Design rules for 316H nuclear components clad with nickel or tungsten

Applied Materials Division

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March 2021

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ABSTRACT

The existing Class A metallic materials qualified in the ASME Boiler & Pressure Vessel Code Section III, Division 5 rules for high temperature nuclear reactors are not ideally suited for long term molten salt corrosion resistance in high temperature molten salt reactors. Potentially, corrosion or corrosion driven environmentally assisted cracking could limit the design life of structural components in molten salt reactors. A solution to this limitation is the use of clad components – overlay the Class A material with a thin layer of some non-qualified, corrosion-resistant material. However, this necessitates the development of design methods for clad components that do not require long-term testing of clad materials in order to support the near-term deployment of molten salt reactors. This report develops such a methodology along with a complete set of rules presented in a format compatible with an ASME nuclear Code Case. These design rules are for 316H Class A components clad with either nickel or tungsten. The report also discusses the development of a set of *general* criteria for selecting clad materials beyond the specific 316H/tungsten and 316H/nickel systems and *general* acceptance tests for checking the mechanical integrity of the clad/base metal interface. Finally, the report includes a set of fully-documented sample problems detailing the application of the rules to high temperature clad components.

TABLE OF CONTENTS

Abstract	i
Table of Contents	iii
List of Figures	v
List of Tables	ix
1 Introduction	1
2 Proposed Design Rules	3
3 Commentary on the Draft Design Rules	23
3.1 Existing rules in ASME Section III, Division 5	23
3.2 Commentary on design method development.....	23
3.3 Commentary on properties of nickel.....	42
3.4 Tungsten properties.....	56
3.5 Commentary on general requirements	56
4 Sample Problems	58
4.1 Sample problem 1: A 316H heat exchanger clad with nickel	58
4.2 Sample problem 2: A 316H flat head vessel clad with nickel	65
4.3 Sample problem 3: A 316H flat head vessel clad with tungsten.....	72
5 Clad Selection Criteria.....	81
5.1 Development of the criteria	81
5.2 Assessment of the criteria	84
5.3 Proposed clad selection criteria for Class A components	93
6 Acceptance Test for Checking Clad/Base Metal Interface Integrity	95
6.1 Approach and assumptions	95
6.2 Development of the acceptance test procedure.....	96
6.3 Proposed step-by-step procedure of the acceptance test.....	103
6.4 Determination of interfacial shear stress from finite element calculation	105
7 Tungsten Test Results	107
7.1 Material, specimens, and evaluation method.....	107
7.2 Mechanical testing results on pure tungsten	107
7.3 Summary of mechanical testing on pure tungsten	116
8 Conclusions.....	117
Acknowledgements.....	119
Bibliography	121

LIST OF FIGURES

Figure 3.1: (a) Geometry of the bent heat exchanger tube (figure shows half of the tube) [6], (b) thermal loading profile, (c) symmetric FE model of the tube. Simulation results are analyzed at location-1 and location-2 indicated in c.	26
Figure 3.2: Steady cyclic equivalent strain range in base and clad materials plotted over thickness in (a) location-1 and (b) location-2. Results are from a full inelastic simulation of 316H cladmed with nickel and a compliant clad analysis [6].	27
Figure 3.3: Steady cyclic creep damage in base material plotted over thickness in (a) location-1 and (b) location-2. Results are from a full inelastic simulation of 316H cladmed with nickel and a compliant clad analysis [6].	28
Figure 3.4: Steady cyclic equivalent strain range in base and clad materials plotted over thickness in (a) location-1 and (b) location-2. Results are from a full inelastic simulation of 316H cladmed with molybdenum and an elastic clad analysis [6].	28
Figure 3.5: Steady cyclic creep damage in base material plotted over thickness in (a) location-1 and (b) location-2. Results are from a full inelastic simulation of 316H cladmed with molybdenum and an elastic clad analysis [6].	29
Figure 3.6: (a) Typical stress relaxation in a typical soft clad material. (b) Schematic showing quick saturation of the time-dependent fatigue (EPP cyclic creep) curves due to fast stress relaxation in soft clad material.	31
Figure 3.7: (a) Geometry of the heat exchanger bent tube (figure shows half of the tube); (b) finite element models of the bent tube without and with clad material; (c) applied thermal and pressure loading profiles.	33
Figure 3.8: Equivalent strain range in the 316H base material of the bent tube (a) without clad and (b) with nickel clad, computed using EPP cyclic creep analysis.	34
Figure 3.9: Equivalent strain range in the nickel clad material of the cladmed bent tube.	34
Figure 3.10: A two bar model comprising a creeping bar, representing the base material behavior and an elastic bar, representing the hard clad material behavior.	37
Figure 3.11: Example results showing plastic shakedown of the bent tubes.	38
Figure 3.12: Example results showing elastic shakedown of the bent tubes.	39
Figure 3.13: Maximum equivalent strain range in the (a) 316H base material and (b) TZM clad material of the cladmed bent tube.	40
Figure 3.14: Nickel nominal fatigue curves through fitting the elastic and plastic (inelastic) parts separately.	45
Figure 3.15: Comparison between experimental data and nominal fatigue curves constructed based on based on option-a (solid lines) and option-b (dashed lines). The ‘all temperatures’ curve is based on option-b using combined test data.	46
Figure 3.16: Final fatigue design curve, i.e. EPP cyclic creep curve with time=0, compared with experimental data.	47
Figure 3.17: Curve fit to the experimental fatigue and creep-fatigue data of nickel at 650°C using the modified Coffin-shift model.	48
Figure 3.18: Schematic demonstrating two different approaches for extrapolating high strain range, short hold time experimental data to low strain range, long hold time [13].	50
Figure 3.19: Nominal EPP cyclic creep curves based on different extrapolation approaches compared with creep-fatigue test data for nickel at 650°C with different hold times.	52
Figure 3.20: Nominal EPP cyclic creep curves based on different extrapolation approaches compared with creep-fatigue test data for Grade 91 at different temperatures and hold times.	53
Figure 3.21: Nominal EPP cyclic creep curves based on different extrapolation approaches compared with creep-fatigue test data for 316H at different temperatures and hold times.	54

Figure 3.22: Nominal EPP cyclic creep curves based on different extrapolation approaches compared with creep-fatigue test data for Alloy 617 at different temperatures and hold times.	55
Figure 3.23: Final nominal EPP cyclic creep curves for nickel at 650°C with different hold times.	56
Figure 4.1: (Sample problem 1) An axisymmetric representation of a single tube in a tube-shell heat exchanger of a molten salt reactor. The base material is 316H and the clad material is nickel. Loading profile shows the temperature and pressure of the primary salt flowing inside tube and the secondary salt flowing in the shell under Service Level-A and Service Level-B loadings.	59
Figure 4.2: (Sample problem 1) Overall tube temperature distributions and through thickness temperature at maximum wall averaged temperature location during holds under Service Level-A and Service Level-B loadings.	60
Figure 4.3: (Sample problem 1) Composite cycle.	60
Figure 4.4: (Sample problem 1) Through thickness temperature and steady cyclic equivalent strain ranges at the maximum wall-averaged temperature location under Level-A and combined Level-A and Level-B Service loading conditions. Results are from EPP cyclic creep analysis of the clad tube with 5% nickel cladding on both inner and outer face of 316H base material.	64
Figure 4.5: (Sample problem 2) An axisymmetric representation of a 316H flat head vessel in a molten salt reactor. The vessel is clad with nickel on the inner surface. The plot shows the temperature profile of the salt inside the vessel. Hot air with controlled temperature flows on the outer surface of the vessel.	66
Figure 4.6: (Sample problem 2) Over all temperature distribution and through thickness temperature at different locations of the vessel 10% nickel (Case-2) during hold under Service Level-A loading.	67
Figure 4.7: (Sample problem 2) Overall temperature distribution and through thickness temperature at different locations of the vessel clad with 10% nickel (Case-2) during hold under Service Level-B loading.	68
Figure 4.8: (Sample problem 2) Composite cycle.	68
Figure 4.9: (Sample problem 2) Through thickness temperature and steady cyclic equivalent strain ranges at the knuckle under Level-A and combined Level-A and Level-B Service loading conditions. Results are from EPP cyclic creep analysis of the clad tube with 10% nickel cladding on the inner face of 316H base material.	71
Figure 4.10: (Sample problem 3) An axisymmetric representation of a 316H flat head vessel in a molten salt reactor. The vessel is clad with tungsten on the inner surface. The plot shows the temperature profile of the salt inside the vessel. Hot air with controlled temperature flows on the outer surface of the vessel.	72
Figure 4.11: (Sample problem 3) Overall temperature distribution and through thickness temperature at different locations of the vessel clad with 10% tungsten during hold under Service Level-A loading.	73
Figure 4.12: (Sample problem 3) Overall temperature distribution and through thickness temperature at different locations of the vessel clad with 10% tungsten during hold under Service Level-B loading.	74
Figure 4.13: (Sample problem 3) Composite cycle.	75
Figure 4.14: (Sample problem 3) Results from EPP analyses of the vessel are compared for different trial times. Trial times are used to determine the pseudoyield stress for the elastic-perfectly plastic model of the base material.	78
Figure 4.15: (Sample problem 3) Through thickness temperature and steady cyclic equivalent strain ranges at the knuckle under Level-A and combined Level-A and Level-B Service Loadings. Results are from the EPP elastic shakedown analysis based on a trial time equal to 110,000 hr.	79
Figure 5.1: Geometry of a flat head vessel and load definition.	85

Figure 5.2: Through thickness von Mises stress (after cycle heat up) at the knuckle (shown with an arrow on the left figures) of the 316H flat head vessel. The plots compare results from full inelastic analysis and elastic clad analysis for 10% and 1% clad thickness. The clad material is the “hypothetical” hard clad material.	86
Figure 5.3: Through thickness equivalent strain range at the knuckle (shown with an arrow on the left figures) of the 316H flat head vessel. The plots compare results from full inelastic analysis and elastic clad analysis for 10% and 1% clad thickness. The clad material is the “hypothetical” hard clad material.	87
Figure 5.4: Through thickness equivalent strain range at the knuckle (shown with an arrow on the left figures) of the 316H flat head vessel. The plots compare results from full inelastic analysis and elastic clad analysis for 10% and 1% clad thickness. The clad material is tungsten.	88
Figure 5.5: Creep tests of nickel at 550°C under 77 MPa stress.	90
Figure 5.6: Through thickness equivalent strain range at the shell and the knuckle of the 316H flat head vessel. The plots compare results from full inelastic analysis and compliant clad analysis for 10% and 1% clad thickness. The clad material is the “hypothetical” soft clad.	91
Figure 5.7: Through thickness equivalent strain range at the shell (top) and the knuckle (bottom) of the 316H flat head vessel. The plots compare results from full inelastic analysis and compliant clad analysis for 10% and 1% clad thickness. The clad material is nickel.	92
Figure 6.1: Geometry and finite element model of the clad button and the thermal loading profile for structural finite element calculation.	97
Figure 6.2: Contour plot of shear strain range at 50th cycle for different temperature range – (a) 30°C, (b) 60°C, (c) 90°C. Both the initial heating rate and heating/cooling rate during thermal cycling are 10°C/min.	98
Figure 6.3: Comparison of the maximum interfacial shear strain range between the analytical and finite element solutions for different clad percentages and different E ratios between the clad and base materials. Material properties are $E_b = 140$ GPa, $\nu_b = \nu_c = 0.27$, $\alpha_b = 18.6 \times 10^{-6}$, and $\alpha_c = 4 \times \alpha_b$ and $\Delta T = 100^\circ\text{C}$	100
Figure 6.4: Comparison of the maximum interfacial shear strain range between the analytical and finite element solutions for different clad percentages and different α ratios between the clad and base material. Material properties are $E_b = E_c = 140$ GPa, $\nu_b = \nu_c = 0.27$, and $\alpha_b = 18.6 \times 10^{-6}$ and $\Delta T = 100^\circ\text{C}$	101
Figure 6.5: Comparison of the maximum interfacial shear strain range between the analytical and finite element solutions for different clad percentages and different ν ratios between the clad and base materials. Material properties are $E_b = E_c = 140$ GPa, $\nu_b = 0.27$, $\alpha_b = 18.6 \times 10^{-6}$, and $\alpha_c = 0.25 \times \alpha_b$ and $\Delta T = 100^\circ\text{C}$	102
Figure 6.6: Geometry and thermal cyclic loading profile for the button test specimens.	105
Figure 7.1: Specimen geometry for fatigue evaluation. Units are in inches.	108
Figure 7.2: Room temperature tensile stress-strain curve of the pure tungsten.	109
Figure 7.3: Tensile stress-strain curves of pure tungsten at elevated temperatures.	109
Figure 7.4: Photographs of the tensile test specimens.	110
Figure 7.5: Photographs of the Charpy impact specimens.	111
Figure 7.6: Ductile to Brittle Transition of the pure tungsten.	112
Figure 7.7: Hysteresis loops of representative fatigue cycles at 0.6% strain range and 550°C.	112
Figure 7.8: Maximum and minimum stresses of fatigue test at 0.6% strain range and 550°C.	113
Figure 7.9: Comparison of the stress-strain responses of load-controlled fatigue, strain-controlled fatigue and the tensile test at 550°C.	113
Figure 7.10: Hysteresis loops of the load-controlled fatigue at 550°C.	114
Figure 7.11: Maximum and minimum stresses of fatigue test at 1% strain range and 550°C.	114
Figure 7.12: Maximum and minimum stresses of fatigue test at 1% strain range and 704°C.	115

Figure 7.13: Hysteresis loops of the strain-controlled fatigue at 0.3% strain range and 760°C.	115
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LIST OF TABLES

Table 3.1: Material properties of nickel and molybdenum used in full inelastic analysis of problem described in Figure 3.1.	27
Table 3.2: Percent of initial stress in TZM clad (thickness: 1% of the base material thickness) at the end of the design life of 316H base material.	37
Table 3.3: Percent of initial stress in TZM clad (thickness: 10% of the base material thickness) at the end of the design life of 316H base material.	37
Table 3.4: Effect of hard material cladding on ratcheting and creep-fatigue design lives of the base metal in the bent tubes.	40
Table 3.5: Summary of the design method for 316H Class A components clad with either nickel and tungsten.	41
Table 3.6: Summary of fatigue test results used in constructing EPP cyclic creep curves for nickel. * indicates run out tests.	43
Table 3.7: Summary of creep-fatigue test results used in constructing EPP cyclic creep curves for nickel.	44
Table 3.8: Parameters for the modified Coffin-shift model for nickel at 650°C.	49
Table 4.1: (Sample problem 1) Base material primary load checks. P_m is the maximum general primary membrane stress intensity, $PL + Pb$ is the maximum combined primary membrane plus bending stress intensity, K is the section factor, and $K_t = K + 12$. All limits are checked at maximum wall-averaged temperature location. Definition of all the allowable stresses can be found in HBB-3216.	61
Table 4.2: (Sample problem 1) Base material ratcheting limit check. S_y is the average of the yield strength values at the maximum and minimum wall averaged temperatures during the cycle and S_t is at the highest wall averaged temperature and a time value of 104 hr.	62
Table 4.3: (Sample problem 1) Base material creep-fatigue evaluation.	63
Table 4.4: (Sample problem 1) Clad material creep-fatigue evaluation.	65
Table 4.5: (Sample problem 2) Base material primary load checks. P_m is the maximum general primary membrane stress intensity, $PL + Pb$ is the maximum combined primary membrane plus bending stress intensity, K is the section factor, and $K_t = K + 12$. All limits are checked at the knuckle. Definition of all the allowable stresses can be found in HBB-3216.	69
Table 4.6: (Sample problem 2) Base material ratcheting limit check. S_y is the average of the yield strength values at the maximum and minimum wall averaged temperatures during the cycle and S_t is at the highest wall averaged temperature during the cycle and a time value of 104 hr.	69
Table 4.7: (Sample problem 2) Base material creep-fatigue evaluation.	70
Table 4.8: (Sample problem 2) Clad material creep-fatigue evaluation.	71
Table 4.9: (Sample problem 3) Properties of tungsten used in thermal and structural analysis.	72
Table 4.10: (Sample problem 3) Base material primary load checks. P_m is the maximum general primary membrane stress intensity, $PL + Pb$ is the maximum combined primary membrane plus bending stress intensity, K is the section factor, and $K_t = K + 12$. All limits are checked at the knuckle. Definition of all the allowable stresses can be found in HBB-3216.	75
Table 4.11: (Sample problem 3) Base material ratcheting limit check. S_y is the average of the yield strength values at the maximum and minimum wall averaged temperatures during the cycle and S_t is at the highest wall averaged temperature during the cycle and a time value of 104 hr.	76
Table 4.12: (Sample problem 3) Base material creep-fatigue damage evaluation.	79
Table 5.1: Properties of the “hypothetical” hard clad material.	86

Table 5.2: Properties of tungsten.	88
Table 5.3: Properties of the “hypothetical” soft clad material.	89
Table 5.4: Properties of nickel and 316H base metal.....	89
Table 6.1: Simulated maximum interfacial shear strain range in the clad button during the thermal cycling for different loading conditions.	98
Table 6.2: Ratio of the maximum interfacial shear stress range between the analytical and finite element solutions, f as a function of E and t ratios between the clad and base materials.....	102
Table 6.3: Determination of f in Equation 6.3.	104
Table 7.1: Chemical compositions of the pure tungsten rod (wt.%).	107
Table 7.2: Tensile properties of the pure tungsten	110
Table 7.3: Charpy impact test results of the pure tungsten	110

1 Introduction

The Kairos Power's KP-FHR design is a novel advanced reactor that leverages accident-resistant solid fuel and a low-pressure, high boiling point fluoride salt coolant. These design features result in uniquely large fuel temperature margins for the KP-FHR and help enable the use of currently approved ASME Section III, Division 5 structural materials. To reduce cost and simplify construction and supply chain compared to more unconventional materials, Type 316 stainless steel has been identified as a construction material for the KP-FHR primary coolant boundary components.

While Type 316 stainless steel and its weld filler metal 16-8-2 provide adequate high temperature strength for the operating conditions of KP-FHR, the alloy is known to exhibit dealloying type corrosion in fluoride salts, whereby chromium is lost from the alloy into the salt. Depending on the environmental conditions and component function, this corrosion could place restrictions on the design lifetime of primary coolant boundary components in order to retain the required structural margins [41]. One solution is to use a corrosion resistant cladding [2][3] for Type 316 stainless steel components to lessen, or possibly eliminate, such restrictions.

The current ASME Section III Division 5 Code Rules [1] for clad structural components in elevated temperature service are quite limited. Division 5 Paragraph HBB-2121 allows non-Code qualified materials to be used for cladding if the clad thickness is 10% or less of the thickness of the base material. Division 5 Paragraph HBB-3227.8 specifies that no structural strength shall be attributed to the cladding in satisfying the primary load stress limits. It also requires that the cladding shall be considered in design evaluation related to limits on deformation-controlled quantities, i.e., strain accumulations due to ratcheting and creep-fatigue damage but does not provide guidance or requirements for that assessment.

The 10% clad thickness rule would allow the designers to select corrosion resistant cladding materials that are non-Code qualified. However, the lack of design rules presents challenges in the design and subsequent NRC approval of these clad components. Kairos Power and the Argonne National Laboratory collaborated through the DOE GAIN Voucher Program to develop design rules and associated materials data for the design of clad components that are constructed of Type 316 stainless steel and clad with nickel and tungsten.

Use of clad components is a well-established practice in petrochemical industry. Clad vessels are also used in low temperature Light Water Reactors (LWRs) – typically stainless steel cladding on low alloy steel. However, there is no set of design rules currently suitable for designing clad components for high temperature nuclear service. This work attempts to address this deficiency by developing a new design method along with a complete set of design rules for 316H Class A components clad with either nickel or tungsten. Chapter 2 provides the new design methodology in a format compatible with an ASME nuclear Code Case.

There are two reasons for choosing nickel and tungsten as clad materials for use with 316H components for high temperature molten salt reactor structures. The first reason is based on their corrosion performance in fluoride salts. Young and Sham [2] assessed several metals and alloys for use as corrosion resistant clad materials in structural components for high temperature molten

salt reactors. Their assessment recommended five materials that provide corrosion resistance in molten salts. Nickel and tungsten are found to be in their list of recommended alloys.

The second reason for choosing nickel and tungsten is related to the design method developed in this work. As discussed above the goal of the new design method for clad components is to avoid long-term test data for the clad materials in order to support the near-term deployment of high temperature molten salt reactors. Using only short-term properties for the clad material, the proposed design method relies on one of two bounding approximations for the clad material response – treating the clad material either as linear elastic or as perfectly compliant. To treat a clad material as linear elastic it must have higher yield stress and creep much slower than the base material [7][17]. For the perfectly compliant clad approximation the clad must creep much faster than the base material [7][17]. The former type of clad materials can be called hard clad materials while the latter can be called soft clad materials. As verified in Chapter 5, nickel falls under the soft clad material category while tungsten falls under the hard clad material category for 316H base material. Details of the bounding approximations for soft and hard clad materials are discussed in Chapter 3. Chapter 3 is also a commentary describing the rationale behind the design rules along with the development of material design data for nickel. The draft rules do not include material design data for tungsten and therefore no commentary is provided. Although test data were collected for tungsten as part of this project, the test results, as presented in Chapter 7, indicate the tungsten tested as part of this project do not qualify as a hard clad material for 316H base material. This result contradicts a preliminary assessment using literature data and may suggest that process conditions play a significant role in determining tungsten and tungsten-alloy material properties and, ultimately, whether the material meets the hard clad criteria described in this report. If future testing on tungsten demonstrates that some processing conditions meet the hard clad criteria then the draft rules could be altered to include qualified material properties.

Chapter 4 provides an extensive set of worked sample problems detailing the application of the rules to clad components for high temperature nuclear service.

Chapter 5 develops a set of *general* criteria for selecting soft and hard clad materials for Class A base material for the implementation of the developed design method. These criteria could be used to extend the draft rules, covering only nickel and tungsten clads, to additional materials. The chapter also assessed nickel and tungsten as clad materials for 316H base material using the developed criteria.

The design rules provided in Chapter 2 assumes that the interface between the clad and base materials remains fully bonded during the service life. In practice the clad/base interface may fail before the end of the design life of the component. Therefore, Chapter 6 develops a *general* acceptance test for checking the mechanical integrity of the base/clad metal interface. Chapter 7 summarizes the tungsten testing effort at Oak Ridge National Laboratory. Finally, Chapter 8 summarizes the work presented in this report.

2 Proposed Design Rules

This chapter provides a new design method for Type 316 stainless steel Class A components clad with either nickel or tungsten in the format of a nuclear Code Case. Note 316H is referred as Type 316 stainless steel in the design rules following the convention used in ASME Code. Tables and figures are deliberately numbered as internal to the proposed design method and not included in the global table and figure numbering scheme nor in the list of tables and figures for this report.

Nickel or tungsten may be used as cladding to mitigate molten salt corrosion of Section III, Division 5, Subsection HB, Subpart B, Type 316 stainless steel Class A components in elevated temperature service, provided that the following requirements are met:

- (a) The modifications and additions to the rules provided in Subsection HB, Subpart B defined in these rules shall be met.
- (b) All other applicable requirements of Section III, Division 5, Subsection HB, Subpart B shall be met.
- (c) This Case number shall be listed on the Data Report Form for the component.

1. INTRODUCTION

Molten Salt Reactors operate using fuel and/or coolant salts which can result in corrosion. The existing Section III, Division 5 Class A materials are not optimal for long-term molten salt corrosion resistance. An alternative is to use clad components. However, both practical design considerations and the available salt chemistries tend to limit the types of clad materials. These rules cover two types of clad materials to use with Type 316 stainless steel Class A components in elevated temperature service to mitigate the adverse impact of molten salt corrosion: tungsten, a hard elastic clad, and nickel, a soft clad with creep strength insufficient for high temperature load carrying pressure boundary applications. The strength characteristics of these two clad materials present unique design requirements to take advantage of their differences with respect to Type 316 stainless steel.

2. GENERAL REQUIREMENTS

2.1 Material

- 2.1.1 The requirements of these rules apply to Section III, Division 5, Type 316 stainless steel, Class A construction for elevated temperature service when clad with either nickel or tungsten.
- 2.1.2 In these rules “component” refers to the entire Type 316 stainless steel Class A component, including the nickel or tungsten clad. The term “base” refers to the Type 316 stainless steel base material and its associated weldments in the “component” under evaluation.
- 2.1.3 Nickel and tungsten clad materials in these rules are not required to conform to the requirements of one of the specifications for material given in Section II, Part D, Subpart 1, Tables 2A, 2B, and 4, as provided in HBB-2121 (c). However, nickel clad material shall conform to ASTM B160 specification and tungsten clad material shall conform to ASTM B760 specification. Material properties of nickel and tungsten provided in Appendix B and Appendix C, respectively, may be used for the implementation of these rules.

