temperatures and to ensure conservative design limits. The maximum number of allowable cycles (N_1) over which f=1 and the range over which the factors apply vary with the material involved and are shown in Table HCB-I-2000-2. The approach to determining equivalent cycles in HCB-I-3000 for cases where the temperature varies with time, as described in this article, involves the same methodology described in ASME BPVC.III.1.NC-2017, Article NC-3611.2, "Stress Limits," which the NRC has endorsed.

As described above in Section 4.3, a significant effort was made to obtain the underlying data used by ASME to develop Tables HCB-I-2000-1 and HCB-I-2000-2. Both ASME staff and members of Division 5 who were directly involved in the development of these original tables as far back as 1977 were contacted. The discussions confirmed the conservative approach used to develop the tables, and therefore, Mandatory Appendix HCB-I is recommended for endorsement.

Mandatory Appendix HCB-II, "Allowable Stress Values for Class B Components," and Mandatory Appendix HCB-III, "Time-Temperature Limits for Creep and Stress-Rupture Effects"

Mandatory Appendices HCB-II and HCB-III (which has only a single article) are closely related and, therefore, are reviewed together. Both appendices address the allowable stresses applicable for Class B components when creep and stress rupture are either negligible or must be accounted for.

Appendix HCB-II provides the allowable stresses for materials for Class B components. The extensive list of materials covered in that appendix corresponds generally with those used at lower temperatures in Subsection NC. In Appendix HCB-II, two sets of allowable stresses are provided for all the materials: one set where creep effects are not significant (negligible creep), and the other set for the general case where creep is significant. The allowable stresses in Appendix HCB-II are based on the same criteria as those used to develop the allowable stresses for pressure vessels constructed in accordance with the rules for Section VIII, Division 1, for nonnuclear applications. However, reduction factors are also provided to account for the reduction in creep-rupture strength of weld metal and weldments.

HCB-II and HCB-III include many material grades for each of the seven material categories covered by Curves A–G in Figure HCB-III-1000-1. For the purpose of this review, one example case for each of the material sets was selected for further examination. The allowable stress values for all service conditions were calculated as described in the flowchart as a function of time per the recommendation for the four designators: creep (A1), with weldments (A2), creep-significant event less than 1 hour (A3), and negligible creep (A4). The analysis of these cases indicated the following:

- The values for allowable stresses for “all service conditions” (A1) and their respective “weldments” (A2) for these cases do generally provide lower bound conservative values. Therefore, these options are recommended for endorsement, especially as they are based on values from ASME BPVC.II.D.C-2017, which has already been endorsed by the NRC. However, some inconsistencies were noted in cases where Designators A1 and A4 were not the most conservative values.
- For those cases where there are inconsistencies in the values of the allowable stresses (which may need to be resolved by ASME), this review recommends that the most conservative value of the allowable stress be used in every case.

With the above caveats, Mandatory Appendices HCB-II and HCB-III are both recommended for endorsement.

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Appendix A: Material Property Assessment of Isochronous Stress-Strain Curves

This appendix examines the material data used to develop the isochronous stress-strain curves listed in HBB-T-1820. As shown in Figure A-1, the curves are constructed from creep strain data (top of Figure A-1) where the stresses are picked off at constant time values (isochronous or “constant time”) and plotted as seen on the bottom illustration in the figure. The isochronous curves actually represent total strains and include elastic, plastic, and creep strains in the bottom illustration in Figure A-1. Such curves are plotted at various temperatures as seen in HBB-T-1820 with a set of curves for each temperature of interest in the design. The isochronous curves represent creep strain reached in a given time over a range of stresses.

The isochronous stress-strain curve is a long-established method of representing creep data in a manner that, under certain circumstances, provides a quick and often surprisingly accurate approximate solution to time-dependent structural problems. Despite criticisms of the foundations of the method, it has survived over the years because it has either been the only method feasible at the time, or it is capable of providing solutions that are often good enough for practical purposes. The alternative is to use full inelastic analysis where an accurate visco-plastic constitutive model is used within the context of nonlinear finite element modeling. Such analyses are possible today by some of the vendors who have extensive high-performance computing power.

Marriott (2011) provides an excellent overview of the life prediction methods based on isochronous stress-strain curve approaches and corresponding justification and validation. Several efforts over the years have shown that the use of isochronous curves to estimate total creep strains is reasonable and can provide conservative predictions (e.g., Clinard, 1979) by comparing predictions made using this approach to full elastic-plastic-creep finite element models. An isochronous curve simply presents, in a plot of stress against strain, the locus of total strains accumulated when different constant stresses are applied for a fixed time.

The curves have been traditionally used over the years graphically, and this is the case in the 2017 Edition of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC). However, the 2021 BPVC will include equations that will permit the use of either the graphical curves or the equations as desired. Use of equations will be preferred as interpolation between curves can be difficult for arbitrary times, temperatures, stresses, and strains.

The remainder of this appendix discusses the isochronous curves in HBB-T-1820 for the five different code materials in the 2017 BPVC. The code’s isochronous stress-strain curves are compared to other data to verify the conservative nature of the code. The isochronous stress-strain curves include elastic, plastic, and creep strains. Some of the comparisons made below are made to creep strains only. Because creep data are highly variable with a large statistical scatter, the validation provided relies on some interpretation by the authors.

The isochronous curves in the code are meant to be “average” curves or represent data averaged over different tests. However, in reality, large parts of the curves were developed from only a few sets of data. In general, as shown below, this review considers most of the isochronous curves in the code to be adequate. However, some of the curves for very long times, where extrapolation was required when the curves were developed, show small nonconservatism for some materials based on more recent data where tests were carried out for very long times, in some cases for up to 200,000 hours.

To develop the comparisons in the rest of this appendix, a set of complicated spreadsheets was developed that can produce the isochronous curves for any temperature and time for all materials in Division 5. These spreadsheets will be provided to the U.S. Nuclear Regulatory Commission (NRC) staff so that, during license review, HBB rules, many of which rely on isochronous curves, can easily be assessed.

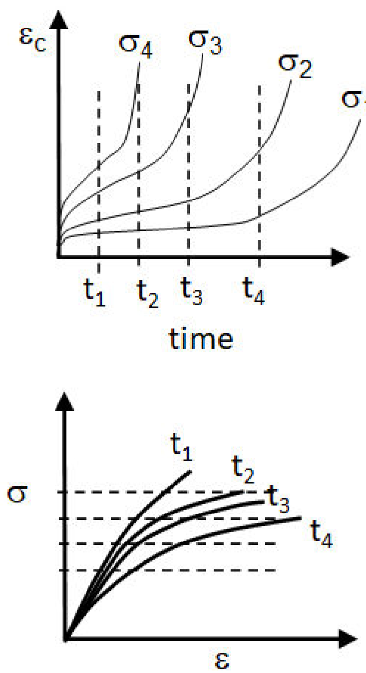

Figure A-1 Schematic of isochronous stress-strain curves

304 Stainless Steel

Figure HBB-T-1800-A in ASME BPVC, Section III, “Rules for Construction of Nuclear Facility Components,” Division 5, “High-Temperature Reactors” (BPVC-III-5), provides the isochronous stress-strain curves for 304 stainless steel (SS) up to 816 degrees C (1500 degrees F). A paper by Blackburn (1972) describes the original technical basis for the curves for 304 SS. The isochronous stress-strain curves were computed from a complex and extensive set of analytical equations based on a modification of the Garofalo creep equation form (multiple exponential form) that completely characterizes the strain response as it depends on stress, temperature, and time. The analytical equations represent the magnitude of time-independent and elastic and plastic strain and the magnitude and time dependence of the transient creep strain. The original derivation is based on creep test data for several heats of steel. The test specimens consisted of both bar and tube specimens. However, extensive other data, both published and unpublished, were used to verify the specific features of the analysis in the original Blackburn paper. Therefore, these data are considered representative of the 304 SS over the temperature range of interest.

The plastic strain equation and creep equation form are based on data averaged from this series of tests by Blackburn. Swindeman (1979) also examined isochronous curves based on creep relaxation data on two additional heats of plate material. The form of the equation represents the average of multiple sets of data by the current author and Swindeman and extensive comparisons of the equations, are compared in several figures in Blackburn (1972). Swindeman (1979) showed that relaxation isochronous curves are not affected much by prestrain or heat number. Blackburn's original hot tensile model includes two branches designed to capture a shift in work hardening slope at high values of strain. For the most part, this kink occurs above the conventional 2.2-percent strain limit in the code so is not considered important and was ignored in the curve development.[1]

The equations were programmed within a spreadsheet, and the isochronous stress-strain curves were calculated and plotted for different tempera Hi Jordan, Hi Jordan, Jordan Jordan tures. These spreadsheets will be provided to the NRC as part of this program deliverable so that, during licensing, staff will be able to perform confirmatory analyses of advanced nonlight-water reactor designs. The results from these spreadsheets were compared to the curves in HBB-T-1800-A. As an example, Figures A-2 and A-3 show the calculation of the isochronous stress-strain curves for 304 SS at 649 degrees C (1200 degrees F) and 816 degrees C (1500 degrees F), respectively. Comparison of these figures to Figure HBB-T-1800-A-9 or Figure HBB-T-A-15 showed a very slight difference indicating that the curves developed from equations are correct. This was done for all cases considered in this Appendix. This negligible difference is apparent only for the hot tensile curves. This difference is entirely due to the hot tensile portion of the curve, or the contribution from the plastic strain component. For example, the hot tensile curve of Figure HBB-T-1800-A-9 has an upper limit strain of 2.2 percent at a stress of 165 megapascals (MPa), while Figure A-2 below shows a value of about 169 MPa. The original equations of Blackburn (1972) presented the plastic strain as true strain. The reason for mixing the true plastic strain with the engineering creep strain was not apparent. During the development of the equations for the isochronous curves for the code by Dr. Messner of Argonne National Laboratory, it was decided to neglect this slight increase in stress and use the true plastic strain contribution for 304 SS. The equations used in this study apply the true plastic strain, as will be used in the 2021 BPVC. Given the uncertainty in creep strains at high temperature, this small difference is not considered important.

[1] The authors appreciate the help of Dr. M. Messner of Argonne National Laboratory who provided some of the references for this material and also helped doublecheck the spreadsheets used in this study.

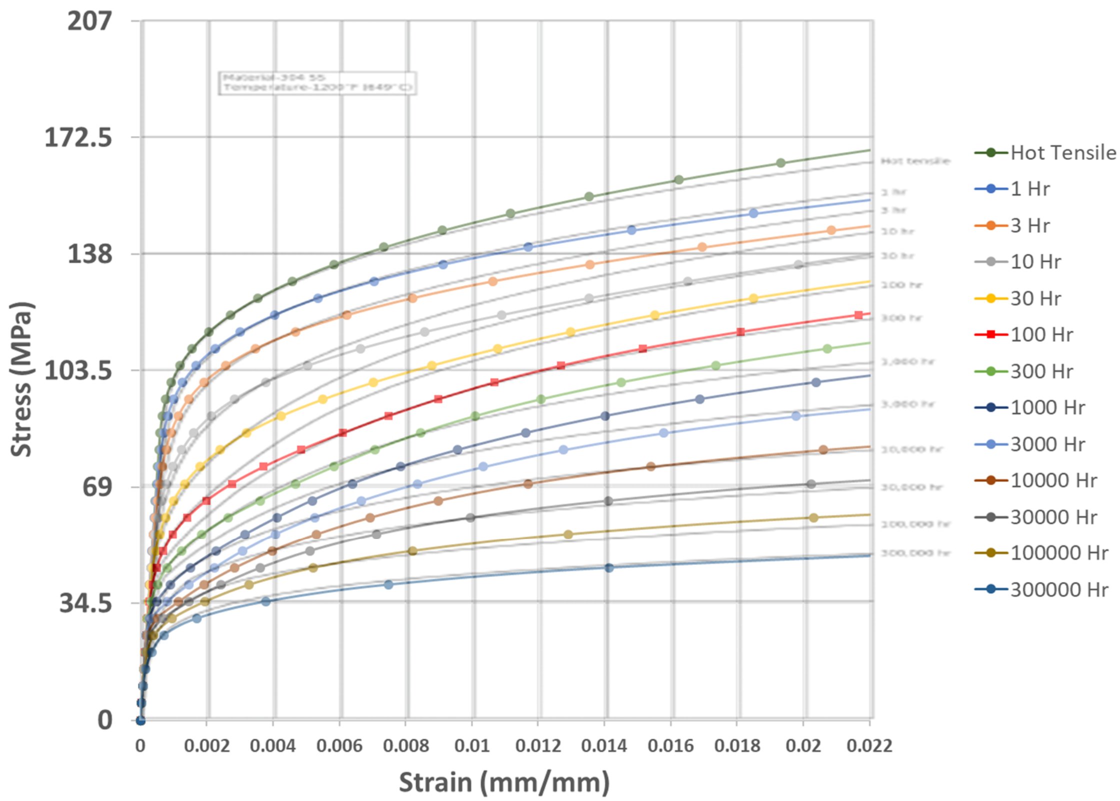

Figure A-2 Calculated isochronous stress-strain curves for 304 SS at 649 degrees C (1200 degrees F). The calculated isochronous stress-strain curve is nearly identical to Figure HBB-T-1800-A-9 from BPVC-III-5.

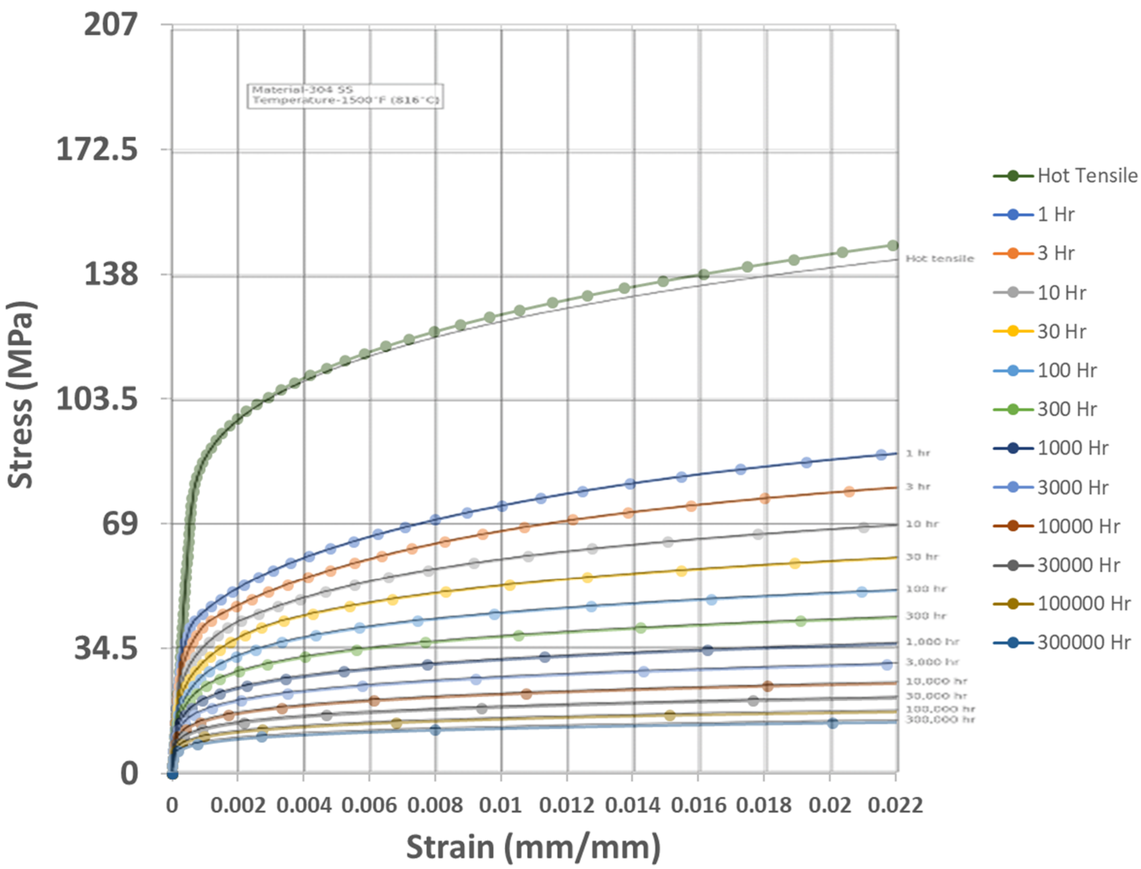

Figure A-3 Calculated isochronous stress-strain curves for 304 SS at 816 degrees C (1500 degrees F). The calculated isochronous stress-strain curve is nearly identical to Figure HBB-T-1800-A-15 from BPVC-III-5.

With the isochronous calculation and plotting routine verified, the next step is to compare these curves to other data in the literature to determine if the code curves are conservative for 304 SS. It is not possible to compare the curves to all data that might possibly exist in the literature, therefore “spot checks” of these curves with other data were made to verify the accuracy of the curves to the extent possible. The spot checks provided here are considered adequate for endorsement purposes. First, Figure A-4 compares the code’s isochronous stress-strain curves with data produced by Braun (1970) at 593 degrees C (1100 degrees F). In Figure A-4, the solid squares with the dashed red lines represent data from Braun, which result from a different data set than used in Blackburn (1972). The comparisons are good for times of 1,000 and 10,000 hours. However, at the longer times of 100,000 and 500,000 hours, the code curves are a little nonconservative (i.e., the Braun curves are lower than the code curves). For example, the BPVC-predicted total strain at 100,000 hours for a stress of 82.5 MPa is 0.013, while the curves of Braun suggest a total strain of 0.018.

