ANL/AMD-21/1

Historical Context and Perspective on Allowable Stresses and Design Parameters in ASME Section III, Division 5, Subsection HB, Subpart B

Applied Materials Division

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ACRONYMS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
C&S	Codes and Standards
CRBR	Clinch River Breeder Reactor
DOE	Department of Energy
EPRI	Electric Power Research Institute
GMA	Gas Metal Arc
GTA	Gas-Tungsten Arc
HBB	Subsection HB, Subpart B
HTGR	High Temperature Gas-Cooled Reactor
ISSC	Isochronous Stress Strain Curve
LWR	Light Water Reactor
MCM	Minimum Commitment Method
NGNP	Next Generation Nuclear Plant
NIMS	National Institute for Materials Science
NQA	Nuclear Quality Assurance
NRC	Nuclear Regulatory Commission
NRR	Nuclear Reactor Regulation
ORNL	Oak Ridge National Laboratory
RG	Regulatory Guide
SA	Submerged Arc
SMA	Shielded Metal Arc
SRS	Stress Range Splitting
TWG	Technology Working Group
UTS	Ultimate Tensile Strength

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) is reviewing the 2017 edition of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) Section III, Division 5 for endorsement. This supports part of the NRC Implementation Action Plan under Strategy 4: Facilitate industry code and standards development needed to support the non-light water reactor (LWR) lifecycle, including fuels and materials. The NRC review of Section III, Division 5 will emphasize the "Reasonable Assurance of Adequate Protection" standard. The NRC review team consists of materials, mechanical, and inspection staff from the Office of Nuclear Reactor Regulation (NRR), NRC Region II (RII), and the Office of Nuclear Regulatory Research (RES). In October 2018, the NRC core team sent the ASME BPVC Section III, Division 5 standard and the technical background documents to Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL), and NUMARK Associates, Inc. for a peer review on the technical adequacy of Section III, Division 5.

In January 2020, the NRC initiated efforts to review the PNNL, ORNL, and NUMARK reports and to begin drafting the Regulatory Guide (RG) and the supporting technical basis document, the NUREG. NRC has contracted Argonne National Laboratory (ANL) to provide the NRC review team with the technical basis and historical perspective on ASME BPVC Section III, Division 5 and the technical assistance to facilitate the staff's efforts in drafting the RG and the NUREG.

Elevated-temperature design rules for nuclear components were initiated in 1963 with ASME Code Case 1331. Complete construction rules for elevated-temperature pressure boundary metallic components under cyclic service were first published in the early 1970s in a series of ASME Code Cases (1592 through 1596). These Code Cases were referenced by NRC in RG 1.87, Rev 1, June 1975, to provide interim licensing guidelines to aid applicants in implementing the 10 CFR Part 50 requirements with respect to ASME BPVC Class 1 components operating at elevated temperatures for high-temperature gas-cooled reactors, liquid-metal fast-breeder reactors, and gas-cooled fast-breeder reactors.

These rules have undergone continued development and improvement as the 159x series of Code Cases evolved into the current Section III, Division 5, Subsection HB, Subpart B (HBB). For example, the weldment design guidance was quite minimal in the early stage of BPVC development. In response to the NRC concern about weldment cracking during the evaluation of the Clinch River Breeder Reactor Plant, weldment design procedures were introduced to improve the overall high-temperature design methodology for welded construction. In addition to primary load design, the HBB rules for cyclic loading also address loss of ductility and creep-fatigue failure in weldment. The latter are unique to the HBB rules within the ASME BPVC.

Similar to Section III, Division 1, Subsection NB rules for LWR construction, the HBB rules are based on the identification of, and protection against, structural failure modes. In addition to those for low-temperature cyclic service, structural failure modes for elevated-temperature cyclic service are further emphasized in HBB. Design rules and supporting

allowable stresses and design parameters for specific construction materials were developed to guard against these structural failure modes for the full range of operating temperatures of the pressure boundary components. The material data requirements and criteria for the allowable stresses and design parameters flow from the design evaluation methods for the failure modes and apportionment of design margins relative to the design rules. Thus, assessment of the adequacy of the allowable stresses and design parameters must be fully cognizant of the interrelationship between the material properties and the elevated-temperature design rules, but not just the material properties in isolation.

Development of the technical basis of the HBB allowable stresses and design parameters is an enormous task. The current allowable stresses and design parameters were established through many years of development by many ASME volunteers and were approved for code use through the Codes and Standards consensus process. This process provided valuable checks and balances whereby the code intent, use experience, and engineering judgment were rendered about the impact of the proposed item on the overall adequacy of the HBB construction rules to provide a reasonable assurance of structural integrity.

The materials section and material properties in HBB were reviewed by ORNL for the NRC. Materials data from various sources were first assembled, and the technical basis of the allowable stresses and design parameters were recreated by conducting data analyses on the assembled data. ORNL assessed the adequacy of the HBB allowable stresses and design parameters by comparing them against the recreated technical basis. It is unlikely that the data supporting the ORNL review and those underlying the values in HBB are identical; thus, it should be expected that there will be some numerical differences between the two sets of allowable stresses.

In this report, the general conservatism in the HBB design procedures is first discussed with respect to (i) primary load-controlled stress limits, (ii) displacement-controlled deformation limits, and (iii) creep-fatigue. This is followed by a discussion about the conservatisms inherent in determining the allowable stresses and design parameters and the conservatism in the weldment design procedure in HBB. The relevant criteria for the allowable stresses and design parameters are then summarized.

Assessment of the HBB allowable stresses and design parameters is then conducted. This includes assessment of the weldment design parameters that were not reviewed by ORNL, per NRC request. Instead of recreating the technical basis, code intent, historical code committee information, various publications on code criteria, and background information on code actions were leveraged in this assessment.

The 2017 HBB is the edition of record for the NRC endorsement effort. However, revisions of some of the allowable stresses and design parameters have been made in the 2019 edition and the to-be-issued 2021 edition. Further, there are revisions slated for actions in the 2023 edition. Thus, in order to render a meaningful assessment, temperature limits on the 2017 HBB values judged to provide a reasonable assurance of adequate protection, where applicable, are provided. They can be updated when NRC endorsement of a future code edition is made. Overall, the allowable stresses and design parameters in the 2017 edition of HBB are adequately

conservative, except for some of the situations in comparison with subsequent code editions noted above, and further detailed in the report.

Assessment of the ORNL review of the allowable stresses and design parameters is also provided in the report. Critical evaluation of the data assembled by ORNL with respect to the ASME material specifications and additional Section III requirements was not conducted in this report, nor were the data analyses by ORNL verified, as they are outside the scope of this work. While the ORNL effort in recreating the technical basis of the allowable stresses and design parameters is commendable, it is no substitute for the Codes and Standards review and the consensus approval process.

A significant finding concerning the ORNL review is that, while a considerable effort went into its preparation, it contains errors such as application of non-code criteria, e.g., the thermal aging criteria; misinterpretation of the code intent, e.g., the design loadings allowable stress criteria; and the selection of non-permissible material, e.g., the inclusion of the normalized and tempered condition for the 2.25Cr-1Mo steel in the database.

Further, assessment of the adequacy of the allowable stresses and design parameters was performed without due consideration of the context of the design rules. For example, effort was expended on data analysis for the design loading allowable stresses, S_0, which are, instead, defined by reference in HBB to the allowable stresses for Section I and Section VIII, Division 1 and are used merely as a consistency check and do not control the primary load design. Another example is the use of the expected minimum stress-to-rupture in the context of primary load design where extrapolation to full design life is important versus creep-fatigue evaluations where creep damage increments calculated toward the end of a cycle period under high temperature, low stress, and long rupture time conditions generally are negligibly small.

The collection of recent data by ORNL is a valuable effort that would be helpful for code improvement. However, deficiencies of the ORNL review documented in this report need to be recognized in addressing the adequacy of the allowable stresses and design parameters of HBB to provide a reasonable assurance of adequate protection. Although, with the conservatisms and redundancies in the design procedures as discussed in this report, the allowable stresses and design parameters in the 2017 edition of HBB would arguably still lead to a design that provides a “reasonable assurance of adequate protection” for the intended service life.

However, to provide a path forward strategy for the NRC Section III, Division 5 endorsement effort, the approach herein is to assess limitations on the use of the contested 2017 properties, if applicable, that would permit current advanced reactor design activities to proceed pending resolution by all the applicable ASME Code consensus committees. It is noted that some of these updates have already been incorporated in newer editions of HBB.

Assessment of the NUMARK review on the isochronous stress-strain curves for 9Cr-1Mo-V steel was also conducted, as requested by NRC. Contrary to the recommendation of NUMARK, it is judged that all the isochronous stress-strain curves in HBB, including 9Cr-1Mo-V, are adequate to support conservative creep-fatigue designs, as detailed in this report.

1 INTRODUCTION

In the 1970s, the U.S. Nuclear Regulatory Commission (NRC) issued Regulatory Guide (RG) 1.87 (Rev 1, June 1975) to provide interim licensing guidelines to aid applicants in implementing the 10 CFR Part 50 requirements with respect to American Society of Mechanical Engineers (ASME) Boiler Pressure and Vessel Code (BPVC) Class 1 components operating at elevated temperatures for high-temperature gas-cooled reactors, liquid-metal fast-breeder reactors, and gas-cooled fast-breeder reactors. RG 1.87 referenced ASME Code Case 1592 for materials and design and Code Cases 1593, 1594, 1595, and 1596 for fabrication and installation, examination, testing, and overpressure protection, respectively.

When the nuclear code cases were separated from the non-nuclear code cases by ASME, the Code Case 1592 series was converted to Code Case N-47, which was used by the Clinch River Breeder Reactor (CRBR) project, with additional U.S. Department of energy (DOE) requirements for the structural design of CRBR. A license application for a construction permit for CRBR was submitted to the NRC for approval in the late 1970s. Assessment of the construction rules of Code Case N-47 was carried out by the NRC. The NRC licensing evaluations were in progress when the Government cancelled the CRBR project; hence, there was no ruling on the adequacy of the construction rules of Code Case N-47. Continued improvements of the rules of N-47 were made, and Code Case N-47 was subsumed into a new Section III, Division 1, Subsection NH by ASME in 1995.

In 2007, wording was added to 10 CFR 50.55a to the effect that Subsection NH may only be used for the design and construction of Type 316 stainless steel pressurizer heater sleeves where service conditions do not cause the component to reach temperatures exceeding 900°F (483°C). That led to uncertainty in the use of Subsection NH by advanced reactor developers for their licensing efforts.

In the mid-2000s, ASME was requested to develop a new division within Section III to consolidate all high-temperature construction rules in Subsection NH and other Division 1 code cases, and to add graphite rules to the new division, to support the Next Generation Nuclear Plant (NGNP) Project. The new Section III, Division 5 was published in the 2011 Addenda of the ASME BPVC. Continued updating and improvement of the construction rules of Section III, Division 5 have taken place since its initial publication.

Information on the scope and need for Division 5, the structure of Division 5, where the rules originated, and the basis for the elevated-temperature rules specified in Division 5 is provided in a chapter of the companion guide to the ASME BPVC [1]. A recent review [2] provides background information on the development and scope of the elevated-temperature design and construction rules of metallic components in Section III, Division 5. The information is provided through reference to existing background documentation and identification of key references and their relationships to the current rules.

A lack of NRC endorsement of ASME construction rules for high-temperature reactors represents a significant regulatory risk for the commercial deployment of advanced nuclear. This

subject was brought to the forefront in 2015 after a White House meeting on nuclear energy, leading to a series of DOE/NRC advanced non-light water reactor (LWR) workshops and a broad recognition of the adverse impacts of a lack of NRC endorsement of Division 5. With support from the High Temperature Gas-Cooled Reactor (HTGR) Technical Working Group (TWG), Fast Reactors TWG, and two advanced reactor developers, the ASME Board on Nuclear Codes and Standards made a request to NRC in 2018 for the endorsement of Section III, Division 5 [3]. NRC subsequently agreed to initiate efforts to review the 2017 edition of ASME BPVC Section III, Division 5 [4].

This report provides the code basis and perspective on some of the issues raised by NRC contractor on the assessment of Section III, Division 5, Subsection HB, Subpart B. Discussions will be made with respect to the 2017 code edition, unless otherwise specified.

2 SECTION III, DIVISION 5

ASME Section III, Division 5 rules govern the construction of vessels, piping, pumps, valves, supports, core support structures, and nonmetallic core components for use in high-temperature reactor systems and their supporting systems. Construction, as used in the ASME Section III context, is an all-inclusive term that includes material, design, fabrication, installation, examination, testing, overpressure protection, inspection, stamping, and certification. High-temperature reactor systems include gas-cooled reactors, liquid metal reactors, and molten salt reactors that include either liquid fuel or solid fuel.

Division 5 contains six subsections, covering Code Classes A, B, and SM for metallic coolant boundary or pressure boundary components and Code Class SN for nonmetallic core components, as shown in FIGURE 1.

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

FIGURE 1 Section III, Division 5 Organization.

Division 5 is a "component" code and not a "system" code. It recognizes the different levels of importance associated with the function of each component as related to the safe operation of an advanced reactor plant. The code classes allow a choice of rules that provide a reasonable assurance of structural integrity and quality commensurate with the relative importance assigned to the individual components of the advanced reactor plant.

For Class A metallic components, Section III, Division 5 Subsection HB, Subpart B (HBB) provides requirements for new construction to guard against structural failure modes caused by mechanical and thermal stresses due to cyclic operation and high-temperature creep. Apart from thermal aging effects on tensile properties, the requirements do not cover deterioration that may occur in service as a result of radiation effects, corrosion, erosion, thermal embrittlement, or instability of the material. These effects shall be accounted for by the owner/operator to realize the design or the specified life of the components and supports. Thus,

these materials degradation effects are outside the scope of Section III, Division 5, and they shall be addressed by owner/operators for their specific reactor design.

The structural integrity of reactor components can be reasonably assured only when the Section III, Division 5 rules are used in conjunction with other codes and standards, e.g., Section II on materials specifications, Section V on non-destructive examination, Section IX on weld procedure qualifications, Nuclear Quality Assurance (NQA)-1 on quality assurance conformity assessment, and Section XI on in-service inspection.

2.1 GENERAL CONSERVATISM IN THE DESIGN PROCEDURE IN SECTION III, DIVISION 5 FOR CLASS A COMPONENTS

2.1.1 Primary, load-controlled stress limits

The approach to primary, load-controlled stress limits for elevated temperature is somewhat different than that for components operating below the creep regime. As discussed in more detail below, there are limits for design loadings that are conceptually different than the limits for service loadings. The limits for design loadings, except for a few cases for long times at lower temperatures, are defined to be the same as those given for Section I and Section VIII, Division 1. The intent is to provide assurance to the original ASME BPVC Main Committee that the then new elevated temperature design rules with time-dependent allowable stress criteria for operating conditions with durations less than 100,000 hours would not result in component thicknesses less than would be achieved under the design rules and allowable stress criteria for Section VIII, Division 1 based on extrapolated 100,000-hour properties. It was later recognized that at lower temperatures there was a limited regime where the Section II, Part D Tables 1A and 1B allowable stress values based on time independent tensile properties could be lower than the S_{mt} intensities at 300,000 hours, leading to thicknesses greater than those governed by the S_{mt} intensities at 300,000 hours for service level conditions. This was considered to be contrary to the intent of the criteria for design loadings addressing the shorter lifetimes, and, thus, the current allowable stresses for design loadings, S_0, are based on the higher of the S values in Section II, Part D or the value of S_{mt} at 300,000 hours in HBB.

The approach for primary allowable stresses for service limits in Division 5 is different in that they are specifically based on the expected service life for service loadings as specified in the design specification for the component. Recognizing that there is typically a margin between design loadings and service loadings for Service Level A, the allowable primary stress criteria for service loadings were selected such that the required thickness for a service life of 100,000 hours would approximate the thickness required for Section I and VIII, Division 1 components.

The situation is different for a long service life Division 5 component. For example, the allowable stress in Section II, Part D, Tables 1A and B based on creep rupture properties is the lower of 0.67 times the average or 0.80 times the minimum creep rupture strength in 100,000 hours. Whereas, for Class A components in Division 5, the corresponding criterion is 0.67 times the minimum creep rupture strength for the specified service life. Thus, as would be

expected, for most Class A and similarly specified components, the required wall thickness for a specified life of 300,000 hours is greater than that for a Section 1 or VII1, Division 1 component operating at the same conditions.

The HBB service loading rules for Class A components are based on elastic analysis, which are conceptually equivalent to the primary stress limits for Section III, Division 1 Class 1 components, but with allowable stress values that take into consideration the effects of creep, e.g., time-dependent deformation and rupture. This is accomplished by the use of two sets of allowable stresses, one time-independent, using the same approach as the allowable stress for Division 1 Class 1 components below the creep regime, and another set using allowable stress values determined from time-dependent creep properties. There has been extensive discussion in the NRC contractor documents relative to the determination of the allowable stress values, but not in the context of how they are implemented in the design rules. The following is an example of the additional conservatism of the HBB rules.

In Section III, Division 1 Subsection NB for Service Level B, the primary stress allowable from Appendix XIII Table 3110-1 is $1.2\ S_m$. This means that the allowable primary membrane stress from a seismic event categorized as Service Level B is 1.2 times the value of S_m as given by the criteria in Section II, conceptually the lesser of $\frac{2}{3}S_y$ or $\frac{1}{3}S_u$. In the HBB rules, the corresponding allowable stress for a time-independent Service Level B event is S_m without the 1.2 factor increase and with a reduction in S_y and S_u to account for the detrimental effects of thermal aging. For Service Level C, the allowable primary membrane stress in Subsection NB is the higher of $1.2\ S_m$ or S_y, and in HBB, it is just $1.2\ S_m$ without the increase in the allowable for work-hardening material like austenitic stainless steel. Generally, the Service Level D requirements are more complex and not so easily comparable to those of Subsection NB. Thus, the allowable stress in HBB for a time-independent B or C event is generally more conservative than the equivalent event in Subsection NB.

Another example of conservatism in the HBB primary stress rules is the use of a section factor, K_t, conservatively based on a power law creep exponent in the range of 2–3 instead of the nominally higher creep rate exponent of 5 for many materials. The resultant value of K_t is 1.25 vs. a factor of 1.5 for a perfectly plastic redistribution.

Also, in comparing the S_t values in the 2017 edition of HBB, the values for Type 304 and 316 stainless steels and Alloy 800H that are governed by 1% total strain are based on the original criteria of 100% of the minimum stress to reach 1% that goes back several decades, and not the more recent criterion of the average stress reaching 1%. The strain criterion of the total strain of 1% in the design life is more conservative than the analogous criterion based on 100% of the average stress to produce a creep rate of 0.01% in 1000 hr. (Interesting historical note: the criterion based on 1% of total strain was at the insistence of a NRC committee member in the original group formed to develop the criterion, W. F. Anderson (d.c.), who wanted a parameter that could be measured in the field.)

2.1.2 Displacement-controlled limits

Ordinarily, the values of S_m and S_t are thought of in the context of limits on load-controlled stresses. However, the displacement-controlled limits in Division 5 Appendix HBB-T also contain direct and indirect limitations on load-controlled stresses. Several examples are cited below.

The B-1 and B-2 tests under HBB-T-1330 establish a bounding membrane strain limit of 1% accumulated inelastic principal strain that is a function of a core stress that is a function of the maximum displacement-controlled (secondary) stress range and the applied primary stress. The minimum value of the core stress is the primary stress loading, and the strain is calculated from an isochronous stress strain curve that is based on average properties.

Another place where the limits in Appendix HBB-T are applicable to load-controlled stresses is in the limits on creep damage in the creep-fatigue rules using elastic analysis in HBB-T-1430. In those rules, the creep damage is computed from stress relaxation curves which have a lower bound, S_{LB}, that is given by 1.25 times the core stress given in the B tests under HBB-T-1330 discussed above. For elastic analysis, the damage calculated from the stress relaxation curve are further increased by a factor of $1/K'$ where K' for elastic analysis equals 0.9 for all the Class A materials except Grade 91 where it equals 1.0, in consideration of other conservatisms for that material.

It is interesting to note that, conceptually, Appendix HBB-T covers a complete basis for component design, since it covers both load- and displacement-controlled loadings that are both cyclic and sustained. In that sense, the load-controlled stress limits based on S_m and S_t are redundant to the design rules in Appendix HBB-T.

2.1.3 Creep-fatigue

The strain limits and creep-fatigue design checks in the HBB rules, detailed in Appendix HBB-T, provide redundant production for the failure modes prevented by the primary load design rules in HBB-3220 when the time-dependent properties control the primary load allowable stress S_{mt}, i.e., $S_t \leq S_m$. Components in high-temperature reactors will almost certainly operate in this time-dependent regime.

Recall the definition of S_t as the lesser of (HBB-T-3221):

a) 100% of the average stress required to obtain a total (elastic, plastic, primary, and secondary creep) strain of 1%;

b) 80% of the minimum stress to cause the onset of tertiary creep; and

c) 67% of the minimum stress to cause rupture, S_r.

Of these three criteria, two reflect actual design limits – the 1% strain and rupture criteria – and the tertiary creep criterion, discussed elsewhere in this report, was originally intended to guard against leakage failure in biaxially stressed tubes. The Appendix HBB-T deformation-controlled design limits on strain accumulation and creep-fatigue provide redundant protection against all three of the S_t criteria. Even if the allowable stress S_t in the code does not match the actual material data, these redundant checks would still adequately guard against these three design limits, provided the code minimum stress-to-rupture data was reasonably accurate.

The deformation limits given in Appendix HBB-T provide a redundant check on the 1% strain criteria in S_t. The stated limits in HBB-T-1310 are that the maximum accumulated inelastic strain shall not exceed:

a) 1%, averaged through the thickness;
b) 2%, linearized through a section; or
c) 5%, at any point.

The first two criteria (1% averaged through the thickness and 2% linearized) provide redundant protection against the first of the S_t criteria. The primary load S_t allowable stress check considers only the primary membrane and primary membrane plus bending stresses. The membrane and bending components are analogous to the 1% averaged and 2% linearized strain criteria. The Appendix HBB-T deformation limits include the effect of both primary and secondary stress, and so are generally more conservative than the allowable primary stress check, as the stresses under consideration are greater than just the primary membrane and bending stresses. Appendix HBB-T provides several alternatives for meeting the deformation limits, up to and including a full inelastic analysis. These methods have an extensive technical background demonstrating that they adequately protect against the strain limits criteria, which in turn provide a conservative, redundant check against the S_t 1% criterion.

The Appendix HBB-T creep-fatigue design check provides redundant protection against the third S_t criterion: 67% of the minimum stress-to-rupture. Again, Appendix HBB-T provides multiple methods for meeting the creep-fatigue limits, either using elastic or inelastic stress analysis. These approaches have an extensive technical background demonstrating that they adequately prevent the initiation of creep-fatigue failure, which includes steady-state rupture as a limiting case (specifically, the limiting case where the fatigue damage is zero).

The creep-fatigue design approaches (HBB-T-1400) consider the full stress history of the component, not just the primary stresses, as in the allowable stress check. As all realistic components will include some secondary and peak stress, this means that the stresses used in the creep-fatigue evaluation are greater than the primary stress used in the allowable stress check. Moreover, the creep-fatigue limits include the detrimental effect of fatigue on creep strength. Applying a higher stress and reducing the creep strength of the material means the Appendix HBB-T creep-fatigue checks provide a conservative redundant check on the S_t rupture criterion.

However, consider the limiting case of a component under a steady primary load. Even in this case, the creep-fatigue rules provide redundant protection. In this special, unrealistic case, the creep-fatigue rules would allow a creep damage fraction of 1.0, and the stress to evaluate the

creep damage would be constant (not relaxing). Under these conditions the creep-fatigue rules would degenerate to

$$\frac{t_{design}}{t_R(\sigma/K')} \leq 1$$

where t_{design} is the design life, t_R the time corresponding to the minimum stress-to-rupture, σ the effective stress, and K' a safety factor. This check alone provides redundant, conservative protection against rupture, as the factored stress could not exceed the material minimum-stress-to-rupture for the design life.

Most realistic components would include bending and peak stresses. In this case, the code creep-fatigue criterion is even more conservative. In the case of non-uniform stresses across a section, the creep-fatigue criterion limits the design life to the time at which the first point exceeds the creep-fatigue limit. Conceptually, this represents the initiation of a creep crack at the most stressed location. In service, the creep crack would then need to propagate through the component section before net section rupture or leakage could occur. The creep-fatigue design rules conservatively do not credit the design with the time required to propagate the initial flaw, which can be substantial for actual in-service components.

