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Comprehensive Report For Proposed Elevated Temperature Elastic Perfectly Plastic (EPP) Code Cases Representative Example Problems

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Comprehensive Report
For Proposed
Elevated Temperature Elastic Perfectly Plastic (EPP) Code Cases
Representative Example Problems

June 26, 2014

This Comprehensive Report is an assembly of two related documents, which -- in combination -- provide a comprehensive report on the implementation of two proposed Subsection NH Code Cases for strain limits and creep-fatigue using elastic-perfectly plastic (EPP) methodology defined in the Code Cases:

Report 20362-R-001: Limited Scope Design Specification
Report 20362-R-002: Design Report

The Limited Scope Design Specification provides the two proposed EPP Code Cases and description of the example problems used to demonstrate implementation of the two Code Cases. Dimensions, material properties and loads are defined in the Design Specification.

The Design Report provides the results of implementing the two proposed EPP Code Cases using the Representative Example Problems (REP-B and REP-W). The two Representative Example Problems are based on the same nozzle-head-juncture: with base metal only termed, “REP-B” and with a full-penetration butt weld, “REP-W”.

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Elevated Temperature Code Case Representative Example Problem Specifications Report

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Contents

1.0 Background and Introduction

This report is a "limited scope design specification" for the Representative Example Problem (REP).

1. The Scope of Work is summarized as follows.
   a. Define the model, loadings and methodology for the Representative Example problem (REP).
   b. Use a nozzle-sphere intersection rather than the Section III Appendix A-6230 [Ref. 3] hemispherical head, cylinder, flat plate assembly.
   c. The nozzle-sphere intersection is in accordance with the construction specified in Fig. NB-3338-2(a)-2 and Fig. NB-4244(a)-1.
   d. Loadings are internal pressure, thermal time-dependent loads for Level A, B and Level C which are used to create the required composite load combination required by the Code Cases. Deadweight is ignored as negligible and seismic loading (static) is included as an initiating short-term load for the Level C load.
   e. Axial, bending and torsional piping reaction nozzle loads are specified (Design, Level A, B, C).

2. Section 2 provides the latest proposed Strain Limit Code Case [Ref. 4] and Creep-Fatigue Code Case [Ref. 5].
3. Section 3 describes the Representative Example Problem (REP), including geometry, loading, general conditions to the extent necessary to provide the basis for creating the analytical model of the REP.
4. Section 4 provides a suggested layout of the finite element model and other related suggestions.
5. Attachment 1 provides the "design sizing" of the REP using pressure and mechanical loads at conservatively defined times and temperatures at those times.

2.0 Code Cases

The latest proposed Strain Limit Code Case [Ref. 4] and Creep-Fatigue Code Case [Ref. 5] are shown below. These are the Code Cases as written at the time of this report. They have changed as the project has proceeded, and they may continue to change based on further in-progress results of the use of the Code Cases.

(4/14/2014)

Code Case XXXX. Satisfaction of Strain limits for Class 1 Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis.

Inquiry: What alternative rules may be used for the evaluation of strain limits in compliance with NH-3252 and Subsection NH, Appendix T.

Response: Strain limits may be evaluated using elastic-perfectly plastic material models instead of the procedures of NH-T-1320, NH-T-1330 and NH-T-1713 when performed in accordance with the requirements of this Code Case.

1. General Requirements

Except as identified herein, all requirements of Section III, Subsection NH and applicable Code Cases apply to components designed in accordance with this Code Case.

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 Appendix 1. In this code case 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 paragraph 4.2.

2. Load Definition.

Define all applicable loads and load cases per NH-3113.2 Service Loadings.

2.1. 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.

2.1.1. An individual cycle as defined in the Design Specifications cannot be further subdivided into individual cycles to satisfy these requirements.

2.1.2. Except as described in paragraph 2.1.3, 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.

2.1.3. 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 2.1.2. 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.

3. Numerical Model.

Develop a numerical model of the component 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 conditions determined from the loading conditions defined in paragraph 2.

4. Requirements for satisfaction of strain limits

Perform a ratcheting analysis for each of the composite cyclic histories defined in paragraph 2.1. Each of these cyclic histories must be shown to be free from ratcheting based on the pseudo yield stress S_{xT} as defined in paragraph 4.2. 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 paragraph 5.

4.1. 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.

4.2. Step 2: Select a target inelastic strain, x, where $0 < x < \varepsilon_{avg}$ 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 below in 4.2.1. and 4.2.2.

4.2.1. The yield strength S_y given in Table I-14.5 of Subsection NH as modified by Subarticle NH-2160; 4.2.2. The stress to cause x inelastic strain in time t_{design}, as determined from the isochronous stress strain curves in Figure T-1800 in Appendix T of Subsection NH.

4.3. Step 3: Perform a cyclic elastic-perfectly plastic analysis for each composite cycle defined in paragraph 2.1.2 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

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

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.

4.4. Step 4. Assess acceptability in accordance with 4.4.1. and 4.4.2. below by using the plastic strains, ε_p, from Step 3. If the requirements of both 4.4.1. and 4.4.2. are satisfied, then the strain limits of NH-T-1310 for base metal and NH-T-1713 for weldments are also considered satisfied. This condition is illustrated in Figure 1(a).

4.4.1. The requirement, $x + \varepsilon_p \le \varepsilon_{avg}$, 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 1(b).

4.4.2. The requirement, $x + \varepsilon_p \le \varepsilon_{local}$, 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 1(c).

4.4.3. In order to proceed if either of the requirements of 4.4.1. or 4.4.2. 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 paragraph 2 applied to the component configuration defined in paragraph 3 do not met the requirements of this code case.

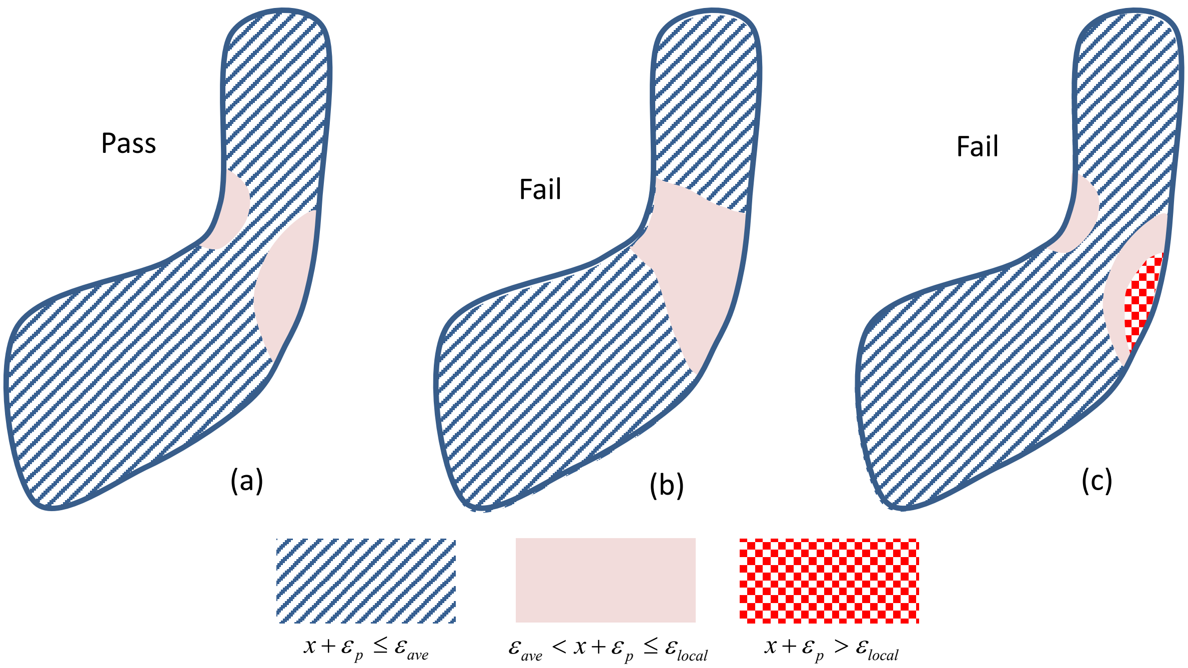


Figure 1. Strain limits Pass/Fail criteria illustrated

5. Weldments

Implementation of the strain limits for weldments defined above in paragraph 4 requires additional consideration.

5.1. Weld region model boundaries

The weld shown in Figure 2 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 subsection NH. Subsection NH-4200 refers to various Subsection NB-4000 paragraphs for weld configurations and requirements. These Subsection NB weld configurations are represented by the shaded region.

Figure 2 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 subparagraph NH-T-1714.

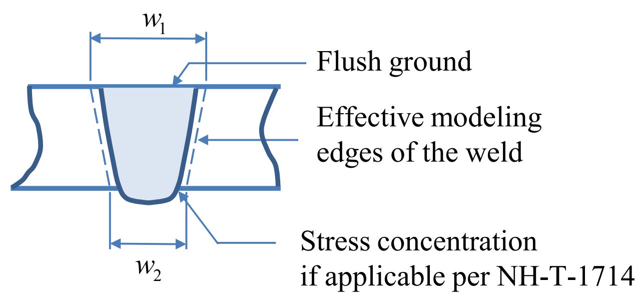


Figure 2. Weld region model boundaries

5.2. The requirements for analysis of geometry of subparagraph NH-T-1714 of Subsection NH are applicable for satisfaction of the requirements of this Code Case.

5.3. 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 Table NH-I-14.10.

5.4. Dissimilar metal welds

5.4.1. Requirements for dissimilar metal welds are in the course of preparation.

APPENDIX 1 - RATCHETING ANALYSIS

The steps to perform a ratcheting analysis to demonstrate compliance with strain limits are as follows:

i) Define Composite Cycle Load Time-Histories & Step(s):

   a. It may consist of histories of mechanical loads, pressure loads, displacements, temperatures and thermal boundary conditions.

   b. Time-independent parts of the cycle may be truncated.

   c. 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.

   d. Subject to the requirements in (ii), the composite cycle time does not affect the result of the ratcheting analysis.

   e. Temperatures, thermal boundary conditions, boundary displacements and mechanical loads over a cycle should be cyclic; that is, begin and end at the same value.

   f. 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.

ii) Define Analysis Types:

   a. 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.

b. 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.

iii) Define Material Properties:

a. For the thermal analyses, density, and temperature-dependent specific heat and conductivity will in general be required.

b. For the mechanical analyses the temperature-dependent properties required are modulus, Poisson's ratio and mean expansion coefficient. Density may also be required.

c. In addition the mechanical analyses temperature-dependent yield stress will need to be adjusted based on the selected pseudo yield stress S_{xT} defined in paragraph 4.2.

iv) Perform Analyses:

a. Perform an elastic-perfectly plastic cyclic mechanical and thermal stress analysis using the temperature-dependent pseudo yield property defined above. Enough cycles are required to demonstrate ratcheting or the absence of ratcheting.

b. 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 (i)(f) of this appendix.

v) Detect Ratcheting:

a. 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.

b. 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.

Rev 7, 04/15/2014
Code Case XXXXXXXXXX
Calculation of Creep-Fatigue for Class 1 Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis.
Inquiry: What alternative rules may be used for the calculation of creep-fatigue damage in compliance with NH-3252 and Appendix T.
Response: Fatigue and cyclic creep damage may be evaluated using elastic-perfectly plastic material models instead of the procedures of T-1420, T-1430 and T-1715 when performed in accordance with the requirements of this Code Case.

1. General Requirements

Except as identified herein, all requirements of Section III, Subsection NH and applicable Code Cases apply to components designed in accordance with this Code Case.
The design methodology employed for evaluation of cyclic 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 Code Case, "shakedown" refers to the achievement

of cyclic elastic behavior throughout the part, based on real or pseudo yield properties. In this code case the term "pseudo yield stress" refers to a temperature dependent minimum stress-to-rutpure 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 4.2. Guidance on shakedown analysis is provided in Appendix 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:

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

where

D = total creep-fatigue damage as limited by FIG. T-1420-2 in Subsection NH.
D_c = cyclic creep damage as determined in paragraph 4, below, of this Code Case
D_f = fatigue damage as determined paragraph 5, below, of this Code Case

2. Load Definition

Define all applicable loads and load cases per NH-3113.2 Service Loadings

2.1. Composite Cycle Definition

For the purpose of performing an elastic perfectly plastic shakedown 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.

2.1.1. An individual cycle as defined in the Design Specifications cannot be split into individual cycles to satisfy these requirements.

2.1.2. Except as described in 2.1.3., 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 creep-fatigue.

2.1.3. Level C Service Loadings may be combined with the applicable Level A and B Service Loadings to define a composite cycle(s) to be evaluated separately from the cycle defined in 2.1.2. 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.

3. Numerical Model

Develop a numerical model of the component 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 conditions determined from the loading conditions defined in 1.1 above.