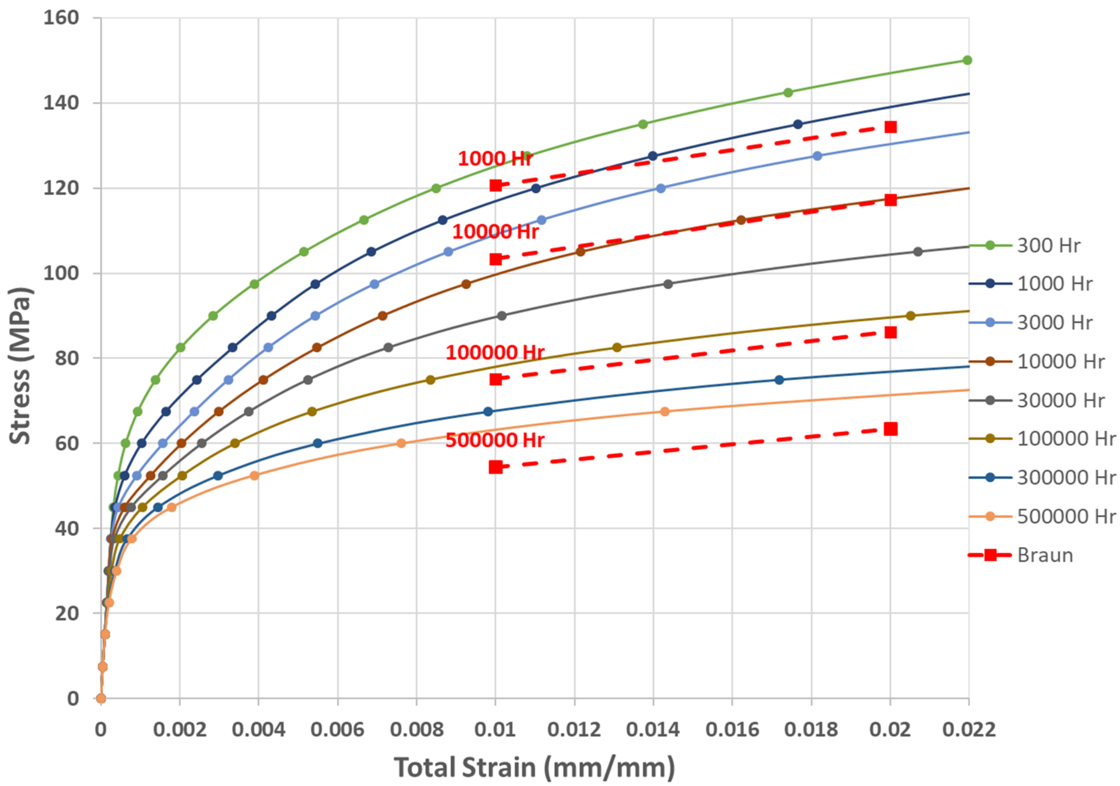

Figure A-4 Comparison of calculated BPVC-III-5 isochronous curves for 304 SS to curves of Braun for 304 SS at 593 degrees C (1100 degrees F).

In Figure A-5 the Braun data points, plotted against the code's isochronous stress-strain curves, which compare reasonably well with the curves at higher times. At 1,000 and 10,000 hours the Braun data is a little higher and is thus conservative, while the data at 100,000 hours is less conservative. The 500,000-hour data of Braun compares well to the 300,000-hour data in the code, which means the code data is less conservative. However, considering the large uncertainty in creep data, this difference is not considered to be an issue.

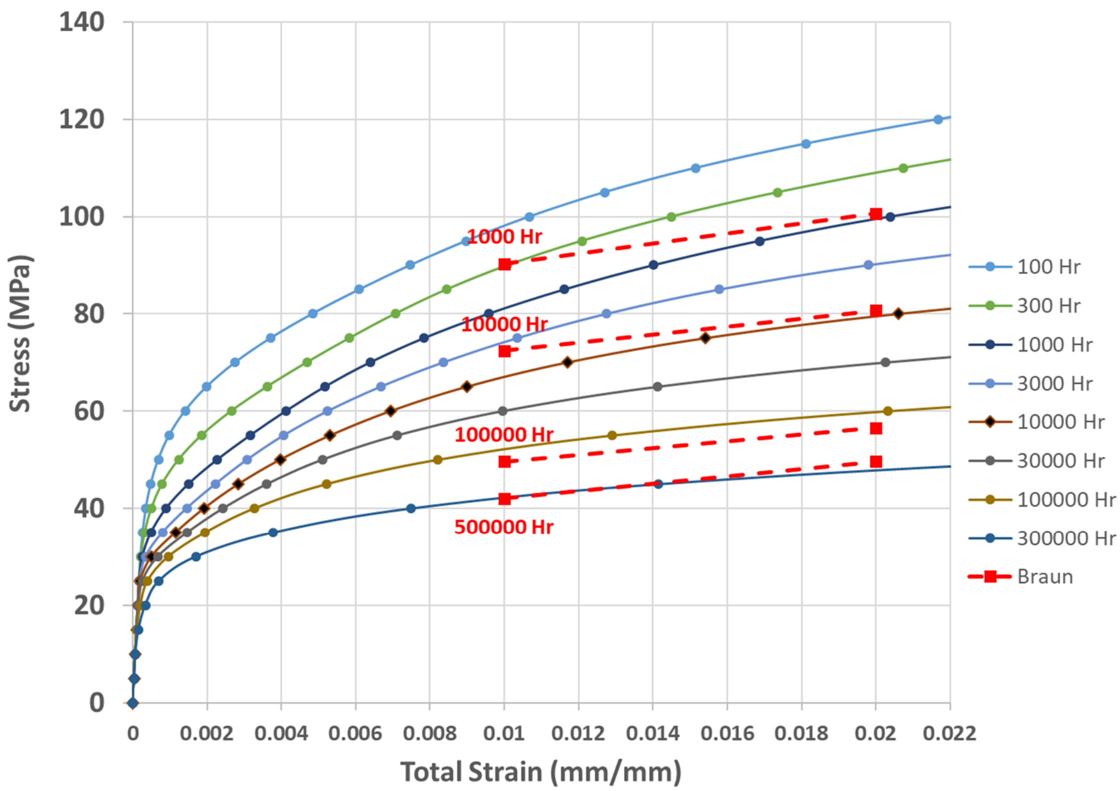

Figure A-5 Comparison of calculated BPVC-III-5 isochronous curves for 304 SS to curves of Braun for 304 SS at 649 degrees C (1200 degrees F).

Additional creep material data are compared to the BPVC-III-5 isochronous stress-strain curves that were obtained from the National Institute of Materials Science (NIMS) creep database (MatNavi, 2020), which is managed by a Japanese consortium. The creep data in this material database are based on test data more modern than the data that produced the BPVC-III-5 isochronous stress-strain curves for 304 SS. The NIMS data sheets also provide total strains.

To further validate the code's isochronous stress-strain curves, they are compared to 304 SS data from NIMS. Figures A-6 and A-7 plot the isochronous stress-strain curves for 304 SS at 649 degrees C (1200 degrees F) and 700 degrees C (1292 degrees F), respectively. The plots of the code curves were made using the spreadsheet discussed above, which included the elastic and plastic strains so that direct comparison to total strain data from the NIMS data sheets could be made.

As seen in Figure A-6 for 304 SS at 649 degrees C (1200 degrees F), the NIMS data are plotted as points with the time to reach the various strain levels listed (e.g., the 645-hour NIMS data point at a stress of 98 MPa and a creep strain of 0.005 millimeter (mm)/mm). This point falls close to the isochronous data curve for 10 hours from BPVC-III-5. Since the 100-hour curve is below this point, this means that the code creep values are conservative.

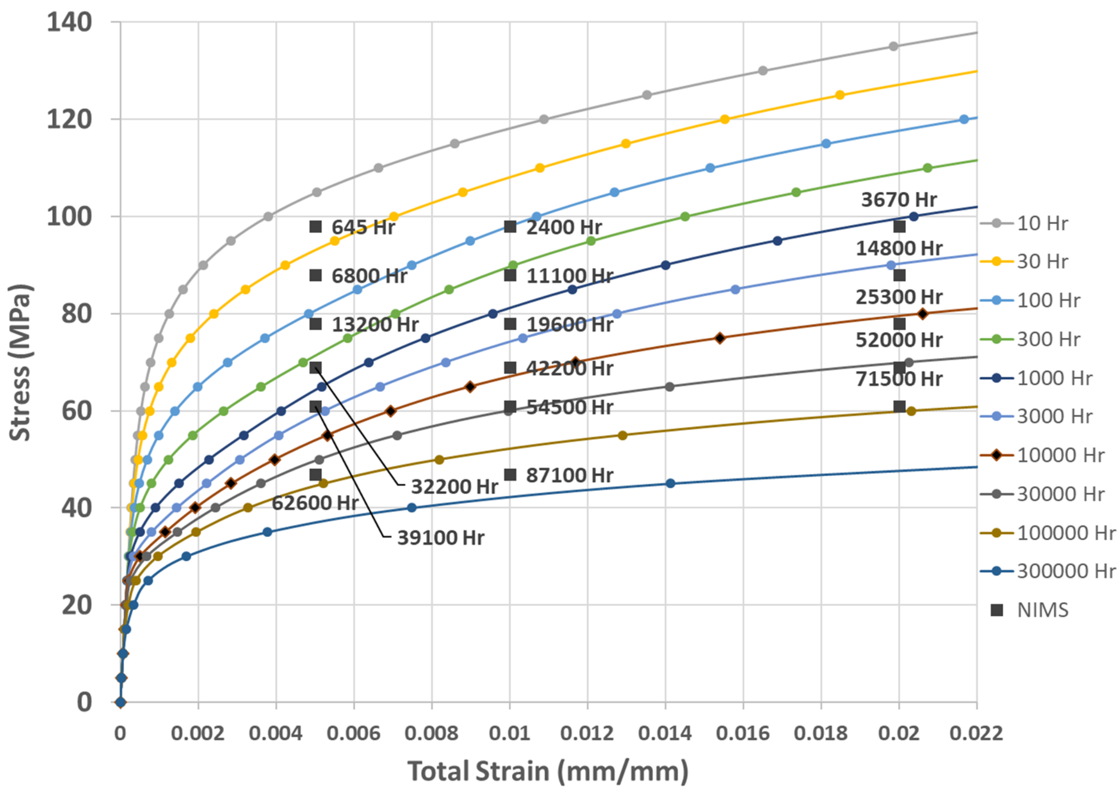

Figure A-6 Comparison of calculated BPVC-III-5 isochronous curves for 304 SS at 649 degrees C (1200 degrees F) to data points from the NIMS database.

Many other points are directly compared to the code curves on this plot for 649 degrees C (1200 degrees F). At this temperature, of all the NIMS data points fall above the corresponding isochronous curves of the code except for several data points at long times. Note that the NIMS data are available for tests performed for long periods of time. The curves in BPVC-III-5 were extrapolated to obtain the curves for long times (for example, 100,000 or 300,000 hours) since data did not exist. The NIMS data point at 47 MPa with creep strain of 0.01 falls slightly below the 100,000-hour code-based curve as seen in Figure A-6. The code curves are conservative except for this one data point, which is considered within the uncertainty band of creep data.

Likewise, Figure A-7 compares the isochronous stress-strain curves of BPVC-III-5 to NIMS data at 700 degrees C (1292 degrees F). Again, the code curves are conservative compared to the new data for all times except when longer times are considered. For example, a NIMS data point at 29 MPa with creep strain of 0.02 mm/mm (76,200 hours) falls on the isochronous creep curve of the code for the time of 500,000 hours. Similar NIMS data points also fall below curves at longer times.

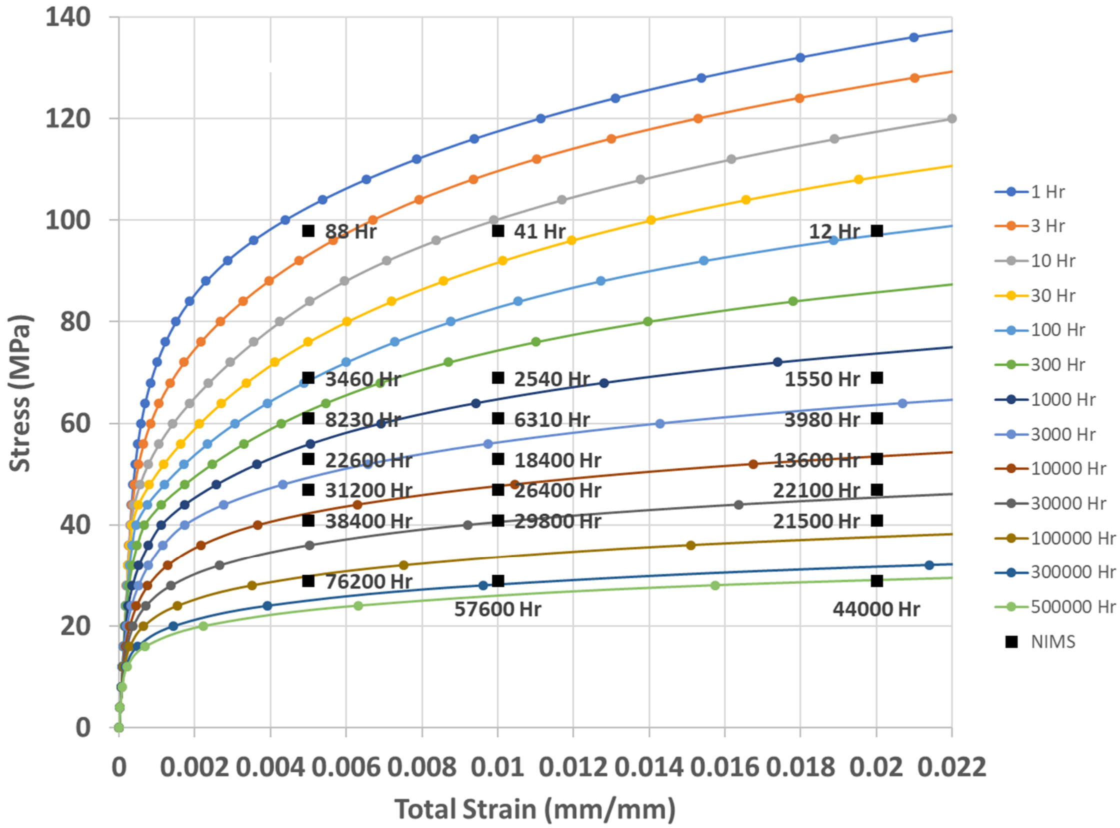

Figure A-7 Comparison of calculated BPVC-III-5 isochronous for 304 SS curves at 700 degrees C (1292 degrees F) to data points from the NIMS database.

Therefore, in general, the code's isochronous curves are considered conservative for almost all cases. There may be a need to reconsider the BPVC-III-5 isochronous stress-strain curves for higher temperatures (perhaps above 700 degrees C ((1292 degrees F)) for long times, since the extrapolation used to produce the code curves may need improvement.

316 Stainless Steel

Figures HBB-T-1800-B-1 through HBB-T-1800-B-15 in BPVC-III-5 provide the isochronous stress-strain curves for 316 SS up to 816 degrees C (1500 degrees F). The original technical basis for the curves for 316 SS also came from the work of Blackburn (1972). The isochronous stress-strain curves were computed from a complex and extensive set of analytical equations based on a modification of the Garofalo creep equation form (multiple exponential form) that completely characterizes the strain response as it depends on stress, temperature, and time. The form of the equation and the numerous temperature-dependent material constants are complex and are not reproduced here. The equations used here apply the true plastic strain as will be used in the 2021 BPVC. Given the uncertainty in creep strains at high temperature, this small difference is not considered important. The analytical equations represent the magnitude of time-independent elastic and plastic strain and the magnitude and time dependence of the transient creep strain. For the present report, a spreadsheet was developed, based on the

Blackburn equations, to validate the conservative nature of the code's isochronous curves. This spreadsheet will be provided to the NRC staff for future licensing needs.

Figures A-8 and A-9 shows the spreadsheet-developed curves for 316 SS at 649 degrees C (1200 degrees F) and 816 degrees C (1500 degrees F), respectively. Comparing these curves with Figures HBB-T-1800-B-9 and HBB-T-1800-B-15 from BPVC-III-5 shows very little difference. The checks were also made by pasting the curves from BPV-III-5 on the spreadsheet calculated curves, and then making the code figure partially transparent. This validates the programming of the BPVC-III-5 curves so that validation comparisons in the subsequent plots can be made properly. These curves, or modifications of these curves where the time-independent strains were removed, are applied to validate the data used to develop the code curves in the later figures in this appendix.

