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# Technical Input for the U.S. Nuclear Regulatory Commission Review of the 2017 Edition of ASME Boiler and Pressure Vessel Code, Section III, Division 5, "High-Temperature Reactors." Review of Code Case N-861 and N-862: Elastic-Perfect Plastic Methods for Satisfaction of Strain Limits and Creep-Fatigue Damage Evaluation in BPV-III-5 Rules

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# TABLE OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ADAMS | Agencywide Documents Access and Management System |
| ANL | Argonne National Laboratory |
| ANLWR | advanced nonlight-water reactor |
| ASME | American Society of Mechanical Engineers |
| BPV | boiler and pressure vessel |
| C | Celsius |
| $Emc^2$ | Engineering Mechanics Corporation of Columbus |
| EPP | elastic-perfectly plastic |
| F | Fahrenheit |
| FEA | finite element analysis |
| ISCC | isochronous stress-strain curve |
| NRC | U.S. Nuclear Regulatory Commission |
| NPT | National Pipe Tapered |
| NUMARK | NUMARK Associates, Inc. |
| ORNL | Oak Ridge National Laboratory |
| PNNL | Pacific Northwest National Laboratory |
| PVP | pressure and vessel piping |
| RG | regulatory guide |
| SMT | simplified model test |
| SS | stainless steel |

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# EXECUTIVE SUMMARY

This report recommends Code Cases N-861 and N-862 for endorsement, contingent upon several items discussed further in the report.  Use of these Code Cases is expected to lead to conservative results.  Bounding theorems, mainly developed in the 1960s and 1970s, before the widespread use of computational modeling, form the basis for the conservative nature of these Code Cases.  They represent an alternative to satisfying the strain limits (Code Case N-861) and creep-fatigue damage (Code Case N-862) using elastic-perfectly plastic finite element modeling where the perfectly plastic “yield” stress is defined to account for creep damage.  Validation tests, with both full inelastic computational modeling and new test data, were used to validate the conservative nature of these Code Cases.  However, Code Case N-862 may be overly conservative in practice.

# 1 INTRODUCTION

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

In a letter dated June 21, 2018 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML18184A065), the American Society of Mechanical Engineers (ASME), based on letters from both industry consortia and individual companies interested in developing ANLWR designs, requested that the NRC review and endorse the 2017 Edition of ASME Boiler and Pressure Vessel (BPV) Code, Section III, "Rules for Construction of Nuclear Facility Components," Division 5, "High-Temperature Reactors" (BPV-III-5). The NRC responded in a letter dated August 16, 2018 (ADAMS Accession No. ML18211A571), that it is initiating efforts to endorse (with conditions, if necessary) the 2017 Edition of ASME BPV-III-5 in a new regulatory guide (RG) as one way of meeting the NRC's regulatory requirements.

To support the review and endorsement effort, the NRC requested the technical support of NUMARK Associates, Inc. (NUMARK), and its subcontractor, Engineering Mechanics Corporation of Columbus (Emc$^2$). This report documents NUMARK and Emc$^2$'s technical input for the NRC's review of the 2017 Edition of ASME BPV-III-5. The NRC will use it as part of the agency's review and to support its findings in the associated RG.

# 2 OVERVIEW

## 2.1 Review Approach

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

(1) SECY-18-0060, "Achieving Modern Risk-Informed Regulation," dated May 23, 2018 (ADAMS Package Accession No. ML18110A186), which provided the findings of the NRC Transformation Team

(2) an NRC memorandum from Frederick Brown, Director, Office of New Reactors, "Expectations for New Reactor Reviews," dated August 29, 2018 (ADAMS Accession No. ML18240A410)

One of the memorandum's expectations for new reactor reviews is to base the NRC's regulatory findings upon the principle of "reasonable assurance of adequate protection" (of public health and safety) but not on absolute certainty or risk avoidance. This is the legal standard for the NRC's licensing decisions. The memorandum discusses the basis for using the terms "reasonable" and "adequate."

The NRC will base its endorsement of ASME BPV-III-5 in the RG on the finding that the rules in Division 5 provide reasonable assurance of adequate protection. In accordance with the memorandum, new or novel designs or design features may need additional review or requirements, or both. Furthermore, the NRC should consider any technical areas that ASME BPV-III-5 does not address and that would lead to a demonstrably increased likelihood or consequence of failure.

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

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

The NRC conducted research to establish the scope of the review. This research includes a historical review of previous high-temperature design rules and NRC approvals. The final RG or another accompanying NRC document will fully explain the NRC's specific historical findings relevant to this report, as discussed below.

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

In accordance with discussions with the former Office of New Reactors, the Office of Nuclear Regulatory Research, and NUMARK's project manager, Emc$^2$ performed a detailed review of the following portions of the 2017 ASME BPV-III-5 relating to metallic materials:

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

- Mandatory Appendix HBB-II, "Use of SA-533 Type B, Class 1 Plate and SA-508 Grade 3, Class 1 Forgings and Their Weldments for Limited Elevated Temperature Service"; pp. 140–162

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

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

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

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

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

## 2.2 Historical Basis

The NRC researched previous high-temperature design rules and NRC approvals to establish the scope of the review. These reviews included historical RGs, Code Cases, and preapplication and construction permit safety evaluation reports. The NRC found that it had accepted the following ASME Code Cases for use, with conditions, in NRC RG 1.87, “Guidance for Construction of Class 1 Components in Elevated-Temperature Reactors (Supplement to ASME Section III Code Cases 1592, 1593, 1594, 1595, and 1596),” Revision 1, issued June 1975:

- ASME Code Case 1592, “Class 1, Components in Elevated Temperature Service Section III,” Division 1, Revision 0, dated April 29, 1974

- ASME Code Case 1593, “Fabrication and Installation of Elevated Temperature Components Section III, Class 1,” Revision 0, dated November 5, 1973

- ASME Code Case 1594, “Examination of Elevated Temperature Components Section III, Class 1,” Revision 0, dated November 5, 1973

- ASME Code Case 1595, “Testing of Elevated Temperature Components Section III, Class 1,” Revision 0, dated November 5, 1973

- ASME Code Case 1596, “Protection Against Overpressure or Elevated Temperature Components Section III, Class 1,” Revision 0, dated November 5, 1973

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

## 2.3 Review Scope

Table 1 lists the specific portions of the ASME BPV Code (e.g., subsection, article, Code Case) and the reviewing organization.

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

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

**Table 1 Review Assignments**

**General Requirements, Low-Temperature Metallic Components, and Supports**

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

**Elevated Temperature Metallic Components**

| ASME BPV Code Section (Subsection) | Reviewer |
|---|---|
| Class A Metallic Pressure Boundary Components, Elevated Temperature Service (HBB) | |
| 1000 Introduction | NRC Staff |
| 2000 Material | ORNL |
| 3000 Design | PNNL |
| 4000 Fabrication and Installation | PNNL |
| 5000 Examination | PNNL |
| 6000 Testing | PNNL |
| 7000 Overpressure Protection | NRC Staff |
| 8000 Nameplates, Stamping with the Certification Mark, and Reports | NRC Staff |
| Mandatory Appendix HBB-I-14, "Tables and Figures" | ORNL |
| Mandatory Appendix HBB-II, "Use of SA-533 Type B, Class 1 Plate and SA-508 Grade 3, Class 1 Forgings and Their Weldments for Limited Elevated Temperature Service" | NUMARK |
| Nonmandatory Appendix HBB-T, "Rules for Strain, Deformation, and Fatigue Limits at Elevated Temperatures" | NUMARK |

| ASME BPV Code Section (Subsection) | Reviewer |
|---|---|
| Nonmandatory Appendix HBB-U, “Guidelines for Restricted Material Specifications to Improve Performance in Certain Service Applications” | ORNL |
| Nonmandatory Appendix HBB-Y, “Guidelines for Design Data Needs for New Materials” | Not reviewed |
| Class B Metallic Pressure Boundary Components, Elevated Temperature Service (HCB) | |
| 1000 Introduction | NRC Staff |
| 2000 Material | ORNL |
| 3000 Design | PNNL |
| 4000 Fabrication and Installation | PNNL |
| 5000 Examination | PNNL |
| 6000 Testing | PNNL |
| 7000 Overpressure Protection | NRC Staff |
| 8000 Nameplates, Stamping with the Certification Mark, and Reports | NRC Staff |
| Mandatory Appendix HCB-I, “Stress Range Reduction Factor for Piping” | NUMARK |
| Mandatory Appendix HCB-II, “Allowable Stress Values for Class B Components” | NUMARK |
| Mandatory Appendix HCB-III, “Time-Temperature Limits for Creep and Stress-Rupture Effects” | NUMARK |
| Class A Metallic Core Support Structures, Elevated Temperature Service (HGB) | |
| 1000 Introduction | NRC Staff |
| 2000 Material | ORNL |
| 3000 Design | PNNL |
| 4000 Fabrication and Installation | PNNL |
| 5000 Examination | PNNL |
| 8000 Nameplates, Stamping with the Certification Mark, and Reports | NRC Staff |
| Mandatory Appendix HGB-I, “Rules for Strain, Deformation, and Fatigue Limits at Elevated Temperatures” | PNNL |
| Mandatory Appendix HGB-II, “Rules for Construction of Core Support Structures, Extended for Restricted Service at Elevated Temperature, Without Explicit Consideration of Creep and Stress-Rupture” | PNNL |
| Mandatory Appendix HGB-III, “Buckling and Instability” | PNNL |
| Mandatory Appendix HGB-IV, “Time–Temperature Limits” | PNNL |

**Graphite and Composites**

| ASME BPV Code Section (Subsection) | Reviewer |
|---|---|
| General Requirements, Graphite and Composite Materials (HAB) | |
| 1000 Introduction<br>2000 Classification of Graphite Core Components<br>3000 Responsibilities and Duties<br>4000 Quality Assurance<br>5000 Authorized Inspection<br>7000 Reference Standards<br>8000 Certificates and Data Reports<br>9000 Glossary | NRC Staff |

| ASME BPV Code Section (Subsection) | Reviewer |
|---|---|
| Mandatory Appendix HAB-I, “Certificate Holder's Data Report Forms, Instructions, and Application Forms for Certificates of Authorization” | NRC Staff |
| Class A Nonmetallic Core Components, Graphite Materials (HBB-T) | |
| 1000 Introduction<br>2000 Material<br>3000 Design<br>4000 Fabrication and Installation<br>5000 Examination | NUMARK |
| 8000 Nameplates, Stamping with the Certification Mark, and Reports | NRC Staff |
| Mandatory Appendix HBB-T-I, “Graphite Material Specifications” | NUMARK |
| Mandatory Appendix HBB-T-II, “Requirements for Preparation of a Material Data Sheet” | NUMARK |
| Mandatory Appendix HBB-T-III, “Requirements for Generation of Design Data for Graphite Grades” | NUMARK |

**Code Cases**

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

# 3 TECHNICAL REVIEW SYNOPSIS

## 3.1 Code Case N-861, “Satisfaction of Strain Limits for Division 5 Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis”

This Code Case provides an alternative method for evaluating strain limits to satisfy compliance with BPV-III-5, Subsection HB, Subpart B, HBB-T-1320 (“Satisfaction of Strain Limits Using Elastic Analysis”), and HBB-T-1330 (“Satisfaction of Strain Limits Using Simplified Inelastic Analysis”). This Code Case is termed a simplified method because it does not require the use of comprehensive full inelastic constitutive equations that account for both time-independent plasticity and time-dependent creep. This elastic-perfectly plastic (EPP) simplified analysis method also demonstrates compliance with code strain and stress limits without the use of stress classification procedures. Strain limits for Type 304H stainless steel (SS) and 316H SS, as approved for use in BPV-III-5, Table HBB-I-14.1(a), may be satisfied when performed in accordance with the requirements of this Code Case. The EPP analysis is very simple to use.