Finally, the creep-fatigue rules also provide a redundant protection against the tertiary creep criterion in the definition of S_t. Originally, this criterion was included in the allowable stress to guard against leakage and failure under creep conditions for multiaxial stress states, for example, pressurized tubes. The Appendix HBB-T creep-fatigue rules provide protection against multiaxial rupture. For the design by elastic analysis rules, this protection is a correction to the uniaxial stress relaxation profile to account for multiaxiality (HBB-T-1433, Step 5a) or by applying the very conservative isochronous stress-strain curve relaxation approach (HBB-T-1433, Step 5b). For design by inelastic analysis, the protection is provided by using the Huddleston effective stress to account for the effects of stress multiaxiality (HBB-T-1411). All three approaches have an extensive technical background demonstrating that they adequately account for the effect of multiaxial load on rupture life. Combined with the generally conservative creep-fatigue damage approach, discussed previously, they provide a conservative, redundant protection against the S_t time-to-tertiary criterion.

2.2 CONSERVATISMS INHERENT IN DETERMINING THE MATERIALS PROPERTIES AND ALLOWABLE STRESSES FOR SECTION III, DIVISION 5 CLASS A COMPONENTS

As presented in the Forward of each of the ASME code books, "The objective of the rules is to afford reasonably certain protection of life and property, and to provide a margin for deterioration in service to give a reasonably long, safe period of usefulness." This is consistent with NRC guidance that regulatory findings be based upon the principle of "Reasonable Assurance of Adequate Protection."

The primary load design provisions of Division 5 HBB express an allowable stress design methodology. The underlying allowable stresses and other design data, including the thermal aging and stress rupture factors, are set by the relevant code committees so that, in the committees' judgment, the values will produce safe, reliable designs that afford reasonably certain protection of life and property. To rationalize the process of determining allowable stresses and the other design data, the code committees have established criteria based on material properties (e.g., the rupture, time-to-1% strain, and time-to-tertiary criteria for time-dependent allowable stress values, St). Supplementary but less rigorous factors are also provided for behavioral trends to account for the degradation of yield and tensile strength due to long-term thermal aging and the potential for reduced-weldment creep rupture strength as compared to base metal strength.

The average trends of degradation of yield and tensile strength due to long-term aging are used in the code procedures, but no benefits are taken when there is an increase in the yield and tensile strength due to aging.

As stated in Appendix HBB-Y on materials data requirements, the intent of the stress rupture factors for weldments is to provide a reasonable approximation of the loss of creep rupture strength in welded construction. Although, conceptually, the data needed to develop such stress rupture factors for weldments would correspond to the requirements for base metal, in practice, the requirements are less rigorous because of the number of qualified combinations of base metal/filler metal/welding technique and the difficulty in collecting weldment rupture data. The average trends of the stress rupture factors are used in the code procedure, and again, no benefits are taken if the creep rupture strength of the weldment is greater than that of the base metal. Permissible weld/base metal combinations are given in Table HBB-I-14.1(b), and combinations not listed could not be used. The values of stress rupture factors in Tables HBB-I-14.10A through HBB-I-14.10.E are for these specific weld-metal and base-metal combinations.

New data occasionally suggests that design-allowable stresses need to be reduced. Examples include the 304H/316H data discussed below and the wider discussion in both the nuclear and non-nuclear community on Grade 91 (modified 9Cr-1Mo) steel. While one outcome may be code action to reduce the relevant allowable stresses, that action need not happen immediately once the new data is disseminated. The ASME allowable stress design practice includes substantial conservatism in both the design methodology, as discussed previously, and the factors in the material data used to define the allowable stresses to ensure structures designed and constructed with any given edition of the BPVC Section III rules will be safe and effective even if new material data comes to light. Thus, these factors cover additional, unspecified, uncertainties deemed prudent by the code committees.

2.3 CONSERVATISM IN THE WELDMENT DESIGN PROCEDURE IN SECTION III, DIVISION 5 FOR CLASS A COMPONENTS

Weldment design guidance in BPVC was quite minimal until the mid-1980s. Weldment cracking of elevated temperature components under repeated thermal transient loadings was identified as a structural integrity concern by NRC in the Safety Evaluation Report [5] related to

the construction of the CRBR plant. A confirmatory test program was planned to address the NRC concerns but was not formally executed due to the cancellation of the CRBR project. However, efforts from DOE structural materials programs and ASME code committees led to the introduction of a weldment design procedure in Code Case N-47-26 in 1987 to improve the overall high-temperature design methodology for welded construction. The current rules in HBB provide provisions to evaluate weldment in the primary load, strain limits, and creep-fatigue checks.

For the primary load check, a stress rupture factor is introduced in HBB-3220 to account for the potential reduction in the time-dependent allowable stresses for the weldment under Service Level A, B, C, and D Loadings.

Special deformation-controlled requirements at welds were developed to address the potential for limited ductility of weld metal at elevated temperatures and high strain concentrations (both metallurgical and geometric) in the heat-affected zone of weldments. The potential for reduced ductility often precludes locating welds in regions of high loading. These requirements shall be met for all Service Level A, B and C Loadings. For the strain limits check, the inelastic strain accumulations in the weld region are reduced to one-half the strain values permitted for the parent base material.

For the creep damage evaluation in the creep-fatigue check, the allowable time duration is determined using the rupture strength for the weld, obtained through the stress rupture factor and the rupture strength of the parent base metal. Further, the design factor K' on the effective stress used for the parent base material is still required in the allowable time duration calculation. For the fatigue damage evaluation, the number of allowable fatigue cycles is one-half the value permitted for the parent base material.

Further conservatism was introduced in the design evaluation procedures where the stress and strain concentration factors appropriate for the worst surface geometry of a given weld are used for strain-accumulation and creep-fatigue interactions at welds.

2.3.1 Perspective on weldment evaluation procedures

Rules in other BPVC books basically employ a design-by-rule approach and address weldment only through the use of a weld strength reduction factor on allowable stress. There are no provisions for strain limits and creep-fatigue damage evaluations for welds. The HBB rules are essentially based on a design-by-analysis approach. Through the strain limits and creep-fatigue provisions for welds, the HBB design-by-analysis approach considers the evaluation of as-built constraints, consequent stress and strain redistributions, and the existence of relatively weak weldment zones that go beyond the weld strength reduction factor on allowable stress. In other BPVC books, the allowable stress is based on expected properties evaluated at 100,000 hours. In HBB, the allowable stress is based on the intended service life, and only the identified welding processes and weld compositions in Table HBB-I-14.1(b) are permitted. Assessment of HBB stress rupture factors for weldment must not be taken in isolation, but should be considered in the context of the overall design evaluation procedures.

3 CRITERIA FOR ALLOWABLE STRESSES AND DESIGN PARAMETERS

3.1 ALLOWABLE STRESS INTENSITIES

The stress intensity limits used to evaluate primary load designs are defined for Class A base materials and at weldments as follows.

3.1.1 Base materials

The S_{mt} intensity for service loadings is defined as the lower of:

a) S_m, time-independent stress intensity and
b) S_t time-dependent stress intensity.

The time-independent stress intensity S_m is defined as the lower of $\frac{2}{3}S_y$ and $\frac{1}{3}S_u$, where S_y and S_u are the yield and tensile strengths that are defined in Section II, Part D as criteria for determining S_m. In HBB, the S_m values are extended to elevated temperatures by using the same criteria.

As described in HBB-2160(d), it may be necessary to adjust the values of S_m to account for the effects of longtime service at elevated temperature on S_y and S_u through the yield and tensile strength reduction factors in Table HBB-3225-2. They are based on the ratio of the average strength after exposure to elevated temperature to the tabulated yield strength (Table HBB-I-14.5) or tabulated tensile strength (Table HBB-3225-1), as applicable. There is no credit for strength increase, so the maximum factor is 1.0.

The S_t intensity is temperature- and time-dependent; the data considered in establishing these intensities are obtained from long-term, constant-load, uniaxial tests. The criteria for the S_t intensity have already been defined in Section 2.1.3. but they are repeated here for completeness. For each specific time, t, the S_t intensity is the lesser of:

a) 100% of the average stress required to obtain a total (elastic, plastic, primary, and secondary creep) strain of 1%;

b) 80% of the minimum stress to cause initiation of tertiary creep; and

c) 67% of the minimum stress to cause rupture, S_r.

The S_0 intensity for design loadings is defined as the higher of:

a) The maximum allowable stress value S in Section II, Part D Table 1A (ferrous materials) or Table 1B (nonferrous materials) and

b) The S_{mt} stress intensity at 300,000 hours in HBB.

As discussed in the background material [2], these design loading allowable stress intensities were intended to provide assurance to the original ASME BPVC Main Committee that the then new elevated-temperature design rules with time-dependent allowable stress criteria for operating conditions with durations less than 100,000 hours would not result in component thicknesses less than would be achieved under the design rules and allowable stress criteria for Section VIII, Division 1 based on extrapolated 100,000-hour properties. It was later recognized that at lower temperatures, there was a limited regime where the Section II, Part D Tables 1A and 1B allowable stress values based on time-independent tensile properties could be lower than the S_{mt} intensities at 300,000 hours, leading to thicknesses greater than those governed by the S_{mt} intensities at 300,000 hours for service level conditions. This was considered to be contrary to the intent of the criteria for design loadings addressing the shorter lifetimes, and, thus, the current allowable stresses for design loadings, S_0, are based on the higher of the S value in Section II, Part D or the value of S_{mt} at 300,000 hours in HBB.

Note that the S_0 intensities for design loadings are determined from tabulated values in Section II, Part D and HBB. As such, the tabulation of the S_0 values in Table HBB-I-14.2 is somewhat redundant. Sometimes, there is lag or a failure in coordination when the values in Section II, Part D or HBB are modified and the S_0 values in Table HBB-I-14.2 are not updated simultaneously, creating inconsistency. Experience, however, suggests that the service loadings, rather than the design loadings, control the primary load design.

Going forward, code action will be initiated to remove Table HBB-I-14.2 and to reference the S_0 intensities directly in terms of the S values in Section II, Part D and the 300,000-hour S_{mt} values in HBB.

3.1.2 Weldments

The weldment S_{mt} intensity for service loadings is defined as the lower of:

a) The tabulated base material S_{mt} value in HBB and

b) $0.8 \times S_r \times R$.

As described in HBB-2160(d), it may be necessary to adjust the values of S_m, which is involved in the determination of the base material S_{mt} value, to account for the effects of long-time service at elevated temperature.

The temperature- and time-dependent stress intensity S_t at a weldment is defined as the lower of:

a) The tabulated base material S_t value in HBB and

b) $0.8 \times S_r \times R$.

The factor R is the stress rupture factor defined as the ratio of the average weld material creep rupture strength to the average base material creep rupture strength. The S_r value has already been defined in Section 2.1.3 as the base material expected minimum stress-to-rupture.

3.2 YIELD STRENGTH AND TENSILE STRENGTH

Section II, Part D, Mandatory Appendix 2 gives the criteria for the yield and tensile strengths used by HBB. They are:

a) Yield strength at temperature = $S_Y \times R_Y$

b) Tensile strength at temperature = $1.1 \times S_T \times R_T$

where

R_Y = ratio of the average temperature-dependent trend curve value of yield strength to the room temperature yield strength.
R_T = ratio of the average temperature-dependent trend curve value of tensile strength to the room temperature tensile strength.
S_Y = specified minimum yield strength at room temperature.
S_T = specified minimum tensile strength at room temperature.

The values of the yield strength at temperature are tabulated in Section II, Part D, Table Y-1, and the values of the tensile strength at temperature are tabulated in Section II, Part D, Table U.

3.2.1 Aging factors

Long-time, elevated-temperature service may result in the reduction of the subsequent yield and tensile strengths. The yield and tensile strength reduction factors (Table HBB-3225-2) are based on the ratio of the average strength after exposure to elevated temperature to the tabulated yield strength (Table HBB-I-14.5) or tabulated tensile strength (Table HBB-3225-1), as applicable. There is no credit for strength increase, so the maximum factor is 1.0.

4 ASSESSMENT OF HBB ALLOWABLE STRESSES AND DESIGN PARAMETERS AND NRC CONTRACTOR COMMENTS

As part of the NRC effort in assessing ASME Section III, Division 5 for endorsement, NRC contractors were tasked to provide reviews of various parts of Section III, Division 5. Oak Ridge National Laboratory (ORNL) was contracted by NRC to provide reviews of the following parts of HBB:

1. Article HBB-2000 Material,
2. Article HCB-2000 Material,
3. Article HGB-2000 Material,
4. Mandatory Appendix HBB-I-14 Tables and Figures, and
5. Nonmandatory Appendix HBB-U Guidelines for Restricted Material Specifications to Improve Performance in Certain Service Applications.

The NRC contractor has recreated the technical basis of the allowable stresses and design parameters by first assembling materials data from various sources and then conducting analysis of the assembled data. Based on the analysis results, assessments of the HBB design properties were made and comments were provided.

The work is documented in the NRC Technical Letter Report ORNL/SPR-2020/1653, entitled, “Oak Ridge National Laboratory Technical Input for the Nuclear Regulatory Commission Review of the 2017 edition of the ASME Boiler and Pressure Vessel Code, Section III, Division 5, High Temperature Reactors,” by Weiju Ren, Jude Foulds, Roger Miller, and Wolfgang Hoffelner [6].

The recreation of the technical basis of the HBB allowable stresses and design parameters is an enormous task. The current allowable stresses and design parameters were established through many years of development by many ASME volunteers. They were approved for code use through the codes and standards consensus process in which the proposals were reviewed and commented upon by a large segment of the BPVC code committees. This process provides valuable checks and balances where the code intent, use experience, and engineering judgment on the impact of the proposed item on the overall adequacy of the HBB construction rules to provide a reasonable assurance of structural integrity are rendered.

Critical evaluation of the data with respect to the material specifications and additional Section III requirements was not conducted in this report, nor were the data analyses by the contractor verified, as they are outside the scope of this work. Instead, code intent, historical code committee information, various publications on code criteria, and background information on code actions were leveraged.

In the following, assessment of the NRC contractor review of items 1 and 4 is provided. As elaborated in the following sections, non-code criteria were applied in some places and non-permissible materials data were used in others. These deficiencies should be recognized in the drafting the Regulatory Guide by NRC on the endorsement of ASME Section III, Division 5.

4.1 EXPECTED MINIMUM STRESS-TO-RUPTURE S_r AND ALLOWABLE STRESS INTENSITY S_t

4.1.1 304H and 316H stainless steels

In support of the effort to extend the design lifetime of Class A materials from 300,000 to 500,000 hours, a task under the DOE/ASME Gen IV Materials Project was initiated to extend the S_r and S_t values of 304H and 316H to 500,000 hours. It led to the results published in the report STP-NU-063 [7]. The STP-NU-063 results would suggest that the S_r and S_t values for 304H and 316H may need to be reduced in view of new time-to-tertiary data. The ASME code committees were informed of the outcome of the report. There have been extensive on-going discussions regarding the report, and no code action has been taken. The reason is that it is not clear that the time-to-tertiary criterion should be included in the calculation of the allowable stress, to begin with, or that accepting reduced allowable stresses is reasonable, as discussed below.

When the original criterion for the onset of tertiary creep was selected, it was based on thin-walled pressurized capsule tests that leaked before they ruptured. In these biaxial tests, the time to rupture correlated with the onset of tertiary creep in uniaxial tests. The time-to-tertiary criterion was included in the allowable stresses at the time; however, with the limited tertiary creep data then available, the onset of tertiary creep did not control any of the allowable stress values. A historical perspective on the tertiary creep criterion was recently provided by Jetter et al. [8]. The results reported in STP-NU-063 are substantially different and would result in significantly lower allowable stress values, which could have an impact on basic component thickness calculations. Because lowering the allowable stress values by this magnitude would be at odds with commercial practice and other international standards, it was deemed appropriate to reexamine the original time-to-tertiary criterion rather than immediately change the allowable stresses. The goal of this revaluation was to see if the tertiary creep criterion was more generally applicable to thicker walled components such as in the ORNL nozzle-to-sphere test by Corum and Battiste [9]. The current status of these assessments is that the original capsule failures were equally or better explained by multiaxial effects, the data used to establish the onset of tertiary was compromised by irregularities in the creep curves, and the nozzle-to-sphere failure data did not correlate with the onset of tertiary creep.

Code committee consensus on the role of the onset of tertiary creep as one of the criteria for the time-dependent allowable stress S_t, and hence the stress intensity S_{mt} for primary load design check, has yet to be achieved. Though, as noted in Section 2.1, the HBB primary load design approach does not rely on exactly capturing the minimum stress to tertiary creep in the values of S_t to maintain safe designs, given the conservatism included in the factors of the individual S_t criteria (i.e. 80% for tertiary creep), the general conservatism of the Section III, Division 5 design-by-elastic-analysis procedure, and the redundant protection against the onset of creep rupture provided by the creep-fatigue design provisions.

While the role of the onset of tertiary creep remains to be clarified, Dabrow and Nestell [10] have recently re-examined the treatment of the tertiary creep data for 304H and 316H.

Nestell reported the following findings to the ASME Working Group on Allowable Stress Criteria, which has cognizance over this issue.

The tertiary creep criterion was introduced as a refinement of the other allowable stress criteria that was not expected to control most of the S_t values in the STP-NU-063 analysis of 304H and 316H data. Reasons the tertiary creep criterion controlled the S_t values in the STP-NU-063 results were thought to be:

1. Tertiary creep data are sensitive to the shape of the creep curve and identifying the point of onset of tertiary creep is sometimes difficult,

2. Carbide precipitation during creep testing can markedly affect the shape of the creep curve,

3. The actual number of tertiary creep data is very small compared with the available rupture data, causing statistical uncertainties and poor extrapolation of the test data to operating times and temperatures.

An empirical observation, first made by Leyda and Rowe [11] in the 1960s and subsequently by others, indicated that the ratio of the time to the onset of tertiary creep to the time to rupture is relatively constant over a range of temperatures and stress levels. Using the tertiary creep data, Dabrow and Nestell determined an average tertiary-to-rupture time ratio. They then applied this average Leyda-Rowe correlation to the time-to-rupture regression results to arrive at a time-to-tertiary-creep correlation. Since the creep rupture database is much more robust, the adoption of the creep rupture statistics essentially mitigates some of the issues associated with the tertiary creep database discussed above. Dabrow and Nestell [10] combined this more accurate time-to-tertiary-creep correlation with the time-to-1%-strain and time-to-rupture correlations established in STP-NU-063 to arrive at new S_t values. These new S_t values and the S_r values determined in STP-NU-063 are shown in TABLE 1 and FIGURE 2, respectively, for 304H, and in TABLE 2 and FIGURE 3 for 316H.

HBB revision based on the S_t values from Dabrow and Nestell, the corresponding S_{mt} intensities, and the S_r values from STP-NU-063 will be proposed for ASME code committees approval through Codes and Standards (C&S) Records 16-792 and 16-793 for 304H and 316H, respectively.

The Dabrow-Nestell S_t values and the STP-NU-063 S_r values are compared with the corresponding design values from the 2017 code edition of HBB using the following measures:

$$D_1 \equiv \frac{(S_t)_{Dabrow-Nestell} - (S_t)_{2017}}{(S_t)_{2017}} \times 100\%$$

$$D_2 \equiv \frac{(S_r)_{STP-NU-063} - (S_r)_{2017}}{(S_r)_{2017}} \times 100\%$$

A negative D_1 or D_2 denotes that the Dabrow-Nestell S_t value or the STP-NU-063 S_r value is more restrictive than the corresponding HBB value in the 2017 code edition. The D_1 and D_2 values for 304H are shown in TABLE 3 and TABLE 4, respectively. Similar values for 316H are shown in TABLE 5 and TABLE 6.

The S_t values from the 2017 code edition for 316H are adequate with respect to the new values. The S_t and the S_r values for 304H and the S_r values for 316H from the 2017 code edition are adequate up to 700°C. There are some larger negative D_2 values for 316H at lower temperatures and long times (100,000 to 300,000 hours). The S_r values are used in the creep damage evaluations. These temperature-time conditions are within the negligible creep regime, and the contributions to the creep damage are negligible. Thus, while the S_r values from the 2017 code edition are higher than those from STP-NU-063, there is no impact on the creep damage evaluation.

TABLE 1 S_t intensities for 304H based on the more accurate treatment of the tertiary creep criterion by Dabrow and Nestell [10], S_t in MPa

Temp., °C	Time, h										
	1	10	30	100	300	1k	3k	10k	30k	100k	300k
425	179.37	179.37	179.37	179.37	179.37	179.37	179.37	179.37	179.37	179.37	169.11
450	175.88	175.88	175.88	175.88	175.88	175.88	175.88	175.88	175.88	157.56	138.90
475	172.57	172.57	172.57	172.57	172.57	172.57	172.57	170.52	149.85	129.77	113.54
500	169.24	169.24	169.24	169.24	169.24	169.24	164.50	141.99	123.88	106.38	92.34
525	166.00	166.00	166.00	166.00	166.00	158.07	137.53	117.76	101.94	86.77	74.68
550	162.76	162.76	162.76	162.76	155.30	132.63	114.54	97.23	83.48	70.39	60.04
575	159.54	159.54	159.54	151.88	130.89	110.86	94.99	79.90	68.01	56.77	47.95
600	156.32	156.32	152.01	128.51	109.92	92.30	78.42	65.33	55.09	45.49	38.02
625	153.11	151.32	129.26	108.37	91.96	76.51	64.43	53.12	44.35	36.20	29.92
650	150.00	129.23	109.55	91.05	76.61	63.12	52.66	42.95	35.47	28.58	23.33
675	146.70	110.03	92.53	76.20	63.55	51.81	42.79	34.48	28.15	22.38	18.02
700	134.85	93.37	77.87	63.50	52.46	42.30	34.56	27.50	22.16	17.35	13.76
725	115.99	78.96	65.27	52.68	43.09	34.33	27.72	21.75	17.29	13.31	10.37
750	99.49	66.53	54.48	43.50	35.19	27.68	22.07	17.06	13.35	10.08	7.71
775	85.08	55.84	45.28	35.72	28.57	22.16	17.43	13.24	10.19	7.53	5.63
800	72.53	46.66	37.44	29.17	23.04	17.61	13.63	10.16	7.67	5.53	4.03

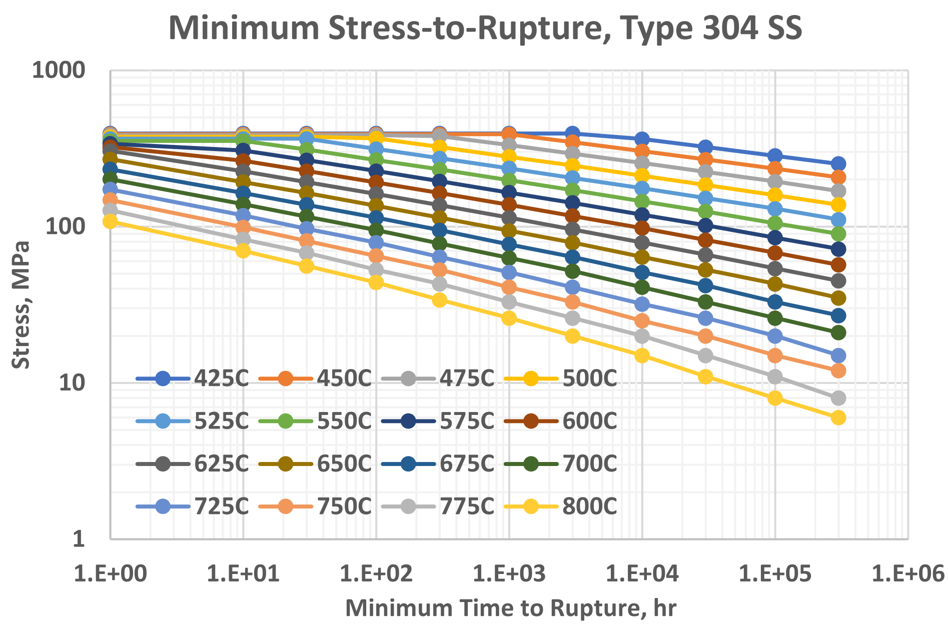


FIGURE 2 Expected minimum stress-to-rupture for 304H, data from STP-NU-063 [7].