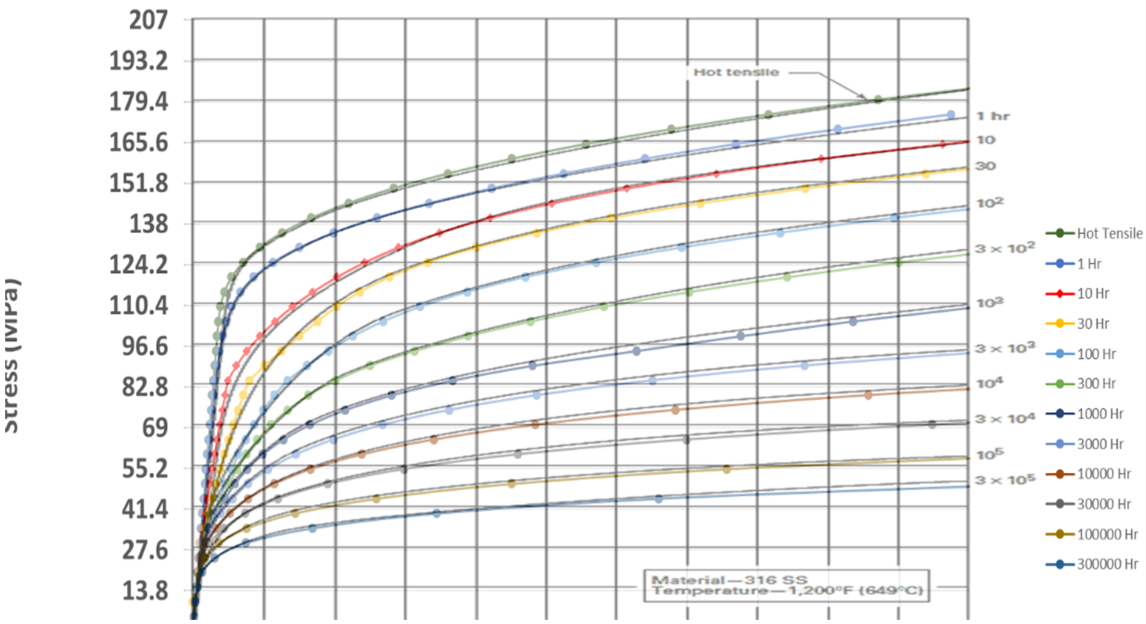

Figure A-8 Calculated isochronous stress-strain curves for 316 SS at 649 degrees C (1200 degrees F). The calculated isochronous stress-strain curve is nearly identical to Figure HBB-T-1800-B-9 from BPVC-III-5.

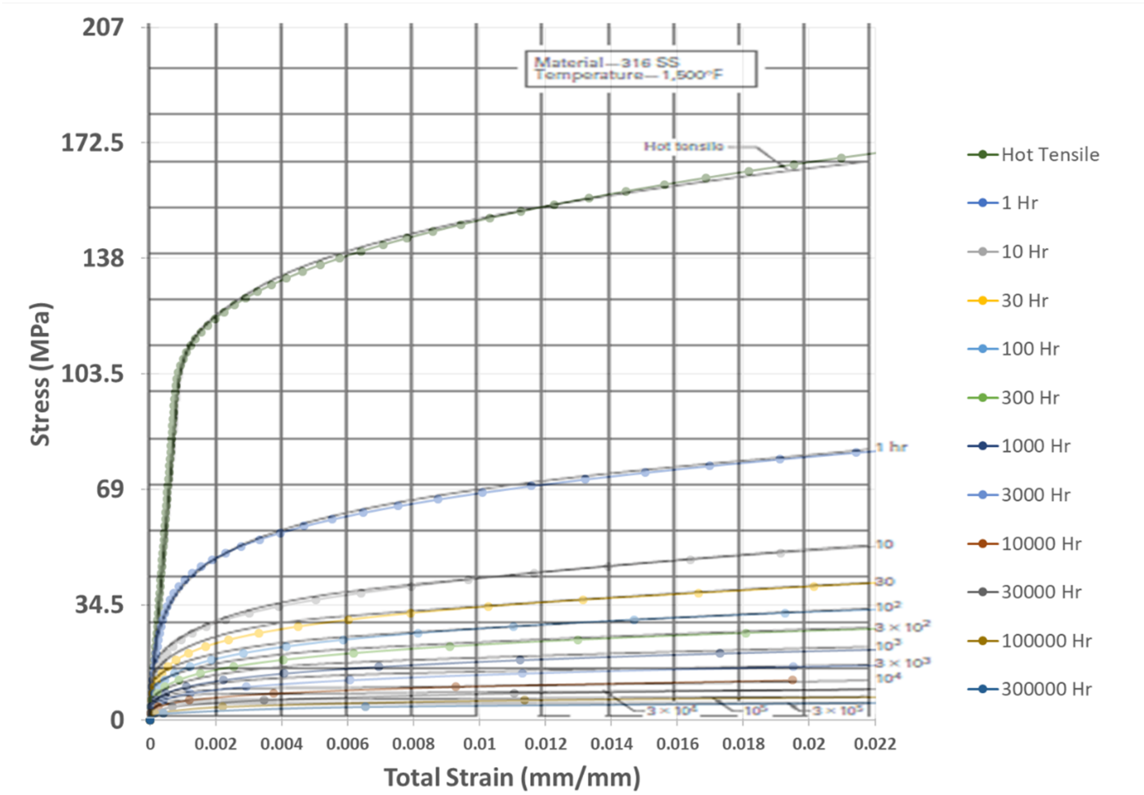

Figure A-9 Calculated isochronous stress-strain curves for 316 SS at 816 degrees C (1500 degrees F). The calculated isochronous stress-strain curve is nearly identical to Figure HBB-T-1800-B-15 from BPVC-III-5.

Extensive other data, both published and unpublished, were also used to verify the specific features of the analysis for 316 SS. Therefore, these new data are considered representative of 316 SS over the temperature range of interest. Comparison to other data follows to verify the adequacy of the code-based isochronous curves for 316 SS. The solid red squares and dashed lines in Figure A-10 represent isochronous data from Braun (1970), which reflect the results from a data set different than the Blackburn (1972) data for 316 SS. The Braun data points, plotted with the BPVC-III-5 curves of Figure HBB-T-1800-B-9, compare reasonably well with the current BPVC-III data curves. At 1,000 and 100,000 hours, the Braun data are somewhat higher, which means the code data are a little more conservative, but still considered reasonable in view of the uncertainty in creep data. At 10,000 hours the Braun data is reasonably close to the code data. The Braun data at 500,000 hours lies on the code data for 300,000 hours. This suggests that the code data, when extrapolated to long times from short time data, may be a little nonconservative—at least compared to the Braun data. The following figures show other comparisons.

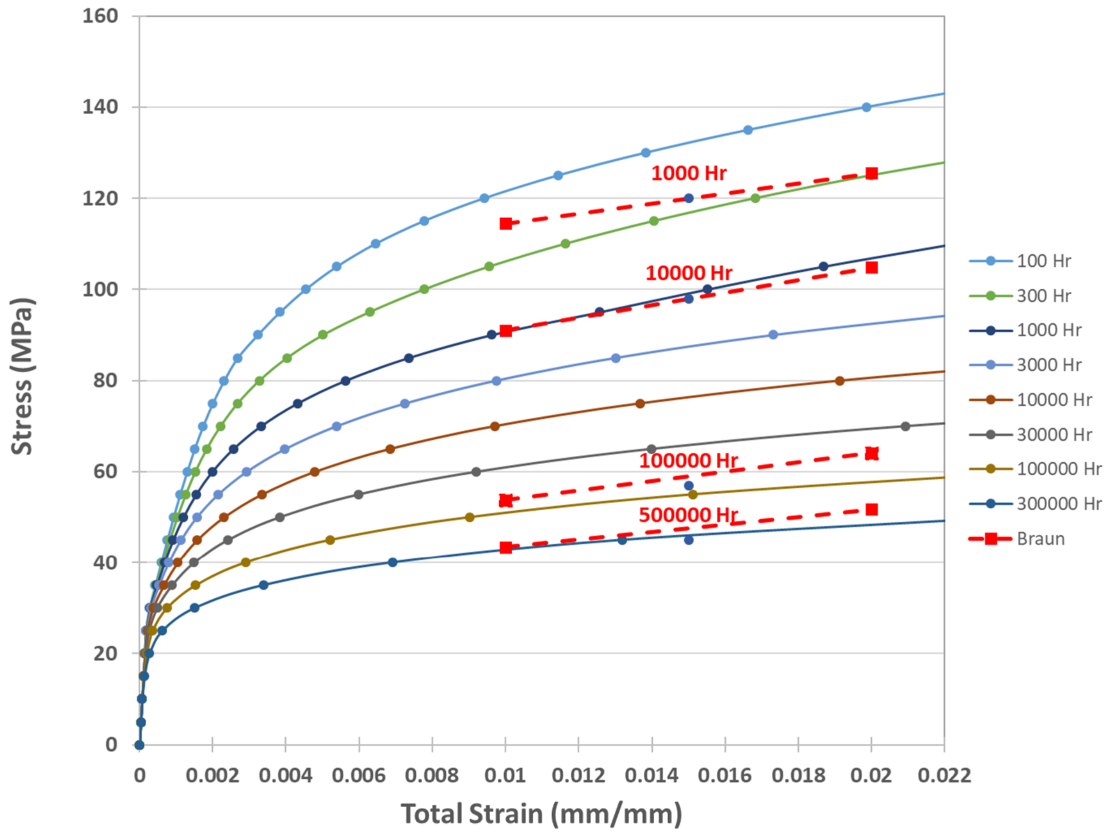

Figure A-10 Calculated isochronous stress-strain curves for 316 SS at 649 degrees C (1200 degrees F) (Figure HBB-T-1800-B-9) compared to data from Braun.

Additional creep material data are compared to the BPVC-III-5 isochronous stress-strain curves for 316 SS that were obtained from the NIMS creep database (MatNavi, 2020). The creep data in this material database are based on test data more modern than the data that produced the BPVC-III-5 isochronous stress-strain curves for 304 SS, and some of the new data have been accumulated for long times. The NIMS data sheets provide total strain data, while the classical isochronous stress-strain curves plot total strain versus time.

It is not possible to compare the code isochronous curves with data for every temperature of interest. However, several other checks of 316 SS curves compared with other data are presented next. Figure A-11 compares the code isochronous curves to NIMS data at 600 degrees C (1112 degrees F). All of the code curves are conservative except for one NIMS data point at a stress of 108 MPa at creep strain 0.02 (52,500 hours). This is considered conservative given creep data variability.

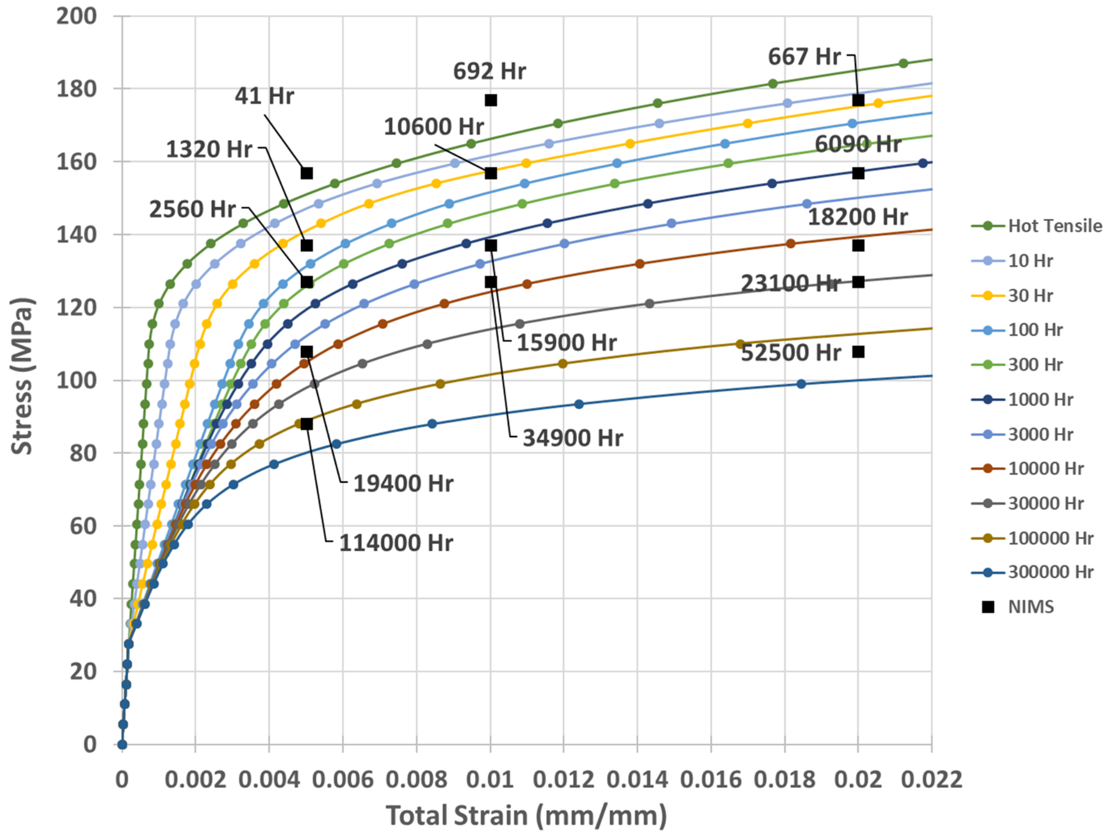

Figure A-11 Calculated isochronous creep stress-strain curves for 316 SS at 600 degrees C (1112 degrees F) compared to data from the NIMS database.

Figure A-12 compares the code isochronous curves with NIMS data and that from Sikka et al. (1980) at 649 degrees C (1200 degrees F) from 13 heats of material. All of the NIMS data are above the code-based curves for all times, indicating that the code curves are conservative at this temperature. Note that there is a datum point from the NIMS data for a time of 225,000 hours (61 MPa) that lies just above the 100,000-hour code curve. This indicates that the extrapolation in the code of the creep isochronous curves to long times is quite conservative at this temperature. Comparisons of the curves to the Sikka et al. data are a little non-conservative at longer times. For example, the Sikka et al. datum point of 0.02 strain at a stress of 69 MPa for 10,000 hours is approximately what the code would predict at 30,000 hours. The Sikka et al. data were extracted from hand plots of creep strain accumulation versus time, and there may be some error in this interpretation.

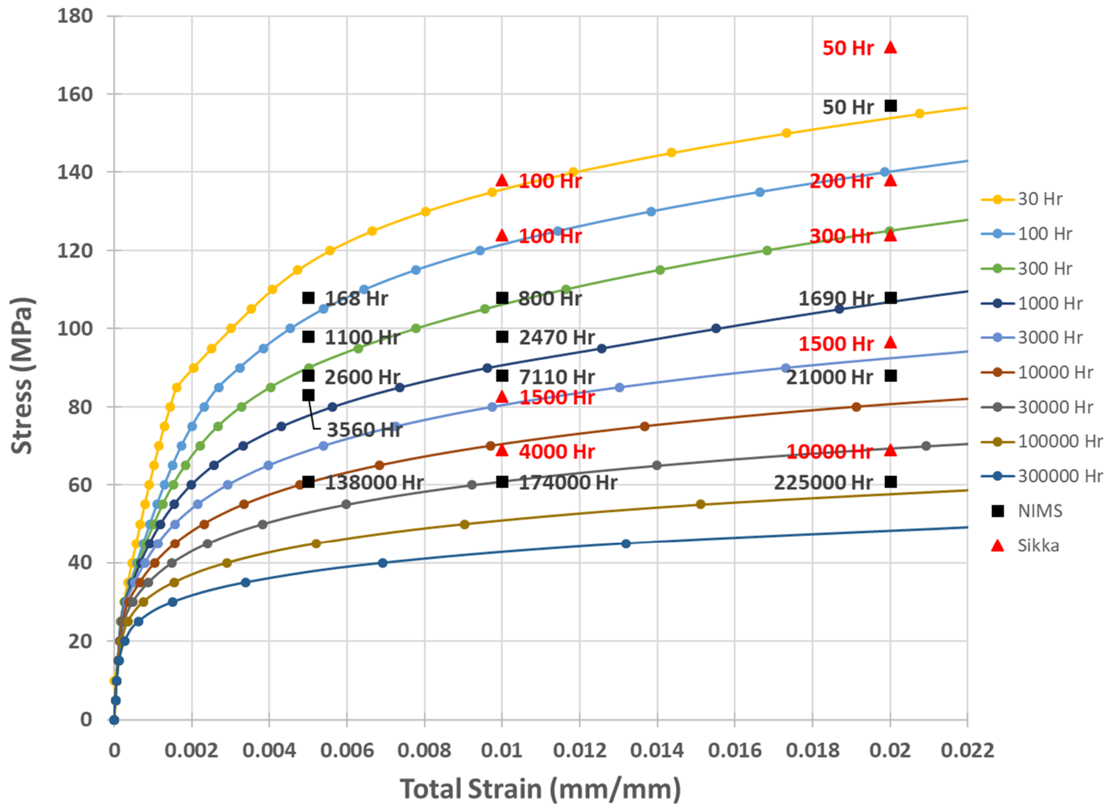

Figure A-12 Calculated isochronous stress-strain curves for 316 SS at 649 degrees C (1200 degrees F) (Figure HBB-T-1800-B-9) compared to data from the NIMS database and Sikka et al. (1980).

