ASME NTB-3-2020

Gap Analysis for Addressing Adequacy or Optimization of ASME Section III, Division 5 Rules for Metallic Components

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GAP ANALYSIS FOR ADDRESSING ADEQUACY OR OPTIMIZATION OF ASME BPVC SECTION III, DIVISION 5 RULES FOR METALLIC COMPONENTS

Prepared by:

Robert I. Jetter, RI Jetter Consulting
Mark C. Messner, Argonne National Laboratory
James Nestell, MPR Associates Inc.
T.-L. Sham, Argonne National Laboratory
Yanli Wang, Oak Ridge National Laboratory

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Date of Issuance: July 31, 2020

This publication has been co-authored by UChicago Argonne, LLC under Contract No. DE-AC02-06CH11357 and by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the United States (U.S.) Department of Energy ("DOE"). The United States Government retains, and by accepting the work for publication, the publisher acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes. The DOE will provide public access to these results of federally-sponsored research in accordance with the DOE Public Access Plan: (https://www.energy.gov/downloads/doe-public-access-plan).

The American Society of Mechanical Engineers

Two Park Avenue, New York, NY 10016-5990

ISBN No. 978-0-7918-7377-9

TABLE OF CONTENTS

LIST OF TABLES

FOREWORD

The goal of this publication is to provide an assessment of an integrated list of 39 issues that have been assembled from three prior reviews of various forerunners of ASME Boiler and Pressure Vessel Code ("BPVC"), Section III *Rules for Construction of Nuclear Facility Components*, Division 5 *High Temperature Reactors*, Code rules for metallic coolant boundary components and core supports. The focus of the assessment has been on whether the current BPVC Section III, Division 5 Code rules provide reasonable assurance of adequate protection against identified structural failure modes with respect to these issues.

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EXECUTIVE SUMMARY

This gap analysis report provides an assessment of an integrated list of 39 issues assembled from three prior reviews of various forerunners of BPVC Section III, Division 5 Code rules for metallic coolant boundary components and core supports. The focus of the assessment has been on whether the current BPVC Section III, Division 5 Code rules provide reasonable assurance of adequate protection against identified structural failure modes with respect to these issues. If gaps are identified, an attempt was made to assess whether they are related to the adequacy or the optimization of the Code rules. For example, extension to cover longer design lifetimes that does not affect the adequacy of the underlying technical basis of the rules corresponds to optimization. The 39 gaps and issues evaluated in this report originated from four references: O'Donnell, Hull and Malik's 2008 paper [1]; O'Donnell and Griffin's 2007 STLLC STP-NU-010 report [2]; the 1985 paper by Griffin [3]; and the 1993 Nuclear Regulatory Commission (NRC) NUREG report by Huddleston and Swindeman [4].

The comprehensive STP-NU-010 report by O'Donnell and Griffin [2] itemized 25 items that are listed in Table 1. Each of the items is assigned a distinct item number for ease of reference. O'Donnell, Hull and Malik's paper in 2008 [1] summarized these issues and is largely based on the STP-NU-010 report [2].

Table 1: Safety Issues for Structural Design of Very High Temperature Reactor and Gen IV Systems in O'Donnell, Hull and Malik 2008 [1] and O'Donnell and Griffin 2007 [2]

Original Item number	Item title	Corresponding Issue number in this report
OG- 1	Transition joints	III.1
OG- 2	Weld residual stresses	III.2
OG- 3	Design loading combinations	VII. 1
OG- 4	Creep-rupture and fatigue damage	I.4
OG- 5	Simplified bounds for creep ratcheting	I.2
OG- 6	Thermal striping	I.8
OG- 7	Creep-fatigue analysis of Class 2 and 3 piping	I.5
OG- 8	Are limits of Case N-253 for elevated-temperature Class 2 and 3 components met?	VI.1
OG- 9	Creep buckling under axial compression – design margins	I. 11
OG- 10	Identify areas where Appendix T rules are not met	I.1
OG- 11	Rules for component supports at elevated-temperature	V.1
OG- 12	Strain and deformation limits at elevated-temperature	I.3
OG- 13	Evaluation of weldments	III.3
OG- 14	Material acceptance criteria for elevated-temperature	II. 2
OG- 15	Creep-rupture damage due to forming and welding	II. 1
OG- 16	Mass transfer effects	VII. 2
OG- 17	Environmental effects	VII. 3
OG- 18	Fracture toughness criteria	VII. 5

Original Item number	Item title	Corresponding Issue number in this report
OG- 19	Thermal aging effects	II. 4
OG- 20	Irradiation effects	VII. 4
OG- 21	Use of simplified bounding rules at discontinuities	I. 9
OG- 22	Elastic follow-up	I.6
OG- 23	Design criteria for elevated-temperature core support structures and welds	V.2
OG- 24	Elevated-temperature data base for mechanical properties	II. 3
OG- 25	Basis for leak-before-break at elevated temperatures	VII. 6

Note: The issues were not ranked in any particular order by the authors.

In the 1985 paper by Griffin "Elevated Temperature Structural Design Evaluation Issues in LMFBR Licensing" [3], nine issues associated with elevated temperature structural design identified by the NRC licensing review of Clinch River Breeder Reactor Plant (CRBRP) for a construction permit were described. These nine items are listed in Table 2. It was noted in the paper that "the design criteria and basic approach to design evaluation were accepted and that no major inadequacies were discovered."

Table 2: Elevated Temperature Structural Design Issues in Liquid Metal Fast Breeder Reactor Licensing Identified by Griffin [3]

Original Item number	Item title	Corresponding Issue number in this report
G-3. 1	Weldment Safety Evaluation	III.2; III.3
G-3. 2	Notch Weakening	IV.3
G-3. 3	Design Analysis Methods, Codes and Standards	II. 7
G-3. 4	Steam Generator	I. 10
G-4. 1	Elevated-temperature seismic effects	VI. 5
G-4. 2	Elastic follow-up in elevated-temperature piping	I.6
G-4. 3	Creep-fatigue evaluation	I.5
G-4. 4	Plastic strain concentration factors	I.7
G-4. 5	Intermediate heat transport system transition weld	III.1

Note: The issues were not ranked in any particular order by the authors.

In addition, 23 items were identified in the 1993 NRC NUREG report by Huddleston and Swindeman [4]. The perspective of the Huddleston-Swindeman report is somewhat different in that it is intended "to identify any code design basis issues that could negatively impact (delay) the design certification process." Many of the identified issues are taken from Volume 1 of the four-part Welding Research Council (WRC) series edited by A. K. Dhalla, *Recommended Practices in Elevated Temperature Design* [5], which is discussed in more detail in the ASME NTB-2-2019 report *Background Information for Addressing Adequacy or Optimization of ASME BPVC Section III, Division 5 Rules for Metallic Components* [6]. The WRC report is quoted extensively in the Huddleston-Swindeman report. However, in terms of reactor types considered, the scope of Huddleston-Swindeman [4] is much broader and the operating conditions potentially more demanding. Also, significantly, the full list of issues is narrowed to ten major issues in the report. The 23 items identified by Huddleston-Swindeman are listed in Table 3, and those identified as major issues by the authors are marked.