Code Case N-861 permits use of EPP finite element analysis (FEA) to show compliance with strain limits and ratcheting. Bounding theorems, discussed in Section 4.2 and the Code Case N-861 appendix in Section 4.2.7, confirm that EPP analysis will produce conservative results. Validation problems performed to date have shown Code Case N-861 always produces conservative results. This review recommends the Code Case for endorsement except for a few items discussed below.

### 3.1.1 Article 1 General Requirements

General requirements provide conservative predictions based on long-established bounding theorems with the exception of structures where geometrical nonlinearities exist. This review recommends endorsing the general requirements as written, except as noted below. Bounding theorems ensure conservative predictions, except where nonlinearities exist, such as skeletal structures, because bounds cannot be established.

The bounding theorems, discussed in more detail in Section 4 and the N-861 Appendix I described in Section 4.2.7, ensure the prediction of conservative strain limits using the EPP methods, augmented with reduced pseudo-yield stress with guidance from Mandatory Appendix I to Code Case N-861. Verification and validation tests (analytical, numerical, and comparison with experiments) conducted to date have shown that conservative predictions result except for “skeletal” structures. Skeletal structures (e.g., a bar with uniform axial load throughout) are precluded for use with the Code Case at present. For example, Jetter et al. (2017) investigated the “two bar” skeletal problem, conducted tests, and analyzed the test results using Code Case N-861. The investigation obtained nonconservative results for some of the design space. Work is continuing on skeletal structures, but it is not yet complete (see the appendix in Section 4.2.7 for examples).

This review recommends expanding and clarifying the definition of skeletal structures in the general requirements of Code Case N-861. It is clear structures that experience nonlinear geometric changes cannot use the Code Case.

### 3.1.2 Article 2 Load Definition

This review recommends endorsing the load definitions article. The composite load definitions in the Code Case ensure conservative predictions of ratcheting.

The load definitions comply with BPV-III-5 service load definitions. The lumping of service cycles into composite load cycles, as in Code Case N-861, Appendix I, will always provide conservative results. The elimination of hold times in the composite cycle(s) (resulting in what is termed rapid cycles) permits practical finite element solutions within reasonable times within the EPP framework, which is the main advantage of using this Code Case.

### 3.1.3 Article 3 Numerical Model

This review recommends endorsing numerical model requirements except those for solution accuracy.

The numerical model requirements are properly defined to include all details, including holes and fillets. Good examples for application of the Code Case, including mesh requirements, exist in Carter et al. (2005a, 2005b, 2011, 2012a, 2012b), Jetter et al. (2016, 2017), Sham et al. (2015), and Messner and Sham (2018), as well as in many other references they cite. Requirements for solution accuracy, however, are not specified. Modeler advice to ensure numerical convergence and solution accuracy during the analysis might be considered. For example, elastic-plastic finite element codes typically increase the increment size automatically based on convergence history as the solution progresses. Therefore, care must be taken to ensure that details in loading are not missed. The current requirement stating that the "model must also be accurate for small details" is not sufficiently specific for FEA. Recent work (Jetter et al., 2017) has also identified possible problems with convergence using EPP methods due to numerical roundoff issues.

### 3.1.4 Article 4 Requirements for Satisfaction of Strain Limits

The present rules are consistent with HBB-T rules except the strains are obtained from the numerical solution. The rules for defining the pseudo-yield stress are consistent with the bounding theorems ensuring conservatism. The iterative procedure described to determine the target strain is adequate and provides design safety using this Code Case.

This review recommends endorsing the satisfaction of strain limits for ratcheting analysis using the Code Case four-step procedure in this article, as conservative predictions of ratcheting will occur and the strain limit definitions of BPV-III-5, Subsection HB, Subpart B, are followed, subject to the following caveats. The assessment of HBB-2000 values of yield stress at high temperature for 304 SS found that yield-stress values may be slightly nonconservative. In addition, the isochronous stress-strain curves (ISSCs), evaluated in the assessment of HBB-T-1800, may be slightly nonconservative for high temperatures and long times for both 304 SS and 316 SS.

### 3.1.5 Article 5 Weldments

This review recommends endorsing the satisfaction of strain limits for weldments for ratcheting analysis using the four-step procedure in this article. Additional validation cases for examples with weldments could be useful as this Code Case is extended to additional materials. The strain limit rules for welding are consistent with HBB-T rules (half the base metal limits). This is not considered to be a safety-related issue.

#### *3.1.5.1 Weld Region Model Boundaries*

This review recommends endorsing the definition of the weld region boundaries as written. Various weld configurations in BPV-III-5, HBB-4000, and corresponding reference to NB-4000 are consistent with ASME BPV Code weld configuration definitions. Also, the definition of the weld region boundaries is consistent with HBB-T rules.

#### *3.1.5.2 Requirements*

This review recommends endorsing this article, as the Code Case rules are consistent with HBB-T-1714 requirements directly. The requirements for weld analysis of the geometry of HBB-T-1714 are consistent for use with this Code Case and must be justified in the design report.

#### *3.1.5.3 Properties*

This review recommends endorsing Subparagraph 5.3 of Code Case N-861 as written because the thermal and physical properties of weldments and base metal are to be the same. These are to be used for the thermal portion of the EPP analysis for the base metal/weld combinations in the properties in BPV-III-5, Table HBB-1-14.10. The design report should justify these values.

#### *3.1.5.4 Dissimilar Metal Welds*

The review makes no recommendation, as Subarticle 5.4 is still under preparation.

### 3.1.6 Mandatory Appendix I Ratcheting Analysis

A series of steps in Mandatory Appendix I to Code Case N-861 specifies the details of the Code Case's ratcheting analysis procedures. The goal is to bound the ratcheting strains using EPP analysis to provide a simple alternative to HBB. The Code Case N-861 analysis procedure is based on finite element solutions to satisfy ratcheting strain assessment requirements for code acceptance. As mentioned above, the bounding theorems ensure conservative results and will be produced for structures that satisfy Code Case definitions. Moreover, validation cases examined to date (see Carter et al., 2012a, 2012b, 2016; Sham et al., 2015; Jetter et al., 2016, 2017; Messner et al., 2018; and Becht Engineering, 2014) have all produced conservative results when compared to analytical solutions and experimental results. Moreover, results compare favourably with current code procedures. These methods in the appendix detail the procedures discussed above for this Code Case.

The following steps (a) to (e) outline the ratcheting analysis procedure:

(a) <u>Define Composite Cycle</u>

The use of composite cycles ensures conservative predictions, so this review recommends endorsing this paragraph. Five steps describe how to define the simplified composite cycle for the EPP assessment. The composite cycles must include histories of mechanical, pressure, and thermal loads, along with applied displacements. The analysis methodology is EPP, so there is no explicit consideration of cycle time duration, as time is introduced only with the choice of the pseudo-yield stress for each cycle.

(b) Define Analysis Types

This review recommends endorsing this paragraph. In a sequentially coupled computational analysis, the results of the thermal analysis feed into the EPP structural finite element solution. This is considered adequate for the EPP assessment.

(c) Define Material Properties

This review recommends endorsing this paragraph since material property definitions are consistent with the rules in BPV-III-5. The thermal and mechanical portions of the analysis require temperature-dependent thermal physical properties and mechanical properties, respectively. These rules are specified here and should be justified in the design report.

(d) Perform Analyses

This review recommends endorsing this paragraph, since the EPP-based finite element solutions are consistent with good finite element solution procedures. Elastic-plastic finite element codes typically control solution increment steps based on convergence. The modeler must ensure that the increments automatically chosen by the code do not become so large as to miss loading details within the composite step.

(e) Ratcheting

This review recommends endorsing this paragraph, since the rules for ratcheting, as obtained from the EPP finite element solution, are consistent with the present rules in BPV-III-5, Subsection HB, Subpart B.

## 3.2 Code Case N-862, "Calculation of Creep-Fatigue for Division 5 Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis Section III, Division 5"

This Code Case provides an alternative method for evaluating creep-fatigue damage to satisfy compliance with BPV-III-5, Subsection HB, Subpart B, HBB-3252 and Nonmandatory Appendix HBB-T. This is termed a simplified method because it does not require the use of comprehensive full inelastic constitutive equations that account for both time-independent plasticity and time-dependent creep. The EPP method is significantly more straightforward to implement compared with the current HBB methods. Validation of Code Case N-862 has been shown by comparison to a number of example cases (see the appendix in Section 4.3.8 for examples). The use of this Code Case may be advantageous to designers.

The conservative nature of EPP FEAs of this Code Case is based on a series of bounding theorems (see Section 4.3.8 of this report). Example validation cases include a comparison of Code Case-based EPP assessments with full inelastic analysis (finite element and analytically based) and a comparison to experimental results for selected creep-fatigue, high-temperature components expected to be used in high-temperature reactors. Moreover, Code Case N-862

EPP assessments generally provide greater creep-fatigue life compared with the very conservative current HBB procedures.