Figure A-13 compares the creep strains obtained from the NIMS database and one point from Sikka et al. to the code-based isochronous curves at 750 degrees C (1382 degrees F).[2] The code curves are conservative for all times less than about 1,000 hours. Several NIMS data points are nonconservative for times greater than 3,000 hours.

[2] Note that BPVC-III-5 does not explicitly provide curves for 750 degrees C (1382 degrees F), but since the curves were programmed into a spreadsheet, the curves can be developed for any temperature of interest.

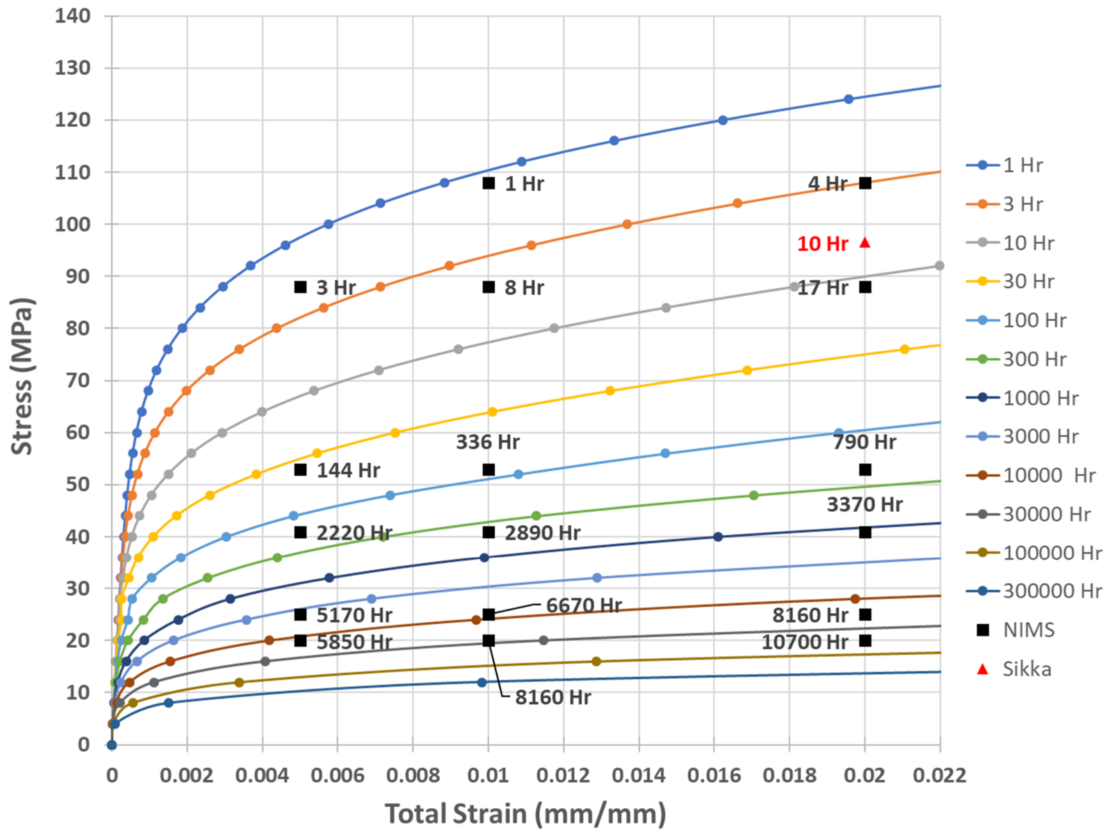

Figure A-13 Calculated isochronous creep stress-strain curves for 316 SS at 750 degrees C (1382 degrees F) compared to data from the NIMS database and Sikka et al. (1980).

In summary, it appears that the BPVC-III-5 isochronous stress-strain curves for 316 SS are conservative for most temperatures and times. For higher temperatures (greater than about 700 degrees C (1292 degrees F) and times of 100,000 hours) some of the curves may be nonconservative. This was probably due to the need to extrapolate the data to produce the code isochronous curves.

2.25Cr-1Mo Material

The isochronous stress-strain curves for 2.25Cr-1Mo steel, originally developed by Klueh and Hebble (1976) and Booker (1977), are provided in Figure HBB-T-1800-D in BPVC-III-5 up to 649 degrees C (1200 degrees F). These equations were entered in a spreadsheet, so that data for any time and temperature can be easily obtained. Figure A-14 shows an example of curves produced from the spreadsheet for this steel at 538 degrees C (1000 degrees F) for many times and for all code temperatures. The comparison of curves from the spreadsheet and Figure HBB-T-1800-D-7 are identical.

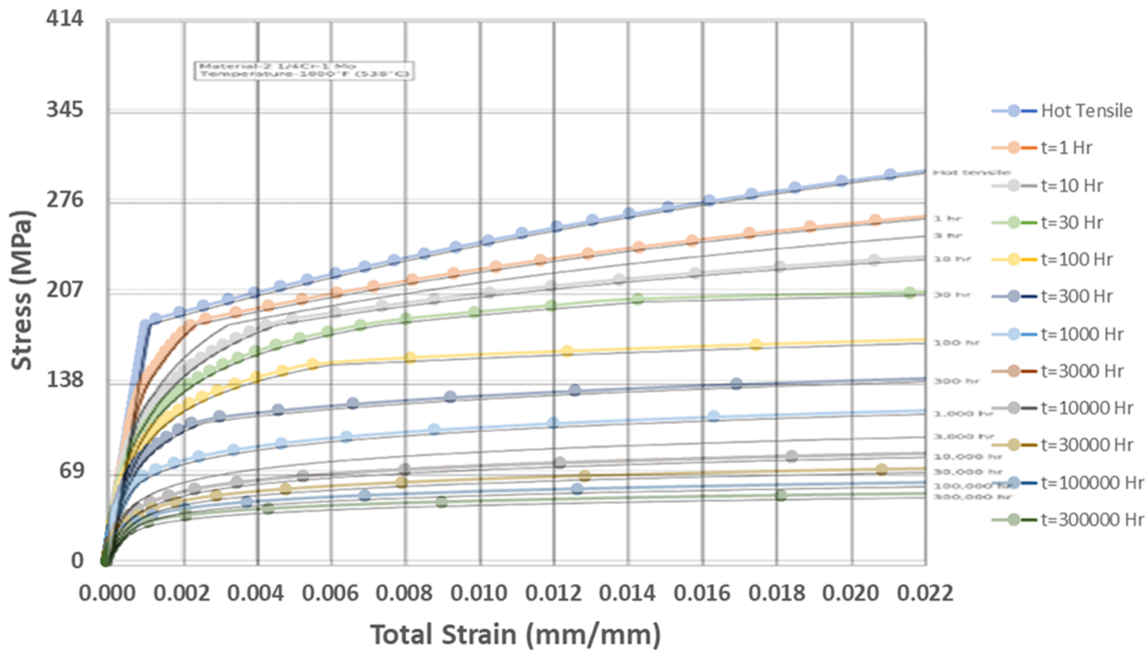

Figure A-14 Calculated isochronous stress-strain curves for 2.25Cr-1Mo at 538 degrees C (1000 degrees F). The calculated isochronous stress-strain curve is nearly identical to Figure HBB-T-1800-D-7 from BPVC-III-5.

Figures A-15 and A-16 compare the isochronous stress-strain curves developed independently by Braun (1970) with the BPVC-III-5 isochronous curves for 2.25Cr-1Mo at 538 degrees C (1000 degrees F) and 593 degrees C (1100 degrees F), respectively. The BPVC-III-5 curves are generally very close to Braun's data, indicating that they are conservative.

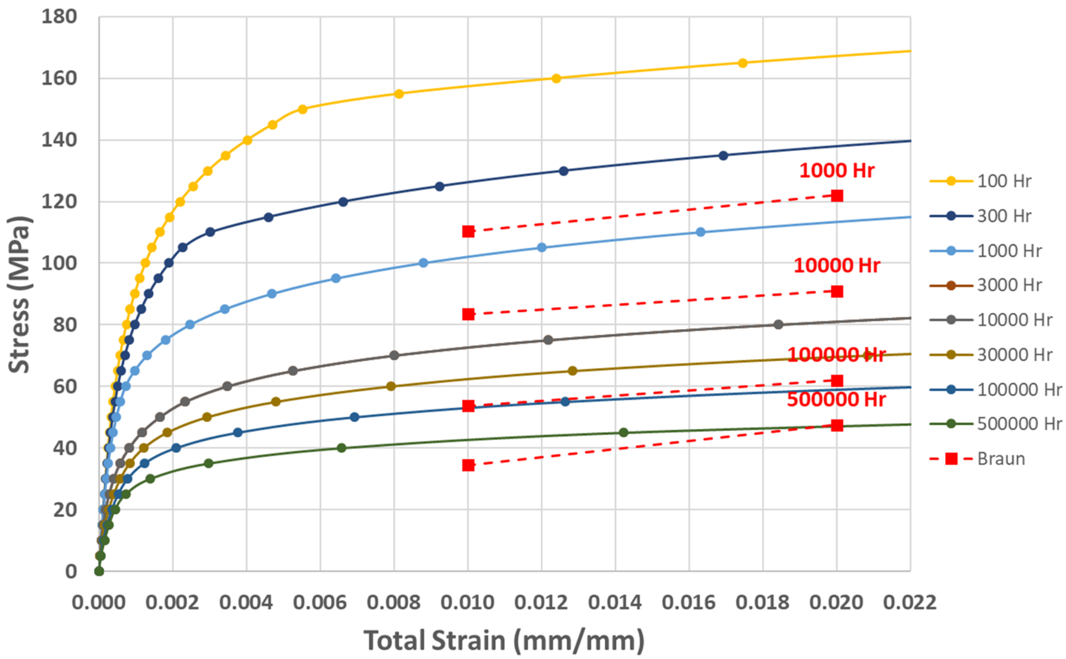

Figure A-15 Comparison of calculated code isochronous curves for 2.25Cr-1Mo at 538 degrees C (1000 degrees F) with data from Braun (1970).

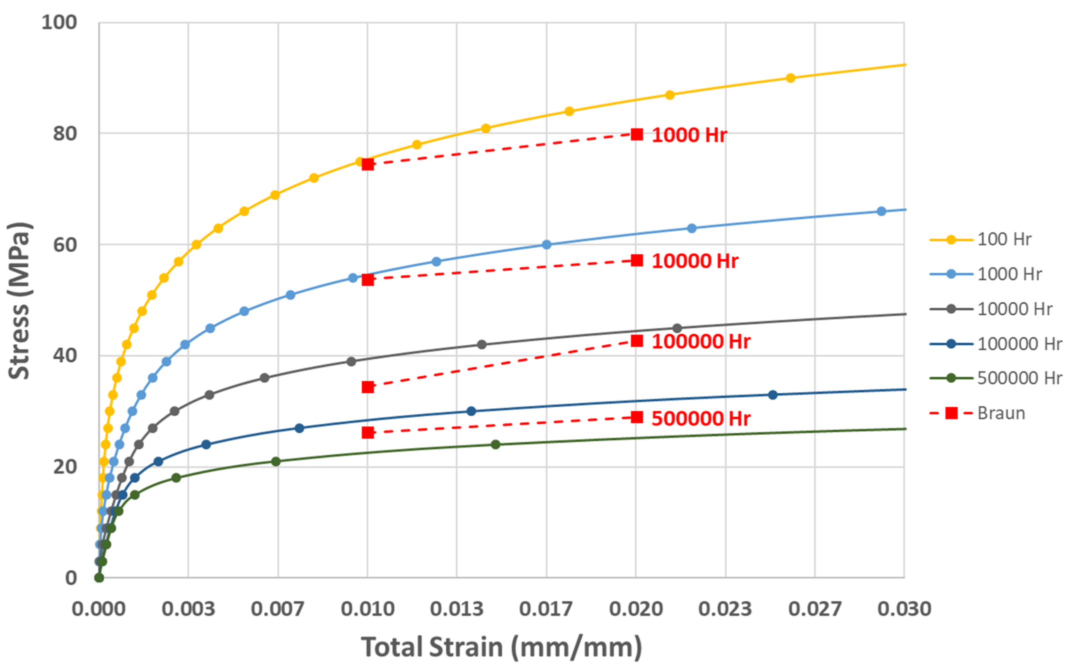

Figure A-16 Comparison of calculated code isochronous curves at 593 degrees C (1100 degrees F) with data from Braun (1970).

Additional creep material data obtained from the NIMS creep database (MatNavi, 2020) are compared to the BPVC-III-5 isochronous stress-strain curves. Figures A-17 and A-18 compare NIMS data points with the BPVC-III-5 creep isochronous curves at 500 degrees C (932 degrees F). Some of the NIMS data in Figure A-17 are a little lower than the code curves. For example, the NIMS data point at 4,500 hours lies on the 10,000-hour code isochronous curve. However, most of the long-time NIMS data in Figure A-18 are seen to be conservative or about the same as the code curves. NIMS data are considered to lie within the uncertainty band of typical creep data, and the code curves are considered similar, but perhaps slightly nonconservative, at 500 degrees C (932 degrees F) compared to the NIMS data here.

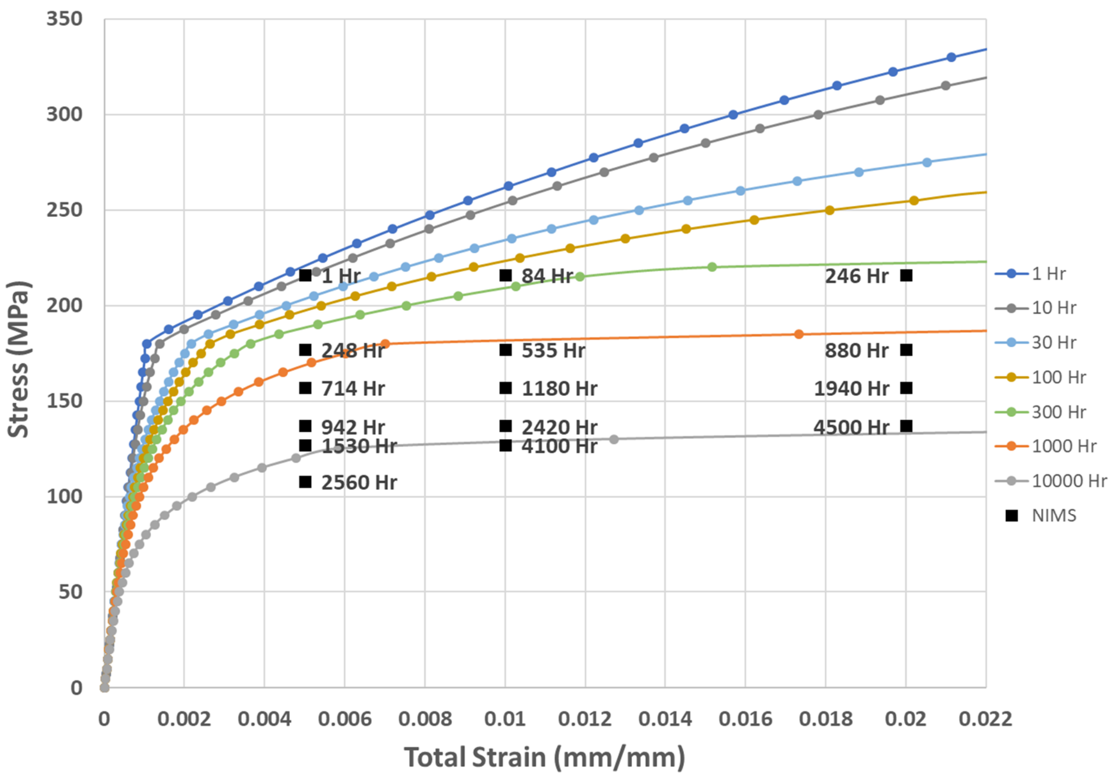

Figure A-17 Comparison of calculated code isochronous curves for 2.25Cr-1Mo at 500 degrees C (932 degrees F) with data from NIMS database for less than 5000 hours.

