ASME NTB-2-2019

Background Information for Addressing Adequacy or Optimization of ASME BPVC Section III, Division 5 Rules for Metallic Components

ASME
SETTING THE STANDARD

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

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Date of Issuance: October 31, 2019

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. 978-0-7918-7333-5

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FOREWORD

The goal of this publication is to provide background information on the development and scope of the elevated temperature design and construction rules in the ASME Boiler and Pressure Vessel Code ("BPVC"), Section III *Rules for Construction of Nuclear Facility Components*, Division 5 *High Temperature Reactors*. Subsection HB, *Class A Metallic Pressure Boundary Components*, Subpart B *Elevated Temperature Service*, is the primary focus; but additional information is provided for Subsection HC, *Class B Metallic Pressure Boundary Components*, Subsection HG, *Class A Metallic Core Support Structures*, *and Code Cases*. This information is provided through reference to existing background documentation and identification of key references and their relationships to the current rules. In other words, this document is an annotated directory of where to find the actual background information.

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EXECUTIVE SUMMARY

BPVC Section III *Rules for Construction of Nuclear Facility Components*, Division 5, *High Temperature Reactors* is structured to provide a central location for all aspects of construction for high temperature reactors. In ASME code terminology, "construction" covers all aspects of Materials (HBB-2000), Design (HBB-3000), Fabrication and Installation (HBB-4000), Examination (HBB-5000), Testing (HBB-6000), Overpressure Protection (HBB-7000), and Nameplates, Stamping etc. (HBB-8000). The scope of BPVC Section III, Division 5 covers high temperature gas-cooled reactors, liquid metal reactors and molten salt reactors. Although the primary focus of this document will be on the design and related material considerations for Class A elevated temperature metallic components, the other aspects of BPVC Section III, Division 5 for metallic components will also be briefly addressed.

The rules for metallic components evolved over many years. There were initially a series of code cases ("CC"), CC 1331-1 through CC 1331-4; but the first code case that comprehensively addressed all the relevant failure modes was CC 1331-5 in 1971. The focus of CC 1331-5 was primarily restricted to design. The CC-1331 design series was replaced by the CC 1592-1596 series that were structured in traditional code format and cover all aspects of construction, as discussed above. When the nuclear code cases were separated from the non-nuclear code cases, the CC 1592 series was converted to the CC N-47 series. The CC N-47 series was subsequently converted to BPVC Section III, Subsection NH. In 2011, BPVC Section III, Division 5 was issued, but the construction rules for elevated temperature nuclear components were covered mostly by reference to Subsection NH and applicable code cases. Effective with the 2015 edition of BPVC Section III, the rules in Subsection NH and related code cases were transferred to BPVC Section III, Division 5, and Subsection NH was discontinued.

First reference of interest

The first reference of interest is the *Companion Guide to the ASME Boiler and Pressure Vessel Code* Volume 1, Fifth Edition (2017), K. R. Rao, Editor, Chapter 17 "Division 5 – High Temperature Reactors", by R. I. Jetter and D. K. Morton [1]. Quoting from the Chapter 17 Introduction:

> *This chapter provides information on the scope and need for Division 5, the structure of Division 5, where the rules originated, the basis for the elevated temperature rules specified in Division 5, the various changes made in finalizing Division 5 and the future near term and long term expectations for Division 5 development.*

Chapter 17 of the *Companion Guide* is based on the 2015 edition of BPVC Section III, Division 5 and covers all rules of construction (e.g., materials, design, fabrication and installation, examination, testing, overpressure protection, stamping and reports) for high-temperature, gas-cooled reactors, liquid metal reactors, and molten salt reactors. Both metallic and nonmetallic (e.g., graphite and composite) components are covered. Frequent reference is made to the low-temperature codes (i.e., NB, NC, ND, NF, and NG) for those components or portions thereof that operate below the creep range. Chapter 17 provides an overall discussion of elevated temperature design criteria with sixty-seven additional references. It also discusses specific provisions in BPVC Section III, Division 5; however, to facilitate the background for specific articles, paragraphs, and subparagraphs of BPVC Section III, Division 5, the annotated background information is structured as a cross reference of specific code rules to the relevant section where background information is provided in Chapter 17.