Table 3: Material and Design Bases Issues in ASME Code Case N-47 Identified by Huddleston and Swindeman [4]

Original Item number	Item title	One of the 10 major issues	Corresponding Issue number in this report
HS- 1	Lack of Material Property Allowable Design Data/Curves for 60-Year Design Life	Yes	**II. 2; II. 3**
HS- 2	Degradation of Material Properties at High Temperatures due to Long-Term Irradiation	Yes	**VII. 4**
HS- 3	Degradation of Material Properties due to Long-Term Thermal Aging	No	**II. 4**
HS- 4	Degradation of Material Properties due to Corrosion Phenomena	Yes	**VII. 3**
HS- 5	Lack of Property Allowables Based on Current Melting and Fabrication Practices	No	**II. 2; II. 3**
HS- 6	Degradation Effect of Small Cyclic Stresses	No	**VI.2**
HS- 7	Creep Induced Failures at Temperatures Below CCN47 Limits	No	**VI.3**
HS- 8	Use of Average vs Minimum Material Properties in Design	No	**II. 6**
HS- 9	Lack of a Design Methodology for Modified 9Cr-1Mo Steel	No	**II. 5**
HS- 10	Lack of Understanding/Validation of Effects of Short-Term Overload Events on Subsequent Mechanical Properties	No	**VI. 4**
HS- 11	Lack of Validated Thermal Striping Materials and Design Methodology	Yes	**I. 8**
HS- 12	Lack of Reliable Creep-Fatigue Design Rules	Yes	**I.5**
HS- 13	Difficult, Overly Conservative Ratcheting Design Rules	No	**I.2**
HS- 14	Lack of a Validated Weldment Design Methodology	Yes	**III.2; III.3**
HS- 15	Lack of Flaw Assessment Procedures	Yes	**VII. 7**
HS- 16	Uncertainty of Multiaxial Stress State Effect	No	**IV.1**
HS- 17	Uncertainty of Nonradial (Nonproportional) Loading Effect	No	**IV.2**
HS- 18	Lack of Understanding/Validation of Notch Weakening Effects	Yes	**IV.3**
HS- 19	Lack of Conservatism in Code Rules for Simplified Fatigue Evaluations Based on Plastic Strain Concentration Factors	No	**I.7**
HS- 20	Lack of Validated Rules/Guidelines to Account for Seismic Effects at Elevated, Temperature	Yes	**VI. 5**
HS- 21	Lack of Inelastic Design Procedures for Piping	Yes	**II. 7**
HS- 22	Overly Conservative Buckling Rules	No	**I. 11**
HS- 23	Need for Thermal Stratification Design Guidelines	No	**VI. 6**

Note: The issues were not ranked in any particular order by the authors.

There is considerable overlap in the identified issues among these sources [1], [2], [3], [4]. Combining all the items from these references, a total of 39 issues are recognized and are further grouped into 6 categories: (1) Issues Relating to Strain, Deformation, and Fatigue Limits; (2) Issues Relating to Materials Properties; (3) Welds and Core Supports; (4) Multiaxiality; (5) Miscellaneous Issues; and (6) Issues Outside of Division 5 Scope. Table 4 lists these 6 categories and the issues under each category. The origins of these issues are also identified in Table 4.

Table 4: Issues for Assessing the Adequacy or Optimization of the Current BPVC Section III, Division 5 Rules and Code Cases in Construction of High-Temperature Reactors

Issue Number	Origin of Issue*	Issue Title
Category I: Relating to Strain, Deformation, and Fatigue Limits		
Issue I. 1	OG-10	Identify areas where Appendix T rules are not met
Issue I. 2	OG-5, HS-13	Simplified bounds for creep ratcheting
Issue I. 3	OG-12	Strain and deformation limits at elevated-temperature
Issue I. 4	OG-4	Creep-rupture and fatigue damage
Issue I. 5	OG-7, G-4.3, HS-12	Creep-fatigue analysis of Class 2 and 3 piping
Issue I. 6	OG-22, G-4.2	Elastic follow-up
Issue I. 7	G-4.4, HS-19	Plastic strain concentration factors/Lack of Conservatism in Code Rules for Simplified Fatigue Evaluation Based on Plastic Strain Concentration Factors
Issue I. 8	OG-6, HS-11	Thermal striping
Issue I. 9	OG-21	Use of simplified bounding rules at discontinuities
Issue I. 10	G-3.4	Steam generator tubesheet evaluation
Issue I. 11	OG-9, HS-22	Creep buckling under axial compression – design margins
Category II: Relating to Materials Properties		
Issue II. 1	OG-15	Creep-rupture damage due to forming and welding
Issue II. 2	OG-14, HS-1, HS-5	Material acceptance criteria for elevated-temperature
Issue II. 3	OG-24, HS-1, HS-5	Elevated-temperature data base for mechanical properties
Issue II. 4	OG-19, HS-3	Thermal aging effects
Issue II. 5	HS-9	Lack of a design methodology for Modified 9Cr-1Mo steel
Issue II. 6	HS-8	Use of average vs. minimum material properties in design
Issue II. 7	G-3.3, HS-21	Material property representation for inelastic analysis/Lack of inelastic design procedures for piping
Category III: Welds		
Issue III. 1	OG-1, G-4.5	Transition joints
Issue III. 2	OG-2, G-3.1, HS-14	Weld residual stresses
Issue III. 3	OG-13, G-3.1, HS-14	Evaluation of weldments
Category IV: Multiaxiality		
Issue IV. 1	HS-16	Uncertainty of multiaxial stress state effects
Issue IV. 2	HS-17	Uncertainty of non-radial (non-proportional) loading
Issue IV. 3	G-3.2, HS-18	Notch weakening/Lack of understanding/validation of notch weakening effects
Category V: Components and Core Supports		
Issue V. 1	OG-11	Rules for component supports at elevated-temperature
Issue V. 2	OG-23	Design criteria for elevated-temperature core support structures and welds
Category VI: Miscellaneous Issues		
Issue VI. 1	OG-8	Are limits of Case N-253 for elevated-temperature Class 2 and 3 components met?
Issue VI. 2	HS-6	Degradation effect of small cyclic stresses
Issue VI. 3	HS-7	Creep-induced failures at temperatures below Code Case N-47 limits
Issue VI. 4	HS-10	Lack of understanding/validation of effects of short term overload events on subsequent material properties.
Issue VI. 5	G-4.1, HS-20	Elevated-temperature seismic effects/Lack of validated rules/guidelines to account for seismic effects at elevated temperature
Issue VI. 6	HS-23	Need for thermal stratification guidelines

Issue Number	Origin of Issue*	Issue Title
Category VII: Issues Outside of Division 5 Scope		
Issue VII. 1	OG-3	Design loading combinations
Issue VII. 2	OG-16	Mass transfer effects
Issue VII. 3	OG-17, HS-4	Environmental effects
Issue VII. 4	OG-20, HS-2	Irradiation effects
Issue VII. 5	OG-18	Fracture toughness criteria
Issue VII. 6	OG-25	Basis for leak-before-break at elevated temperatures
Issue VII. 7	HS-15	Lack of flaw assessment procedures

Note: (1) * Origin of Issue refers to the item numbers in Table 1, Table 2 and Table 3.
(2) The issues are not ranked in any particular order.

The issues discussed in this report, as well as those identified in the four references, were not ranked in any particular order by the authors.

The discussions of these 39 issues in this document use the O'Donnell, Hull and Malik 2008 paper [1] as the baseline, and the text explaining the issues is taken from that report. Duplication from the Griffin and Huddleston-Swindeman document is noted and discussed as appropriate. Additional issues beyond those identified by O'Donnell, Hull and Malik [1] are discussed.

In addition to the Summary of each tabulated issue, there is a General Assessment of its significance, Material Specific Remarks as applicable, Required Actions, if any, and Conclusions regarding gaps or actions addressing the adequacy or optimization of BPVC Section III, Division 5. Thus, for each tabulated issue, there are five subheadings expanding on the issue and its determination from a gap analysis perspective.