2.1.4 Tungsten shall meet the requirements in Section III, Division 1, NB-2331 to establish a nil-ductility transition temperature that is less than the minimum clad temperatures for any Service Level A, B, C, D or Test Loadings.

2.2 Clad Thickness

2.2.1 The maximum clad thickness shall not exceed 10% of the Class A component thickness.

2.3 Thermal Analysis

2.3.1 The clad shall always be included in the thermal analysis for determining the temperature distribution in the component.

3. DESIGN

The rules of 3.1 through 3.5 below apply to the evaluation of components constructed under these rules. The component must meet the requirements for the Load Controlled Stresses in Section III, Division 5, HBB-3220 and the Deformation-Controlled Quantities in Section III, Division 5, HBB-3251. A summary of design evaluation is provided in Table 1. The following rules specify how the component shall be considered in these design analyses.

3.1 Load-controlled Stresses

Clad shall not be included in the design analysis in satisfying the following requirements for the component.

- (a) Load- controlled stress limits defined in Section III, Division 5, HBB-3200 and -3300, -3400, -3500 or -3600. Note that HBB-3200 above includes Service Level D
- (b) Bearing Loads defined in Section III, Division 5, HBB-3227.1.

3.2 Strain Limits

3.2.1 Strain limits design of the base

The base must meet the strain and deformation limits described in HBB-3252 and Nonmandatory Appendix HBB-T. The following design guidance applies to evaluating the base against the strain and deformation limits:

- (a) The clad shall not be included in the design analysis.
- (b) The following methods may be used to satisfy the strain and deformation limits criteria:
 - (i) Design by elastic analysis in Section III, Division 5, HBB-T-1320 or HBB-T-1330.
 - (ii) Design by inelastic analysis in Section III, Division 5, HBB-T-1310.
 - (iii) Design by elastic-perfectly plastic (EPP) analysis as shown in Appendix-A of these rules.

3.2.2 Strain limits design of the clad

The clad is not required to satisfy the strain and deformation limits.

3.3 Creep-fatigue Evaluation of Components with Nickel Clad

3.3.1 Creep-fatigue design of the base

The base must meet the creep-fatigue limits described in HBB-3252 and Nonmandatory Appendix HBB-T. The following design guidance applies to evaluating the base against the creep-fatigue limits:

- (a) Clad should not be included in the design analysis.
- (b) Use any of the methods in (i), (ii), and (iii) below.
 - (i) Design by elastic analysis in Section III, Division 5, HBB-T-1430.
 - (ii) Design by inelastic analysis in Section III, Division 5, HBB-T-1420.
 - (iii) Design by elastic-perfectly plastic (EPP) analysis as shown in Appendix A of these rules.

3.3.2 Creep-fatigue design of a nickel clad

The designer shall demonstrate the adequacy of a nickel clad against creep-fatigue damage for the full component design life. The clad shall be included in the design analysis. The following design criteria apply to the creep-fatigue design of the nickel clad:

- (a) Use either of the methods in (i) or (ii) below to determine the cyclic strain history in the clad.
 - (i) Design by inelastic analysis method
Model the clad as elastic-perfectly plastic with a near zero yield stress and the base as inelastic.
 - (ii) Design by EPP cyclic creep analysis method
 - a. Develop a composite cycle for the analysis per Appendix D.
 - b. Model the clad as elastic-perfectly plastic with a near zero yield stress and the base as elastic-perfectly plastic with a pseudo-yield stress determined from the isochronous stress-strain curves for a 0.2% offset in strain from the elastic slope at a given temperature and for a time equal to the composite cycle period.
 - c. Run multiple repetitions of the cyclic loading defined in (a) until the strain range within a cycle becomes constant for all points in the component. Follow the instructions in Appendix D for establishing the steady cyclic strain range throughout the component.
- (b) Determine a representative maximum equivalent strain range for each point in the clad for each cycle type in accordance with Section III, Division 5, HBB-T-1413, or HBB-T-1414 when applicable, with $v^* = 0.5$.
- (c) Determine the creep-fatigue damage fraction for each point in the clad for each cycle type as the ratio between number of applied repetitions and number of allowed cycles determined from the EPP cyclic creep design curves of the clad, provided in Appendix B, corresponding to the cycle period and the maximum temperature during the cycle.
- (d) The acceptance criteria is $\sum D \leq 1.0$, where D is the creep-fatigue damage fraction for each cycle type computed in (c). The acceptance criteria must be met at all points in the clad.

3.4 Creep-fatigue Evaluation of Components with Tungsten Clad

3.4.1 Creep-fatigue design of the base

The base must meet the creep-fatigue limits described in HBB-3252 and Nonmandatory Appendix HBB-T. The clad shall be included in the design analysis. The following design guidance applies to evaluating the base against the creep-fatigue limits:

- (a) Model the clad as linear elastic with material properties given in Appendix C.
- (b) Use any of the methods in (i) and (ii) below to evaluate creep-fatigue in the base.
 - (i) Design by inelastic analysis per Section III, Division 5, HBB-T-1420.
 - (ii) Design by elastic-perfectly plastic (EPP) analysis as described in Appendix A of this Code Case.

3.4.2 Creep-fatigue design of a tungsten clad

The design shall demonstrate the adequacy of the clad against fatigue damage for the full component design life. The following criteria apply to this fatigue evaluation:

- (a) The analysis results from the creep-fatigue evaluation of the base in either 3.4.1(b)(i) or 3.4.1(b)(ii) shall be used for fatigue evaluation of the clad. Determine the cyclic strain history in the clad from these analysis results.
- (b) Determine a representative maximum equivalent strain range for each point in the clad for each cycle type in accordance with Section III, Division 5, HBB-T-1413, or HBB-T-1414 when applicable, with $\nu^* = 0.3$.
- (c) Determine the fatigue damage fraction for each point in the clad for each cycle type from the ratio between number of applied repetitions and number of allowed cycles determined from the fatigue design curves of the clad, provided in Appendix C, corresponding to the maximum temperature during the cycle.
- (d) The acceptance criteria is $\sum D \leq 1.0$, where D is the fatigue damage fraction for each cycle type computed in (c). The acceptance criteria must be met at all points in the clad.

3.5 Buckling Criteria

3.5.1 Design of the base

The base must meet the buckling and instability limits described in HBB-3252 and Nonmandatory Appendix HBB-T. The clad shall not be included in design analysis for assessing the component against the buckling limits.

3.5.2 Design of the clad

The clad is not required to satisfy the buckling and instability limits.

	Clad material	Type of Design Check			
		Primary load	Strain limits	Creep-fatigue	Buckling
Design check for the base	nickel	<ul style="list-style-type: none"> Ignore clad in design analysis Use design by elastic analysis Rules are provided in 3.1 	<ul style="list-style-type: none"> Ignore clad in design analysis Use design by elastic analysis, inelastic analysis or EPP for the base Rules are provided in 3.2.1 	<ul style="list-style-type: none"> Ignore clad in design analysis Use design by elastic analysis, inelastic analysis or EPP for the base Rules are in 3.3.1 	<ul style="list-style-type: none"> Ignore clad in design analysis Use design by elastic or inelastic analysis Rules are provided in 3.5
	tungsten			<ul style="list-style-type: none"> Clad included in design analyses and modeled as linear elastic Use design by inelastic analysis or EPP for the base Rules are provided in 3.4.1 	
Design check for the clad	nickel	No check is required	No check is required	<ul style="list-style-type: none"> Clad included in design analysis and modeled as elastic perfectly plastic with near zero yield stress Use inelastic analysis or EPP cyclic creep analysis for the base Rules are provided in 3.3.2 	No check is required
	tungsten			<ul style="list-style-type: none"> Clad included in design analyses and modeled as linear elastic Use inelastic analysis or EPP for the base Rules are provided in 3.4.2 	

Table 1: Summary of design evaluations for component with nickel or tungsten clad

Appendix-A Elastic-Perfectly Plastic (EPP) Methods for Evaluation of Strain Limits and Creep-fatigue Damage in the Base

The design rules in Appendix-A apply only the base and not the clad. As mentioned in 2.1.2 of the Code Case, the term “base” refers to the Type 316 stainless steel base material and its associated weldments in the component under evaluation.

A-1 GENERAL REQUIREMENTS

Strain and deformation limits and creep-fatigue damage may be evaluated using Elastic-Perfectly Plastic (EPP) methods for the base of the component conforming to Section III, Division 5, Table HBB-I-14.1(a) and HBB-I-14.1(b) when performed in accordance with this Appendix. Except as identified herein, all requirements of Section III, Division 5, Subsection HB, Subpart B apply to components designed in accordance with this Appendix.

A-1.1 Composite Cycle Definition

For the purpose of performing an elastic-perfectly plastic ratcheting analysis an overall cycle must be defined which includes all relevant features from the individual Level A, B and C Service Loadings identified in the Design Specification. Relevant features include as a minimum the time dependent sequence of thermal, mechanical and pressure loading including starting and ending conditions. Such an overall cycle is defined herein as a composite cycle subject to the following requirements.

- (a) An individual cycle as defined in the Design Specifications cannot be further subdivided into individual cycles to satisfy these requirements.
- (b) Except as described in paragraph (c), below, a single cycle from each Level A, B and C Service Loading cycle type shall be included in the composite cycle for evaluation of strain limits.
- (c) Level C Service Loadings may be combined with the applicable Level A and B Service Loadings to define an additional composite cycle(s) to be evaluated separately from the composite cycle defined in paragraph (b). Multiple composite cycles that include Level C Service Loadings may be defined for separate evaluation. The total number of Level C Service Loading cycles shall not exceed 25.

A-1.2 Numerical Model

Develop a numerical model of the base including all relevant geometry characteristics. The model used for the analysis shall be selected to accurately represent the component geometry, boundary conditions, and applied loads. The model must also be accurate for small details, such as small holes, fillets, corner radii, and other stress risers. The local temperature history shall be determined from a thermal transient analysis based on the thermal boundary of the component, which includes the clad. Requirements for representation of the cladding in the structural analysis are defined for the particular design limit under consideration.

A-1.3 Weldment Characterization

The weld shown in Figure A-1 represents a general full-penetration butt weld in a shell. Other weld configurations are needed for construction of an elevated temperature component in accordance with Section III, Division 5, Subsection HB, Subpart B. Article HBB-4200 refers to

various Section III, Division 1, Article NB-4000 paragraphs for weld configurations and requirements. These Division 1, Subsection NB weld configurations are represented by the shaded region.

Figure A-1. Weld region model boundaries.

Figure A-1 shows a full-penetration butt weld as an example. As shown, w_1 and w_2 , as needed to define the weld region for use of this Case, are approximations consistent with the specified weld configuration and parameters. The specified weld region must include applicable stress concentrations in accordance with the requirements for analysis of geometry of Section III, Division 5, HBB-T-1714.

A-2 STRAIN LIMIT EVALUATION

The design methodology employed for evaluation of strain limits is based on rapid cycle ratcheting analyses using a small strain theory elastic-perfectly plastic material model where the yield stress is adjusted based on a pseudo yield stress selected to bound accumulated inelastic strain. Guidance on ratcheting analysis is provided in Annex A-1. For strain limit evaluation the term “pseudo yield stress” refers to a temperature dependent isochronous stress based on the total time duration of high temperature service and a target inelastic strain, not to exceed the yield strength of the material at temperature and is explicitly defined in *Step 2*.

Perform a ratcheting analysis for each of the composite cyclic histories defined in paragraph A-1.1. Each of these cyclic histories must be shown to be free from ratcheting based on the pseudo yield stress S_{xT} as defined in *Step 2*. In the following steps, inelastic strain for a particular stress, time and temperature is obtained by subtracting the elastic strain from the total strain as given by the isochronous stress strain curve at the same stress, time and temperature. Additional requirements for weldments are shown in A-2.1.

Step 1. Define t_{design} as the total time duration of high temperature service for all Level A, B, and C Service Loadings when the temperature is above the range covered by Tables 2A, 2B, and 4 of Section II, Part D.

Step 2. Select a target inelastic strain, x , where $0 < x < \epsilon_{avg}$ and ϵ_{avg} is equal to 0.01 for base metal or 0.005 for weldments. Define a pseudo yield stress S_{xT} at each location, using the temperature determined from the transient thermal analysis. This pseudo yield stress is equal to the lesser of the quantities defined in (a) and (b) below.

- (a) The yield strength S_y given in Section III, Division 5, Table HBB-I-14.5.
- (b) The stress to cause x inelastic strain in time t_{design} , as determined from the isochronous stress strain curves in Section III, Division 5, Figure HBB-T-1800.

Step 3. Perform a cyclic elastic-perfectly plastic analysis for each composite cycle defined in paragraph 1.1 above with temperature-dependent pseudo yield stress S_{xT} . If ratcheting does not occur, obtain the plastic strain distribution throughout the component. The plastic strain, ε_p , is evaluated according to

$$\varepsilon_p = \sqrt{\frac{2}{3} \left[(\varepsilon_x^p)^2 + (\varepsilon_y^p)^2 + (\varepsilon_z^p)^2 + 2(\varepsilon_{xy}^p)^2 + 2(\varepsilon_{yz}^p)^2 + 2(\varepsilon_{zx}^p)^2 \right]}$$

where the plastic strain components, ε_x^p , ε_y^p , ε_z^p , ε_{xy}^p , ε_{yz}^p and ε_{zx}^p , are those accumulated at the end of the composite cycle.

Step 4. Assess acceptability in accordance with (a) and (b) below by using the plastic strains, ε_p , from *Step 3*. If the requirements of both (a) and (b) are satisfied, then the strain limits of Section III, Division 5, HBB-T-1310 for base metal and HBB-T-1713 for weldments are also considered satisfied. This condition is illustrated in Figure A-2(a).

- (c) The requirement, $x + \varepsilon_p \leq \varepsilon_{avg}$, must be satisfied at least at one point for all through-thickness locations. As defined in *Step 2*, ε_{avg} is equal to 0.01 for base metal or 0.005 for weldments. Failure of this requirement is illustrated in Figure A-2(b).
- (d) The requirement, $x + \varepsilon_p \leq \varepsilon_{local}$, must be satisfied at all points. The local strain limit, ε_{local} , is equal to 0.05 for base metal and 0.025 for weldments. Failure of this requirement is illustrated in Figure A-2 (c).
- (e) In order to proceed if either of the requirements of (a) or (b) are not satisfied, return to *Step 2* and select a smaller value of the target inelastic strain, x . If it is not possible to find a value of x that does not ratchet and also satisfies the requirements of *Step 4*, then the loading conditions of A-1.1 applied to the component configuration defined in paragraph A-1.2 do not met the requirements of this Appendix.

Figure A-2. Strain limits Pass/Fail criteria illustrated

A-2.1 Weldment Strain Limit Evaluation

Implementation of the strain limits for weldments defined above in paragraph A-2 requires additional consideration.

- (a) The requirements for analysis of geometry of Section III, Division 5 HBB-T-1714 are applicable for satisfaction of the requirements of this Appendix.
- (b) The thermal/physical properties of weldments may be assumed to be the same as the corresponding base metal for the base metal - weld combinations listed in Section III, Division 5 Table HBB-I-14.10.

A-3 CREEP-FATIGUE EVALUATION

The design methodology employed for evaluation of creep damage is based on rapid cycle elastic shakedown analyses using an elastic-perfectly plastic material model, small strain theory and a “pseudo” yield strength selected to bound creep damage. In this Appendix, “shakedown” refers to the achievement of cyclic elastic behavior throughout the base, based on real or pseudo yield properties. In this Appendix the term “pseudo yield stress” refers to a temperature dependent expected minimum stress-to-rupture value based on a selected trial time duration, not to exceed the yield strength of the material at temperature and is explicitly defined in paragraph A-3.1.1, *Step2*. Guidance on shakedown analysis is provided in Annex A-1.

The combination of Levels A, B, and C Service loadings shall be evaluated for accumulated creep and fatigue damage, including hold time and strain rate effects. For a design to be acceptable, the creep and fatigue damage at each point in the component shall satisfy the following relation:

$$D_c + D_f \leq D \quad (1)$$

where

D = total creep-fatigue damage, as limited by Section III, Division 5, Figure HBB-T-1420-2

D_c = creep damage as determined in paragraph 3.1, below

D_f = fatigue damage as determined in paragraph 3.2, below

A-3.1 Calculation of Cyclic Creep Damage

A-3.1.1 Shakedown procedure

Perform a shakedown analysis for each of the composite cyclic histories defined in paragraph A-1.1. Each of these cyclic histories must be shown to shakedown based on the pseudo yield stress defined in *Step 2* below. Additional requirements for welds are found in A-3.3.

Step 1. Define t_{design} as the total time duration for all Level A, B, and C Service Loadings when the temperature is above the range covered by Tables 2A, 2B, and 4 of Section II, Part D.

Step 2. Select a trial time duration, T'_d in order to define a pseudo yield stress, $S_{T'_d}$, at each location, using the temperature determined from the transient thermal analysis. This pseudo yield stress is equal to the lesser of the quantities defined in (a) and (b) below.

(a) The yield strength S_y given in Table I-14.5.

(b) S_r , where S_r is the expected minimum stress to rupture in time T'_d from Section III, Division 5, Figure HBB-I-14.6 multiplied by the factor, K' , from Section III, Division 5, Table HBB-T-1411-1 using the tabulated values for elastic analysis.

Step 3. Perform a cyclic elastic-perfectly plastic analysis for each composite cycle defined in A-1.1 above with temperature-dependent pseudo yield stress $S_{T'_d}$. The assessment temperature shall be taken as the local instantaneous temperature at every location in the numerical model of the component. If shakedown occurs, that is, cycles with eventual elastic behavior everywhere, proceed to *Step 4*.

Step 4. The maximum creep damage over the structure for the composite cycle under consideration is

$$D_c = \frac{t_{design}}{T'_d} \quad (2)$$

The above value of D_c is used to evaluate total damage in Eq. (1). If the pseudo yield strength in *Step 2* is governed by the yield strength as defined in 5.1 *Step 2(a)*, then the trial time duration for use in Eq. (2) is given by the time at which the minimum stress to rupture is equal to the yield strength; $S_r = S_y$. Linear extrapolation of S_r values corresponding to the two longest tabulated times can be used to obtain the trial time duration when necessary.

Steps 2, 3 and 4 may be repeated to revise the value of D_c by selecting alternative values of the trial time duration, T'_d . Longer values of T'_d will reduce the calculated creep damage. However, these longer values will lead to lower values of the pseudo yield stress, $S_{T'_d}$, which will make shakedown more difficult.

A-3.1.2 Non-shakedown procedure

If shakedown cannot be demonstrated in A-3.1.1, *Step 3* for any value of trial time T'_d then the following alternative procedure can be used to calculate the creep damage fraction.

Step 1. From the original composite cycle defined in A-3.1.1, *Step 1* select some number of Service Level A, B, or C loadings to analyze separately. The designer may remove any number of Service Loadings from the composite cycle.

Step 2. For each Service Load removed in *Step 1* calculate

$$t_i^{(total)} = n_i t_i \quad (3)$$

where n_i is the number of repetitions of loading type i from the Design Specification and t_i is the associated time for a single repetition of loading type i , again from the Design Specification.

Step 3. Form a composite cycle from the remaining Service Loadings, excluding those removed in Step 1. Use A-3.1.1 to calculate the creep damage associated with these loads, except replace the design life t_{design} in A-3.1.1 with the modified design life

$$t'_{design} = t_{design} - \sum_i t_i^{(total)} \quad (4)$$

where the sum proceeds over each loading type i removed from the composite cycle in Step 1. Call the creep damage associated with the reduced composite cycle $D_c^{(base)}$. If there are no cycles remaining to form a composite cycle then $D_c^{(base)} = 0$ and move to Step 4.

Step 4. For each loading type i removed from the composite cycle calculate the relaxation stress history associated with a single repetition of that particular Service Load using the isochronous stress-strain curve procedure in Section III, Division 5, HBB-T-1433(b) where the starting strain ϵ_t is the strain associated with a stress equal to S_y , the yield strength from Section III, Division 5, Table I-14.5 for the maximum metal temperature associated with the Service Load, in the hot tensile curves given in Section III, Division 5, HBB-T-1800 and the lower bound stress S_{LB} is S_{mt} , the value of the allowable stress given in Section III, Division 5, HBB-I-14.3 for the maximum temperature associated with Service Load i and a time t_i . Calculate the creep damage associated with a single repetition of this stress relaxation history using the procedure in Section III, Division 5, HBB-T-1410, using the values of K' for design by elastic analysis.

The relaxation time for this single repetition is t_i and the relaxation temperature is the maximum metal temperature associated with the Service Load.

The single cycle creep damage is $D_{ss}^{(i)}$. The total creep damage associated with all repetitions of loading type i is

$$D_c^{(i)} = n_i D_{ss}^{(i)} \quad (5)$$

Step 5. The total creep damage for all Service Loadings to be used in the total damage calculation in A-3, Eq. (1) is

$$D_c = D_c^{(base)} + \sum_i D_c^{(i)} \quad (6)$$

A-3.2 Calculation of Fatigue Damage

A-3.2.1 Shakedown procedure

If the creep damage was calculated using the shakedown procedure in A-3.1.1 then calculate fatigue damage as follows.

The fatigue damage summation, D_f , in A-3, Eq. (1) is determined in accordance with Steps 1 through 3 below. Additional requirements for welds are found in A-3.3.

Step 1. Determine all the total, elastic plus plastic, strain components for the composite cycle at each point of interest from the shakedown analysis performed in A-3.1.1, Step 3 above.

Step 2. Calculating the equivalent strain range in accordance with Section III, Division 5, HBB-T-1413, or HBB-T-1414 when applicable, with Poisson's ratio $\nu^* = 0.3$.

Step 3. Determine the fatigue damage for each composite cycle from the expression:

$$D_f = \sum_j \frac{n_j}{(N_d)_j} \quad (7)$$

where

n_j = number of applied repetitions of cycle type, j

$(N_d)_j$ = number of design allowable cycles for cycle type, j , determined from one of the design fatigue curves from Section III, Division 5, Figures HBB-T-1420-1 corresponding to the maximum metal temperature occurring during the cycle.

The value of D_f used to evaluate total damage in A-3, Eq. (1) is the maximum value at any location in the numerical model.

A-3.2.2 Non-shakedown procedure

If the creep damage was calculated using the non-shakedown procedure in A-3.1.2 then calculate fatigue damage as follows. Additional requirements for welds are found in A-3.3.

Step 1. Calculate the fatigue damage fraction resulting from the modified composite cycle from A-3.1.2, Step 1 with Service Loadings removed using the procedure in A-3.2.1. Call this fatigue damage fraction $D_f^{(base)}$.

Step 2. Run an elastic-perfectly plastic analysis using the original composite cycle with all Service Loads including those removed in A-3.1.2, Step 1, as defined by A-1.1. The local metal temperature is defined by the transient heat transfer analysis and the pseudoyield stress at each location of the model, for each point in time is given by the yield strength S_y in Section III, Division 5, Table I-14.5 for the local metal temperature.

Step 3. Regardless of whether this new composite cycle analysis shakes down, use the strain history resulting from the analysis to calculate a fatigue damage fraction $D_f^{(all)}$ using A-3.2.1, replacing the composite cycle strains in A-3.1.1, Step 1 with the new composite cycle strains defined in Step 2.

Step 4. The creep damage fraction used to evaluate total damage in A-3, eq. (1) is the maximum of $D_f^{(base)}$ and $D_f^{(all)}$.

A-3.3 Weldment Creep-Fatigue Evaluation

Implementation of the evaluation of creep-fatigue damage in A-3 above for weldments requires additional consideration.

Step 1. In the weld region, the pseudo yield stress value defined by T'_d in A-3.1 Step 2 (b) is reduced further by multiplying the value of S_r for the base metal by the applicable weld strength reduction factor from Section III, Division 5, Table HBB-I-14.10.

Step 2. The number of allowable cycles, $(N_d)_j$, in the weld region is one half the number of allowable cycles from Section III, Division 5, Figures HBB-T-1420-1 for base materials.

Step 3. The requirements for analysis of geometry of Section III, Division 5, Figures HBB-T-1714 are applicable for satisfaction of the requirements of this Appendix.

Step 4. The thermal/physical properties of weldments may be assumed to be the same as the corresponding base metal for the base metal - weld combinations listed in Section III, Division 5, Table HBB-I-14.10.

Annex A-1 Ratcheting and Shakedown Analysis

The steps to perform ratcheting and shakedown analysis are as follows:

(a) Define Composite Cycle Load Time-Histories and Step(s).