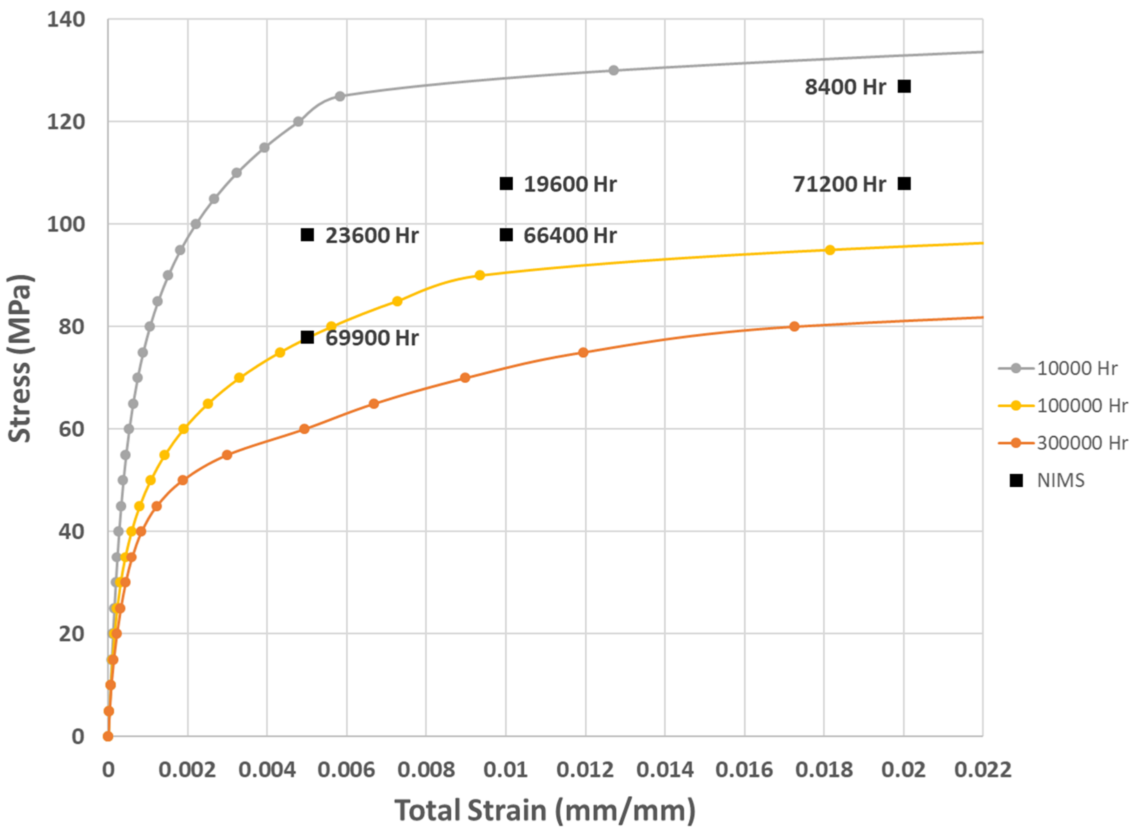

Figure A-18 Comparison of calculated code isochronous curves for 2.25Cr-1Mo at 500 degrees C (932 degrees F) with data from NIMS database for greater than 5000 hours.

Figures A-19 and A-20 compare NIMS data points with the BPVC-III-5 creep isochronous curves at 550 degrees C (1022 degrees F). All NIMS data are higher than the corresponding code curves, and therefore, the code curves are conservative for design purposes at this temperature.

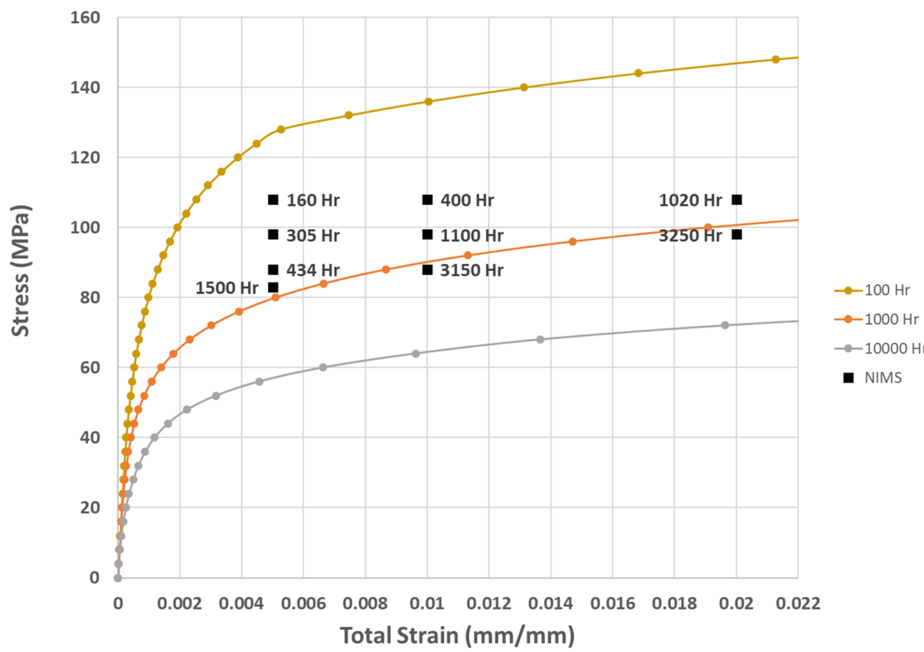

Figure A-19 Comparison of calculated code isochronous curves for 2.25Cr-1Mo at 550 degrees C (1022 degrees F) with data from NIMS database for less than 5000 hours.

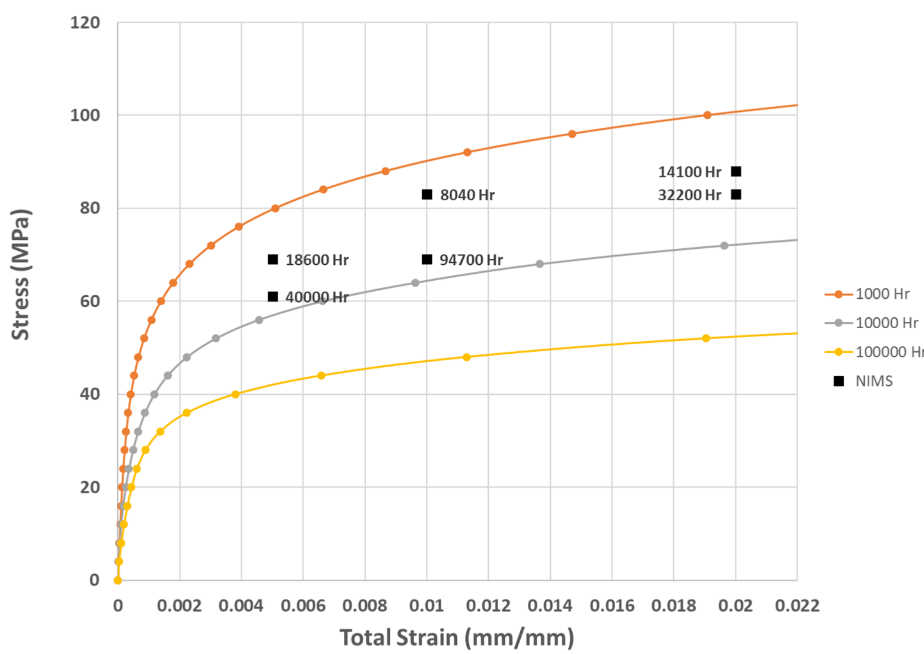

Figure A-20 Comparison of calculated code isochronous curves for 2.25Cr-1Mo at 550 degrees C (1022 degrees F) with data from NIMS database for greater than 5000 hours.

Finally, Figure A-21 compares NIMS data points with the BPVC-III-5 creep isochronous curves at 600 degrees C (1112 degrees F). The code curves go up to a maximum temperature of

649 degrees C (1200 degrees F) for this material, and this is the highest temperature for which data were found. The BPVC-III-5 isochronous creep at this high temperature is still conservative for most times. However, the NIMS data points, some of which came from creep tests carried out for long times, are lower than the code curves for long time periods. For example, the NIMS data point at 104,000 hours lies on the 300,000-hour isochronous curves. This suggests that the code curves are not conservative for long time periods and high temperatures.

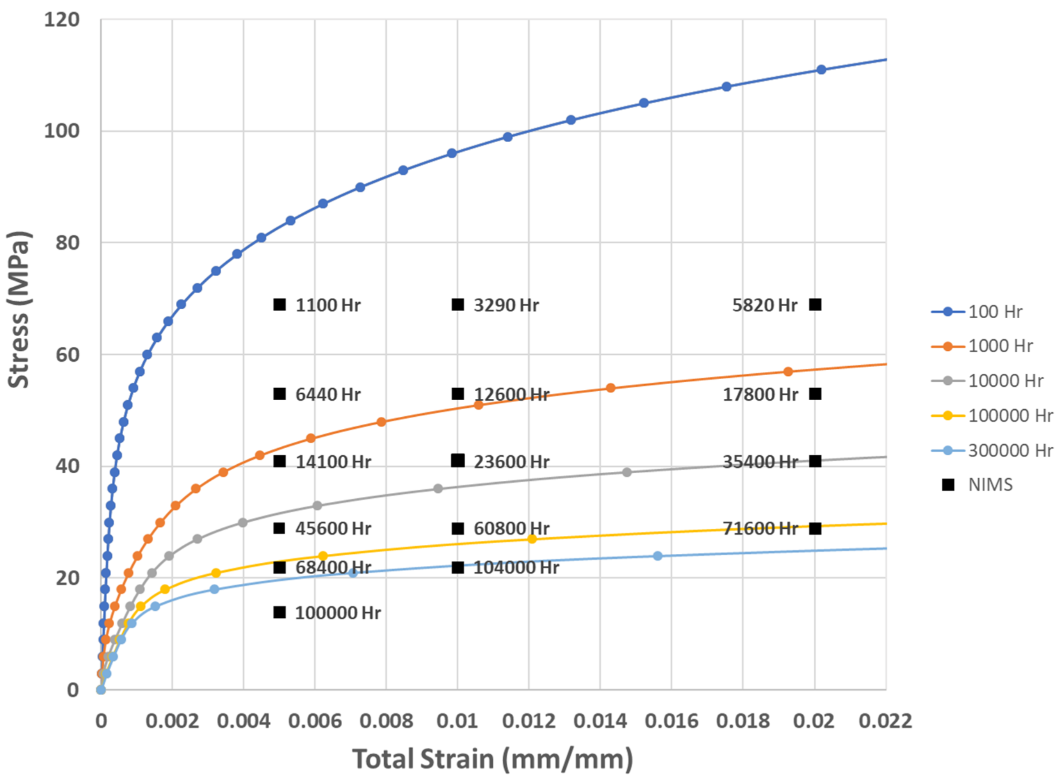

Figure A-21 Comparison of calculated code isochronous curves for 2.25Cr-1Mo at 600 degrees C (1112 degrees F) with data from NIMS database.

In summary, as has been seen with the materials discussed thus far, the code curves are quite conservative for most times and temperatures. However, for 600 degrees C (1112 degrees F) and higher, the extrapolation procedure used to obtain the code curves may need to be modified. Additional data should be checked as well. In addition, the curves at 500 degrees C (932 degrees F) may be a little high compared to these data, but this is not considered outside the uncertainty band of creep data.

Alloy 800H

The BPVC-III-5 isochronous curves in the 2017 version of the ASME BPVC-III-5 go up to a temperature of 760 degrees C (1400 degrees F) for Alloy 800H. In BPVC-III-5, Figures HBB-T-1800C-1 through HBB-T-1800C-12 provide the isochronous stress-strain curves for Alloy 800H up to 760 degrees C (1400 degrees F). The code-based curves were developed from work by Smith (1976). The equations were programmed into a spreadsheet so that additional comparisons to other data can be made. Figure A-22 shows an example of isochronous stress-strain curves at 649 degrees C (1200 degrees F), which compare exactly with Figure HBB-T-1800-C-8 in ASME BPVC-III-5 and demonstrates perfect correspondence. Comparisons were also made at other temperatures by overlaying the BPV-III-5 curves for Alloy 800H with the spreadsheet calculation curves.

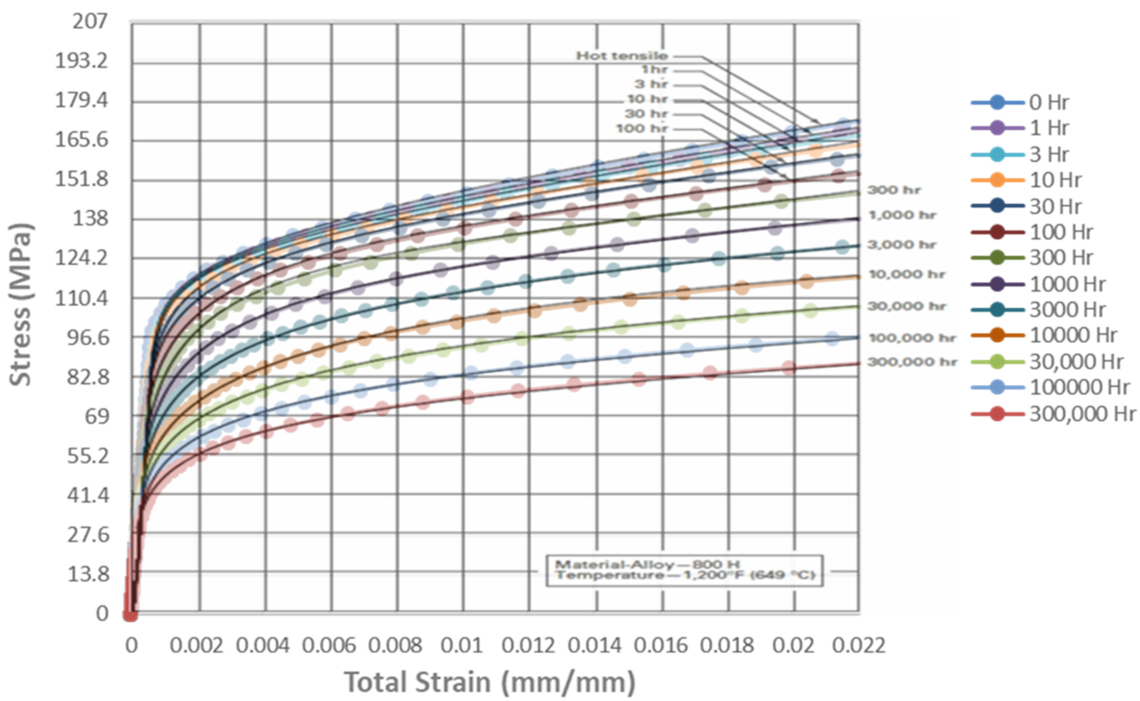

Figure A-22 Comparison of calculated code isochronous curves for Alloy 800H at 649 degrees C (1200 degrees F). The calculated isochronous stress-strain curve is nearly identical to Figure HBB-T-1800-C-8 from BPV-III-5.

Comparison to some other data sets is shown. Figure A-23 compares the NIMS database (MatNavi, 2020) to the code isochronous curves at 649 degrees C (1200 degrees F). The isochronous curves are conservative up to about 10,000 hours. However, some data points are not conservative at longer times (for example, the set of points at 86 MPa at 29,600 and 42,900 hours). However, these latter two data points are not representative, as shown below.

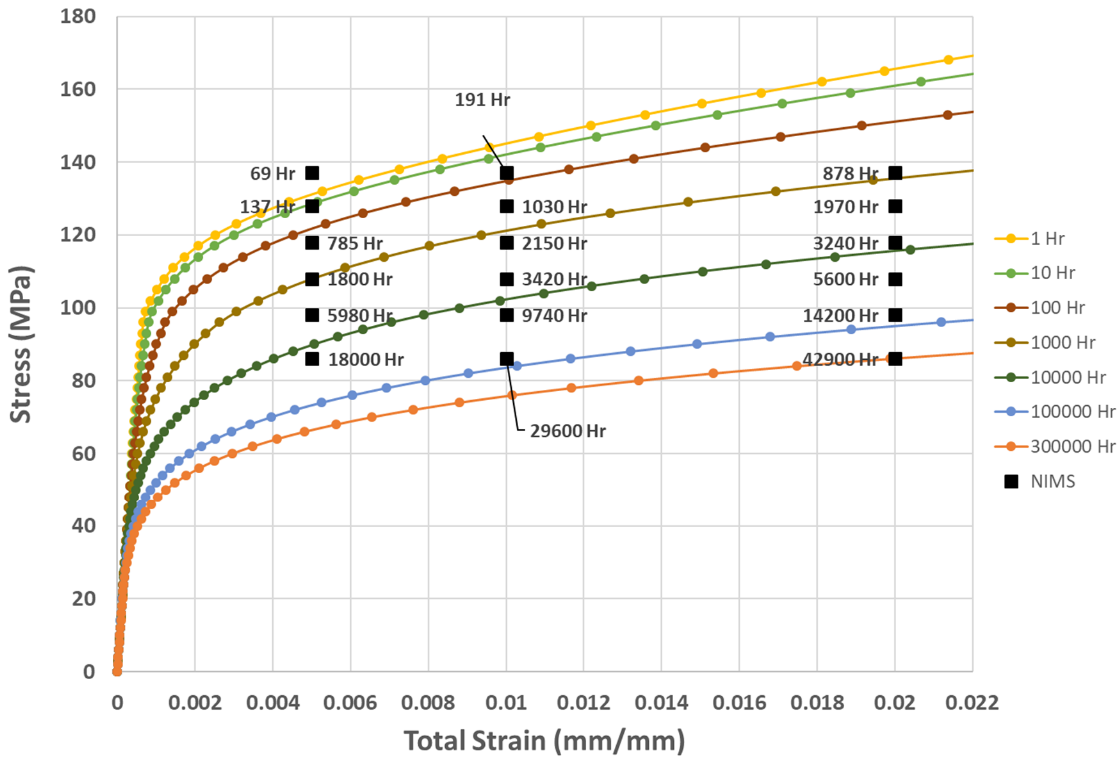

Figure A-23 Comparison of calculated code isochronous curves for Alloy 800H at 649 degrees C (1200 degrees F) to data from the NIMS database. The data points identify the time to reach the strain at 649 degrees C (1200 degrees F).