TABLE 2 S_t intensities for 316H based on the more accurate treatment of tertiary creep criterion by Dabrow and Nestell [10], S_t in MPa

Temp., °C	Time, h										
	1	10	30	100	300	1k	3k	10k	30k	100k	300k
425	179.83	179.83	179.83	179.83	179.83	179.83	179.83	179.83	179.83	179.83	179.83
450	177.71	177.71	177.71	177.71	177.71	177.71	177.71	177.71	177.71	177.71	177.71
475	175.67	175.67	175.67	175.67	175.67	175.67	175.67	175.67	175.67	175.67	163.43
500	173.66	173.66	173.66	173.66	173.66	173.66	173.66	173.66	173.66	152.13	132.09
525	171.66	171.66	171.66	171.66	171.66	171.66	171.66	167.28	144.83	123.29	106.13
550	169.67	169.67	169.67	169.67	169.67	169.67	161.64	137.22	117.82	99.34	84.73
575	167.67	167.67	167.67	167.67	167.67	155.43	133.16	112.00	95.31	79.54	67.17
600	165.62	165.62	165.62	165.62	153.10	128.51	109.16	90.91	76.63	63.25	52.85
625	163.59	163.59	163.59	147.77	127.17	105.75	89.02	73.36	61.21	49.92	41.23
650	161.66	161.66	143.49	125.06	105.17	86.58	72.18	58.81	48.53	39.07	31.85
675	159.72	138.66	122.05	103.88	86.56	70.50	58.16	46.82	38.18	30.30	24.35
700	155.36	118.25	103.43	85.88	70.87	57.06	46.55	36.98	29.75	23.25	18.39
725	133.75	100.48	87.30	70.65	57.69	45.89	36.98	28.96	22.97	17.63	13.70
750	114.79	85.06	72.55	57.81	46.69	36.64	29.15	22.45	17.52	13.19	10.04
775	98.20	71.71	59.74	47.03	37.52	29.02	22.75	17.22	13.20	9.71	7.22
800	83.71	60.19	48.94	38.02	29.94	22.79	17.58	13.04	9.79	6.99	4.98

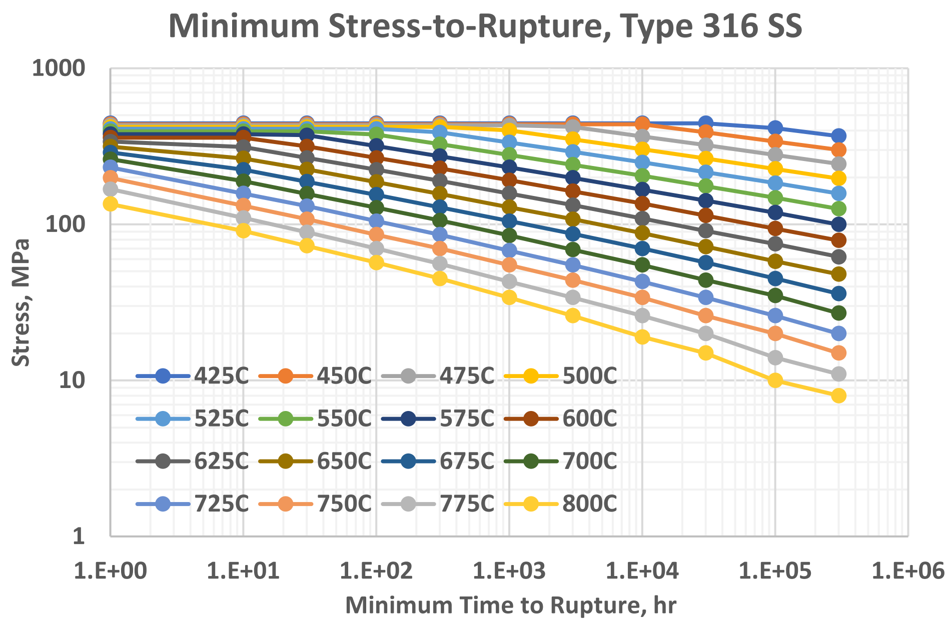


FIGURE 3 Expected minimum stress-to-rupture for 316H, data from STP-NU-063 [7].

TABLE 3 304H, difference in S_t between 2017 code and Dabrow-Nestell [10] values, D_1, %

Temp., °C	Time, h										
	1	10	30	100	300	1k	3k	10k	30k	100k	300k
425	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	19.9
450	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	15.0	3.7
475	26.9	26.9	27.8	27.8	27.8	28.8	30.7	31.2	16.2	3.0	-2.1
500	27.2	27.2	28.2	29.2	32.2	35.4	33.7	17.3	5.9	-0.6	-0.7
525	27.7	28.7	30.7	36.1	40.7	37.5	21.7	9.0	1.9	-0.3	2.3
550	29.2	30.2	34.5	41.5	41.2	24.0	11.2	3.4	1.8	0.6	3.5
575	29.7	31.9	37.5	38.1	24.7	10.9	4.4	2.4	3.0	1.4	4.2
600	30.3	35.9	39.5	26.0	13.3	4.9	4.6	3.7	2.0	3.4	2.8
625	32.0	41.4	28.0	16.5	5.7	3.4	3.9	4.2	3.1	0.6	3.2
650	36.4	31.9	19.1	8.4	4.9	3.5	3.3	2.3	1.3	2.1	1.4
675	43.8	22.3	11.5	5.8	4.2	1.6	1.9	-1.5	0.5	1.7	-5.2
700	45.0	16.7	9.7	4.1	4.9	0.7	1.6	-1.8	-3.7	-3.6	-8.3
725	34.9	12.8	7.0	1.3	0.2	-1.9	-4.4	-1.1	-3.9	-11.3	-13.6
750	27.6	10.9	4.8	-1.1	-2.3	-4.6	-4.0	-5.2	-11.0	-16.0	-14.3
775	23.3	9.5	2.9	-0.8	-1.5	-7.7	-8.3	-11.7	-15.1	-16.3	-19.6
800	20.9	8.5	1.2	0.6	0.2	-2.2	-9.1	-7.6	-14.8	-21.0	-19.4

TABLE 4 304H, difference in S_r between 2017 code and STP-NU-063 values, D_2, %

Temp., °C	Time, h 1	10	30	100	300	1k	3k	10k	30k	100k	300k
425	0.3	0.3	0.3	0.3	0.3	0.3	0.3	-7.6	-8.8	-7.8	-7.4
450	0.0	0.0	0.0	0.0	0.0	0.0	-1.7	-6.5	-6.3	-5.6	-5.5
475	-0.3	-0.3	-0.3	-0.3	4.4	-2.4	-2.3	-3.8	-3.4	-3.5	-4.0
500	-0.5	-0.5	3.3	4.9	1.9	-1.4	-1.6	-2.3	-1.6	-1.2	-1.4
525	-0.8	2.0	11.3	4.3	2.6	0.0	0.0	-0.6	-0.7	0.8	-2.6
550	-0.6	10.0	9.1	5.1	4.0	1.5	1.8	0.7	0.8	1.0	-1.1
575	1.8	12.0	10.4	6.1	3.7	2.5	2.2	5.3	2.0	2.4	2.9
600	8.4	13.3	10.7	6.7	4.5	3.0	3.5	3.2	2.5	3.0	1.8
625	19.1	14.1	10.3	7.3	5.4	2.7	3.2	1.3	3.1	1.9	2.3
650	22.7	14.2	11.6	7.1	3.6	2.2	2.6	1.6	1.9	0.0	2.9
675	23.3	13.1	10.4	5.6	4.4	2.7	3.2	0.0	0.0	-5.7	-3.6
700	24.1	13.0	9.4	4.4	4.0	0.0	0.0	0.0	-2.9	-3.7	-4.5
725	23.6	11.3	6.6	2.6	0.0	-3.8	-4.7	-5.9	-7.1	-9.1	-16.7
750	22.3	11.2	5.2	-3.0	-1.9	-6.8	-5.7	-10.7	-13.0	-16.7	-14.3
775	21.0	9.2	3.0	-3.6	-4.4	-8.3	-10.3	-13.0	-16.7	-21.4	-27.3
800	18.7	7.7	0.0	-4.3	-8.1	-10.3	-16.7	-21.1	-21.4	-20.0	-33.3

TABLE 5 316H, difference in S_t between 2017 code and Dabrow-Nestell [10] values, D_1, %

Temp., °C	Time, h 1	10	30	100	300	1k	3k	10k	30k	100k	300k
425	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8
450	25.1	25.1	25.1	25.1	25.1	25.1	25.1	25.1	25.1	25.1	26.9
475	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	25.5	27.3	21.1
500	24.0	24.0	24.0	24.0	24.0	24.9	24.9	25.8	29.6	16.1	5.7
525	24.4	24.4	24.4	24.4	24.4	26.2	28.1	28.7	14.9	4.5	-1.7
550	24.8	24.8	25.7	26.6	28.5	32.6	29.3	15.3	4.3	-1.6	-2.6
575	26.1	26.1	28.0	32.0	35.2	30.6	16.8	6.7	0.3	0.7	0.3
600	26.4	28.4	31.4	36.9	32.0	16.8	4.0	-0.1	2.2	2.0	3.6
625	28.8	35.2	38.6	33.1	23.5	12.5	3.5	1.9	3.7	4.0	3.1
650	31.4	39.4	32.9	28.9	25.2	20.3	12.8	3.2	1.1	2.8	2.7
675	35.4	30.8	29.8	29.8	25.4	21.6	14.0	6.4	0.5	1.0	1.5
700	38.7	29.9	32.6	32.1	31.2	24.1	13.5	8.8	6.3	5.7	2.2
725	32.4	34.0	38.6	35.9	31.1	27.5	19.3	15.8	9.4	10.2	5.4
750	30.4	37.2	42.3	41.0	33.4	26.4	21.4	18.2	9.5	19.9	11.5
775	32.7	43.4	49.4	47.0	39.0	26.2	26.4	23.0	10.0	21.4	3.1
800	37.2	50.5	52.9	52.1	42.6	34.1	35.2	30.4	22.4	39.7	24.6

TABLE 6 316H, difference in S_r between 2017 code and STP-NU-063 values, D_2, %

Temp., °C	Time, h										
	1	10	30	100	300	1k	3k	10k	30k	100k	300k
425	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-7.0	-17.3
450	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	-6.9	-13.9	-19.4
475	0.0	0.0	0.0	0.0	0.2	0.5	2.9	-5.9	-8.5	-12.0	-14.7
500	0.5	0.5	0.5	0.5	5.0	5.0	0.6	-5.9	-7.4	-8.5	-10.0
525	0.7	0.7	5.4	10.2	14.4	9.1	6.2	0.8	-4.4	0.5	0.0
550	0.5	3.7	12.9	16.7	13.1	4.1	4.8	1.0	1.7	0.7	0.8
575	-0.3	9.2	19.9	12.4	10.0	4.0	2.6	-1.2	0.0	-0.8	0.0
600	0.8	20.0	18.8	10.8	8.0	3.8	2.5	0.0	1.8	0.0	0.0
625	7.6	20.8	16.6	9.3	6.1	1.9	2.3	-0.9	2.2	4.2	5.1
650	14.5	18.3	13.1	6.3	4.0	0.0	0.9	0.0	2.9	1.8	4.3
675	18.4	15.5	10.6	3.3	1.6	-2.8	-2.2	-1.4	0.0	2.3	2.9
700	23.6	13.2	6.8	0.0	0.0	-4.5	-4.2	-3.5	-2.2	2.9	0.0
725	24.7	9.7	3.1	-2.8	-6.5	-10.5	-8.3	-8.5	-5.6	-3.7	-4.8
750	22.1	5.6	-0.9	-5.5	-7.9	-12.7	-12.0	-10.5	-10.3	-4.8	-6.3
775	16.7	0.9	-5.3	-10.3	-12.5	-17.3	-17.1	-13.3	-13.0	-12.5	-8.3
800	8.9	-1.1	-7.6	-12.3	-16.7	-19.0	-18.8	-20.8	-16.7	-16.7	-11.1

4.1.2 Alloy 800H

As part of the effort to extend the design lifetime of Class A materials from 300,000 to 500,000 hours, another task under the DOE/ASME Gen IV Materials Project was initiated to extend the S_r and S_t values of Alloy 800H to 500,000 hours. The work led to the results published in the report STP-NU-035 by Swindeman et al. [12]. Based on the results in STP-NU-035, the S_r values of Alloy 800H were revised in the 2013 code edition to extend them to longer times (500,000 hours) and higher temperatures (816°C). However, similar to the S_t values for 304H and 316H found in the STP-NU-063 analysis, the Alloy 800H S_t values in STP-NU-035 were also found to be significantly lower in view of the new time-to-tertiary data. In addition, the S_t values were mostly controlled by the tertiary creep criterion, again, similar to the STP-NU-063 results for stainless steels.

The NRC contractor essentially reproduced the STP-NU-035 results for the S_t values of Alloy 800H.

The approach developed by Dabrow and Nestell [10] on the use of the Leyda and Rowe correlation in the treatment of the 304H/316H creep data can also be equally well applied to the analysis of the Alloy 800H data in establishing the revised values of S_t. This action will be initiated by the ASME BPV III Working Group Allowable Stress Criteria in 2021. For a preliminary assessment of the potential impact of such an action on the S_t values of Alloy 800H in the 2017 code edition, the following consideration is made. The S_r values of Alloy 800H from

the 2017 code edition, multiplied by the factor 0.67, are shown in TABLE 7. The S_t values of Alloy 800H from the 2017 code edition are shown in TABLE 8.

TABLE 7 $0.67 \times S_r$ for Alloy 800H from the 2017 code edition, $0.67 \times S_r$, in MPa

Temp., °C	Time, h										
	1	10	30	100	300	1k	3k	10k	30k	100k	300k
425	259	259	259	259	259	259	259	259	259	251	221
450	258	258	258	258	258	258	258	258	237	206	181
475	257	257	257	257	257	257	257	223	196	169	147
500	256	256	256	256	256	247	215	185	161	139	121
525	254	254	254	254	242	207	180	153	133	113	98
550	236	236	236	235	203	173	149	127	109	92	80
575	229	229	229	199	171	145	124	105	90	76	64
600	222	222	199	168	143	121	103	86	74	62	52
625	212	198	169	141	121	101	85	71	60	50	42
650	202	169	143	119	101	84	70	58	49	41	34
675	191	144	121	101	84	70	58	48	40	33	27
700	177	123	103	84	70	58	48	40	33	27	22
725	152	104	86	71	59	48	40	32	27	21	17
750	131	88	73	60	49	40	33	26	21	17	14

TABLE 8 S_t values of Alloy 800H from 2017 code edition S_t, in MPa

Temp., °C	Time, h										
	1	10	30	100	300	1k	3k	10k	30k	100k	300k
425	132	132	132	132	132	132	132	132	132	132	132
450	130	130	130	130	130	130	130	130	130	130	130
475	129	129	129	129	129	129	128	128	128	127	126
500	128	128	128	128	128	128	127	126	126	125	124
525	126	126	126	126	126	125	124	124	122	119	109
550	124	124	124	124	124	123	122	121	113	103	88
575	123	123	123	122	121	120	117	111	96	83	72
600	121	121	120	119	117	114	107	91	79	67	58
625	119	118	116	115	109	102	89	75	64	55	47
650	117	115	112	109	101	85	74	62	53	45	39
675	114	109	105	98	85	72	61	52	44	37	31
700	110	100	94	82	70	59	50	41	35	29	25
725	99	88	82	70	58	49	41	34	29	24	20
750	94	80	69	58	49	40	34	28	24	20	16

The two sets of values in TABLE 7 and TABLE 8 can be compared using the following measure:

$$D_3 \equiv \frac{0.67 \times (S_r)_{2017} - (S_t)_{2017}}{(S_t)_{2017}} \times 100\%$$

The comparison is shown in TABLE 9.

TABLE 9 D_3 values for Alloy 800H D_3, %

Temp., °C	Time, h										
	1	10	30	100	300	1k	3k	10k	30k	100k	300k
425	96	96	96	96	96	96	96	96	96	90	68
450	98	98	98	98	98	98	98	98	82	58	39
475	99	99	99	99	99	99	101	74	53	33	17
500	100	100	100	100	100	93	69	47	28	11	-3
525	102	102	102	102	92	66	45	24	9	-5	-10
550	90	90	90	90	64	41	22	5	-3	-10	-9
575	86	86	86	63	41	21	6	-6	-6	-9	-11
600	83	83	66	41	23	6	-4	-5	-7	-8	-10
625	78	68	46	23	11	-1	-4	-5	-6	-9	-10
650	73	47	28	9	0	-1	-5	-6	-8	-9	-12
675	68	32	15	3	-1	-3	-4	-7	-9	-11	-11
700	61	23	9	3	1	-2	-4	-4	-6	-8	-12
725	54	18	5	1	2	-3	-4	-5	-8	-11	-13
750	39	11	6	3	0	-1	-3	-7	-11	-13	-12

With other sources of conservatism in the overall HBB design procedure, as discussed in Section 2.1.1, it is judged that the S_t values of Alloy 800H from the 2017 code edition for temperatures up to 760°C and design lives up to 300,000 hours are adequate for primary load assessment. It is noted that there is a planned ASME code action to extend the S_t values of Alloy 800H from 300,000 to 500,000 hours and to temperatures higher than 760°C. It is anticipated that the Dabrow-Nestell [10] approach will be employed in the treatment of the Alloy 800H tertiary creep data.

4.1.3 2.25Cr-1Mo steel (Grade 22 Class 1, annealed)

The 2.25Cr-1Mo steel, which is designated as Grade 22, has two strength levels. The nominally annealed material (Class 1) has a strength level of 30 ksi minimum yield strength and 60 ksi minimum tensile strength. The microconstituents in the annealed material are generally ferrite and pearlite. This strength level is produced by slowly cooling from the austenitizing

temperature. The normalized and tempered Grade 22 (Class 2) has a strength level of 45 ksi minimum yield strength and 75 ksi minimum tensile strength. The microconstituent in this material is bainite, although some proeutectoid ferrite could be present. The annealed material, Grade 22 (Class 1), was selected for inclusion in Section III, Division 5 to take advantage of its better metallurgical stability and creep strength at temperatures in the range of 1000 to 1100°F (538 to 593°C).

The issue of a potential lack of conservatism in the long-term, high-temperature allowable stress values for 2.25Cr-1Mo has been recognized for many years. See, for example, the ORNL report by McCoy [13]. This has not been a priority item for the cognizant ASME code committee, now the Subgroup on High Temperature Reactors, because the historical applications were at relatively low temperatures, less than 950°F, and the development of Grade 91 was intended to replace 2.25Cr-1Mo as a more effective steam generator material. In light of potential renewed interest in 2.25Cr-1Mo, including more general applications and longer design lifetimes, it is judged that the S_r and S_t values of 2.25Cr-1Mo in Tables HBB-I-14 of the 2017 edition of Section III, Division 5 be restricted to a maximum temperature of 950°F (510°C) until a consensus position on these allowable stress values can be established in the applicable ASME BPV committees. The background for this judgment follows.

McCoy [13] used the so-called minimum commitment method (MCM) to analyze the creep rupture data from four heats of 2.25Cr-1Mo. A major conclusion was that the values of the 100,000-hour creep rupture stress from the ORNL analysis were comparable to those in ASME Code Case N-47, up to 1000°F (538°C). But they were lower than the N-47 values at temperatures higher than 1000°F.

In the assessment of the 2.25Cr-1Mo database for extrapolation of design lives to 500,000 hours, Swindeman [14] also found that the high-temperature, long-term allowable stress values were unconservative using a much larger data base from National Institute for Materials Science (NIMS). Importantly, he also discussed difficulties in assessing the 2.25Cr-1Mo creep curves, noting that for most heats and testing conditions, the creep curves are mostly in third-stage creep with a little primary creep, as opposed to the classical curves assumed for the initial allowable stress development. This is generally analogous to the tertiary creep issues in the austenitic stainless steels as discussed by Sengupta and Nestell in STP-NU-063 [7] and by Dabrow and Nestell [10].

In [14] Swindeman used a Stress Range Splitting (SRS) approach similar to that introduced by the NIMS for Grade 91 steel to analyze seven heats of 2.25Cr-1Mo tubing materials from NIMS. Curves of applied stress versus average creep rupture life produced by the SRS analysis in combination with the Larson-Miller approach are compared with the test data in FIGURE 4. The vertical red line in the figure shows the 300,000 hours mark. From the standpoint of establishing a temperature bound for the use of the allowable stresses in Tables HBB-I-14 of the 2017 code edition, it is seen that the data fit at 500°C shows no excursion into the regime of rapid life degradation and a slight excursion at 525°C starting at 200,000 hours.

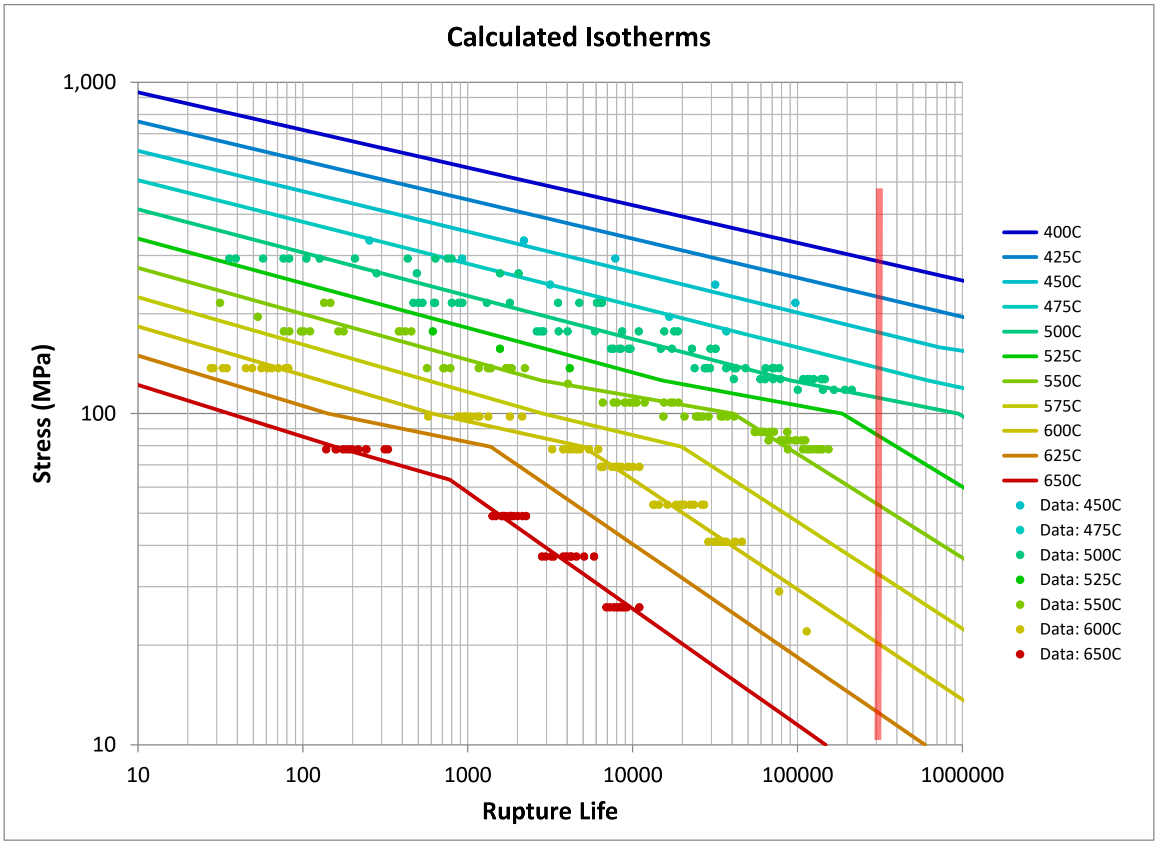


FIGURE 4 Comparison of average values from SRS and Larson-Miller analysis with the seven heats of NIMS 2.25Cr-1Mo tubing data, following Swindeman [14].