### 3.2.1 Article 1 General Requirements

This review recommends endorsing the general requirements, because using the Code Case procedures guarantees compliance with HBB rules, and the bounding theorems ensure conservative predictions. Currently, Code Case N-862 can be used for 304 SS and 316 SS, although it is currently being evaluated by ASME for other materials.

General requirements of the procedure ensure conservative predictions and compliance with HBB code requirements based on long-established bounding theorems (see Section 4.3.8 of this report). The bounding theorems ensure conservative predictions of creep damage and "shakedown" when using EPP analyses following the procedures of the Code Case. Shakedown is a high-temperature design requirement that refers to the achievement of cyclic elastic behavior throughout the component with time and cycles. The pseudo-yield stress for the EPP analysis is chosen as a temperature-dependent minimum stress-to-rupture value to ensure shakedown occurs with guidance from Mandatory Appendix I to Code Case N-862. The Code Case does not necessarily predict the actual component creep-fatigue life, but following these procedures will ensure a conservative design basis for metallic components at high temperature that pass code requirements.

### 3.2.2 Article 2 Load Definition

This review recommends endorsing load definitions because the bounding theorems ensure conservative creep-fatigue life predictions from using the simplified composite load spectrum, which eliminates hold times. The validation references (e.g., Jetter et al., 2017 and Sham et al., 2015) refer to these cycles as "rapid cycles," since all the complicated hold cycles need not be included as they must for full inelastic analysis. The elimination of hold times in the composite cycle(s) (or rapid cycles) permits practical solutions within a reasonable time, which is an advantage for designers.

The definitions comply with the BPV-III-5 service load definitions for Levels A, B, and C. The lumping of service cycles into composite cycles, as in Appendix I to Code Case N-862, for assessment using this Code Case provides conservative results based on the bounding theorem interpretations.

### 3.2.3 Article 3 Numerical Model

This review recommends endorsing numerical model requirements, with the exception of requirements for solution accuracy.

Code Case N-862 specifies the numerical model requirements that must include all details, including holes and fillets. It does not, however, specify requirements for solution accuracy. Accuracy must be established for both the thermal and structural solution processes. Modeler advice to ensure numerical convergence during the analysis might be included (e.g., mesh convergence studies) for clarity. Recent work (Jetter et al., 2017) has also identified possible issues with convergence using EPP methods due to numerical roundoff errors. The modeler must ensure that the automatic time incrementation in modern finite element codes does not skip important load step features. While designers are assumed to be experienced finite element modelers, it would be prudent to provide advice on possible numerical solution issues within the Code Case.

### 3.2.4 Article 4 Calculation of Creep Damage

This review recommends endorsing the creep damage assessment using the four-step procedure in this article, contingent upon the endorsement of the appropriate table and figures in Mandatory Appendix HBB-I-14 (Table I-14.5 and Figure HBB-I-14.6). The evaluation of HBB-2000 found some possible nonconservative values for creep rupture at high temperatures for 304 SS and 316 SS. However, once this potential issue is clarified, this review recommends this endorsement because the Code Case uses the results of the EPP analysis to calculate the creep damage time fraction using the appropriate pseudo-yield stress.

The present Code Case rules are consistent with HBB rules, except the creep damage is obtained from the EPP numerical solution. The rules for defining the pseudo-yield stress and, therefore, creep damage time fraction are consistent with the bounding theorems ensuring conservative assessments. The iterative procedure described to determine the pseudo-yield stress ensures that shakedown will occur after the eventual proper choice of the trial time duration.

### 3.2.5 Article 5 Calculation of Fatigue Damage

This review recommends endorsing the satisfaction of strain limits for ratcheting analysis using the four-step procedure in this article. The assessment of HBB-T determined that the linear damage creep-fatigue rules, with all appropriate safety factors, ensure conservative designs. The rules of HBB-T-1413, with margins and safety factors, along with the fatigue curves in HBB-T-1420, ensure conservative predictions using the EPP analysis procedure for the fatigue damage assessment.

The shakedown analysis using the Code Case EPP procedure obtains the total strains (elastic plus plastic). The equivalent strain range is then determined using HBB-T-1413 (or HBB-T-1414) when principal strains do not rotate. The design fatigue curves of Figure HBB-T-1420-1 are then used to obtain the allowable cycles for each cycle type. Therefore, the procedure follows current Subsection HB, Subpart B rules, except the shakedown strains are determined from the EPP analysis. The bounding theorems ensure that the strains from the EPP analysis are conservative and, therefore, this review recommends endorsement.

### 3.2.6 Article 6 Weldments

This review recommends endorsing the satisfaction of strain limits for weldments for shakedown analysis using this article, because it is consistent with current code rules for weldments. Section 4 and the appendix for Code Case N-862 discussed in Section 4.3.8 discuss the source of rules for welds.

#### *3.2.6.1 Strain Limit Rules for Welding*

These limits are consistent with HBB-T rules (half the base metal limits.) This is not considered to be a safety-related issue.) This review recommends endorsing the weld reduction factors used to determine the trial definition of the time duration, contingent on the endorsement of the weld reduction factors from BPV-III-5, Table HBB-I-14.10. The procedures used to determine the pseudo-yield stress are consistent with HBB by including the weld reduction factors.

#### *3.2.6.2 Allowable Cycles*

This review recommends acceptance of this paragraph as written, since it reduces the allowable cycles in the weldments by one half.

#### *3.2.6.3 Requirements*

Code Case N-862 will use the strain concentration factors for analysis of weld geometry of HBB-T-1714. This review recommends accepting this paragraph as is, since it follows the HBB-T-1714 requirements directly. The requirements for weld analysis of the geometry of HBB-T-1714 are consistent for use with this Code Case and must be justified in the design report.

#### *3.2.6.4 Properties*

This review recommends accepting Subparagraph 6.4 of Code Case N-862 as written, because the thermal and physical properties of weldments and base metal are to be the same. These are to be used for the thermal portion of the EPP analysis for the base metal/weld combinations in BPV-III-5, Table HBB-1-14.10, properties. The design report should justify these values.

#### *3.2.6.5 Weld Region Model Boundaries*

BPV-III-5, HBB-4200, specifies the weld region boundaries, with many requirements referring to ASME BPV Code, Section III, Division 1, Article NB-4000. The stress and strain concentrations must be accounted for as in BPV-III-5, HBB-T-1714. This article is consistent with HBB-T-procedures and should be endorsed if the NRC endorses HBB-T-1714.

#### *3.2.6.6 Dissimilar Metal Welds*

The review makes no recommendation, as Subarticle 6.6 is still under preparation.

### 3.2.7 Mandatory Appendix I Shakedown Analysis

Code Case N-862 represents a new alternative design method based on general analysis procedures with minimal rules and is consistent with the current code requirements of HBB and HBB-T. A series of steps in Mandatory Appendix I to Code Case N-862 specifies the details of the Code Case N-862 shakedown analysis procedures. This review recommends endorsing all the following steps in this appendix, since they conform to the rules of the bounding theorems:

(a) Define Composite Cycle

Five steps describe how to define the simplified composite cycle for the EPP assessment. The composite cycles must include histories of mechanical, pressure, and thermal loads, along with applied displacements. The analysis methodology is EPP, so there is no explicit consideration of cycle time duration, as time is introduced only with the choice of the pseudo-yield stress for each cycle. Incremental steps need only be included while loads or temperatures, or both, are changing in the composite cycle, and no additional incremental steps are necessary once these solutions have stabilized. Carter et al. (2011) outlines the development of the composite load cycles, and Jetter et al. (2017) gives a detailed example for a typical ANLWR component. The composite load cycle definitions ensure conservative predictions of shakedown based on the bounding theorems.

(b) Define Analysis Types

In a sequentially coupled computational analysis, the results of the thermal analysis feed into the EPP structural finite element solution. This is considered adequate for the EPP assessment.

(c) Define Material Properties

The thermal and mechanical portions of the analysis require temperature-dependent thermal physical properties and mechanical properties, respectively. This includes the temperature-dependent pseudo-yield stress defined in a fashion to permit compliance with the creep-fatigue design rules. The design report must provide justification.

(d) Perform Analyses

EPP-based finite element solutions are performed. Elastic-plastic finite element codes typically control solution increment steps based on convergence. The modeler must ensure that the increments automatically chosen by the code do not become so large as to miss loading details within the composite step.

(e) Shakedown

Shakedown occurs when elastic behavior is achieved by plotting equivalent plastic strain histories during the cycles. Failure to achieve shakedown requires another iteration with different design parameters or this Code Case cannot be satisfied.

# 4 TECHNICAL REVIEW DETAIL

## 4.1 Code Case N-861, "Satisfaction of Strain Limits for Division 5 Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis"

The following are the current BPV-III-5 design bases for high temperature life assessment (BPV-III-5 HBB Elevated Temperature Service):

- The assessments are based on accepted legacy high-temperature design procedures developed before widespread use of computational methods.

- The assessments are complex to use and overly conservative because they are based on elastic analysis methods. This often presents designers with challenges to meet the rules.

- Legacy approaches in BPV-III-5 are difficult to develop and apply for newer materials.

The EPP-based Code Cases procedure permits FEA to make the assessment as an alternative for some design features. This is considered good practice today with FEA now dominating design and analysis procedures. The following present some additional complications:

- The actual cyclic high-temperature response requires material behavior, including temperature-dependent creep and plasticity damage assessment. Mathematical bounding theorems (Goodall et al., 1979; Penny and Marriott, 1995; and Carter, 1985, 1997), originally developed in the 1960s and 1970s and enhanced in the 2000s by Carter et al. (2005, 2011), demonstrate EPP analysis results for strain limits and ratcheting and will bound both plastic and creep strains and creep-fatigue damage in component assessments. After extensive review of these references and others they cite, the reviewers agree with these theorems and approach.

- This Code Case permits a designer to perform an EPP FEA to assess strain limits through a simplified service load block using desktop computers. This is much simpler and practical compared to a complete inelastic computational analysis assessment using complex visco-plastic material models that must account for each load-hold cycle individually. Solutions with complete inelastic models using the complete load sequences will require high-performance computing facilities and codes that run efficiently within that framework. Vendors will undoubtably perform this for some components, since the current computational capability of many vendors is significant.

- Code Case N-861 does not necessarily predict the actual component strain limits. However, following these procedures will ensure a conservative design basis for metallic components at high temperature.

Reviewers consider Code Case N-861 to be very important to improve the design process and possibly reduce “overconservatism” in BPV-III-5 and recommend endorsement.