- (1) Composite cycle load may consist of histories of mechanical loads, pressure loads, displacements, temperatures and thermal boundary conditions.
- (2) Time-independent parts of the cycle may be truncated because the elastic-perfectly plastic analysis is not time dependent.
- (3) The cycle should not have discontinuities. Discontinuities arising from the selection of the specified cycles to form a composite cycle should be eliminated by a simple and reasonable transition from one state to the next.
- (4) Subject to the requirements in (b) the composite cycle time does not affect the result of the shakedown analysis.
- (5) Temperatures, thermal boundary conditions, boundary displacements and mechanical loads over a cycle should be cyclic; that is, begin and end at the same value.
- (6) A single analysis step may represent one cycle. Dividing a single cycle into more than one step to facilitate definition of the load cycle, and to ensure that maximum loads are analyzed, is often helpful.

(b) Define Analysis Types.

A sequentially coupled thermal-mechanical analysis of the composite cycle may be performed. First a thermal analysis is performed to generate temperature histories. Next the mechanical analyses are performed using these temperature histories as inputs. Care must be taken that times in the mechanical analysis step and in the previous thermal analysis are the same or do not conflict, depending on the requirements of the analysis software. Alternatively, a coupled thermal-mechanical analysis may be performed. The composite temperature history to be used in the mechanical analysis should be cyclic, that is the beginning and end temperature distributions should be the same.

(c) Define Material Properties.

- (1) For thermal analyses, density, temperature- dependent specific heat and conductivity will generally be required.
- (2) For the mechanical analyses the temperature-dependent properties required are modulus, Poisson's ratio and mean expansion coefficient. Density may also be required.

(d) Perform Analyses.

Perform an elastic-plastic cyclic mechanical and thermal stress analysis using the temperature-dependent yield property defined above. Enough cycles are required to demonstrate shakedown or otherwise. Care must be taken to ensure that the analysis deals with all the changes within a cycle. Elastic-plastic routines increase increment size where possible, and may miss a detail in the loading. A conservative limit to maximum increment size can address this problem, or division of the cycle into more than one step as in paragraph (a)(3) of this annex.

(e) Detect Strain Limit Ratcheting.

Ratcheting is defined as repeated non-cyclic deflections, that is between the beginning and end of a cycle, a repeated finite displacement change occurs somewhere in the structure. Detecting ratcheting is most easily done by plotting nodal deflections over time. Cyclic (repeated) behavior indicates non-ratcheting. History plots of equivalent plastic strains will also identify ratcheting.

(f) Creep-Fatigue Shakedown.

Shakedown is defined as eventual elastic behavior everywhere in the model. Failure to shakedown may be identified by plotting histories of equivalent plastic strain.

Appendix-B Properties of nickel

B-199Ni-Low C (UNS No. N02201, ASME Spec. No. SB-160)

B-1.1 Physical Properties

Thermal conductivity values are provided in Section II, Part D, Subpart 2, Table TCD

Thermal expansion values are provided in Section II, Part D, Subpart 2, Table TE-4

Modulus of elasticity values are provided in Section II, Part D, Subpart 2, Table TM-4

Poisson's ratio is provided in Section II, Part D, Subpart 2, Table PRD

Density is provided in Section II, Part D, Subpart 2, Table PRD

B-1.2 EPP Cyclic Creep Design Curves

Figure B-1.1 EPP cyclic creep design curves for low carbon nickel (UNS No. N02201).

Number of Allowable Cycles	Strain Range (mm/mm) at Temperature $\leq 650^{\circ}\text{C}$ and Time			
	0	1 min	10 min	≥ 1 hr
2	-	-	0.025772	0.021635
4	-	-	0.016700	0.014037
10	0.027361	0.025550	0.009533	0.008071
20	0.018194	0.016625	0.006341	0.005410
40	0.012272	0.010855	0.004303	0.003711
10^2	0.007535	0.006314	0.002704	0.002379
2×10^2	0.005391	0.004286	0.001989	0.001781
4×10^2	0.004004	0.002998	0.001534	0.001402
1×10^3	0.002890	0.001980	0.001177	0.001105
2×10^3	0.002389	0.001528	0.001014	0.000973
4×10^3	0.002055	0.001242	0.000912	0.000875
1×10^4	0.001781	0.001014	0.000714	0.000657
2×10^4	0.001444	0.000912	0.000588	0.000552
4×10^4	0.001194	0.000764	0.000508	0.000486
1×10^5	0.000992	0.000587	0.000446	0.000437
2×10^5	0.000900	0.000508	0.000418	0.000406
4×10^5	0.000842	0.000456	0.000404	0.000403
1×10^6	0.000796	0.000417	0.000399	0.000396

Table B-1.1 Tabulated data for EPP cyclic creep design curves for low carbon Nickel (UNS No. N02201).

Appendix-C Properties of tungsten

C-1.1 Physical Properties

To be determined.

C-1.2 Fatigue Design Curves

To be determined.

Appendix-D EPP analysis of a nickel clad

The following steps shall be used to determine the stable strain range for use in the creep-fatigue evaluation of a nickel clad:

(a) Define Composite Cycle Load Time-Histories and Step(s).

- (1) Composite cycle load may consist of histories of mechanical loads, pressure loads, displacements, temperatures and thermal boundary conditions.
- (2) Time-independent parts of the cycle may be truncated because the elastic-perfectly plastic analysis is not time dependent.
- (3) The cycle should not have discontinuities. Discontinuities arising from the selection of the specified cycles to form a composite cycle should be eliminated by a simple and reasonable transition from one state to the next.
- (4) Subject to the requirements in (b) the composite cycle time does not affect the result of the shakedown analysis.
- (5) Temperatures, thermal boundary conditions, boundary displacements and mechanical loads over a cycle should be cyclic; that is, begin and end at the same value.
- (6) A single analysis step may represent one cycle. Dividing a single cycle into more than one step to facilitate definition of the load cycle, and to ensure that maximum loads are analyzed, is often helpful.

(b) Define Analysis Types.

A sequentially coupled thermal-mechanical analysis of the composite cycle may be performed. First a thermal analysis is performed to generate temperature histories. Next the mechanical analyses are performed using these temperature histories as inputs. Care must be taken that times in the mechanical analysis step and in the previous thermal analysis are the same or do not conflict, depending on the requirements of the analysis software. Alternatively, a coupled thermal-mechanical analysis may be performed. The composite temperature history to be used in the mechanical analysis should be cyclic, that is the beginning and end temperature distributions should be the same.

(c) Perform Analyses.

Perform an elastic-plastic cyclic mechanical and thermal stress analysis, where the pseudoyield stress of the base and clad materials defined in the main body of the Code Case. Repeat the composite cycle until the structure achieves a stable strain range at all locations, both base and clad, as described in (d). Care must be taken to ensure that the analysis deals with all the changes within a cycle. Elastic-plastic routines increase increment size where possible, and may miss a detail in the loading. A conservative limit to maximum increment size can address this problem, or division of the cycle into more than one step as in paragraph (a)(3) of this appendix.

(d) Detect Constant Cyclic Strain Range Over Cycles.

- (1) Repeat the composite cycle loading for N cycles, where a good starting value of N is typically 5.
- (2) For each point in the structure calculate the strain difference from the beginning of repetition N to the end of repetition N . Call this strain difference $\Delta\epsilon_N$.
- (3) For each point in the structure calculate the strain difference from the beginning of repetition $N-1$ to the end of repetition $N-1$. Call this strain difference $\Delta\epsilon_{N-1}$.
- (4) If $\Delta\epsilon_N = \Delta\epsilon_{N-1}$ everywhere in the component, then stop. No additional repetitions of the composite cycle are required and structure has reached a steady cyclic condition.

- (5) If not, repeat the composite loading cycle for an additional repetition and repeat this procedure with repetitions $N+1$ and N . Continue until the structure achieves the steady cyclic condition defined in (4). All structures will eventually achieve this steady cyclic condition for the EPP material models used in the analysis.

3 Commentary on the Draft Design Rules

The purpose of the design rules provided in Chapter 2 is to enable the design of 316H Class A components clad with either nickel or tungsten for high temperature molten salt reactors. The use of nickel and tungsten as clad material is to mitigate corrosion concerns in high temperature molten salt environment for 316H Class A components. The goal of the design rules is to prevent both the base and clad materials from potential failure modes without requiring long-term testing of the clad materials. Note the term ‘base material’ as used in the rest of this report refers to the base component, not the clad. This term encompasses base components using welded construction.

The chapter discusses the gaps in the existing ASME Section III, Division 5 rules for clad components, development of bounding analysis methods that avoids requiring long-term creep test data for both nickel and tungsten clad materials, and development of design rules that not only fill the gaps in current Code rules but also conform the bounding analysis methods developed for the clad materials to avoid long-term creep test data.

Executing the design rules requires material data for nickel and tungsten clad materials. The developed Code Case currently includes material data only for nickel, while the material data for tungsten are to be added in the future. This chapter contains a commentary on nickel material data provided in the Code Case.

Finally, the chapter includes a commentary on the general requirements in the draft Code Case.

3.1 Existing rules in ASME Section III, Division 5

The existing rules for designing clad component for high temperature nuclear service in HBB rules of Section III, Division 5. HBB-2121(c) allows the use of materials that do not meet the Code requirements for high temperature nuclear service if they are used as clad with thickness less than 10% of the vessel wall. In HBB-3227.8 the Code contains three relevant provisions for clad design:

1) when designing a clad component for primary load ignore the clad material – do not attribute any material strength to it;

2) similarly, ignore the clad in buckling design; and

3) however, the designer must consider the clad and the interaction of the clad and base materials when designing the vessel to meet the Division 5 deformation controlled quantity limits – creep-fatigue damage and ratcheting strain accumulation.

The third provision is the most important one and requires designing the clad/base system to meet the Code creep-fatigue and ratcheting strain limits. However, the Code does not provide any design rules. The goal is then to develop a set of design rules that ensure the integrity of both clad and base materials under long-term, high temperature nuclear service, with the added constraint of not requiring long-term testing of clad materials.

3.2 Commentary on design method development

Successful design rules should provide a reasonable assurance of protection against likely failure modes. Currently, HBB rules guard a structure against six failure modes [6][14][15][16]:

- 1) time-independent plastic instability,
- 2) time-dependent creep-rupture,
- 3) creep-fatigue damage,
- 4) time-dependent cyclic excessive deformation i.e. ratcheting,
- 5) time-independent buckling, and
- 6) time-dependent buckling.

A design method for clad components to be embedded in the Section III, Division 5 of ASME Pressure Vessel and Boiler Code should guard both base and clad materials against these failure modes. The design method should also account for the mechanical interaction between the clad and base materials. Furthermore, there are two additional failure modes that should be considered for clad components [6][15]:

- 1) failure of the clad/base interface and
- 2) brittle failure of hard clad materials

Brittle failure of the hard clad material is addressed in the design rules developed here. However, the design method does not address the failure of the clad/base interface and considers perfect bonding between the clad and base materials over the service life of the component. The mechanical integrity of the clad/base metal interface can be checked by a general acceptance test [28] independent of the fabrication method used to bond the clad and base materials. Development of such acceptance test is discussed in Chapter 6.

A complete design-by-analysis method has two components – a method of analysis and design checks on the analysis results to guard the structure against each potential failure mode. In the context of clad components, the analysis method must account for the mechanical interaction between the clad and base materials – how the clad material affects the structural response of the base material without clad and vice-versa. Development of such analysis method and design rules are discussed below.

3.2.1 Bounding analysis strategies

A general objective for a design analysis method is simplicity. A designer will need to analyze many structures for different combination of loading conditions. The second goal for a clad analysis method developed here is to avoid long term testing of the clad materials. This requirement limits the type of analysis that could be done for the clad material. Without the long-term test data, constitutive models for creep cannot be calibrated for the clad materials.

Section III, Division 5 and associated nuclear Code cases [1][4][5] describe three potential methods of analysis:

- 1) Design by elastic analysis

- 2) Design by elastic perfectly-plastic (EPP) analysis
- 3) Design by inelastic analysis

The analysis strategy could use any of these methods. However, the key questions here are how to treat nickel and tungsten clad material in design analysis if long term test data are not available and whether the treatment is bounding for both the base and clad material response in the design analysis. How we treat a clad material in the design analysis will depend on its properties relative to the base material.

In general, we can divide clad materials into three categories – soft, hard, and neither – depending on their relative properties to the base material. A soft clad material has a lower yield stress and lower flow stress than the base material and creeps faster than the base material. nickel falls under this category of clad materials. Chapter 5 discusses the criteria developed to select soft clad materials for 316H base material and also verifies that nickel can be considered as a soft clad material for 316H base material. Alternatively, a hard clad has a higher yield stress than the base material and creeps at a slower rate than the base metal. Example of this type of clad materials are refractory metals and alloys. At least some variants of tungsten and tungsten-alloys likely fall into this category, as will other refractory metal alloys. Again Chapter 5 discusses the development of hard clad selection criteria. The remaining type of clad materials do not fall into either soft or hard category. An example of these kind of clad materials might be another Class A material.

We propose to analyze the soft clad material, such as nickel, as perfectly compliant and hard clad material as linear elastic in the design analysis. The base material constitutive response is then the standard representation of the underlying design method: elastic for design by elastic analysis, elastic-perfectly plastic for design by EPP, and inelastic for design by inelastic method. The former of the two clad analysis methods can be called compliant clad analysis method and the latter can be called elastic clad analysis method. Note to treat the soft clad material as perfectly compliant in the finite element calculations the proposed analysis method models the soft clad material as an elastic perfectly-plastic material with a very small, near zero yield stress. The proposed analysis methods do not require long term material properties. The only properties required to conduct design analysis are temperature dependent elastic modulus and coefficient of thermal expansion. Both properties can be measured through standard short term tests.

To assess whether the proposed analysis methods are bounding for both the clad and base material response we analyzed several soft clad/base and hard clad/base material systems through simulating simplified as well as full-scale axisymmetric and 3D models of representative clad reactor components. Details of the study along with results verifying the proposed analysis methods bounding base and clad material response from full inelastic analysis can be found in [6], but for the sake of completeness of this report results from a 3D analysis of a bent heat exchanger tube are briefly discussed below.

Figure 3.1 illustrates the problem. The model represents a single bent tube of a fuel salt primary heat exchanger in a molten salt reactor. Fuel salt flows through the tubes and dissipates the fission heat to the coolant salt flowing in the shell. The heat exchanger tubes are often bent to accommodate the differential thermal expansion between the inner and outer banks of tubes. The tube is 60 mm long, including the 20 mm bent section, and made of 316H stainless steel. The tube

is 0.2 mm thick and includes 5% thick clad material on both inner and outer surfaces. The clad material considered for this problem is either nickel, a soft clad material for 316H base material or molybdenum, a hard clad material for 316H base material.

Figure 3.1: (a) Geometry of the bent heat exchanger tube (figure shows half of the tube) [6], (b) thermal loading profile, (c) symmetric FE model of the tube. Simulation results are analyzed at location-1 and location-2 indicated in c.

Two sets of structural analyses were performed using the same geometry and loading condition. In the first set, results from a compliant clad analysis of nickel/316H/nickel tube is compared with that from a full inelastic analysis. The second set compares the elastic clad analysis with the full inelastic analysis of molybdenum/316H/molybdenum tube. In all the cases the constitutive response of 316H base material is modeled using an inelastic model, conceptually considering the Section III, Division 5 design by inelastic analysis rules. For nickel/316H/nickel tube, nickel was modeled as inelastic material in the full inelastic analysis while it was modeled as perfectly compliant in the compliant clad analysis. Similarly, molybdenum is modeled as inelastic material in the inelastic analysis of molybdenum/316H/molybdenum tube but modeled as linear elastic in the elastic clad analysis. Table 3.1 lists the material properties used to model nickel and molybdenum in these simulations. The creep rates of nickel and molybdenum were modeled using a power law creep model ($\dot{\epsilon}_{creep} = A\sigma^n$) and the values of creep prefactor, A and creep exponent, n listed in Table 3.1 are based on the theoretical models provided in [8].

To examine whether the compliant clad analysis bounds the material response from full inelastic analysis, the steady cyclic strain range from two analyses of the nickel/316H/nickel tube

are compared in Figure 3.2. As indicated by the figure, the equivalent strain ranges from the compliant clad analysis is greater than those from full inelastic analysis in the clad material and very close in the base material. Creep damage in the base material from two simulations are compared in Figure 3.3. Results show that the compliant clad analysis bounds the calculated creep damage from the full inelastic simulation at location-1 (straight section). At location-2 (bent section) the creep damage from compliant clad analysis is found to be little less than that from full inelastic analysis, however, the difference is not very significant. Moreover, the creep damage values at location-2 are much lower than those at location-1, indicating the design of the tube will be controlled by the damage in location-1. Overall then, these results demonstrate that the compliant analysis method is a reasonable approach for designing soft clad systems such as 316H base material cladded with nickel.

<i>Properties</i>	<i>nickel</i>	<i>molybdenum</i>
Young's modulus, E (MPa)	174000	222000
Coefficient of thermal expansion, CTE ($^{\circ}\text{C}$)	15.8×10^{-6}	5.5×10^{-6}
Creep prefactor, A ($\text{MPa}^{-n}/\text{hr}$)	4.66×10^{-19}	5.33×10^{-27}
Creep exponent, n	6	4.85

Table 3.1: Material properties of nickel and molybdenum used in full inelastic analysis of problem described in Figure 3.1.

Figure 3.2: Steady cyclic equivalent strain range in base and clad materials plotted over thickness in (a) location-1 and (b) location-2. Results are from a full inelastic simulation of 316H cladded with nickel and a compliant clad analysis [6].

The second set of comparison was performed between results from the full inelastic analysis and the elastic clad analysis of molybdenum/316H/molybdenum tube. Figure 3.4 compares the steady cyclic equivalent strain range in the clad and base material, while Figure 3.5 compares the creep damage fraction in the base material. The results are very close from both analyses, indicating elastic clad analysis is a reasonable design analysis approach for hard clad systems such as 316H base metal cladded with tungsten.

Figure 3.3: Steady cyclic creep damage in base material plotted over thickness in (a) location-1 and (b) location-2. Results are from a full inelastic simulation of 316H clad with nickel and a compliant clad analysis [6].

Figure 3.4: Steady cyclic equivalent strain range in base and clad materials plotted over thickness in (a) location-1 and (b) location-2. Results are from a full inelastic simulation of 316H clad with molybdenum and an elastic clad analysis [6].

Figure 3.5: Steady cyclic creep damage in base material plotted over thickness in (a) location-1 and (b) location-2. Results are from a full inelastic simulation of 316H clad with molybdenum and an elastic clad analysis [6].

These results demonstrate the feasibility of the hard and soft clad bounding analysis methods. In addition to analysis method, a complete design method requires design checks to guard against all the potential failure modes. Again these design checks should not require long-term material properties for clad materials. Section 3.2.2 and 3.2.3 describe approaches for designing Class A components clad with either soft clad or hard clad materials. Note that the approaches along with reasoning are discussed in the general sense, i.e. without specifying the base and clad materials. However, these are the underlying ideas for the design rules provided in Chapter 2 for 316H Class A components clad with either nickel – a soft clad material for 316H base material – or tungsten – a hard clad material for 316H base material.

3.2.2 Design rules for Soft clad/base material system

3.2.2.1 Primary load and buckling design

In our proposed compliant clad analysis method, no load is attributed to soft clad materials. Therefore, the soft clad material can be neglected when conducting the primary load analysis and design. This approach is essentially what the existing HBB design rules, as mentioned in Section 3.1, require for clad components. This approximation is always conservative for the base material primary load design because it completely neglects any strength of the clad material. It is also conservative for buckling design provided that the clad material remains fully bonded to the base material, i.e. neglecting clad debonding buckling modes.

Our proposed design method also assumes the clad material will not fail by plastic collapse or creep rupture under long-term, steady loading condition. This is a reasonable assumption considering the soft clad material creeps much faster than the base material. The soft clad material will quickly redistribute whatever stress it develops due to loadings onto the base material. This means the soft clad material will be at low stress level for the most of the component life and should not rupture under steady load. We therefore do not propose to check the soft clad material for primary load design and buckling.

The base material then can be checked for primary load design and buckling using the rules in the Code and ignoring soft clad material in the analysis.

3.2.2.2 Creep-fatigue and ratcheting limits

3.2.2.2.1 Creep-fatigue in the clad material

The soft clad material may fail under cyclic load. Since the primary concern of Class A design is high temperature, the design method will require an evaluation of the creep-fatigue damage in the clad material. All the current design methods in the Code require creep-fatigue and creep-rupture test data for creep-fatigue evaluation. Implementing current design rules for creep-fatigue evaluation would require substantially large data base. Recently, the authors and others [9][10][11][12][13] have developed a simplified creep-fatigue design method based on a combination of EPP analysis and Simplified Model Test (SMT) approach. The EPP-SMT approach is much simpler than the current Division 5 design approaches and does not require a substantially larger test database. We propose to adopt this method for creep-fatigue evaluation of the soft clad material.

The compliant clad analysis method will produce a conservative estimation for the strain ranges in the soft clad material which then can be used to determine the allowable number of cycles from the EPP-SMT design curves for a representative hold time equal to design cycle period. EPP-SMT design curves are essentially modified fatigue design curves plotting an effective strain range versus the number of cycles. In addition to the effect of strain range and temperature, as in the conventional fatigue design curves, the EPP-SMT design curves also account for the effect of hold time and elastic follow up. However, there is negligible elastic follow up in a soft clad. This can be explained by considering a simple two bar model – an elastic bar in series with a perfectly compliant bar representing the soft clad material. Under the application of creep-fatigue loading the elastic bar will always be infinitely rigid relative to the perfectly compliant bar.

Since the purpose of SMT test data in EPP-SMT design method is to capture the effect of elastic follow-up and because there is negligible elastic follow up in a soft clad material, there is no need of generating SMT test data for a soft clad material. The EPP-SMT design curves are then just time-dependent fatigue design curves and can be generated from standard fatigue and creep-fatigue tests. Typically, the stress in soft clad materials will relax quickly to a point that the continued accumulation of creep damage will be negligible. This means the shift in the time-dependent fatigue curves to account for creep damage will saturate quickly, as described in Figure 3.6. Therefore, only short term creep-fatigue tests are required for constructing these design curves for the soft clad material. Section 3.3.1 discusses the construction of these design curves in detail.

The implementation of the EPP-SMT method without the use of SMT test data is soft clad material specific and therefore calling it EPP-SMT method could be confusing. We can simply call it design by EPP cyclic creep analysis method. Similarly, the time-dependent fatigue design curves can be named EPP cyclic creep curve. However, as required by EPP-SMT design methodology, the base material should still be modeled as elastic-perfectly plastic with a pseudo-yield stress determined from the Code isochronous curves for a 0.2% offset in strain from the elastic slope at a given temperature and for a time equal to the cycle period.

Figure 3.6: (a) Typical stress relaxation in a typical soft clad material. (b) Schematic showing quick saturation of the time-dependent fatigue (EPP cyclic creep) curves due to fast stress relaxation in soft clad material.

To assess the applicability of the EPP cyclic creep design approach for creep-fatigue evaluation in the soft clad material, we performed a comparative analysis of a bent tube without and with cladding. The geometry and finite element models of the tube are shown in Figure 3.7. This model represents a single tube of a fuel salt primary heat exchanger in a MSR. The figure also shows the thermal and pressure loading profiles considered in the structural finite element calculation. The loading profile has a cycle period of 4500 hr. The tube is symmetric about the XY plane along x and about the YZ plane at x=150 mm. The axial boundary conditions allow free expansion of the net section, but prevents warping deformation. The tube without clad has an outer radius of 5 mm and a thickness of 1 mm, whereas the clad tube has 0.05 mm thick clad on both the outer and inner walls. We considered Class A material 316H as the base material and nickel as the clad material. We ran finite element analysis of the tube using an elastic-perfectly plastic material model for both the base and clad materials. The base material yield stress was adjusted to a pseudo-yield stress determined according to the method mentioned above, while the clad material yield stress was set to a value near zero, as required by the compliant analysis method for soft clad materials. Analyses were run for multiple repetitions of the cyclic loading until the strain range over the cycle became constant for all the points in the structure.