The statistical fits can then be used to calculate the expected minimum stress-to-rupture values, S_r. The S_r values at 100,000 hours from the SRS analysis are compared to those from HBB (2017 edition) in TABLE 10. The $0.67 \times S_r$ values at 100,000 hours from the SRS analysis are compared to the S_t values from HBB (2017 edition) in TABLE 11. The percentage differences, D_4 and D_5, shown in the tables are defined as:

$$D_4 = \frac{(S_r)_{SRS} - (S_r)_{2017}}{(S_r)_{2017}} \times 100\%$$

$$D_5 = \frac{0.67 \times (S_r)_{SRS} - (S_t)_{2017}}{(S_t)_{2017}} \times 100\%$$

TABLE 10 Comparison of S_r at 100,000 hours from SRS analysis and HBB for 2.25Cr-1Mo

Temp., °C	$(S_r)_{SRS}$ at 100k hr, MPa	$(S_r)_{2017}$ at 100k hr, MPa	D_4, %
400	289	256	13
425	226	191	18
450	176	151	17
475	138	121	14
500	108	96	12
525	84	71	18
550	65	58	13
575	41	43	-5

TABLE 11 Comparison of $0.67 \times S_r$ and S_t at 100,000 hours from the respective SRS analysis and HBB for 2.25Cr-1Mo

Temp., °C	$0.67 \times (S_r)_{SRS}$ at 100k hr, MPa	$(S_t)_{2017}$ at 100k hr, MPa	D_5, %
400	194	172	13
425	151	125	21
450	118	101	17
475	92	80	15
500	72	64	13
525	56	48	17
550	44	38	15
575	27	29	-6

It is seen that the tabulated values of S_r from HBB-I-14.6D are significantly more conservative with respect to the corresponding values from the SRS analysis of the NIMS data up to 1022°F (550°C). Similarly, the tabulated values of S_t from HBB-I-14.4D are significantly more conservative with respect to the values of $0.67 \times S_r$ from the SRS analysis of the NIMS data up to 1022°F (550°C).

The above, in combination with the observation from McCoy [13] that: "The 2.25Cr-1Mo steel has been in service for many years in steam environments up to 1050°F (566°C), and the material has a very good service record under these operating conditions," suggests 950°F (510°C) as a conservative bound for the use of the current tabulated values of allowable stresses S_r and S_t for 2.25Cr-1Mo. The key is to avoid the regime of rapid rupture life degradation.

It should be noted that the NRC contractor has analyzed a database that consists of solution-annealed and normalized and tempered 2.25Cr-1Mo materials. It is generally known

that the normalized and tempered condition gives higher tensile strength but weaker creep strength at longer times and higher temperatures. Thus, it is not appropriate to combine these two material conditions into a single database for analysis.

The impact of using material data from both heat treatment conditions on the allowable stresses of 2.25Cr-1Mo is not assessed, as it is outside the scope of this work. But that would definitely influence the allowable stresses so determined.

4.1.4 9Cr-1Mo-V steel (Grade 91)

The allowable stresses S_r and S_t for 9Cr-1Mo-V (Grade 91) have been extended to 500,000 hours in the 2019 edition of HBB. However, the revised values are more conservative than the corresponding values in the 2017 edition of HBB for temperatures higher than 525°C and lifetimes from 100,000 to 300,000 hours. Thus, it is judged that the S_r and S_t values from the 2019 edition of HBB up to 300,000 hours should be used.

4.2 ALLOWABLE STRESS INTENSITY S_0 FOR DESIGN LOADINGS

As discussed in Section 3.1, the allowable stress intensity for design loadings, S_0, is defined as the larger of (i) the maximum allowable stress S in Section II, Part D Table 1A (ferritic) or Table 1B (austenitic), and (ii) the S_{mt} intensity at 300,000 hours in HBB.

In the following, the tabulated S_0 values from HBB, the S value from Section II, Part D, and the S_{mt} intensity at 300,000 hours from HBB are compared.

4.2.1 304H stainless steel

The comparison of the values of S, S_{mt} at 300,000 hours and S_0 for 304H is shown in TABLE 12. The highlighted cells in TABLE 12 show the difference between the tabulated S_0 values in HBB and the values obtained from the calculations as shown in the table, where the HBB S_0 values are more conservative.

TABLE 12 Comparison of S, S_{mt} at 300k hours, and S_0 values for 304H

Temp. (°F)	S (ksi) Table 1A, pp. 86-89, Line 32	S_{mt} at 300k hrs (ksi) Table HBB-I-14.3A	Larger of (S, $S_{mt} - 300kh$)	S_0 (ksi) Table HBB-I-14.2
800	15.2	15.2	15.2	15.2
850	14.9	14.8	14.9	14.8
900	14.6	14.6	14.6	14.6
950	14.3	12.2	14.3	14.2

TABLE 12 (Cont.)

Temp. (°F)	$\boldsymbol{S}$ (ksi) Table 1A, pp. 86-89, Line 32	$\boldsymbol{S_{mt}}$ at 300k hrs (ksi) Table HBB-I-14.3A	Larger of ($\boldsymbol{S}$, $\boldsymbol{S_{mt} - 300kh}$)	$\boldsymbol{S_0}$ (ksi) Table HBB-I-14.2
1000	14	9.3	14.0	11.1
1050	12.4	7.3	12.4	10.1
1100	9.8	5.7	9.8	9.8
1150	7.7	4.4	7.7	7.7
1200	6.1	3.4	6.1	6.1
1250	4.7	2.7	4.7	4.7
1300	3.7	2.1	3.7	3.7
1350	2.9	1.6	2.9	2.9
1400	2.3	1.2	2.3	2.3
1450	1.8	0.9	1.8	1.8
1500	1.4	0.6	1.4	1.4

4.2.2 316H stainless steel

The comparison of the values of S, S_{mt} at 300,000 hours and S_0 for 316H is shown in TABLE 13. There is no discrepancy between the tabulated S_0 values in HBB and the values obtained from the calculations as shown in the table.

TABLE 13 Comparison of $\boldsymbol{S}$, $\boldsymbol{S_{mt}}$ at 300k hours and $\boldsymbol{S_0}$ values for 316H

Temp. (°F)	$\boldsymbol{S}$ (ksi) Table 1A, pp. 74-77 Line 23	$\boldsymbol{S_{mt}}$ at 300k hrs (ksi) Table HBB-I-14.3A	Larger of ($\boldsymbol{S}$, $\boldsymbol{S_{mt} - 300kh}$)	$\boldsymbol{S_0}$ (ksi) Table HBB-I-14.2
800	11.8	15.9	15.9	15.9
850	11.6	15.7	15.7	15.7
900	11.5	15.6	15.6	15.6
950	11.4	15.5	15.5	15.5
1000	11.3	14.0	14.0	14.0
1050	11.2	10.7	11.2	11.2
1100	11.1	7.8	11.1	11.1
1150	9.8	5.9	9.8	9.8
1200	7.4	4.5	7.4	7.4
1250	5.5	3.3	5.5	5.5
1300	4.1	2.5	4.1	4.1
1350	3.1	1.8	3.1	3.1
1400	2.3	1.2	2.3	2.3
1450	1.7	0.9	1.7	1.7
1500	1.3	0.5	1.3	1.3

4.2.3 Alloy 800H

The comparison of the values of S, S_{mt} at 300,000 hours and S_0 for Alloy 800H is shown in TABLE 14. There is no discrepancy between the tabulated S_0 values in HBB and the values obtained from the calculations as shown in the table.

TABLE 14 Comparison of S, S_{mt} at 300k hours, and S_0 values for Alloy 800H

Temp. (°F)	S (ksi) Table 1B, pp. 234-237 Line 30	S_{mt} at 300k hrs (ksi) Table HBB-I-14.3A	Larger of (S, $S_{mt} - 300kh$)	S_0 (ksi) Table HBB-I-14.2
800	11.1	15.3	15.3	15.3
850	10.9	15.1	15.1	15.1
900	10.7	14.8	14.8	14.8
950	10.5	14.6	14.6	16.6
1000	10.4	14.1	14.1	14.1
1050	10.2	11.2	11.2	11.2
1100	10.0	8.9	10.0	10.0
1150	9.3	7.0	9.3	9.3
1200	7.4	5.6	7.4	7.4
1250	5.9	4.4	5.9	5.9
1300	4.7	3.5	4.7	4.7
1350	3.8	2.8	3.8	3.8
1400	3.0	2.2	3.0	3.0

4.2.4 2.25Cr-1Mo steel (Grade 22, Class 1, annealed)

The comparison of the values of S, S_{mt} at 300,000 hours and S_0 for 2.25Cr-1Mo (annealed) is shown in TABLE 15. There is no discrepancy between the tabulated S_0 values in HBB and the values obtained from the calculations as shown in the table.

As remarked elsewhere, the permissible 2.25Cr-1Mo steel for use in HBB is Grade 22, Class 1, solution annealed. The normalized and tempered heat treatment for Grade 22, Class 1 is not permitted. The impact of combining these two heat-treatment conditions for Grade 22, Class 1 by the NRC contractor on the values of S_0 of 2.25Cr-1Mo is not assessed, as it is outside the scope. But that would definitely influence the values of S_0 so determined.

TABLE 15 Comparison of S, S_{mt} at 300k hours and S_0 values for 2.25Cr-1Mo (annealed)

Temp. (°F)	S (ksi) Table 1A, pp. 38-41 Line 26	S_{mt} at 300k hrs (ksi) Table HBB-I-14.3A	Larger of (S, $S_{mt} - 300kh$)	S_0 (ksi) Table HBB-I-14.2
700	16.6	17.9	17.9	17.9
750	16.6	17.9	17.9	17.9
800	16.6	16.1	16.6	16.6
850	16.6	12.3	16.6	16.6
900	13.6	9.6	13.6	13.6
950	10.8	7.3	10.8	10.8
1000	8.0	5.2	8.0	8.0
1050	5.7	4.0	5.7	5.7
1100	3.8	2.7	3.8	3.8

4.2.5 9Cr-1Mo-V steel (Grade 91)

For 9Cr-1Mo-V steel, the values of S and the S_{mt} stress intensities were revised in the 2019 code edition of Section II, Part D, and Section III, Division 5, respectively. These two actions were carried out independently. However, the S_0 values for 9Cr-1Mo-V were not revised. The comparison of the values of S, S_{mt} at 300k hours and S_0 for 9Cr-1Mo-V in the respective code edition is shown in TABLE 16. The highlighted cells in TABLE 16 show the difference between the tabulated S_0 values in HBB and the values obtained from the calculations as shown in the table.

It has already been discussed in Section 4.1 that the values of the expected minimum stress-to-rupture, S_r, and the time-dependent allowable stress intensity for the operating loadings, S_t, for 9Cr-1Mo-V in the 2019 code edition of HBB should be used. Similarly, it is judged that the S_0 values for 9Cr-1Mo-V should be based the larger of the S values in Section II, Part D and the S_{mt} values at 300k hours in HBB, both from the 2019 code edition.

TABLE 16 Comparison of S, S_{mt} at 300k hours and S_0 values of 9Cr-1Mo-V in 2017 and 2019 code edition

	2017 Edition			2019 Edition			2017 & 2019 Edition
Temp. (°F)	S (ksi) Table 1A, pp. 38-41 Line 26	S_{mt} at 300k hrs (ksi) Table HBB-I-14.3A	Larger of (S, $S_{mt} - 300kh$)	S (ksi) Table 1A, pp. 48-51 Line 6	S_{mt} at 300k hrs (ksi) Table HBB-I-14.3A	Larger of (S, $S_{mt} - 300kh$)	S_0 (ksi) Table HBB-I-14.2
700	22.9	26.7	26.7	22.9	26.7	26.7	26.7
750	22.2	25.9	25.9	22.2	25.9	25.9	25.9
800	21.3	24.9	24.9	21.3	24.9	24.9	24.9
850	20.3	23.7	23.7	20.3	23.7	23.7	23.7
900	19.1	21.9	21.9	19.1	21.5	21.5	21.9
950	17.8	17.4	17.8	17.8	16.0	17.8	17.8
1000	16.3	13.7	16.3	16.1	11.6	16.1	16.3
1050	14	10.5	14.0	12.2	8.2	12.2	12.9
1100	10.3	7.8	10.3	8.7	5.5	8.7	9.6
1150	7.0	4.5	7.0	5.7	3.4	5.7	7.0
1200	4.3	2.5	4.3	3.5	1.8	3.5	4.3

4.2.6 Discussion

The previous sections show that the tabulated values of S_0 in Table HBB-I-14.2 of the 2017 edition of HBB are consistent with the definition of S_0 in HBB-3221. An exception is 9Cr-1Mo-V where the tabulated values of S_0 in both the 2017 and 2019 editions of HBB have not been updated to reflect the revision to the S values in Section II, Part D, Table 1A (2019 edition).

The tabulated S_0 values for 9Cr-1Mo-V in the 2017 and 2019 editions of HBB are still judged adequate, as they are used as a consistency check and experience has indicated that the service loadings, not the design condition loadings, control the primary load designs. However, it was discussed in Section 4.1.4 that the allowable stresses for 9Cr-1Mo-V should be based on the values in the 2019 edition of HBB. Thus, for consistency, it is judged that the values of S_0 should be determined as the greater of the S values and the S_{mt} values at 300,000 hours tabulated in the respective part of the 2019 edition of Section II, Part D and Section III, Division 5 HBB, instead of the tabulated S_0 values in Table HBB-I-14.2 of both 2017 and 2019 editions of HBB.

As a future code action, Table HBB-I-14.2 could be removed and the definition of S_0 in HBB-3221 appropriately modified so that S_0 is based consistently on the most up-to-date values of a particular code edition.

In the assessment of the values of S_0, the NRC contractor has assembled an independent database and conducted data analyses to recreate the technical basis for the S values in Section II, Part D Tables 1A and 1B for the HBB Class A materials.

The criteria for determining the S values in the creep regime are given in the Mandatory Appendix 1 of Section II, Part D, and S is given as the lesser of:

a) 100% of the average stress to produce a creep rate of 0.01%/1000 hr;
b) $100F_{avg}$% of the average stress to cause rupture at the end of 100,000 hr; or
c) 80% of the minimum stress to cause rupture at the end of 100,000 hr.

As discussed in Section 3.1.1, the code intent of the S_0 values was to provide a consistency check so that the component wall thicknesses obtained from the service loadings – a new concept at the time when the HBB rules were introduced into the ASME BPVC – are not less than those obtained from the then accepted practice in the Section VIII, Division 1 design-by-rule methods. It was not the code intent to develop a separate set of S values that are not consistent with Section II, Part D. The S values are used in Section VIII, Division 1 for a fixed rupture life of 100,000 hours, while the S_t values in HBB are used for service loadings with variable rupture lives, up to 300,000 hours. The creep rupture data requirements for S and S_t are completely independent.

The recreation of the technical basis for the assessment of Division 5 rules could be a valuable effort. But it cannot be a substitute for the Codes and Standards consensus process where a diverse expertise is brought to bear on the background of the construction rules, their code intent, use experience, and engineering judgment on the adequacy of the HBB rules in their totality to provide a reasonable assurance of structural integrity.

4.3 AGING FACTORS

Assessments performed by the NRC contractor have suggested that the HBB aging factors (2017 edition) are non-conservative for 2.25Cr-1Mo and 9Cr-1Mo-V. It was further suggested that there is a potential for non-conservatism for Alloy 800H at 1350°F (730°C) or higher temperatures. These assignments were based on calculating the aging factor as the ratio of the aged to unaged material property. As described in Section 3.2.1, the values of the aging factor in HBB are calculated as the ratio of the average aged material property to the corresponding design property (i.e., tabulated S_y or S_u value in HBB).

4.3.1 Alloy 800H

The yield and tensile strength aging factors in the 2017 edition of HBB for Alloy 800H have a value of 0.9 in the temperature range of 1350 to 1400°F, where 1400°F is the maximum allowable service temperature for Alloy 800H. The aging factors have a value of 1.0 for temperatures lower than 1350°F. These values for the aging factors are supported by test and service exposed data, as shown in FIGURE 5 below from a report by Trester et al. [15].

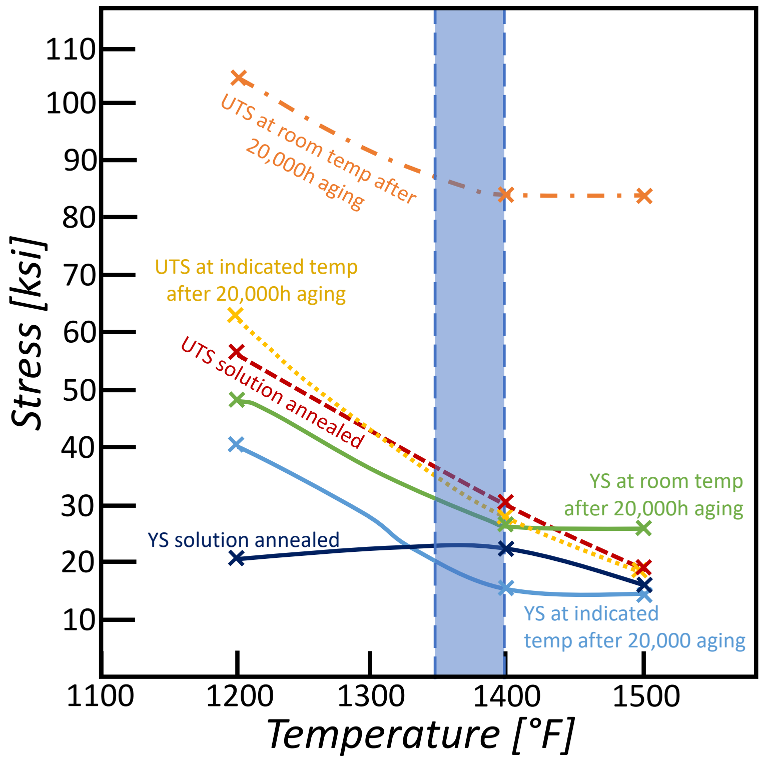


FIGURE 5 Effects of thermal aging (in air) on the strength of Alloy 800H at room temperature and at the aging temperature, after Trester et al. [15]. The shaded region shows the temperature range where the HBB aging factors are 0.9.

More recent data from service-exposed Alloy 800H material were reported by Swindeman et al. [16]. These were the data that caused the NRC contractor to raise questions about the conservatism of the aging factors of Alloy 800H in the 2017 edition of HBB. The service-exposed materials were sampled from three different components, and they were labeled as sections A, B, and C. The photos of these components can be found in [16].

As reported by Swindeman at al. [16], the service temperature for section C, with the lowest measured strengths, was in the reported range of 1425 to 1490°F. Since that temperature range is above the maximum allowable temperature in the 2017 edition, these data are not applicable when determining the aging factors for comparison with HBB. Additionally, these specimens were under load during their exposure, so the measurements conflate the effect of thermal aging and creep damage. There is, further, an apparent anomaly in the section C data in that the measured ultimate tensile strength (UTS) is 24% higher at 1300°F than at 1100°F after aging at the same temperature (1425–1490°F).

At a service temperature of 1385–1425°F, section B, the next most critical location, had a calculated aging factor on UTS at 1300°F of 0.91, as reported by the NRC contractor. However, that calculation was not based on the HBB criteria for the aging factors. Correctly calculating the aging factor based on the tabulated properties yielded a factor of 1.01. Based on these

observations, modification of the current Alloy 800H aging factors is not indicated. However, these and other recent data will be assessed in conjunction with the effort to provide allowable stress values for Alloy 800H up to 1500°F and extending to 500,000 hours.

4.3.2 2.25Cr-1Mo steel (Grade 22, Class 1, annealed)

Based on the analysis of the 2.25Cr-1Mo thermal aging data reported by Klueh [17], the NRC contractor suggested that the aging factors for 2.25Cr-1Mo in the 2017 edition of HBB are unconservative. The degree of unconservatism was up to about 10% that peaked out at about 1000°F and 3000 hours. However, the analysis was based on using different criteria for the aging factors as compared with the code. As described in Section 3.2.1, the aging factors in HBB are based on the ratio of average properties due to aging to the corresponding design values in the absence of thermal aging. These unaged design values are the tabulated S_y and S_u values in HBB. However, the NRC contractor determined the ratios of average aged properties to average unaged properties and used them to compare against the aging factors in HBB which were established using the code criteria.

FIGURE 6 shows a comparison of the measured yield strengths due to aging, as reported by Klueh [17], to the calculated yield strengths using the aging factors per the HBB procedure. The values of S_y, unaged or aged, are used in HBB design procedures as some minimum property, but not in the vigorous statistical sense. Thus, it is expected that the majority of the aged data points should be above the one-to-one line, which is the case.

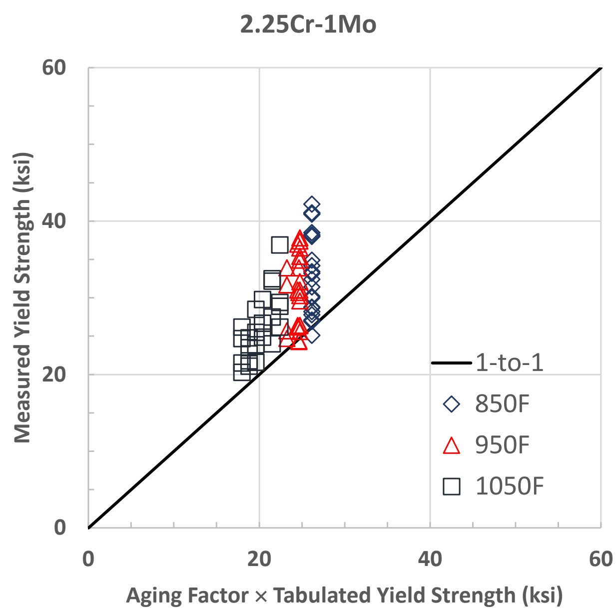


FIGURE 6 Comparison of measured yield strength after aging with the calculated strength using the HBB code procedure for 2.25Cr-1Mo.

FIGURE 7 shows a comparison of the measured tensile strengths due to aging, as reported by Klueh [17], to the calculated tensile strengths using the aging factors per the HBB procedure. The values of S_u, unaged or aged, are used in HBB design procedures as some average property, though not in the vigorous statistical sense. Thus, it is expected that the majority of the aged data points would scatter around the one-to-one line. Data that are above the one-to-one line would not impact the conservatism of the aging factors.

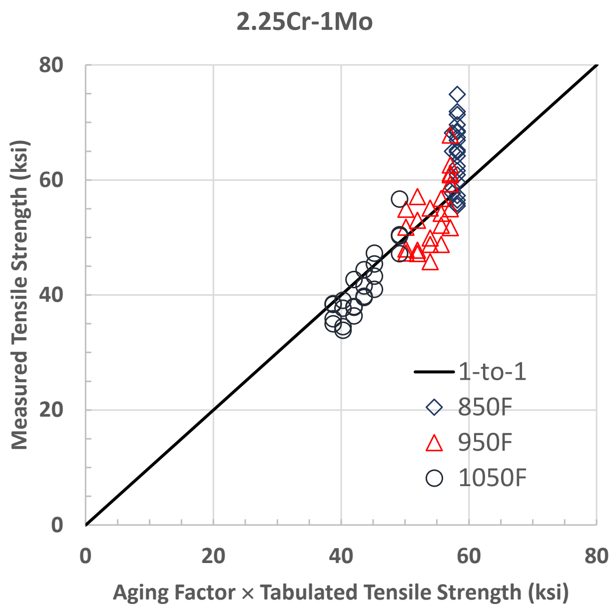


FIGURE 7 Comparison of measured tensile strength after aging with the calculated strength using the HBB code procedure for 2.25Cr-1Mo.

Based on these observations, modification of the current 2.25Cr-1Mo aging factors is not indicated. It is concluded that the aging factors in the 2017 edition of HBB for Alloy 800H provide a reasonably certain protection of life and property and a margin for deterioration in service. However, these and other recent data will be reassessed in conjunction with the effort to extend the allowable stress values for 2.25Cr-1Mo to 500,000 hours.

4.3.3 9Cr-1Mo-V steel (Grade 91)

The extension of the aging factors for yield and tensile strengths to longer times is part of the effort to support increasing the design life of 9Cr-1Mo-V from 300,000 to 500,000 hours. Significant progress has been made on this task that the code committees are currently balloting the revision through C&S Record 19-411. The yield strength aging factor in the 2017 edition of HBB has a value of 1 for all applicable time and temperature conditions. The extension to 500,000 hours did not change the 2017 values (to 300,000 hours). There are some minor changes to the aging factors for the tensile strength. The new values are lower than those from the 2017 code edition only at 300,000 hours and for temperatures at 500°C (932°F) or higher. A comparison of the two sets of aging factors is shown in TABLE 17. The differences are highlighted in the table. The largest decrease in the new aging factor is 6.7% which occurs at 550°C (1022°F) and 300,000 hours.