Figure A-24 compares some NIMS data with BPVC-III-5 curves at 700 degrees C (1292 degrees F). For the NIMS data, tests were performed at the same stress, with the time to the given strain given as a range. For example, at 98 MPa at 0.01 strain, the time range was 903 to 1,650 hours. At 61 MPa at 0.02 strain, the time range is 14,000 to 97,100 hours. This illustrates the large scatter in creep data that results in the isochronous curves. This latter data point is near the isochronous curve of 100,000 hours, and some of the data may be nonconservative. The NIMS data used in Figure A-24 is also provided in Table A-1 shows the variability in creep data.

Table as A-1 NIMS data for Alloy 800H at 700 degrees C (1292 degrees F).

Stress (MPa)	Strain	Hours to Failure	Strain	Hours to Failure	Strain	Hours to Failure
137	0.005	5	0.01	25	0.02	98
118	0.005	17.8	0.01	74.8	0.02	221
98	0.005	770	0.01	1650	0.02	2760
98	0.005	487	0.01	903	0.02	1240
88	0.005	581	0.01	726	0.02	898
79	0.005	10000	0.01	15200	0.02	20500
61	0.005	6790	0.01	10000	0.02	14000
61	0.005	13800	0.01	19300	0.02	22900
61	0.005	5780	0.01	9790	0.02	16200
61	0.005	28500	0.01	50400	0.02	97100

Based on Figure A-24 and Table A-1, the isochronous curves for Alloy 800H material at 700 degrees C (1292 degrees F), may be nonconservative at times of 100,000 hours and above.

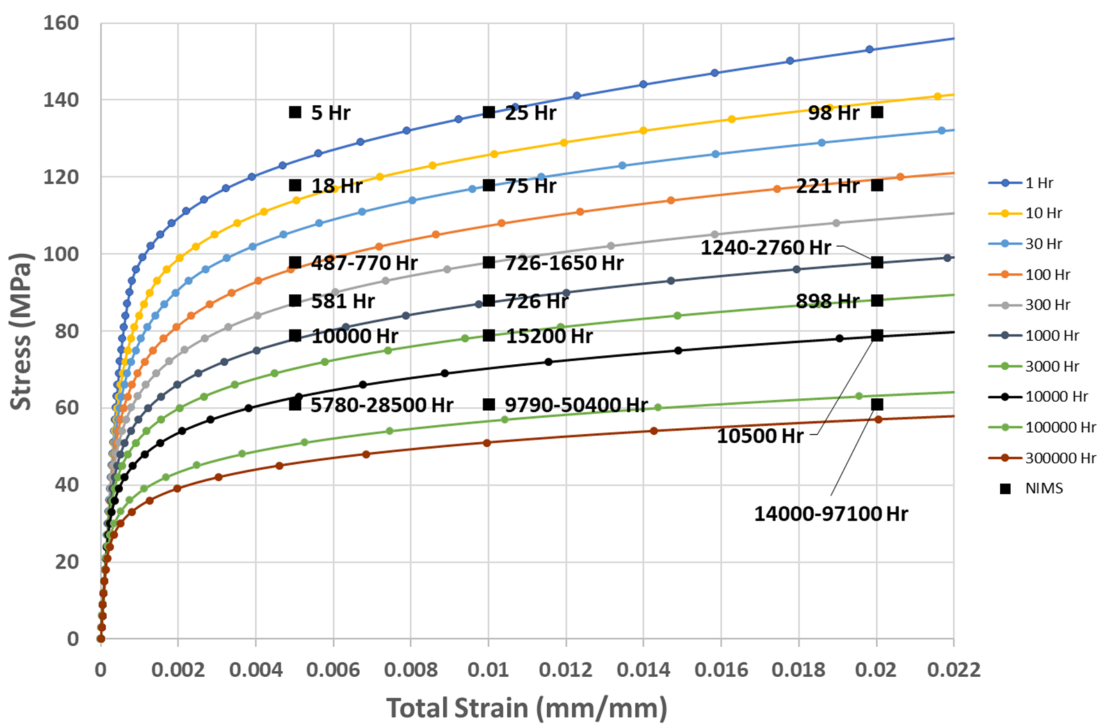

Figure A-24 Comparison of calculated code isochronous curves for Alloy 800H at 700 degrees C (1292 degrees F) to data from the NIMS database.

Figure A-25 compares NIMS data to the isochronous curves at 750 degrees C (1382 degrees F), which is near the maximum temperature permitted (760 degrees C) (1400 degrees F). All of the isochronous curves at this temperature are conservative. However, the time in the NIMS data only goes up to 4,370 hours maximum.

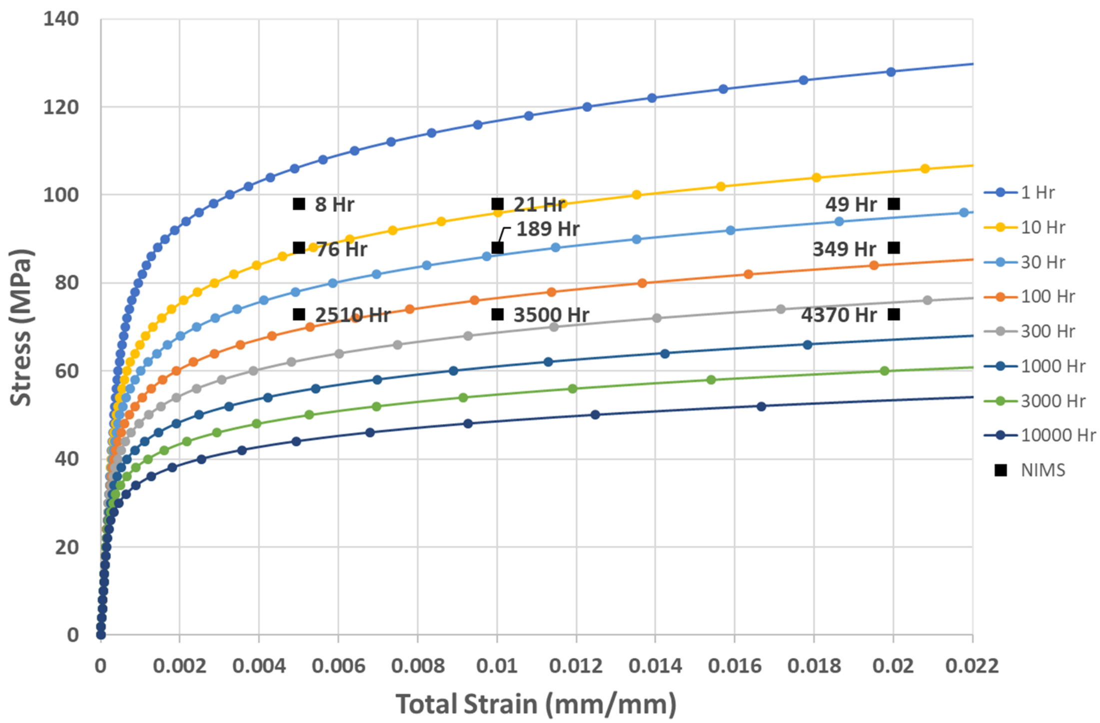

Figure A-25 Comparison of calculated code isochronous curves for Alloy 800H at 750 degrees C (1382 degrees F) to data from the NIMS database.

Finally, McCoy and King (1983) developed data for Alloy 800H welds under several time-at-temperature aging conditions. These data were developed at a number of temperatures under conditions of 0, 1,000, and 2,000-hour aging. Figure A-26 provides an example of these data compared to the isochronous curves at 760 degrees C (1400 degrees F). The figure shows that the isochronous curves are conservative. In fact, the curves were conservative at all other temperatures examined.

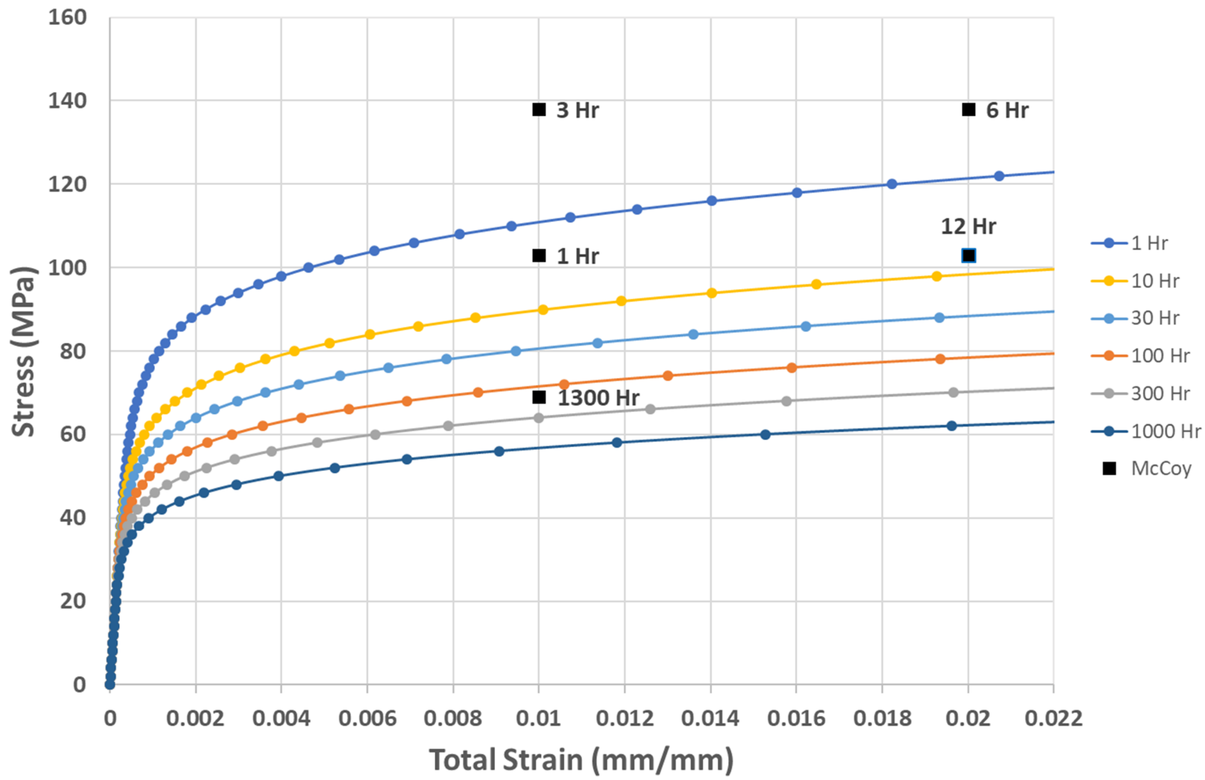

Figure A-26 Comparison of calculated code isochronous curves for Alloy 800H at 760 degrees C (1400 degrees F) to data from McCoy and King (1983).

In summary the isochronous curves for Alloy 800H material may be nonconservative for temperatures at 700 degrees C (1292 degrees F) and above, at times of 100,000 hours and above.

Grade 91 (9CrMo) Material

The BPVC-III-5 isochronous curves in the 2017 version of ASME BPVC-III-5 go up to a temperature of 649 degrees C (1200 degrees F) for Grade 91 (9CrMo) steel. In BPVC-III-5, Figures HBB-T-1800E1 through HBB-T-1800E11 provide the isochronous stress-strain curves for Grade 91 up to 649 degrees C (1200 degrees F). The code-based curves were developed from work by Swindeman (1999). As with the other materials, the equations were programmed into a spreadsheet so that additional comparisons to other data could be made. Figure A-27 shows an example of the calculated isochronous curves at 649 degrees C (1200 degrees F). If these are compared to ASME BPVC-III-5 isochronous stress-strain curves, perfect correspondence is observed. These comparisons were made at other temperatures as well.

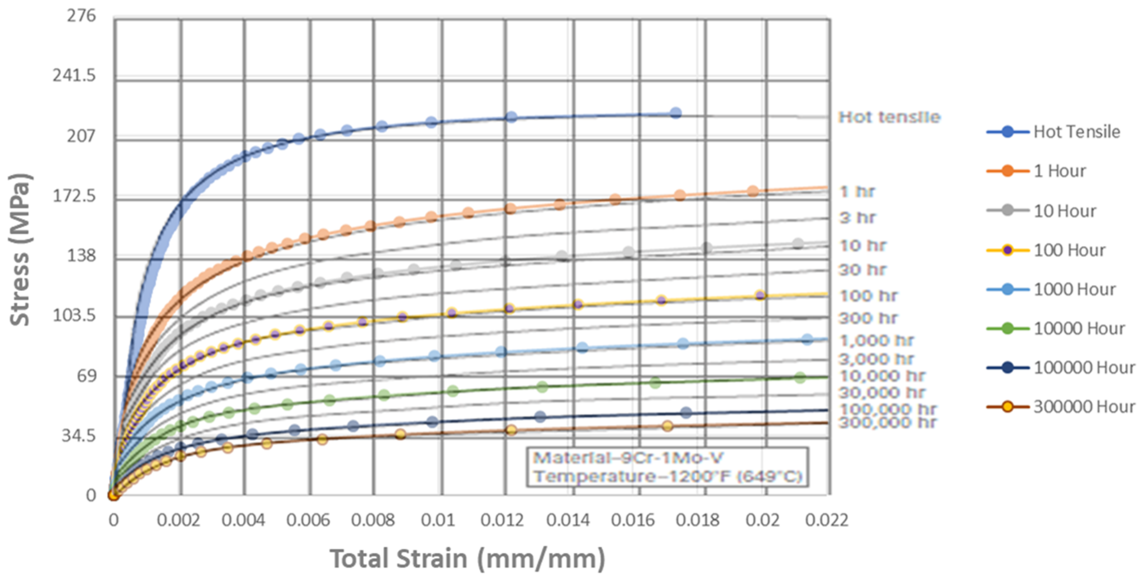

Figure A-27 Comparison of calculated code isochronous curves for Grade 91 at 649 degrees C (1200 degrees F). The calculated isochronous stress-strain curve is nearly identical to Figure HBB-T-1800-E-11 from BPV-III-5.

Jawad et al. (2016) recently developed isochronous stress-strain curves for Grade 91 with data obtained from the NIMS database (MatNavi, 2020). Figures A-28 and A-29 compare the two sets of isochronous curves at 649 degrees C (1200 degrees F) and 438 degrees C (820 degrees F), respectively. For both temperatures, the curves from the NIMS database developed from Jawad et al. (2016) are generally lower than the BPVC-III-5 curves.

In summary, the discrepancy between the current BPVC-III-5 curves and those recently developed by Jawad et al. (2016) should be explained because the data developed by Jawad et al. from the NIMS database are lower, especially at longer times. This suggests that the current curves may not be conservative.

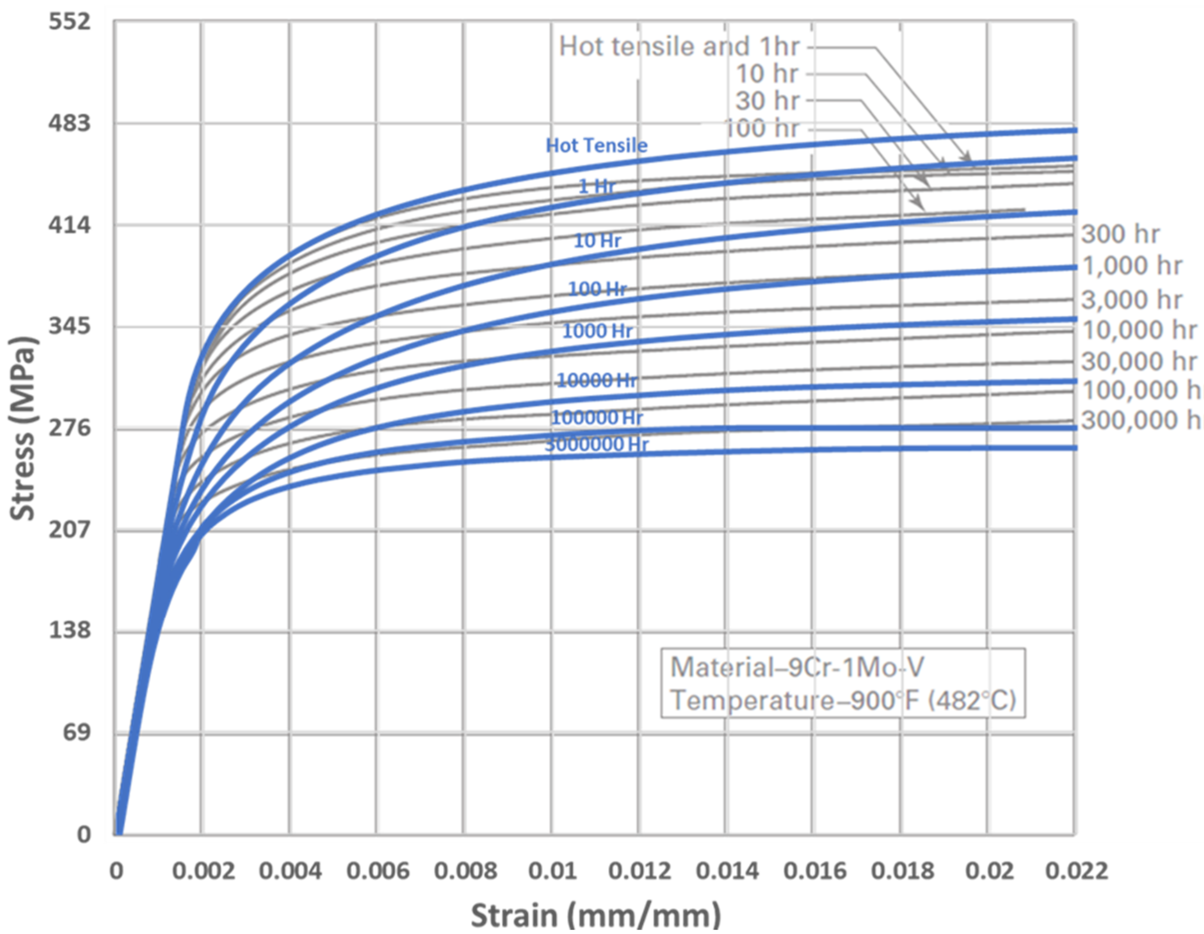

Figure A-28 Comparison of code isochronous curves at 438 degrees C (820 degrees F) from programmed equations to the new curves developed by Jawad et al. (2016) for Grade 91.