ABBREVIATIONS AND ACRONYMS

ACRS	Advisory Committee on Reactor Safeguards
ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
CC	Code Case
CRBR	Clinch River Breeder Reactor
CRBRP	Clinch River Breeder Reactor Plant
DMW	Dissimilar Metal Weld
DOE	Department of Energy
EPP	Elastic Perfectly Plastic
FEA	Finite Element Analysis
FFTF	Fast Flux Test Facility
Gr91	Modified 9Cr-1Mo
HTGR	High Temperature Gas-cooled Reactor
HTR	High Temperature Reactor
ISI	In-Service Inspection
JSME	Japan Society of Mechanical Engineers
LMFBR	Liquid Metal Fast Breeder Reactor
LWR	Light Water Reactor
MHTGR	Modular High Temperature Gas-cooled Reactor
N/A	Not Applicable
NGNP	Next Generation Nuclear Plant
NIMS	National Institute for Materials Science
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
R&D	Research and Development
SMT	Simplified Model Test
STLLC	ASME Standards Technology, LLC
UK	United Kingdom
VHTR	Very High Temperature Reactor
WRC	Welding Research Council

1 RELATING TO STRAIN, DEFORMATION, AND FATIGUE LIMITS

1.1 Issue I. 1 – Identify Areas Where Appendix T Rules are not Met

1.1.1 Summary

O'Donnell, Hull and Malik [1] summarized this issue in Item OG- 10 as follows:

> Appendix T in NH [7] provides three expressions for determining strain range [8] using elastic analysis and, if these rules cannot be satisfied, additional rules are provided, presumably less conservative, based on the results of inelastic analyses which require detailed constitutive models of material behavior under time varying loading conditions. For the CRBR, these behavioral models were a contractual provision based on RDT Standards. These applicable standards are no longer maintained and there have been numerous technical developments in this area since then [9]. Appendix T rules cover strain, deformation, creep and fatigue limits at elevated temperatures for 304SS/316 SS (816°C), Alloy 800H (760°C), 2.25Cr-1Mo (593°C), 9Cr-1Mo-V (649°C). Development of material models for materials not currently covered or for temperatures beyond their original range of verification will be a considerable effort. Modifications in Appendix T rules for higher temperatures and additional materials (e.g., Alloy 617, Hastelloy X/XR) may be needed.

1.1.2 General Assessment

Appendix HBB-T of BPVC Section III, Division 5 provides procedures to evaluate strain limits and creep fatigue damage using elastic analysis. Alternatively, for some Class A materials, recent code cases provide procedures based on Elastic-Perfectly plastic (EPP) analysis. If these rules cannot be satisfied, additional rules are provided which are based on results of inelastic analyses. However, inelastic analysis requires detailed constitutive models of material behavior under time varying loading conditions. For the CRBR, these behavioral models were based on Nuclear Standard NE F9-5T. This standard is no longer maintained, and numerous technical developments have been made since. However, ASME has established a working group to develop inelastic analysis methods and constitutive models for Class A materials for incorporation into BPVC Section III, Division 5. Models for several materials have been developed and are ready for ASME Code action [10], and the development process continues in the working group for the remaining materials.

1.1.3 Material Specific Remarks

None.

1.1.4 Action Required

(1) Complete the extension of the EPP methods to the remaining Class A materials, and (2) proceed to ballot the recommended constitutive equations developed in the Working Group on Analysis Methods.

1.1.5 Conclusion

Categorized as Optimization.

1.2 Issue I. 2 – Simplified Bounds for Creep Ratcheting

1.2.1 Summary

From O'Donnell, Hull and Malik [1] Item OG- 5:

> The Draft Code Case for Alloy 617 imposes ratcheting strain limits that are similar to the limits given in Subsection NH, but is restricted to an upper temperature limit of 649°C. Simplified ratcheting evaluation procedures require development for temperatures above 649°C [11]. New work has been proposed to ensure that recent technology developments are incorporated [9].

Huddleston and Swindeman stated this issue in Item HS- 13 as "difficult, overly conservative ratcheting design rules" and noted that the rules have been improved since the CRBRP to include applicability to structural discontinuities and application to nonaxisymmetric geometries and nonlinear temperature gradients. It is considered a design basis economic issue and is not included as one of the top ten major issues.

1.2.2 General Assessment

The current strain accumulation rules have geometric and service level transient design restrictions. The rules are also complicated to apply. The BPVC Section III, Division 5 elastic rules for strain limits evaluation are based on the decoupling of creep and plasticity. For temperatures above a certain cut off, the decoupling of creep and plasticity can no longer be justified and a unified viscoplastic model is necessary to describe the deformation behavior. The recently developed EPP methodology for strain limits evaluation of Type 304 and 316 stainless steels does not depend on the decoupling of creep and plasticity. It has been demonstrated by tests to be applicable to the full temperature range permitted code allowable stresses, including very high temperatures where creep and plasticity are no longer decoupled. Cut off temperatures for the Class A materials have recently been established [12].

1.2.3 Material Specific Remarks

An Alloy 617 Code Case that includes the EPP methodologies which do not depend on the decoupling of creep and plasticity, and hence do not have the 649°C upper temperature limit for Alloy 617 as in the current strain accumulation rules, is being balloted by ASME Code committees.

1.2.4 Action Required

(1) Complete the ASME approval process for the Alloy 617 Code Case, and (2) complete the extension of the EPP methods to the remaining Class A materials.

1.2.5 Conclusion

Tentatively categorized as optimization.

1.3 Issue I. 3 – Strain and Deformation Limits at Elevated-Temperature

1.3.1 Summary

From O'Donnell, Hull and Malik Item OG- 12:

> Current NH rules address these issues; however, extrapolation of creep- fatigue data is an ongoing challenge particularly at the extremes of the creep regime. At the low temperature end the concern involves the definition of negligible creep and at the very high temperature end one of the issues is whether or not plasticity and creep can be separated. Although there can probably be improvement in the current NH approaches, the major issues identified

> with NH, particularly with respect to other international Codes, is that NH is too conservative by comparison [9]. The extrapolation of time-dependent data where fatigue is present represents a very significant challenge to the design [13].

1.3.2 General Assessment

The temperature cut off issue is the same as the simplified bounds discussed in Issue I. 2 above. The conservativism of the current BPVC Section III, Division 5 elastic rules for strain limits evaluation above the cut off temperature is currently being evaluated by ASME.

1.3.3 Material Specific Remarks

None.

1.3.4 Action Required

Complete the extension of the EPP methods to the remaining Class A materials.

1.3.5 Conclusion

Categorized as Optimization.

1.4 Issue I. 4 – Creep-Rupture and Fatigue Damage

1.4.1 Summary

From O'Donnell, Hull and Malik Item OG- 4:

> Creep is expected to be a problem for VHTR (hot vessel option) and Gen IV. Subsection NH design rules need extension to higher temperatures to account for creep rupture, excessive creep deformation, creep buckling, cyclic creep ratcheting, and creep-fatigue damage. Fatigue, creep, and creep-fatigue interactions are expected to be technical issues of concern [14], [15]. Improved correlations for creep and creep-fatigue have been developed from research of the 1990s but are not yet included in the ASME Code [16]. New work has been proposed to ensure that recent technology developments are incorporated [9].

1.4.2 General Assessment

The conservatism of the current creep-fatigue rules was increased with a more conservative design factor based on the results from the Eddystone Power Plant (supercritical steam plant) failure and subsequent thermal shock tests results and analysis through a Department of Energy (DOE)/United Kingdom collaborative program. As a result, the current BPVC Section III, Division 5 creep-fatigue design rules are considered to be overly conservative and very complex to apply. There are efforts by ASME to reduce the complexity by developing EPP technology. The over conservatism is being addressed by the development of integrated EPP and Simplified Model Test (SMT) creep-fatigue design methodology.

1.4.3 Material Specific Remarks

None.

1.4.4 Action Required

Continue development of EPP and integrated EPP plus SMT design methodologies.

1.4.5 Conclusion

Tentatively categorized as optimization.

1.5 Issue I. 5 – Creep-Fatigue Analysis of Class 2 and 3 Piping

1.5.1 Summary

From O'Donnell, Hull and Malik's Item OG- 7:

> If the operating temperatures for Class 2 and 3 piping are in the creep range for the materials then creep-fatigue analysis should be done that is beyond the scope of the current Subsection NC (Class 2) and Subsection ND (Class 3). There are simplified creep-fatigue analysis procedures for piping in the current Code Case N-253 [17] which supplement Subsection NC and Subsection ND in the high temperature range.

Griffin's [3] Item G-4. 3 "Creep-fatigue evaluation" discusses three specific CRBRP issues that were resolved. The first was taking credit for increased creep damage resistance of 304SS and 316SS during compressive holds vs. tensile holds. (Note that this is incorporated in the current Huddleston effective stress factors used in inelastic analysis.) The second was consideration of high cycle fatigue beyond the then limit at 1E6 cycles. The issue was resolved by demonstrating the conservatism of the projects' extrapolation to 1E8 cycles. The third concern was 2.25Cr-1Mo fatigue which was resolved by the use of the then new fatigue curves that were approved by the ASME Code.