Since the reduction in the new values of the tensile strength aging factor is relatively small, it is judged that the use of the values from the 2017 code edition can provide a reasonable assurance of structural integrity.

TABLE 17 Tensile strength aging factors from 2017 edition and RC 19-411, respectively, for 9Cr-1Mo-V

Temp., °C	Source	Aging time, hours										
		1	10	30	100	300	1,000	3000	10,000	30,000	100,000	300,000
375	Old[1]	1	1	1	1	1	1	1	1	1	1	1
	New[2]	1	1	1	1	1	1	1	1	1	1	1
400	Old	1	1	1	1	1	1	1	1	1	1	1
	New	1	1	1	1	1	1	1	1	1	1	1
425	Old	1	1	1	1	1	1	1	1	1	1	1
	New	1	1	1	1	1	1	1	1	1	1	1
450	Old	1	1	1	1	1	1	1	1	1	1	1
	New	1	1	1	1	1	1	1	1	1	1	1
475	Old	1	1	1	1	1	1	1	1	1	1	0.98
	New	1	1	1	1	1	1	1	1	1	1	0.98
500	Old	1	1	1	1	1	1	1	1	1	0.97	0.97
	New	1	1	1	1	1	1	1	1	1	0.97	0.91
525	Old	1	1	1	1	1	1	1	1	1	0.94	0.91
	New	1	1	1	1	1	1	1	1	1	0.94	0.87
550	Old	1	1	1	1	1	1	1	1	0.94	0.92	0.89
	New	1	1	1	1	1	1	1	1	0.94	0.92	0.83
575	Old	1	1	1	1	1	1	1	0.95	0.92	0.88	0.83
	New	1	1	1	1	1	1	1	0.95	0.92	0.88	0.83
600	Old	1	1	1	1	1	1	0.96	0.92	0.89	0.85	0.84
	New	1	1	1	1	1	1	0.96	0.92	0.89	0.85	0.82
625	Old	1	1	1	1	1	0.97	0.94	0.9	0.87	0.83	0.81
	New	1	1	1	1	1	0.97	0.94	0.9	0.87	0.83	0.80
650	Old	1	1	1	1	0.98	0.94	0.91	0.87	0.84	0.81	0.78
	New	1	1	1	1	0.98	0.94	0.91	0.87	0.84	0.81	0.76

[1] Aging factors from the 2017 code edition.
[2] Aging factors proposed in ASME C&S Record 19-411.

5 STRESS RUPTURE FACTOR, *R*

The weldment design guidance in BPVC was quite minimal until the mid-1980s. But as discussed in Section 2.3, new design provisions were introduced subsequently to address primary load, strain limits, and creep-fatigue for weldment. For the primary load check, a stress rupture factor (denoted as R) is introduced in HBB-3220 to account for the potential reduction in the time-dependent allowable stresses for the weldment under Service Level A, B, C, and D loadings.

The potential for limited ductilities of weld metal at elevated temperatures and high strain concentrations (both metallurgical and geometric) in the heat-affected zone of weldments are addressed by special deformation-controlled requirements.

In this section, the adequacy of the R values in Table HBB-I-14.10 of the 2017 edition of HBB is assessed. The recreation of the technical basis of the stress rupture factors is outside the scope of this work. The definition of R and how its values are used in setting allowable stresses have already been discussed in Section 3.1.2.

The expected minimum stress-to-rupture of the weld is an important design parameter in the weldment design procedures for primary load and creep-fatigue. Its value is parametrized in terms of the stress rupture factor R and the tabulated base metal expected minimum stress-to-rupture S_r in HBB. Thus, the approach taken in the assessment of the R values is to check the available creep rupture data of welds and weldments against the expected minimum stress-to-rupture of the weld, determined as $R \times S_r$.

It is further noted that the R values used in the weldment design procedure for Type 304 and 316 stainless steels and Alloy 800H and 2.25Cr-1Mo parent materials were determined mainly from weld metal creep rupture data, with some limited cross-weld and component-weld data used for validation. For the 9Cr-1Mo-V parent material, the creep rupture data were predominately from cross-weld testing, with some limited weld metal data. For Alloy 617 welds, cross-weld creep rupture data were used in determining R.

5.1 DATA SOURCES

The weld metal and weldment data used in this assessment for 308 and 16-8-2 filler materials for Type 304 and 316 parent materials were taken from the STP-PT-077 report by Shingledecker et al. [18].

The creep rupture data for the 308 weld metal and 304/308 weldment assembled in STP-PT-077 were obtained from weld metal and cross-weld specimens fabricated from 308, 308L, and 308CRE filler materials using gas-tungsten arc (GTA), gas metal arc (GMA), shielded metal arc (SMA), and submerged arc (SA) welding processes. Only data from 308 and 308L filler materials are used in the assessment.

The creep rupture data for the 16-8-2 weld metal and 16-8-2/Type 316 weldment assembled in STP-PT-077 were obtained from weld metal and some limited cross-weld specimens fabricated from 16-8-2 filler material using GTA and SA welding processes.

The creep rupture data for the 316 filler material used for Type 304 and 316 parent materials were more difficult to retrieve. Some limited weld metal data from the GTA welding process were found from Rowe and Stewart [19], Ward [20], and Hill [21].

The weld metal and weldment data used in this assessment for Alloy A and Alloy 82 filler materials for Alloy 800H parent material were taken from the STP-PT-077 report. The creep rupture data for the Alloy A and Alloy 82 weld metal and their weldment with Alloy 800H parent material assembled in STP-PT-077 were obtained from weld metal and some limited cross-weld specimens fabricated from Alloy A filler material using SMA, and Alloy 82 filler material using the GTA welding process. The test temperatures of all of the assembled Alloy A/Alloy 800H cross-weld data were higher than the maximum use temperature of 1400°F (760°C) of Alloy 800H base metal, and hence a comparison with $R \times S_r$ is not possible. Similarly, some of the temperatures for the cross-weld data for Alloy 82/Alloy 800H also exceed 1400°F.

The information on 2.25Cr-1Mo welds was obtained from a very comprehensive assessment conducted in Electric Power Research Institute (EPRI) report TR-110807 by Warke [22].

The 9Cr-1Mo-V weld data came from the background data package of ASME BPVC Record 17-2817. The majority of the rupture data were from cross-weld tests, with a limited number of data from weld metal testing.

The creep rupture data for the Alloy 617 welds were taken from the background data package of the ASME C&S Record 16-0994 that supported the Alloy 617 Code Case (N-898). The filler material was ERNiCrCoMo-1 and the parent material was Alloy 617. Most of the data were from cross-weld specimens, and there were some data from specimens in the longitudinal direction (weld metal). The welding processes consisted of GTA, GTA-orbital, GMA, and pulsed arc gas metal arc. It is noted that only the GTA welding process is permitted in N-898.

There was no attempt to trace the data from the originating documents. In a rare occasion when a data point is an obvious outlier, cross-checking with the originating document, when available, was done to determine if that was due to a transcription error.

5.2 TYPE 304 WELDS

5.2.1 308 filler materials

The creep rupture data for the 308 weld metal and 308/Type 304 weldment assembled in STP-PT-077 for the assessment were from 308 and 308L filler materials. The welding processes were GTA, GMA, SMA, and SA. The resulting creep rupture stresses for the 308 weld metal and 308/Type 304 weldment are plotted against the $R \times S_r$ values in FIGURE 8. The R value is determined from Table HBB-I-14.10A-1 for the 308 filler materials and S_r from Table HBB-I-14.6A for Type 304 parent material. Data with rupture time less than 10 hours were not used in the plot to reduce uncertainty.

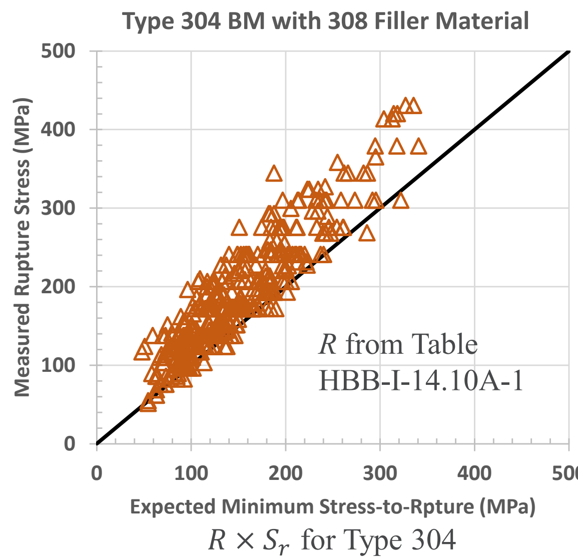


FIGURE 8 Comparison of measured creep rupture data against HBB prediction for Type 304 stainless with 308 filler material.

5.2.2 16-8-2 filler material

The creep rupture data for 16-8-2 filler material and Type 316 parent material assembled in STP-PT-077 consisted of 16-8-2 weld metal data and 16-8-2/Type 316 cross-weld data. The rupture stresses from the 16-8-2 weld metal data are compared against $R \times S_r$ for Type 304 stainless steel in FIGURE 9. The R values are determined from Table HBB-I-14.10A-2 for the 16-8-2 filler material, and the S_r values are from Table HBB-I-14.6A for Type 304 parent material.

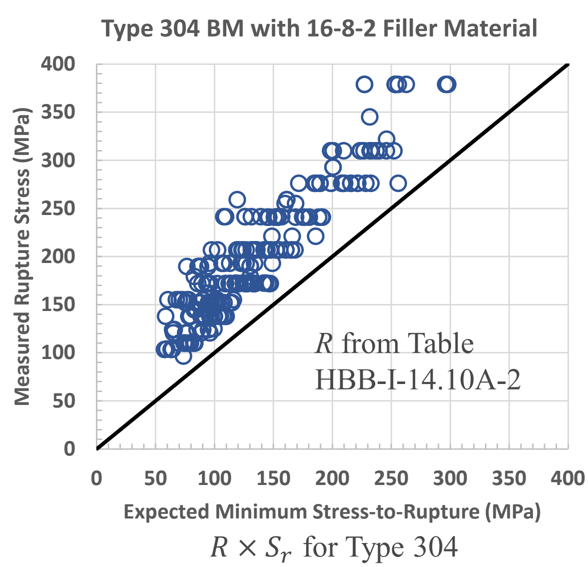


FIGURE 9 Comparison of measured creep rupture data against HBB prediction for Type 304 stainless with 16-8-2 filler material.

5.2.3 316 filler material

The creep rupture data for 316 filler material and Type 316 parent material assembled from [19-21] contained 316 weld metal data. These rupture stress data are compared against $R \times S_r$ for Type 304 stainless steel in FIGURE 10. The R values are determined from Table HBB-I-14.10A-3 for the 316 filler material, and the S_r values are from Table HBB-I-14.6A for Type 304 parent material.

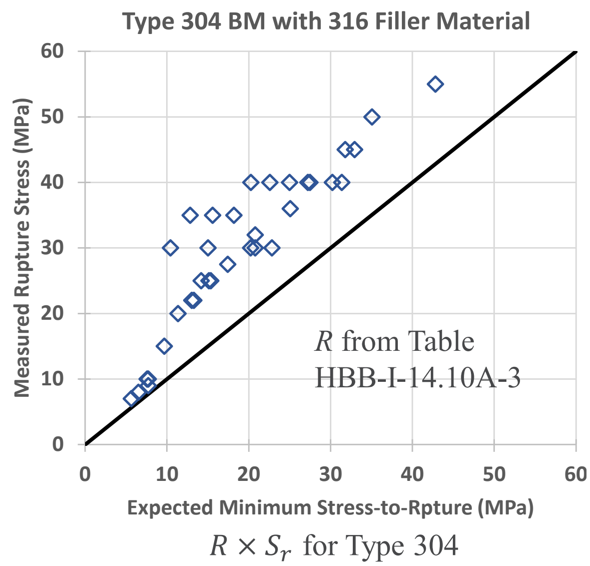


FIGURE 10 Comparison of measured creep rupture data against HBB prediction for Type 304 stainless with 316 filler material.

5.3 TYPE 316 WELDS

5.3.1 308 filler materials

The creep rupture data for 308 filler materials and Type 304 parent material assembled in STP-PT-077 consisted of 308 weld metal data and 308/Type 304 cross-weld data. The rupture stress from only weld metal data and 308 and 308L filler materials are compared against $R \times S_r$ for Type 316 stainless steel in FIGURE 11. The R values are determined from Table HBB-I-14.10B-1 for the 308 filler materials, and the S_r values are from Table HBB-I-14.6B for Type 316 parent material. Again, data with rupture time less than 10 hours were not used in the plot to reduce uncertainty.

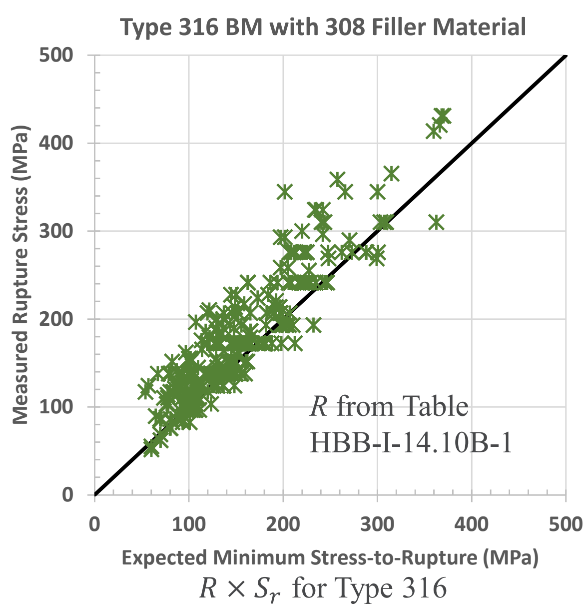


FIGURE 11 Comparison of measured creep rupture data against HBB prediction for Type 316 stainless with 308 filler material.

5.3.2 16-8-2 filler material

The creep rupture data for 16-8-2 filler material and Type 316 parent material assembled in STP-PT-077 consisted of 16-8-2 weld metal data and 16-8-2/Type 316 cross-weld data. The rupture stresses from both weld metal and cross-weld data are compared against $R \times S_r$ for Type 316 stainless steel in FIGURE 12. The R values are determined from Table HBB-I-14.10B-2 for the 16-8-2 filler material, and the S_r values are from Table HBB-I-14.6B for Type 316 parent material.

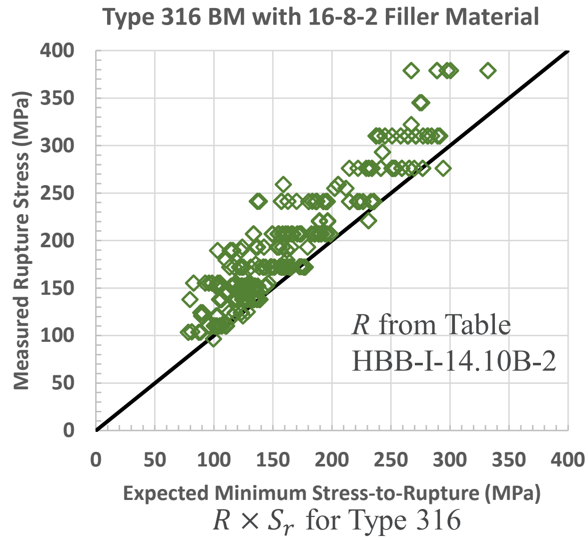


FIGURE 12 Comparison of measured creep rupture data against HBB prediction for Type 316 stainless with 16-8-2 filler material.

5.3.3 316 filler material

The creep rupture data for 316 filler material and Type 316 parent material assembled from [19-21] contained 316 weld metal data. These rupture stress data are compared against $R \times S_r$ for Type 316 stainless steel in FIGURE 141. The R values are determined from Table HBB-I-14.10B-3 for the 316 filler material, and the S_r values are from Table HBB-I-14.6B for Type 316 parent material.

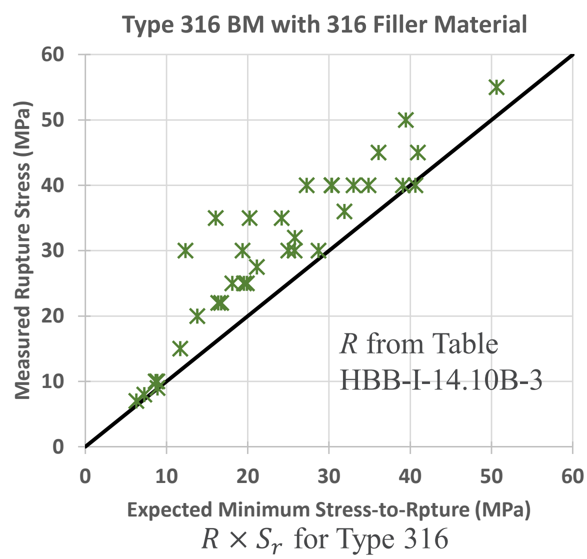


FIGURE 13 Comparison of measured creep rupture data against HBB prediction for Type 316 stainless with 316 filler material.

5.4 ALLOY 800H WELDS

5.4.1 Alloy A filler material

The creep rupture data for Alloy A filler material and Alloy 800H parent material assembled in STP-PT-077 at or below 1400°F (760°C) were all weld metal data. These rupture stress data are compared against $R \times S_r$ for Alloy 800H in FIGURE 14. The R values are determined from Table HBB-I-14.10C-1 for the Alloy A filler material, and the S_r values are from Table HBB-I-14.6C for Alloy 800H parent material.

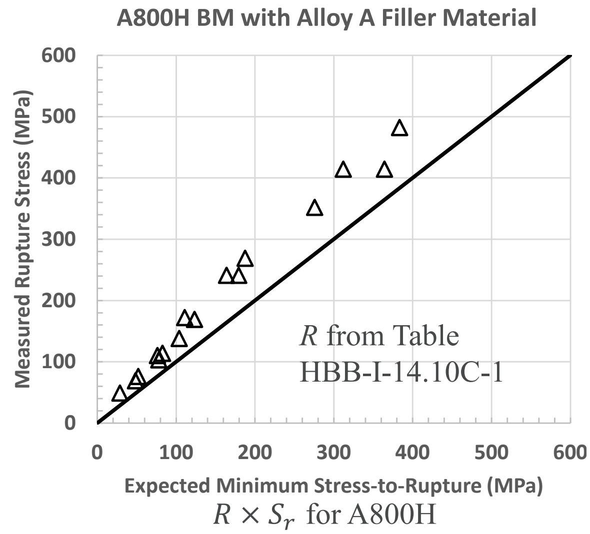


FIGURE 14 Comparison of measured creep rupture data against HBB prediction for Alloy 800H with Alloy A filler material.

5.4.2 Alloy 82 filler material

The creep rupture data for Alloy 82 filler material and Alloy 800H parent material assembled in STP-PT-077 at or below 1400°F (760°C) consisted of weld metal and cross-weld data. These rupture stress data are compared against $R \times S_r$ for Alloy 800H in FIGURE 15. The R values are determined from Table HBB-I-14.10C-2 for the Alloy 82 filler material, and the S_r values are from Table HBB-I-14.6C for Alloy 800H parent material.

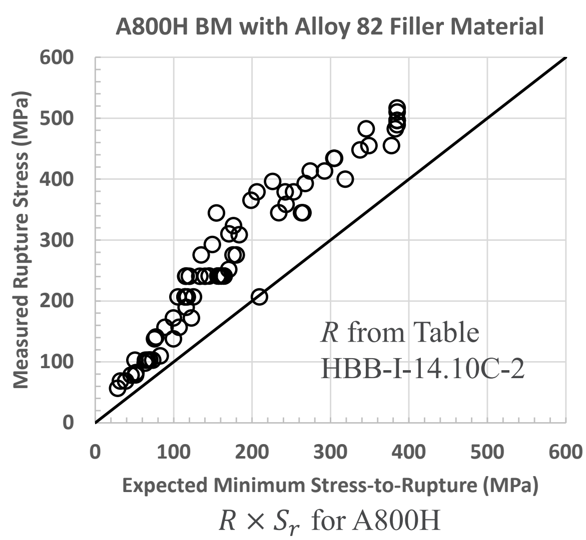


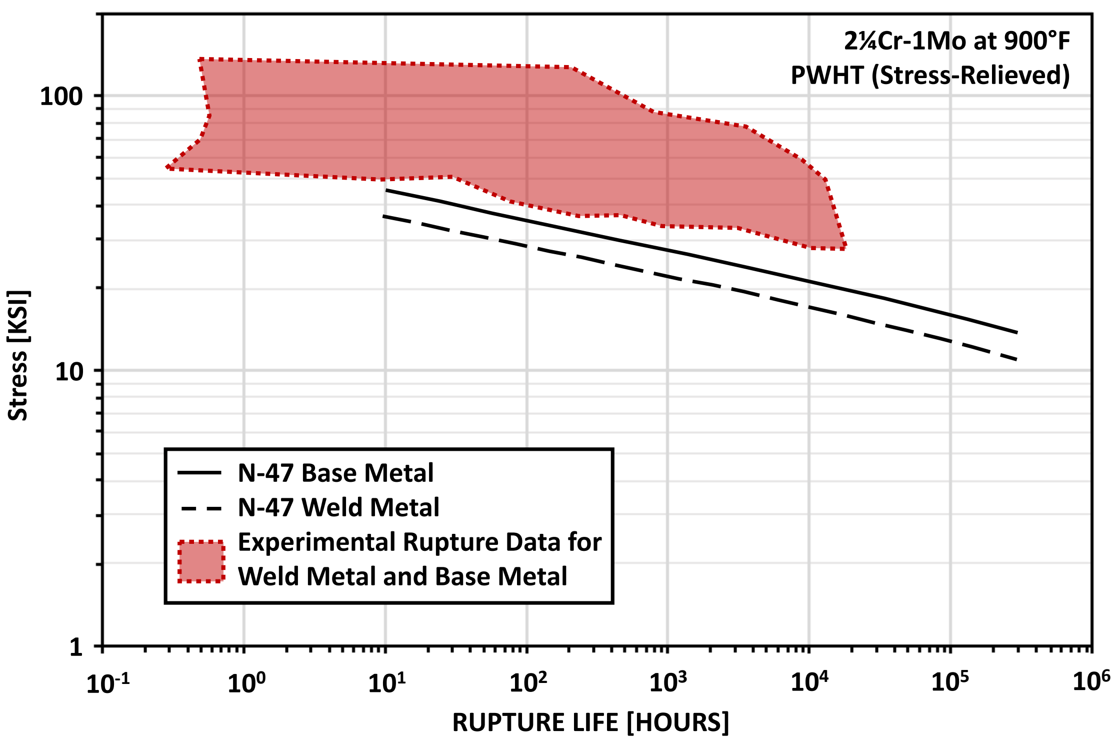
FIGURE 15 Comparison of measured creep rupture data against HBB prediction for Alloy 800H with Alloy 82 filler material.