Second reference of interest

The second reference of interest is the MPC publication *Recommended Practices in Elevated Temperature Design: A Compendium of Reactor Experiences (1970–1987)* Edited by A. K. Dhalla [2]. This is a four-volume compendium of experience and lessons learned in the application of elevated structural design methods to sodium-cooled, fast breeder reactor components. Each volume has multiple individually authored chapters. In addition to inputs from U.S. authors, there was significant input from Germany, France, and Japan. All of the chapters are of general interest, but the main focus is not on the background for the design rules themselves, however, there are a number of chapters that will be highlighted for their influence on design rule development. Note that the chapters are numbered sequentially, chapter numbers in the next volume pick up where the chapter numbers in the preceding volume left off.

Third reference of interest

The third reference of interest is *Criteria for Design of Elevated Temperature Class 1 Components in Section III, Division 1, of the ASME Boiler and Pressure Vessel Code*, ASME, May 1976 [3]. This is the first of the background documents addressing elevated temperature design rules and covers CC 1331-5 through CC 1331-8 and its successor, the 1974 edition of CC 1592. Quoting from the document Introduction:

> *This publication first provides a brief discussion of metal behavior when operated at elevated temperatures (i.e. in the creep range) under sustained and cyclic loadings. Then the relevant structural failure modes are described, and an explanation of the associated design rules and limit are provided. Special limits and considerations relative to the design procedure are also presented. Throughout this publication, comparisons of elevated temperature and low temperature design rules are made.*

The document material had several authors and numerous reviews prior to publication. Some of the material presented has been subsequently updated and revised in later revisions of the rules and associated background material. There are seventy-three references.

These three references of interest are discussed in the following sections.

1 *COMPANION GUIDE TO THE ASME BOILER AND PRESSURE VESSEL CODE*, VOLUME 1, FIFTH EDITION (2017), K. R. RAO, EDITOR, CHAPTER 17 "DIVISION 5 – HIGH TEMPERATURE REACTORS", BY R. I. JETTER AND D. K. MORTON [1]

1.1 Subsection HB Class A Metallic Pressure Boundary Components Subpart B Elevated Temperature Service

ARTICLE HBB-1000

INTRODUCTION

As briefly mentioned in Section 17.4.4.1, this article addresses the scope and organization of HBB. The failure modes addressed in HBB are discussed in Section 17.4.4.3.3.

ARTICLE HBB-2000

MATERIALS

Section 17.4.4.2 highlights the choice of materials, some unique characteristics of 9Cr-1Mo-V (Grade 91) steel, aging effects, and the creep-fatigue acceptance test for 304 stainless-steel ("SS") and 316 SS.

ARTICLE HBB-3000

DESIGN

HBB-3000 Design

HBB-3100 General Requirements for Design

HBB-3110 Scope, Acceptability and Loadings

The need for more specific information on the component loading history as required for the rules of Appendix HBB-T is discussed in Section 17.4.4.3.9.6, *Design Specifications and Load Histograms*. Also identified are some of the additional considerations that must be identified in the Design Specification.

HBB-3138 Elastic Follow-up

Section 17.4.4.3.9.3, *Consideration for Elastic Follow-up*, provides a fairly extensive discussion of what constitutes elastic follow-up, where it is considered in the current rules, and guidance on how to implement that consideration. Also addressed is the background for the provisions for pressure-induced discontinuity stresses in the HBB-T-1330 rules for strain limits and the HBB-T-1430 rules for creep-fatigue damage evaluation.

HBB-3200 Design by Analysis

Some of the critical features of elevated temperature material behavior and how they differ from material response below the creep regime are discussed in Section 17.4.4.3.2, *Elevated Temperature Material Behavior*. These critical features apply to both load-controlled and displacement-controlled loading. How the limits on loading and material response at elevated temperature were separated into load-controlled and displacement-controlled quantities is discussed in Section 17.4.4.3.4, *Stress and Strain Categories and Controlled Quantities*. The load-controlled quantities are covered in HBB-3000 and the displacement-controlled quantities in HBB Appendix T. Also shown is the flow diagram for elevated temperature analysis, Figure HBB-3221-1, that replaces the hopper diagrams used to illustrate the sequential application of the design rules below the creep regime. The various regimes of creep behavior are described.