4. Calculation of Cyclic Creep Damage

Perform a shakedown analysis for each of the composite cyclic histories defined in paragraph 2.1. Each of these cyclic histories must be shown to shakedown based on the pseudo yield stress defined in paragraph 4.2. Additional requirements for welds are found in paragraph 6.

4.1. 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.

4.2. Step 2: Select a trial time duration, T_d' in order to define a pseudo yield stress, S_{ct1}, 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 below in 4.2.1. and 4.2.2.

4.2.1. The yield strength S_y given in Table I-14.5 of Subsection NH as modified by Subarticle NH-2160; 4.2.2. S_{rt1}, where S_{rt1} is the minimum stress to rupture in time T_d' from Figs. I-14.6 of Subsection NH multiplied by the factor, K', from Table T-1411-1 of Subsection NH using the tabulated values for Elastic Analysis.

4.3. Step3: Perform a cyclic elastic-plastic analysis for each composite cycle defined in paragraph 2 above with temperature-dependent pseudo yield stress S_{ct1}. 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.

4.4. Step 4: Determine the maximum cyclic creep damage value applicable to every location in the numerical model from the expression:

$$D_c = (t_{design})/(T_d')$$

The above value of D_c is used to evaluate total damage in Eq (1).

4.4.1. 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_{ct1} , which will make shakedown more difficult.

5. Calculation of Fatigue Damage

The fatigue damage summation, D_f , in Equation 1 is determined in accordance with Steps 1 through 3 below. Additional requirements for welds are found in paragraph 6.

5.1. 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 Step 3 of paragraph 4 above.

5.2. Step 2: Calculating the equivalent strain range in accordance with NH-T-1413, or NH-T-1414 when applicable, of Subsection NH with Poisson's ratio $v^* = 0.3$.

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

$$D_f = \Sigma(n/N_d)_j$$

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 (Figs. T-1420-1 of Subsection NH) corresponding to the maximum metal temperature occurring during the cycle.

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

6. Weldments

Implementation of the evaluation of creep-fatigue damage in paragraphs 4 and 5 above for weldments requires additional consideration.

6.1. In the weld region, the pseudo yield strength value defined by T_d' in 4.2.2. is reduced further by multiplying the value of S_{rt1} for the base metal by the applicable weld strength reduction factor from Table NH-I-14.10.

6.2. The number of allowable cycles, $(N_d)_j$, in the weld region is one half the number of allowable cycles from Figs. T-1420-1 for base materials.

6.3. The requirements for analysis of geometry of subparagraph T-1714 of Subsection NH are applicable for satisfaction of the requirements of this Code Case.

6.4. 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 Table NH-I-14.10.

6.5. Weld region model boundaries

The weld shown in Figure 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 subsection NH. Subsection NH-4200 refers to various Subsection NB-4000 paragraphs for weld

configurations and requirements. These Subsection NB weld configurations are represented by the shaded region.
Figure 1 shows a full-penetration butt weld as an example. As shown, w1 and w2 , 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 subparagraph T-1714.

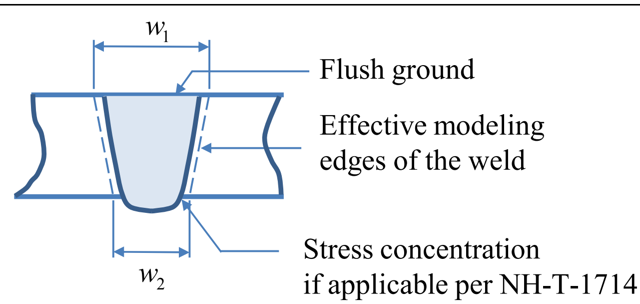


Figure 1. Weld region model boundaries

6.5. Dissimilar metal welds
6.5.1. The requirements for dissimilar metal welds are in the course of preparation.

Appendix 1. Shakedown Analysis.

The steps to perform a shakedown analysis to calculated bounding cyclic creep damage are as follows:

vi) Define the load cycle to be considered.
   a. It may consist of histories of mechanical loads, pressure loads, displacements, temperatures and thermal boundary conditions.
   b. Time-independent parts of the cycle may be truncated.
   c. 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.
   d. The composite cycle time does not affect the result of the shakedown analysis.
   e. The loading and boundary conditions must be cyclic, that is all values at the beginning and at the end of the cycle must be identical.

vii) Define analysis types
   a. A thermal analysis of the composite cycle may be performed to generate temperature histories for use in the mechanical analysis. 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.
   b. Alternatively, a coupled thermal-mechanical analysis may be performed. For the thermal analyses, density, and temperature-dependent specific heat and conductivity will in general be required.

viii) Define material properties

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

ix) Perform analyses

a. 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.
b. 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 vi).

x) Shakedown

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

END OF PROPOSED CODE CASES

3.0 The Limited Scope Design Specification for the Representative Example Problem

This Section is a “Limited Scope Design Specification” for the REP. The term “Limited Scope” means that only the items necessary to perform the evaluation of the component are included, and not the fabrication, inspection, test and administrative requirements which are not necessary for this scope of work. In that regard, the following items are stated to be the basis for analysis of this REP using the two proposed Code Cases [Ref. 4] and [Ref. 5].

3.1 Component Classification and Basis for Selecting the Representative Example Problem Geometry

The Representative Example Problem (REP) is chosen to represent one typical portion of a nuclear, high-temperature Section III, Division 1, Class 1 vessel – a radial nozzle in a spherical head. NOTE: The REP was initially suggested to be the head-shell-flat head geometry in A-6230 of Appendix A [Ref. 3].

3.2 Description of the REP Geometry

The REP Geometry and associated dimensions are shown in Figure 3.1. The geometry is part of an elevated temperature pressure vessel consisting of a hemispherical head and an attached nozzle using Figure NB-3338-2(a)-2 Sketch (c) and NB-4244(a)-1 Sketch (b) and (d) [Ref. 16]. The dimensions of the head and nozzle cylinder are set to meet the design pressure and design temperature, operating pressures and temperatures and the corresponding mechanical pipe loadings on the nozzle. The transition reinforcement region is set to meet the reinforcement requirements of NB-3330. The nozzle and head are attached by a full-penetration butt weld at the required distance (1.5t) from the transition reinforcement region as shown in Figure NB-4244(a)-1 Sketch (b).

3.3 Materials of Construction.

The materials of construction are 316 forged stainless steel for both the spherical head and nozzle. The weld material for the weld between the nozzle forging and the spherical head is as shown below.

a. Material Specifications: Table NH-I-14.1(a): SA-182, F316 (forgings for nozzle and head, S_u 70 ksi)
b. Welding Specifications: Table NH-I-14.1(b): SFA-5.4 E316
c. Weld profile: full-penetration butt weld per code case with w_1 = 4 in and w_2 = 1.5 in.

3.4 Design Life and Working Fluid

d. The Design Life is 100,000 hr for Levels A, B and C.
e. The working fluid is inert gas with thermal conditions specified by fluid temperature and heat transfer (film) coefficients specified herein.

3.5 Corrosion/erosion allowance

No Corrosion/erosion allowance is applicable.

3.6 Radiation

The component is not exposed to radiation.

3.7 Environmental Conditions.

The exterior of the component is insulated such that heat transfer to ambient 70°F atmosphere is negligible.

3.8 Loadings

a. The loadings for the REP include Design and Level A, B and C Service/Operating loads.
b. No Level D loads are specified.
c. No Test Loads are specified.

3.8.1 Design Level Loading

a. Internal Pressure; Design Conditions; $P_{int.des}$ = 700 psig at $T_{.des}$ = 1,200°F
b. Mechanical Loads Design Condition; piping reaction loads on the end of the nozzle
    i. Axial Load; F_{des} = 30,000 lb (tension)
    ii. Shear Force, $V_{.X.des}$ = 4,000 lb
    iii. Bending moment; $M_{Z.des}$ = 53,500 lb-in (4,458 ft-lb) due to the shear force induced moment developed at the mid-thickness of the shell.
    iv. Torsional moment; $M_{Y.des}$ = 20,000 lb-in
c. Thermal Loads (Π); isothermal at 1,200°F

3.8.2 Service/Operating Level Loading (Levels A, B and C.

a. Internal Pressure (Levels A, B and C)
    v. Level A Conditions; $P_{int.Lev.A}$ = 675 psig (maximum); see Fig. 3.2
    vi. Level B Conditions; $P_{int.Lev.B}$ = 750 psig (maximum); see Fig. 3.3
    vii. Level C Conditions $P_{int.Lev.B}$ = 775 psig (maximum); see Fig. 3.4

b. Mechanical Loads (Levels A, B and C); piping reaction loads, "FVMT" on the end of the nozzle; Axial loads are labeled F(t); bending moment is labeled M_Z(t); torsional moment is labeled "T" or M_Y(t). Maximum Level B loads are 125% of the Design Loads and Maximum Level C loads are 200% of the Design Loads in accordance with Figures 3.2, 3.3 and 3.4. The values are summarized below.

		Nozzle Axial	Nozzle Shear	Nozzle Bending **	Nozzle Torsion
	%	F_Y (lb)	V_X (lb)	M_z (lb-in)	M_Y (lb-in)
Design (100 %)	100	30000	4000	53500	20000
Level A max	100	30000	4000	53500	20000
Level A min	0	0	0	0	0
Level B max	125	37500	5000	66875	25000
Level B min	100	30000	4000	53500	20000
Level C max	200	60000	8000	107000	40000
Level C min	-150	-45000	-6000	-80250	-30000
Max		60000	8000	107000	40000
Min		-45000	-6000	-80250	-30000

** $M_Z = V_X(d_Y + t_{.shell}/2)$

c. Thermal Loads (Π, Levels A, B and C)

i. Level A Conditions; see Fig. 3.2

ii. Level B Conditions; see Fig. 3.3

iii. Level C Conditions; see Fig. 3.4

3.8.3 Load Combinations (Levels A, B and C)

$\Pi_{(t)}$: signifies working fluid conditions (Temperature, T and film coefficient, h) on the inside surfaces. Thermal boundary conditions are shown in Fig. 3.5. M: signifies the mechanical (pipe reaction loads on the nozzle) $P_{.int}$: signifies internal pressure

Four load combinations are specified:

1. Design Level: $P_{int.des} + M_{.des}$ at design temperature, $T_{.D}$ isothermal conditions
2. Service Level A: $P_{int.Lev.A(t)} + M_{.Lev.A(t)} + \Pi_{(t)Level\ A}$; see Figure 3.2
3. Service Level B: $P_{int.Lev.B(t)} + M_{.Lev.B(t)} + \Pi_{(t)Level\ B}$; see Figure 3.3
4. Service Level C: $P_{int.Lev.C(t)} + M_{.Lev.C(t)} + \Pi_{(t)Level\ C}$; see Figure 3.4

3.3.4 Composite Cycles for Code Case Evaluation

The Code Cases [Ref. 4], [Ref. 5] require development of a Level A, B and C Composite Cycle. The requirements for the Composite Cycle are described in Section 1.2 of the Strain Code Case and in Section 2.1 of the Creep-Fatigue Code Case. However, the PVP papers [Ref. 12] and [Ref. 13] explain that it is useful, if not necessary, to create a separate Level C composite cycle. This work defines a separate Level C Composite Cycle. The Level A and B and Level C Composite Cycles are specified as follows.