## 4.2 Overview of Code Case

BPV-III-5 now provides some simplified finite-element-based high-temperature design methodologies to satisfy design rules more easily. Historically, the rules in ASME BPV Code, Section III, NH, (precursor to BPV-III-5) which are the precursor to BPV-III-5 rules, are complicated to apply and are based on elastic design methods with stress classification rules. Finite-element-based simple design rules are the subject of these current studies within BPV-III-5. Code Case N-861 uses EPP analysis methods and is applicable to Class A austenitic 304H SS and 316H SS.[1] These permit simplified finite element procedures to aid in high-temperature design. These simplified methods capture the effects of complex material behavior but do not require a complex analysis. The use of elastic-plastic limit analysis methods for low-temperature designs in BPV ASME Code, Section III, Division I, is analogous to the use of these simplified methods for high-temperature designs. The strain limit Code Case is intended as an alternative to the rules in HBB-T-1320 and HBB-T-1330.

Code Case N-861, approved in February 2016, is now a computational-based design approach, which can help the designer comply with some of the design rules for BPV-III-5, Subpart B. The standard analysis-based high-temperature design methods are based on elastic FEA with stress classification rules. As an alternative, simplified code analysis methods are more efficient and reliable and eliminate the need for stress classification. This is good practice since computational methods are now well established and will be heavily used in the design of ANLWRs.

The simple cyclic load design analysis procedures in Code Case N-861 rely on key bounding theorems developed in the 1970s (and earlier) by Goodall et al. (1979) that state a cyclic elastic-plastic solution provides an upper bound to displacements, strains, and local damage rates from a full creep analysis. These methods represent the extension of methods summarized in by Penny and Marriott (1995). References discussing the bounding theorems that justify the use of EPP methods include Penny and Marriott (1995), Carter (1985, 1997), and Leckie and Hayhurst (1977). This approach is valid for low-temperature (NB) and high-temperature (HB) primary load design methods (Carter, 2005a, 2005b), and for high-temperature cyclic load designs (Carter et al., 2012a, 2012b). This work is an important development, and additional computational-based BPV-III-5 design rules should further use the power of nonlinear finite element methods for design. Section 4.2.7 of this report provides more details on the bounding theorems and describes validation cases for the Code Case, as well as its use and application.

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1 Current efforts are underway to extend the rules to 9Cr-1Mo-V (Grade 91) ferritic-martensitic steel, which cyclically softens, compared with the austenitic steels that cyclically harden. The bounding theorems underlying the simplified EPP methods prevent application to cyclically softening materials. The extension of EPP methods to Grade 91 may be relevant when applied to the saturated softened state that can develop.

### 4.2.1 Article 1 General Requirements

The EPP strain limits for Code Case N-861 have several advantages:

- Stress classification is not necessary as finite element solutions are convenient to apply.
- The method applies to the complex combined creep and plasticity coupled response.
- It is a simple pass/fail check to permit designers to rapidly assess designs for code compliance. The EPP checks, if passed, ensure that the system does not experience ratcheting strains and the system passes the BPV-III-5 strain limits criteria.

Finally, HBB-3214.2 and HBB-Y-3600 state the following:

> decoupling of plastic and creep strains in the classical constitutive framework is generally a poor representation of the true material behavior. Unified constitutive equations, which do not distinguish between rate-dependent plasticity and time-dependent creep, represent the rate dependence and softening that occur, particularly at higher temperatures.

Therefore, the use of EPP methods to bound full visco-plastic results has been fully justified. Indeed, the full visco-plastic strains are included within the ISSC used in the code with EPP methods. The ISSCs define the pseudo-yield stress, which is the crux of the bounding theorems.

### 4.2.2 Article 2 Load Definition

The lumping of service cycles into composite cycles, as in Code Case N-861 Appendix I, for assessment using this Code Case is expected to provide conservative results. The elimination of hold times in the composite cycle(s) (termed rapid cycles) permits practical solutions within reasonable times. Section 4.2.7 (Appendix Code Case N-861 Appendix) includes more discussion of the development of the composite load cycles.

### 4.2.3 Article 3 Numerical Model

The numerical model requirements (usually using a finite element mesh) are properly defined to include all details, including holes and fillets. Requirements for solution accuracy are not specified, however. For example, modeler advice to ensure numerical convergence during the analysis would be useful, as the requirement stating that the "model must also be accurate for small details" is not sufficiently specific for FEA. Recent work (Jetter et al., 2017) has also identified possible issues with convergence using EPP methods due to numerical roundoff issues.

The numerical model requirements are properly defined to include all details, including holes and fillets. Good examples for application of the Code Case, including mesh requirements, appear in Carter et al. (2005a, 2005b, 2011, 2012a, 2012b); Jetter et al. (2016, 2017), Sham et al. (2015), and Messner and Sham (2018), as well as many other references they cite. Requirements for solution accuracy, however, are not specified. Modeler advice to ensure numerical convergence and solution accuracy during the analysis might be considered. For example, elastic-plastic finite element codes typically increase the increment size automatically based on convergence history as the solution progresses. Therefore, care must be taken to ensure that details in loading are not missed. The current requirement that the "model must also be accurate for small details" is not sufficiently specific for FEA. Recent work (Jetter et al., 2017) has also identified possible issues with convergence using EPP methods due to numerical roundoff issues.

The design organizations using Code Case N-861 will likely have experienced finite element modelers to conduct these analyses. However, it is considered prudent to add a few cautions for the modeler.

### 4.2.4 Article 4 Requirements for Satisfaction of Strain Limits

The present rules are consistent with those in HBB-T except the strains are obtained from the numerical solution. The rules for defining the pseudo-yield stress are consistent with the bounding theorems. The iterative procedure that determines the target strain is well described and provides design safety using this Code Case. Section 4.2.7 of this report includes more discussion and examples on using the Code Case and validation. Results using Code Case N-861 are directly compared to results using the BPV-III-5, HBB, Elevated Temperature Service rules in the Code Case N-861 appendix in Section 4.2.7 of this report.

This review recommends this endorsement, subject to the following caveats. The assessment of HBB-2000 found that yield-stress values of 304 SS may be slightly nonconservative at high temperature. In addition, the ISSCs, evaluated in the assessment of HBB-T-1800, may be slightly nonconservative for high temperatures and long times for both 304 SS and 316 SS.

### 4.2.5 Article 5 Weldments

Jetter (2017, pages 17-1 to 17-43) includes an excellent summary of the reduction factors required for welds. These reduction factors are based on four considerations: (1) creep rupture strength of welds is typically lower than that of base metal, (2) creep ductility (or strain to failure) is typically lower in welds operating at high temperature, (3) long time exposure of welds at high temperature can lead to diffusion processes and time-dependent changes to mechanical properties, and (4) local variations in stress-strain and creep response in the various weld regions (weld, heat-affected zone) could redistribute stresses and strains and reduce life. The considerably conservative reduction factors used for welds were introduced to ensure that designers locate welds in regions of low strain.

Corum (1989) examined in detail the reduction factors for welds using extensive domestic and foreign test data on weldments. This study found that reduction factors for tests performed transverse to the welds are necessary with a reduction equivalent to, at most, a 50-percent reduction in life. Moreover, the reduction factors in HBB-1-14-10 are considered to add additional margin in weld assessments.

This review recommends accepting the satisfaction of strain limits for weldments for ratcheting analysis using the four-step procedure in this article, as the strain limit rules for welding are consistent with HBB-T rules (half the base metal limits). This is not considered a safety-related issue.

*4.2.5.1 Weld Region Model Boundaries*

This review recommends endorsing the definition of the weld region boundaries, as it is consistent with HBB-T rules.

*4.2.5.2 Requirements*

This review recommends endorsing the requirements for the analysis of geometry in HBB-T-1714, as they are consistent for use with this Code Case.

*4.2.5.3 Properties*

This review recommends endorsing the properties to be used for analysis, which must come from HBB-I-14.

*4.2.5.4 Dissimilar Metal Welds*

This review will not comment on these rules, as they are under preparation at present.

### 4.2.6 Mandatory Appendix I Ratcheting Analysis

A series of steps in this appendix specifies the details of the Code Case N-861 ratcheting analysis procedures. The goal is to bound the ratcheting strains using EPP analysis to provide a simple alternative to HBB. The Code Case N-861 analysis procedure is based on finite element solutions to satisfy ratcheting strain assessment requirements for code acceptance. The bounding theorems of references in Goodall et al. (1979), Penny and Marriott (1995), Carter (1985, 1997), Leckie and Hayhurst (1977), Carter and Marriott (2005), and Penny and Marriott (1971) ensure conservative results for structures, which satisfy Code Case definitions. These appendix methods detail the procedures discussed above for this Code Case.

The following steps (a) to (e) outline the ratcheting analysis procedure:

(a) <u>Define Composite Cycle</u>

Five steps describe how to define the simplified composite cycle for the EPP assessment. The composite cycles must include histories of mechanical, pressure, and thermal loads along with applied displacements. For components in ANLWRs, about 10 or more distinct types of transients specific for Level A, B, and C Service Loadings should be considered. The total number of such service loadings may be on the order of 1,000 (Carter, Sham, and Jetter, 2011).

Because the analysis methodology is EPP, cycle time duration is not explicitly considered, as time is introduced only with the choice of the pseudo-yield stress for each cycle, which incorporates the rupture stress in a selected design time. Incremental steps need only be included while loads or temperatures, or both, are changing in the composite cycle, and no additional incremental steps are necessary once these have stabilized.

(b) Define Analysis Types

In a sequentially coupled computational analysis, the results of the thermal analysis feed into the EPP structural finite element solution. Care must be taken to ensure that time synchronization between the thermal and mechanical portions of the load cycles are captured properly. This is considered adequate for the EPP assessment.

(c) Define Material Properties

The thermal and mechanical portions of the analysis require temperature-dependent thermal physical properties and mechanical properties, respectively. These rules are specified here. This includes the temperature-dependent pseudo-yield stress defined in a fashion to permit compliance with the creep ratcheting design rules.

(d) Perform Analyses

EPP-based finite element solutions are performed. Elastic-plastic finite element codes typically control solution increment steps based on convergence. The modeler must ensure that the increments automatically chosen by the code do not become so large as to miss loading details within the composite step.

(e) Ratcheting

Ratcheting occurs when elastic behavior is achieved by plotting nodal deflections from the EPP finite element solution during repeated cycles. If ratcheting is not achieved, then this Code Case cannot be satisfied with these trial design parameters, and changes must be made, along with a reanalysis.