Representations of creep data are also illustrated, including the effect of hold times at constant strain on cyclic life. This is a broad-brush treatment that sets the stage for further detailed discussions.

HBB-3214.2 Inelastic Analysis

Inelastic analysis may be required to satisfy strain limits and creep-fatigue damage evaluation; however, only general guidance is presented in HBB-3214.2, however, specific guidance was provided for early liquid metal fast breeder reactor ("LMFBR") programs. Section 17.4.4.3.9.4, *Inelastic Analysis Methods*, provides an overview of that guidance. More details on the early guidance are provided in Welding Research Council, Inc. ("WRC") Bulletin 365, Volume III- *Inelastic Analysis*, July 1991, as discussed in Section 3.3 of this background document.

HBB-3220 Design Rules for Load Controlled Stresses in Structures Other than Bolts

HBB-3221 General Requirements

Allowable stress criteria for Design Limits are discussed in Section 17.4.4.3.5.1 and criteria for Service Limits in Section 17.4.4.3.5.2. As discussed above, how the limits on loading and material response at elevated temperature are classified into load-controlled and displacement-controlled quantities is discussed in Section 17.4.4.3.4, *Stress and Strain Categories and Controlled Quantities*. Also shown in Section 17.4.4.3.4 is the flow diagram for elevated-temperature analysis, Figure HBB-3221-1, that replaces the hopper diagrams used to illustrate the sequential application of the design rules below the creep regime. Weld metal rupture strength factors are discussed as well in Section 17.4.4.3.5.2.

HBB-3222.1 Design Limits

Section 17.4.4.3.5.1 describes the limits for Design Loadings, which are analogous to the allowable stress values in BPVC Section I and BPVC Section VIII, Division 1.

HBB-3223 Level A and B Service Limits, HBB- 3224 Level C Service Limits, and HBB-Level D Service Limits

The limits for the primary membrane portion of the combined membrane and bending loading in HBB-3223, HBB-3224, and HBB-3225 are described in Section 17.4.4.3.5.3. The limits for the primary bending portion of the combined membrane and bending loading in HBB-3223, HBB-3224, and HBB-3225 are described in Section 17.4.4.3.5.4. This also includes the rationale for the bending stress load factors that address the reduced load carrying capacity in bending with creep as compared to the ideal elastic-plastic distribution applicable below the creep regime. Section 17.4.4.3.5.5 discusses the use fraction approach to account for a component not operating at a single temperature and/or primary load level throughout its operating history. The applicable code paragraph for use-fraction is HBB-3224(b).

HBB-3227.8 Cladding

Although cladding is not addressed in Chapter 17 of the *Companion Guide*, it is included here as an item of interest for proposed molten salt reactors. The current rules provide limited requirements on primary stress limits (i.e., no credit for cladding strength) and similarly limited requirements for deformation-controlled limits (i.e., cladding shall be considered for deformation-controlled limits) but no specific requirements are defined. No additional cladding requirements are provided in Division 5 for fabrication, inspection, or testing. There is a recent technical paper by Messner et al, *The Mechanical Interaction of Clad and Base Metal for Molten Salt Reactors*, PVP2018-84101 [4], that addresses design issues with the goal of improved code provisions for cladding.

HBB-3230 Stress Limits for Load Controlled Stress on Bolts

Section 17.4.4.3.9.2 provides the background for the primary stress Design Limits for bolts in HBB-3232, Service Level A and B limits in HBB-3233, Service Level C in HBB-3234, and Service Level D in HBB-3235. Also discussed are the rules for deformation-controlled stress and the special provisions in HBB-T-1721 and HBB-T-1722 for creep-fatigue damage evaluation.

COMPONENT DESIGN RULES

Section 17.4.4.3.10, *Component Design Rules*, discusses the use of Subsection NB component design rules for primary (load-controlled) stress levels and the use of NB rules for deformation controlled limits.