3.3.4.1 Level A and B Composite Cycle; see Figure 3.5

3.3.4.1 Level C composite Cycle; see Figure 3.6

Table 3.1 – Time Periods for Level A, B and C Load Combinations

Time Period	Tim (min)	No. cycles	total time (min)	total time (hr)	total time (sec)
$t_{A.up}$	3,000	90	270,000	4,500	16,200,000
$t_{A.SS}$	24,000	90	2,160,000	36,000	129,600,000
$t_{.A.down}$	4,500	90	405,000	6,750	24,300,000
$t_{.B.up}$	20	782	15,640	261	938,400
$t_{B.down}$	540	782	422,280	7,038	25,336,800
$t_{B.HS}$	1,440	782	1,126,080	18,768	67,564,800
$t_{B.recover}$	2,040	782	1,595,280	26,588	95,716,800
$t_{C.SSE.up}$	1	25	25	0.417	1,500
$t_{C.SSE.down}$	1	25	25	0.417	1,500
$t_{C.SSE.recover}$	1	25	25	0.417	1,500
$t_{C.up}$	25	25	625	10.417	37,500
$t_{C.down}$	150	25	3,750	62.500	225,000
$t_{c.recover}$	60	25	1,500	25	90,000
TOTAL			6,000,230	100,004 **	360,013,800

** Design Life set to 100,000 hr.

Table 3.2 – Loading Parameters Average Ramp Rates for Level A, B and C Load Combinations

Ramp Rates	time (sec)	time (sec)	time (sec)	parameter	parameter	parameter	ramp rate
Ramp Designation	initial	duration (above)	final (calc)	initial	delta (calc)	final	per hr
$A_{.T.up}$	0	180000	180000	70	1030	1100	20.600
$A_{.T.SS}$	180000	1440000	1620000	1100	0	1100	0.000
$A_{.T.down}$	1620000	270000	1890000	1100	-1030	70	-13.733
$A_{.P.up}$	0	180000	180000	0	675	675	13.500
$A_{.P.SS}$	180000	1440000	1620000	675	0	675	0.000
$A_{.P.down}$	1620000	270000	1890000	675	-675	0	-9.000
$A_{.FVMT.up}$	0	180000	180000	0	100	100	2.000
$A_{.FVMT.SS}$	180000	1440000	1620000	100	0	100	0.000
$A_{.FVMT.down}$	1620000	270000	1890000	100	-100	0	-1.333
$B_{.T.up}$	0	1,200	1200	1100	75	1175	225.000
$B_{.T.down}$	1200	32400	33600	1175	-775	400	-86.111
$B_{.T.HS}$	33600	86400	120000	400	0	400	0.000
$B_{.T.recover}$	120000	122400	242400	400	700	1100	20.588
$B_{.P.up}$	0	1,200	1200	675	75	750	225.000
$B_{.P.down}$	1200	32400	33600	750	-75	675	-8.333
$B_{.P.HS}$	33600	86400	120000	675	0	675	0.000
$B_{.P.recover}$	120000	122400	242400	675	0	675	0.000
$B_{.FVMT.up}$	0	1,200	1200	100	25	125	75.000
$B_{.FVMT.down}$	1200	32400	33600	125	-25	100	-2.778
$B_{.FVMT.HS}$	33600	86400	120000	100	0	100	0.000
$B_{.FVMT.up.recover}$	120000	122400	242400	100	0	100	0.000
$C_{.FVMT.up}$	0	60	60	100	100	200	6000.000
$C_{.FVMT.down}$	60	60	120	200	-350	-150	-21000.000
$C_{.FVMT.recover}$	120	60	180	-150	150	0	9000.000
$C_{.T.up}$	0	1500	1500	1100	200	1300	480.000
$C_{.T.down}$	1500	9000	10500	1300	-1230	70	-492.000
$C_{.P.up}$	0	1500	1500	675	100	775	240.000
$C_{.P.down}$	1500	9000	10500	775	-775	0	-310.000

Table 3.3 – Level A Loading Parameters Versus Time

Level A Up/Down	time (sec)	Temperature (^oF)	Pressure (psi)	FVMT (%)
start up	0	70	0	0
middle up	90000	585	337.5	50
end up	180000	1100	675	100
ss end	1620000	1100	675	100
middle down	1755000	585	337.5	50
end down	1890000	70	0	0

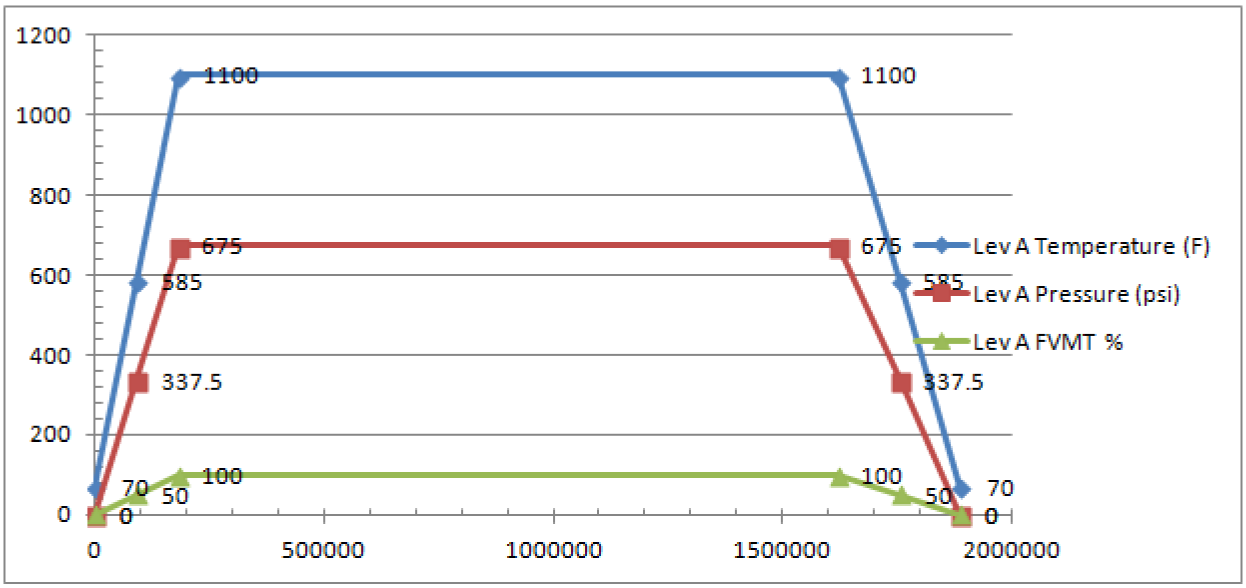


Table 3.4 – Level B Loading Parameters Versus Time (Up-Down Portion)

Level B Up/Down	time (sec)	Temperature (°F)	Pressure (psi)	FVMT (%)
start	0	1100	675.0	100.0
	1100	1170.0	743.8	122.9
	1120	1171.0	745.0	123.3
	1140	1172.0	746.3	123.8
	1160	1173.0	747.5	124.2
	1170	1174.0	748.1	124.4
	1180	1174.5	748.8	124.6
	1190	1175.0	749.4	124.8
peak	1200	1175	750.0	125.0
	1210	1174.8	750.0	125.0
	1220	1174.5	750.0	125.0
	1230	1174.3	749.9	125.0
	1240	1174.0	749.9	125.0
	1300	1172.6	749.8	124.9
	3000	1131.9	745.8	123.6
	10000	850.0	729.6	118.2
	30000	425.0	683.3	102.8
end	33600	400	675.0	100.0

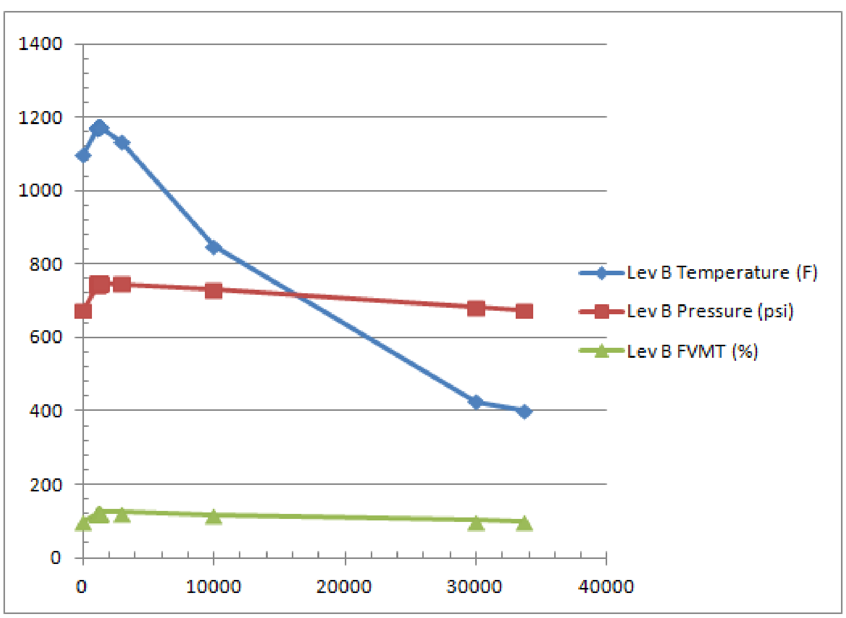


Table 3.5 – Level B Loading Parameters Versus Time (Recover Portion)

Level B Recover	time (sec)	Temperature (°F)	Pressure (psi)	FVMT (%)
start	120000	400	675	100
middle	181200	750	675	100
end	242400	1100	675	100

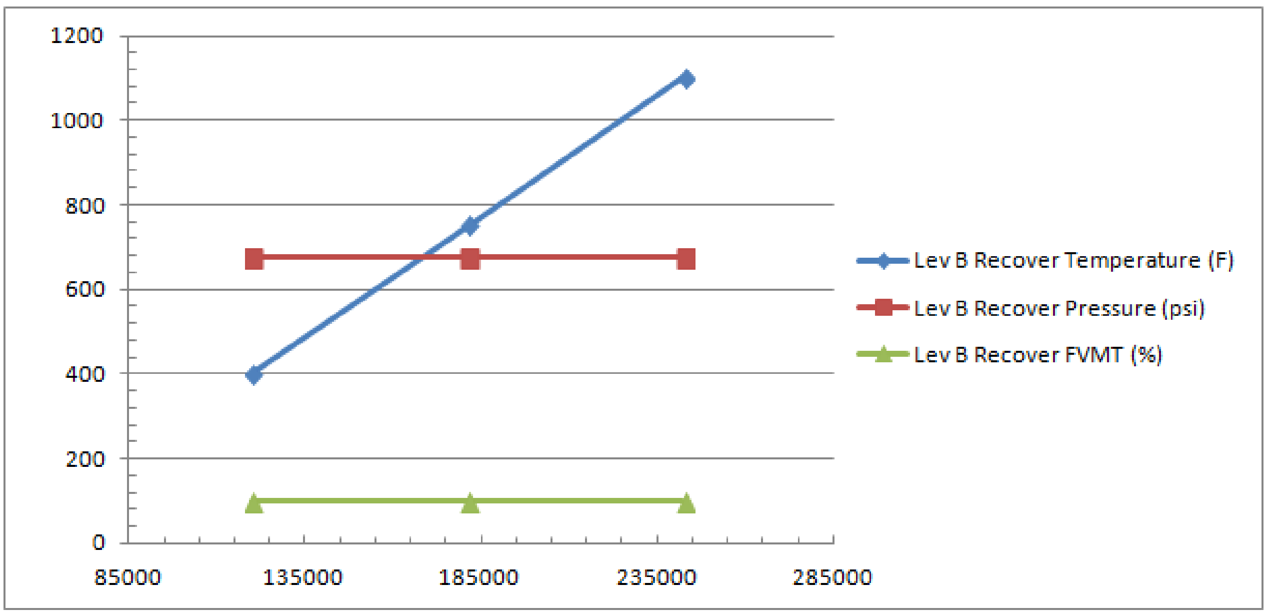


Table 3.6a– Level C Loading Parameters Versus Time (SSE initiating loads)

Level C SSE Initiation	time (sec)	Temperature (°F)	Pressure (psi)	FVMT (%)
start	-180	1100	675	100
peak	-120	1100	675	200
reaction	-60	1100	675	-150
recover	0	1100	675	100

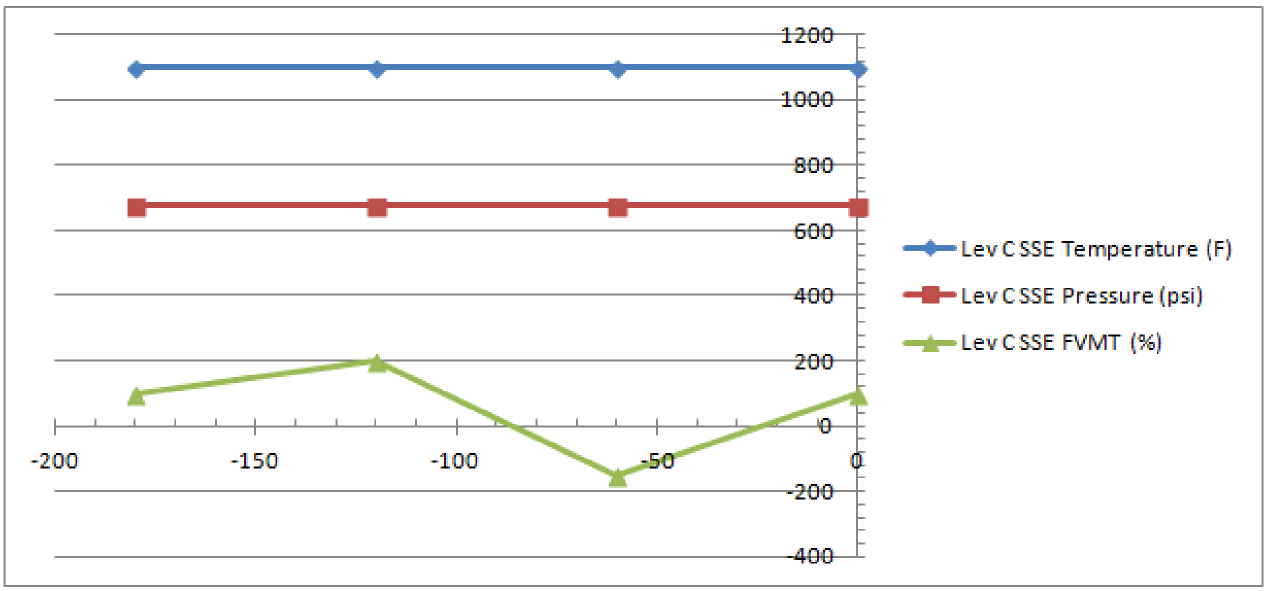


Table 3.6b– Level C Loading Parameters Versus Time (portion after SSE initiating loads)