### 4.2.7 Code Case N-861 Appendix

*4.2.7.1 Code Case Background and Overview*

BPV-III-5 now provides simplified finite-element-based high-temperature design methodologies to ensure compliance with code rules and satisfy design rules more easily. Historically, rules in BPV Code, Section III, NH (precursor to BPV-III-5), which are the precursor to BPV-III-5 rules, are complicated to apply and are based on elastic design methods with stress classification rules. Finite-element-based simple design rules are the subject of these current studies within BPV-III-5.

Code Case N-861 uses EPP finite-element-based analysis methods and is applicable for Class A austenitic 304H SS and 316H SS[2] at present. This Code Case permits the use of

[2] Current efforts are underway to extend the rules to 9Cr-1Mo-V (Grade 91) ferritic-martensitic steel, which cyclically softens compared with the austenitic steels that cyclically harden. The bounding theorems underlying the simplified EPP methods prevent application to cyclically softening materials. The extension

simplified finite-element procedures to aid in high-temperature design. The simplified methods capture the effects of complex material behavior but do not require a complex analysis. The use of elastic-plastic limit analysis methods for low-temperature design in ASME BPV, Section III, Division I, is analogous to the use of these simplified methods for high-temperature designs. The strain limit Code Case is intended as an alternative to the rules in HBB-T-1320 and HBB-T-1330.

The simple cyclic load design analysis procedures in Code Case N-861 rely on key bounding theorems developed in the 1960s and 1970s by Goodall et al. (1979) (and many references they cite) that state the cyclic elastic-plastic solution provides an upper bound to displacements, strains, and local damage rates from a full creep analysis. These methods represent the extension of methods summarized by Penny and Marriott (1971). Section 6 of this report includes other references discussing the bounding theorems that justify the use of EPP methods (Goodall et al., 1979; Penny and Marriott, 1995; Carter, 1985, 1997; Leckie and Hayhurst, 1977; Carter and Marriott, 2005; and Penny and Marriott, 1971). This approach is valid for low-temperature (NB) and high-temperature (HB) primary load design (Carter, 2005a, 2005b) and for high-temperature cyclic load designs (Carter et al., 2012a, 2012b). This work is an important development, and additional computational-based Division 5 design rules should be developed to further use the power of nonlinear finite element methods for design.

Code Case N-861 was approved in February 2016 by ASME. The standard analysis-based high-temperature design methods use FEA with stress classification rules. Simplified code analysis methods are more efficient and reliable and eliminate the need for stress classification. Moreover, complicated design considerations, such as “elastic followup,” are naturally accounted for with finite element-based approaches because they properly model creep response and the corresponding effect on the stresses and strains in the entire structural system. Elastic followup occurs in structural component systems (such as piping), which are subject to secondary loading (e.g., thermal stresses, residual stresses). When creep occurs, stresses naturally decrease under displacement control secondary loading conditions. However, actual structural behavior is more complex in structural systems. Thus, elastic followup, depending on the magnitude of the effect, can cause deformation-controlled stresses to approach the characteristics of load-controlled stresses when elastic analysis is used. The ASME BPV Code companion guide (Jetter, 2017, pp. 17-1 to 17-43) discusses elastic followup, and Jawad and Jetter (2009) give a number of examples of this effect and how to design for it using complicated current code procedures. This is good practice, since computational methods are now well established and will be used heavily in the design of ANLWRs.

Carter (1985, 1997), who was part of the team in the United Kingdom in the early 1980s that developed these methods for use in the British codes, has been the driving force behind these developments and their introduction into BPV-III-5. U.S. Department of Energy laboratories (i.e., Oak Ridge National Laboratory (ORNL), Argonne National Laboratory (ANL), Idaho National Laboratory) conducted many of the developments and validation cases for Code Case N-861 in recent years. In addition, Carter (2005, 2011) has participated with extending

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of EPP methods to Grade 91 may be applicable when applied to the saturated softened state that can develop.

the bounding theorems since the 1980s that form the basis of the use of EPP methods to assess creep and creep-fatigue damage.

#### *4.2.7.2 Code Case Technical Justification*

The technical justification for the use of bounding theorems to ensure conservative predictions using EPP methods has a very sound theoretical basis. The validation to date appears appropriate, although this review recommends more study to confirm the Code Case is conservative under additional cases. It might be useful to compare Code Case analyses to results of analyses using more appropriate constitutive material laws, and to more test data.

Mathematical proofs justifying the use of EPP methods to assess strain ratcheting limits were developed before the advent of the advanced finite element-based solutions available today, and their use pioneered the development of R5 rules (Carter, 1985, and numerous references it cites). The correct, detailed modeling approach would consist of obtaining a constitutive law properly accounting for both time-independent (plastic) and time-dependent (creep) inelastic deformation. Use of an advanced constitutive material law requires temperature-dependent material properties and obtaining the material constants for such a unified creep/plasticity law can be challenging, depending on the form of the law. Moreover, with the use of such complicated material laws, the solution time step requirements to ensure finite element convergence may be small, and as a result, the availability of computational power may limit the ability to conduct an analysis over all the actual load steps. This Code Case permits the user to minimize the load step cycle requirements by using composite cycles. These composite cycles are chosen to ensure all inelastic deformations predicted are upper bounds to the actual strains. In addition, EPP analysis is much less demanding from a numerical standpoint compared with a full visco-plastic analysis. These simplifications permit a reasonable analysis, and the bounding theorems ensure conservative strain limits. Carter et al. (2011), Jetter et al. (2017), Carter (2005a, 2005b), Carter, Jetter, and Sham (2012a, 2012b), and Sham et al. (2015) summarize the advantages for this approach and introduction into BPV-III-5.

The following is a simple “intuitive” overview of why the bounding theorems produce upper bounds on strains. The energy dissipation rates in the structure, augmented by a decreased (or pseudo) yield stress with the EPP analysis for the bounding solution, will not reduce the deformation compared with results from a full visco-plastic FEA. Thus, a “rapid” cyclic solution with the EPP analysis is possible without considering hold times and creep relaxation during the cycle, as would be required with the full visco-plastic solution. The pseudo-yield stress is prescribed to ensure that the EPP analysis will demonstrate shakedown to guarantee compliance throughout the structure with the selected limit. The strain limits are, thus, guaranteed by a ratcheting analysis with the pseudo-yield stress defined by the stress to cause the target inelastic strain in a selected time.

#### *4.2.7.3 Code Case N-861 Conservatism Validation*

A series of steps verify the Code Case approach more fully discussed in Carter et al. (2011), Jetter et al. (2017), Carter (2005a, 2005b), Carter et al. (2012a, 2012b), Sham et al. (2015), Jetter et al. (2016, 2017), Messner and Sham (2018), Sham et al. (2015), and Becht

Engineering (2014), as well as other references they cite. Figure 1 depicts a representative example problem defined with sustained and transient loading on a nozzle-to-sphere joint. Simplified examples were evaluated to compare the results of the EPP strain limit Code Case that showed the results to be approximately equivalent. A series of tests on two cylindrical specimens loaded in parallel with superimposed sustained and cyclic loading identified an anomaly in the applicability of the strain limit Code Case, which was resolved through inelastic analysis. The text below briefly discusses some of the results that were achieved for both Code Cases N-861 and N-862.

The use of a time-independent analysis to characterize these processes is not necessarily intuitively obvious. Therefore, their justification by the judicious use of proofs based on general material models is essential for complex high-temperature designs and life assessment.

#### *4.2.7.4 Nozzle Example Problem (Spherical to Pipe with Weld)*

Sham et al. (2015) chose and solved this problem to illustrate the use of Code Cases N-861 and N-862 on a representative ANLWR component with representative load cases throughout the design life. The material was 316H SS. The composite load cycles are first defined using the procedures discussed in Sections 3.1.2, 3.1.6, 3.2.2, and 3.2.7 of this report. Figures II-2 to II-4 in Sham et al. (2015) show the composite cycles for Service Levels A, B, and C. These include typical load cases of mechanical (including pressure) and thermal loading. A three-dimensional mesh of this component was developed, and sensitivity studies verified mesh refinement (Becht Engineering, 2014). Analyses used the EPP method through the composite cycles. The implementation evaluation of the strain limits Code Case was successful for ratcheting prediction and design against ratcheting. The implementation requires trial-and-error finite element EPP runs with the starting target as in the Code Case to determine strain limits.

#### *4.2.7.5 Pipe and Nozzle Example Case*

Analyses on tube geometries with radius-to-thickness ratios on the order of 3 and 4 included those for plane pipe analyses and one for two pipes connected with a tapered reducer section. The analyses used the procedures in the current Subsection HB, Subpart B, and the Code Case N-861 ratcheting analysis procedures. The load case considered combined pressure and defined thermal gradient loading and composite load cycles. Sham et al. (2015) provided details of both the Subsection HB and the Code Case N-861 analysis procedures. A comparison of Subsection HB, Subpart B, and EPP procedures shows similar conclusions (validation) for both pipes and the taper. Results are approximately equivalent for the EPP analysis and the standard BPV-III-5, HBB procedures. However, the Code Case N-861 procedure is simpler to perform.