Apart from the compliant clad pseudoyield stress there is one additional significant analysis change between this EPP-SMT approach and the current EPP Code Cases (N-861 and N-862): there is no shakedown requirement for the cyclic analysis. The current EPP Code Cases require the designer to demonstrate elastic shakedown (N-862) or plastic shakedown (N-861) before using the analysis results to calculate creep-fatigue damage. The stabilized cyclic solution is sufficient purely for the sake of finding a strain *range* for use in the design method, which is all the EPP-SMT approaches require. While the Frederick-Armstrong theorem [42] guarantees that this type of EPP cyclic analysis will eventually reach a stable strain range everywhere in the component, this stabilized cycle may have non-zero ratcheting. This type of solution is sufficient for a strain-range-based creep-fatigue life assessment, but not to bound creep damage or strain accumulation in the existing Code Cases. The guidance in the proposed Code rules suggests that five repetitions

of the composite cycle may be enough to reach this steady condition. This suggestion is based on our experience with the method, in theory the steady loading condition may only occur asymptotically. The full design procedure directs the designer to continue cycling until stable strain ranges occur.

Figure 3.8 compares the strain ranges in the base material between the tube without and with clad material. The strain ranges are found to be very close. Since the clad material is modeled as perfectly compliant, it does not affect the strain range in the base material significantly. Therefore, the design by EPP cyclic creep analysis approach can be used for creep-fatigue evaluation of the soft clad material. Figure 3.9 shows the equivalent strain ranges in the clad material of the clad tube, computed from the analysis results. These strain range values can be used to evaluate the clad material for creep-fatigue damage using the EPP-SMT design curves.

Figure 3.7: (a) Geometry of the heat exchanger bent tube (figure shows half of the tube); (b) finite element models of the bent tube without and with clad material; (c) applied thermal and pressure loading profiles.

Figure 3.8: Equivalent strain range in the 316H base material of the bent tube (a) without clad and (b) with nickel clad, computed using EPP cyclic creep analysis.

Figure 3.9: Equivalent strain range in the nickel clad material of the cladged bent tube.

Given an appropriate inelastic constitutive model for the base material, design by inelastic analysis could be used to check the clad for creep-fatigue damage. In this approach, the base material constitutive response is modeled by inelastic material model and the clad material is treated as perfectly compliant. Section 3.2.1 verifies this approach by comparing the clad material response from a full inelastic analysis with that from a compliant clad analysis for representative cladged reactor components. Note that the full inelastic analysis uses inelastic material model for both the clad and base materials. The strain ranges in the clad material from a compliant clad analysis always bounds those from a full inelastic analysis. Again the steady-cyclic strain ranges in the clad material from the design by inelastic analysis can be compared with the EPP cyclic creep design curves discussed above for creep-fatigue evaluation in the clad material.

Since the clad material is modeled as perfectly compliant in both design by EPP cyclic creep analysis and design by inelastic analysis methods, we propose to use $v^* = 0.5$ when calculating maximum equivalent strain range in the soft clad material using methods provided in Section III, Division 5, HBB-T-1413, or HBB-T-1414.

3.2.2.2.2 Creep-fatigue in the base material

We propose to entirely neglect the clad material strength for creep-fatigue damage check in the base material. This will provide a conservative estimation of the creep-fatigue damage in the base material. Since the clad material is neglected, the base material of a soft clad/base system can be evaluated for creep-fatigue using any of the existing design methods.

3.2.2.2.3 Ratcheting in clad and base materials

A soft clad material will essentially deform following the deformation of the base material. Satisfaction of strain limit in the base material with completely neglecting the clad material will safeguard the both the base and clad materials from excessive strain accumulation. The strain in the soft clad material may exceed the Code strain limits for cases where the base material strain marginally passes the Code strain limits. However, this potential some small amount of accumulated strain over the Division 5 limits is not a concern because of high ductility of the soft clad material and also because the extent the clad material strain exceeds the base strain is limited by thermal bending strains induced over the clad thickness – which is, by the 10% thickness criteria, quite thin. We therefore propose to not explicitly check the clad material for ratcheting.

The base material ratcheting check then can be completed using any of the existing design methods, neglecting the clad material in the design analysis.

3.2.3 Design rules for hard clad/base material system

3.2.3.1 Primary load design and buckling

For primary load and buckling design of the hard clad/base material system, the proposed analysis method assumes the hard clad material remains elastic and can only fail under short-term failure modes such as time-independent plastic collapse and time-independent buckling. Therefore, evaluation of these design checks from analysis results require only short-term material properties of the clad material – notably yield strength and ultimate tensile strength. However, as typical hard clad materials have high yield and tensile strengths, the time-independent failure of the hard clad material is unlikely to control over the Section III, Division 5, Subsection HB Subpart B primary load design of the base material.

Since this approach assumes no creep in the hard clad material, creep-rupture design check is not required for the clad material. However, there is a potential concern of stress redistribution over time from the base material to clad material. The creep deformation of the base material will result in relaxation of stress in the base material which will increase stress in the clad material. This requires an investigation to check whether this stress redistribution significantly increases stress in the clad material over the life time of the base material, eventually causing it to exceed the Code “time-independent” allowable stress S_m .

To study the amount of load transfer from the base material to clad material, we created a two bar model – an elastic bar representing the hard clad material and a creeping bar representing the base material. Figure 3.10 shows the model. If both the bars are pulled equally by a constant load, $F = \sigma(a_b + a_c)$, stresses in base, σ_b and clad, σ_c at time, t can be determined from the following expressions.

$$\sigma_b = {}^{(-n+1)}\sqrt{((-A)(-n+1)mE_c tW + (\sigma W)^{(-n+1)})}; n \neq 1 \quad (3.1)$$

$$\sigma_c = \frac{\sigma - (1-m)\sigma_b}{m} \quad (3.2)$$

where $W = \frac{E_b}{mE_c + (1-m)E_b}$; E_b and E_c are the elastic modulus of base and clad materials, respectively; A and n are, respectively, the power law creep prefactor and creep rate exponent of

the base material considering its behavior can be represented by a power law creep model; and m is the ratio between the cross-sectional area of the clad bar and the total cross-sectional area of both bars, i.e. $m = \frac{a_c}{a_b + a_c}$.

We performed several scoping studies considering different hard clad/base systems at different temperatures and for different clad thicknesses. All these studies indicate that the base material relaxation at elevated temperature results in negligible stress increase in the clad material at the end of base material design life. Table 3.2 and Table 3.3 list some example results. These sample calculations are for TZM/316H clad/base systems using ASME Section III, Division 5 allowable stress, S_{mt} values of 316H. The tables show stresses in the clad at the end of the S_{mt} design life of 316H base material for 1% and 10% clad thickness. Note that, stresses at the end of design life are shown in percentage of initial stress values. For these sample calculations, elastic moduli of 316H are taken from Section II, Part D of ASME Boiler and Pressure Vessel Code, power law creep constants of 316H are calculated using relevant equations and parameters given in [8] and elastic modulus of TZM are from [18]. The tables indicate negligible stress increase in TZM clad at the end of design life due to the stress relaxation of 316H base material during elevated temperature operation. Based on these results, we do not propose to check primary load stress redistribution between the base and clad materials in the clad material design rules.

3.2.3.2 Creep-fatigue and ratcheting limits

The fundamental definition of a hard clad material is that it does not creep significantly. Therefore, it will not accumulate excessive deformation. However, the hard clad material may significantly slow the ratcheting of the base/clad system. Being relatively stiff the hard clad material will tend to restrain accumulated creep deformation in the creeping base material. Similarly, creep-fatigue interaction can be neglected for hard clad materials as, by definition, creep is negligible. However, hard clad materials should be checked for fatigue damage. The design information required for this check is design fatigue curves which can be generated in relatively short time frame with strain controlled fatigue tests at operating temperatures. The proposed elastic clad analysis method should produce a reasonable strain range in the clad material which can be used for fatigue damage evaluation.

To assess the applicability of this approach and how the mechanical interaction between hard clad and base materials influence the creep-fatigue and ratcheting design life of the base metal, we performed a comparative design study of a bent tube – without and with cladding. Analyses for this comparative design study are performed by using an elastic perfectly-plastic analysis approach for the base material and modeling the clad as an elastic material. Code Case N-861 design by EPP analysis [4] and Code Case N-862 design by EPP analysis [5] were used respectively for ratcheting and creep-fatigue design checks in the base material.

Figure 3.7 describes the problem but now the clad material is TZM alloy instead of nickel. Design data as provided in the Code were used for 316H base material, while elastic modulus of TZM clad material was taken from [18]. Note that, although the thermal loading profiles have a hold time of 1000 hr between heat up and cool down, the hold time was not considered for the finite element calculations as it is unnecessary for EPP analysis.

Figure 3.10: A two bar model comprising a creeping bar, representing the base material behavior and an elastic bar, representing the hard clad material behavior.

	<i>Time (hr)</i>					
<i>Temp(°C)</i>	<i>1000</i>	<i>3000</i>	<i>10000</i>	<i>30000</i>	<i>100000</i>	<i>300000</i>
600	101.7%	105.2%	107.9%	106.3%	105.6%	104.4%
625	102.6%	104.2%	104.1%	103.1%	102.5%	102.2%
650	101.0%	101.4%	102.0%	101.9%	101.2%	100.9%
675	100.5%	100.7%	100.8%	100.9%	100.6%	100.4%
700	100.2%	100.3%	100.3%	100.2%	100.2%	100.1%
725	100.1%	100.1%	100.1%	100.1%	100.0%	100.0%
750	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 3.2: Percent of initial stress in TZM clad (thickness: 1% of the base material thickness) at the end of the design life of 316H base material.

	<i>Time (hr)</i>					
<i>Temp(°C)</i>	<i>1000</i>	<i>3000</i>	<i>10000</i>	<i>30000</i>	<i>100000</i>	<i>300000</i>
600	101.1%	103.3%	104.9%	103.9%	103.5%	102.7%
625	101.6%	102.6%	102.6%	102.0%	101.6%	101.3%
650	100.6%	100.9%	101.3%	101.2%	100.8%	100.6%
675	100.3%	100.4%	100.5%	100.5%	100.4%	100.2%
700	100.1%	100.2%	100.2%	100.1%	100.1%	100.1%
725	100.1%	100.1%	100.0%	100.0%	100.0%	100.0%
750	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 3.3: Percent of initial stress in TZM clad (thickness: 10% of the base material thickness) at the end of the design life of 316H base material.

Code Case N-861 ratcheting design by EPP analysis method uses finite element simulation to establish non ratcheting deformation i.e. plastic shakedown of the overall structure. An elastic-perfectly plastic analysis approach is used in the finite element calculation for the base material where the yield stress in the analysis model is adjusted based on a pseudo-yield stress selected to

bound the accumulated inelastic strain. As per Code Case N-861, the pseudo-yield stress of 316H base material is determined from the Code isochronous stress-strain curves at a target inelastic strain, x , where $0 < x < 0.01$ but not higher than the yield strength. Note that, for cladded tube simulation, the hard clad material is modeled as linear elastic and therefore a pseudo-yield stress is not required for the clad. Criteria for a design to be acceptable per Code Case N-861 are $x + \epsilon_p \leq 0.01$ at least at one point for all through-thickness locations and $x + \epsilon_p \leq 0.05$ at all points. Here, ϵ_p is the Code defined scalar measure of the plastic strain components. Figure 3.11 shows examples of plastic shakedown in the base material. Table 3.4 compares the ratcheting design life of the base material in tubes with and without clad.

Figure 3.11: Example results showing plastic shakedown of the bent tubes.

Code Case N-862 creep-fatigue design by the EPP analysis method bounds the creep damage directly with a pseudo-yield stress and through establishing elastic shakedown in the finite element simulation. In this Code Case, the pseudo-yield stress refers to a temperature dependent minimum stress-to-rupture value based on a selected trial time duration but not to exceed the yield strength. Again, the pseudo-yield stress is required to conduct the EPP analysis of the base metal, while the hard clad material is elastic and only elastic properties are needed. Once elastic shakedown is established in the base material, creep damage is determined by dividing total time by the trial time. Examples of elastic shakedown in the finite element simulations of the bent tubes are shown in Figure 3.12. Fatigue damage is then calculated by extracting a representative maximum strain range from the simulation results and converting it into an allowable number of cycles using design fatigue curves. Figure 3.13 shows the computed maximum strain range in the base and clad materials of the cladded bent tube. Finally, the creep and fatigue damages of base material are compared to the creep-fatigue interaction diagram to determine if the design passes the creep-fatigue evaluation check. The maximum equivalent strain range, as shown in Figure 3.13, in the

clad material can be used to evaluate the clad material against fatigue failure. Table 3.3 compares the creep-fatigue design life of the base material in tubes without and with clad.

Figure 3.12: Example results showing elastic shakedown of the bent tubes.

The comparison of the evaluated base material ratcheting life for the tubes without and with hard clad material, as tabulated in Table 3.4, shows that design life of the base metal is higher when the tube is clad. This is expected as the hard clad material TZM serves as a stiff constraint for the 316H base material, and therefore restrains the deformation that can be accumulated in the creeping 316H. Therefore, ignoring the hard clad material in the analysis will be a conservative evaluation of ratcheting in the base material. This will allow the use of any existing design methods for ratcheting check in the base material. The ratcheting design check is not required for the hard clad material.

However, the interaction between base and hard clad materials must be considered in design analysis for creep-fatigue evaluation of the base material. We propose to use design by EPP analysis, as used for the example clad bent tube problem above and design by inelastic analysis for creep-fatigue evaluation of base material. For design by inelastic analysis the base material is modeled with an appropriate inelastic material model and the clad is again linear elastic. Section 3.2.1 verifies the design by inelastic analysis approach by comparing the clad material response from a full inelastic analysis with that from an elastic clad analysis for representative reactor components. Note that, design by elastic analysis method cannot be used for creep-fatigue evaluation of the base material as it requires stress classification and linearization which cannot be performed when clad material is included in the design analysis.

The maximum equivalent strain range in the hard clad material from any of the design by EPP analysis and inelastic analysis methods can be used for clad material fatigue evaluation. Since the hard clad material is modeled as elastic in both methods, we propose to use $\nu^* = 0.3$ when calculating maximum equivalent strain range in the clad material using methods provided in Section III, Division 5, HBB-T-1413, or HBB-T-1414.

Figure 3.13: Maximum equivalent strain range in the (a) 316H base material and (b) TZM clad material of the cladded bent tube.

	<i>Ratcheting design life (cycles)</i>	<i>Creep-fatigue design life (cycles)</i>
<i>Tube without clad</i>	~98	~18
<i>Cladded tube</i>	>300	~22

Table 3.4: Effect of hard material cladding on ratcheting and creep-fatigue design lives of the base metal in the bent tubes.

3.2.3.3 Brittle failure of the hard clad materials

Brittle failure could be a concern for hard clad materials, especially for pure refractory metals and their alloys such as tungsten, molybdenum, TZM, W-Re. These materials have relatively low ductile-to-brittle transition temperatures and will be susceptible to brittle failure if the temperature under any Service loading condition descends below the ductile-to-brittle transition temperatures. Therefore, the ductile-to-brittle temperature of the hard clad material must be less than the minimum clad temperature under any service loading condition. We included this provision as a material requirement for tungsten under “General Requirements” section in the Code Case provided in Chapter 2.

3.2.4 Summary of the design method

Based on the commentary provided above, Table 3.5 summarizes the design method developed for 316H Class A components cladded with either nickel – a soft clad material for 316H or tungsten – a hard clad material for 316H. As indicated in the table, both nickel and tungsten clad materials are not required to check for primary load, buckling, and ratcheting design.

The base material can be checked for primary load, buckling, and ratcheting design by ignoring the clad material in the design analysis. The draft Code Case provided in Chapter 2 refers to the rules in Section III, Division 5 for checking the base material for primary load and buckling design. For ratcheting check of 316H base material there are three options – design by elastic analysis, design by inelastic analysis, and design by EPP analysis. The draft Code Case refers to Section III, Division 5 rules for first two options. The Section III, Division 5 rules do not contain design by EPP analysis for ratcheting check. This method is in Code Case N-861. Since a Code Case cannot

be referred in another Code Case, the design by EPP analysis method is provided in Appendix A in the draft Code Case.

	<i>Clad + base combination</i>	<i>Primary load and buckling design</i>	<i>Ratcheting design</i>	<i>Creep-fatigue design</i>
<i>316H Class A base material design</i>	nickel clad + 316H	Ignore clad in design analysis	<ul style="list-style-type: none"> Ignore clad in design analysis Use design by Elastic/EPP/Inelastic analysis 	<ul style="list-style-type: none"> Ignore clad in design analysis Use design by Elastic/EPP/Inelastic analysis
	tungsten clad + 316H			<ul style="list-style-type: none"> Include clad in design analysis and represent it as linear elastic Use design by EPP/Inelastic analysis
<i>Clad material design</i>	nickel clad + 316H	No check is required	No check is required	<ul style="list-style-type: none"> Use EPP cyclic creep/Inelastic analysis Model the clad as elastic perfectly plastic with near zero yield stress
	tungsten clad + 316H			<ul style="list-style-type: none"> Use EPP/Inelastic analysis Model the clad as linear elastic

Table 3.5: Summary of the design method for 316H Class A components clad with either nickel and tungsten.

Table also indicates that the nickel clad can be ignored when the 316H base material is evaluated for creep-fatigue damage. Again there are three options – design by elastic analysis, design by inelastic analysis, design by EPP analysis methods. The draft Code Case refers to Section III, Division rules for first two options. The EPP analysis option is provided in Appendix A as it partly comes from Code Case N-862. The design by EPP analysis for creep-fatigue check in Appendix also contain a new option – a non-shakedown procedure. This procedure is not part of the original Code Case N-862 but has been developed recently and currently under review process for Code committee approval. As Code Cases cannot be incorporated by reference into other Code Cases we reproduce the rules in their entirety, under the expectation that the modification to N-862 will be approved by the time these rules are presented to the ASME for approval.

However, the tungsten clad must be included in design analysis when 316H base material is evaluated for creep-fatigue damage. The draft Code Case provides two options – design by inelastic analysis and design by EPP analysis. Again, the draft Code Case refers to Section III, Division 5 for design by inelastic analysis and provides design EPP analysis in Appendix A. Results from the design analysis of 316H base material for creep-fatigue check should be used for creep-fatigue design checks of the tungsten clad. The creep-fatigue design check of tungsten clad is basically a fatigue damage evaluation, comparing the maximum equivalent strain ranges with the design fatigue curves.

The creep-fatigue design check of nickel clad material can be performed using two options – design by EPP cyclic creep analysis and design by inelastic analysis. Both methods are discussed in details in Section 3.2.2.2.1 above. For creep-fatigue damage evaluation of the nickel clad the maximum equivalent strain ranges are compared with EPP cyclic creep design curves. The development of the EPP cyclic creep curves for nickel is discussed in a subsequent section in this chapter.

As indicated in Table, the clad material is ignored in design analysis for some of the design checks of 316H base material. In such cases calculating the pressure load on the base material surface could be difficult for complex geometry. A conservative way to resolve this issue is to directly apply the internal pressure load at inner face and the external pressure load at the outer face of the base material. This approach also avoids complication in applying the pressure load in finite element analysis when clad material is not included.

Note the Code Case explicitly covers Service Levels A, B and C. The reason that Service Level D is not included is that it is clear that clad strength cannot be included in the evaluation of load controlled stresses and Service Level D only considers load controlled stresses.

3.3 Commentary on properties of nickel

The Code Case provides material data for 99Ni-Low C nickel with UNS No. N02201 and Spec. No. SB-201. The underlying data for these design data are from the literature and from a dedicated test program run by Kairos Power for this research program. The ASME Section II, Part D contains physical properties of this specific nickel. The Code Case then just directly refers to the appropriate tables in Section II, Part D for finding physical properties of nickel.

The nickel material data in the Code Case also includes EPP cyclic creep design curves. While the physical properties are required for thermal and structural analyses, the EPP cyclic creep design curves are required for creep-fatigue damage evaluation of nickel clad material using the structural analysis results. The below discusses development of the EPP cyclic creep design curves for nickel.

3.3.1 Construction of EPP cyclic creep design curves

3.3.1.1 Experimental data collection

The EPP cyclic creep design curves are basically time-dependent fatigue curves. Constructing the EPP cyclic creep design curves for nickel requires fatigue and short-term creep-fatigue test data. Typical high temperature fatigue tests cycle a specimen over a fully-reversed strain range, holding temperature constant using a temperature-controlled furnace or induction heater. The test cycle is repeated until the sample fails. To protect equipment and specimens, however, failure may be defined by a set percentage drop in the maximum stress due to the presence of a crack. Creep-fatigue tests are also strain-controlled cyclic experiments at fixed temperature and fixed fully-reversed strain range but they are different from fatigue tests in that a hold period at fixed strain is included in the cycle either at the maximum tensile, maximum compression, or both ends of the cycle. Table 3.6 lists the fatigue test data and Table 3.7 lists the creep-fatigue test data used to construct the EPP cyclic creep design curves for nickel. All the tests were run at Kairos Power Inc. as part of this project. Fatigue tests were performed at three different temperatures – 550°C, 600°C, and 650°C; while creep-fatigue tests were performed at a single temperature – 650°C.

<i>Temperature (°C)</i>	<i>Strain range (%)</i>	<i>Cycles to failure</i>
550	2	410
550	2	456
550	1.5	764
550	1.5	790
550	1	1412
550	1	2127
550	0.7	2330
550	0.7	2613
550	0.4	9729
550	0.4	3562
550	0.25	163465
550	0.25	597783
550	0.2	1000000*
550	0.2	1000000*
550	0.1	1000000*
550	0.1	1000000*
600	2	393
600	2	376
600	1.5	549
600	1.5	681
600	1	1146
600	1	3385
600	0.6	6679
600	0.6	4537
600	0.4	8415
600	0.4	68827
600	0.25	52777
600	0.25	5003
600	0.16	25016
600	0.16	24829
600	0.09	1000000*
600	0.09	1000000*
650	2	364
650	2	352
650	1.5	469
650	1.5	872
650	1	1560
650	1	1976
650	0.5	4549
650	0.5	1362
650	0.3	22668
650	0.3	13661
650	0.2	87714
650	0.2	1000000*
650	0.15	1000000*
650	0.15	1000000*
650	0.08	1000000*
650	0.08	1000000*

Table 3.6: Summary of fatigue test results used in constructing EPP cyclic creep curves for nickel. * indicates run out tests.

<i>Temperature (°C)</i>	<i>Strain range (%)</i>	<i>Hold time (min)</i>	<i>Cycles to failure</i>
650	2	6	124
650	2	6	117
650	1.5	6	165
650	1.5	6	177
650	1	6	300
650	1	6	222
650	2	60	73
650	2	60	66
650	1.5	60	91
650	1.5	60	92
650	1	60	141
650	1	60	140
650	1.5	300	60
650	1.5	300	71
650	2	300	43
650	2	300	52
650	1	300	109
650	1	300	141

Table 3.7: Summary of creep-fatigue test results used in constructing EPP cyclic creep curves for nickel.

3.3.1.2 Fatigue curve

An EPP cyclic curve is a relation between a fixed cyclic strain range at a fixed temperature, hold time and the resulting number of cycles to failure. Design correlations should use creep-fatigue data for the more damaging of tensile and compressive holds, as the resulting design correlation would then bound the worst effect on cyclic life. The curve at a zero hold time is basically a fatigue curve, describing the relation between cyclic strain range and number of cycles to failure at a fixed temperature. Therefore, we first generated the fatigue design curve using the fatigue test data provided in Table 3.6. We explored two options for the fatigue curves:

- (a) This option [19] first decomposes the strain range into elastic and plastic (inelastic) parts using the midlife stress range data. This gives two sets of data – elastic strain range versus cycles to failure and plastic strain range versus cycles to failure. Each set of data are then separately fit to appropriate model equations. Finally, adding these two model equations gives the relation between the strain range and cycles to failure.
- (b) Direct fitting of the test data.

Figure 3.14 show the curve fitting to the fatigue test data using option-a. The following equations are used for fitting the test data using least square regression.

$$\Delta\epsilon_{el} = a_1 N^{a_2} \quad (3.3)$$

$$\Delta\epsilon_{pl} = a_3 N^{a_4} + a_5 \quad (3.4)$$

$$\Delta\epsilon = \Delta\epsilon_{el} + \Delta\epsilon_{pl} \quad (3.5)$$

where $\Delta\epsilon_{el}$ is the elastic strain range, $\Delta\epsilon_{pl}$ is the plastic strain range, $\Delta\epsilon$ is the applied strain range during fatigue test, N is the cycles to failure, and a 's are the coefficients. $\Delta\epsilon_{el}$ is determined by dividing the midlife stress range by elastic modulus.

Option-b uses the following equation for direct fitting of the fatigue test data.

$$\Delta\epsilon = b_1 N^{b_2} + b_3 N^{b_4} + b_5 \quad (3.6)$$

where b 's are the coefficients.

Figure 3.14: Nickel nominal fatigue curves through fitting the elastic and plastic (inelastic) parts separately.