Level C	time (sec)	Temperature (°F)	Pressure (psi)	FVMT (%)
Start	0	1100	675	100.0
	1440	1290	771.00	86.3
	1450	1292	771.67	86.2
	1460	1294	772.33	86.1
	1470	1296	773.00	86.0
	1480	1298	773.67	85.9
	1490	1299	774.33	85.8
Peak	1500	1300	775	85.7
	1510	1299	774.14	85.6
	1520	1298	773.28	85.5
	1530	1296	772.42	85.4
	1540	1294	771.56	85.3
	1550	1292	770.69	85.2
	1560	1290	769.83	85.1
	1600	1280	766.39	84.8
	2000	1150	731.94	81.0
	5000	700	473.61	52.4
End	10500	70	0	0.0

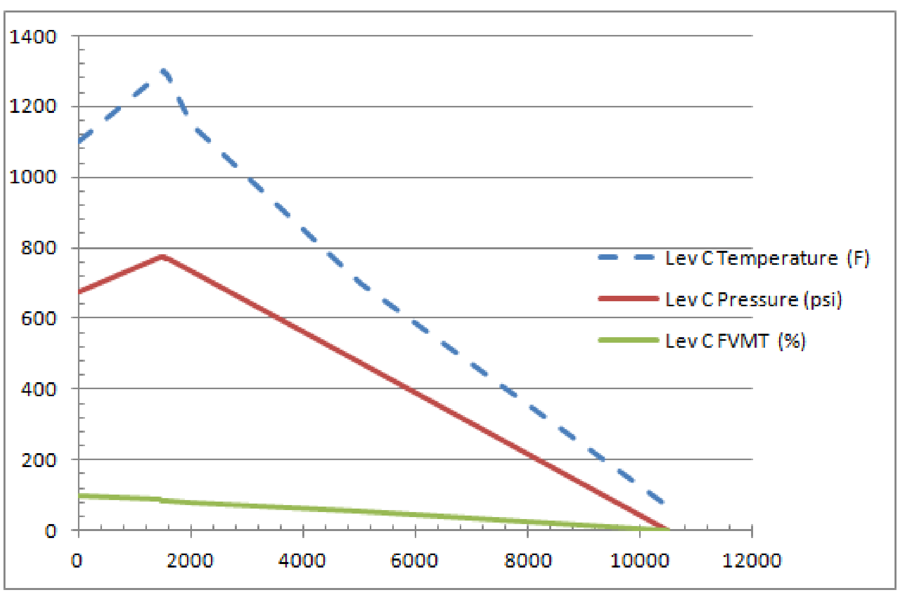


Figure 3.1 – Representative Example Problem (REP) Geometry Sketch

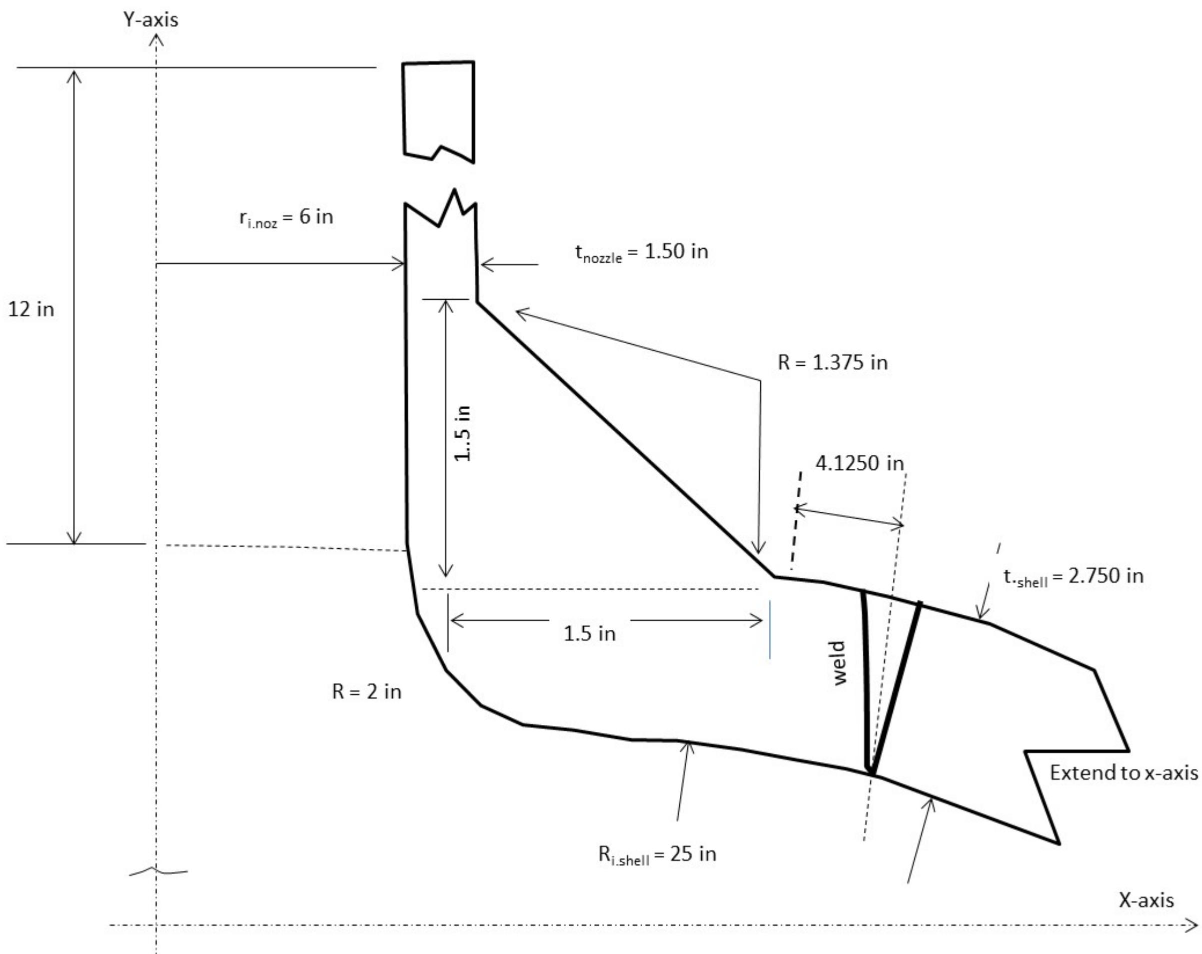


Figure 3.2 – Service Level A Loads and Load Combinations; loadings versus time

Times and ramp rates shown in Tables

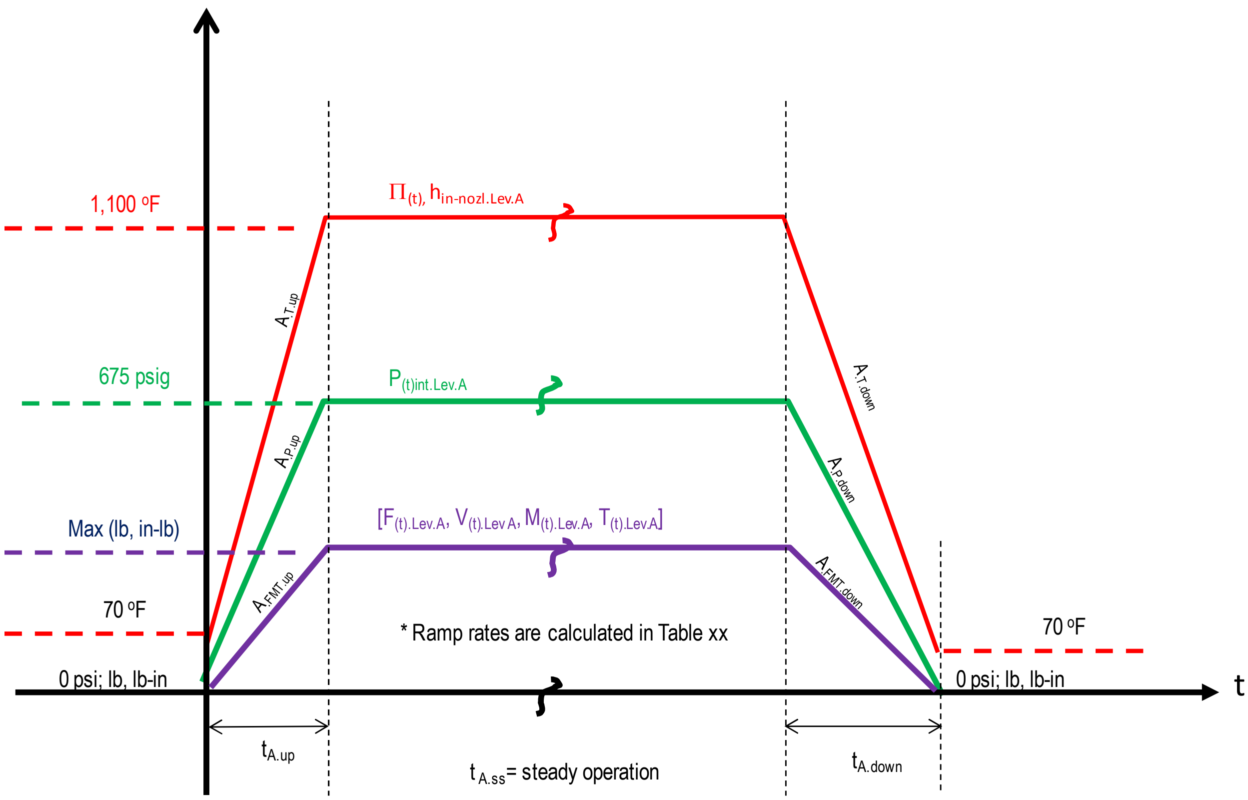


Figure 3.3 – Service Level B Loads and Load Combinations; loadings versus time

Times and ramp rates shown in Tables

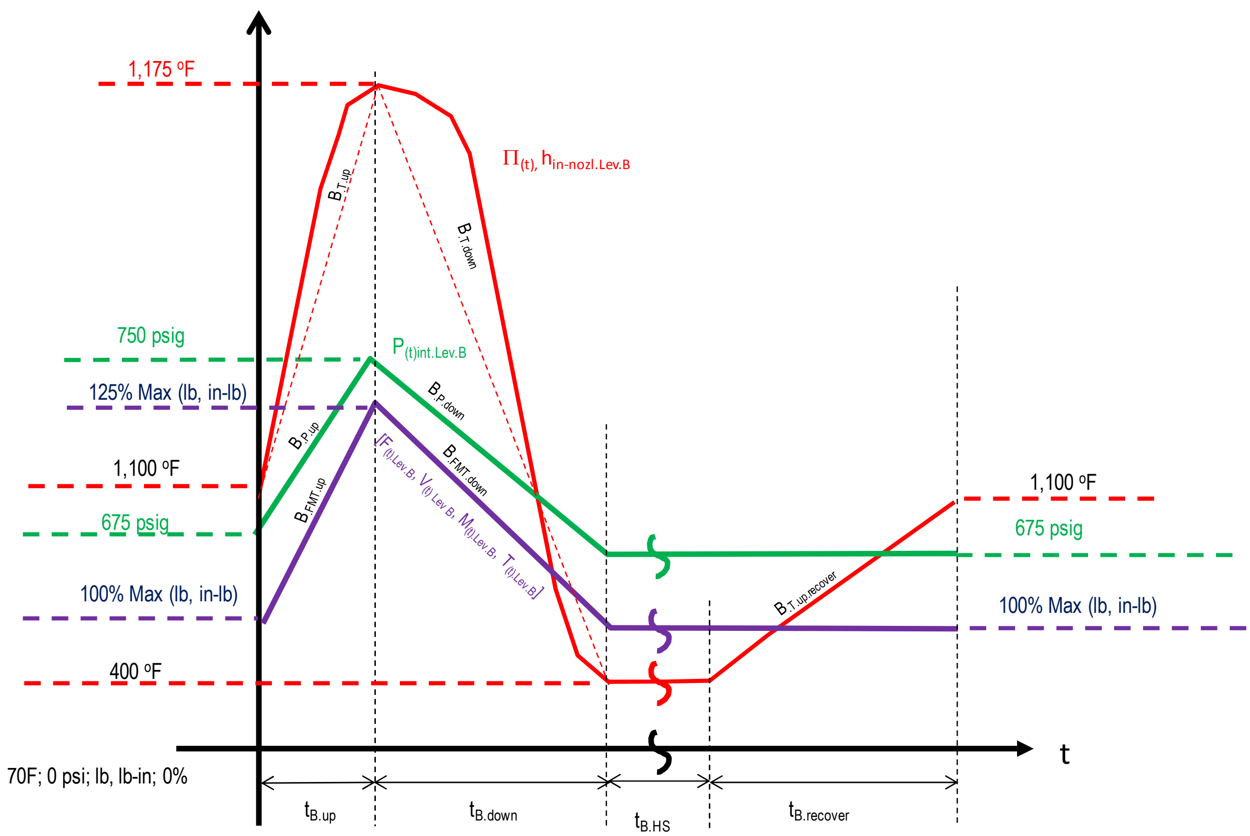


Figure 3.4 – Service Level C Loads and Load Combinations; loadings versus time

Times and ramp rates shown in Tables

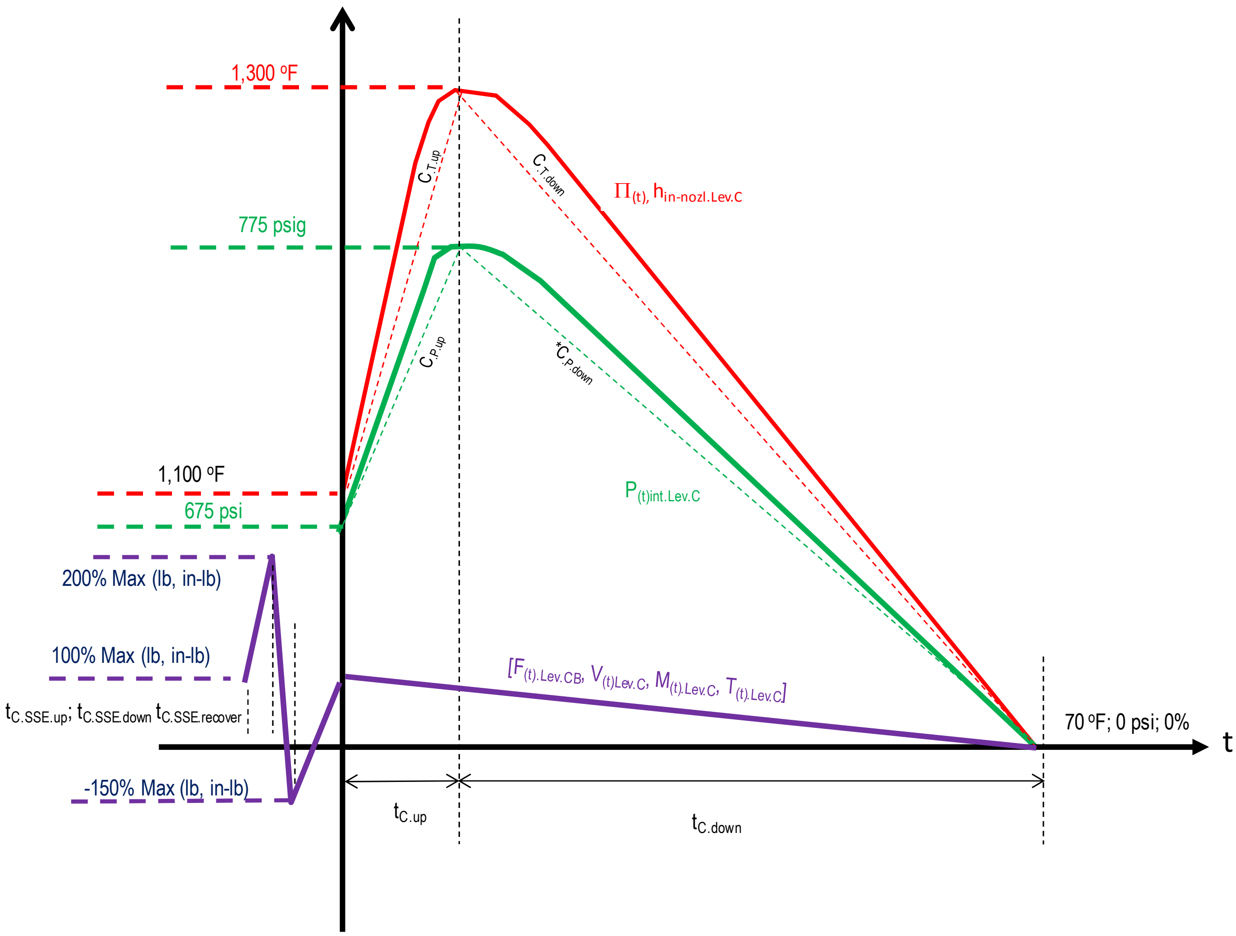


Figure 3.5 – Level A and B Composite Cycle

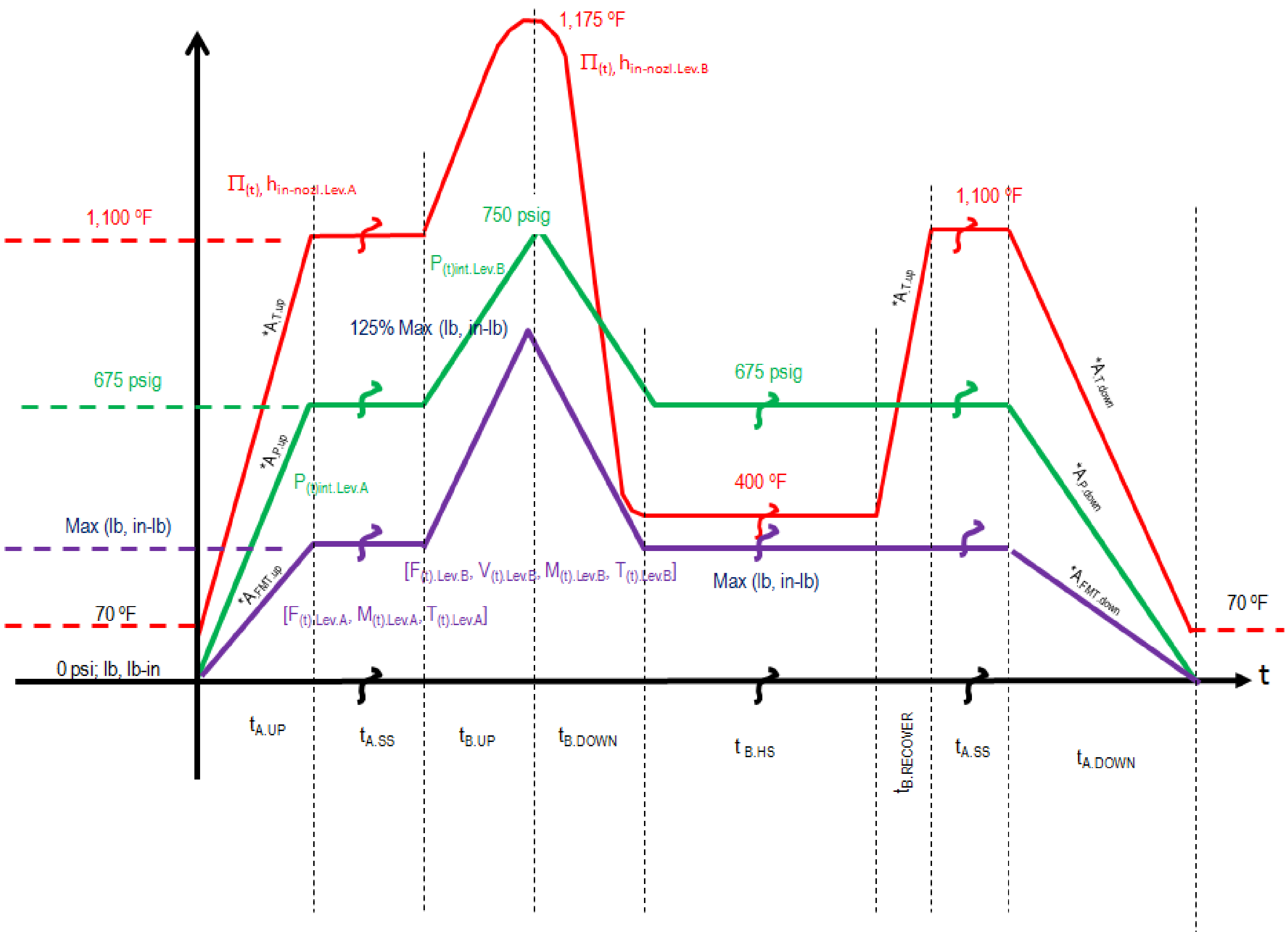
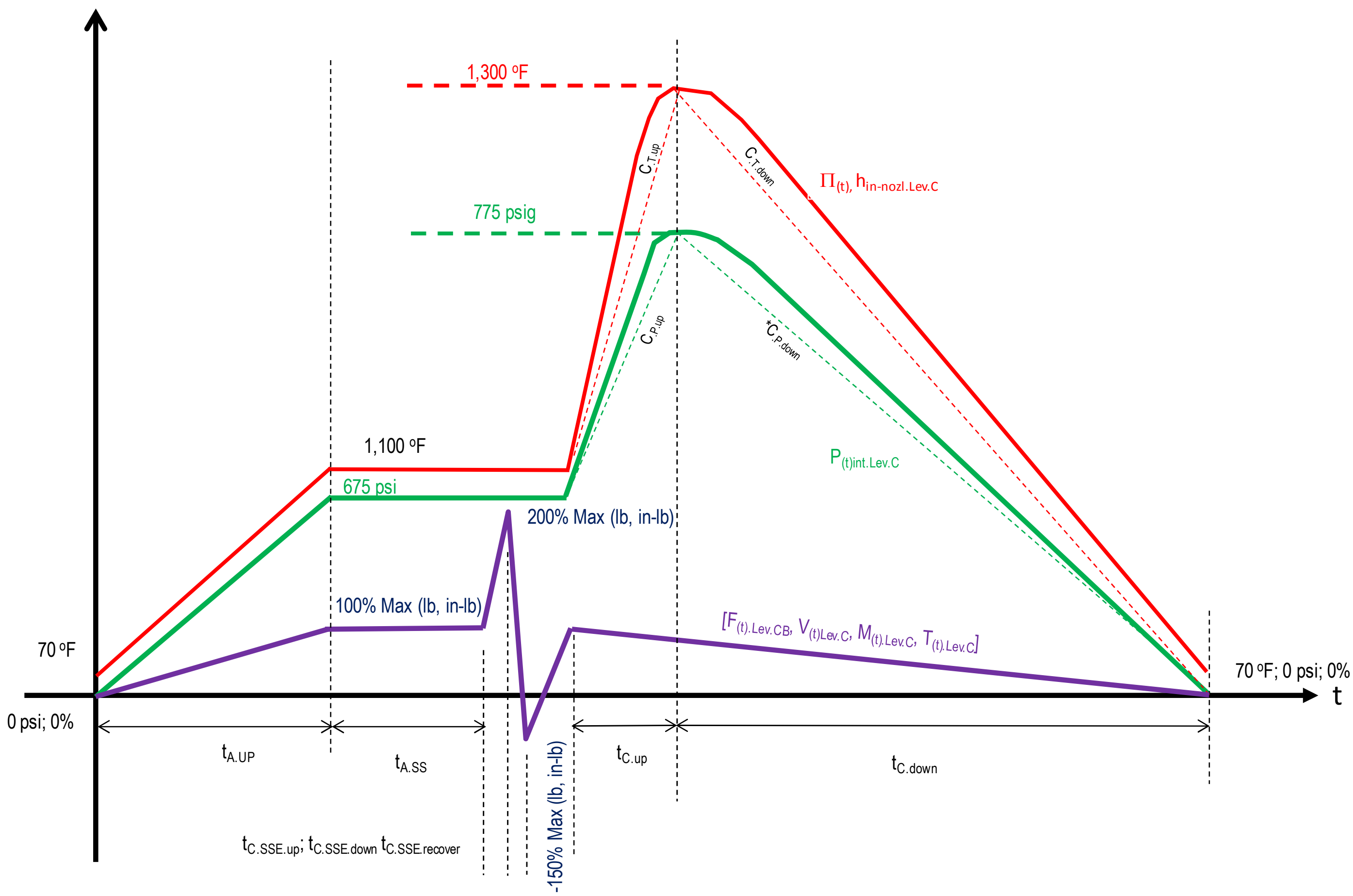


Figure 3.6 – Level C Composite Cycle



4.0 Suggested ABAQUS Finite Element Model and Material Properties

A suggested ABAQUS finite element model geometric layout in a 2D X-Y planar cut representation is shown in Fig. 4.1. Suggested characteristics include:

a. The weld between the nozzle forging and head is not explicitly modeled, i.e., the material properties of the weld are the same as the base material properties and the geometric boundaries of the weld are not explicitly defined. Section 2.1 of the proposed strain limit Code Case [Ref. 4] requires specific treatment of weld material for ratchet screening criteria.
b. The model will need to be 3D to capture the 3D loading, even though the geometry is axisymmetric.
c. The model should be of 3D solid elements (8-node or 20-node). Other element types may be used in an auxiliary fashion, such as for application of the piping loads to the end of the nozzle.
d. Element aspect ratios should be maintained within limits of accuracy for the selected element type.
e. Triangular-faced elements should be avoided or used only away from expected regions of high stress or strain.
f. Full-integration element should be used.
g. Non-linear geometry need not be used.