*4.2.7.7 Pipe with Pressure and Thermal Gradient—Comparison to Inelastic Material Law (Analytical Comparison Validation)*

FEAs using an inelastic constitutive law compared a pipe with a thermal gradient through the pipe wall to EPP solutions. The results showed the following:

- good validation for a number of cases comparing EPP and inelastic model results
- EPP conservatism shown for many cases

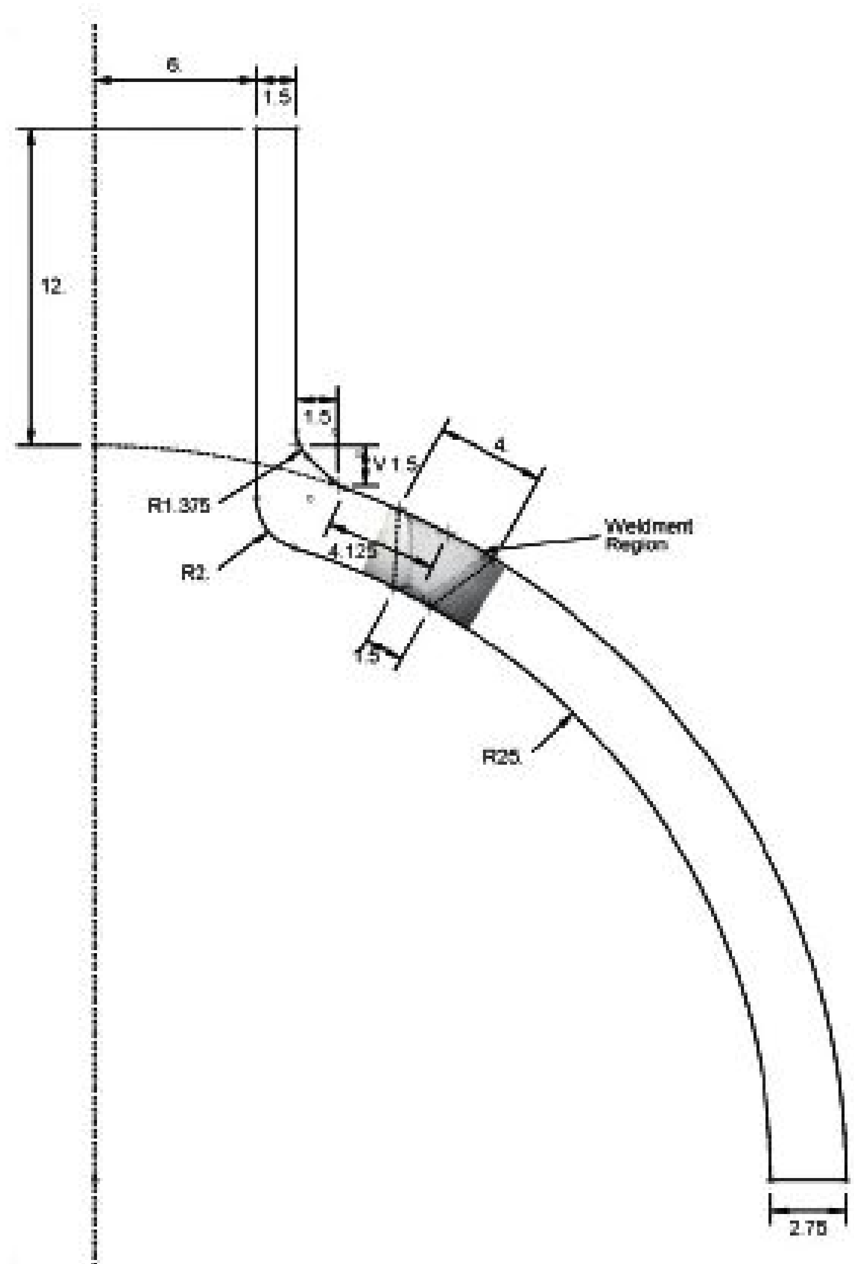


**Figure 1 Representative example problem (inches) (adapted from Sham et al., 2015)**

#### *4.2.7.8 Two-Bar Experiment Test*

The two-bar example case was tested using Code Case N-861 (Figure 2). A two-bar test case consists of applying different temperatures to the two different bars and applying a cyclic load. It is convenient, since closed-form solutions are available, allowing a comparison of the EPP Code Case to full inelastic solutions. Conceptually, the two-bar problem can be thought of as representing the inner and outer walls of a pressurized cylinder subjected to a cyclic temperature gradient. Comparing results from the Code Case N-861 procedure to analytical solutions using an inelastic constitutive model and experimental results showed an anomaly. The Code Case predictions were nonconservative for higher temperature differences. This led to the stipulation that Code Case N-861 cannot be used for “skeletal structures.” The analytical results compared reasonably well with experimental results.

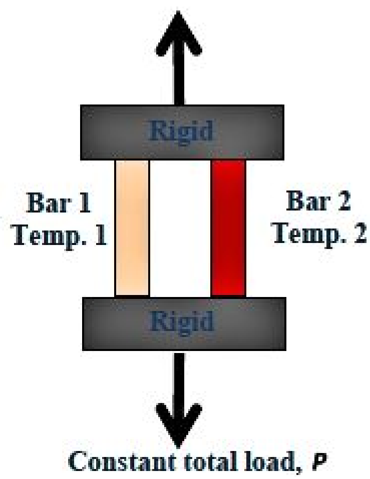


**Figure 2 Two-bar test case (adapted from Sham et al., 2015)**

#### *4.2.7.9 Other Validation Cases*

The results of other validation example cases appear in the references cited above and other references they cite. These validation cases compare Code Case N-862 EPP results to (1) experimental test results, (2) current BPV-III-5, Subsection HB, Subpart B, predictions, (3) analytical solutions for simple geometries using visco-plastic material laws where closed-form solutions are available, and (4) finite element solutions using visco-plastic material laws. For all cases, the EPP results for ratcheting and shakedown are conservative. In some cases, the use of the Code Case may be too conservative and not useful for design.

The strain limits Code Case (1) can be implemented on a representative component configuration with realistic loading conditions, (2) provides comparable results to current NH procedures at moderate creep temperatures, and (3) with a combination of test data and inelastic analysis, can represent the strain accumulation bounds at very high temperatures.

## 4.3 Code Case N-862, "Calculation of Creep-Fatigue for Division 5 Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis Section III, Division 5"

This Code Case provides an alternative method for evaluating creep-fatigue damage and shakedown to satisfy compliance with BPV-III-5, Subsection HB, Subpart B. This is termed a simplified method because it does not require the use of comprehensive full inelastic constitutive equations that account for both time-independent plasticity and time-dependent creep. This EPP simplified analysis method also demonstrates compliance with code strain and stress limits without the use of stress classification procedures. Strain limits for 304 SS and 316 SS in BPV-III-5, Table HBB-I-14.1(a), may be satisfied when they are in accordance with the requirements of this Code Case. Section 4.3.8 describes the bounding theorems and validation cases.

### 4.3.1 Article 1 General Requirements

General requirements are expected to provide conservative predictions based on long-established bounding theorems with the exception of structures where geometric nonlinearities exist because bounds cannot be established. The bounding theorems, discussed in more detail in Section 4.3.8, ensure that conservative creep-fatigue predictions use the EPP methods augmented with a reduced pseudo-yield stress with guidance from Code Case N-862, Mandatory Appendix I. Verification and validation tests (analytical, numerical, and comparison with experiments) conducted to date have shown conservative prediction results. It is noted that Code Case N-862 is not applicable to structures that nonlinear geometry changes. For some design conditions, Code Case N-862 may produce overly conservative results (Messner and Sham, 2018), and predictions are more conservative than the corresponding Code Case N-861 results for ratcheting.

### 4.3.2 Article 2 Load Definition

This review recommends endorsing the load definitions, which comply with BPV-III-5 service load definitions. The lumping of service cycles into composite cycles, as in Mandatory Appendix I, for assessment using this Code Case is expected to provide conservative results. The elimination of hold times in the composite cycle(s) (termed rapid cycles) permits practical solutions within reasonable times.

### 4.3.3 Article 3 Numerical Model

The review does not recommend endorsing numerical model requirements until the requirements for solution accuracy are specified.

The definition of the numerical model requirements (usually using a finite element mesh) is properly defined to include all details, including holes and fillets. Requirements for solution accuracy are not specified, however. For example, modeler advice to ensure numerical convergence during the analysis would be useful, as the statement that the "model must also be accurate for small details" is not sufficiently specific for FEA. Recent work (Jetter et al., 2017) has identified possible issues with convergence using EPP methods due to numerical roundoff issues. The design organizations using Code Case N-861 will likely have experienced finite element modelers to conduct these analyses. However, it is considered prudent to add a few cautions for the modeler.

### 4.3.4 Article 4 Calculation of Creep Damage

The present rules are consistent with HBB-T rules, except the creep-fatigue damage is calculated from the numerical solution. The rules for defining the pseudo-yield stress are consistent with the bounding theorems. The iterative procedure that determines the target strain is well described and provides design safety using this Code Case. Predictions of the creep damage produced from the EPP analysis, for use in the creep-fatigue interaction diagrams, are ensured to be conservative based on the bounding theorems.

### 4.3.5 Article 5 Calculation of Fatigue Damage

The present rules are consistent with HBB-T rules, except the strains are obtained from the numerical solution. The rules for defining the pseudo-yield stress are consistent with the bounding theorems. The iterative procedure described to determine the target strain is well described and provides design safety using this Code Case. Predictions of the fatigue damage produced from the EPP analysis, for use in the creep-fatigue interaction diagrams, are ensured to be conservative based on the bounding theorems.

### 4.3.6 Article 6 Weldments

Code Cases N-861 and N-862 should be used in tandem. Code Case N-862 should also explicitly state that satisfying strain limits should be addressed.

Jetter (2017, pp. 17-1 to 17-43) includes an excellent summary of the reduction factors required for welds. These reduction factors are based on four considerations: (1) creep rupture strengths of welds are typically lower than base metal, (2) creep ductility (or strain to failure) is typically lower in welds operating at high temperature, (3) long-time exposure of welds at high temperature can lead to diffusion processes and time-dependent changes to mechanical properties, and (4) local variations in stress-strain and creep response in the various weld regions (weld, heat-affected zone) could redistribute stresses and strains and reduce life. The considerably conservative reduction factors used for welds were introduced to ensure that designers locate welds in regions of low strain.

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

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

#### 4.3.6.1 Weld Region Model Boundaries

This review recommends endorsing the definition of the weld region boundaries, as it is consistent with HBB-T rules.

#### 4.3.6.2 Requirements

The requirements for analyzing the geometry of HBB-T-1714 are consistent for use with this Code Case.

#### 4.3.6.3 Properties

This review recommends endorsing the properties to be used for analysis, which must come from HBB-I-14.

#### 4.3.6.4 Dissimilar Metal Welds

The review will not comment on these rules, as they are under preparation at present.

### 4.3.7 Mandatory Appendix I Shakedown Analysis

Code Case N-862 represents a new alternative design method based on general analysis procedures with minimal rules and is consistent with current code requirements of HBB and HBB-T. A series of steps in this appendix specifies the details of the Code Case N-862 shakedown analysis procedures. The analysis procedure is based on finite element solutions whose purpose is to satisfy creep-fatigue damage assessment requirements for code acceptance. The bounding theorems ensure conservative results for both shakedown and the cyclic strain limits. The creep damage is bounded based on bounding theorems and the creep damage fraction is calculated. The fatigue damage is calculated using the conservative predicted strain limits, as modified in HBB-T-1420 or HBB-T-1430, and the fatigue design curves are used to calculate the fatigue damage portion. This is done without analyses using complicated visco-plastic material models.