Figure 3.15 compares the nominal fatigue curves at three temperatures generated based on two options discussed above. The difference between the two sets of curves is slight except for 600°C curves in the high cycle regimes. The figure indicates significant uncertainty in the test data, especially for 600°C. There is also not a very clear temperature dependent trend in the data although the fitted curves seem to show some trend in the very high and very low cycle regime. However, the variation in the test data points toward having a single curve bounding all the temperature data. The figure, therefore, also plots a single fitted curve using option-b generated by combining data at all temperatures. The 650°C option-b curve is the most conservative among all the different curves. We, therefore, selected this curve to determine the bounding fatigue design curve for temperatures equal to or less than 650°C.

Design fatigue curve includes factors of safety. The ASME nuclear code uses a factor of 2 on the strain range and 20 on the cycles to failure. After applying these factors, the final design fatigue relation for nickel is:

$$\Delta\varepsilon = \text{minimum of } \begin{cases} (0.73342N^{-0.63185} + 2.57451 \times 10^{-4}N^{-0.13087} + 1.41104 \times 10^{-3})/2 \\ 0.73342(20N)^{-0.63185} + 2.57451 \times 10^{-4}(20N)^{-0.13087} + 1.41104 \times 10^{-3} \end{cases} \text{ for } T \leq 650^\circ\text{C}$$

Figure 3.16 shows the final design fatigue curve bounds all the test data.

Figure 3.15: Comparison between experimental data and nominal fatigue curves constructed based on based on option-a (solid lines) and option-b (dashed lines). The ‘all temperatures’ curve is based on option-b using combined test data.

Figure 3.16: Final fatigue design curve, i.e. EPP cyclic creep curve with time=0, compared with experimental data.

3.3.1.3 Extrapolation of creep-fatigue test data

As discussed in Section 3.2.2.2.1, the basis of the EPP cyclic creep design method is the EPP-SMT design method. Constructing design charts for EPP-SMT design method requires fatigue, creep-fatigue and SMT data [13]. The SMT are to directly assess the effect of elastic follow up on cyclic creep-fatigue life. However, being a soft clad material nickel will exhibit negligible elastic follow up which means SMT data are not required for generating the design charts. The EPP cyclic creep design method, without using the SMT data, is then a simplified version of the EPP-SMT design method. Previous EPP-SMT works [11][13] are referred in the rest of this subsection for adopting different approaches in constructing the EPP cyclic creep design curves.

In addition to the effect of strain range and temperature, as in the conventional fatigue design curves, the EPP cyclic design curves must account for the effect of hold time and requires creep-fatigue test data. Typically, creep-fatigue tests are conducted in the high strain regime with short hold. Performing creep-fatigue tests at low strain ranges with long holds, typical for structural components under operating conditions, is not practically possible. Therefore, constructing the EPP cyclic curves requires extrapolation of the creep-fatigue test results at high strain range regime and with short hold times to the low strain range regime and long holds. Two approaches – (a) direct extrapolation and (b) classical approach – have been discussed in [11][13] for this purpose. Both approaches use a modified Coffin-shift model for the extrapolation. The below discusses the modified Coffin-shift model and how the model parameters are used in the direct extrapolation and classical approaches for generating the EPP cyclic creep curves. An average approach by taking the average of the curves generated from direct extrapolation and classical approaches is also discussed. The EPP cyclic creep curves from all different approaches are then compared with

the creep-fatigue test data not only for nickel but also for several Class A construction materials – 316H, Grade 91, and Alloy 617 – because of their larger creep-fatigue database compared to nickel. Based on these comparisons a final approach is selected for constructing the EPP cyclic creep design curves for nickel.

3.3.1.3.1 Modified Coffin-shift model

The base Coffin-shift model originates from the frequency-modified fatigue equations proposed by Coffin [20] for time-dependent fatigue.

$$N = \frac{C}{\Delta \varepsilon^n} \left(\frac{1}{1+t_h} \right)^p \quad (3.7)$$

where N is the cycles to failure, $\Delta \varepsilon$ is the strain range, t_h is the hold time, and n , C and p are some constants.

Messner et al. [11] found that the base Coffin-shift model for time-dependent fatigue exaggerates the effect of hold time on cyclic life. Fundamentally, stress generated by creep-fatigue loading relaxes over time and for a long enough hold time will reach to a point where it accumulated negligible creep damage. This saturation of creep damage accumulation with increase hold time is not reflected in the base model as it predicts zero cyclic life for an infinite hold time. To capture the saturation of the creep damage the base model is modified to:

$$N = \frac{C}{\Delta \varepsilon^n} \frac{\left(\frac{1}{1+t_h} \right)^{p+D}}{1+D} \quad (3.8)$$

where D is a constant. Figure 3.17 shows the modified Coffin-shift model fit to the fatigue and creep-fatigue experimental data for nickel at 650°C. Note the model can only capture the test results at the high strain range regime. Table 3.8 lists the best-fit parameters.

Figure 3.17: Curve fit to the experimental fatigue and creep-fatigue data of nickel at 650°C using the modified Coffin-shift model.

C	p	D	n
1.3050	20.6839	0.1282	1.4945

Table 3.8: Parameters for the modified Coffin-shift model for nickel at 650°C.

3.3.1.3.2 Direct extrapolation

In this approach creep-fatigue test results are directly extrapolated to low strain range regime and long hold time using the modified Coffin-shift model. Essentially, it uses the parameters listed in Table 3.8 and Equation 3.8 to determine the cycles to failure at a given strain range and hold time.

$$N_{creep-fatigue}^{Direct} = \frac{C}{\Delta \epsilon^n} \frac{\left(\frac{1}{1+t_h}\right)^{p+D}}{1+D} \quad (3.9)$$

An illustration of this approach is sketched in Figure 3.18. The creep-fatigue trendline is first determined using high strain range, short hold test data which is then extrapolated to realistic long hold times and low strain range regime.

3.3.1.3.3 Classical approach

The standard fatigue equation $N = \frac{C}{\Delta \epsilon^n}$, that is used in the Coffin-shift model and subsequently in the direct extrapolation approach, cannot capture the behavior of the material in the low strain range regime. An alternate to this approach is classical approach. In this approach, the entire fatigue curve is shifted to the longer hold times. Figure 3.18 includes a schematic of the approach.

The classical approach is still based on the modified Coffin-shift model but shifts the fatigue curve instead of the trendline determined using high strain range data.

$$N_{creep-fatigue}^{Classical} = N_{fatigue} \left\{ \frac{\left(\frac{1}{1+t_h}\right)^{p+D}}{1+D} \right\} \quad (3.10)$$

Figure 3.18: Schematic demonstrating two different approaches for extrapolating high strain range, short hold time experimental data to low strain range, long hold time [13].

3.3.1.3.4 Average approach

This approach is essentially taking the average of curves from direct extrapolation and classical approaches. As shown for different Class A construction materials in 3.3.1.4, both direct extrapolation and classical approaches predict the test results in the high strain range regime. In the low strain range regime, direct extrapolation approach seems to be overly conservative while the classical approach appears to over predict the cyclic life. As a compromised, the average curve is determined by taking the algebraic average of the strain ranges from the direct extrapolation and classical approaches as a function of cycles to failure.

$$\Delta\epsilon_{average}(N) = \Delta\epsilon_{direct}(N) + \Delta\epsilon_{classical}(N) \quad (3.11)$$

3.3.1.4 Cycle creep design curves

Figure 3.19 plots the nominal cyclic creep curves for nickel based on different approaches along with creep-fatigue test data at different hold times. The figure also plots the nominal fatigue curves determined in 3.3.1.2. The figure indicates all the cyclic creep curves closely match with the experimental data and also with each other in the high strain range regime. In the low strain range regime, the curves diverge. All the creep-fatigue test data for nickel are in the very high strain range regime. Determining which of the three approaches closely predicts the material behavior would require test data in the low strain range regime, at least in the regime where the curves from different approaches start diverging from each other. Performing creep-fatigue tests in the very low strain range regime is not practical given the term of this project.

Since the available creep-fatigue test data for nickel are in the very high strain range regime and hence not sufficient to make a decision on the final approach for constructing the cyclic creep curves, we investigated the competing extrapolation approaches for several Class A materials. These materials have large creep-fatigue test database which includes some tests in the strain range regime that is much lower than the strain range regime for the nickel test data.

Figure 3.20, Figure 3.21, and Figure 3.22 compare the creep-fatigue test data with cyclic creep nominal curves for Grade 91, 316H, and Alloy 617, respectively. Some of these plots include creep-fatigue test data in the regime where the nominal curves from different approaches start diverging from each other. It is evident from these plots that the average approach represents the experimental test data better than both the direct extrapolation and classical approaches. For most of the cases the average approach curve either closely matches with or bounds the experimental data. Although a few creep-fatigue tests, especially for Alloy 617, seem to a bit far on the left side of the average approach curve, those will be bounded after applying design margin on the nominal curves. We, therefore, decide to use the average approach for constructing the cyclic creep design curves. Figure 3.23 plots the nominal cyclic creep curves for nickel at 650°C using the average approach. The figure indicates very quick saturation of the cyclic creep curves with increasing hold time.

Similar to the fatigue design curves, we apply a margin of 2 on the strain range and 20 on the cycles to failure for the EPP cyclic creep curves.

Figure 3.19: Nominal EPP cyclic creep curves based on different extrapolation approaches compared with creep-fatigue test data for nickel at 650°C with different hold times.

Figure 3.20: Nominal EPP cyclic creep curves based on different extrapolation approaches compared with creep-fatigue test data for Grade 91 at different temperatures and hold times.

Figure 3.21: Nominal EPP cyclic creep curves based on different extrapolation approaches compared with creep-fatigue test data for 316H at different temperatures and hold times.

Figure 3.22: Nominal EPP cyclic creep curves based on different extrapolation approaches compared with creep-fatigue test data for Alloy 617 at different temperatures and hold times.

Figure 3.23: Final nominal EPP cyclic creep curves for nickel at 650°C with different hold times.

3.4 Tungsten properties

As discussed in Chapter 7, the tungsten test data collected as part of this project was not sufficient to demonstrate that the particular heat of tungsten meets the hard clad requirements.

3.5 Commentary on general requirements

The general requirements of the draft Code Case include three sections – material, clad thickness, and thermal analysis.

The material section provides three provisions. The first provision in material section simply tells that the Code Case is applicable to 316 SS base material approved for Section III, Division 5, Class A components when clad with either nickel or tungsten. Here, 316 SS base material approved in Section III, Division 5 is basically 316H. The second provision allows the clad material to bypass the material specification requirements of the base Code, reflecting the HBB-2121(c) provision for clad material in Section III, Division 5. However, both nickel and tungsten shall conform to appropriate ASTM specification. The third provision is related to tungsten and states that the nil-ductility temperature of tungsten should be less than the minimum temperature the clad material will see in service. This is to avoid brittle failure of tungsten as discussed above in the commentary on the design method development.

The provision on the clad thickness limits the maximum clad thickness to 10% of the base material thickness. This provision also comes from Section III, Division 5, HBB-2121(c).

The thermal analysis provision simply tells designers to always include clad material in thermal analysis even if it is ignored in structural analysis for some of the base material design checks as

listed in Table. This ensures accurate calculation of the component temperature field and resulting thermal stresses.

4 Sample Problems

This chapter walks through three sample design problems applying the design rules of the draft Code Case provided in Chapter 2. The base material used in all sample problems is 316H, with design properties from the Code. The clad material in sample problems 1 and 2 is nickel with design properties provided in the Code Case. For sample problem 3 the clad material is tungsten. Since the Code Case does not include the design properties for tungsten clad, this problem uses properties from literature for performing structural and thermal analysis but does not evaluate the clad material for creep-fatigue damage as it requires fatigue design curves. The sample problem, however, does walk through the fatigue evaluation process and presents results that can be used for fatigue damage evaluation of tungsten clad if fatigue design curves become available.

As discussed below, we used the hbbanalysis package for some of the base material design checks. This package was developed at Argonne National Laboratory for automatic execution of the ASME Section III, Division 5 Code rules for primary load checks and design by elastic analysis and design by EPP analysis rules for ratcheting limit and creep-fatigue damage checks. Stress results from structural analysis are first entered in an Excel spreadsheet which is then read by hbbanalysis package for checking the Code rules. Interested readers can submit a request to the U.S. Nuclear Regulatory Commission (NRC) to obtain the hbbanalysis package. The official name of the package is “ASME Section III, Division 5 Design Tool” [21].

4.1 Sample problem 1: A 316H heat exchanger clad with nickel

4.1.1 Problem Description

Figure 4.1 illustrates the first problem considered for evaluating the design method developed. The problem represents a single straight tube of a primary heat exchanger in a molten salt reactor. The primary salt flows through the tubes and heat is transferred to the secondary salt flowing in the shell. The tube is constructed with 316H Class A base material with nickel cladding applied on both the inner and outer surface to mitigate corrosion of the base material due to molten salt. Service Level-A loading includes start-up and shut-down transients and normal operating condition. Total time between the start-up and shut-down is 1000 hr. Service Level-B loading includes a transient caused by a loss in load for about 10 hr which results in salt temperature increase by about 10%. This transient is expected to happen once in every 2000 hr, as depicted by the loading profile in Figure 4.1. The design life of the heat exchanger is 300,000 hr.

The design of tube is evaluated for two different clad thicknesses:

- 1) Case-1: 1% (0.5% on the inner face and 0.5% on the outer face) of the base material thickness
- 2) Case-2: 10% (5% on the inner face and 5% on the outer face) of the base material thickness

Figure 4.1: (Sample problem 1) An axisymmetric representation of a single tube in a tube-shell heat exchanger of a molten salt reactor. The base material is 316H and the clad material is nickel. Loading profile shows the temperature and pressure of the primary salt flowing inside tube and the secondary salt flowing in the shell under Service Level-A and Service Level-B loadings.

4.1.2 Thermal analysis

We used MOOSE (Multiphysics Object Oriented Simulation Environment) [22], an open source finite element solver to perform thermal analysis of the tube. As instructed in the Code Case, clad was always included in thermal analysis for determining temperature distribution in the base material even when the clad is ignored in structural analysis of the base material. Figure 4.2 shows example results from thermal analysis of the tube.

4.1.3 Composite cycle

Some of the design analysis discussed below requires defining an overall cycle including all relevant features from the individual Level A, B and C Service Loadings. This sample problem has one Service Level-A cycle and one Service Level-B cycle. Figure 4.3 shows the composite cycle combining these two cycles.

Figure 4.2: (Sample problem 1) Overall tube temperature distributions and through thickness temperature at maximum wall averaged temperature location during holds under Service Level-A and Service Level-B loadings.

Figure 4.3: (Sample problem 1) Composite cycle.

4.1.4 Primary load checks

The cladded structure can be checked for load-controlled stress limits by ignoring the clad material in design analysis and following the rules in Section III, Division 5. Since the clad material is ignored in the design analysis, the internal pressure load should be directly applied at the inner face of the base material and the external pressure load directly at the outer face of the base material. We used MOOSE for structural analysis of the tube under pressure load and using a linear elastic model for 316H base material. Results from structural analysis were fed into the hbbanalysis package for evaluating the structure against the load-controlled stress limits.

Table 4.1 summarizes the primary load checks of the tube for both cases of clad thickness. Note that although the stresses in the tube are same for both the cases as clad material is ignored in structural analysis, the temperature distributions are not the same as clad material is included in thermal analysis. Results in the table indicate that the design passes all the primary load checks for both cases.

Per the Code Case the load-controlled stress limits do not apply to the clad material itself.

Checks	Stress intensity (MPa) or use fraction	Case-1: 0.5% clad on both inner and outer faces		Case-2: 5% clad on both inner and outer faces		Relevant provision in Section III, Division 5 rules
		Allowable stress (MPa) or use fraction limits	Pass?	Allowable stress (MPa) or use fraction limits	Pass?	
Design stress limit	$P_m = 3.56$	$S_o = 62.02$	Yes	$S_o = 62.15$	Yes	HBB-3222.1(a)
	$P_L + P_b = 4.34$	$1.5S_o = 93.04$	Yes	$1.5S_o = 93.23$	Yes	HBB-3222.1(b)
Service level A stress limits	$P_m = 3.56$	$S_{mt} = 40.01$	Yes	$S_{mt} = 40.11$	Yes	HBB-3223(a)
	$P_L + P_b = 4.34$	$KS_m = 151.20$	Yes	$KS_m = 151.23$	Yes	HBB-3223(c)(eq.4)
	$P_L + \frac{P_b}{K_t} = 4.18$	$S_t = 40.01$	Yes	$S_t = 40.11$	Yes	HBB-3223(c)(eq.5)
Service level B stress limits	$P_m = 3.56$	$S_{mt} = 77.49$	Yes	$S_{mt} = 77.73$	Yes	HBB-3223(a)
	$P_L + P_b = 4.34$	$KS_m = 149.64$	Yes	$KS_m = 149.67$	Yes	HBB-3223(c)(eq.4)
	$P_L + \frac{P_b}{K_t} = 4.18$	$S_t = 77.49$	Yes	$S_t = 77.72$	Yes	HBB-3223(c)(eq.5)
Use fraction associated to P_m	Case-1: 0.00678 Case-2: 0.00676	1.0	Yes	1.0	Yes	HBB-3224(b)
Use fraction associated to $P_L + P_b$	Case-1: 0.00739 Case-2: 0.00739	1.0	Yes	1.0	Yes	HBB-3224(d)

Table 4.1: (Sample problem 1) Base material primary load checks. P_m is the maximum general primary membrane stress intensity, $P_L + P_b$ is the maximum combined primary membrane plus bending stress intensity, K is the section factor, and $K_t = \frac{K+1}{2}$. All limits are checked at maximum wall-averaged temperature location. Definition of all the allowable stresses can be found in HBB-3216.

4.1.5 Ratcheting check

According to the Code Case, the clad material is not required to satisfy the strain limit. The base material ratcheting check can be performed using either design by elastic analysis, design by inelastic analysis, or design by EPP analysis method. We used design by elastic analysis method following the simple A-1 ratcheting test in HBB-T-1322. Similar to the primary load checks the clad material is ignored in structural analysis but included in thermal analysis. Again this requires applying the internal pressure load at the inner face of the base material and external pressure at the outer face of the base material. Results from structural analysis were fed into hbbanalysis package for executing the ratcheting limit check.

Note A-1 ratcheting test requires defining at least one cycle that includes the maximum secondary stress intensity range, Q_R and the maximum value of $P_L + \frac{P_b}{K_t}$, where P_L is the local primary membrane stress, P_b is the primary bending stress, and K_t is a factor accounting for the reduction in extreme fiber bending stress due to the effects of creep. For this problem the maximum values of these two quantities happen under Service Level A plus Service Level-B loading which is basically the composite cycle defined in Figure 4.3.

Table 4.2 summarizes the ratcheting limit check of 316H base material which indicate the base material passes the ratcheting check for both cases of clad percentages.

	<i>Case-1: 0.5% clad on both inner and outer faces</i>	<i>Case-2: 5% clad on both inner and outer faces</i>
$X = \frac{(P_L + \frac{P_b}{K_t})_{max}}{S_y}$	0.0363	0.0363
$Y = \frac{(Q_R)_{max}}{S_y}$	0.3305	0.3283
$S_a = \min(1.25S_t, S_y)$	78.6334 MPa	78.8332 MPa
$\frac{S_a}{S_y}$	0.6825	0.6842
<i>Pass criteria, $X + Y < \frac{S_a}{S_y}$?</i>	Yes	Yes

Table 4.2: (Sample problem 1) Base material ratcheting limit check. S_y is the average of the yield strength values at the maximum and minimum wall averaged temperatures during the cycle and S_t is at the highest wall averaged temperature and a time value of 10^4 hr.

4.1.6 Creep-fatigue damage check

4.1.6.1 Base material creep-fatigue evaluation

As per the draft Code Case, base material creep-fatigue check of a 316H Class A component cladged with nickel is done by ignoring the clad material in the design analysis and using any of the design by elastic analysis, design by inelastic analysis, or design by EPP analysis rules. We used design by elastic analysis method. Ignoring clad material in the structural analysis means applying the internal pressure load at the inner face and external pressure load at the outer face of

the base material. We used MOOSE for structural analysis and hbbanalysis package for executing the design rules on the results from structural analysis.

Creep-fatigue damage evaluation of 316H base material requires calculating the fatigue damage fraction, D_f and creep damage fraction, D_c separately and then compare those with creep-fatigue damage envelop provided in the Code. If (D_f, D_c) falls inside the creep-fatigue damage envelop the design passes base material creep-fatigue damage check. In Section III, Division 5, HBB-T-1430 the Code provides several options for calculating strain range which is then used to determine fatigue and creep damages. We used option (e). The Code also provides several options for creep damage calculation. We used HBB-T-1433(a)(b).

	<i>Case-1: 0.5% clad on both inner and outer faces</i>	<i>Case-2: 5% clad on both inner and outer faces</i>
Fatigue damage fraction, D_f	6.69×10^{-7}	4.65×10^{-7}
Creep damage fraction, D_c	0.048	0.047
Does (D_f, D_c) fall inside the creep-fatigue damage envelop of 316H?	Yes	Yes

Table 4.3: (Sample problem 1) Base material creep-fatigue evaluation.

4.1.6.2 Clad material creep-fatigue evaluation

Creep-fatigue evaluation of nickel clad material can be done using either design by inelastic analysis or design by EPP cyclic creep analysis. We used the latter option. For the EPP cyclic creep analysis a composite cycle must be defined. Figure 4.3 shows the composite cycle. The 316H base material is modeled as elastic-perfectly plastic with temperature dependent pseudo-yield stress determined from the isochronous stress-strain curves for a 0.2% offset in strain from the elastic slope and for a time equal to the cycle period. The cycle period of the composite cycle is 1000 hr. The clad material is modeled as elastic-perfectly plastic with a pseudo yield stress of 2 MPa. For this design check, we performed coupled thermal-structural simulation of the clad tube using MOOSE. Figure 4.4 shows some example results.

Table 4.4 summarizes the creep-fatigue damage evaluation of the clad material. Note the Code Case provides one set of cyclic creep design curves for temperatures equal to or less than 650°C. The maximum clad temperature in this sample problem is always less than 650°C, so these design curves can be used. Figure 4.4 indicates that the maximum clad strain range is not at the maximum temperature location. Since the design curves are temperature independent, we used the through thickness maximum strain range at the maximum wall averaged temperature location for evaluating creep-fatigue damage from the cyclic creep design curves. As indicated by the table, the design passes clad material creep-fatigue damage check for both cases of clad percentages.

Figure 4.4: (Sample problem 1) Through thickness temperature and steady cyclic equivalent strain ranges at the maximum wall-averaged temperature location under Level-A and combined Level-A and Level-B Service loading conditions. Results are from EPP cyclic creep analysis of the clad tube with 5% nickel cladding on both inner and outer face of 316H base material.

		<i>Case-1: 0.5% clad on both inner and outer faces</i>	<i>Case-2: 5% clad on both inner and outer faces</i>
	<i>Maximum strain range in clad</i>	<i>0.00126</i>	<i>0.00124</i>
<i>Under Service Level-A loading only</i>	<i>Total repetitions of Level-A only Service loading</i>	150	150
	<i>Cycle period for Level-A only Service loading</i>	1000 hr	1000 hr
	<i>Total allowable cycles from cyclic creep design curves</i>	576	603
	<i>Creep-fatigue damage fraction</i>	0.26	0.25
<i>Under combined Service Level-A and Level-B loading</i>	<i>Maximum strain range in clad</i>	<i>0.00140</i>	<i>0.00138</i>
	<i>Total repetitions</i>	150	150
	<i>Cycle period for combined Level-A and Level-B Service loading</i>	1000 hr	1000 hr
	<i>Total allowable cycles from cyclic creep design curves</i>	390	416
	<i>Creep-fatigue damage fraction</i>	0.39	0.36
	<i>Total creep-fatigue damage fraction, $\sum D$</i>	0.65	0.61
	<i>Pass criteria $\sum D < 1$</i>	Yes	Yes

Table 4.4: (Sample problem 1) Clad material creep-fatigue evaluation.

4.1.7 Buckling check

The clad material is not required to satisfy buckling limits. Base material buckling checks are done following HBB-T-1500 rules in Section III, Division 5 and ignoring the clad material in the structural evaluation.

Since buckling of the base material is not expected under the internal pressure loading condition considered in this problem, this design check was not performed.

4.2 Sample problem 2: A 316H flat head vessel clad with nickel

4.2.1 Problem Description

Figure 4.5 illustrates the second design problem. This is a 316H flat head vessel in a molten salt reactor with nickel cladding on the inner surface to mitigate corrosion of the base material. Temperature of the salt inside the vessel changes following the profile in Figure 4.5. The problem does not consider a gradient in salt temperature between top and bottom of the vessel. Hot air flows around the vessel to reduce through thickness thermal gradient.