The sources for required material properties are in Table 4.1. Values for these properties are in subsequent Tables. Values for Specific Heat of 316 Stainless Steel are in accordance with references [Ref. 18], [Ref. 10], [Ref. 20]. [Ref. 21], [Ref. 22].

C_p in units of BTU/lb-F

$a_0 = 1.071939 \times 10^{-1}$
$a_1 = 6.034521 \times 10^{-5}$
$a_2 = -4.397679 \times 10^{-8}$
$a_3 = 1.438572 \times 10^{-11}$

$$C_p = \sum_{n=0}^{3} a_n T^n$$

where T is in F.

To obtain C_p in units of J/kg-K, multiply the values in by 4.18680×10^3

Table 4.1 – Material Parameter References

Material Parameter	Reference	Temperature Limit	Value or Table for Values
Coefficient of Thermal Expansion, α	Section II, Part D, Table TE-1, Group 3; coefficient B	1,500°F	4.2
Thermal Conductivity and Diffusivity (X, Δ)	Section II, Part D, Table TCD, Group K	1,500°F	4.2
Young's Modulus, E	Section II, Part D, Table TM-1, Group G	1,500°F	4.3
Isochronous Stress Strain Curves	Figures NH-T-1800-B-1 through B-13 for 316SS	To 1400 °F	See NH
S_o	Table NH-I-14.2; 316SS	1,500°F	4.4
S_{mt}	Table NH-I-14.3B; 316SS	1,500°F	4.5
S_t	Table NH-I-14.4B; 316SS	1,500°F	4.5
S_y	Section II, Part D Table Y-1 (to 1,000F) Table NH-I-14.5 316SS	1,500°F >1,000°F to 1,500°F	4.6
S_{TR}	Table NH-I-14.6B (by equation by ORNL)	1,500°F	---
ν	Poisson's Ratio, Section II, Part D, Table PRD	RT- 1,500°F	0.31
ρ	Density, Section II, Part D, Table PRD	1,500°F	0.290 lb/in^3
cp	Specific Heat	1,500°F	4.2

Table 4.2 – Coefficient of Expansion, Thermal Conductivity X and Thermal Diffusivity Δ

α units: in/in/°F; X (TC) units: BTU/hr – ft - °F; Δ (TD) units: ft²/hr; C_p units: BTU/lb-°F

T	α avg "B"	TC	TD	Cp
70	8.5	8.200	0.139	0.1100
100	8.6	8.300	0.140	0.1128
150	8.8	8.600	0.142	0.1153
200	8.9	8.800	0.145	0.1176
250	9.1	9.100	0.147	0.1198
300	9.2	9.300	0.150	0.1217
350	9.4	9.500	0.152	0.1235
400	9.5	9.800	0.155	0.1252
450	9.6	10.000	0.157	0.1268
500	9.7	10.200	0.160	0.1282
550	9.8	10.500	0.162	0.1295
600	9.9	10.700	0.165	0.1307
650	9.9	10.900	0.167	0.1318
700	10.0	11.200	0.170	0.1328
750	10.0	11.400	0.172	0.1338
800	10.1	11.600	0.175	0.1347
850	10.2	11.900	0.177	0.1355
900	10.2	12.100	0.180	0.1364
950	10.3	12.300	0.182	0.1372
1000	10.3	12.500	0.184	0.1379
1050	10.4	12.800	0.187	0.1387
1100	10.4	13.000	0.189	0.1395
1150	10.5	13.200	0.191	0.1403
1200	10.6	13.400	0.194	0.1411
1250	10.6	13.600	0.196	0.1420
1300	10.7	13.800	0.198	0.1429
1350	10.7	14.100	0.200	0.1439
1400	10.8	14.300	0.203	0.1450
1450	10.8	14.500	0.205	0.1461
1500	10.8	14.700	0.207	0.1473

Table 4.3 – Young's Modulus, E

T (°F)	E (mpsi)
70	28.3
200	27.5
300	27.0
400	26.4
500	25.9
600	25.3
700	24.8
800	24.1
900	23.5
1000	22.8
1100	22.0
1200	21.2
1300	20.3
1400	19.2
1500	18.1

Table 4.4 – Allowable Stress Intensity S_o

T (°F)	S_o (ksi)
800	15.9
850	15.7
900	15.6
950	15.5
1000	14.0
1050	11.2
1100	11.1
1150	9.8
1200	7.4
1250	5.5
1300	4.1
1350	3.1
1400	2.3
1450	1.7
1500	1.3

Table 4.5 – Allowable Stress Intensities S_{mt} and S_t at 1, 10 and 100,000 hr (ksi)

T	S_{mt}; 1 hr	S_{mt}; 10 hr	S_{mt}; 10^5 hr	T	S_t; 1 hr	S_t; 10 hr	S_t; 10^5 hr
800	15.9	15.9	15.90	800	20.8	20.8	20.8
850	15.7	15.7	15.70	850	20.6	20.6	20.6
900	15.6	15.6	15.60	900	20.4	20.4	19.9
950	15.5	15.5	15.50	950	20.1	20.1	18.4
1000	15.4	15.4	15.40	1000	19.8	19.8	16.2
1050	15.1	15.1	12.50	1050	19.4	19.4	12.5
1100	14.8	14.8	9.50	1100	19.1	19.0	9.5
1150	14.7	14.7	7.20	1150	18.5	17.7	7.2
1200	14.6	14.6	5.50	1200	17.8	16.8	5.5
1250	14.2	14.2	4.20	1250	17.1	15.2	4.2
1300	13.8	12.8	3.10	1300	16.1	12.8	3.1
1350	12.8	10.3	2.10	1350	14.2	10.3	2.1
1400	11.3	8.2	1.50	1400	12.0	8.2	1.5
1450	9.7	6.4	1.00	1450	9.7	6.4	1.0
1500	7.8	4.9	0.65	1500	7.8	4.9	0.65

Table 4.6 – Yield Strength, S_y

T (°F)	S_y (ksi)
70	30.0
150	27.4
200	25.9
250	24.6
300	23.4
400	21.4
500	20.0
600	18.9
650	18.5
700	18.2
750	17.9
800	17.7
850	17.5
900	17.3
950	17.1
1000	17.0
1050	16.8
1100	16.6
1150	16.3
1200	16.0
1250	15.5
1300	14.9
1350	14.2
1400	13.3
1450	12.3
1500	10.9

Figure 4.1 – Suggested ABAQUS Finite Element Model Layout

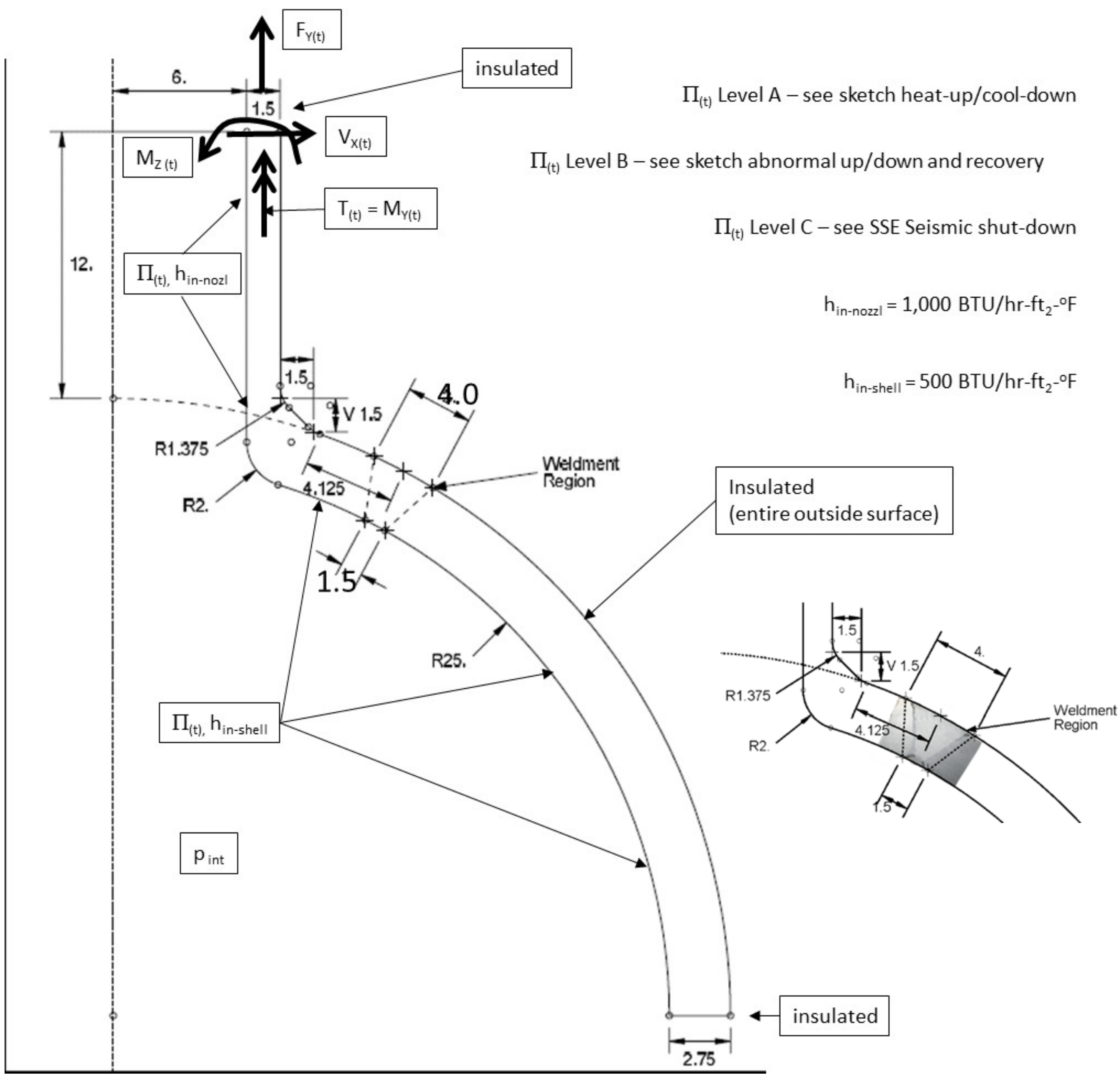
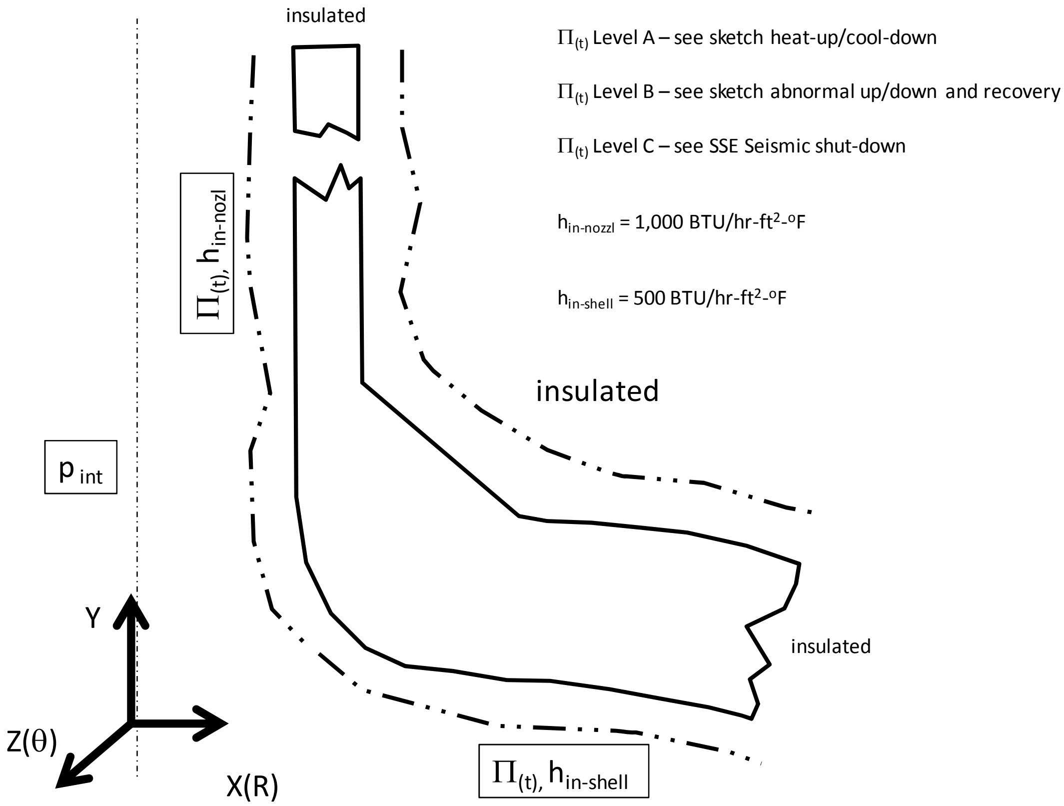


Figure 4.2 – Expected Thermal Boundary Conditions



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Record of Revisions

Revision	Date	Description	By
0	NA	There is no Rev. 0	
1	9/30/2013	Original Release	GLH
2	10/31/2013	Revised for new example geometry and loadings and editorial updates Section 1: Reference to Rev. 2 Section 2: no changes Section 3.2: change geometry sizes Section 3.3: Change Level C composite cycle to include Level A start-up Section 3.8 reduce internal pressures; reduce piping loads, adding shear; editorial changes in 3.8.2.b; update Tables and Figures for new loads and geometry. Section 4: update Table 4.1 including density from 0.291 to 0.290 and units to pci; update Table 4.2 for TC and TD values for ASME II-D Group, K; add specific heat; update Figures 4.1 and 4.2. References: add Cp data references Attachment 1: updated for new geometry and loadings; editorial changes; additional parameters defined; nozzle radii calculations added.	GLH
3	5/28/2014 6/26/2014	Revised for updated code cases; consistent model with weld zone modeled in accordance with the code cases; eliminate Level C evaluations; editorial changes and updates.	GLH

Attachment 1 – Design Sizing of the Component

Calculations are performed in MathCad [Ref. 14].