Huddleston and Swindeman (Item HS- 12) provide a more comprehensive discussion of postulated inadequacies in the current (then CC N-47) linear damage summation based design rules for evaluation of creep-fatigue damage. It is noted that the current simplified rules have been criticized as "empirical, excessively conservative, and difficult to understand and apply". Specifically identified is the need for long term data, noting that current laboratory tests with a few hold times as long as 10 h fall far short of actual reactor hold times that may range up to 1500 h.

1.5.2 General Assessment

Regarding the Item OG- 7, BPVC Section III, Division 1, Class 2 and 3 elevated-temperature components are re-designated as Class B components in BPVC Section III, Division 5. The BPVC Section III, Division 5 design rules for Class B components are essentially the same as the BPVC Section III, Division 1 Code Case N-253. Piping is the only component with a specified creep-fatigue design procedure in the Class B rules. Recent ASME Code action permits the use of Class A rules for Class B components provided all the requirements for Class A construction are satisfied.

The specific CRBRP issues discussed by Griffin under Item G-4. 3 were resolved by subsequent revisions to the Code rules. No further action is required to address Class 2 and 3 piping nor the CRBRP issues.

The Huddleston and Swindeman discussion (Item HS- 12) was more broadly defined. As noted above in Issue I. 4 "Creep-rupture and fatigue damage", the complexity and difficulty of the current rules is being addressed through efforts by ASME in developing EPP technology. The over conservatism is being addressed by the development of integrated EPP and SMT creep-fatigue design methodology.

1.5.3 Material Specific Remarks

None.

1.5.4 Action Required

Continue development of EPP and integrated EPP plus SMT design methodologies.

1.5.5 Conclusion

Categorized as Optimization.

1.6 Issue I. 6 – Elastic Follow-Up

1.6.1 Summary

From O'Donnell, Hull and Malik (Item OG- 22), this is related to Item OG- 21 on the use of simplified bounding rules at discontinuities:

> Accounting for the effects of elastic follow-up is a significant part of simplified bounding rules. This concern may depend on the specific design features of components (e.g. piping, local reduction in size of a cross section or local use of a weaker materials) that may cause only a small portion of the structure to undergo inelastic strains while the major portion of the structural system behaves in an elastic manner, then certain highly stressed areas may be subjected to strain concentrations due to the elastic follow-up of the rest of the connected structure [18].

From Griffin's Item G-4. 2 "Elastic follow-up in elevated-temperature piping":

> The issue was resolved by agreement between the NRC and the Project on a method for quantifying elastic follow-up and a criterion for determining the portion of thermal expansion stress to be treated as primary.

It is further noted that elastic follow-up was confirmed to be negligible in the CRBRP hot leg piping.

1.6.2 General Assessment

Current rules do not provide explicit guidance for piping systems with large elastic follow up. This can lead to potentially over conservative design due to the consideration of stresses from restrained thermal expansion as being load controlled in estimating the resultant strain accumulation. The EPP methodology for strain limits can be used to assess piping systems. However, further assessment is needed for creep fatigue damage evaluation of piping systems with large elastic follow-up, using either the EPP method or the integrated EPP and SMT methodology that is currently being developed.

1.6.3 Material Specific Remarks

None.

1.6.4 Action Required

(1) Establish a limit for the applicability of the BPVC Section III, Division 5 simplified bounding rules to piping systems with significant elastic follow-up, and (2) complete the development of the EPP method and the integrated EPP and SMT methodology for creep fatigue for piping systems.

1.6.5 Conclusion

Categorized as Optimization (since one can always fall back to full inelastic analysis.)

1.7 Issue I. 7 – Plastic Strain Concentration Factors / Lack of Conservatism in Code Rules for Simplified Fatigue Evaluation Based on Plastic Strain Concentration Factors

1.7.1 Summary

As described by Griffin in Item G-4. 4 "Plastic strain concentrations": the NRC concern was with the use of the Subsection NB factor, Ke, which allows the stress concentration to be taken as unity until the range of primary plus secondary stress exceeds 3Sm.

Huddleston and Swindeman's Item HS- 19 " Lack of Conservatism in Code Rules for Simplified Fatigue Evaluation Based on Plastic Strain Concentration Factors" is a repeat of the discussion in Griffin's Item G-4. 4. This is not one of Huddleston and Swindeman's ten major issues.

1.7.2 General Assessment

This issue is no longer relevant as the procedures for determination and use of the stress concentration factor, K, are defined in HBB-T-1432 and the use of the Ke factor is restricted such that the NRC concern is addressed.

1.7.3 Material Specific Remarks

None.

1.7.4 Actions Required

None.

1.7.5 Conclusion

Categorized as N/A.

1.8 Issue I. 8 – Thermal Striping

1.8.1 Summary

From O'Donnell, Hull and Malik Item OG- 6:

> Generally, the issue is determination of thermal hydraulic response. Thermal striping may be significant in liquid-metal (e.g., sodium) cooled reactors e.g. CRBR and lead-cooled fast reactors (LFRs) that may be considered for Gen IV options [19], but is not expected to be such a significant issue for gas-cooled reactors. Thermal striping is considered possible for internal structures of the hot duct in NGNP options and there is still some concern about lack of validated thermal striping materials and design methodology [20]. The reactor pressure vessel head and the absorber (control) rod "standpipes" have to be protected against hot coolant convections (e.g., thermal striping) after a loss of forced helium circulation [13]. Current NH rules already provide a framework for assessment of structural response.

Huddleston and Swindeman's Item HS- 11 "Lack of Validated Thermal Striping Materials and Design Methodology" discusses the results of thermal stripping tests and sometimes conflicting conclusions developed by programs at Westinghouse and Rockwell. Abstracting again from reference [5] "Extension of the ASME Code fatigue curves into the high cycle regime will ultimately be necessary for resolution of the thermal striping issue. Procedures for characterizing the actual fluid and metal temperatures under realistic mixing conditions are also needed." This was categorized as both a "material and data base" and a "design bases issue" and was considered one of the top ten major issues.

1.8.2 General Assessment

Current Subsection HB, Subpart B rules provide a framework for assessment of structural response. Generally, the thermal striping problem is determining the thermal-hydraulic response at the component's surface rather than determining the structural response. Computational fluid dynamics techniques may be need for the thermal-hydraulic analysis.

1.8.3 Material Specific Remarks

None.

1.8.4 Action Required

High cycle fatigue data are needed for fatigue damage evaluation under thermal striping conditions. Extension of the fatigue design curves for Class A materials to higher cycle counts is needed, e.g., 1E9 cycles.

1.8.5 Conclusion

Categorized as adequacy.

1.9 Issue I. 9 – Use of Simplified Bounding Rules at Discontinuities

1.9.1 Summary

From O'Donnell, Hull and Malik Item OG- 21:

> Current simplified inelastic methods and stress classification techniques need to be assessed for very high temperature applications, and improved or alternate approaches developed [21]. This is an important issue that is the subject of ongoing R&D efforts [9].

1.9.2 General Assessment

Appendix HBB-T currently contains "simplified" bounding rules for the evaluation of strain limits and creep-fatigue damage at discontinuities. However, these so-called simplified rules are actually quite complex. A new methodology based on EPP analysis has been developed which avoids the complexities of the current rules. The current rules have restrictions on geometry and service level transients. The current rules are also based on the separation of creep and plasticity, as discussed under Issue I. 3. The new EPP Code Cases for strain limits and creep-fatigue damage evaluations have been approved by the ASME for application to some Class A materials. Development of the EPP methodology for other Class A materials is in progress. The current BPVC Section III, Division 5 simplified bounding rules for strain limits and creep-fatigue are being evaluated by the ASME.