HBB-3300 Vessel Design

Discussed in Section 17.4.4.3.10.1 is the use of NB reinforcement rules and stress indices from NB-3338.

HBB-3400 Design of Class A Pumps and HBB-3500 Design of Class A Valves

Discussed in Section 17.4.4.3.10.2 is the use of NB-3400 and NB-3500 for primary stresses and limitations on the stress indices for deformation-controlled limits, generally to the negligible creep regime.

HBB-3600 Piping Design

Discussed in Section 17.4.4.3.10.3 is the use of stress indices for load-controlled limits and strain limits and the use of detailed indices for creep-fatigue evaluation.

ARTICLE HBB-4000

FABRICATION AND INSTALLATION

Section 17.4.4.4 discusses why and how the Subsection NB rules are supplemented with limitations on cold work. (Note that the reference for some key background information on the derivation of the limitations for 304 SS and 316 SS has only recently been located: Moen and Farwick [5]).

ARTICLE HBB-5000

EXAMINATION

The additional volumetric examinations are discussed in Section 17.4.4.5.

ARTICLE HBB-6000

TESTING

The use of pneumatic testing as an alternative to hydraulic testing and the use of helium leak testing are reviewed in Section 17.4.4.6.

ARTICLE HBB-7000

OVERPRESSURE PROTECTION

Section 17.4.4.7 discusses additional features for sodium-cooled reactors, including the use of rupture disks.

MANDATORY APPENDIX HBB-II

MATERIALS FOR SHORT TERM ELEVATED TEMPERATURE SERVICE

Section 17.4.4.8.2 discusses the use of SA-533 Type B, Class 1 plates and SA-508 Grade 3, Class 1 forgings for limited off-normal service conditions experiencing temperatures above the limits of Subsection NB.

NON-MANDATORY APPENDIX HBB-T

RULES FOR STRAIN, DEFORMATION, AND FATIGUE LIMITS AT ELEVATED TEMPERATURES

Section 17.4.4.3.6 provides a brief general overview of Appendix HBB-T.

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

HBB-T-1310 Limits for Inelastic Strains

Section 17.4.4.3.6.1 provides a description of, and rationale for, the specific values of the strain limits in HBB-T-1310.

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

HBB-T-1321 General Requirements

HBB-T-1332 Test No. A-1 and HBB-T-1323 Test No. A-2

The rationale for the use of the Bree diagram for evaluation of strain limits using the results of elastic analyses and the importance of cycle definition are discussed in Section 17.4.4.3.6.2. It is generally applicable to HBB-T-1321, HBB-T-1332, and HBB-T-1323. These are the so called simplified methods for evaluation of strain limits based on elastic analysis.

HBB-T-1324 Test No. A-3

Also included in Section 17.4.4.3.6 is an overview of the approach to determining when the rules for evaluation of primary plus secondary stress in Subsection NB can be used when creep effects are not significant, instead of the strain limits in HBB. The negligible creep rules are in HBB-T-1324.

HBB-T-1330 Strain Limits for Simplified Inelastic Analysis

Section 17.4.4.3.6.3 provides the background for the simplified analysis ratcheting rules based on the work of O'Donnell and Porowski [6], and Sartory [7]. Note that the use of "simplified inelastic analysis" is somewhat misleading, as the computed quantities in the evaluation are determined by elastic analysis. It includes a table summarizing characteristics of all the elastic analysis "tests" in HBB terminology, for evaluation of strain limits.

HBB-T-1400 Creep-Fatigue Evaluation

Section 17.4.4.3.7, *Design Rules and Limits for Creep-Fatigue Damage*, provides a discussion of the advantages and disadvantages of various creep-fatigue damage evaluation methods and a rationale for the selected time fraction approach.

HBB-T-1411 Damage Equation

The background and data supporting the creep-fatigue damage equation and its implementation in Figure HBB-T-1420-2, *Creep-Fatigue Damage Diagram*, are covered in Section 17.4.4.3.7.1. Also covered in that section are the Huddleston equations [8], [9] for the effects of multiaxiality on effective stress using inelastic analysis. Section 17.4.4.3.7.2 discusses the fatigue design curves and their derivation plus the creep rupture curves and the application of the safety factors for the evaluation of the creep-fatigue damage equation in HBB-T-1411. The fatigue curves are Figures HBB-T-1420-1A through HBB-T-1420-1E. The creep rupture curves are in Table HBB-I-14.6 and the weld strength reduction factors are in Table HBB-I 14.10.