Service Level-A loading includes start-up and shut-down transients and normal operation of the reactor. Total time between the start-up and shut-down is 1000 hr. Service Level-B loading includes a transient caused by a loss in load for about 10 hr which results in a salt temperature increase by about 10%. This transient is expected to happen once in every 2000 hr. The design life of the vessel is 300,000 hr.

The design is evaluated for two different clad thicknesses:

- 1) Case-1: 1% of the base material thickness
- 2) Case-2: 10% of the base material thickness

Figure 4.5: (Sample problem 2) An axisymmetric representation of a 316H flat head vessel in a molten salt reactor. The vessel is clad with nickel on the inner surface. The plot shows the temperature profile of the salt inside the vessel. Hot air with controlled temperature flows on the outer surface of the vessel.

4.2.2 Thermal analysis

Figure 4.6 and Figure 4.7 show some example results from thermal analysis of the vessel. These results are for 10% clad thickness. Similar analysis was also done for the vessel with 1% clad thickness.

4.2.3 Composite cycle

Figure 4.8 shows the composite cycle for the salt temperature profile.

4.2.4 Primary load checks

The clad material is not required to satisfy the limits on primary stresses.

Table 4.5 summarizes the primary load checks for the 316H base material. Clad material was not included in the structural analysis for these checks. All calculations in the table are for a through thickness section at the knuckle as stresses at this location controls the design of the vessel. Results in the table indicate the design passes all the primary load checks for the base material.

4.2.5 Ratcheting check

Any of design by elastic analysis, design by inelastic analysis, or design by EPP analysis method can be used for evaluating the base material for strain limits. The clad material is ignored in the structural analysis. We used HBB-T-1322, Test A-1 in design by elastic analysis rules in Section III, Division 5. Table 4.6 summarizes the results. As indicated in the table, the 316H base material passes the ratcheting check for both the clad percentages.

The clad material is not required to satisfy the strain limits.

At the beginning of Service Level-A hold

After reaching steady state during Service Level-A hold

Figure 4.6: (Sample problem 2) Over all temperature distribution and through thickness temperature at different locations of the vessel 10% nickel (Case-2) during hold under Service Level-A loading.

Figure 4.7: (Sample problem 2) Overall temperature distribution and through thickness temperature at different locations of the vessel clad with 10% nickel (Case-2) during hold under Service Level-B loading.

Figure 4.8: (Sample problem 2) Composite cycle.

Checks	Stress intensity (MPa) or use fraction	Case-1: 1% clad		Case-2: 10% clad		Relevant provision in Section III, Division 5 rules
		Allowable stress (MPa) or use fraction limits	Pass?	Allowable stress (MPa) or use fraction limits	Pass?	
Design stress limit	$P_m = 3.97$	$S_o = 59.10$	Yes	$S_o = 61.94$	Yes	HBB-3222.1(a)
	$P_L + P_b = 26.88$	$1.5S_o = 88.65$	Yes	$1.5S_o = 92.92$	Yes	HBB-3222.1(b)
Service level A stress limits	$P_m = 3.97$	$S_{mt} = 37.40$	Yes	$S_{mt} = 39.95$	Yes	HBB-3223(a)
	$P_L + P_b = 26.88$	$KS_m = 150.49$	Yes	$KS_m = 151.19$	Yes	HBB-3223(c)(eq.4)
	$P_L + \frac{P_b}{K_t} = 25.63$	$S_t = 37.40$	Yes	$S_t = 39.95$	Yes	HBB-3223(c)(eq.5)
Service level B stress limits	$P_m = 3.97$	$S_{mt} = 70.01$	Yes	$S_{mt} = 75.75$	Yes	HBB-3223(a)
	$P_L + P_b = 26.88$	$KS_m = 148.64$	Yes	$KS_m = 149.42$	Yes	HBB-3223(c)(eq.4)
	$P_L + \frac{P_b}{K_t} = 25.63$	$S_t = 70.01$	Yes	$S_t = 75.75$	Yes	HBB-3223(c)(eq.5)
Use fraction associated to P_m	Case-1: 0.0085 Case-2: 0.1840	1.0	Yes	1.0	Yes	HBB-3224(b)
Use fraction associated to $P_L + P_b$	Case-1: 0.0072 Case-2: 0.1411	1.0	Yes	1.0	Yes	HBB-3224(d)

Table 4.5: (Sample problem 2) Base material primary load checks. P_m is the maximum general primary membrane stress intensity, $P_L + P_b$ is the maximum combined primary membrane plus bending stress intensity, K is the section factor, and $K_t = \frac{K+1}{2}$. All limits are checked at the knuckle. Definition of all the allowable stresses can be found in HBB-3216.

	Case-1: 1% clad	Case-2: 10% clad
$X = \frac{\left(P_L + \frac{P_b}{K_t}\right)_{max}}{S_y}$	0.068	0.068
$Y = \frac{(Q_R)_{max}}{S_y}$	0.373	0.356
$S_a = \min(1.25S_t, S_y)$	72.18 MPa	77.14 MPa
$\frac{S_a}{S_y}$	0.63	0.67
Pass criteria, $X + Y < \frac{S_a}{S_y}$?	Yes	Yes

Table 4.6: (Sample problem 2) Base material ratcheting limit check. S_y is the average of the yield strength values at the maximum and minimum wall averaged temperatures during the cycle and S_t is at the highest wall averaged temperature during the cycle and a time value of 10^4 hr.

4.2.6 Creep-fatigue damage check

4.2.6.1 Base material creep-fatigue evaluation

The base material of a 316H component clad with nickel is evaluated for creep-fatigue damage using any of the design by elastic analysis, design by inelastic analysis, or design by EPP analysis. The nickel clad material is ignored in the structural analysis for this check. We used design by elastic analysis rules in Section III, Division 5, HBB-T-1430. We used HBB-T-1432(e) for calculating strain range from the structural analysis and HBB-T-1433(a)(b) for creep damage calculation. Table 4.7 summarizes the creep-fatigue damage evaluation of the 316H base material. The location of the maximum creep-fatigue damage is at the knuckle. The table indicates the design passes creep-fatigue damage check for the base material.

	<i>Case-1: 1% clad</i>	<i>Case-2: 10% clad</i>
Fatigue damage fraction, D_f	9.76×10^{-7}	8.91×10^{-7}
Creep damage fraction, D_c	0.16	0.12
Does (D_f, D_c) fall inside the creep-fatigue damage envelop of 316H?	Yes	Yes

Table 4.7: (Sample problem 2) Base material creep-fatigue evaluation.

4.2.6.2 Clad material creep-fatigue evaluation

Any of the design by inelastic analysis or design EPP cyclic creep analysis can be used for creep-fatigue damage evaluation of the nickel clad material. We used design by EPP cyclic creep analysis. The EPP analysis method uses a composite cycle of the all the Service Loadings. Figure 4.8 shows the composite cycle. The time period of the composite cycle is 1000 hr. The 316H base material was modeled as elastic-perfectly plastic with temperature dependent pseudoyield stress determined from the isochronous stress-strain curves for a 0.2% offset in the strain from the elastic slope and for a time equal to the cycle period. The clad material was modeled as elastic-perfectly plastic with a pseudoyield stress equal to 2 MPa. Figure 4.9 shows some example results from coupled thermal-structural simulation of the vessel.

Table 4.8 summarizes the creep-fatigue damage evaluation of the clad material. We used the cyclic creep design curves of nickel provided in the Code Case for calculating the creep-fatigue damage fractions. The design passes the clad material creep-fatigue damage check for both cases of clad thickness.

4.2.7 Buckling check

A buckling check is not required for the clad material. Base material buckling checks are done following HBB-T-1500 rules in Section III, Division 5 and ignoring the clad material in the structural evaluation.

Since buckling of the base material is not expected under the internal pressure loading condition considered in this problem, this design check was not performed.

Figure 4.9: (Sample problem 2) Through thickness temperature and steady cyclic equivalent strain ranges at the knuckle under Level-A and combined Level-A and Level-B Service loading conditions. Results are from EPP cyclic creep analysis of the clad tube with 10% nickel cladding on the inner face of 316H base material.

		Case-1: 1% clad	Case-2: 10% clad
Under Service Level-A Loading only	Maximum strain range in clad	0.00122	0.00122
	Total repetitions	150	150
	Cycle period	1000 hr	1000 hr
	Total allowable cycles	640	640
	Creep-fatigue damage fraction	0.23	0.23
Under combined Service Level-A and Level-B Loading	Maximum strain range in clad	0.00135	0.00136
	Total repetitions	150	150
	Cycle period	1000 hr	1000 hr
	Total allowable cycles	452	440
	Creep-fatigue damage fraction	0.53	0.34
Total creep-fatigue damage fraction, $\sum D$		0.56	0.56
Pass criteria $\sum D < 1$		Yes	Yes

Table 4.8: (Sample problem 2) Clad material creep-fatigue evaluation.

4.3 Sample problem 3: A 316H flat head vessel cladded with tungsten

4.3.1 Problem Description

Figure 4.10 illustrates the problem. This problem has the same structural configuration as the sample problem-2 but now the clad material is tungsten. This problem also has slightly different loading conditions – salt shut down temperature and hot air temperature are now 600°C. The design life of the vessel is 100,000 hr. The design of the vessel was evaluated only for 10% clad thickness.

Figure 4.10: (Sample problem 3) An axisymmetric representation of a 316H flat head vessel in a molten salt reactor. The vessel is cladded with tungsten on the inner surface. The plot shows the temperature profile of the salt inside the vessel. Hot air with controlled temperature flows on the outer surface of the vessel.

Performing thermal and structural analysis of the cladded vessel requires material properties of tungsten. These properties were collected from literature and material datasheet [29][30][31][32], as the Code Case does not include properties for tungsten. Table 4.9 lists the properties. The Code Case also requires to check the minimum clad temperature with the ductile-brittle transition temperature (DBTT) of tungsten. Lassila et al. [33] reported the DBTT of several types of tungsten based on three-point bend tests. The reported values ranged from 150°C to 450°C depending on the fabrication method used for tungsten.

Temperature (K)	Thermal conductivity ($\text{Wm}^{-1}\text{K}^{-1}$)	Heat capacity ($\text{Jkg}^{-1}\text{K}^{-1}$)	Poisson's ratio	Elastic modulus (GPa)	Coefficient of thermal expansion (10^{-6} K^{-1})
500	147.5	138	0.28	397	5.36
1000	122.0	148	0.29	374	5.65

Table 4.9: (Sample problem 3) Properties of tungsten used in thermal and structural analysis.

4.3.2 Thermal analysis

Figure 4.11 and Figure 4.12 show some example results from thermal analysis of the clad vessel.

Figure 4.11: (Sample problem 3) Overall temperature distribution and through thickness temperature at different locations of the vessel clad with 10% tungsten during hold under Service Level-A loading.

Figure 4.12: (Sample problem 3) Overall temperature distribution and through thickness temperature at different locations of the vessel clad with 10% tungsten during hold under Service Level-B loading.

4.3.3 Requirement on nil-ductility transition temperature

According to the Code Case, the nil-ductility transition temperature, i.e. DBTT, of tungsten should be less than the minimum clad temperatures during any Service A, B, C, or Test loadings. The minimum clad temperature of the vessel is 600°C which is greater than the DBBT listed in Section 4.3.1.

4.3.4 Composite cycle

Figure 4.13 shows the composite cycle.

Figure 4.13: (Sample problem 3) Composite cycle.

4.3.5 Primary load checks

Table 4.10 summarizes the primary load checks. The clad material is ignored in the design analysis for the primary load checks. The table indicates the base material satisfies the load-controlled stress limits. The clad material is not required to satisfy these limits.

Checks	Stress intensity (MPa) or use fraction	Allowable stress (MPa) or use fraction limits		Relevant provision in Section III, Division 5 rules
		$S_o = 53.23$	Pass?	
Design stress limit	$P_m = 3.97$	$1.5S_o = 79.84$	Yes	HBB-3222.1(a)
	$P_L + P_b = 26.88$	$S_{mt} = 39.84$	Yes	HBB-3222.1(b)
Service level A stress limits	$P_m = 3.97$	$KS_m = 149.05$	Yes	HBB-3223(a)
	$P_L + P_b = 26.88$	$S_t = 39.84$	Yes	HBB-3223(c)(eq.4)
	$P_L + \frac{P_b}{K_t} = 25.63$	$S_{mt} = 78.77$	Yes	HBB-3223(c)(eq.5)
Service level B stress limits	$P_m = 3.97$	$KS_m = 148.51$	Yes	HBB-3223(a)
	$P_L + P_b = 26.88$	$S_t = 78.77$	Yes	HBB-3223(c)(eq.4)
	$P_L + \frac{P_b}{K_t} = 25.63$	1.0	Yes	HBB-3223(c)(eq.5)
Use fraction associated to P_m	0.004	1.0	Yes	HBB-3224(b)
Use fraction associated to $P_L + P_b$	0.112			HBB-3224(d)

Table 4.10: (Sample problem 3) Base material primary load checks. P_m is the maximum general primary membrane stress intensity, $P_L + P_b$ is the maximum combined primary membrane plus bending stress intensity, K is the section factor, and $K_t = \frac{K+1}{2}$. All limits are checked at the knuckle. Definition of all the allowable stresses can be found in HBB-3216.

4.3.6 Ratcheting check

Any of design by elastic analysis, design by inelastic analysis, or design by EPP analysis method can be used for evaluating the base material for strain limits. The clad material is ignored in the structural analysis. We used HBB-T-1322, Test A-1 in design by elastic analysis rules in Section III, Division 5. Table 4.11 summarizes the results. As indicated in the table, the 316H base material passes the ratcheting check.

The clad material is not required to satisfy the strain limits.

$X = \frac{(P_L + \frac{P_b}{K_t})_{max}}{S_y}$	0.070
$Y = \frac{(QR)_{max}}{S_y}$	0.097
$S_a = \min(1.25S_t, S_y)$	71.33 MPa
$\frac{S_a}{S_y}$	0.64
Pass criteria, $X + Y < \frac{S_a}{S_y}$?	Yes

Table 4.11: (Sample problem 3) Base material ratcheting limit check. S_y is the average of the yield strength values at the maximum and minimum wall averaged temperatures during the cycle and S_t is at the highest wall averaged temperature during the cycle and a time value of 10^4 hr.

4.3.7 Creep-fatigue damage check

4.3.7.1 Base material creep-fatigue evaluation

Creep-fatigue evaluation of the base material of a 316H component clad with tungsten can be performed using either design by inelastic analysis or design by EPP analysis. The clad material must be included in the design analysis. We used the design by EPP analysis method.

The design by EPP method requires establishing elastic shakedown of the clad structure in the finite element simulation considering the clad material as linear elastic and the base material as elastic-perfectly plastic with a pseudoyield stress. As described in Appendix-A of the Code Case, the pseudoyield stress of the 316H base material refers to temperature dependent minimum stress-to-rupture values based on a selected trial time duration but not to exceed the yield strengths. Once elastic shakedown is established in the finite element simulation, creep damage fraction is determined by taking the ratio of the total time duration for all Service Loadings to the trial time. Strain results from the elastic shakedown analysis are used to determine the fatigue damage fraction. Both the fatigue and creep damage fractions are then compared with the damage envelop in creep-fatigue interaction diagram for creep-fatigue evaluation of the base material.

Figure 4.14 compares results from EPP analyses of the vessel for different trial times. The figure indicates elastic shakedown of the vessel in finite element simulation when a trial time of 102,000 hr or less is used to determine the pseudoyield stress of the base material. The EPP

analysis results based on 102,000 hr trial time were used for creep-fatigue evaluation of the base

material.

Figure 4.15 shows example equivalent strain range results. Finally, Table 4.12 summarizes the creep-fatigue evaluation of the base material. As the table indicates, the base material passes creep-fatigue design check.

Figure 4.14: (Sample problem 3) Results from EPP analyses of the vessel are compared for different trial times. Trial times are used to determine the pseudoyield stress for the elastic-perfectly plastic model of the base material.

Figure 4.15: (Sample problem 3) Through thickness temperature and steady cyclic equivalent strain ranges at the knuckle under Level-A and combined Level-A and Level-B Service Loadings. Results are from the EPP elastic shakedown analysis based on a trial time equal to 110,000 hr.

<i>Creep damage calculation</i>	Trial time		1020000 hr
	Total time under all Service Loadings		100000 hr
	Creep damage fraction, D _c		0.981
<i>Fatigue damage calculation</i>	Under Service Level-A Loading only	Maximum equivalent strain range	0.00079
		Maximum temperature	645.4
		Total repetitions	50
		Total allowable cycles	4997410
	Under combined Service Level-A and Level-B Loading	Maximum equivalent strain range	0.00088
		Maximum temperature	649.9
		Total repetitions	50
		Total allowable cycles	1819998
	Total Fatigue damage fraction, D _f		3.74x10 ⁻⁵
<i>Does (D_f, D_c) fall inside the creep-fatigue damage envelop of 316H ?</i>			Yes

Table 4.12: (Sample problem 3) Base material creep-fatigue damage evaluation.

4.3.7.2 Clad material fatigue evaluation

Results from the EPP elastic shakedown analysis performed for the base material creep-fatigue evaluation should be used for evaluating fatigue of tungsten clad material.

Figure 4.15 shows example results from the EPP analysis, plotting temperature and equivalent strain range in tungsten clad at the knuckle of the vessel. The strain ranges and temperatures in the clad material are compared with the design fatigue curves to determine fatigue damage fraction for each cycle type. The sum of the fatigue damage fraction should be less than or equal to 1 for a design to pass clad material creep-fatigue damage check. However, the Code Case does not provide fatigue design curves for tungsten and therefore this design check was not performed.

4.3.8 Buckling check

A buckling check is not required for the clad material. Buckling of the base material is not expected under the internal pressure loading condition considered in this problem, so this design check was not performed.

5 Clad Selection Criteria

The design rules provided in the draft Code Case in Chapter 2 guard nickel and tungsten against all the potential failure modes in high temperature nuclear service when they are used as a clad material for 316H Class A components, assuming perfect bonding between the clad and base materials. However, these rules do not require long-term test data for both nickel and tungsten clad materials which was the central objective of developing these design rules. As discussed in Section 3.2, the solution to avoiding long-term test data of the clad material in the design rules is to limit the type of clad/base combinations that can be used for Class A service. The concept is based on two bounding approximations for the clad material response – treat the clad material either as linear elastic or as perfectly compliant. To treat a clad material as linear elastic it must have higher yield stress and creep much slower than the base material. While perfectly compliant treatment of a clad material means it must creep much faster than the base material. The former type of clads are called as hard clad material while the latter are called as soft clad materials. It will be shown later in this chapter that nickel qualifies as a soft clad material and tungsten qualifies as a hard clad material for 316H base material. Note that the material properties of tungsten used in this chapter come from literature rather than from Chapter 7. As indicated by the test results presented in Chapter 7, the tungsten we purchased for this project does not qualify as hard clad material for 316H base material.

Since the underlying concept of these design rules only allows the use of either hard or soft clad materials, criteria for selecting such clad materials are essential for broader implementation of the concept. For example, finding a different soft or hard clad material for another Class A base material. This chapter develops such clad selection criteria for Class A base material for high temperature nuclear service for a clad thickness in the range of 1% to 10% of the base material thickness.

5.1 Development of the criteria

5.1.1 Hard clad materials

Since our proposed design analysis method treats a hard clad material as linear elastic, both the time-independent plastic deformation and time-dependent creep deformation must be avoided in the hard clad material. Time-independent plastic deformation, i.e. yielding of the clad material can be avoided if the elastically distributed stress in the clad material is less than its yield strength.

$$\sigma_{clad} < \sigma_{clad}^{0.2\% \text{ offset yield}} \quad (5.1)$$

Considering that both the clad and base materials deform equally under a uniform membrane time-independent load, the correlation between stresses in the clad and base materials is:

$$\sigma_{clad} = R_E * \sigma_{base} \quad (5.2)$$

where R_E is the ratio of the elastic modulus between the clad and base materials. Combining Equations 5.1 and 5.2 and setting the time-independent stress limit of the base material to its 0.2% offset yield strength we get:

$$\sigma_{hard\ clad}^{0.2\% \text{ offset yield}} > R_E * \sigma_{base}^{0.2\% \text{ offset yield}} \quad (5.3)$$

The elastic stress distribution between the clad and base materials in actual components, however, may not exactly follow Equation 5.2. Therefore, if we consider $R_E = 1$ the clad material may yield before the base material starts yielding. This requires setting a minimum limit on the yield stress of the hard clad material. Several scoping studies showed yielding of the clad material can be avoided by adding an additional 50% margin on the yield stress requirement for the clad material. This gives the first criteria for selecting hard clad materials.

Hard clad criteria-1:

$$\sigma_{hard\ clad}^{0.2\% \text{ offset yield}} > \max(1.5, R_E) * \sigma_{base}^{0.2\% \text{ offset yield}} \quad (5.4)$$

Note all the quantities in Equation 5.4 are temperature dependent and therefore a condition for selecting the temperature is also required. Since yield stress decreases with temperature, the base material is most likely to have the proportionally highest yield stress at the minimum temperature. The criteria-1 provided in Equation 5.4 then shall be checked at the cold leg reactor inlet temperature under Service Level-A operating condition.

A second criteria should be set to limit the creep deformation in the hard clad material. This can be done either by the creep threshold temperature, i.e. negligible creep deformation in the clad material under the operating temperatures of the component, or by allowing some creep deformation in the clad material satisfying the bounding approximation made for the hard clad material. The criteria for the former of the two options is:

Hard clad criteria-2a:

$$T_{hard\ clad}^{creep\ threshold} > T_{clad}^{max} \quad (5.5)$$

where T_{clad}^{max} is the maximum clad temperature of the component under Service Level-A operating condition. The creep threshold temperature of metal can be determined from its melting point in absolute units.

$$T^{creep\ threshold} = f * T^{melting\ point} \quad (5.6)$$

where f is 0.3 for pure metal and 0.4 for alloys.

For the second option, we can bound the experimental creep strain, $\epsilon_{hard\ clad}^{creep}$ by a calculated elastic strain, $\epsilon_{hard\ clad}^{elastic}$. Both strains shall be computed at a stress level equal to 2/3 times $\sigma_{hard\ clad}^{0.2\% \text{ offset yield}}$ and the creep strain assumed to scale proportionally with time.

This can simply be checked from a creep test following:

$$\epsilon_{hard\ clad}^{creep} < \frac{t_{hard\ clad}^{test}}{t_{design}} * \epsilon_{hard\ clad}^{elastic} \quad (5.7)$$

where $\epsilon_{hard\ clad}^{creep}$ is the creep strain at the test time, $t_{hard\ clad}^{test}$ and t^{design} is the design life of the component. The creep test shall be performed at a stress level equal to $\frac{2}{3}$ times $\sigma_{hard\ clad}^{0.2\% offset\ yield}$. T_{clad}^{max} under Service Level-A operating condition can be conservatively chosen as the temperature for the creep test and the nominal hold time of 1000 hr can be chosen as $t_{hard\ clad}^{test}$. Due to slow creep rate, creep tests of potential hard clad materials may take too long to complete. Setting t_{test} in Equation 5.7 to nominal hold time of 1000 hr limits the required test time.

Equation 5.7 limits the total creep deformation of the hard clad material at the end of the component design life, t^{design} to the elastic deformation caused by a load equal to $\frac{2}{3} * \sigma_{hard\ clad}^{0.2\% offset\ yield}$. Therefore, t^{design} in Equation 5.7 can be conservatively set to 300,000 hr. This simplifies Equation 5.7 to the following criteria:

Hard clad criteria-2b:

$$\epsilon_{hard\ clad}^{creep} < R_t * t_{hard\ clad}^{test} * \epsilon_{hard\ clad}^{elastic} \quad (5.8)$$

where $R_t = 3.33 * 10^{-3} / hr$

Equation 5.8 can be rearranged to

$$t_{hard\ clad}^{test} > \frac{\epsilon_{hard\ clad}^{creep}}{R_t * \epsilon_{hard\ clad}^{elastic}} \quad (5.9)$$

The criteria 2a and 2b are provided as two options to check the creep deformation of the hard clad material. A clad material must satisfy one of these two criteria along with criteria-1 provided in Equation 5.4 to be considered as a hard clad material for use with Class A base material in high temperature nuclear service.

5.1.2 Soft clad materials

The bounding approximation of our proposed design method treats the soft clad material as perfectly compliant in the design analysis. Therefore, the selection criteria must ensure the soft clad material – (1) creeps much faster than the base material under time-dependent loading and (2) yields before the base material under time-independent loading. The latter of the two conditions can be set by:

Soft clad criteria-1:

$$\sigma_{soft\ clad}^{0.2\% offset\ yield} < \min(1, R_E) * \sigma_{base}^{0.2\% offset\ yield} \quad (5.10)$$

Two criteria can be introduced for the creep deformation requirement of the soft clad materials.