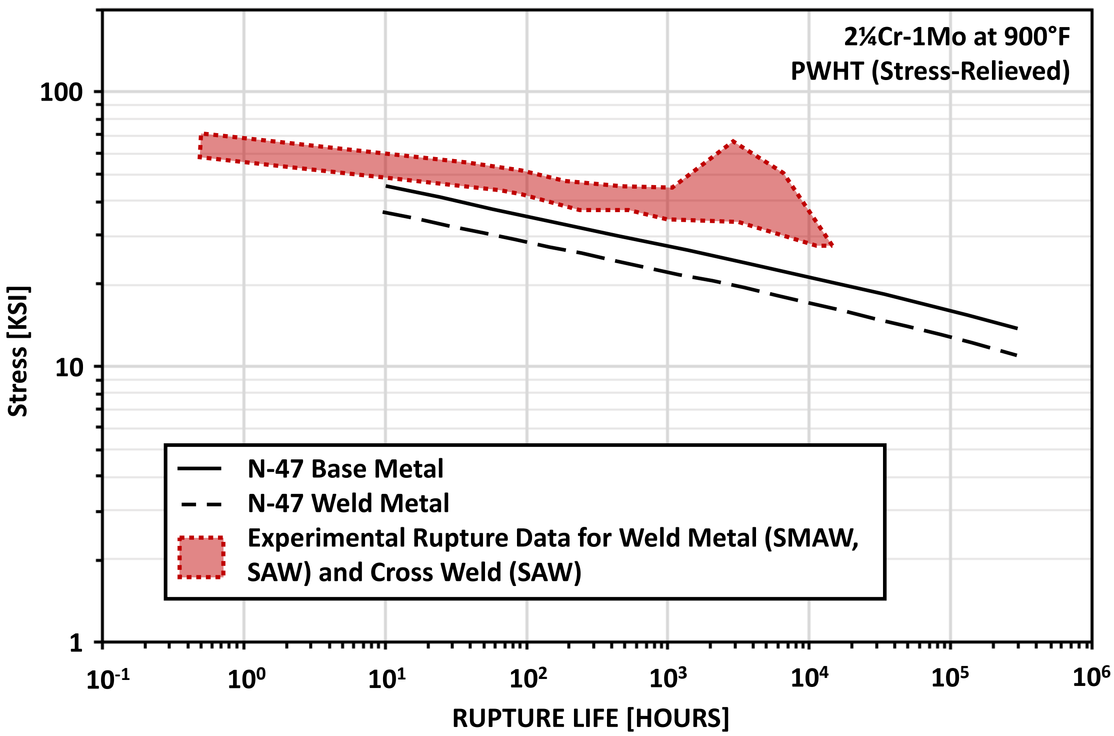
5.5 2.25Cr-1Mo WELDS

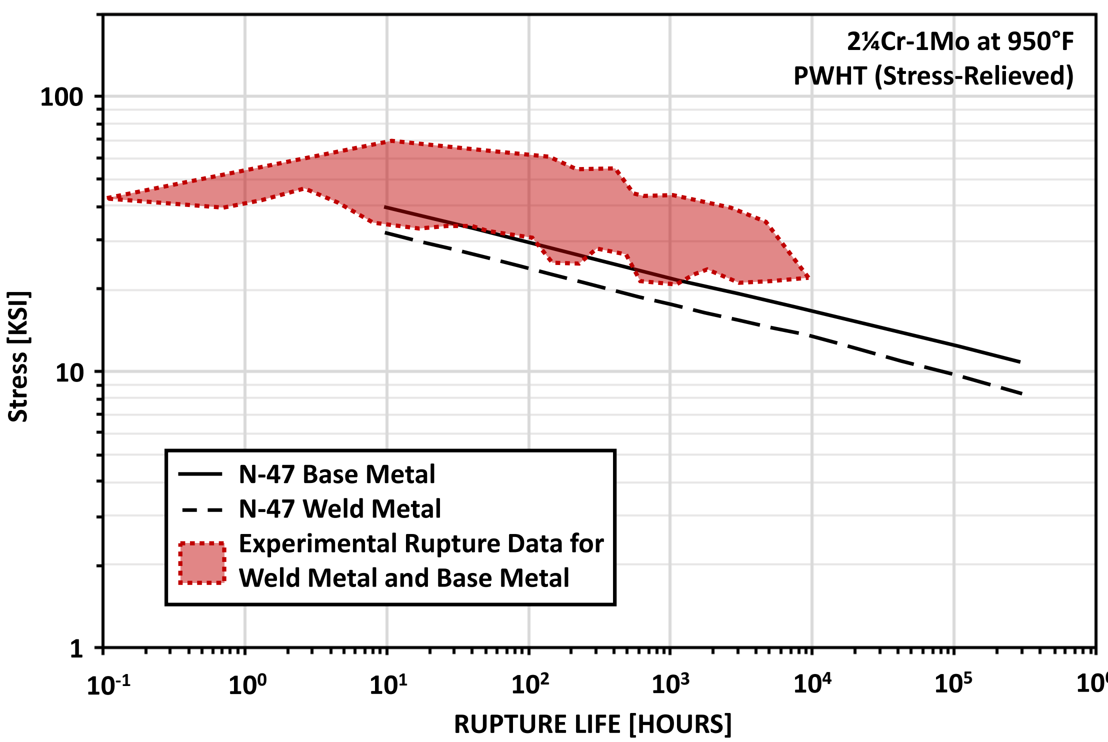
A comprehensive review of the 2.25Cr-1Mo weld data was conducted by R.W. Warke of Edison Welding Institute for EPRI. The results were documented in the EPRI report TR-110807 [22]. Comparisons of the 2.25Cr-1Mo weld data against the HBB design values (then Code Case N-47) were made. FIGURE 16 shows qualitative comparisons between the weld and base metal data and HBB design values at various temperatures. Quantitative comparisons of the data points with the HBB design values at these temperatures can be found in [22]. The TR-110807 review showed that the HBB design values for 2.25Cr-1Mo welds are adequately conservative.

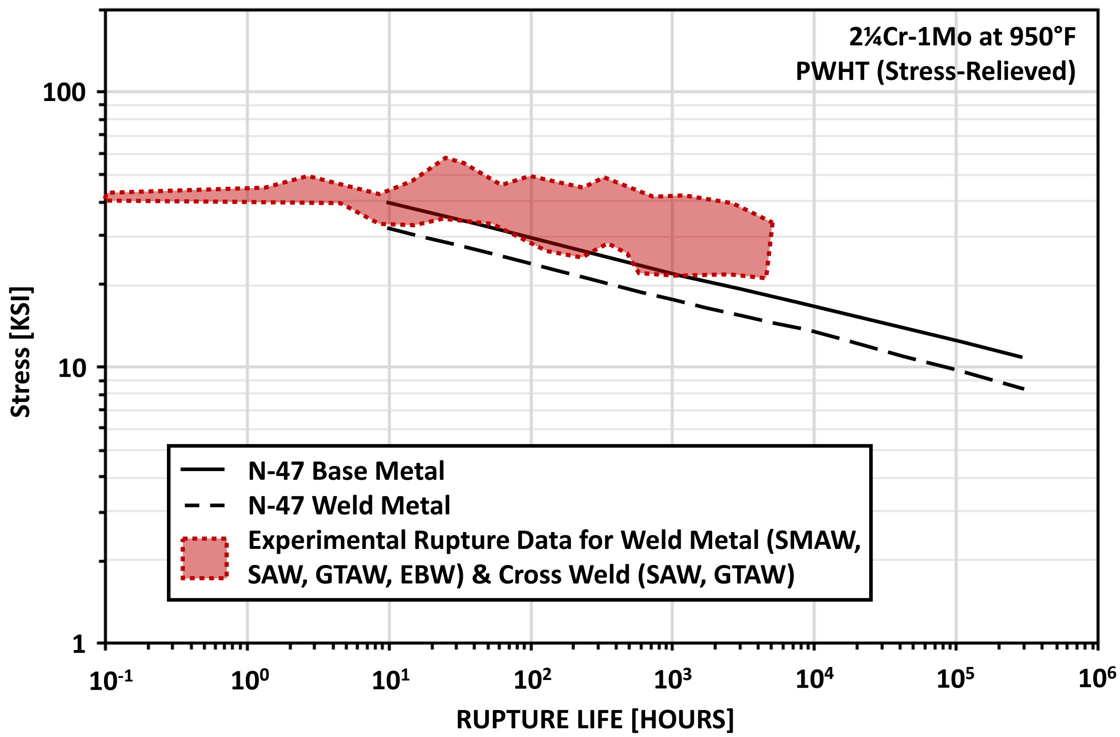
For a perspective on the conservatism of the HBB rules for 2.25Cr-1Mo welds, the following conclusion from TR-110807 is noted:

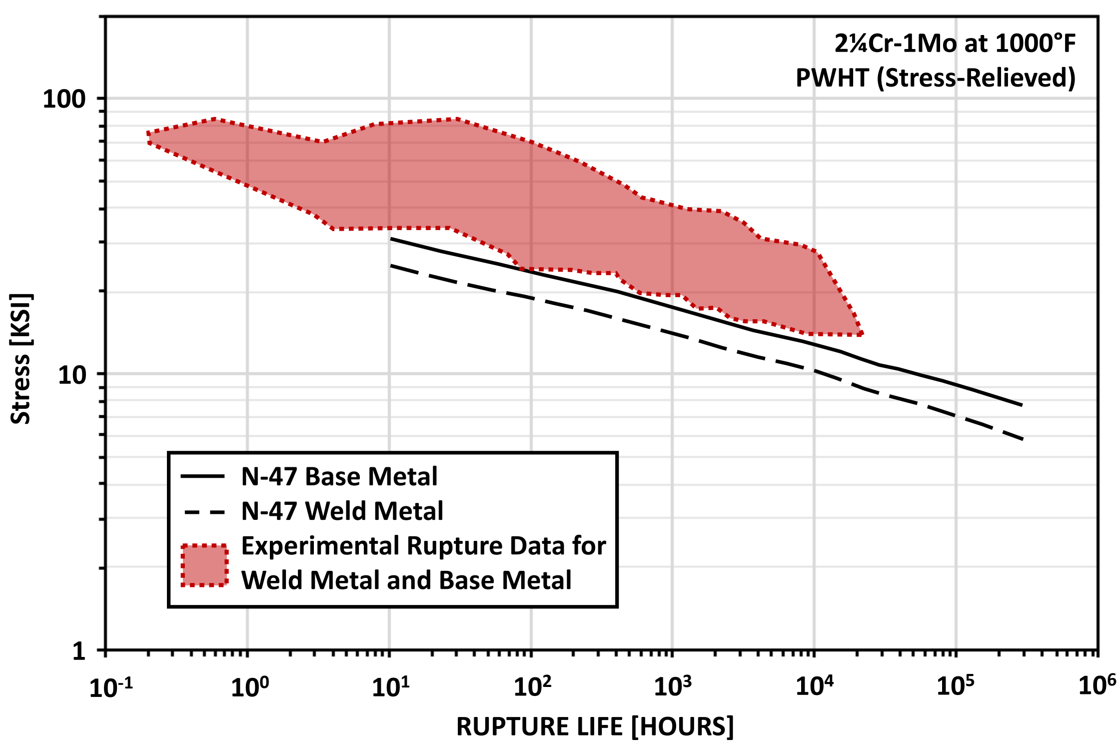
> "In terms of currently available creep rupture data, combining the weld reduction factors given in Code Case N-47 with the maximum allowable stresses prescribed by ASME Sections I and VIII and B31.1 represents an unwarranted level of conservatism for partially inspected weldments."

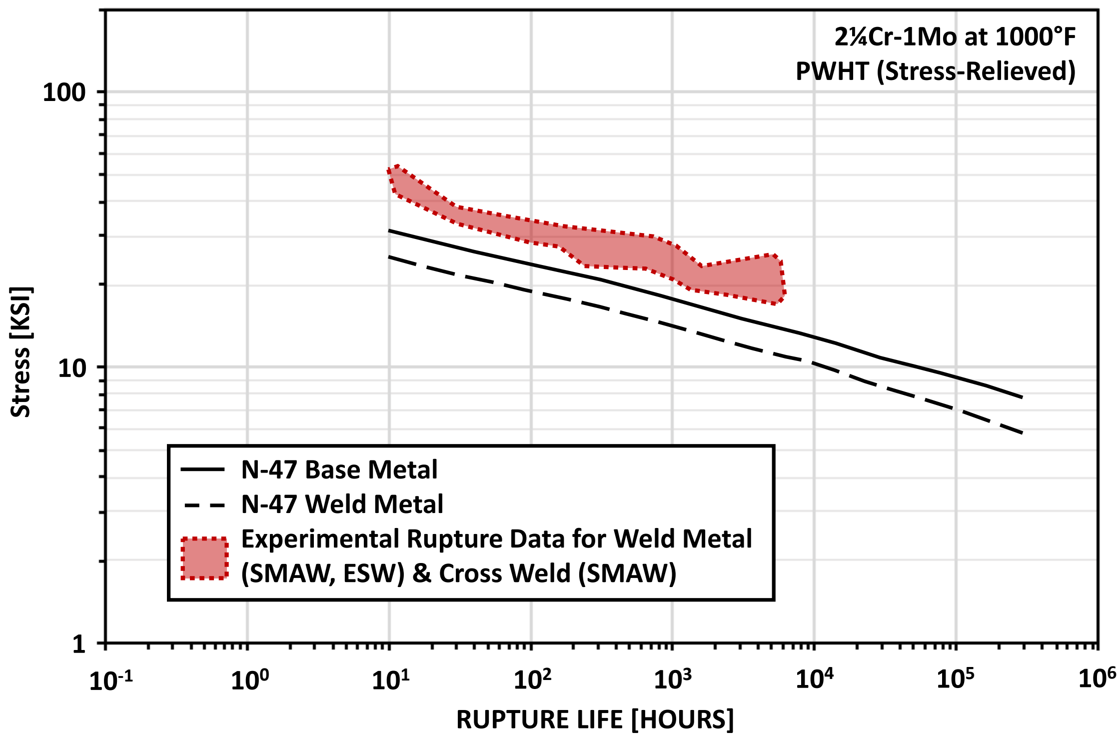



2¼Cr-1Mo at 900°F
PWHT (Stress-Relieved)
Stress [KSI]
100
10
1
10-1
100
101
102
103
104
105
106
RUPTURE LIFE [HOURS]
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for Weld Metal (SMAW, SAW) and Cross Weld (SAW)

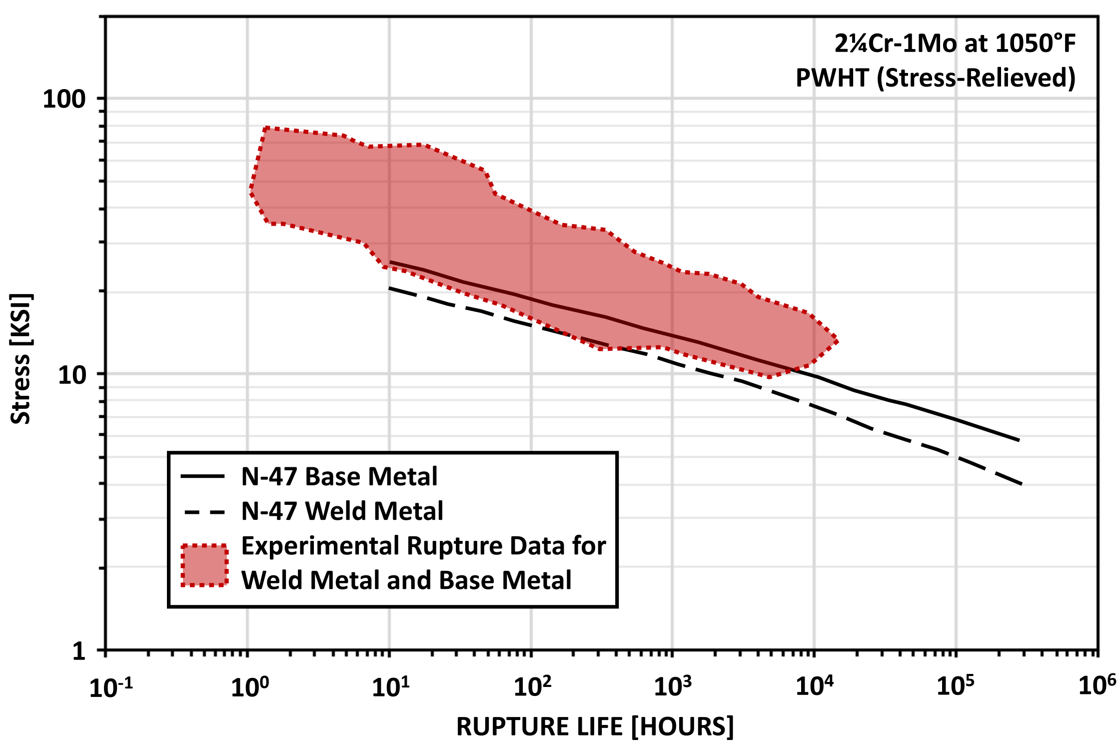

2¼Cr-1Mo at 950°F
PWHT (Stress-Relieved)
Stress [KSI]
100
10
1
10-1
100
101
102
103
104
105
106
RUPTURE LIFE [HOURS]
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for Weld Metal and Base Metal


2¼Cr-1Mo at 950°F
PWHT (Stress-Relieved)
Stress [KSI]
100
10
1
10-1
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
RUPTURE LIFE [HOURS]
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for Weld Metal (SMAW, SAW, GTAW, EBW) & Cross Weld (SAW, GTAW)

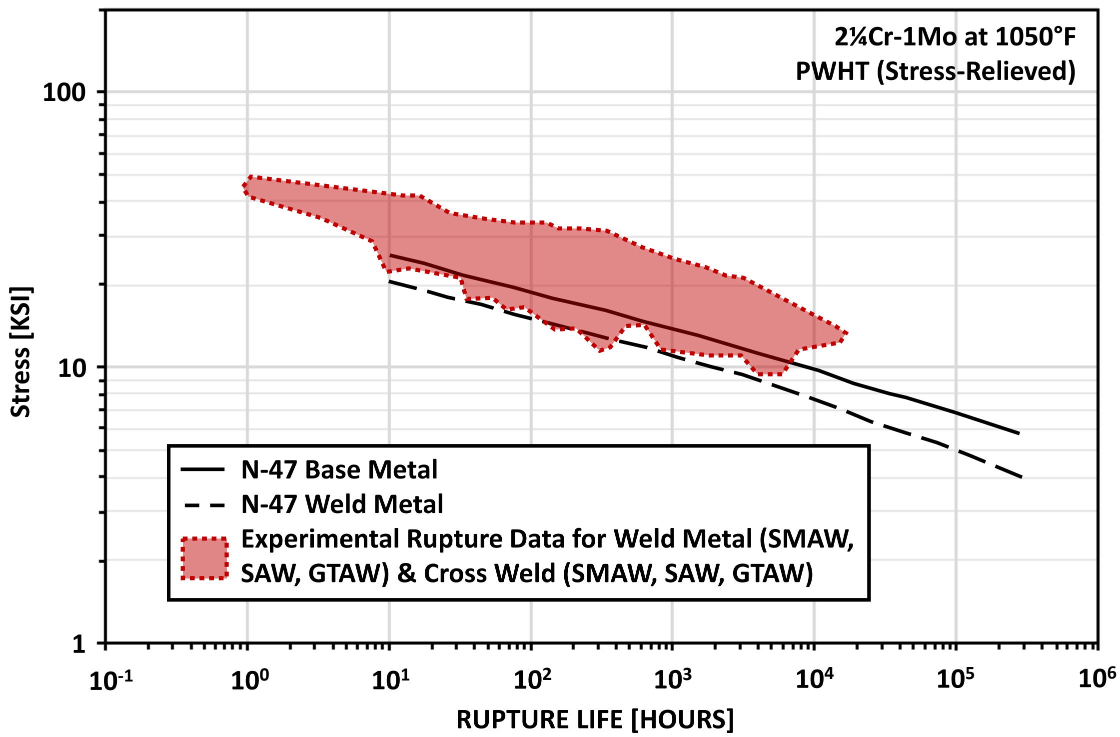

2¼Cr-1Mo at 1000°F
PWHT (Stress-Relieved)
Stress [KSI]
100
10
1
10-1
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
RUPTURE LIFE [HOURS]
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for Weld Metal and Base Metal

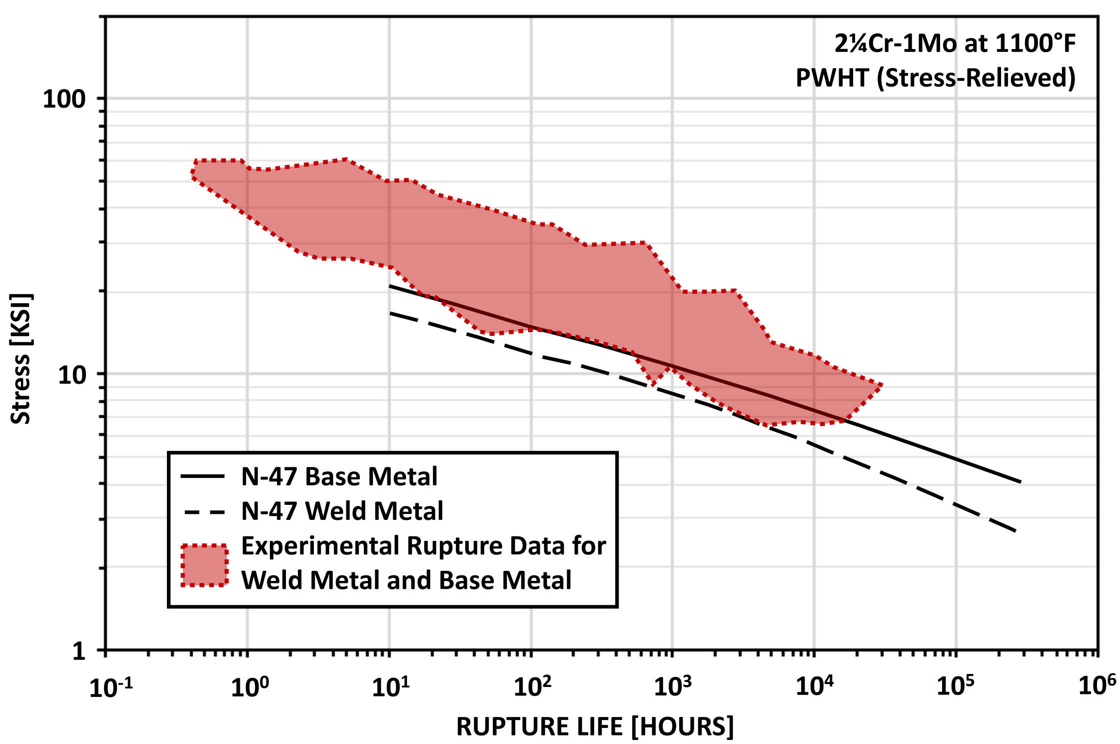


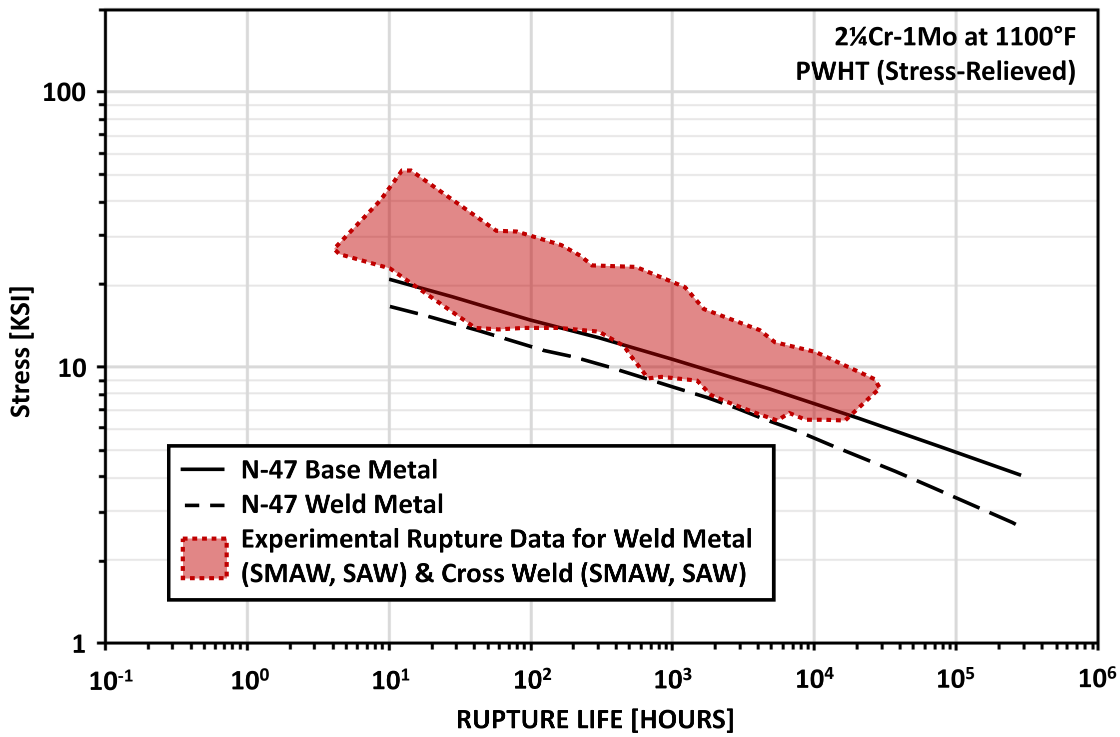
2¼Cr-1Mo at 1000°F
PWHT (Stress-Relieved)
Stress [KSI]
100
10
1
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for Weld Metal
(SMAW, ESW) & Cross Weld (SMAW)
10-1
100
101
102
103
104
105
106
RUPTURE LIFE [HOURS]