HBB-T-1413 Equivalent Strain Range and HBB-T-1414 Alternative Calculation Method

Section 17.4.4.3.7.3 discusses strain range determination and the rationale for not considering mean stress effects at elevated temperature.

HBB-T-1420 Limits Using Inelastic Analysis

There is a brief reference to the difficulty in determining the stress-strain history under Section 17.4.4.3.7.4, *Inelastic Analysis Methods*. Specific guidance for inelastic analysis was provided for early LMFBR programs. Section 17.4.4.3.9.4 provides an overview of that guidance. More details on the early guidance are provided in WRC Bulletin 365, July 1991, as discussed below in Section 3.3 of this document, Volume III- *Inelastic Analysis*.

HBB-T-1430 Limits Using Elastic Analysis

The discussion in Section 17.4.4.7.5 is an overview of the creep-fatigue damage evaluation procedure developed by Severud [10]; it was developed in response to concerns that the original procedures were overly conservative and did not account for stress relaxation. The provisions for consideration of inelastic strain concentration, elastic follow-up, stress relaxation, creep shakedown and multiaxial effects are described. The categorization of pressure induced secondary stress as primary for the purposes of creep-damage evaluation in HBB-T-1430 is supported by references [11] and [12]. The background on elastic follow-up, which led to the overly conservative restrictions in the original procedure, is discussed in Section 17.4.4.3.9.3, *Considerations for Elastic Follow-Up*.

HBB-T-1500 Buckling and Instability

HBB-T-1510 Time Independent Buckling and Instability Limits

In Section 17.4.4.3.8 there is a general discussion comparing the approach to evaluation of buckling and instability in Subsection NB, which does not consider creep, to the approach in HBB, which does. Also included is a description of how time-dependent creep buckling differs from time-independent buckling and the difference between load-controlled and strain-controlled buckling.

HBB-T-1520 Buckling Limits

HBB-T-1521 Time Independent Buckling

Section 17.4.4.3.8.1 provides the basis for the time-independent rules in HBB-T-1521.

HBB-T-1522 Time-Dependent Buckling

Section 17.4.4.3.8.2 provides the basis for the time-dependent limits in HBB-T-1522. When interaction between load-controlled and strain-controlled buckling is present the load-controlled rules of HBB-T-1522 apply. Section 17.4.4.3.8.4 describes the temperature limit figures in HBB-T-1522 that permit the use of Subsection NB buckling and instability charts when satisfied.

HBB-T-1710 Special Strain Requirements at Welds

The various factors influencing weld integrity are discussed and the precautions taken to account for them in HBB-T-1710 are described in Section 17.4.4.3.9.1. Note that this also includes a discussion of the creep rupture strength reduction factors. Additional fabrication and inspection requirements related to weld configuration analyses are in HBB-3353.

HBB-T-1720 Strain Requirements for Bolting

Section 17.4.4.3.9.2 provides the background for the primary stress Design Limits for bolts in HBB-3232, Service Level A and B limits in HBB-3233, Service Level C in HBB-3234, and Service Level D in HBB-3235. Also discussed are the rules for deformation controlled stress and the special provisions in HBB-T-1721 and HBB-T-1722 for creep-fatigue damage evaluation.

HBB-T-1800 Isochronous Stress-Strain Relations

The isochronous stress-strain curves discussed in section 17.4.4.3.2, *Elevated Temperature Material Behavior*, are located in HBB-T-1800. They are part of the strain limit evaluation in HBB-T-1330, *Satisfaction of Strain Limits Using Simplified Inelastic Analysis*; and in the evaluation of creep-fatigue damage in HBB-T-1432, *Strain Range Determination*, and HBB-T-1433, *Creep Damage Evaluation*.