Soft clad criteria-2:

$$T_{soft\ clad}^{creep\ threshold} < T_{clad}^{max} \quad (5.11)$$

Soft clad criteria-3:

$$\epsilon_{soft clad}^{creep} > 10 * \epsilon_{base}^{creep} \quad (5.12)$$

Criteria-2 in Equation 5.11 ensures the creep threshold temperature of the soft clad material is below the maximum clad temperature. Criteria-3 in Equation 5.12 sets a minimum limit on the creep deformation of the soft clad material, $\epsilon_{soft clad}^{creep}$ – the soft clad material must deform 10 times more than the base material, ϵ_{base}^{creep} . The stress level for measuring the creep deformation in Equation 5.12 can be set to 2/3 times their respective 0.2% offset yield stress, i.e. $\frac{2}{3} * \sigma_{soft clad}^{0.2\% offset yield}$ for determining $\epsilon_{soft clad}^{creep}$ from a creep test and $\frac{2}{3} * \sigma_{base}^{0.2\% offset yield}$ for calculating ϵ_{base}^{creep} from Code isochronous stress strain curves.

Equation 5.12 also needs a time, $t_{soft clad}^{test}$ for creep strain determination.

$$t_{soft clad}^{test} = \min(1000 \text{ hr}, \frac{2}{3} * t_{soft clad}^{rupture}) \quad (5.13)$$

The reason to have two different time durations in Equation 5.13 is that a soft clad material may exhibit high creep under a stress of $\frac{2}{3} * \sigma_{soft clad}^{0.2\% offset yield}$ and the creep test duration could be short. Finally, a temperature must be defined for calculating the creep strain in Equation 5.12. Conservatively, this temperature can be set to the cold leg reactor inlet temperature under Service Level-A operating condition.

A clad material must satisfy all three soft clad selection criteria provided above to be considered as soft clad material for use with Class A base material in high temperature nuclear service.

5.2 Assessment of the criteria

We considered a 316H flat head vessel with cladding on the inner surface to assess the clad selection criteria developed above. Figure 5.1 shows the geometry of the vessel. The vessel is subjected to an internal pressure, $p=0.2$ MPa and a through thickness temperature gradient, $\Delta T=20^\circ\text{C}$ with a maximum inner surface temperature, $T_{max} = 650^\circ\text{C}$. The hold time at the maximum temperature is 1000 hr. The sample calculations consider two clad thicknesses – 10% and 1% of the base material thickness. The cold leg reactor inlet temperature is 550°C .

Figure 5.1: Geometry of a flat head vessel and load definition.

5.2.1 Hard clad selection criteria

We assessed the hard clad selection criteria on two materials – a “hypothetical” hard clad material that barely passes the hard clad selection criteria and tungsten that has much higher yield stress and higher creep resistance than the 316H base material. Results from two types of analyses – a full inelastic analysis and an elastic clad analysis – are compared to check whether the linear elastic response of the clad material bounds the results from the full inelastic analysis. Both analyses use inelastic material model for the constitutive response of the 316H base material, conceptually considering the Section III, Division 5 design by inelastic analysis rules for the base material. The clad material’s constitutive response is modeled with an inelastic material model in the full inelastic analysis while it is modeled as linear elastic in the elastic clad analysis.

Table 5.1 lists the properties of the “hypothetical” hard clad material. As indicated in the table the properties of the “hypothetical” hard clad material barely pass the hard clad selection criteria. Figure 5.2 and Figure 5.3 compare results from the full inelastic and elastic clad analysis for two clad thicknesses. According to the hard clad selection criteria-1, the clad should not yield. Figure 5.2 verifies this as stress in the clad from full inelastic simulation matches with that from elastic clad analysis after first cycle heat up, i.e. under time-independent load. Results in Figure 5.3 verify

negligible creep of the clad material as the strain ranges from two analyses closely match with each other.

<i>Property</i>	<i>Value</i>
Elastic modulus	Elastic modulus of 316H
0.2% offset yield stress	0.2% offset yield stress of 316H times 1.5 following criteria-1 in Equation 5.4
Creep rate	creep rate of 316H times a factor determined following criteria 2b in Equation 5.8

Table 5.1: Properties of the “hypothetical” hard clad material.

Figure 5.2: Through thickness von Mises stress (after cycle heat up) at the knuckle (shown with an arrow on the left figures) of the 316H flat head vessel. The plots compare results from full inelastic analysis and elastic clad analysis for 10% and 1% clad thickness. The clad material is the “hypothetical” hard clad material.

Figure 5.3: Through thickness equivalent strain range at the knuckle (shown with an arrow on the left figures) of the 316H flat head vessel. The plots compare results from full inelastic analysis and elastic clad analysis for 10% and 1% clad thickness. The clad material is the “hypothetical” hard clad material.

The second verification of the hard clad material selection criteria was done for tungsten. Properties of tungsten found in literature and material data sheet [8][29] are provided in Table 5.2. Note the creep rate of tungsten is not an experimentally determined creep rate, rather it is a theoretical creep rate determined using the creep model found in [8]. Comparing with the yield stress of 316H, the yield stress of tungsten passes the hard clad selection criteria-1 provided by Equation 5.4. The creep threshold temperature of tungsten, as provided in Table 5.2, is much higher than the clad maximum temperature in the sample vessel problem, satisfying hard clad selection criteria-2a. This means tungsten qualifies as a hard clad material for 316H base material without the need for checking criteria-2b. However, we can still use the theoretical creep rate of tungsten provided in Table 5.2 and check if tungsten satisfies the hard clad selection criteria-2b as well as the elastic clad analysis bounding approximation. Using the creep rate equation in Table 5.2, the creep strain of tungsten, $\epsilon_{Tungsten}^{creep} \left(\frac{2}{3} * \sigma_{Tungsten}^{0.2\% \text{ offset yield}}, 650C, 1000 \text{ hr} \right)$ is found to be 2×10^{-11} which is much less than 4.15×10^{-6} set by $R_t * 1000 \text{ hr} * \frac{2}{3} * \epsilon_{hard \text{ clad}}^{elastic} \left(\frac{2}{3} * \sigma_{Tungsten}^{0.2\% \text{ offset yield}} \right)$. Figure 5.4 shows the results from full inelastic and elastic clad analysis of the sample flat head vessel cladded with tungsten. Similar to the results of “hypothetical” hard clad flat vessel analyses, tungsten clad exhibits negligible creep and therefore the full inelastic analysis results exactly match the elastic clad analysis results.

<i>Property</i>	<i>Value</i>
Melting point	3422°C
Creep threshold temperature	835°C using Equation 5.6
Elastic modulus	380 GPa at 550°C and 376 GPa at 650°C [29]
0.2% offset yield stress	774 MPa at 550°C and 703 MPa at 650°C [29]
Creep rate	$6.05 \cdot 10^{-27} \cdot (\text{stress})^{4.7} / \text{hr}$ at 650°C [8]

Table 5.2: Properties of tungsten.

Figure 5.4: Through thickness equivalent strain range at the knuckle (shown with an arrow on the left figures) of the 316H flat head vessel. The plots compare results from full inelastic analysis and elastic clad analysis for 10% and 1% clad thickness. The clad material is tungsten.

5.2.2 Soft clad selection criteria

Similar to the hard clad selection criteria verification the soft clad selection criteria were also verified for two materials – a “hypothetical” soft clad material that barely satisfies all the criteria and a potential soft clad material, nickel which in general has much lower creep resistance compared to the Section III Division 5 Class A base materials such as 316H. Two types of analyses were performed – a full inelastic analysis with inelastic material models for both the 316H base and clad materials and a compliant clad analysis in which the 316H base material is modeled as inelastic but the clad material is modeled as elastic-perfectly plastic with a near zero pseudo-yield stress.

Table 5.3 lists the properties of the “hypothetical” soft clad material and how those are determined from the properties of the 316H base material.

Table 5.4 compares the properties of nickel with 316H base material and indicates that nickel satisfies the soft clad selection criteria. Properties of nickel were extracted from test data provided by Kairos Power, LLC. As indicated in the table nickel satisfies all the soft clad material selection criteria for 316H base material. Note a creep test data was not available for nickel at a stress equal to 2/3 times the 0.2% offset yield stress and at the cold leg reactor inlet temperature of 550°C. The 0.2% offset yield stress at 550°C is 87.2 MPa for nickel but creep tests were performed at 77 MPa which is significantly less than 87.2 MPa. However, satisfying the soft clad selection criteria-3 using creep strain from tests at a stress lower than the 0.2% offset yield stress of nickel is a conservative outcome.

<i>Property</i>	<i>Value</i>
Elastic modulus	Elastic modulus of 316H
0.2% offset yield stress	0.2% offset yield stress of 316H times 1.5 following criteria-1 in Equation 5.10
Creep rate	10 times the creep rate of 316H according to criteria-3 in Equation 5.13

Table 5.3: Properties of the “hypothetical” soft clad material.

<i>Property</i>	<i>nickel</i>	<i>316H</i>	<i>Comments</i>
Creep threshold temperature	244.7°C	Not required	Satisfies criteria-2 in Equation 5.11
Elastic modulus (GPa)	176 (550°C) 168 (650°C)	156 (550°C) 146 (650°C)	
2/3 times 0.2% offset yield stress (MPa)	87.2 (550°C) 54.8 (650°C)	96.7 (550°C) 54.8 (650°C)	Satisfies criteria-1 in Equation 5.10
Creep strain at 0.2% offset yield stress, 550°C, and $t_{Nickel}^{test} = \min(1000 \text{ hr}, \frac{2}{3} * t_{Nickel}^{rupture})$	6.92 x10 ⁻² from creep test-1 (Figure 5.5) conducted at 77 MPa which is less than 87.2 MPa	7.85x10 ⁻⁴ determined using Code Isochronous stress-strain curves at 550°C, 96.7 MPa, and 1000 hr	Satisfies criteria-3 in Equation 5.13
Note: From Figure 5.5 $t_{Nickel}^{test} = 1000 \text{ hr}$ and 754.1 hr for test-1 and test-2, respectively.	1.34 x10 ⁻² from creep test-2 (Figure 5.5) conducted at 77 MPa which is less than 87.2 MPa	7.19x10 ⁻⁴ determined using Code Isochronous stress-strain curves at 550°C, 96.7 MPa, and 754.7 hr	

Table 5.4: Properties of nickel and 316H base metal.

Figure 5.6 and Figure 5.7 compare results from an analysis using an inelastic model for the clad material with results from compliant clad analysis, respectively, for the “hypothetical” soft clad material and nickel. A perfectly compliant soft clad material should deform following the base material and should not significantly affect the deformation of the base material. This can easily be seen in results from 1% cladded vessel – the base material strain range from both the compliant clad analysis and the full inelastic analysis exactly match with each other for both the “hypothetical” soft clad material and nickel. However, results from analyses of 10% cladded vessel

do not exactly match but they can be considered as sufficiently close, indicating the soft clad selection criteria satisfies the compliant clad bounding approximation.

Figure 5.5: Creep tests of nickel at 550°C under 77 MPa stress.

Figure 5.6: Through thickness equivalent strain range at the shell and the knuckle of the 316H flat head vessel. The plots compare results from full inelastic analysis and compliant clad analysis for 10% and 1% clad thickness. The clad material is the “hypothetical” soft clad.

Figure 5.7: Through thickness equivalent strain range at the shell (top) and the knuckle (bottom) of the 316H flat head vessel. The plots compare results from full inelastic analysis and compliant clad analysis for 10% and 1% clad thickness. The clad material is nickel.

5.3 Proposed clad selection criteria for Class A components

The clad selection criteria are summarized below.

5.3.1 Criteria for hard clad materials

The clad must satisfy criteria-1 and either criteria-2a or criteria-2b below:

Criteria-1: The 0.2% offset yield strength of the clad material must be greater than R_E times the 0.2% offset yield strength of the base material, where R_E is the ratio of the elastic modulus between the clad and base materials but not less than 1.5. The strength and modulus are at the cold leg reactor inlet temperature.

Criteria-2a: The maximum clad temperature under Service Level A must be less than the creep threshold temperature of the clad material. The creep threshold temperature is given by f times the melting point of the clad material in absolute units, where f is 0.3 for pure metals and 0.4 for alloys.

Criteria-2b: The test time for a clad creep test must be greater than or equal to 1000 hr to reach a clad creep strain of R_t times the elastic strain at $2/3$ times the 0.2% offset yield strength of the clad material. $R_t = 3.3 \times 10^{-3}$ unless otherwise justified and documented in the Design Report (NCA-3550) and the Design Specifications (NCA-3250). The measured creep strain and yield strength are at the maximum clad temperature during Service Level A.

5.3.2 Criteria for soft clad materials

The clad must satisfy all the criteria below:

Criteria-1: The 0.2% offset yield strength of the clad material must be less than R_E times the 0.2% offset yield strength of the base material, where R_E is the ratio of the elastic modulus between the clad and base materials but not greater than 1. The strength and modulus are at the cold leg reactor inlet temperature.

Criteria-2: The maximum clad temperature under Service Level A must be greater than the creep threshold temperature of the clad material. The creep threshold temperature is given by f times the melting point of the clad material in absolute units, where f is 0.3 for pure metals and 0.4 for alloys.

Criteria-3: The clad creep strain at test time, t_{test} and $2/3$ times the 0.2% offset yield strength of the clad material must be greater than 10 times the creep strain of the base material at time t_{test} and $2/3$ times the 0.2% offset yield strength of the base material, where t_{test} is the lesser of the nominal hold time of 1000 hr and $2/3$ times the creep rupture time measured from the creep test of the clad material. The measured creep strain and yield strength are at the Service Level A cold leg reactor inlet temperature.

6 Acceptance Test for Checking Clad/Base Metal Interface Integrity

The design method developed for clad components in this work are based on a *priori* assumption of perfect bonding between the clad and base materials, i.e. the interface between the clad and base materials remains fully bonded during the service life. In practice, however, the clad/base interface may fail before the end of the design life of the component. Therefore, criteria must be developed to check the mechanical integrity of clad/base metal interface.

Some examples of commercially available bonding and deposition methods feasible for joining the clad and base materials are weld overlay [23], explosion bonding [24], coextrusion/corolling [25], thermal spray [26], and cold spray [27]. The strength and reliability of the clad/base metal interface produced by these methods must be evaluated for high temperature nuclear service. One approach to assess the interface could be the use of some design by analysis method. The analysis would provide realistic estimates of the interface tractions that would lead to potential delamination. However, evaluating the strength of the interface will be challenging as it will depend on the details of the bonding method.

An alternate to a design by analysis approach is acceptance testing under accelerated loading conditions. If the clad/base bond remains intact throughout an appropriately designed accelerated test, the interface will be considered reliable under the service loading conditions for the full component design life. The objective of the acceptance testing would be then to assess only the bonding integrity between the base and clad materials, without specifying the cladding methods. Structural integrity of the bulk of the base and clad materials are covered by the design rules provided in Chapter 2. The rest of this chapter develops an acceptance testing procedure for checking the mechanical integrity of the clad/base metal interface.

6.1 Approach and assumptions

A unique feature of the acceptance method developed here is that the acceptance test conditions are derived from some bounding operating conditions for the clad component under consideration. Several considerations were made while developing such an acceptance testing protocol. It is desirable to have the testing method and specimen geometry to be as simple as possible. Determination of the test condition should not require much effort from the designer. Finally, and most importantly, the duration of the test should be reasonably short.

NASA [34] has used simple thermal cycling tests on button specimens to evaluate the bond strength in plasma-sprayed thermal barrier coating systems for high temperature applications. The idea is simple – when a bimetallic disc is heated thermal stress develops due to the difference in the coefficient of thermal expansions between the two metals. The maximum thermally induced interfacial shear stress occurs at the edge of the disc [35]. This is an important phenomenon because the edge of the disc can be easily checked for potential interface delamination using NDE techniques such as dye penetrant examination, radiography, and optical microscopy. Because of simplicity in the test method and specimen geometry, we adopted similar thermal cycling tests on 12.7 mm (0.5 in) diameter clad button specimens for the acceptance test.

The thermal cycling test begins with heating the clad buttons from room temperature to the maximum operating temperature and then cycles the temperature over a range that creates an

interfacial shear stress range at the edge of the button exceeding the maximum interfacial shear stress range experienced by the component in operation. The total number of temperature cycles equals to the total number of component design transients. The load cycle periods are reduced by eliminating hold times and increasing temperature ramp rates to achieve the required number of cycles in a short period of time. The button specimens would be inspected at the edge before the thermal cycling test to ensure the specimens had complete bonding in the as-received condition. After the thermal cycling test is completed, the specimens would be inspected again for potential debonding of the interface at the edge.

However, an acceptance test based on the procedure discussed above requires:

- 1) Development of a correlation between the temperature range applied to the button specimens during the thermal cycling and the interfacial shear stress range at the edge of the button. Note the correlation should be simple for easy determination of the temperature range.
- 2) Defining the heating and cooling rates during the temperature cycling.
- 3) Defining the heating rate for the initial heat up from room temperature and cooling rate during the final cool down to room temperature.

6.2 Development of the acceptance test procedure

6.2.1 Analytical expression for estimating temperature range

As discussed above, the first step in developing the acceptance test procedure is to define a correlation between the temperature range applied during the thermal cycling test and the resulting interfacial shear stress/strain range at the edge of the button specimens. A simple correlation would allow an estimation of the shear stress/strain range using the elastic properties of the base and clad materials. As this simple, analytic correlation assumes a linear elastic response, the following presents a validation study demonstrating the elastically-calculated stress/strain ranges are reasonable even when accounting for creep and plasticity provided the load cycle parameters meet certain criteria.

We performed finite element structural analyses of a clad button for the validation study. The base material is 316H while the clad material is TZM. Figure 6.1 shows the geometry of the button along with the finite element model and the temperature loading profile used. The clad button is first heated from RT to $T^{max} - \Delta T$ and then cycled between $T^{max} - \Delta T$ and T^{max} . We performed several finite element calculations considering different initial heating rates from RT to $T^{max} - \Delta T$, heating/cooling rates during the thermal cycling, and three different ΔT . Table 6.1 lists all the different loading conditions. In all the cases $T^{max} - \Delta T = 670^\circ C$. We considered both the base and clad materials linear elastic for elastic calculations of the stress/strain range. For inelastic analysis, we modeled both the base and clad materials with elastic perfectly-plastic power law creep inelastic models. Figure 6.2 shows the contour plot of the shear strain range from the inelastic analysis at the 50th cycle for three different loading conditions. As indicated in the figure, the maximum shear strain range in the clad button occurs at the edge of the button.

Table 6.1 compares the maximum interfacial shear strain ranges calculated from inelastic analysis for different heating and cooling rates and temperature ranges are compared with the elastically calculated values. The table lists the strain range values from inelastic analysis for the 10th and 50th thermal cycles. The strain range values at 50th cycle are the cyclic steady-state response of the structure. As indicated in the table, the steady-state strain range values from inelastic calculations are very close to the elastically calculated values for all the different loading conditions. This means the maximum interfacial shear strain range during the thermal cycling can be estimated using simple elastic analysis and does not require sophisticated inelastic material models. Since the strain range can be estimated using elastic analysis, an analytical relationship between the maximum interfacial shear strain range and the temperature range, ΔT applied during the thermal cycling is possible. This would allow the estimation of ΔT from the maximum interfacial shear strain range computed in the finite element analysis of clad components under design transients and use the ΔT for performing thermal cycling tests on the button specimens for checking the mechanical integrity of the clad/base metal interface.

Figure 6.1: Geometry and finite element model of the clad button and the thermal loading profile for structural finite element calculation.

ΔT (°C)	Heating rate between RT and $T^{max} - \Delta T$ (°C/min)	Heating/cooling rate between $T^{max} - \Delta T$ and T^{max} (°C/min)	Elastic	$\Delta \epsilon_{rz}$ (%)	
				Inelastic	
				10 th cycle	50 th cycle
60	1	1	0.061	0.070	0.063
	1	5		0.065	0.062
	1	10		0.064	0.061
	1	20		0.063	0.061
	1	30		0.063	0.061
	10	10		0.064	0.061
30	10	10	0.031	0.032	0.030
90	10	10	0.096	0.109	0.097

Table 6.1: Simulated maximum interfacial shear strain range in the clad button during the thermal cycling for different loading conditions.

Figure 6.2: Contour plot of shear strain range at 50th cycle for different temperature range – (a) 30°C, (b) 60°C, (c) 90°C. Both the initial heating rate and heating/cooling rate during thermal cycling are 10°C/min.

Suhir [35] developed an analytical solution predicting interfacial stresses in a circular substrate/thin-film structure experiencing thermally induced bending deformations. The solution is based on two important assumptions – (a) the substrate can be treated as a thin circular plate experiencing small deflections and the engineering theory of bending plates can be used to predict stresses in the substrate and (b) thin film layers cannot withstand bending i.e. they are subjected to tension and compression only. According to the analytical solution, the maximum interfacial shear stress range is,

$$\Delta\tau_{interface}^{max} = \left| \sqrt{\frac{3}{2} \frac{(1+\nu_c)E_bE_c}{(1-\nu_c)(1+\nu_b)}} \frac{t_c}{t_b} (\alpha_c - \alpha_b) \Delta T \right| \quad (6.1)$$

where E is the modulus of elasticity, ν is Poisson's ratio, α is the coefficient of thermal expansion, t is the thickness, ΔT is the change in temperature, and subscripts b and c are for base and clad material, respectively. Since the assumptions do not consider bending in the film, i.e. clad in our problem, it is important to investigate how the analytical solution differs from the finite element solution.

We ran several finite element calculations with different base and clad material properties and with several clad percentages ranging from 1% to 10%. Figure 6.3, Figure 6.4, and Figure 6.5 show some example results comparing the maximum interfacial shear strain range computed from finite element calculations with that from analytical expression in Equation 6.1. As indicated by the figures, the analytical solutions differ from the finite element solutions. Although no bending in the clad material is assumed for the analytical solution, it may still experience significant bending depending on the relative stiffness between the clad and base materials. An important observation from this parametric study is that the difference between the analytical and finite element solutions is not significantly affected by the difference in Poisson's ratio and the coefficient of thermal expansion between the clad and base materials. For example, as indicated by the results in Figure 6.4 and Figure 6.5 the ratio between analytical and finite element solutions does not vary significantly with the change in the ratio of Poisson's ratio and the coefficient of thermal expansion between the clad and base materials. However, the difference between analytical and finite element solution does vary significantly with the change in clad percentage and the elastic modulus ratio between the clad and base materials.

To match the analytical solution to the finite element solution the analytical expression in Equation 6.1 can be modified to:

$$\Delta\tau_{interface}^{max} = \left| \frac{1}{f} \sqrt{\frac{3}{2} \frac{(1+\nu_c)E_bE_c}{(1-\nu_c)(1+\nu_b)}} \frac{t_c}{t_b} (\alpha_c - \alpha_b) \Delta T \right| \quad (6.2)$$

where f is the ratio between the analytical and finite element solutions and a function of $\frac{E_c}{E_b}$ and $\frac{t_c}{t_b}$. Table 6.2 lists the values of f determined from the parametric study. As indicated in the table, the values of f are less than 1 for a clad percentage of 3% or less and also for 5% clad for some elastic modulus ratios. In the proposed acceptance test procedure, we changed these values to 1. Since ΔT will be estimated from the maximum interfacial shear stress computed in the finite element analysis of the component, increasing these values to 1 would be a conservative estimation of the temperature range for the thermal cycling test.

Figure 6.3: Comparison of the maximum interfacial shear strain range between the analytical and finite element solutions for different clad percentages and different E ratios between the clad and base materials. Material properties are $E_b = 140 \text{ GPa}$, $\nu_b = \nu_c = 0.27$, $\alpha_b = 18.6 \times 10^{-6}$, and $\alpha_c = 4 * \alpha_b$ and $\Delta T = 100^\circ\text{C}$.

Figure 6.4: Comparison of the maximum interfacial shear strain range between the analytical and finite element solutions for different clad percentages and different α ratios between the clad and base material. Material properties are $E_b = E_c = 140 \text{ GPa}$, $\nu_b = \nu_c = 0.27$, and $\alpha_b = 18.6 \times 10^{-6}$ and $\Delta T = 100^\circ\text{C}$.

Figure 6.5: Comparison of the maximum interfacial shear strain range between the analytical and finite element solutions for different clad percentages and different v ratios between the clad and base materials. Material properties are $E_b = E_c = 140 \text{ GPa}$, $\nu_b = 0.27$, $\alpha_b = 18.6 \times 10^{-6}$, and $\alpha_c = 0.25 \times \alpha_b$ and $\Delta T = 100^\circ\text{C}$.