1.9.3 Material Specific Remarks

The EPP Code Cases have been approved for use for Type 304 and 316 stainless steels. They are under Code Committee approval process for Alloy 617. The modification of the EPP methodologies for cyclic-hardening materials to cyclic-softening material (Gr91) has been established and will be submitted to Code Committee consideration.

1.9.4 Action Required

Complete the development of EPP methodology for the other Class A materials.

1.9.5 Conclusion

Categorized as Optimization.

1.10 Issue I. 10 – Steam Generator Tubesheet Evaluation

1.10.1 Summary

This issue is discussed by Griffin in Item G-3. 4 “Steam Generator”:

> The major NRC concern is assurance of adequacy of the tubesheet for the intended life. Tubesheets are complex three-dimensional structures that are difficult to analyze. Section III provides a simplified method of analysis based on the equivalent plate concept. However, this method is not applicable for the CRBRP tubesheet where the loading is dominated by large thermal gradients, and deformations are inelastic.

1.10.2 General Assessment

The major advances in Finite Element Analysis (FEA) technology and computing capacity since CRBRP have made this issue obsolete although simplified approximations could be useful in preliminary design evaluations.

1.10.3 Material Specific Remarks

None.

1.10.4 Actions Required

None.

1.10.5 Conclusion

Categorized as N/A.

1.11 Issue I. 11 – Creep Buckling Under Axial Compression – Design Margins

1.11.1 Summary

From O’Donnell, Hull and Malik Item OG- 9:

> Load controlled time-dependent creep buckling factors in Appendix T (T-1522) to Subsection NH [7] may perhaps need to be reviewed for higher temperature expected in VHTR (hot vessel option) and Gen IV. Neither generic issues nor inconsistencies within the creep-buckling rules are expected to be of major concern – particularly for thick walled components. There may be concerns that should be reviewed such as local crimping issue for very large diameter, thin walled vessels [9].

The Huddleston and Swindeman discussion in Item HS- 22 “Overly Conservative Buckling Rules” focuses on buckling in the plastic regime in general and piping elbows specifically. There is particular concern regarding the requirement that combined displacement-controlled loading and load controlled loading use the more conservative load factors required for load controlled buckling.

1.11.2 General Assessment

Subsection HB, Subpart B does not provide explicit guidance for evaluating creep buckling but does require that creep buckling be assessed for complex geometries and/or components that do not meet the time-dependent buckling exemption criteria. The Code committee responsible for Subsection HB, Subpart B is not aware of any generic issues or inconsistencies with the provided load factors and exemption charts. The current requirements were successfully implemented for the CRBRP.

1.11.3 Material Specific Remarks

None.

1.11.4 Action Required

While the current BPVC Section III, Division 5 rules permit creep buckling to be evaluated, guidelines on the use of inelastic analysis methods for the creep buckling analysis should be developed by ASME.

1.11.5 Conclusion

Categorized as Optimization.

2 RELATING TO MATERIAL PROPERTIES

2.1 Issue II. 1 – Creep-Rupture Damage due to Forming and Welding

2.1.1 Summary

From O'Donnell, Hull and Malik's Item OG- 15:

> This is related to elevated temperature structural integrity issue, Item OG- 2, concerning weld residual stresses. Damage accumulation data are needed due to long-time high temperature exposure. Particular attention is needed in the area of welding to ensure that the issues of hot cracking and premature creep failures in the heat-affected-zones of ferritic/martensitic and ferritic steels, observed in the fossil industry, are adequately addressed [21]. There are also still forming/cold work issues [22].

2.1.2 General Assessment

The issue relating to weld residual stress is covered under Issue III. 2 in Category III: Welds below. BPVC Section III, Division 5 HBB-4212 provides rules and restrictions related to forming/cold work for all Class A materials.

2.1.3 Material Specific Remarks

The phenomenon of Type IV cracking is only applicable to ferritic/martensitic steel (Gr91) and ferritic steel (2.25Cr-1Mo) and is not applicable to Type 304 and 316 stainless steels, Alloy 800H and Alloy 617.

2.1.4 Action Required

None.

2.1.5 Conclusion

Categorized as N/A.

2.2 Issue II. 2 – Material Acceptance Criteria for Elevated-Temperature

2.2.1 Summary

From O'Donnell, Hull and Malik Item OG- 14:

> This may need to be re-evaluated for use in Gen IV systems. Concerns about material property allowable design data/curves for 60-yr design life are still germane [20]. The target design life of Gen IV components is generally 60 years (526,000 h), which significantly exceeds lifetimes currently allowed by Subsection NH. The extension of the required data bases and ASME Code acceptance of the materials for RPV service will need to be developed and closely coordinated with the high- temperature design methodology activities [21]. The recent DOE/ASME Materials Project Task 1 has pointed the way for the methodology and data required to extend NH coverage for both time and temperature. Although the reactor may have a 60-yr design life at 900-950ºC outlet, the components generally have much lower temperatures and/or shorter design lives. The HTGR concepts isolate pressure boundary components from the full extremes of both time and temperature. It is not clear that Code action is required until more details are available in component design specifications regarding material choices and component design and operating temperatures [9].

In Item HS- 1 "Lack of Material Property Allowable Design Data/Curves for 60-Year Design Life", Huddleston and Swindeman similarly note the need to extend property allowable design data/curves to 60-yr. In Item HS- 5 "Lack of Property Allowables Based on Current Melting and Fabrication Practices", examples of premature failures associated with unintended consequences of melting and fabrication processes are cited. In addition, it is noted that melting practice has changed for 304 and 316 stainless steel and more modern representative data should be incorporated in the determination of allowable stress values. Item HS- 1 is one of Huddleston and Swindeman's ten major issues, but Item HS- 5 is not.

2.2.2 General Assessment

The current time dependent allowable stresses in BPVC Section III, Division 5 are based on extrapolating creep data out to a 300,000-h design life. Based on the availability of additional data, design needs and operating experience, allowable stress values are subject to re-assessment. The need for a 60-year design lifetime, or longer, has been identified. Since the development of the 300,000-h allowable stresses a much larger data base, including longer term data, has been accumulated by the international community. ASME Code Committees are re-assessing the current allowable stresses, including the extension to 500,000 h.

Extrapolation of creep data out to 500,000 h is challenging and the methodology for extrapolation, recognizing the potential changes in the creep deformation mechanisms, is continually being assessed. For example, a new "region-split" extrapolation method has recently been developed and applied to some BPVC Section III, Division 5 material. Extrapolation of the creep data to 500,000 h is being done and is in accordance with the time-factor guideline described in BPVC Section III, Division 5, Appendix HBB-Y.

Currently, reassessment of the allowable stress values resulting from the application of the onset of tertiary creep criterion has led to increased conservatism in the allowable stress values for some Class A materials. The significance of the onset of tertiary creep criterion is currently being re-evaluated based on experimental component test results.

The current efforts to extend allowable stress values also incorporate more modern data from the National Institute for Materials Science (NIMS) database in Japan and available European data. Additional restrictions have been placed on certain grades of material and fabrication induced strains are limited.

Surveillance specimens could be used to supplement the rules of BPVC Section III, Division 5 to provide verification of extrapolation methodologies.

2.2.3 Material Specific Remarks

Alloy 617 is being considered for incorporation into BPVC Section III, Division 5 as a Class A material via a BPVC Section III, Division 5 Code Case. It is expected that the balloting process will be completed in 2020. The maximum use temperature is 1750ºF (954ºC) and a maximum design life of 100,000 h.

2.2.4 Action Required

(1) Complete the extension of the allowable stresses to 500,000 h, (2) complete the incorporation of Alloy 617 Code Case into BPVC Section III, Division 5, and (3) initiate development of long-term surveillance specimens to supplement BPVC Section III, Division 5 rules.

2.2.5 Conclusion

Categorized as Optimization.