NON-MANDATORY APPENDIX HBB-U

GUIDELINES FOR RESTRICTED MATERIAL SPECIFICATIONS TO IMPROVE PERFORMANCE IN CERTAIN SERVICE APPLICATIONS

Section 17.4.4.3.9.5 discusses the motivation for material restrictions, the role of the various elements, grain size effects and melting practice.

NON-MANDATORY APPENDIX HBB-Y

GUIDELINES FOR DESIGN DATA NEEDS FOR NEW MATERIALS

Section 17.4.4.8.1 discusses the much greater testing requirements as compared to the requirements for Subsection NB, which covers temperatures below the creep regime, and BPVC Section I and BPVC Section VIII, Division 1, which are fundamentally design-by-rule based and do not consider actual service lives nor an analytic assessment of deformation controlled failure modes.

1.2 Subsection HC Class B Metallic Pressure Boundary Components, Subpart B Elevated Temperature Service

ARTICLE HCB-1000

INTRODUCTION AND SCOPE

Section 17.4.4.9.1 provides a. brief discussion of the scope for Class B construction rules and their relationship to the rules in Subsection NC for Class 2 components below the creep regime.

ARTICLE HCB-2000

MATERIALS

The materials included for Class B are generally the same as for BPVC Section VIII, Division 1 with similar allowable stresses. Section 17.4.4.9.2 discusses the additional factors applied for Class B construction. (Note: In the 2017 Edition, provisions have been added for the use of Class A materials and design provisions, including the complete construction rules.)

ARTICLE HCB-3000

DESIGN

The design rules are basically the same as for the Subsection NC component design rules with the exception of buckling and instability and piping. Section 17.4.4.9.3 describes the provisions for creep related to restrained thermal expansion in piping and the use of HBB rules for buckling and instability.

ARTICLE HCB-4000

FABRICATION AND INSTALLATION

As noted in Section 17.4.4.9.4, this article is basically the same as NC-4000 but picks up cold-work heat treatment per HBB-4000.

ARTICLE HCB-5000

EXAMINATION

Article HCB-5000 is basically the same as NC-5000 per Section 17.4.4.9.5.

ARTICLE HCB-6000

TESTING

Article HCB-6000 supplements NC-6000 with helium leak testing per Section 17.4.4.9.6.

ARTICLE HCB-7000

OVERPRESSURE PROTECTION

Article HCB-7000 adds requirements similar to HBB-7000 per Section 17.4.4.9.7.

1.3 Subsection HG Class A Metallic Core Support Structures

Section 17.4.4.10 provides a brief overview of how the core support rules relate to the Subsection NG rules when creep effects are negligible and to the HBB rules in BPVC Section III, Division 5 when they are not. It discusses the differences for core support structures and pressure retaining structures with respect to bolting (higher allowable stresses) and testing and overpressure protection (not required). The rules for BPVC Section III, Division 5 core support structures below the creep regime are in Appendix HGB-II. The elevated temperature rules when creep is significant are in HGB-1000 to HGB-8000. The guidance for when creep is negligible is in Appendix HGB-IV.

1.4 Code Cases

N-290-1, Expansion Joints in Class 1, Liquid Metal Piping, Section III, Division 1

Section 17.4.4.11.1 describes the incentive for the use of bellows, the issues addressed, and how they were resolved, including the more significant features. (Note: As the title of the Code Case indicates, it has not been updated in some time and needs to reflect the establishment of BPVC Section III, Division 5 for high temperature reactor components.)

N-812-1, Alternate Creep-Fatigue Damage Envelope for 9Cr-1Mo-V Steel, Section III, Division 5

Section 17.4.4.11.2 explains the justification and limitations for the use of a less conservative interaction intercept point (0.3, 0.3) on the creep-fatigue damage diagram for 9Cr-1Mo-V steel. [Note: The reference to an intercept of (0.1, 0.10) should be (0.1, 0.01) for the unmodified damage diagram]

N-861, Satisfaction of Strain limits for Division 5, Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis; and N-862, Calculation of Creep-Fatigue for Division 5, Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis

The discussion in Section 17.4.4.11.3 explains the rationale, advantages, and supporting information for the application of an Elastic-Perfectly Plastic ("EPP") based analysis methodology for the evaluation of strain limit and creep-fatigue damage. Also of note is a revised, less conservative consideration of Level C events.