		$\frac{t_c}{t_b}$				
		1%	3%	5%	7.5%	10%
$\frac{E_c}{E_b}$	0.125	0.92	1.00	1.11	1.22	1.32
	0.25	0.75	0.86	0.97	1.08	1.19
	0.5	0.67	0.80	1.00	1.05	1.16
	1	0.65	0.81	0.94	1.07	1.22
	2	0.69	0.87	1.00	1.13	1.26
	4	0.69	0.91	1.07	1.24	1.36
	8	0.74	0.97	1.12	1.28	1.41

Table 6.2: Ratio of the maximum interfacial shear stress range between the analytical and finite element solutions, f as a function of E and t ratios between the clad and base materials.

6.2.2 Maximum temperature and number of thermal cycles

The maximum temperature, T^{max} is also needed along with the ΔT for defining the temperature profile for the thermal cycling test. We propose to use the maximum temperature the clad/base metal interface in the component experiences during design loading condition as the T^{max} . In this way, the clad/base interface integrity will be tested at the maximum operating temperature condition.

The total number of thermal cycles should be equal to the total number of design transients. This is conservative because some of the design transients will cause a shear stress range less than $\Delta\tau_{interface}^{max}$.

6.2.3 Heating and cooling rates

Finally, the acceptance test procedure must define the heating and cooling rates during the temperature cycling as well as rates for the initial heat up from room temperature and final cool down to room temperature. A general approach for the initial heating and final cooling should be as slow as possible to avoid breaking of the interface during these two parts of the overall thermal loading applied to the clad button. On the other hand, the heating and cooling rates during the temperature cycling should be selected so the maximum interfacial shear stress/strain range in the clad button matches that in the component.

Results in Table 6.1 for $\Delta T = 60^\circ C$ and the initial heating rate of $1^\circ C/min$ indicate that the maximum interfacial shear strain range from inelastic analysis matches with that from elastic analysis when the heating/cooling rate during thermal cycling is equal to or faster than $10^\circ C/min$. Increasing the initial heating rate to $10^\circ C/min$ does not change the results. We, therefore, propose to use a rate slower than $10^\circ C/min$ for the initial heat up from RT to $T^{max} - \Delta T$ and final cool down from $T^{max} - \Delta T$ to RT and use a heating/cooling rate faster than $10^\circ C/min$ during the thermal cycling.

Note that due to the large temperature difference the initial heating up from RT to $T^{max} - \Delta T$ may develop high level of stress and may cause failure of the clad/base interface. The actual interfacial stress will depend on the residual stress in the button induced by the fabrication method, as creep will be unable to alleviate either the thermal or residual stress during the low temperature part of the heating. Failure during the initial heating or final cooling is not ideal, as the interface conditions are substantially unknown. The selection of a slow initial heating rate will help relax initial stress. Similarly, a slow final cooling rate will avoid stress buildup in the button while cooling down to RT . Additionally, actual clad components at least at the beginning of the service life will experience a similar heat up from room temperature and so the initial, slow part of the thermal cycle can be taken as representative. Finally, even if the initial heating/final cooling causes added interface damage this is a conservative outcome – this damage is in addition to the damage accumulated during the controlled temperature cycling.

6.3 Proposed step-by-step procedure of the acceptance test

The below provides step-by-step procedure for experimental technique to check the mechanical integrity of clad/base metal interface. Tests should be performed on 12.7 mm diameter clad buttons. The thickness ratio between the clad and base materials in the buttons should match that in the actual component.

Step-1: Perform an elastic transient thermo-mechanical analysis of the component.

Step-2: Determine the maximum clad/base interface shear stress intensity range, $\Delta\tau_{interface}^{max}$ and the maximum clad/base interface temperature, T^{max} .

Step-3: Determine a representative number of cycles, N the clad/base interface will be subjected to. Conservatively, this could be the total number of design transients, even though some of these transients will cause a shear stress range of less than $\Delta\tau_{interface}^{max}$.

Step-4: Determine ΔT according to Equation 6.3.

$$\Delta\tau_{interface}^{max} = \begin{cases} \left| \sqrt{\frac{3}{2} \frac{(1+\nu_c)E_bE_c}{(1-\nu_c)(1+\nu_b)} \frac{t_c}{t_b}} (\alpha_c - \alpha_b) \Delta T \right| & ; \text{if } t_{clad} < 3\% t_{base} \\ \left| \frac{1}{f} \sqrt{\frac{3}{2} \frac{(1+\nu_c)E_bE_c}{(1-\nu_c)(1+\nu_b)} \frac{t_c}{t_b}} (\alpha_c - \alpha_b) \Delta T \right| & ; \text{if } 3\% t_{base} \leq t_{clad} \leq 10\% t_{base} \end{cases} \quad (6.3)$$

where,

E_b = elastic modulus of the base material at T^{max}

E_c = elastic modulus of the clad material at T^{max}

α_b = coefficient of thermal expansion of the base material at T^{max}

α_c = coefficient of thermal expansion of the clad material at T^{max}

ν_b = Poisson's ratio of the base material

ν_c = Poisson's ratio of the clad material

t_b = thickness of the base material

t_c = thickness of the clad material

f = a factor determined according to Table 6.3

f	$\frac{t_c}{t_b}$			
	3%	5%	7.5%	10%
$\frac{E_c}{E_b}$				
0.125	1.00	1.11	1.22	1.32
0.25	1.00	1.00	1.08	1.19
0.5	1.00	1.00	1.05	1.16
1	1.00	1.00	1.07	1.22
2	1.00	1.00	1.13	1.26
4	1.00	1.07	1.24	1.36
8	1.00	1.12	1.28	1.41

Table 6.3: Determination of f in Equation 6.3.

Step-5: Perform initial inspection of the clad/base interface to ensure the sample had complete bonding in the as-received condition.

Step-6: Perform temperature cycling tests on the 12.7 mm diameter cladmed buttons as shown in Figure 6.6. The buttons should be heated at a rate slower than $10^\circ\text{C}/\text{min}$ from room temperature

to $T^{max} - \Delta T$ before applying the temperature cyclic loading shown in Figure 6.6. The heating/cooling rate during the temperature cycling test should be faster than $10^\circ\text{C}/\text{min}$. The total number of applied temperature cycles is N .

Figure 6.6: Geometry and thermal cyclic loading profile for the button test specimens.

Step-7: After applying N number of temperature cycles, specimens are cooled down to room temperature at a rate slower than $10^\circ\text{C}/\text{minute}$.

Step-8: Inspect the clad/base interface for debonding. Use the same inspection technique used in Step-5. The test passes if no defects are observed.

6.4 Determination of interfacial shear stress from finite element calculation

The stress/strain solution from finite element structural analysis are in the global reference system which may not align with the natural interface coordinate system. In such cases, a treatment of the finite element analysis results is required to determine the interfacial shear stress. The following provides a procedure for determining the interfacial shear stress from the stress components and the interface surface normal vector in the global reference system.

Define the traction vector on the interface surface as

$$\hat{T}_i = \hat{\sigma}_{ij} \hat{n}_j \quad (6.4)$$

where $\hat{\sigma}_{ij}$ is the stress tensor, $\hat{n}_j$ is the normal vector to the interface surface in the global reference system, i and j are indices x , y , and z identifying the coordinates in the global reference system. The normal and shear components of the traction – $\mathcal{T}_n$, $\mathcal{T}_{s1}$ and $\mathcal{T}_{s2}$ – acting on the interface surface

can be computed by rotating the traction vector, $\hat{T}_i$ from the global reference system to the natural interface coordinate system according to

$$\begin{bmatrix} \mathcal{T}_n \\ \mathcal{T}_{s1} \\ \mathcal{T}_{s2} \end{bmatrix} = \bar{\bar{R}} \begin{bmatrix} \mathcal{T}_x \\ \mathcal{T}_y \\ \mathcal{T}_z \end{bmatrix} \quad (6.5)$$

where $\bar{\bar{R}}$ is the coordinate transformation tensor rotating $\hat{n}_j$ to $\hat{n}_o$. Here, $\hat{n}_o = \{1,0,0\}$ is the normal vector in the natural interface coordinate system. $\bar{\bar{R}}$ can be calculated using Rodrigues' rotation formula

$$\bar{\bar{R}} = I + \sin(\theta)\bar{\bar{K}} + (1 - \cos(\theta))\bar{\bar{K}}^2 \quad (6.6)$$

where I is the identity matrix and $\theta = \arccos(\hat{n} \cdot \hat{n}_o)$ is the angle between $\hat{n}$ and $\hat{n}_o$. K is the skew symmetric matrix defined as

$$\bar{\bar{K}} = \begin{bmatrix} 0 & -k_z & k_y \\ k_z & 0 & -k_x \\ -k_y & k_x & 0 \end{bmatrix} \text{ with } k = \frac{\hat{n} \times n_o}{|\hat{n} \times n_o|} \quad (6.7)$$

The resulting shear tractions, $\mathcal{T}_{s1}$ and $\mathcal{T}_{s2}$ from the transformation in Equation 6.5 have arbitrary directions and therefore the magnitude of the in plane shear traction, $\mathcal{T}_s = \sqrt{\mathcal{T}_{s1}^2 + \mathcal{T}_{s2}^2}$ can be utilized to evaluate the interfacial shear stress.

7 Tungsten Test Results

7.1 Material, specimens, and evaluation method

Pure tungsten rod material with nominal 0.625-inch diameter was procured from a commercial vendor. The chemical compositions of this 99.95% pure tungsten rod are listed in Table 7.1. The density of the tungsten rod is greater than 19.0g/cm³ and the as-received rods were stress relieved.

Heat or lot ID	Fe	Al	Si	Ca	Mg	Ni	O	P	S	N	W
068/21068/052920	≤ 0.0015	≤0.0010	≤0.0011	≤0.0010	≤0.0011	≤0.0020	≤0.0030	≤0.0012	≤0.0009	≤0.0020	≥99.95

Table 7.1: Chemical compositions of the pure tungsten rod (wt.%).

The original plan was to generate fatigue design curve using this pure tungsten rod material to support the clad rules for elastic clad material. However, during the evaluation process, this pure tungsten behaved unexpectedly ductile at elevated test temperatures. The test plan was modified to include evaluation of its tensile properties and the Ductile to Brittle Transition temperature.

Tungsten and its alloys are prone to oxidation at elevated test temperatures. To minimize the effect of oxidation on its mechanical properties the fatigue and tensile tests for this study were performed in an inert environmental chamber, purged and filled with Ultra High Purity Grade Argon gas (99.999% purity). The Charpy impact tests were performed in air with the total duration of less than 15 mins for the specimen exposed at the test temperatures prior to each impact test. All the specimens were inspected post-test and no severe oxidation were observed.

The button-head fatigue specimen geometry used in this study is shown in Figure 7.1. The gage section had 0.25-inch in diameter with 0.75-inch uniform gage length. It is critical for the fatigue specimens to meet the surface finish requirements and with the final grinding along the longitudinal direction. Fatigue tests followed ASTM E606 [123] for strain-controlled testing and ASTM E 466 [123] for load-controlled testing. Both types of fatigue testing were fully reversed with the loading ratio of -1.

The tensile specimens were the same button-head geometry but with longer uniform gage length of 1 inch. The tensile testing procedure followed ASTM E8 at room temperature and ASTM E21 [123] at elevated test temperatures.

The Charpy test specimen used unnotched bar geometry specified for powder metallurgy materials in ASTM E23 [123].

7.2 Mechanical testing results on pure tungsten

7.2.1 Evaluation of the Tensile Properties

Tensile tests were performed at room temperature, 375°C, 450°C, 550°C and 704°C. The stress-strain curves are plotted in Figure 7.2 and Figure 7.3. Photographs of the tensile specimens are shown in Figure 7.4. A summary of the tensile test results is listed in Table 7.2. Note that the tensile tests at 450°C used a shorter gage length specimen but it was not expected to affect the tensile properties.

Figure 7.1: Specimen geometry for fatigue evaluation. Units are in inches.

At room temperature, this pure tungsten is brittle with total elongation of 0.013% and non-measurable cross-sectional area reduction after test. The room temperature tensile strength is 1289MPa. The specimen failed in a typical brittle failure mode (see Figure 7.4). At elevated test temperatures of 375°C and higher, both the strain hardening rate beyond yield and the uniform elongation decreased with increasing test temperature. At 450°C and higher, the ultimate tensile strengths appear at the upper yield points.

All the tests performed at elevated temperatures showed good ductility, with total elongation of 66.8%, 64.1%, 61.4% and 56.4% at 375°C, 450°C, 550°C and 704°C, respectively. All the tensile specimens showed significant necking with the reduction of area of 65% or higher after testing at these elevated temperatures.

7.2.2 Ductile to Brittle Transition

During the project planning stage, the tungsten material was expected to be brittle, and therefore the unnotched bar specimen geometry was selected for Charpy-type impact testing (unnotched bars). The Charpy tests were performed at room temperature, 200°C, 350°C and 715°C. The results are summarized in Table 7.3. This tungsten was brittle at room temperature with low average Charpy impact energy of 7.1 J. The Charpy impact energy increased slightly when the test temperature was increased to 350°C. At 715°C, the specimen did not fracture upon impact but was severely bended, indicating high ductility. Due to the concern of potential damage to the impact machine by the stick anvil, no additional impact tests were performed at elevated temperatures. Photographs of the impact specimens are shown in Figure 7.5.

The impact test results are consistent with brittle tensile behavior at room temperature and the unexpected high ductility at the elevated temperatures. The Charpy impact results are also plotted in Figure 7.6. The tensile stress-strain curves were used to estimate the impact energies at temperatures between 375°C and 715°C although the loading rate effect was not considered. The results confirm that the ductile to brittle transition temperature range is sharp and the upper shelf of the transition temperature is below 375°C.

Figure 7.2: Room temperature tensile stress-strain curve of the pure tungsten.

Figure 7.3: Tensile stress-strain curves of pure tungsten at elevated temperatures.

Figure 7.4: Photographs of the tensile test specimens.

<i>Temp.</i> °C	<i>Ultimate tensile strength,</i> MPa	<i>Total elongation,</i> %	<i>Uniform elongation</i> %	<i>Yield, σ0.2%</i> MPa	<i>Reduction of area,</i> %
RT	1289.0	0.013	0.013	1217	Not measurable
375	545.1	66.8	31.2	461	65
450	504.5	64.1	23	482	83
550	429.0	61.4	21.6	388.5	81
704	441.5	56.4	20	420	90

Table 7.2: Tensile properties of the pure tungsten

<i>Specimen Id.</i>	<i>Test temp.</i>		<i>Dial Energy</i>		<i>Lat. Exp.</i>	
	°F	°C	ft-lbs	J	mils	mm
W 1	72	22	5.5	7.5	0	0.00
W 2	72	22	5.8	7.8	0	0.00
W 3	72	22	4.5	6.1	0	0.00
W 4	392	200	8.5	11.5	3	0.08
W 5	392	200	8.2	11.1	2	0.05
W 6	392	200	6.3	8.5	5	0.13
W 8	662	350	71	96.3	36	0.91
W 9	662	350	25	33.9	18	0.46
W 10	662	350	40	54.2	27	0.69
W 7	1319	715	>297	>402.7	N/A	N/A

Table 7.3: Charpy impact test results of the pure tungsten

Figure 7.5: Photographs of the Charpy impact specimens

Figure 7.6: Ductile to Brittle Transition of the pure tungsten

7.2.3 Fatigue Testing

Strain-controlled fatigue test at strain range of 0.6% and 550°C started with a 1×10^{-3} /sec strain rate and later increased to 2×10^{-3} /sec at cycle number 192. The hysteresis loops of representative cycles are plotted in Figure 7.7 and compared with the tensile curve at the same test temperature. Upon increasing the strain rate, the specimen showed high strain rate sensitivity with an increase of peak tensile stress from initial 360 MPa to 482 MPa.

The maximum and minimum stresses as a function of the applied cycles are shown in Figure 7.8. The discontinuities in the plot were due to restart of the fatigue after adjusting the control extensometer to prevent slippage. This tungsten showed typical cyclic softening behavior. The cycles to failure were 28,104 for this test.

Figure 7.7: Hysteresis loops of representative fatigue cycles at 0.6% strain range and 550°C

Figure 7.8: Maximum and minimum stresses of fatigue test at 0.6% strain range and 550°C.

In order to generate fatigue data with shorter testing duration by increasing the loading frequency, it was decided to switch to load-controlled mode for tests with peak stresses lower than the yield stress at 550°C. The load-controlled fatigue was then performed with stress amplitude of ± 300 MPa, corresponding to an initial strain range of 0.5%. The hysteresis loops of the first two load-controlled fatigue cycles were compared with the strain-controlled fatigue and the tensile test in Figure 7.9. The loading portion of the stress-strain curves were matching reasonably well for all three type of tests. However, the hysteresis loops of the load-controlled fatigue started to ratchet to the compressive strain direction with the second cycle. Additional hysteresis loops of the load-controlled fatigue test are shown in Figure 7.10. The hysteresis loops became wider with increased number of applied cycles, consistent with the cyclic softening behavior. Significant ratcheting was observed, and it reached a compressive strain of $\sim 10\%$ within 1000 cycles. Although the stress amplitude was below yield, the material is apparent not in the pure elastic regime at this stress range. The cycles to failure for this test were 6,900.

Figure 7.9: Comparison of the stress-strain responses of load-controlled fatigue, strain-controlled fatigue and the tensile test at 550°C.

Figure 7.10: Hysteresis loops of the load-controlled fatigue at 550°C.

Strain-controlled fatigue test was performed at 1% strain range and 550°C with 1×10^{-3} /sec strain rate. The maximum and minimum stresses as a function of the applied cycles are shown in Figure 7.11. The cyclic softening behavior was also observed at this strain range. The cycles to failure are 13,230.

Figure 7.11: Maximum and minimum stresses of fatigue test at 1% strain range and 550°C.

In order to assess the temperature effect on fatigue life of this tungsten, strain-controlled fatigue test was performed at the same 1% strain range at 704°C with 1×10^{-3} /sec strain rate. The maximum and minimum stresses as a function of the applied cycles are shown in Figure 7.12. The cyclic softening behavior was also observed at this temperature. The stress ranges at 704°C were lower than those at 550°C when tested at the same strain range of 1%. The cycles to failure for this test are 4,348, much lower than the fatigue cycles at 550°C. The failure location was outside the control extensometer gage.

Figure 7.12: Maximum and minimum stresses of fatigue test at 1% strain range and 704°C.

Strain-controlled fatigue test at strain range of 0.3% and 760°C with 1×10^{-3} /sec strain rate was performed. Representative hysteresis loops are plotted in Figure 7.13. The stress-strain responses were elastic at this low strain range. Unfortunately, the control extensometer slipped at cycle number 27,532 and so the test did not yield a valid number of cycles to failure. The test fixtures were also damaged due to the overload when the slippage of the extensometer occurred, and no additional tests were performed at 760°C.

Figure 7.13: Hysteresis loops of the strain-controlled fatigue at 0.3% strain range and 760°C.

7.3 Summary of mechanical testing on pure tungsten

The stress relieved pure tungsten material used in this study is brittle at room temperature. The tungsten is prone to oxidation at elevated temperatures, and long duration testing at elevated temperatures shall be performed under inert atmosphere. This pure tungsten studied has a sharp Ductile to Brittle Transition temperature range. Tensile tests and Charpy impact tests at elevated temperatures of 375°C and above showed high ductility. Strain-controlled fatigue testing of this tungsten is challenging due to its high yield strength levels at the test temperature range of interest. The fatigue test results show that the increase in the test temperature from 550°C to 704°C does decrease the fatigue life at 1% strain range. In addition, load-controlled fatigue test is not recommended at higher stress ranges below yield because of the plastic deformation prior to yielding.

Overall, these test results do not convincingly support our initial hypothesis that tungsten would behave as a hard clad material on a 316 SS base. The tungsten tested here has significant ductility at the expected operating temperatures for the Kairos Power reactor (550-650°C) and, based on literature values of the material Young's modulus, would not meet the "Hard Clad Criteria-1" discussed in Chapter 5, as the apparent yield stress is too low at elevated temperature. However, both the tensile test results and the fatigue test hysteresis loops indicate that the Young's modulus of this particular batch of material is significantly lower than reference literature values; closer to the values for the 316 SS base. In such case, the material passes both hard clad criteria. However, it is not clear that this specific batch of material represents a reliably specified and reproducible class of material. Hence, the conclusion that the tungsten tested here does not meet the hard clad criteria, contradicting our initial estimate based on literature data on the high temperature yield stress.

This conclusion – that the tungsten tested here does not meet the hard clad criteria – contradicts our initial estimate based on literature data. The material processing conditions may have a significant effect on the strength, creep resistance, and even elastic properties of tungsten, much more so than for conventional structural materials. The literature survey did indicate a large difference in flow strength when comparing stress relieved and as-received material and between different product forms. However, we are not aware of any literature data reporting material as (comparatively) soft and ductile as these measurements. One challenge is that the ASTM standards for tungsten (for example, ASTM B760 and F288) do not include mechanical property test requirements, and so potentially the heat treatment requirements are not sufficient to reliably produce consistent mechanical properties.

8 Conclusions

This report develops a set of design rules for constructing Type 316 stainless steel Class A components clad with either nickel or tungsten for elevated temperature service in molten salt reactors. Long term creep test data of nickel and tungsten are not required in applying these design rules to guard against the ASME Section III, Division 5 failure modes in the clad material.

To avoid long term testing for clad materials the underlying approach of the design rules relies on two bounding approximations for the clad material response – (a) treat a hard clad material as linear elastic, (b) treat a soft clad material as perfectly compliant – and only allows the use of either hard clad or soft clad materials. The report, therefore, develops criteria for selecting such clad materials to use with Class A base materials. The long term testing requirements for the selection criteria are minimal. They require creep tests at only one condition for potential soft clad materials and creep tests at only one condition or no test at all for hard clad materials. This report demonstrates that nickel is a soft clad material relative to 316H base material. Literature data indicates that some forms of tungsten may be a hard clad material.

The design methodology developed here does not require evaluating the clad material for ASME Section III, Division 5 primary load, buckling, and ratcheting design criteria. For creep-fatigue evaluation in the soft clad material, the method uses either a design by EPP cyclic creep analysis or a design by inelastic analysis approach. In the case of hard clad material fatigue evaluation, the design method uses either design by EPP analysis or design by inelastic analysis. For creep-fatigue design of the base material, the methodology ignores the soft clad material in design analysis but includes the hard clad material in design analysis as the interaction between hard clad and base materials affects the creep-fatigue damage accumulation in the base material. Any of the current Section III, Division 5 design approaches can be used for the base material when combined with a soft clad: design by elastic analysis, design by EPP analysis, or design by inelastic analysis. On the other hand, only either design by EPP analysis or design by inelastic analysis can be used for the base material creep-fatigue evaluation for hard clad/base material systems.

The design methodology, however, does not guard the design against the clad/base interface failure and assumes that the interface between the clad and base materials remains fully bonded throughout the service life. In practice the clad/base interface may fail before the end of the design life of the component and therefore this report also develops an acceptance test procedure for checking the mechanical integrity of clad/base metal interface. The acceptance test procedure is simple, uses accelerated loading condition, and could be applied to clads fabricated with a variety of processes.

Evaluating creep-fatigue in nickel clad material requires EPP cyclic design curves. The report develops the EPP cyclic design curves for nickel that can be used for temperatures less than or equal to 650°C and for any hold time. The tungsten test data collected as part of the program did not meet the hard clad criteria. This may be due to the processing conditions used in fabricating the tungsten material obtained for the project testing as literature data suggests that other tungsten variants may be suitable for use as a hard clad.

Finally, the report provides three sample design problems – (a) a single tube in a 316H heat exchanger clad with nickel, (b) a 316H flat head vessel clad with nickel, and (c) a 316H

flat head vessel clad with tungsten – walking through the design rules developed in this work. These sample problems can be used to educate reactor designers and other potential users of the Code Case rules on executing the design process.

Acknowledgements

This research was sponsored by the U.S. Department of Energy, under Contract No. DE-AC02-06CH11357 with Argonne National Laboratory, managed and operated by UChicago Argonne LLC, under Contract No. DE-AC07-05ID14517 with Idaho National Laboratory, managed and operated by Battelle Energy Alliance, and under Contract DE-AC05-00OR22725 with Oak Ridge National Laboratory, managed and operated by UT-Battelle, LLC all supported by the Office of Nuclear Energy, GAIN Nuclear Energy Voucher program. The assistance from John H. Jackson of the GAIN Office is gratefully acknowledged. We greatly acknowledge the contributions of Bob McReynolds at Kairos Power, LLC for providing the nickel test data.

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