These are "sizing calculations" for the example problem consisting of a nozzle attached to a spherical shell in accordance with Section III, Division 1, Subsection NH using a nozzle shell attachment detail in NB-3338.2(a)-2 sketch (c) and Fig. NB-4244-1(a)-1 sketch (d). The sizing calculations are for Design level Conditions per NH-3222.1 and for the operating Level A and B conditions in NH-3323. Level C loading is also evaluated. These sizing calculations are approximate. The sizing calculations will be confirmed by review of the elastic analysis of the finite element model of the example.

NOTES:

1. There is no specified corrosion allowance.
2. NH-3331(c) states that if analysis is performed at the nozzle/shell juncture and limits for membrane and membrane-plus-bending are satisfied, the reinforcement requirements are waived. This is the case for this component, but reinforcement is calculated in advance of the detailed evaluation to set the dimensions of the transition region between the nozzle and shell using NB-3338.2(a)-2 sketch (c) and Figure NB-4424(a)-1 sketch (d).
3. Subsection NH, "Class 1 Components in Elevated Temperature Service," 2013 Edition [Ref. 8].
4. Subsection NB, "Class 1 Components," 2013 Edition [Ref. 16].

Conclusions:

1. The nozzle and shell are sized such that membrane stress intensities are appropriately significant, but not inappropriately close to the operating Level A, B and C limits due to short-term loading.
2. The sizing evaluation does not include thermal stresses.
3. The acceptability of the thermal stresses can be estimated by using Appendix T of Subsection NH once an initial thermal analyses of the Level A, B and C thermal loadings are performed.
4. The thermal stresses from Level B and Level C loads are expected to be severe – maybe too severe-- to be acceptable to Subsection NH or the proposed Code Cases.
5. If the thermal stresses are found to be too severe, the loadings on the REP will be adjusted.

Green shaded areas indicate INPUT.

Nozzle Geometry -- INPUT and related calculations

$d_Y := 12 \cdot in$ specified distance from end of nozzle to OD of shell

$r_{i.n} := 6 \cdot in$ specified inside radius of nozzle

$t_n := 1.50 \cdot in$ specified thickness of nozzle

$r_{m.n} := r_{i.n} + \frac{t_n}{2} = 6.75 \cdot in$ mean radius of nozzle

$d_{i.n} := 2 \cdot r_{i.n} = 12 \cdot in$ inside diameter of nozzle

$r_{o.n} := r_{i.n} + t_n = 7.5 \cdot in$ outside radius of nozzle (calculated from input)

$\frac{r_{o.n}}{t_n} = 5$ $\frac{r_{i.n}}{t_n} = 4$ NOTE: "thick"

$A_n := \pi \cdot \left(r_{o.n}{}^2 - r_{i.n}{}^2\right) = 63.617 \cdot in^2$ nozzle cross-sectional area

$S_n := \frac{\pi}{16} \cdot \frac{\left(r_{o.n}{}^4 - r_{i.n}{}^4\right)}{r_{o.n}} = 48.906 \cdot in^3$ nozzle section modulus

Shell Geometry -- INPUT and related calculations

$R_{i.s} := 25 \cdot in$ specified inside radius of spherical shell

$t_s := 2.75 \cdot in$ specified thickness of nozzle

$R_{o.s} := R_{i.s} + t_s = 27.75 \cdot in$ outside radius of shell (calculated from input)

$R_{m.s} := R_{i.s} + \frac{t_s}{2} = 26.375 \cdot in$ mean radius of shell

$\frac{R_{o.s}}{t_s} = 10.091$ $\frac{R_{i.s}}{t_s} = 9.091$ NOTE: somewhat "thick"

Design Level Loads -- INPUT

$p_{des} := 700 \cdot psi$	Design Level internal design pressure.
$p_{Lev.A.max} := 675 \cdot psi$	Level A maximum pressure
$p_{Lev.B.max} := 750 \cdot psi$	Level B maximum pressure
$p_{Lev.C.max} := 775 \cdot psi$	Level C maximum pressure
$F_{des} := 30000 \cdot lbf$	Design Level "FVMT" axial load, F.
$V_{des} := 4000 \cdot lbf$	Design Level "FVMT" shear load, V.
$M_{des} := \left(d_Y + \frac{t_s}{2}\right) \cdot V_{des} = 5.35000 \times 10^4 \cdot in \cdot lbf$ $M_{des} = 4.458 \times 10^3 \cdot ft \cdot lbf$	Design Level bending moment, M; the resultant bending moment due to specified shear and distance to mid-thickness of the shell.
$Trq_{des} := 20000 \cdot in \cdot lbf$	Design Level "FVMT" torsional moment, T.
$T_{des} := 1200\ °F$	Design Temperature
$T_{max.Lev.A} := 1100\ °F$	maximum Level A temperature
$T_{max.Lev.B} := 1175\ °F$	maximum Level B temperature
$T_{max.Lev.C} := 1300\ °F$	maximum Level C temperature
$k_{Lev.AB} := 1.0$	Factor for Level A maximum up-ramp mechanical loads.
$k_{Lev.B} := 1.25$	Factor for Level B maximum up-ramp mechanical loads.
$k_{Lev.C} := 2$	Factor for Level C maximum up-ramp mechanical loads.
$n_{cyc.Lev.B} := 850$	number of cycles Level B loading
$n_{cyc.Lev.C} := 25$	number of cycles Level C loading

$t_{gt.1100F.Lev.B} := 350 \cdot sec$ time above 1100F in one Level B cycle

$t_{gt.1100F.Lev.C} := 390 \cdot sec$ time above 1100F in one Level C cycle

$t_{max.Lev.A} := 100000 \cdot hr$ time at maximum temperature, level A (conservative at entire design life)

$$t_{max.Lev.B} := n_{cyc.Lev.B} \cdot t_{gt.1100F.Lev.B} = 82.639 \cdot hr$$

time at maximum temperature, Level B; all time above 1100F for number of cycles. NOTE: 1100F is used here to be conservative with respect to the 1200F design temperature for determoining this time.

$$t_{max.Lev.C} := n_{cyc.Lev.C} \cdot t_{gt.1100F.Lev.C} = 2.708 \cdot hr$$

time at maximum temperature, Level C; all time above 1100F for number of cycles. NOTE: 1100F is used here to be conservative with respect to the 1200F design temperature for determoining this time.

NOTE: Deadweight is not significant enough to be included in the sizing calculations.

Material Specification -- INPUT

316 SS as permitted by NH-2000.

Allowable Stress Intensities -- INPUT

$t_{life} := 100000 \cdot hr$ specified component design life

$S_o := 7.4 \cdot ksi$ Design Level basic allowable stress at 1200F; see Section 4 Tables.

$S_{mt.DL} := 5.5 \cdot ksi$ S_{mt} value for Level A, B, C tTemperatures < 1200 F for 100,000 hr (time not covered by other S_{mt} and S_t values below); see Section 4 Tables.

$S_{mt.Lev.B.maxT} := 14.6 \cdot ksi$ 1200F, 100 hr to cover $t_{.max.Lev.B}$

$S_{t.Lev.C.maxT} := 16.1 \cdot ksi$ 1300F, 1 hr to cover $t_{.max.Lev.C}$

Sizing Calculations for Design Level and Level A and B Loadings: Nozzle

First consider loading applicable to beyond steady state operating loads of the design life, i.e., not the transient loading stresses that are the short-term loads , but conservatively use the entire design life for time.

$p_{Lev.AB.max} := p_{des} = 700 \cdot psi$ — conservatively set Level A and B internal pressure to Design Level proessure

$S_{sizing.DL} := \min(S_o, S_{mt.DL}) = 5.5 \cdot ksi$ — covers Design and Level A

$$t_{n.r} := \frac{p_{Lev.AB.max} \cdot r_{i.n}}{S_{sizing.DL} - \frac{p_{Lev.B.max}}{2}} = 0.82 \cdot in$$

required nozzle thickness for pressure

$t_n = 1.5 \cdot in$ — nozzle thinkness provided

$$\frac{t_{n.r}}{t_n} = 0.546$$

ACCEPTABLE when ratio ≤ 1.0

P_m stress intensity

$$\frac{p_{Lev.AB.max} \cdot r_{i.n}}{t_n} = 2.800 \cdot ksi$$

longitudinal due to pressue

$$\frac{F_{des} \cdot k_{Lev.AB}}{A_n} = 0.472 \cdot ksi$$

longitudinal due to axial pipe load

$$\frac{M_{des} \cdot k_{Lev.AB}}{S_n} = 1.094 \cdot ksi$$

longitudinal due to bending pipe load

$$\sigma_{noz.long} := \frac{p_{Lev.AB.max} \cdot r_{i.n}}{2 t_n} + \frac{F_{des} \cdot k_{Lev.AB}}{A_n} + \frac{M_{des} \cdot k_{Lev.AB}}{S_n} = 2.966 \cdot ksi$$

$$\sigma_{noz.hoop} := \frac{p_{Lev.AB.max} \cdot r_{i.n}}{t_n} = 2.8 \cdot ksi$$

$$\tau_{noz.trq} := \frac{Trq_{des} \cdot k_{Lev.AB}}{2 \cdot S_n} = 0.204 \cdot ksi$$

$$S1_{noz} := \frac{\sigma_{noz.long} + \sigma_{noz.hoop}}{2} + \sqrt{\left(\frac{\sigma_{noz.long} - \sigma_{noz.hoop}}{2}\right)^2 + \tau_{noz.trq}^{\ 2}}$$

$$S1_{noz} = 3.103 \cdot ksi$$

$$S2_{noz} := \frac{\sigma_{noz.long} + \sigma_{noz.hoop}}{2} - \sqrt{\left(\frac{\sigma_{noz.long} - \sigma_{noz.hoop}}{2}\right)^2 + \tau_{noz.trq}^{\ 2}}$$

$$S2_{noz} = 2.662 \cdot ksi$$

$$S3_{noz} := \frac{-P_{des}}{2} = -0.35 \cdot ksi$$

$$S12_{noz} := S1_{noz} - S2_{noz} = 0.441 \cdot ksi$$

$$S23_{noz} := S2_{noz} - S3_{noz} = 3.012 \cdot ksi$$

$$S31_{noz} := S3_{noz} - S1_{noz} = -3.453 \cdot ksi$$

$$SI_{noz.Pm} := \max\left(\left|S12_{noz}\right|, \left|S23_{noz}\right|, \left|S31_{noz}\right|\right) = 3.453 \cdot ksi$$

$$\frac{SI_{noz.Pm}}{S_{sizing.DL}} = 0.628$$

ACCEPTABLE when ratio $\leq$ 1.0

Consider the Level B short-term maximum loading at short-term maximum temperatures. The following approximate evaluation is used.

The maximum Level B mechanical loads are 1.25 times the design and Level A loads, and the maximum Level C loads are 2 times the Design and Level A loads. See Section 3.3.
The short-term S_{mt} value for the maximum temperature for Level B is more than double the design load (DL) S_{mt} value as shown below. The S_t value for the short-term Level C maximum loads is even higher, and therefore using the Level B S_{mt} values below cover evaluation of Level C short-term loads and maximum temperatures.
On this basis, the estimated P_m acceptance ratios for both Level B and Level C maximum

$S_{mt.Lev.B.maxT} = 14.6 \cdot ksi$

$S_{mt.DL} = 5.5 \cdot ksi$

$$\frac{S_{mt.Lev.B.maxT}}{S_{mt.DL}} = 2.655$$

Conservatively for Level B and C; factor 2.0 is for Level C FVMT loads.