2.3 Issue II. 3 – Elevated-Temperature Data Base for Mechanical Properties

2.3.1 Summary

From O'Donnell, Hull and Malik Item OG- 234:

> This is related to Item OG- 14 on Material acceptance criteria for elevated-temperature and Item OG- 23 on Design criteria for elevated- temperature core support structures and welds. These data bases eventually need to be extended to higher temperatures regimes expected in VHTR and Gen IV. The synergistic effects of aging, environment, loading, and temperature need to be better understood, and the effects of aging on toughness must be characterized [11]. It is not clear that Code action is required until more details are available about component design specifications regarding material choices and component design and operating temperatures [9]. The issue regarding the effects of aging on toughness is related to Alloy 617 and should also be considered under Item OG- 13 on evaluation of weldments, Item OG- 18 on fracture toughness criteria, and Item OG- 19 on thermal aging effects.

Huddleston and Swindeman's related discussions in Items HS- 1 and HS- 5 are summarized under Issue II. 2 in Section 2.2.

2.3.2 General Assessment

Formal uniform code book guidance on data requirements for mechanical properties was not available at the time of the CRBRP. This issue has been addressed recently in Appendix HBB-Y of BPVC Section III, Division 5. See also remarks under Section 2.2.2 "General Assessment" noted previously. This issue is essentially the same as Issue II. 2 "Material acceptance criteria for elevated-temperature" where the required action is to complete the extension of the allowable stresses to 500,000 h.

Development of an in-situ surveillance program to augment the rules of BPVC Section III, Division 5 would support the assessment of potential long-term degradation due to irradiation and coolant chemistry effects.

2.3.3 Material Specific Remarks

Alloy 617 is identified as a construction material in the heat transport system of a VHTR with core outlet temperatures that could be as high as 950ºC. A BPVC Section III, Division 5 Code Case for Alloy 617 with a maximum use temperature of 1750ºF (954ºC) is being balloted by the ASME Code Committees to support such an application. It is expected that the balloting process will be completed in 2020.

2.3.4 Action Required

(1) Complete the extension of the allowable stresses to 500,000 h, (2) complete the incorporation of Alloy 617 Code Case into BPVC Section III, Division 5, and (3) initiate the development of long-term surveillance specimens to supplement BPVC Section III, Division 5 rules.

2.3.5 Conclusion

This issue is similar to Issue II. 2, and is categorized as Optimization.

2.4 Issue II. 4 – Thermal Aging Effects

2.4.1 Summary

From O'Donnell, Hull and Malik Item OG- 19:

> The potential for long-term thermal aging was identified as being one of the five most significant phenomena in the high temperature materials area [23]. The effects of thermal aging on mechanical properties and code compliance over long term will be critical issues for each option [11], [24]. Thermal aging and sensitization is known for LWR temperatures but may result in less than expected lifetime at HTGR temperatures. Thermal aging effects are currently addressed in ASME BPV Section III Subsection NH. Article NH-2160

addresses deterioration of material in service including how long-time, elevated temperature, service may result in the reduction of the subsequent yield and ultimate tensile strengths (while stating that consideration of deterioration of material caused by service is generally outside the scope of this Subsection). Thermal aging and cyclic softening are important issues for creep-fatigue evaluation of Grade 91 and methods for dealing with these issues are addressed in the DOE/ASME Materials Project and follow-on tasks [9].

In Item HS- 3 “Degradation of Material Properties due to Long Term Thermal Aging”, Huddleston and Swindeman [4] similarly discuss the need to address thermal aging effects with an emphasis on the need for aging data from sufficiently long term to permit safe extrapolation to expected 60-year design lives. It is also noted that “knock down” factors were, at that time, in the Code approval process.

2.4.2 General Assessment

The effects of thermal aging on yield and tensile properties were not considered in the CRBR design, but are now accounted for in the BPVC Section III, Division 5 code rules. The creep data that are used for setting time dependent allowable stresses include the effects of thermal aging. To the extent that creep damage in the creep-fatigue rules is calculated using these time dependent rupture strengths, the creep-fatigue rules also account for the effects of thermal aging.

Long term thermal aging data, as noted, are difficult to obtain. However, incorporation of a surveillance program would enable long term verification of postulated effects before deviations would become critical for reactor operation.

2.4.3 Material Specific Remarks

None.

2.4.4 Action Required

(1) Complete the extension of the yield and tensile strength factors due to thermal aging to 500,000 h, and (2) develop a plan for a surveillance program to supplement extension of the BPVC Section III, Division 5 rules and the In-service Inspection rules of BPVC Section XI.

2.4.5 Conclusion

Categorized as Optimization.

2.5 Issue II. 5 – Lack of a Design Methodology for Modified 9Cr-1Mo Steel

2.5.1 Summary

In Item HS- 9 “Lack of a Design Methodology for Modified 9Cr-1Mo Steel”, Huddleston and Swindeman discuss the advantages of Modified 9Cr-1Mo steel and also areas where its behavior, e.g. cyclic softening and difficulty in distinguishing between creep and rate dependent plasticity, differs from the other Code alloys. Thus, there is a need for appropriate allowable stress values and design methodology. Note that this issue was defined prior to the approval of Modified 9Cr-1Mo in BPVC Section III, Division 5.

2.5.2 General Assessment

Modified 9Cr-1Mo in BPVC Section III, Division 5 is currently approved for use in BPVC Section III, Division 5 applications. A number of the identified issues have already been addressed and additional improvements addressing the effects of cyclic softening on strain limits evaluation using the EPP methodology have been developed and started the Code approval process.

2.5.3 Material Specific Remarks

None.

2.5.4 Actions Required

Complete Code approval process for strain limits modifications for Gr91.

2.5.5 Conclusion

Categorized as Optimization.

2.6 Issue II. 6 – Use of Average vs. Minimum Material Properties in Design

2.6.1 Summary

In Item HS- 8 "Use of Average vs. Minimum Material Properties in Design", Huddleston and Swindeman quote extensively from reference [5]. Briefly, the issue is summarized in the following quote:

> In general, strain accumulation and fatigue damage increase with a decrease in yield strength of the material, whereas, creep damage increases with an increase in yield strength. Therefore, an appropriate selection of material properties for structural analysis is not obvious. For example, when design limits are marginally satisfied, it may be necessary to bound analytical predictions by at least two analyses with average and minimum material property assumptions.

2.6.2 General Assessment

Interestingly, the discussion in Item HS- 8 also states that "in practice, it is not possible to determine, a priori, the worst combination of properties for each loading condition, nor would such a minimum/maximum combination be physically consistent with actual material behavior." There is also a discussion of a probabilistic study at Oak Ridge National Laboratory (ORNL) indicating that while there is about a 50% chance of exceeding strain limits (ibid. this is not necessarily critical since the strain limits are not associated with a failure mode), there is very little chance, 1.8%, of exceeding creep damage, and no chance of exceeding fatigue limits. This supports the ASME Code position as quoted by Griffin [3] in Section 2.7.2 below that strain limits and damage evaluations should be based on average flow characteristics. Note that damage calculations are based on minimum creep-rupture properties in BPVC Section III, Division 5.

2.6.3 Material Specific Remarks

None.

2.6.4 Actions Required

None.

2.6.5 Conclusion

Categorized as N/A.

2.7 Issue II. 7 – Material Property Representation for Inelastic Analysis / Lack of Inelastic Design Procedures for Piping

2.7.1 Summary

Griffin [3] identifies inelastic material property representation in Item G-3. 3 "Design analysis methods, codes and standards". The focus of the NRC concern as identified by Griffin is that

> creep-rupture damage calculated using average properties may be too low when compared with the considerable strain and cyclic hardening that occurs during fabrication and operation, and that the fatigue damage and accumulated strains may be too low if the actual yield strength is below the average value used in design analysis.

In Item HS- 21 "Lack of Inelastic Design Procedures for Piping", Huddleston and Swindeman [4] quote from reference [5], and more specifically, focus on the need to

> reach a consensus agreement on a standardized method of analysis and the associated definitions, to carefully document that method, and then to incorporate the standardized method in the ASME Code or into NRC regulatory guides.

They additionally focus on the need "for an experimentally validated procedure for assessing elastic follow-up" particularly for piping.