Steps (a) to (e) summarize the creep-fatigue analysis procedure (Carter, Sham, and Jetter, 2011). The Code Case N-862 shakedown analysis can provide a conservative prediction of local rupture and, therefore, cyclic creep damage for use in a creep-fatigue assessment. Carter et al. (2011, 2012b, 2016) summarizes the procedure and discusses how the creep-fatigue procedure falls under the bounding theories discussed above. The bounding theorems (Goodall et al., 1979, and references it cites) ensure conservative shakedown estimates. Shakedown refers to the achievement of cyclic elastic behavior throughout the part—based on real or pseudo-yield properties. Pseudo yield refers to the temperature-dependent minimum stress-to-rupture (or yield stress, whichever is lower) value based on selected trial time duration not to be higher than yield stress at temperature. The strains calculated from the EPP analysis bound the component strains, which are then used to obtain the fatigue damage fraction. Example problems by Carter (2011, 2012b, 2016) and from the ANL work show conservative predictions should result. In fact, overly conservative predictions will likely result from using Code Case N-862.

The temperature-dependent pseudo-yield stress is chosen to ensure that a shakedown solution exists. Shakedown ensures that the creep-rupture stress and temperature are not exceeded, and fatigue damage is calculated from local strain values calculated in the EPP analysis using HBB-T procedures. Code Case N-862 EPP analysis procedures provide advantages to the designer since they do not require stress classification. Moreover, the methods are applicable to cycles over the full range of temperatures above and below the creep regime.

This review recommends endorsing all of the following steps in this appendix since they conform to the rules of the bounding theorems, although the neglect of weld residual stresses for weld assessment in the procedures should be explained:

(a) <u>Define Composite Cycle</u>

Six steps describe how to define the simplified composite cycle for the EPP assessment. The composite cycles must include histories of mechanical, pressure, and thermal loads along with applied displacements. For components in ANLWRs, about 10 or more distinct types of transients specific for Levels A, B, and C Service Loadings should be considered. The total number of such service loadings may be on the order of 1,000 (Carter, Sham, and Jetter, 2011).

Because the analysis methodology is EPP, cycle time duration is not explicitly considered, as time is introduced only with the choice of the pseudo-yield stress for each cycle. Incremental steps need only be included while loads or temperatures, or both, are changing in the composite cycle, and no additional incremental steps are necessary once these solutions have stabilized. Carter, Sham, and Jetter (2011) describe the development of the composite load cycles, and Jetter et al. (2017) provides a detailed example for a typical ANLWR component.

(b) <u>Define Analysis Types</u>

In a sequentially coupled computational analysis, the results of the thermal analysis feed into the EPP structural finite element solution. This is considered adequate for the EPP assessment.

(c) <u>Define Material Properties</u>

The thermal and mechanical portions of the analysis require temperature-dependent thermal physical and mechanical properties, respectively. They include the temperature-dependent pseudo-yield stress defined in a fashion to permit compliance with the creep-fatigue design rules, which is considered adequate.

(d) <u>Perform Analyses</u>

EPP-based finite element solutions are performed. Elastic-plastic finite element codes typically control solution increment steps based on convergence. The modeler must ensure that the increments automatically chosen by the code do not become so large as to miss loading details within the composite step. This is adequate.

(e) Shakedown

Shakedown occurs when elastic behavior is achieved by plotting equivalent plastic strain histories during the cycles. Failure to achieve a shakedown either requires another iteration with different design parameters or this Code Case cannot be satisfied. This is adequate.

### 4.3.8 Code Case N-862 Appendix

#### *4.3.8.1 Code Case Background and Overview*

Code Case N-862 establishes methods for evaluating structures against the BPV-III-5 limits on creep-fatigue damage using simplified EPP analysis. Many of the arguments discussed in Section 4.2.7 with regard to the Code Case N-861 appendix apply equally well to Code Case N-862 and are included here for completeness. Code Case N-862 is applicable for Class A austenitic 304H SS and 316H SS at present, although work is ongoing to permit use for other high-temperature code materials, including cyclic softening materials. The simplified methods capture the effects of complex material behavior but do not require a complex analysis. The creep-fatigue Code Case is intended as an alternative to the rules in HBB-T.

The simple cyclic load design analysis procedures in Code Case N-862 rely on key bounding theorems developed in the 1960s and 1970s by Goodall et al. (1979) that state a cyclic elastic-plastic solution provides an upper bound to displacements, strains, and local damage rates from a full creep analysis. The Code Case N-861 appendix describes other references that discuss the bounding theorems that justify the use of EPP methods and also apply here.

Steps (a) to (e) summarize the creep-fatigue analysis procedure (Carter, Sham, and Jetter, 2011). A Code Case N-862 shakedown analysis can make a conservative prediction of local rupture and, therefore, cyclic creep damage for use in a creep-fatigue assessment. Carter et al. (2011, 2012b, 2016) summarizes the procedure and discusses how the creep-fatigue procedure falls under the bounding theories discussed above. The bounding theorems (Goodall et al., 1979, and the references cited) ensure conservative estimates of shakedown. Shakedown refers to the achievement of cyclic elastic behavior throughout the part—based on real or pseudo-yield properties. Pseudo yield refers to a temperature-dependent minimum stress-to-rupture (or yield stress, whichever is lower) value based on selected trial time duration not to be higher than yield stress at temperature. The strains calculated from the EPP analysis bound the component strains, which are then used to obtain the fatigue damage fraction. Example problems by Carter (2011, 2012b, 2016) and from the ANL work show conservative predictions should result. In fact, overly conservative predictions will likely result from using Code Case N-862.

The appendix to Code Case N-862 will provide a more intuitive explanation. A series of ANL reports (Jetter et al., 2016, 2017; Messner et al., 2018; and Sham et al., 2015) and corresponding ASME pressure and vessel piping (PVP) papers based on this work further discuss this bounding concept.

The argument used for the general case of thermal-mechanical loading and creep-plasticity is based on the self-evident assumption for a structure under general loading—from the bounding theorems (Goodall et al., 1979, and Penny and Marriott, 1995), "Reducing the perfectly plastic yield stress does not reduce the deformation." Rather, it should increase the deformation. For the Code Case, reducing the yield stress by using ISSCs and conducting EPP analysis produces larger deformation compared with the corresponding full inelastic solution. Applied to the plastic rapid cycle solution (rapid cycle neglects creep since EPP), this statement means that the cyclic increment in the deformation of a structure is not reduced if the yield stress is reduced, all other factors being unchanged. Therefore, if the yield stress is reduced to the point where ratcheting in a cyclic problem is imminent, then the cyclic incremental deformation is not less than for the original yield stress. Therefore, the energy dissipation and deflection for the reduced yield stress case provide an upper bound of the energy dissipation and deflection in the original cases. This ensures not only ratcheting but cyclic shakedown, which is the basis of Code Case N-862 bounding theorems for the creep damage fraction.

The basis for the Code Case is expressed in terms of energy bounding theorems (Carter, 2012b, 2016). A "hierarchy" of bounding concepts reflects the tradeoff between problem complexity and bounding accuracy. Problems with mechanical load cycles may be bounded by external work, and those with thermal (secondary stresses) and mechanical load cycles may be bounded by internal energy dissipation. The application for displacement-type loading is generally more conservative than for purely mechanical problems, since high internal energy dissipation may be associated with zero net deflection. In both cases, the opportunity for a simplified analysis arises from the use of the "rapid cycle" concept. Rapid cycles have no creep relaxation during the cycle, and no hold times, but they generally have the most advantageous residual stress system, which ensures that deformation rates over the cycle are as low as possible. In terms of deformation and strain accumulation over time, rapid cycles are more conservative than slow cycles. Therefore, if creep-fatigue limits can be demonstrated for rapid cycles, slower cycles with relaxation will also satisfy the creep-fatigue limits. The references cited above further discuss this application to the Code Cases in more detail, and general bounding theorem papers provide higher level proofs.

The pseudo-yield stress is obtained from the lower of the yield strength or the stress from the applicable ISCC. The time duration for entering the ISSC is the total design life. The temperature is the local instantaneous temperature as determined from the transient thermal analysis. The strain used to determine the pseudo-yield strength from the ISSC at a given time and temperature is an iterative procedure.

The next step is a cyclic EPP analysis using the pseudo-yield strengths determined above that vary spatially and temporally. Shakedown is defined as the absence of incremental plasticity or deformation. Note that this permits stable hysteresis loops with plasticity. If the analysis shakes down, then the next step is to determine the local plastic strain from the EPP analysis and add it to the target strain. The local plastic strain from the EPP shakedown analysis is added to the target inelastic to account for strain redistribution due to such issues as elastic followup and redundancy. The sum must satisfy the constraints in Code Case N-862 (i.e., at least at one point for all through-thickness locations and at all points must reach shakedown). The value is equal to 0.05 for base metal and 0.025 for weldments.

Code Case N-862, which was recently approved by ASME, requires values of the material yield stress, $S_y$, and the material isochronous curves. The creep-fatigue Code Case requires fatigue curves, creep rupture curves, and a damage diagram. Jetter et al. (2016) describes obtaining these required data using simulated experiments with the reference inelastic model and the standard ASME approach for converting the (simulated) experimental data into the design charts. This approach would apply when adding new materials to BPV-III-5.

#### *4.3.8.2 Code Case Technical Justification*

Mathematical proofs justifying the use of EPP methods to assess strain ratcheting limits and shakedown were developed before the advent of the advanced finite element-based solutions available today, and their use was pioneered in the development of R5 rules (Carter and Marriott, 2005, and numerous references it cites). The correct, detailed modeling approach would consist of obtaining a constitutive law properly accounting for both time-independent (plastic) and time-dependent (creep) inelastic deformation. Use of an advanced constitutive material law requires temperature-dependent material properties. Obtaining the material constants for such a unified creep/plasticity law can be challenging, depending on the form of the law. Moreover, with the use of such complicated material laws, the solution time step requirements to ensure finite element convergence may be small; and as a result, conducting an analysis over all the actual load steps may be limited by the availability of computational power. This Code Case permits the user to minimize the load step cycle requirements by using composite cycles. These composite cycles are chosen to ensure all inelastic deformations predicted are upper bounds to the actual strains. In addition, EPP analysis is much less demanding from a numerical standpoint, compared with a full visco-plastic analysis. These simplifications permit a reasonable analysis, and the bounding theorems ensure conservative strain limits. The above references summarize the advantages for this approach and introduction into BPV-III-5.