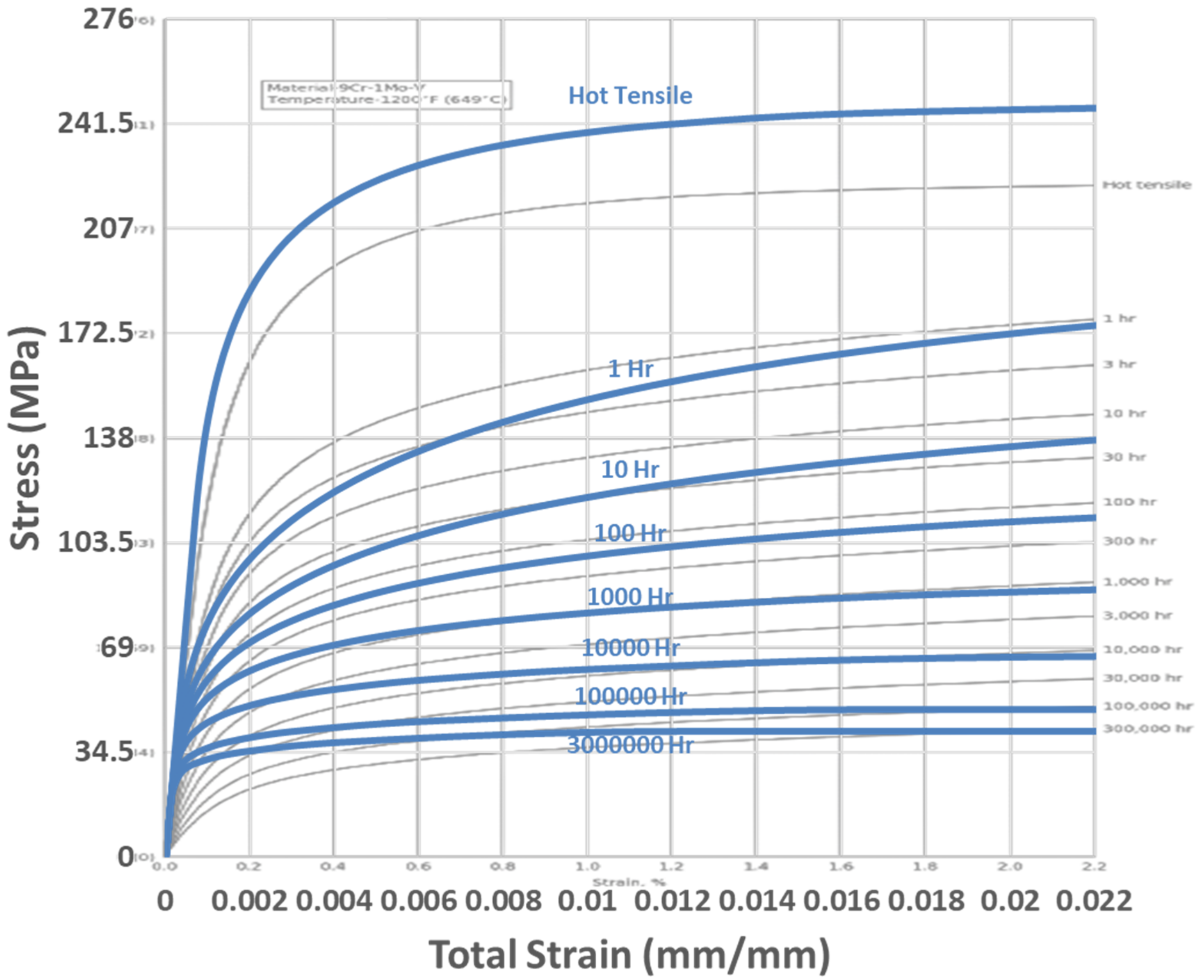

Figure A-29 Comparison of code isochronous curves at 649 degrees C (1200 degrees F) from programmed equations to the new curves developed by Jawad et al. (2016) for Grade 91.

Appendix B: Assessment of Creep-Fatigue Rules

This appendix examines some of the material requirements of the creep-fatigue design rules in the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (BPVC), Section III, Rules for Construction of Nuclear Facility Components," Division 5, "High-Temperature Reactors" (BPVC-III-5), and the conservative nature of these rules. In the design rules, creep and fatigue damage are accumulated on a time and cycle fraction basis, respectively. The creep damage is estimated by accumulating the times at the varying sets of operating conditions (temperature and stress) and normalizing this by the allowable time from the allowable creep-rupture design data. The allowable times based on rupture data are conservative.

Creep-fatigue interaction is a complex, dynamic process involving the combined effects of creep and fatigue on the accumulated damage. The process depends on many mechanical and metallurgical factors, including test temperature, strain rate, hold time, types of hold, thermomechanical treatment, and microstructure. The mechanisms of creep-fatigue damage are not well understood, and consequently, predictive capabilities are limited. It is recognized that the 2017 BPVC-III-5 rules for creep-fatigue assessment are empirical and rely heavily on a large amount of laboratory data from creep-fatigue tests. The damage accumulation rules are often nonconservative unless safety factors are used in the design procedure. The safety margins are applied throughout the many steps that define the creep-fatigue design assessment procedure. For some materials, especially Grade 91 steel, the design rules are overly conservative. However, the large material database used to ensure conservative predictions within BPVC-III-5 does have validation test data up to very long times (for example, 100,000 hours and beyond) and, hence, the predictions are conservative. The safety margins have increased over the years with the accumulation of additional creep-fatigue test data.

Natesan et al. (2008, 2009), in a series of studies for the U.S. Department of Energy, examined the five material needs in BPVC Subsection NH (now BPVC-III-5) with regard to creep-fatigue failure mechanisms. They also summarized the databases used to ensure conservatism in the code rules for the materials. The extensive database of experience includes operating experience with U.S. advanced non-light-water reactors (ANLWRs) and other high-temperature reactors around the world. This work also discussed needs for new materials and the need to extend design life to 500,000 hours (it is now 300,000 hours or 34 years in BPVC-III-5 (2017)). The creep-fatigue design rules in the code at that time were considered conservative based on the large databases examined.

The form of the creep-fatigue damage rule in the code represents Equation 10 in HBB-T-1400. The fatigue damage is accounted for by using Miner's cumulative damage criteria, as done at lower temperatures in Subsection NB. The fatigue damage is accumulated in the same fashion as in NB and is therefore consistent. As discussed by Jetter (2017), the selected linear damage approach is conceptually straightforward to apply and is consistent with other damage assessment procedures in the code. The fatigue design curves are obtained from fully reversed cyclic tests at temperature. Consistent with NB, these curves are constructed by reducing the best-fit continuous cycling data by a factor of 2 on total strain range or a factor of 20 on life. This is very conservative, and further reductions are required for welds. Also, the stress-to-rupture curves used to evaluate the creep-damage fraction use safety factors (K'), the rationale for which is discussed by Jetter (2017), along with reduction factors for welds. This approach is very conservative as discussed below for the different materials.

Satisfying the rules is based on comparing the accumulated creep and fatigue damage on an interaction diagram that is very conservative in BPVC-III-5 compared with the French code (RCC-MR) and Japanese code (DDS). Sartory's 1987 assessment based on thermal shock tests of cylinders also showed that the code rules for creep fatigue are always conservative if safety factors are used. As discussed by Asayama (2009), BPVC-III-5 appears to apply safety margins at every step of the creep-fatigue evaluation (i.e., strain range, initial stress of relaxation, description of the stress relaxation curve during strain hold (due to the use of isochronous curves), and the damage envelope used, among others). This appendix discusses the conservative nature of creep-fatigue procedures for five materials.

As summarized below for the various materials, the creep-fatigue design rules are considered conservative and are recommended for endorsement subject to the caveats discussed for each material. An additional conservative aspect of the code rules for creep-fatigue design are that most code fatigue data are obtained in air tests. This is conservative compared to Larson-Miller or vacuum testing. The code-based time-fraction method is highly conservative when code safety factors are used.

However, the creep-fatigue design rules are primarily based on short-time laboratory test data. Long hold-time creep-fatigue data are needed in the future to ensure that creep-fatigue damage will saturate with increasing hold times, as hold times beyond 1,500 hours are possible in ANLWRs.

304 Stainless Steel and 316 Stainless Steel

The original data used to validate and improve the creep-fatigue design rules for the precursors to NH and BPVC-III-5 rules (Code Cases N-49, N-47) were obtained from careful tests performed by Brinkman et al. (1972). An illustration of the code procedure data comparisons shows the conservatism.

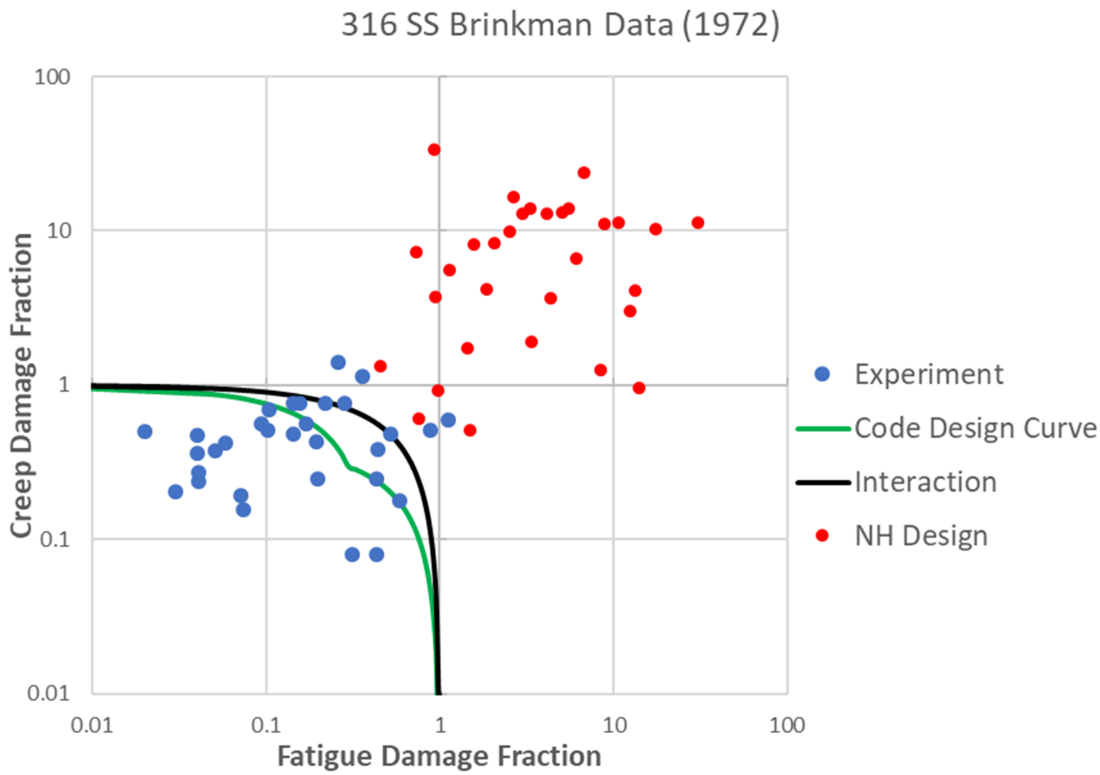

Figure B-1 Comparison of creep-fatigue test data with code design rule predictions (316 SS)

Figure B-1 illustrates the data developed by Brinkman for 316 stainless steel (SS). The black curve represents the linear creep-fatigue damage rule with no interaction diagram safety factor. The green curve represents the BPVC-III-5 interaction rule, with vertex at (0.3, 0.3) for stainless steel. Note that these data are plotted on log-log scale so all the data can be seen. These tests were performed using a variety of load-hold creep-fatigue conditions and for irradiated test specimens as well. The blue data dots represent raw test data from Brinkman et al. (1972) (note that this is not all the data—especially for cases dominated by creep or fatigue failure). The data inside the curve represent nonconservative results compared to the interaction diagram. The first observation is that the test data points do not add up to one (i.e., the black curve). Moreover, much of the raw data (blue curves) are also inside the code interaction curve (green curve) showing that the raw data are nonconservative for most of the data points based on code rules. The red data points represent the data with the code rules applied.[1] All of the red data points are outside the code interaction diagram, which shows conservatism. The conservatism is significant for many of the data points (being greater than 25 in many cases as seen in Figure B-1).

[1] The Code rule safety factors here were those in effect for Code Case N-49 in 1972. These safety factors are even more conservative today based on work performed in the mid-1980s by Sartory and others.

Looking at this same set of test data in the framework of the code rules with no safety factors, the conservatism becomes even more obvious. Figure B-2 illustrates this using the code-based interaction diagram of Figure HBB-T-1420-2, which shows that the interaction curve meets at (creep damage, fatigue damage) = (0.3, 0.3) for 304 SS and 316 SS. The conservatism of the code-based creep-fatigue rules for stainless steel are clearly seen with often very large safety factors.

Similarly, for 304 SS, Figures B-3 and B-4 compare the data, again showing significant conservatism—often with safety factors above 25. The rules for 304 SS and 316 SS were compared with new test data and with industrial experience over many years. As discussed by Jetter (2005) and Natesan et al. (2008), the U.S. Eddystone fossil power plant, Unit 1, experienced significant cracking in main steamlines made of 316 SS in 1983. Because of this, the code rules and safety factors for stainless steel were reevaluated, and several researchers, including Corum and Sartory (1985), developed additional benchmark test data. As a result, the safety factors were increased in Code Case N-47, the precursor to NH and BPVC-III-5.