2.7.2 General Assessment

The Working Group on Analysis Methods is balloting a proposal defining constitutive models to be used in implementing the design evaluation rules for Class A materials based on inelastic analysis. Additionally, the recently adopted rules based on EPP analysis provide a vehicle for assessing inelastic strain distribution in piping systems. There is a current R&D program addressing the use of SMT creep fatigue data that directly incorporates the effects of component elastic follow-up on creep-fatigue damage. With regard to the use of average properties, the following is quoted from Griffin [3]:

> The rationale, which was established and reaffirmed by a strong national consensus, is that it is impractical to determine the worst case combination of minimum and/or maximum strength and deformation properties for each load combination. Nor would it be representative of actual material behavior because the worst case combinations are not physically consistent.

2.7.3 Material Specific Remarks

None.

2.7.4 Actions Required

(1) Proceed to ballot the recommended constitutive equations developed in the Working Group on Analysis Methods; and (2) continue the development of high temperature design methods based on EPP and SMT procedures and data.

2.7.5 Conclusion

Categorized as Optimization.

3 WELDS

3.1 Issue III. 1 – Transition Joints

3.1.1 Summary

From O'Donnell, Hull and Malik Item OG- 1:

> Improper joint design has been a concern in the field for Grade P91 material (modified Fe-9Cr-1Mo steel) joined to dissimilar alloys [24]. The modified 9Cr-1Mo steel is the primary/potential RPV candidate in several Gen-IV HTR programs and the Areva hot vessel concept. Although very high temperature joints are generally not part of the code boundary, other Code boundary transitions joints may be of concern. The code specified approach is to model the joint with base metal properties to the weld centerline and then include differences in the connecting base metal properties in the weldment stress analysis.

Additional discussion from Griffin in Item G-4. 5 "Intermediate heat transport system transition weld" focuses on the tri-metallic joint consisting of type 316H, Alloy 800H and 2.25Cr-1Mo. The issue was resolved by a commitment to perform analysis using the methods and criteria to be developed under a confirmatory program. Note: This was prior to inclusion of stress rupture factors to account for weld strength reduction.

3.1.2 General Assessment

The current Code specified approach is to model the joint with base metal properties to the weld centerline. The stress rupture factors applicable to the base metal on either side of the joint are included in the creep-fatigue damage assessment. The allowable number of cycles is reduced by an additional factor of two at weldments and detailed resolution of as fabricated geometry as compared to the configuration assumed in the initial analysis is required in the Stress Report.

3.1.3 Material Specific Remarks

None.

3.1.4 Required Actions

Vendor has to qualify the Dissimilar Metal Weld (DMW) weld wire and develop appropriate stress rupture factors for BPVC Section III, Division 5 applications.

3.1.5 Conclusions

Categorized as Optimization.

3.2 Issue III. 2 – Weld Residual Stresses

3.2.1 Summary

From O'Donnell, Hull and Malik Item OG- 2:

> CRBR-related safety concerns are applicable to VHTR and Gen-IV systems [1]. There is a need to evaluate potential for crack initiation at weldments due to thermal fatigue, residual stresses, and damage caused by the welding process. Weld residual stresses were not considered in the current NH methodology based on the premise that the initial weld would be ductile and that subsequent load cycling and creep would wipe-out residual stresses.

From Griffin in Item G-3. 1, "Early weldment cracking, particularly in components subjected to repeated thermal transient loadings was identified by NRC as the foremost structural integrity concern." Also noted by Griffin was that "although an experimentally based procedure that accounts for reduction in creep rupture strength of weldments has been developed, it has not yet been adopted by the Code." (Note that this is reference to the stress rupture factors included in the current Code.) Resolution of this issue required the completion of a comprehensive confirmatory program.

Huddleston and Swindeman in Item HS- 14 "Lack of a Validated Weldment Design Methodology", recap some of the discussion in Griffin plus citing further discussion and recommendations from the reference [5]. The Item HS- 14 recommendation is in five phases: (A) problem review and assessment, (B) weldment flaw characterization, (C) design methodology development, (D) confirmatory structural testing (particularly under thermal transient conditions), and (E) Code rule/regulatory guide package development. Item HS- 14 is one of Huddleston and Swindeman's ten major issues.

3.2.2 General Assessment

This issue is not considered in the Subsection HB, Subpart B methodology – the current approach specifies weld wires and welding process to produce ductile welds. Subsequent load cycling and creep reduce residual stresses. (See also Issue III. 3 assessment in Section 3.3.2.)

3.2.3 Material Specific Remarks

None.

3.2.4 Action required

No action is required.

3.2.5 Conclusion

Categorized as N/A.

3.3 Issue III. 3 – Evaluation of Weldments

3.3.1 Summary

From O'Donnell, Hull and Malik Item OG- 13:

> CRBR-related safety concerns identified by NRC are also applicable to VHTR and Gen IV systems [1]. The development of joining and design methodologies are still considered important issues in component construction and long-term performance [20] and concerns previously identified [3], [4] for transition welds and lack of validated weldment design methodology still remain. There are a number of provisions in NH and related documents that assure reliable weld joints. NH methods go far beyond what is currently required for non-nuclear applications and nuclear applications below the creep regime. There are planned investigations to evaluate quantified, creep crack growth approaches for eventual incorporation. Probably a crack growth based methodology would have greatest applicability in assessment of ISI results [9].

Griffin's Item G-3. 1 "Weldment Safety Evaluation" and Huddleston and Swindeman Item HS- 14 "Lack of a Validated Weldment Design Methodology" have discussed this issue and they are summarized in Section 3.2 above.

3.3.2 General Assessment

There are a number of ways in which BPVC Section III, Division 5 addresses welds. Some were implemented after the NRC / Advisory Committee on Reactor Safeguards (ACRS) review of the CRBRP license application.

Stress rupture factors were introduced for the creep rupture strength of a restricted number of weld processes and weld rod compositions to be used in both the initial sizing of the weld and the evaluation of its cyclic life.

Only the identified processes and compositions are permitted.

The accumulated strain at welds is limited to half that of base metal and the allowable number of cycles from a fatigue design curve is half that of base metal.

The analysis of strain and creep-fatigue at welds is based on stress and strain concentrations at the worst as-built surface geometry of the weld.

BPVC Section III, Division 5 has additional limitations on weld joint geometry and requires double volumetric examination, either radiography plus ultrasonic or double angle radiography.

All the other weld and welder qualification requirements of the Code are also required at elevated temperature.

Based on the above, ASME Code committees judge that the BPVC Section III, Division 5 design, inspection and fabrication procedures provide adequate assurance of the structural integrity of the welds fabricated to the BPVC Section III, Division 5 rules. In addition, a joint BPVC Section XI and III Working Group on High Temperature Flaw Evaluation has been formed to develop BPVC Section XI rules for BPVC Section III, Division 5 components.

3.3.3 Material Specific Remarks

None.

3.3.4 Action Required

None.

3.3.5 Conclusion

Categorized as N/A since these are BPVC Section XI rules.

4 MULTIAXIALITY

4.1 Issue IV. 1 – Uncertainty of Multiaxial Stress State Effects

4.1.1 Summary

In Item HS- 16 "Uncertainty of Multiaxial Stress State Effects", Huddleston and Swindeman identify the need for multiaxial laboratory or component experimental tests of sufficient duration (> 10% of design life) to adequately validate the accuracy of the current rules, particularly for a 60-year design life. This is not categorized as a major issue.

4.1.2 General Assessment

These would be very long tests, 5- or 6-year, probably at several different temperatures for each material of interest. In the absence of indications of inadequacy of the current rules, it would be difficult to prioritize this concern.

4.1.3 Material Specific Remarks

None.

4.1.4 Actions Required

None.

4.1.5 Conclusion

Categorized as N/A.

4.2 Issue IV. 2 – Uncertainty of Non-Radial (Non-Proportional) Loading

4.2.1 Summary

In Item HS- 17 "Uncertainty of Non-radial (Non-proportional) Loading", Huddleston and Swindeman state:

> There is almost no laboratory or component data to validate CC N-47 rules as relates to long term (> 10% of design life) non-radial loadings. Current CC N-47 rules treat both creep and fatigue damage as scaler quantities, whereas data show damage accumulation to be tensorial (directional) in nature.