#### *4.3.8.3 Code Case N-862 Conservatism Validation*

Example problems were solved for representative geometries using EPP Code Cases and compared to results from the elastic code methods in HB. Validation also occurred by comparing EPP predictions to full inelastic analysis results and comparing EPP Code Case results to special experimental tests designed to interrogate the methods for conservatism. These are done for 316H SS and are also appropriate for 304H SS. The simplified finite element methods exploit the fact that elastic-plastic methods naturally handle the stress redistribution (and any elastic followup), which is the key to stress classification schemes.

#### *4.3.8.4 Nozzle Example Problem (Spherical to Pipe with Weld)*

Sham et al. (2015) and Becht Engineering (2014) chose this problem and solved it by illustrating the use of Code Cases N-861 and N-862 on a representative ANLWR component with representative load cases throughout the design life. They chose this high-temperature design case to illustrate that the Code Case could be used for design in real components. The material was 316H SS. Figure 3 illustrates this example problem. The weld centerline location represents a V groove with flush ground weld, so both base metal and weld metal were assessed to determine whether creep-fatigue limits could be made. The composite load cycles are first defined using the procedures discussed in Sections 3.1.2, 3.1.6, 3.2.2, and 3.2.7 of this report. Figures II-5 to II-6 in Sham et al. (2015) for Service Levels A, B, and C show the composite cycles. These include typical load cases of mechanical (including pressure) and thermal loading. A three-dimensional mesh of this component was developed, and mesh sensitivity studies were performed to verify mesh refinement (Becht Engineering, 2014).

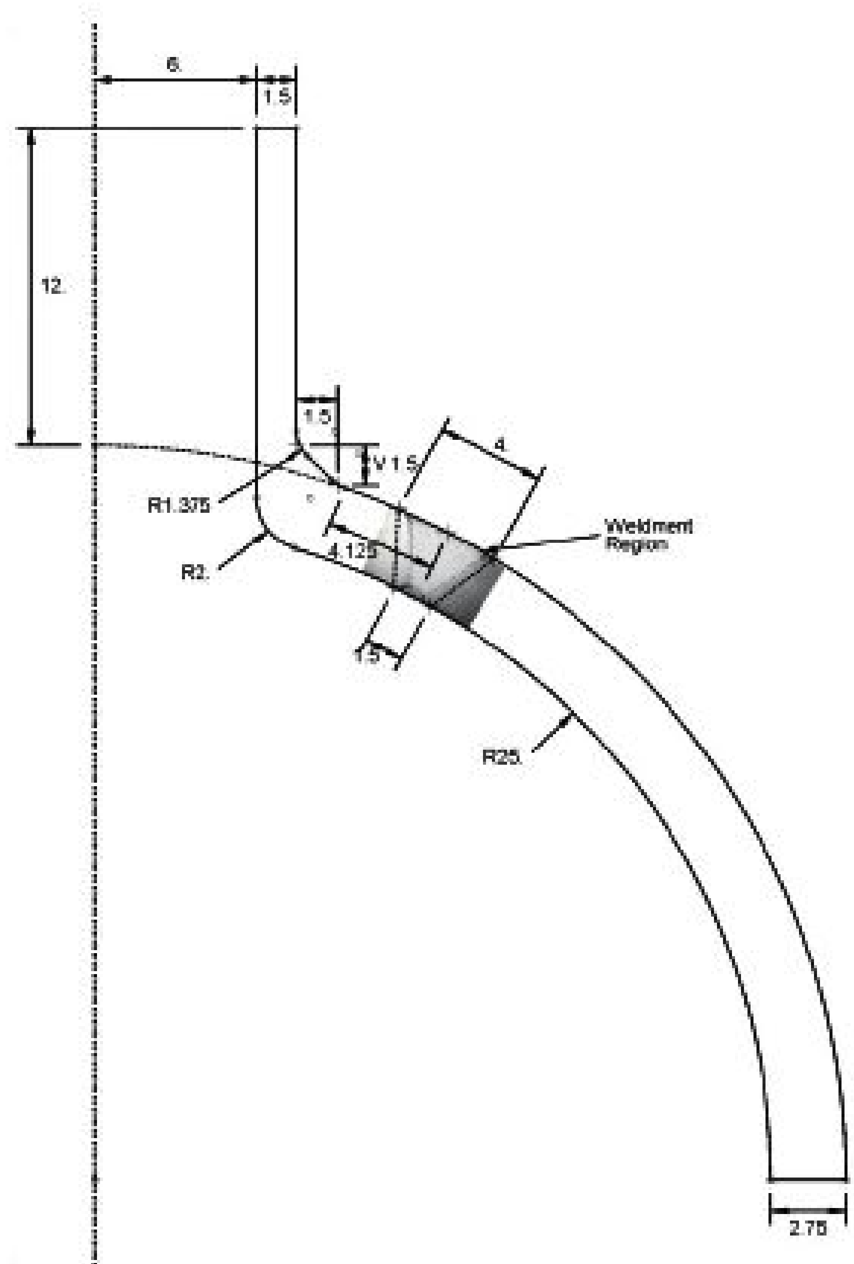


**Figure 3 Representative example problem (inches) (adapted from Sham et al., 2015)**

Analyses used the EPP method through the composite cycles. For Code Case N-862 creep-fatigue evaluations, stress analyses are conducted where the pseudo-yield stress is adjusted based on the allowable time duration for the current trial solution. The analysis continues until the creep-fatigue limits are satisfied and the allowable time duration for the load case is determined. As in the Code Case procedure, shakedown is evaluated at every location in the model by checking that the maximum change in plastic strain is zero (i.e., the solution becomes elastic for each cycle). This exercise illustrated that the Code Case for creep fatigue could be used for this design and evaluated the creep-fatigue damage within the HBB-T-1420-2 creep-fatigue damage interaction curve for 316H SS. For this particular set of design conditions, the Code Case did not pass and would require further design changes.

#### *4.3.8.5 Pipe and Nozzle Example Case*

Analyses on tube geometries with radius-to-thickness ratios on the order of four included those for plane pipe analyses and one for two pipes connected with a tapered reducer section. The analyses used the current Subsection HB, Subpart B, procedures (HBB-T-1413) and the Code Case N-862 shakedown analysis procedures. The load case considered combined pressure and thermal gradient loading and defined composite load cycles. Sham et al. (2015) provided details of the analysis procedures for both the HBB-T-1430 and Code Case N-862 procedures. Subsection, HB, Subpart B, results indicated shakedown in 1,430 hours, while Code Case N-862 predicted shakedown in 10,000 hours.

#### *4.3.8.6 Strain Controlled Creep-Fatigue Test Specimen*

Code Case N-862 predicted shakedown on a standard strain-controlled, creep-fatigue test specimen in this example. These results were compared to closed-form solutions in a complete inelastic analysis using a visco-plastic material. This example validated the bounding characteristics of Code Case N-862 when compared to the full inelastic results. The simplified model test (SMT) specimens described below are cycled to failure and data generated to evaluate the applicability of Code Case N-862.

#### *4.3.8.7 Simplified Model Test*

The SMT represents two bars of different diameters connected in series that are tested in a uniaxial test machine (see Figure 4). The SMT methodology is currently being developed as a possible alternative to the creep-fatigue damage envelope procedure of Figure HBB-T-1420-2. The SMT specimen results in varying degrees of elastic followup, depending on the bar diameter differences. The SMT specimen must be sized to provide stress-strain hysteresis loops under cyclic loading, which envelop the response in service. The results for this series of comparisons showed that Code Case N-862 could not predict shakedown for any of these test cases. Therefore, they showed that results from the EPP analysis are conservative but perhaps too conservative for practical use in some cases.

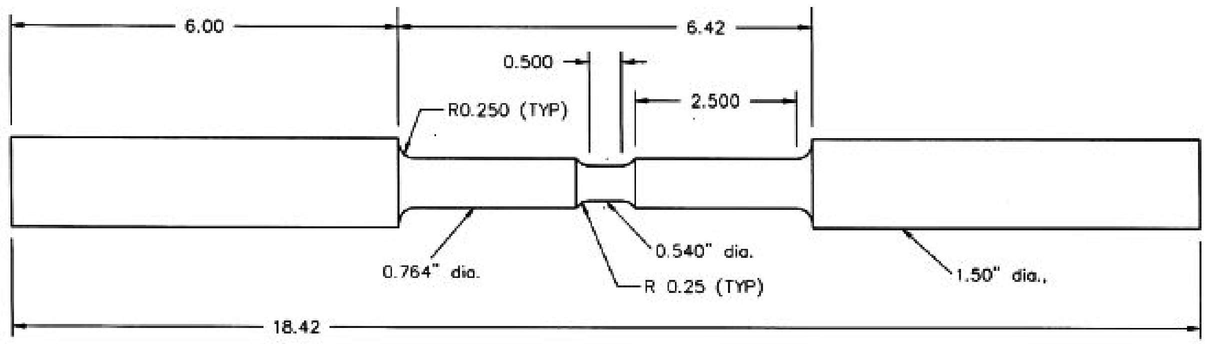


**Figure 4 Representative SMT test specimen (inches) (adapted from Sham et al., 2015)**

*4.3.8.8 Other Validation Cases*

Carter et al. (2011) and Messner and Sham (2018), with other references they cite, show the results of other validation example cases. These compare Code Case N-862 EPP results to (1) experimental test results, (2) current BPV-III-5, Subsection HB, Subpart B, predictions, (3) analytical solutions for simple geometries using visco-plastic material laws where closed form solutions are available, and (4) finite element solutions using visco-plastic material laws. For all cases, the EPP results for shakedown are conservative. In some cases, the use of the Code Case may be too conservative and not useful for design.

# 5 SUMMARY

This review recommends endorsing Code Cases N-861 and N-862, contingent upon several items discussed in Sections 3 and 4. Use of these Code Cases is expected to lead to conservative results. Bounding theorems, mainly developed in the 1960s and 1970s, before the widespread use of computational modeling, form the basis for the conservative nature of these Code Cases. They represent an alternative to satisfying the strain limits (Code Case N-861) and creep-fatigue damage (Code Case N-862) using EPP finite element modeling, where the perfectly plastic "yield" stress is defined to account for creep damage. Validation tests, with both full inelastic computational modeling and new test data, were used to validate the conservative nature of these Code Cases. However, Code Case N-862 may be overly conservative in practice.

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