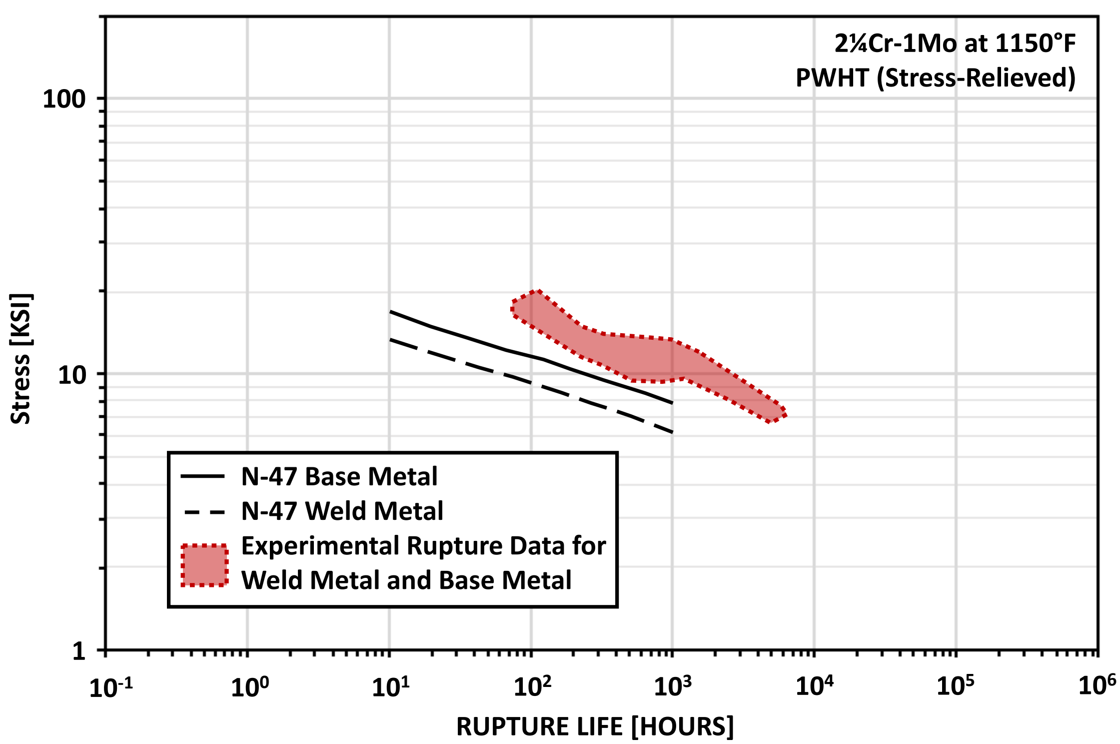


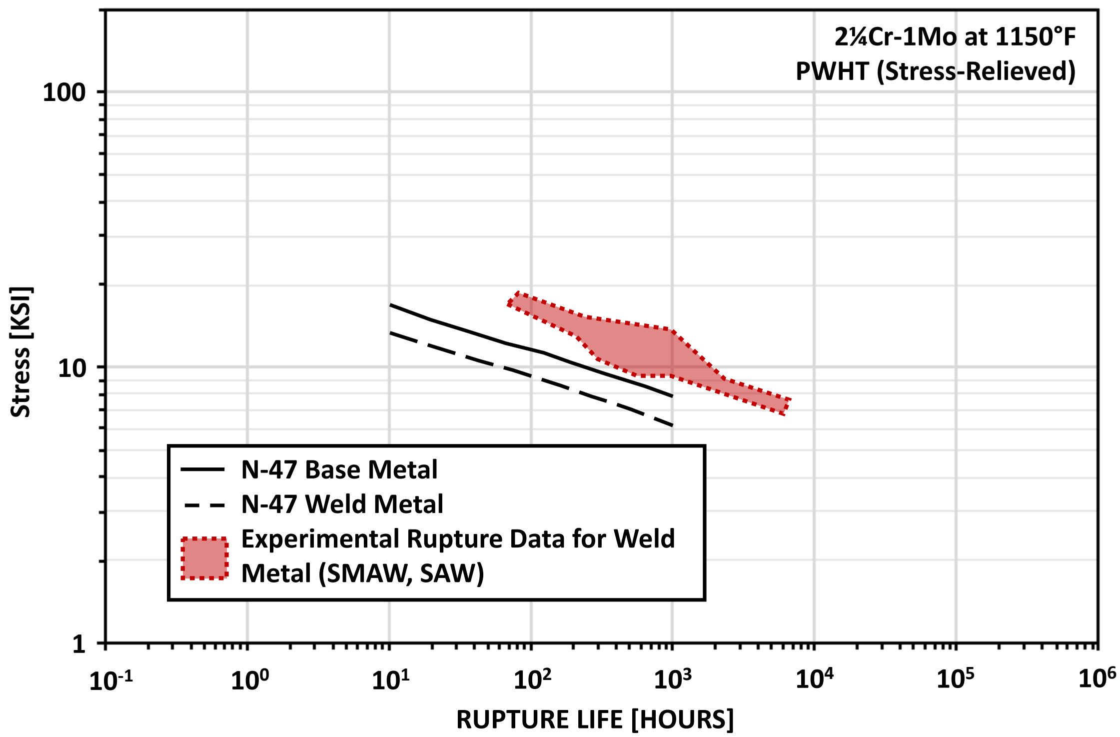
2¼Cr-1Mo at 1050°F
PWHT (Stress-Relieved)
Stress [KSI]
100
10
1
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for
Weld Metal and Base Metal
10-1
100
101
102
103
104
105
106
RUPTURE LIFE [HOURS]


2¼Cr-1Mo at 1050°F
PWHT (Stress-Relieved)
Stress [KSI]
RUPTURE LIFE [HOURS]
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for Weld Metal (SMAW, SAW, GTAW) & Cross Weld (SMAW, SAW, GTAW)
1
10
100
10-1
100
101
102
103
104
105
106

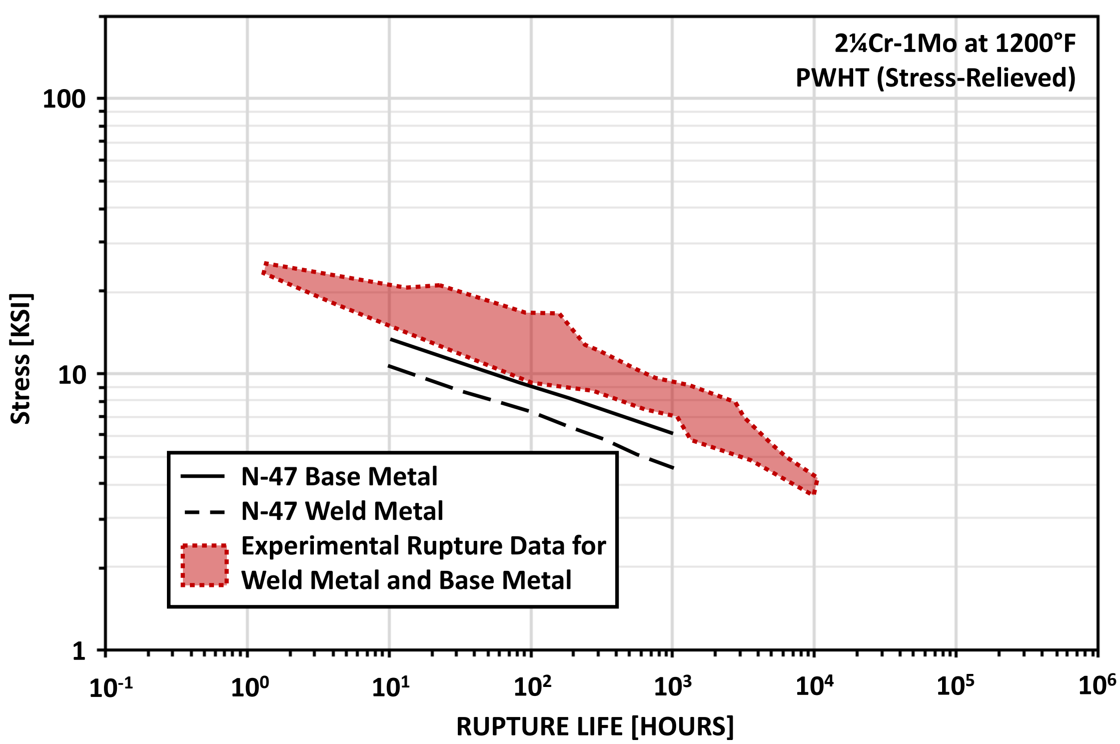

2¼Cr-1Mo at 1100°F
PWHT (Stress-Relieved)
Stress [KSI]
RUPTURE LIFE [HOURS]
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for Weld Metal and Base Metal
1
10
100
10-1
100
101
102
103
104
105
106


2¼Cr-1Mo at 1100°F
PWHT (Stress-Relieved)
Stress [KSI]
100
10
1
10-1
100
101
102
103
104
105
106
RUPTURE LIFE [HOURS]
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for Weld Metal
(SMAW, SAW) & Cross Weld (SMAW, SAW)


2¼Cr-1Mo at 1150°F
PWHT (Stress-Relieved)
Stress [KSI]
100
10
1
10-1
100
101
102
103
104
105
106
RUPTURE LIFE [HOURS]
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for
Weld Metal and Base Metal



2¼Cr-1Mo at 1150°F
PWHT (Stress-Relieved)
Stress [KSI]
100
10
1
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
RUPTURE LIFE [HOURS]
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for Weld Metal (SMAW, SAW)



2¼Cr-1Mo at 1200°F
PWHT (Stress-Relieved)
Stress [KSI]
100
10
1
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
RUPTURE LIFE [HOURS]
N-47 Base Metal
N-47 Weld Metal
Experimental Rupture Data for Weld Metal and Base Metal

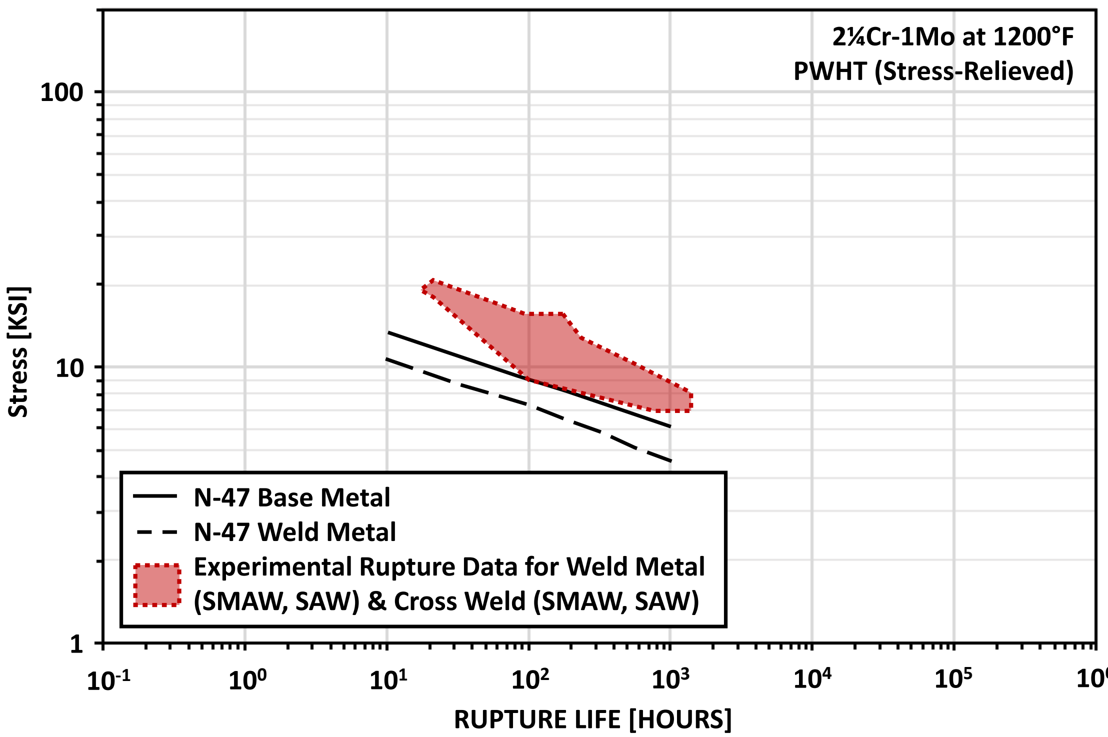


FIGURE 16 Qualitative comparisons of 2.25Cr-1Mo weld data with HBB design values. Quantitative comparisons can be found in the EPRI report prepared by R.W. Warke [22].

5.6 9Cr-1Mo-V STEEL (GRADE 91) WELDS

The stress rupture factors for 304H, 316H, Alloy 800H, and 2.25Cr-1Mo in HBB (2017 edition) are all temperature- and time-dependent. However, the stress rupture factor for 9Cr-1Mo-V is a function only of temperature. For each temperature, a conservative R value was chosen to bound the behavior for all times up to 300,000 hours.

Extension of the allowable stresses of 9Cr-1Mo-V from 300,000 to 500,000 hours was made in the 2019 edition of HBB. However, the values of expected minimum stress-to-rupture, S_r, for 9Cr-1Mo-V are lower than those from the 2017 edition for long design lives (up to 300,000 hours).

Also, there is a currently ASME balloted action, Record No. 17-2817, that provides values of the stress rupture factor, R, that are both time- and temperature-dependent, and that are lower than the R factors in the 2017 and 2019 editions for long design lives as time dependence is introduced in Record 17-2817.

In order to have an understanding of the implications of these changes, the measured creep rupture data for the 9Cr-1Mo-V welds are compared with different combinations of R and S_r. The following notation is used:

R_{2017}	=	R factors from the 2017 edition of HBB (constant in time).
$R_{17-2817}$	=	R factors from the record 17-2817 (time dependent).
$(S_r)_{2017}$	=	S_r values from the 2017 edition of HBB.
$(S_r)_{2019}$	=	S_r values from the 2019 edition of HBB.

The measured weldment creep rupture strength data are plotted versus $R_{2017} \times (S_r)_{2017}$, $R_{2017} \times (S_r)_{2019}$, and $R_{17-2817} \times (S_r)_{2019}$ in FIGURE 17, FIGURE 18, and FIGURE 19, respectively.

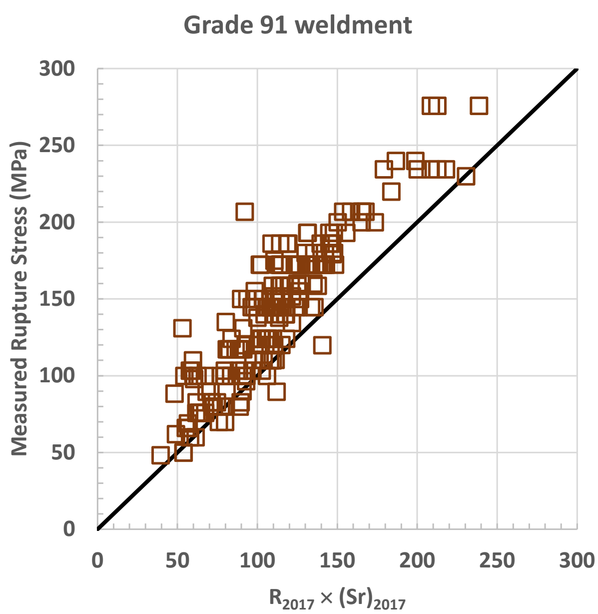


FIGURE 17 Comparison of measured creep rupture data against $R_{2017} \times (S_r)_{2017}$ for 9Cr-1Mo-V.

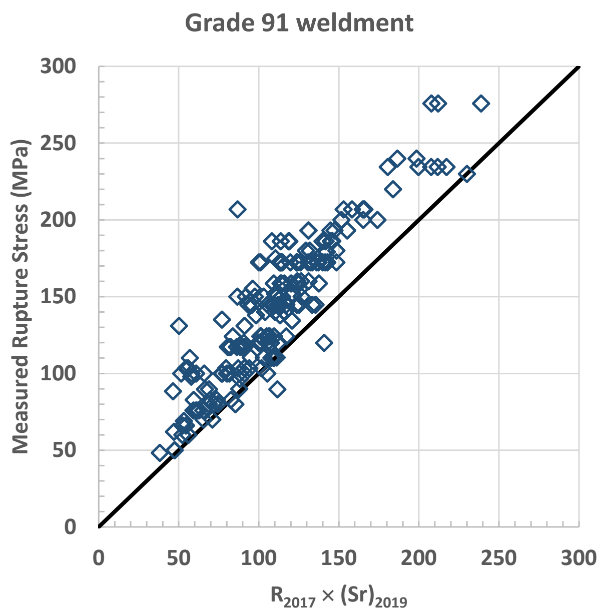


FIGURE 18 Comparison of measured creep rupture data against $R_{2017} \times (S_r)_{2019}$ for 9Cr-1Mo-V.

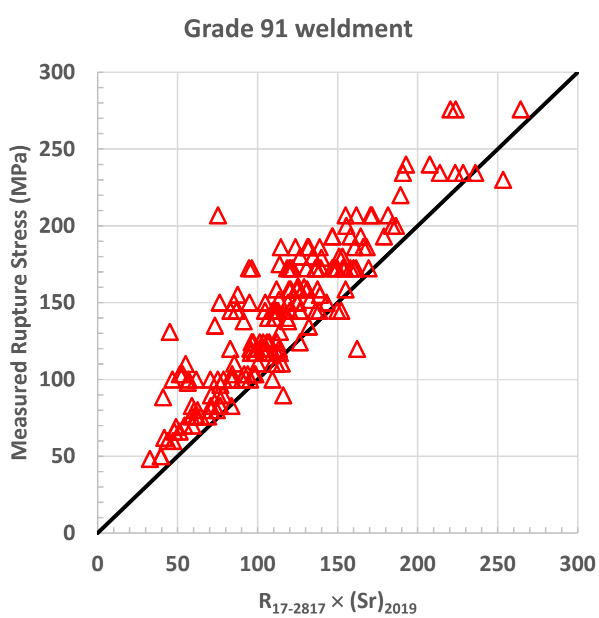


FIGURE 19 Comparison of measured creep rupture data against $R_{17-2817} \times (S_r)_{2019}$ for 9Cr-1Mo-V.

To gain an understanding of the implications of these changes on design considerations, the rupture stresses for the 9Cr-1Mo-V weldment are calculated per the HBB procedure, but with different combinations of R and S_r, in TABLE 18, TABLE 19, and TABLE 20.

TABLE 18 Values of rupture stress for weldment determined from $R_{2017} \times (S_r)_{2017}$, MPa

Temp., °C	10 h	30 h	100 h	300 h	1,000 h	3,000 h	10,000 h	30,000 h	100,000 h	300,000 h
425	459.0	459.0	459.0	459.0	459.0	436.0	412.0	390.0	366.0	345.0
450	418.0	418.0	418.0	397.1	376.2	355.3	332.5	312.6	292.6	274.6
475	389.7	375.7	358.1	335.7	314.3	294.8	274.4	256.7	239.0	223.2
500	344.1	324.8	302.7	282.4	262.2	244.7	227.2	210.7	195.0	180.3
525	293.0	273.9	253.0	235.7	217.5	202.0	185.6	172.0	157.4	144.7
550	243.9	223.4	208.3	192.2	176.2	158.4	147.7	136.2	123.7	113.0
575	201.0	185.3	168.8	155.7	141.8	129.6	117.5	106.1	95.7	86.1
600	161.3	147.8	134.4	122.6	110.9	99.1	89.0	79.0	68.9	60.5
625	127.2	116.0	104.0	93.6	84.0	75.2	64.8	53.6	42.4	33.6
650	98.8	88.9	79.0	70.7	61.6	54.7	41.0	33.4	25.1	19.0

TABLE 19 Values of rupture stress for weldment determined from $R_{2017} \times (S_r)_{2019}$, MPa

Temp., °C	10 h	30 h	100 h	300 h	1,000 h	3,000 h	10,000 h	30,000 h	100,000 h	300,000 h
425	459.0	459.0	459.0	459.0	439.0	419.0	397.0	377.0	356.0	337.0
450	418.0	418.0	409.5	389.5	367.7	348.7	327.8	309.7	289.8	272.7
475	389.7	375.7	354.3	334.8	314.3	294.8	274.4	256.7	239.0	221.3
500	344.1	324.8	302.7	282.4	262.2	244.7	227.2	210.7	195.0	168.4
525	293.0	273.9	253.0	235.7	217.5	202.0	185.6	172.0	148.3	126.5
550	243.9	223.4	208.3	192.2	176.2	158.4	147.7	132.6	109.5	91.7
575	201.0	185.3	168.8	155.7	141.8	129.6	115.7	97.4	79.2	64.4
600	161.3	147.8	134.4	122.6	110.9	98.3	84.8	69.7	54.6	42.8
625	127.2	116.0	104.0	93.6	81.6	71.2	59.2	47.2	36.0	27.2
650	98.8	88.9	79.0	69.2	59.3	50.9	40.3	30.4	22.0	16.0

TABLE 20 Values of rupture stress for weldment determined from $R_{17-2817} \times (S_r)_{2019}$, MPa

Temp., °C	10 h	30 h	100 h	300 h	1,000 h	3,000 h	10,000 h	30,000 h	100,000 h	300,000 h
425	459.0	459.0	459.0	459.0	439.0	419.0	397.0	373.2	345.3	323.5
450	440.0	440.0	431.0	410.0	387.0	363.3	338.1	316.2	292.8	269.8
475	419.0	404.0	381.0	360.0	334.6	310.7	286.2	262.2	241.6	221.3
500	374.0	353.0	329.0	303.9	279.3	258.0	234.7	215.3	197.2	168.4
525	322.0	301.0	275.2	253.8	231.8	210.9	191.8	173.9	146.7	116.8
550	274.0	248.5	229.3	209.5	188.1	167.3	152.7	126.7	97.2	77.3
575	231.0	210.9	188.2	171.8	153.2	137.1	109.1	85.1	65.5	51.8
600	190.1	172.5	153.6	137.2	121.4	95.9	72.7	58.1	44.2	34.7
625	155.8	140.7	122.2	106.5	83.6	65.9	49.6	38.9	29.7	22.4
650	126.1	110.0	93.6	76.4	58.5	45.6	34.5	26.0	18.9	13.7

A percentage difference is defined as:

$$D_6 \equiv \frac{R_{17-2817} \times (S_r)_{2019} - R_{2017} \times (S_r)_{2019}}{R_{2017} \times (S_r)_{2019}} \times 100\%$$

The values of D_6 are shown in TABLE 21.

TABLE 21 Percentage difference, D_6, between the old and new *R* factors for 9Cr-1Mo-V, D_6,%

Temp., °C	10 h	30 h	100 h	300 h	1,000 h	3,000 h	10,000 h	30,000 h	100,000 h	300,000 h
425	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	-3.0	-4.0
450	5.3	5.3	5.3	5.3	5.3	4.2	3.2	2.1	1.1	-1.1
475	7.5	7.5	7.5	7.5	6.5	5.4	4.3	2.2	1.1	0.0
500	8.7	8.7	8.7	7.6	6.5	5.4	3.3	2.2	1.1	0.0
525	9.9	9.9	8.8	7.7	6.6	4.4	3.3	1.1	-1.1	-7.7
550	12.4	11.2	10.1	9.0	6.7	5.6	3.4	-4.5	-11.2	-15.7
575	14.9	13.8	11.5	10.3	8.0	5.7	-5.7	-12.6	-17.2	-19.5
600	17.9	16.7	14.3	11.9	9.5	-2.4	-14.3	-16.7	-19.0	-19.0
625	22.5	21.3	17.5	13.8	2.5	-7.5	-16.3	-17.5	-17.5	-17.5
650	27.6	23.7	18.4	10.5	-1.3	-10.5	-14.5	-14.5	-14.5	-14.5

5.6.1 Summary on 9Cr-1Mo-V stress rupture factors

Based on the information provided in the above figures and tables, it is judged that the R factors in the 2019 edition of HBB (they are the same as those in the 2017 edition) together with the base metal S_r values, also from the 2019 edition, are adequately conservative for 9Cr-1Mo-V welded construction for temperatures up to 525°C and lifetimes up to 300,000 hours. Once the new R factors from Record 17-2817 are approved by ASME and published in a future code edition, they will be adequate for use with the S_r values for 9Cr-1Mo-V in the 2019 edition without any temperature restrictions for 9Cr-1Mo-V welded construction.