However, it is also noted that limited creep-rupture tests at ORNL under non-radial conditions tend to validate the equivalent stress and strain assumption. This is not categorized as a major issue.

4.2.2 General Assessment

These would be very long tests, 5- or 6-years, probably at several different temperatures for each material of interest. Further, it is indicated that available data suggest that the current scaler treatment is conservative.

4.2.3 Material Specific Remarks

None.

4.2.4 Actions Required

None.

4.2.5 Conclusion

Categorized as N/A.

4.3 Issue IV. 3 – Notch Weakening / Lack of Understanding / Validation of Notch Weakening Effects

4.3.1 Summary

This issue is not included in O'Donnell, Hull and Malik.

From Griffin Item G-3. 2 "Notch weakening":

> The major concern of the NRC is that the design limits for fatigue and creep rupture are based on tests of smooth sided specimens that do not include possible effects of stress gradients in notches. They are also concerned about loss of ductility under long term loadings due to prior cyclic and monotonic straining.

Huddleston and Swindeman similarly addressed this concern in Item HS- 18 "Lack of understanding / validation of notch weakening effects". It is additionally noted that there were apparently no in-depth programs addressing this issue at that time. This is classified as one of their ten major issues.

4.3.2 General Assessment

The implied assumption in the current Rules for BPVC Section III, Division 5, Class A materials is that they are "notch strengthening", wherein the creep rupture strength of a notched specimen is greater than the creep rupture strength of an un-notched specimen with the same cross-sectional area as the notched specimen at the root of the notch. A similar assumption is made in other international and domestic elevated temperature design criteria. Materials that preferentially rupture at the notched section are referred to as "notch weakening." Notch weakening is currently a topic of consideration in the relevant ASME committees and there is a DOE sponsored Research and Development (R&D) program specifically chartered to address this issue. The rules currently under consideration for implementing primary sustained loading limits based on EPP analysis methods have provisions for addressing notch weakening behavior. Additionally, there are limitations to the time and temperature allowable stress regime where low creep ductility is considered to be an issue.

4.3.3 Material Specific Remarks

None.

4.3.4 Actions Required

Continue the R&D program and consideration of notch weakening effects.

4.3.5 Conclusion

Categorized as Optimization.

5 COMPONENT AND CORE SUPPORTS

5.1 Issue V. 1 – Rules for Component Supports at Elevated-Temperature

5.1.1 Summary

From O'Donnell, Hull and Malik OG- 11:

> Rules are provided in Code Case N-201 for Core Support Structures. Component supports other than core support structures are not covered in the creep regime nor has there been any indication that they will be needed. The preapplication SER [25] for the modular high-temperature gas-cooled reactor (MHTGR) referenced the 1981 version of NUREG-0800, Section 3.9.3, "ASME Code Class 1, 2 and 3 Components, Component Supports, and Core Support Structures."

This was revised in March 2007 to accommodate new reactors.

5.1.2 General Assessment

Formal, uniform code book guidance on data requirements for mechanical properties was not available at the time of the CRBRP. This has been addressed recently in Appendix HBB-Y of BPVC Section III, Division 5. If supports other than core structures are in the creep regime for a specific design, the Subsection HB, Subpart B rules can be used for the structural evaluation. For example, a code case invoking the appropriate rules from Subsection HB, Subpart B can be generated for such applications.

5.1.3 Material Specific Remarks

None.

5.1.4 Action Required

None.

5.1.5 Conclusion

Categorized as N/A.

5.2 Issue V. 2 – Design Criteria for Elevated-Temperature Core Support Structures and Welds

5.2.1 Summary

From O'Donnell, Hull and Malik Item OG- 23:

> The elevated temperature core support rules where creep is significant are based on Subsection NH. There is an ongoing effort to directly reference NH for much of the N-201 data and rules. ASME Code Case N-201-4 (current max allowable temperatures of 760ºC) and ASME Draft Code Case for Alloy 617 (currently a maximum life of 100,000 h above 427ºC and 815ºC for 304/316 SS for core support structures) may have to be revised to address higher expected temperatures (900 to 1000ºC) and design lives (over 300,000 h) [21]. Interestingly and counter to what one would intuitively expect, the core supports for the current VHTR concepts do not operate at very high temperatures and when they are in the creep regime it is for a short time at relatively low temperatures [9].

It is noted that welds are only identified in the title of this issue in both references [1], [2] and that specific concerns with welds are addressed in Section 3 WELDS above.

5.2.2 General Assessment

In accordance with ASME code policy, environmental effects such as irradiation and coolant chemistry are not considered directly in the BPVC Section III, Division 5 design rules for core support structures and welds. The elevated temperature core support rules where creep is significant are based on Subsection HB, Subpart B and are given in Subsection HG, Subpart B.

Development of an in-situ surveillance program to augment the rules of BPVC Section III, Division 5 would support the assessment of potential long-term degradation due to irradiation and coolant chemistry effects.

5.2.3 Material Specific Remarks

For metallic structural components, it is not realistic to design for very long service lives, e.g., 300,000 h or beyond, at temperatures of 900 to 1000ºC, unless the stresses in the components are negligible. Otherwise, they would have to be designed as replaceable components with more realistic component lifetimes, e.g., 100,000 h. Alloy 617 with a maximum use temperature of 954ºC and design lifetime of 100,000 h is being balloted by ASME Code committees for inclusion in BPVC Section III, Division 5 via a code case.

5.2.4 Action Required

Develop a plan and procedures for in-situ surveillance to supplement the rules of BPVC Section III, Division 5.

5.2.5 Conclusion

Categorized as Optimization.

6 MISCELLANEOUS ISSUES

6.1 Issue VI. 1 – Are Limits of Case N-253 for Elevated-Temperature Class 2 and 3 Components Met?

6.1.1 Summary

From O'Donnell, Hull and Malik's Item OG- 8:

> Code Case N-253 [17] provides rules for Class 2 and 3 components for elevated temperature service. Code Case defaults to Subsection NC and Subsection ND, if the time/temperature criteria in Appendix E are met. If they are not met, then the rules of N-253 apply. The rules in N-253 are essentially the same as in BPVC Section VIII, Division 1 with supplemental rules for cyclic analysis of piping.

6.1.2 General Assessment

As discussed in the General Assessment of Issue I. 5, Division 1, Class 2 and 3 elevated temperature components are re-designated as Class B components in BPVC Section III, Division 5. The BPVC Section III, Division 5 design rules for Class B components are essentially the same as the Division 1 Code Case N-253 except that the use of the design rules for Class A components have recently been approved for Class B components provided that all other requirements for Class A construction are satisfied.

6.1.3 Material Specific Remarks

None.

6.1.4 Action Required

None.

6.1.5 Conclusion

Categorized as N/A.

6.2 Issue VI. 2 – Degradation Effect of Small Cyclic Stresses

6.2.1 Summary

Huddleston and Swindeman define this issue in Item HS- 6 "Degradation Effect of Small Cyclic Stresses". The concern is the acceleration of creep-rupture strength degradation in cyclic softening ferritic steels due to very small cyclic strains superimposed on primary stresses. This is not one of their major issues.

6.2.2 General Assessment

With respect to the degradation effect of small cyclic stresses, the construction of the modified Goodwin diagram is a good approach to establishing whether or not degradation should be expected. The diagram plots creep strength on the abscissa against cyclic strength on the ordinate for specific times. However, curves for times out to 500,000 h would be needed and any frequency effects would alter the trend of the curves in the region of interest (small cyclic stresses). At high temperatures, small cyclic stresses could extend strength (life) and data for nickel alloys suggest this. A small cyclic thermal stress superimposed on the primary pressure stress may lead to degradation and there is some evidence of this in power plant experience, but the specific product form is not known. Jetter et al. [26] reference reports by Riou et al. [27] and Asayama and Tachibana [28] as not attributing any reduction in creep rupture strength to cyclic softening (noting that more testing is required); more recent testing of Modified 9Cr-1Mo does indicate an