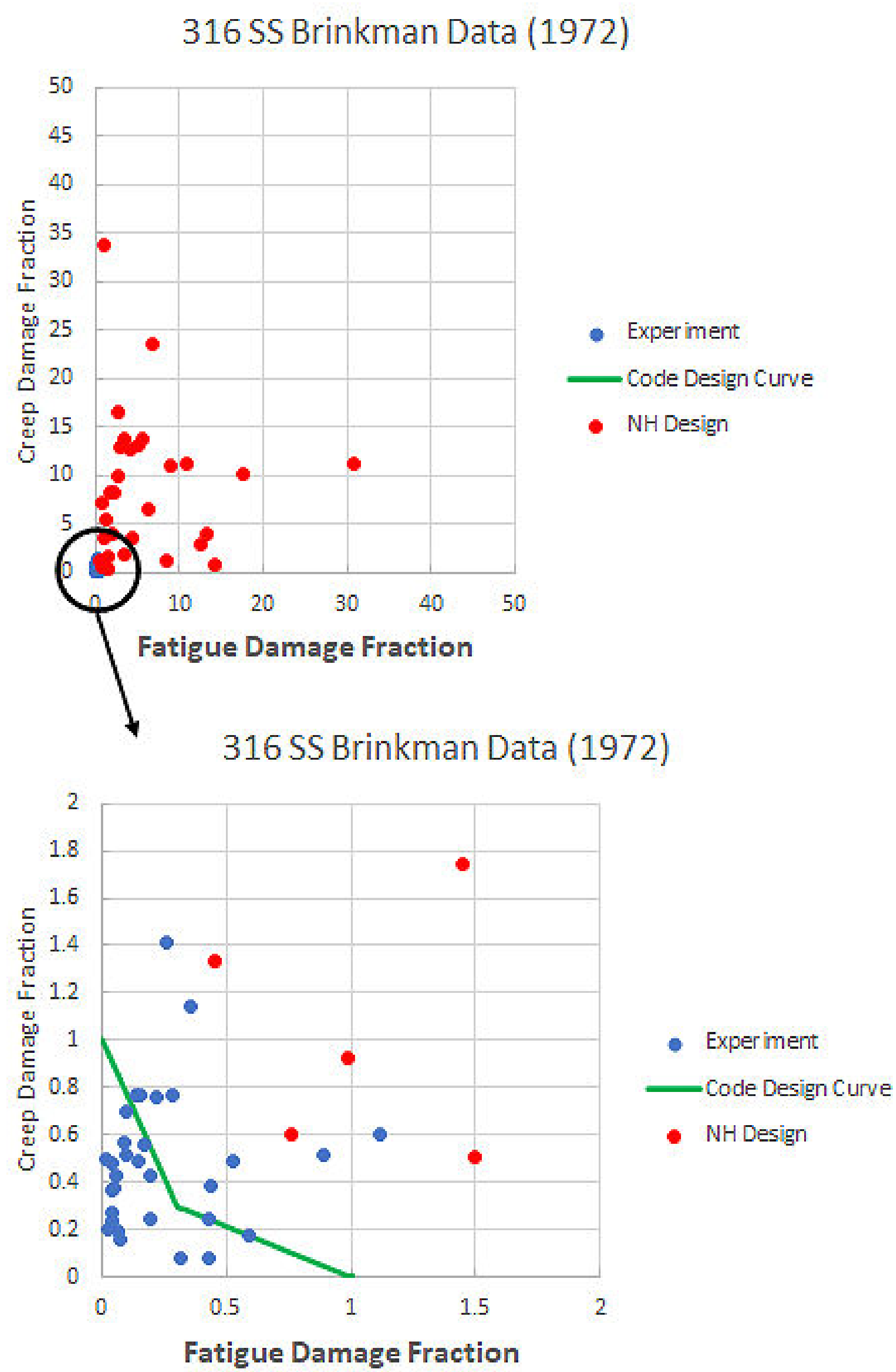

Figure B-2 Comparison of creep-fatigue test data with code design rule predictions (316 SS)

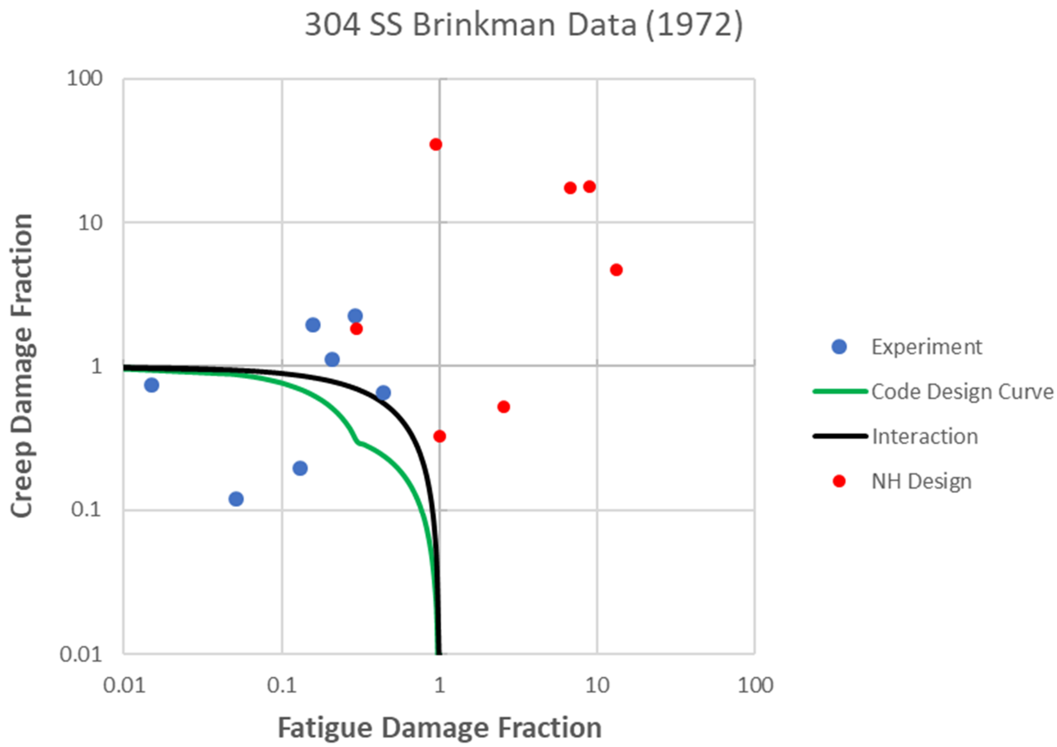

Figure B-3 Comparison of creep-fatigue test data with code design rule predictions (304 SS)

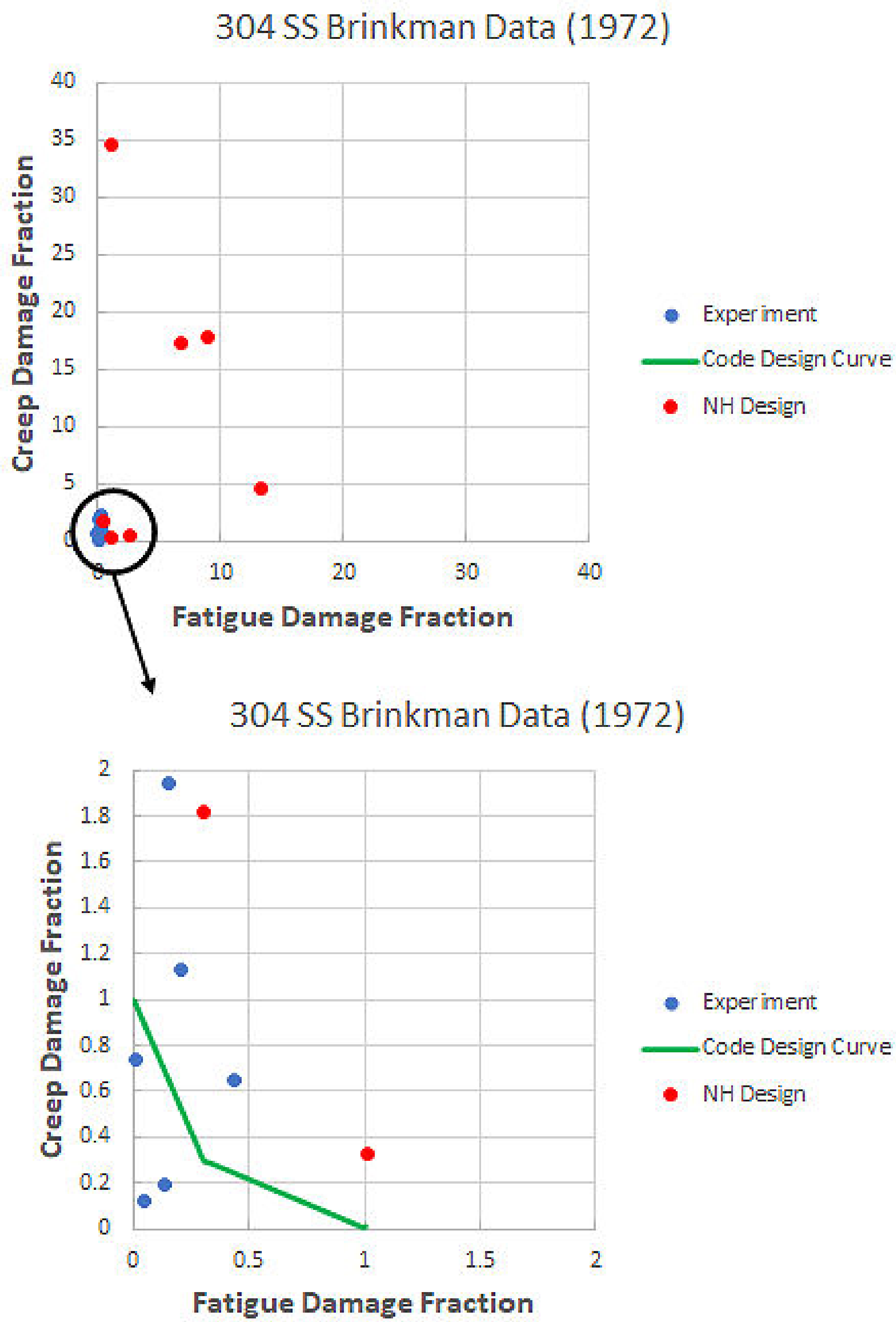

Figure B-4 Comparison of creep-fatigue test data with code design rule predictions (304 SS)

In summary, the rules in BPVC-III-5 for stainless steel are considered to be conservative and, in many cases, overly conservative based on comparison of design to test data when using the code safety factors. However, the creep-fatigue design rules primarily are based on short-time laboratory test data. Long hold-time creep-fatigue data are needed in the future to ensure that creep-fatigue damage will saturate with increasing hold times because hold times longer than 1,500 hours are possible in ANLWRs.

The code rules for stainless steel are recommended for endorsement with the following caveat. The time fraction allowable for each accumulated hold time is calculated by using the isochronous stress-strain curves of HBB-T-1800. As discussed in this document for HBB-T-1800 and Appendix A of this document, these curves are slightly nonconservative for higher temperatures and long hold times (typically greater than 100,000 hours). However, the hold times for evaluating the creep-fatigue time-fraction limits for each accumulated hold cycle are unlikely to be greater than 100,000 seconds. In addition, the allowable time duration is obtained from Figures HBB-I-14.6A through HBB-I-14.6F for the various materials. The data analyses of HBB-2000 at Oak Ridge National Laboratory by Ren et al. (2020) that some of the creep-rupture curves are nonconservative, particularly for higher temperatures and long hold times (similar to the observations from Appendix A for the isochronous curves). Again, the hold times for each portion of the composite cycles may very well be for times shorter than 100,000 hours.

Grade 91 Steel

Asayama (2006), Asayama and Tachibana (2009), and Riou (2007) (along with references sited in those works) provided a detailed discussion of 9Cr-Mo (Grade 91) material and comparisons to large amounts of creep-fatigue test data. Extensive material data for creep-fatigue tests at temperatures higher than 400 degrees C (752 degrees F) were accumulated from the Electric Power Research Institute, Central Research Institute of Electric Power Industry (Japan), ORNL, Japanese Atomic Energy Agency, and the National Institute of Materials Science (Japan), along with two universities. These data were then used to determine the margins for creep-fatigue design in BPVC-III-5, the French RCC-MR, and the Japanese DDS codes. The data were compared to the procedures with the margins removed. In all cases, the BPVC-III-5 failure envelope predictions were conservative compared to the data. The DDS and RCC-MR code design procedure predictions compared well with the failure data under various test conditions of hold time and cycles. When safety margins were applied, as indicated by the codes, BPVC-III-5 was very conservative compared to the failure data. Perhaps the two main causes for the conservatism are the use of monotonic isochronous stress-strain curves to estimate stress relaxation during hold times and the fact that the linear interaction failure diagram in BPVC-III-5 has vertex at (creep damage, fatigue damage) equal to (0.01, 0.1). In RCC-MR and DDS, this vertex is (0.3, 0.3) although the methods used to evaluate the parameters are defined differently. RCC-MR uses cyclic stress-strain curves in its evaluation to account for stress relaxation during hold times, and the relaxation is always lower than BPVC-III-5 and measured stress relaxation from the tests. Moreover, the allowable fatigue curves from Figure HBB-T-1420-1E for 9Cr-1Mo-V steel were quite conservative compared to the data obtained by Asayama (2009) for all temperatures. It is noted that the 2017 version of BPVC-III-5 has a fatigue curve at only one temperature (540 degrees C or 1004 degrees F); this curve was considerably lower than the test data at all temperatures.

In addition, Li et al. (2011) collected data from numerous sources on Grade 91 in an effort to relax the conservatism of the code interaction diagram. Their work showed that the current design procedures are indeed very conservative compared to all the data for the test durations considered. Li et al. are also developing a new creep-fatigue model based on a damage model for future consideration in the code for Grade 91. However, this is not relevant to the 2017 code.

Therefore, despite the observation from Appendix A that the isochronous stress-strain curves for Grade 91 in BPVC-III-5 may be nonconservative for some higher temperatures and longer times, it is judged that the inherent conservatism is adequate to ensure conservative predictions. Moreover, the creep-damage fraction is evaluated using the creep-rupture values from the assessment of HBB-2000. The assessment of HBB-2000 found Grade 91 to be conservative as discussed in the ORNL reports that are part of the complete NRC assessment of the code. Recent additional work by Asayama (2011) further shows that the interaction rule for Grade 91 is overly conservative based on new test data, and he recommends modifying the interaction curve to (0.3, 0.3) in future versions of the code beyond 2017.

2.25Cr-1Mo

The cyclic fatigue data for 2.25Cr-1Mo steel that is used for design in BPVC-III-5 was developed in the 1970s and 1980s at ORNL, Argonne National Laboratory, and Idaho National Laboratory in support of the U.S. liquid metal fast breeder reactor program. Booker (1978, 1979), Majumdar et al. (1981), and Brinkman et al. (1981) provided much of the validation data. Becht and Becht (2009) compiled much of the data, along with additional data from other sources. The BPVC-III-5 safety factors again lead to very conservative creep-fatigue life predictions using the linear fraction damage models. For 2.25Cr-1Mo, the interaction diagram uses (creep damage, fatigue damage) = (0.1, 0.1), which is considered very conservative especially when used with the many safety factors in the design procedure. The reduction factors for welds are also considered very conservative and encourage designers to carefully place welds into the design where cyclic loads are low.

The review of HBB-I-14.6A by ORNL determined that Table HBB-I-14.6D and Figure HBB-1-14.6D are nonconservative for temperatures greater than 525 degrees C (977 degrees F). In addition, as discussed in Appendix A, values of the isochronous curves for higher temperatures may be slightly nonconservative. These issues should be further examined before code endorsement is recommended.

Alloy 800H

Natesan et al. (2008, 2009) also discuss the overly conservative nature of the BPVC-III-5 creep-fatigue rules for design and propose some improvements that have not yet been introduced into the code. In addition, as summarized by Natesan et al. (2003), the fatigue material data of Alloy 800H were evaluated from room temperature to 760 degrees C (1400 degrees F) by researchers at Brookhaven National Laboratory (Soo and Chow, 1978; Chow et al., 1978). Natesan also notes that Alloy 800H, with an interaction diagram intersection of (0.1, 0.1), provides conservative creep-fatigue design lives—perhaps too conservative.

The code rules for stainless steel are recommended for endorsement with the following caveat. The time fraction allowable for each accumulated hold time is calculated by using the isochronous stress-strain curves of HBB-T-1800. As discussed in Appendix A of this document, these curves are slightly nonconservative for higher temperatures and long hold times (typically greater than 100,000 hours). However, the hold times for evaluating the creep-fatigue time-fraction limits for each accumulated hold cycle are unlikely to be greater than 100,000 seconds. The allowable time durations taken from Figure HBB-I-14.6 are judged to be adequate. Again, because the hold times for each portion of the composite cycles may be for times shorter than 100,000 hours, this material is recommended for endorsement.

Appendix C: Procedure to Determine Allowable Stresses for Class B Components

This appendix presents the procedure used to compare the allowable stresses for Class B components for any given material listed in Tables HCB-II-2000-1 through HCB-II-2000-4 to develop the plots such as those shown in Figures 4.4.2-1 through 4.4.2-8. (NOTE: All page numbers referenced in this Appendix C are from ASME BPVC Section III, Division 5)

(1) Select a material from Table HCB-II-2000-1 to HCB-II-2000-4 (for example, one grade of Alloy 800H plate in Table HCB-II-2000-4 on p. 297 of American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section III, “Rules for Construction of Nuclear Facility Components,” Division 5, “High-Temperature Reactors” (2017), which is described as follows:

a.	Composition:	33Ni–42Fe–21Cr
b.	P-No.:	45
c.	Product Form:	Plate
d.	Spec. No.:	SB-409
e.	Grade/Type	800H
f.	Specified Min Strength Sy/Su:	25/65 ksi
g.	Line in Figure HCB-III-1000-1:	Curve G

(2) Copy the allowable stress values at the various temperatures from Table HCB-II-2000-4 into an Excel file. These are the allowable stress values for negligible creep (A4), as given in Figure HCB-II-1000-1.

(3) Copy the reduction factors for aging at the various temperatures from Table HBC-II-2000-5 (p. 298) for Alloy 800H into the Excel file.

(4) Determine the table in ASME BPVC Section II that has the allowable stress values for the specific grade of Alloy 800H from Table HCB-II-3000-4 on p. 306. For the material chosen, the stress values at various temperatures are in Table 1B in Section II, Part D.

(5) Go to ASME BPVC Section II, Subpart 1, Part D, Table 1B, on pp. 234–237, Line 31, to obtain the allowable stresses at various temperatures for the above grade of Alloy 800H. This provides the values for A1 in Figure HCB-II-1000-1.

(6) Copy the weld reduction factors for Alloy 800H at various temperatures from Table HCB-II-3000-7 on p. 307 into the Excel file.

(7) Values for A2 (weldments) are obtained by multiplying those for A1 (Step 5 above) by the weld reduction factors (Step 6 above).

(8) Values of A3 (creep-significant event less than 1 hour) are obtained by multiplying those for A4 (Step 2 above) by the aging factors obtained from Step 3 above.

(9) Figure 4.4.2-8 shows the results from Step 5 (A1), Step 7 (A2), Step 8 (A3), and Step 2 (A4) as a function of temperature.