It is noted that the allowable stresses in the 2019 edition can be used without any temperature restrictions, if there are no welds in the 9Cr-1Mo-V component.

5.7 ALLOY 617 WELDS

Alloy 617, a structural material suitable for use at very high temperatures, was introduction into Section III, Division 5 through Code Case N-898 in 2019.

5.7.1 ERNiCrCoMo-1 filler material

The creep rupture data for ERNiCrCoMo-1 filler material and Alloy 617 parent material assembled in the data package for Code Case N-898 consisted of weld metal and cross-weld data. The rupture stresses data from both weld metals and cross welds are compared against $R \times S_r$ for Alloy 617 in FIGURE 20. The R values are determined from N-898 Table HBB-I-14.10F-1 for the ERNiCrCoMo-1 filler material, and the S_r values are from Code Case N-898 Table HBB-I-14.6G for Alloy 617 parent material.

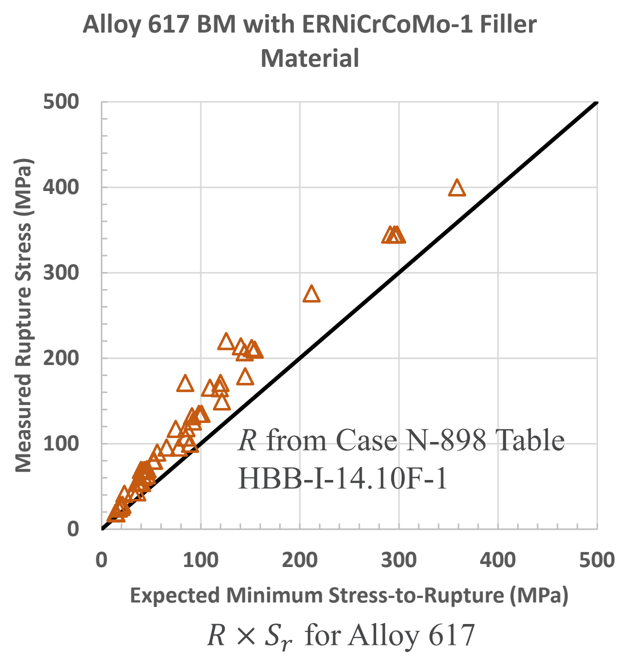


FIGURE 20 Comparison of measured creep rupture data against HBB prediction for Alloy 617 with ERNiCrCoMo-1 filler material.

5.8 SUMMARY COMMENTARY ON WELDS

Provisions in HBB for the treatment of welded construction of Class A components were developed to address weldment integrity concerns. The HBB approach is much more comprehensive than design-by-rule approaches in Sections I and VIII. The nominal trend of the stress rupture factors, when used with the rigorous base metal databases, provides adequately conservative design parameters for use in the overall design evaluation procedures for welded

construction. The HBB rules for strain accumulation and creep-fatigue damage are generally conservative and especially conservative for weldments. These additional checks over the allowable stress criteria provide additional assurance. HBB has additional limitations on weld joint geometry and requires double volumetric examination, either by radiography plus ultrasonic or double-angle radiography, for most welds. All the other weld and welder qualification requirements of the code are also required at elevated temperature. The HBB design and inspection and fabrication procedures, taken as a whole, provide adequate assurance of the structural integrity of the welds fabricated to the HBB rules.

Based on the comparisons with weld data in Section 5 and the overall conservatism of the weldment design provisions of HBB as discussed, it is judged that the stress rupture factor R, when used with the expected minimum stress-to-rupture S_r of the corresponding base material in the same code edition of HBB (2017 for the current assessment), provides adequate margin for Section III, Division 5 Class A welded construction. This also applies to the Division 5 Code Case N-898.

However, for 9Cr-1Mo-V welds, it is judged that the R factors and the base metal S_r values from the 2019 edition of HBB should be used instead for temperatures up to 525°C and lifetimes up to 300,000 hours. This is due to an out-of-phase in the revision of the R factors and the S_r values, as discussed in Section 5.6.1.

6 ASSESSMENT OF OTHER NRC CONTRACTOR COMMENTS

Assessment of other NRC contractor comments in [6] and [23] is provided below.

#	NRC contractor Comments	Assessment
ONRL-1	HBB-2800, Fatigue Acceptance Test: An editorial correction of "paras. 6.1.1 and 6.1.2" to "paras. 8.1.1 and 8.1.2" in HBB-2800 (b) is required.	Agree.
ONRL-2	Table HBB-I-14.1(a). Types 304 and 316 SS: SA-430 is deleted from the list of specifications.	Agree.
ONRL-3	Table HBB-I-14.1(a). Types 304 and 316 SS: Note (2) includes an added requirement, such as: "The heat treatment is to be separately performed, and in process heat treatment such as by direct quenching from hot forming is not permitted."	Do not agree. "In process" heat treatment is not allowed for the H grades of 304 and 316. Addition of this note would be a code action that would need agreement from Section II. Without extensive data demonstrating the need for this restriction, approval would not be forthcoming.
ONRL-4	Table HBB-I-14.1(a). 2.25Cr-1Mo: Under Note (6) clause (c), "Note (4)" is changed to "Note (5)."	Agree.
ONRL-5	Table HBB-I-14.1(a). 2.25Cr-1Mo: In the line for SA-234, "WP22, WP22W" is replaced with "WP22 CL1."	Agree.
ONRL-6	Table HBB-I-14.1(a). 2.25Cr-1Mo: A note for minimum annealing temperature and a normalizing temperature of 1,650°F (900°C) that ensures meeting the strength requirements is added.	Do not agree. Normalized condition is not allowed. The specifications use a metallurgical definition of the annealing temperature – "above the transformation temperature" and specify the required mechanical properties; if the material does not make the specified values, it is rejected. We ensure the mechanical properties by requiring them to be measured and reported. Additional response: None of the recommendations from the NRC contractor report regarding 2.25Cr-1Mo should be accepted. The contractor evaluation is based on data in both the annealed and normalized and tempered condition. As would be expected, the allowable stresses computed from the combined data tend higher at low temperatures and lower at high temperatures as compared to data for only annealed material. The contractor based their use of the combined data on their interpretation that both annealed and normalized and tempered material are permitted. However, it is the intent of notes (5) and (6) in Table HBB-I-14.1(a) that only the annealed condition is acceptable. While some of the specifications generally permit normalized and tempered material with strength and hardness restrictions, others do not. The intent of the acceptable material condition is also clearly spelled out in the background document.

#	NRC contractor Comments	Assessment
ONRL-7	Table HBB-I-14.1(b) Permissible Weld Materials: It is recommended that BPVC 2017 (and 2019) III-5 Table HBB-I-14.1(b), which is referred to in HBB-2539 Repair by Welding, be held for further review before it is accepted as part of the accepted HBB-2400. The materials listed are standard weld materials. However, the weldment properties-related reviews have not been concluded (see review report on Tables HBB-I-14.10A~E), and possible restrictions on the use of this table are currently unknown.	Do not agree. The stress rupture factors have been assessed in Section 5 of this report.
ONRL-8	Table HBB-I-14.5, Yield strength values, S_y, versus temperature. It is recommended that BPVC 2017 (and 2019) III-5 Table HBB-I-14.5 be accepted after consideration is given to review the S_y values for 304 SS at the two highest temperatures that appear non-conservative relative to our analysis results.	Do not agree. Firstly, tensile properties for 304 and 316 permitted in HBB have a room temperature specification minimum ultimate tensile strength of 75 ksi, not 70 ksi. Secondly, the S_y values for 304 SS at the two highest temperatures in question are consistent with other design data.
ONRL-9	Table HBB-I-14.5, Yield strength values, S_y, versus temperature. 2.25Cr-1Mo: While the tabulated S_y are acceptable, the strength of annealed material and of normalized and tempered material differ, with application of the tabulation to normalized and tempered material being less conservative than application to annealed material.	Do not agree. The normalized and tempered heat treatment for 2.25Cr-1Mo is not permitted for HBB use.
ONRL-10	Bolting: No tabulated S_{mt} values for Types 304 and 316 SS bolt materials.	Do not agree. As stated in the Companion Guide chapter for Division 5, [1], and Paragraph HBB-3232 of Division 5, the S_{mt} values for bolt materials are half those of the base metals.
NUMARK-1	Appendix HCB-II: some of the allowable stresses for negligible creep (A4) or creep less than one hour (A3) were lower than some of the stresses for non-negligible creep (A1 and A2), for certain materials.	Agree. Conceptually, the allowable stresses tabulated for A-3 and A-4 should always be equal to or more conservative than those in A-1 and A-2 because they are not governed by time-dependent (creep) properties. However, as noted, there are currently cases where, in the regime where A-1 and A-2 are governed by time-independent properties, the values in A-1 and A-2, are greater than those in A-3 and A-4. The root cause of this issue is that the current allowable stress values in Article HCB-II-2000 "Service Without Creep Effects" have not been maintained in the several decades since they were first established. However, Article HCB-3000 "Service Which May Include Creep Effects" references the allowable stress values in in Tables 1A and B in Section II, Part D which are, by definition, current. Thus, due to the evolution of the Table 1A and B stress values, there are differences in the negligible creep regime with the values in Article HCB-II-2000.

#	NRC contractor Comments	Assessment
		• On that basis, if the A-1 and A-2 values are greater than the A-3 and A-4 values, the A-1 and A-2 values should take precedence. • Conceptually, since the HCB component design rules, HCB -3300, etc., are based on the Class 2, NC-3300, etc., rules which reference the Table 1A and B stress values, the higher stress values given by A-1 and A-2 based on Tables 1A and B should be used in case of conflict. In summary, in the regime where the negligible creep criteria are satisfied, it is acceptable to use the greater of A1 and A2 or A3 and A4.
NUMARK-2	Appendix HBB-T: Isochronous stress-strain curves for Grade 91 not conservative.	Do not agree. See discussion in Section 6.1.
NUMARK-3	There may be a need to reconsider the BPVC-III-5 isochronous stress-strain curves for higher temperatures (perhaps above 700°C (1292°F)) for long times, since the extrapolation used to produce the code curves may need improvement	Do not agree. Considering the scatter in time to reach a given strain at constant stress in the NUMARK plots for other Class A materials, the spot check by NUMARK actually supports the reasonableness of the current ISSCs for all Class A materials.

6.1 ISOCHRONOUS STRESS STRAIN CURVES, 9Cr-2Mo-V

In [23], the NRC contractor recommends the NRC not to endorse the isochronous stress-strain curves (ISSCs) for 9Cr-1Mo-V in the 2017 edition of HBB. The contractor instead endorses the use of new ISSCs for that material developed in the STP-PT-080 report by Jawad et al. in [24] on the basis that: "The isochronous curves for 9 Cr Mo material are higher than the new curves recently produced by ASME Standards Technology, LLC based on new data and may be slightly non-conservative in general."

We disagree with this assessment based on the following discussions. We judge that the ISSCs for 9Cr-1Mo-V in the 2017 edition of HBB are adequate for the design evaluation by analysis of the strain, deformation, and creep-fatigue limits.

We first provide a historical perspective on the ample additional conservativism in the HBB rules to account for the scatter in material deformation data. We then address the specific comments made in [23] about the 9Cr-1Mo-V ISSCs.

6.1.1 Perspective on HBB design procedures to account for scatter in material deformation data

It was well recognized during the early days of the development of the HBB rules to address deformation-controlled failure modes that there is large scatter in material deformation

data. Using either upper or lower bound for the material deformation data would not lead to a robust design methodology, as it could lead to conservative prediction under one deformation condition but non-conservative prediction for another. Instead, the code uses the average material response in the design calculation and includes implicit and explicit conservatism to account for the variation in the material deformation data.

6.1.1.1 Deformation limits

The B-1 and B-2 tests in HBB are based on an O'Donnell-Porowski [25] analysis of a Bree cylinder, which conservatively bounds the strain accumulation in a more complex geometry.

In addition, the deformation limits are based on an engineering judgement of acceptable service limits for strain accumulation in operating high-temperature components. As such, if the actual structure exceeds the HBB limits, there are no immediate consequences on component safety. Thus, average deformation properties are acceptable in calculating the deformation limits, even if the true material creep response is substantially faster or slower than the average response assumed in the design calculation.

6.1.1.2 Creep-fatigue criteria

Creep-fatigue damage initiation can have immediate safety consequences, at least for components where the time between damage initiation and through-section failure is short (for example, a vessel wall at a nearly uniform state of stress). As such, the code should conservatively prevent components from exceeding the creep-fatigue limits, in accounting for the expected variation in material properties.

In the design-by-elastic-analysis creep-fatigue design criteria, the ISSCs can be used to calculate stress relaxation, given some initial strain (modified to account for inelasticity). This is the primary use for the ISSCs in creep-fatigue design.

The creep damage calculation uses the code values of expected minimum stress-to-rupture (S_r), not average properties. As such, any additional conservatism on top of using this expected minimum rupture stress can be reasonably assumed to be aimed at accounting for variations from the component design conditions, geometry, and, especially, variations in the material deformation and stress-relaxation response.

The design-by-elastic-analysis creep-fatigue procedures are based on a bounding analysis. Therefore, there is difficult-to-quantify conservatism inherent in the assumptions about the total strain range used in the analysis, the modifications to that strain range accounting for inelasticity, and in how the method accommodates multiaxial states of stress.

6.1.1.3 Stress relaxation

Finally, there are two sources of explicit conservatism that cover the variation in actual stress relaxation rates.

First, the stresses from the relaxation analysis used to calculate the creep damage fraction are divided by an explicit safety factor, K'. For 9Cr-1Mo-V and design-by-elastic-analysis, this factor is $K' = 1.0$; hence, it does not provide additional margin. However, this factor provides an explicit margin accounting for variation in stress relaxation rates for the remaining Class A materials.

Second, the relaxation procedure using the ISSCs is inherently conservative. FIGURE 21 compares the relaxation profile calculated using the algebraic ISSC relaxation procedure in the design-by-elastic-analysis rules to the relaxation profile given by integrating the actual creep model underlying the 2017 ISSCs through the stress relaxation condition. The ISSC method produces higher stresses and is therefore conservative compared to accurately integrating the relaxation differential equation.

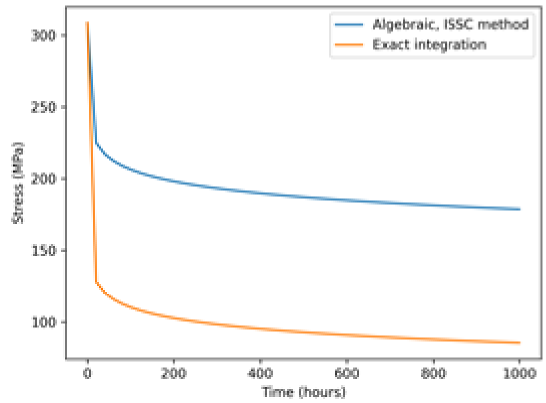


FIGURE 21 Comparison between the stress relaxation profile produced by the design-by-elastic-analysis ISSC method to the profile produced by integrating the creep model underlying the 2017 edition ISSCs through the stress relaxation condition. This example uses an initial stress of 310 MPa (0.5 strain according to the 2017 edition hot tensile curves), a temperature of 550°C, and a hold time of 1000 hours.

TABLE 22 explicitly tabulates the margin provided by the ISSC method for 9Cr-1Mo-V, as an example. This table gives creep damage fraction calculated by integrating the differential creep model underlying the 2017 ISSCs and then calculating creep damage using the time-fraction approach and the 2017 edition values of S_r, a damage calculation similar to using the ISSC relaxation profile, and the ratio between these two creep damage fractions.

TABLE 22 Margin in creep damage fraction between the ISSC relaxation analysis used in the Section III, Division 5 design-by-elastic-analysis creep damage calculation option and an exact integration of the creep equations through the stress relaxation condition.

Temperature, °C	Initial strain, %	Initial stress, MPa	Time, h	$\boldsymbol{D_c}$, ISSC	$\boldsymbol{D_c}$, Exact	Margin
550	0.3	284	500	0.18	0.09	2.05
575	0.3	277	500	0.26	0.10	2.69
600	0.3	241	500	0.39	0.13	3.02
625	0.3	214	500	0.48	0.31	1.57
650	0.3	184	500	0.57	0.37	1.53

The algebraic ISSC method for determining the stress relaxation profile produces a significantly more conservative relaxation profile when compared to an exact integration of the creep deformation equation through the relaxation conditions. As TABLE 22 demonstrates, depending on the temperature, initial strain/stress, and time the margin ranges from 1.5 to 3.0 on the creep damage. This margin encompasses the variation in the actual stress relaxation behavior of a particular sample of material, thereby adequately accounting for the variation in material deformation described here.

6.1.2 Average properties for ISSCs

The ISSCs in HBB should reflect average properties, as there is no generally conservative direction to shift the ISSCs.

The NRC contractor report assumes that "higher" isochronous curves are more conservative. Higher curves imply that the material deforms slower (isochronous curves are closer together) and, following the HBB design procedure, that the material relaxes slower under a fixed stress. This does mean that higher curves, or a constitutive response that creeps slower than the actual material, is conservative for evaluating creep-fatigue damage, as the HBB design procedure assumes that creep damage is proportional to the stress and slower stress relaxation keeps a component at higher states of stress for longer times.

However, the HBB procedure also uses the isochronous curves to calculate the amount of strain accumulated against the deformation limits. Specifically, the B tests in the design-by-elastic-analysis rules use the isochronous curves for this purpose. In this situation, "lower" isochronous curves reflecting faster than actual creep deformation are more conservative, as the component will accumulate strain more quickly.

Given this dichotomy, the HBB rules work with average isochronous curves, reflecting the average material hot tensile curves and the average material creep deformation. Rather than shifting the curves to account for the scatter in measured creep deformation rates, the procedure applies additional safety factors and conservatism to the design calculations to account for the scatter in the material deformation response.

Therefore, the contractor's assumption that higher isochronous curves are always more conservative is not supported and should not be used as the technical basis for not endorsing the ISSCs in the 2017 edition or endorsing alternative ISSCs.

The following then provides a technical basis for accepting the current isochronous curves by comparing the implied material response against experimental data and by detailing the additional conservatism in the code design rules aimed at accounting for the variation in the material deformation response.

6.1.3 Large scatter in the flow strength and creep deformation data

There is a large scatter in the flow strength and creep deformation data, and the current ISSCs fall within this scatter.

The task then for ISSCs used in HBB for the design-by-elastic-analysis deformation and creep-fatigue design criteria is to match the average behavior of the material, as reflected in tensile and creep tests. There is a wide scatter in these measurements for 9Cr-1Mo-V and the other Class A materials.

FIGURE 22 plots the measured yield stress of 9Cr-1Mo-V from a large database versus the yield stress assumed by the 2017 edition HBB ISSCs, with the technical basis given by Swindeman [26], as well as the STP-PT-080 ISSCs.

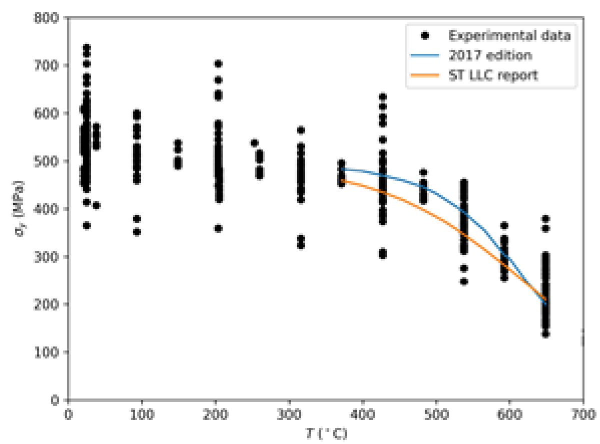


FIGURE 22 Yield stress comparison between experimental data, the 2017 edition HBB hot tensile curves, and the STP-PT-080 hot tensile curves.

This figure illustrates the large scatter in the material flow stress and demonstrates that both the current hot tensile curves and the curves proposed in the STP-PT-080 report fall within the scatter, near the average of the data.

This demonstrates that both the 2017 edition HBB and the STP-PT-080 hot tensile curves are approximately equivalently accurate. A full assessment would include the experimentally observed and model-predicted work hardening or softening. However, given that the ASME curves are only used up to a few percent strain and 9Cr-1Mo-V does not significantly harden or soften over that strain range, this yield stress comparison is adequate to assess the hot tensile curves.

FIGURE 23 provides a similar comparison for creep. This figure plots the results from four creep tests at the same conditions (550°C and 240 MPa) for samples of 9Cr-1Mo-V drawn again from a large database. This figure then illustrates the scatter in creep deformation data within 9Cr-1Mo-V material. The figure superimposes these experimental creep curves with the predictions from the creep models underlying the 2017 edition HBB and STP-PT-080 ISSCs. The plot strain range is (approximately) the strains covered by the code ISSCs. Both the 2017 edition HBB and STP-PT-080 curves fall well within the scatter in the experimental data. This comparison indicates that again both the STP-PT-080 and 2017 edition HBB ISSCs provide a reasonable average-property deformation response for 9Cr-1Mo-V, given the large scatter in the underlying experimental data.

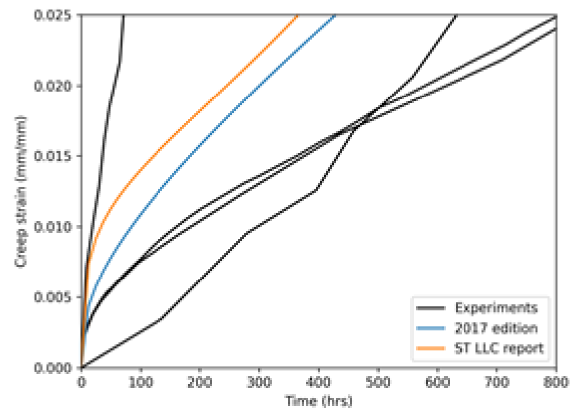


FIGURE 23 Comparison between a set of experimental creep curves at 550°C and 240 MPa load and the predicted creep curves using the models underlying the 2017 edition HBB and STP-PT-080 ISSCs.

A more comprehensive comparison for different temperatures and stress levels is difficult, as there are not many duplicated conditions in the database of creep curves available. However, a similar comparison based on minimum creep rate data, FIGURE 24, shows the discrepancy between the NIMS and U.S. datasets and how the minimum creep rate predictions from the existing ISSCs still easily fall within the data scatter.

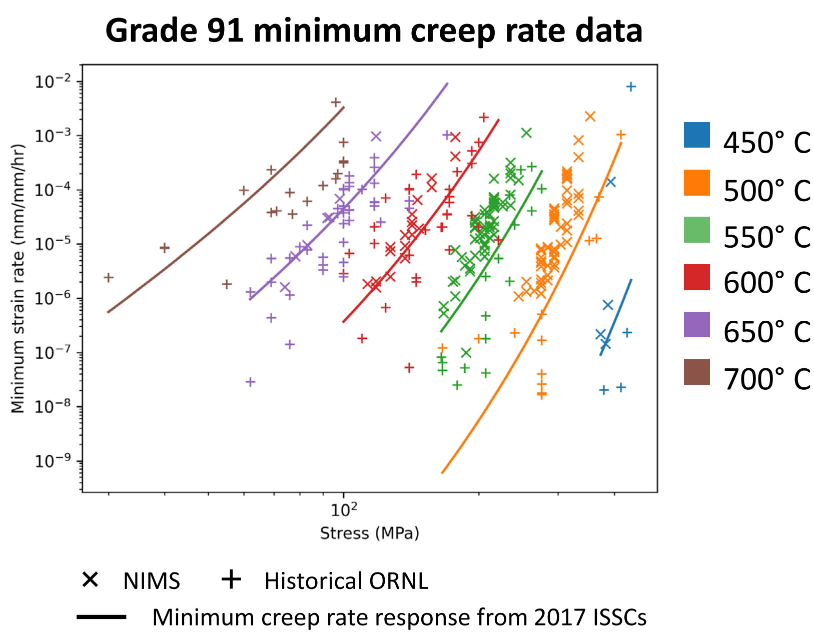


FIGURE 24 Comparison of Grade 91 minimum strain rate data from U.S. and Japan with predictions from strain equation for the 2017 ISSCs.

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