1.5 Annotated List of Near and Long Term Tasks

Table 17.10 on the last page of Chapter 17 is an overview of near and long term goals for elevated temperature metallic components that was developed from a series of whitepapers and roadmaps from several years ago. It has been used for tracking various code development projects since. Generally, it is in good agreement with current accomplishments and ongoing activities.

2 *RECOMMENDED PRACTICES IN ELEVATED TEMPERATURE DESIGN: A COMPENDIUM OF REACTOR EXPERIENCES (1970–1987)*, EDITED BY A.K. DHALLA [2]

As indicated by the title, this is a four-volume compendium of experience and lessons learned in the application of elevated structural design methods to sodium cooled fast breeder reactor components. Each volume has multiple individually-authored chapters. In addition to inputs from U.S. authors, there was significant input from Germany, France and Japan. All of the chapters are of general interest, but the main focus is not on the background for the design rules themselves, however, there are a number of chapters that will be highlighted for their influence on design rule development. Note that the chapters are numbered sequentially, chapter numbers in the next volume pick up where the chapter numbers in the preceding volume left off.

2.1 Volume I- *Current Status and Future Directions*, WRC Bulletin 362, April 1991

The first three chapters are recommended. Chapter 1 provides a short overview of background for the development of elevated temperature design rules. Chapter 2 discusses key features of CC N-47, which eventually evolved to the HBB design rules, and the corresponding features and differences in the high temperature design codes from France and Japan. Table 2-1 of Chapter 2 shows the chronology of the development of CC 1331-4 through CC N-47-17. Chapter 3 is a discussion of the perceived needs and issues for elevated temperature design from the U.S., European and Japanese perspective. (Editorial note: Many, if not most, of these issues have been addressed in subsequent revisions and some are in progress. Many are focused on perceived over-conservatism of the rules at that time. Nonetheless, these inputs will be part of the subsequent gap analysis.)

2.2 Volume II- *Preliminary Design and Simplified Methods*, WRC Bulletin 363, May 1991

This volume has Chapter 5 and Chapter 6. Of particular note in Chapter 5 is the discussion in Section 5.3 *Resolution of Structural Design Problems*, which covers both problems encountered in design and also, in some cases, service related failures. Interspersed in Chapter 6 are discussions of testing and analyses to validate design methodologies. Section 6.2.1.3 *Validation of Thick Cylinder Simplified Methods* includes thermal transient testing of an IHX nozzle mockup. Section 6.2.2.3 *Verification of Thin Cylinder Formulation, Harwell Ratcheting Experiment* covers axial thermal transients (i.e., fluctuating Sodium level in an axial cylinder). Section 6.3 *Inelastic Buckling of Cylinders* covers cylindrical buckling test and related analyses. Section 6.5.2 *Applications and Verifications* describes two creep tests on notched specimens.

2.3 Volume III- *Inelastic Analysis*, WRC Bulletin 365, July 1991

The four chapters in this volume are primarily oriented to the definition of constitutive models and numerous examples of their application to various geometries and loading conditions, however, Chapter 7, Article 7.1.1 *Recommended Method for Inelastic Analysis* includes comparisons to test data on 304 SS and 2.25 Cr-1Mo steel under various loading conditions.

2.4 Volume IV- *Special Topics*, WRC Bulletin 366, August 1991

The four chapters in this volume cover various topics. Chapter 11 *Fracture Mechanics* in its various sub articles has numerous discussions and references to the correlation of fracture mechanics evaluations and supporting experimental data. Similarly, Chapter 12 *Nonlinear Collapse* addresses buckling and instability issues mainly based on nonlinear collapse programs used in France.

There are again numerous references to analytical predictions and experimental data. Chapter 13 *Simplified Stress Classification* is primarily of interest to the analyst. Chapter 14 *German Development Programs for*

High Temperature Reactor (HTR) Design provides a general overview of those programs. What makes each chapter unique is that the programs generally support high temperature gas cooled reactors with consideration of operating temperatures up to 950ºC and corresponding materials, including Alloy 617.