$p_{Lev.C.max} = 0.775 \cdot ksi$ $p_{des} = 0.7 \cdot ksi$ $S_{mt.Lev.B.maxT} = 14.6 \cdot ksi$

$S_{mt.DL} = 5.5 \cdot ksi$ $SI_{noz.Pm} = 3.453 \cdot ksi$ $S_{sizing.DL} = 5.5 \cdot ksi$

$$\frac{k_{Lev.C} \cdot \left(\frac{p_{Lev.C.max}}{p_{des}}\right)}{\frac{S_{mt.Lev.B.maxT}}{S_{mt.DL}}} \cdot \frac{SI_{noz.Pm}}{S_{sizing.DL}} = 0.524$$

ACCEPTABLE when ratio ≤ 1.0

Sizing Calculations for Design Level and Level A and B Loadings: Shell

NOTE: These calculations Ignore piping loads effects in the spherical shell, which cause P_L and P+Q stresses in the shell. P_L and P+Q stress intensiteis are calculated with WRC-107 [17] methodology and eventually by elastic FEA evaluation for elastically checking the FEA model to be used for elastic-perfectly plastic evaluation of the proposed Code Cases.

$$t_{s.r} := \frac{p_{Lev.AB.max} \cdot R_{i.s}}{2S_{sizing.DL} - \frac{p_{Lev.A.max}}{2}} = 1.641 \cdot in$$

required shell thickness for design and Level A pressure.

$t_s = 2.75 \cdot in$ shell thickness provided.

$$\frac{t_{s.r}}{t_s} = 0.597$$

ACCEPTABLE when ratio ≤ 1.0

$$\frac{p_{Lev.AB.max} \cdot R_{i.s}}{2 \cdot t_s} = 3.182 \cdot ksi$$

$0.5 \cdot p_{des} = 0.35 \cdot ksi$

$$SI_{Pm.shell} := \frac{p_{Lev.AB.max} \cdot R_{i.s}}{2 \cdot t_s} + 0.5 \cdot p_{Lev.AB.max} = 3.532 \cdot ksi$$

conservatively covers nearly the entire design life for levels A and B, i.e., $S_{.sizing.DL}$ is for the design temperature and for the entire design life.

$$\frac{SI_{Pm.shell}}{S_{sizing.DL}} = 0.642$$

ACCEPTABLE when ratio $\leq$ 1.0

Applying the same ratios as described above for the nozzle, the shell's acceptance ratio for Level A, B and C is conservatively computed as follows.

$$\frac{k_{Lev.C} \cdot \left(\frac{p_{Lev.C.max}}{p_{des}}\right)}{\frac{S_{mt.Lev.B.maxT}}{S_{mt.DL}}} \cdot \frac{SI_{Pm.shell}}{S_{sizing.DL}} = 0.536$$

ACCEPTABLE when ratio $\leq$ 1.0

The WRC-107 analysis of the nozzle/sphere intersection treating the nozzle as a rigid attachment with an outside radius extending to the end of the transition material in the shell is summarized below. This is an approximate analysis of the interaction loads for this elevated temperature component using the (P+Q) stresses and comparing them to the typical elastic analysis limit of 3S. Showing that the (P+Q) stresses remain less than the $3S_{mt}$ and $3S_t$ limits for design loads and short-term Level A, B and C loads is approximate. It does not include the significant thermal portion of Q, which will be evaluated using the proposed Code Cases.

$PQ_{DL} := 9.0 \cdot ksi$ from WRC-107 analysis of juncture as described

$$\frac{PQ_{DL}}{3 \cdot S_{mt.DL}} = 0.545$$

ACCEPTABLE when ratio $\leq$ 1.0

$PQ_{Lev.B} := k_{Lev.B} \cdot PQ_{DL} = 11.25 \cdot ksi$

from load-ratioing design level B FVMT loads. This $k_{.Lev.B}$ factor conservatively covers the ratio for Level B pressure load, which is less than $k_{.Lev.B}$.

$$\frac{PQ_{Lev.B}}{3.S_{mt.Lev.B.maxT}} = 0.257$$

ACCEPTABLE when ratio $\leq$ 1.0

$PQ_{Lev.C} := k_{Lev.C} \cdot PQ_{DL} = 18 \cdot ksi$

from load-ratioing design level C FVMT loads. This $k_{.Lev.C}$ factor conservatively covers the ratio for Level B pressure load, which is less than $k_{.Lev.C}$.

$$\frac{PQ_{Lev.C}}{3 \cdot S_{t.Lev.C.maxT}} = 0.373$$

ACCEPTABLE when ratio ≤ 1.0

Reinforcement to set transition size using NB-3334 and reference to NB-3338.2(a)-2 sketch c.

NB-3334.1(a) Limits along vessel wall.

$$L_{s.a1} := d_{i.n} - r_{i.n} - t_{n.r} = 5.18 \cdot in$$

$$L_{s.a2} := r_{i.n} + \left(t_n + t_s\right) = 10.25 \cdot in$$

$$L_{s.b1} := r_{i.n} + 0.5 \cdot \sqrt{R_{m.s} \cdot t_s} = 10.258 \cdot in$$

$$L_{s.b2} := r_{i.n} + \frac{2}{3} \cdot \left(t_s + t_n\right) = 8.833 \cdot in$$

NB-3334.1(a) Limits along vessel wall.

$$L_{n.b} := \frac{\sqrt{r_{m.n} \cdot t_n}}{2} = 1.591 \cdot in$$

$A_r := t_{s.r} \cdot 2 \cdot r_{i.n} = 19.695 \cdot in^2$ total reinforcement area both sides

Subtract reinforcement areas in shell and nozzle based on reinforcement dimensions, each size of nozzle centerline.

$$A_{r.net} := \frac{A_r}{2} - L_{s.a2} \cdot \left(t_n - t_{n.r}\right) - L_{n.b} \cdot \left(t_s - t_{s.r}\right) = 1.109 \cdot in^2$$

Compute legs of triangular reinforcement region, x to provide $A_{.r.net} = 1/2x^2$.

$\boxed{x := \sqrt{2 \cdot A_{r.net}} = 1.489 \cdot in}$ basic dimension of triangular transition region

Blend Radii per NB-3338.2(a)-2 Sketch (c) and NB-3339.1(b)-1 Sketch (b)

Although NB-3338 and NB-3339 are not being used, the dimensional information regarding blend radii for the REP is being applied.

NB-3338.2(a)-2 Sketch (c)

$r_{1.3338.min} := 0.1 \cdot t_s = 0.275\,in$

$r_{1.3338.max} := t_s = 2.75\,in$

$r_{2.3338} := \max\left(\frac{t_n}{2}, \frac{t_s}{2}\right) = 1.375\,in$

$\theta_{deg} := 45$

$r_{3.3338} := 0.002 \cdot \theta_{deg} \cdot 2(r_{i.n} + t_n) = 1.35\,in$

NB-3339.1(b)-1 Sketch (b)

$r_{1.3339.min} := 0.1 \cdot t_s = 0.275\,in$

$r_{1.3339.max} := 0.5 \cdot t_s = 1.375\,in$

$r_{3.3339} := \max\left[\sqrt{\frac{\theta_{deg}}{90}(2 \cdot r_{i.n}) \cdot t_{n.r}}, \frac{\theta_{deg}}{90} \cdot t_n\right] = 2.217\,in$

$r_{4.3339} := \left(1 - \sqrt{\frac{\theta_{deg}}{90}}\right)\sqrt{(2 \cdot r_{i.n})t_{n.r}} = 0.918\,in$

The following values are chosen:

1. The inside nozzle radius the range of r_1 for both 3338 and 3339 is between 0.275 in and 2.75 in.; 2.0 inch is chosen.
2. The outside nozzle-to-transition blend radius, r_3, for both 3338 and 3339, the values are either 1.375 or 2.217 in; 1.375 in is chosen.
3. The outside transition-to-shell blend radius r_2 for 3338 or r_4 for 3339 is either 1.375 in or 0.918 in; 1.375 in is chosen.

END OF SIZING CALCULATIONS

Elevated Temperature Code Case Representative Example Problem Analysis

Document No. 20362-R-002

Revision No. 3

Project Number	Project Name	Client
20362	Representative Example Problem Task	UT-Battelle, ORNL

Quality Assurance	Open Items	Preverified Software Used
n/a	n/a	n/a

Originator	Verifier	Approver
Derrick Pease	n/a	Greg L. Hollinger

Table of Contents

1. Purpose and Scope

The purpose of this report is to document the implementation of the strain limits code case and the creep-fatigue code case [Ref. 1, Section 2.0] using the representative example problem (REP) vessel defined in the REP Design Specification [Ref. 1]. To investigate the impact of the weldment on the analyses, two versions of the REP vessel are modeled: one with base metal only (REP-B) and one with the weldment (REP-W).

2. Summary

The implementation evaluations of the strain limits code case and the creep fatigue code case in the Design Specification [Ref. 1] are successful using the two REP models and evaluations. The implementation of the code cases requires trial-and-error finite element EPP runs with starting target inelastic strains (for strain limits evaluation) or target creep damage (for creep-fatigue evaluation), iterated with successively smaller values and adjusted pseudo yield stress curves until the criteria in the code cases are met. The results are summarized as follows.

2.1 Level A & B Composite Cycle Results

The Level A & B Composite Cycle is evaluated using both the REP Base Metal Only model (REP-B) and the REP with Weldment model (REP-W). Both evaluations meet the strain limits code case evaluation criteria and the creep-fatigue code case evaluation criteria.

Level A & B Composite Cycle strain limits code case evaluation: The controlling base metal location for both models is at the outer surface of the shell-to-nozzle transition where nozzle bending due to the nozzle end shear load produces maximum strains. The EPP plastic strain developed at this location for the base metal only model and the model with the weldment is small -- 0.0006% and 0.0009%, respectively. Since the weldment does not yield during the level A & B loadings there is not a controlling weldment location. Furthermore, since the weldment behaves elastically with the same properties as the base metal, both models behave with only a slight difference in base metal plastic strains. That difference is attributed to the differences in the model meshes.

Level A & B Composite Cycle creep-fatigue code case evaluation: The controlling base metal location for both models is at the outer surface of the shell-to-nozzle transition, rotated approximately 45° from where nozzle bending due to the nozzle end shear load produces maximum strains. The Level A & B cycle type maximum equivalent strain range at this location for both the base metal only model and the model with the weldment is 0.110%. However, for the Level B cycle type they are slightly different, 0.076% and 0.077% respectively. The controlling weldment location is on the inside surface of the shell on the outermost weld-base metal interface. The maximum equivalent strain range at this location from both models is 0.083% for the Level B cycle type and 0.037% for the Level A cycle type.

2.2 Level A & C Composite Cycle Results

The Level A & C Composite Cycle is evaluated using only the REP-B model. The evaluation exceeds the strain limit code case evaluation criteria due to significant plastic strains developing within 2 pseudo-cycles. The evaluation exceeds the creep-fatigue code case evaluation criteria due to ratcheting, albeit stable ratcheting and with a target creep damage of 1.0. Further trials of different target creep damages are not performed since reducing the target creep damage only reduces the pseudo yield strength making it even more difficult to achieve shakedown.

No evaluation of the Level A & C Composite Cycle with the REP-W model is performed since based on the criteria not being met for the REP-B model, the same unmet criteria would be obtained.

3. Modeling and Inputs

Both the REP-B and REP-W vessels are modeled in Abaqus 6.13-4 as shown in Figure 3-1.

3.1 Geometry and Mesh

The geometry profile of the REP vessels used to generate the 3D half-symmetric models of the REP vessels is shown in Figure 3.1-1. The REP vessels are modeled using 8-node linear brick elements with full integration (C3D8) for stress analyses and 8-node linear heat transfer brick elements (DC3D8) for heat transfer analyses. The same mesh, as shown in Figure 3.1-2 for the REP-B model and Figure 3.1-3 for the REP-W model, is used for both element types. The selected mesh density is based on the mesh study in Appendix A.

3.2 Materials

The REP vessel base metal is modeled using 316 forged stainless steel properties in accordance with material specification SA-182 grade F316 and the weldment is modeled using 316 stainless steel weld properties in accordance with SFA-5.4 grade E316. The material properties included in the model are: density, specific heat and conductivity for heat transfer analyses and modulus of elasticity, Poisson's ratio, mean thermal expansion coefficient and yield stress for stress analyses. The values used in the FEA model are listed in Table 3.2-1 through Table 3.2-3.

For the strain limits evaluation, the yield stress is set as a temperature dependent "pseudo yield stress" based on the total time duration of high temperature service, t_d, and the selected target inelastic strain, x. This "pseudo yield stress" is equal to the lesser of the yield strength given in Table I-14.5 of Subsection NH as modified by Sub-article NH-2160; and the stress to cause x accumulated inelastic strain in time t_d, as determined from the isochronous stress strain curves in Figure T-1800 in Appendix T of Subsection NH. Appendix B provides the computations used to develop the temperature dependent pseudo yield stress data for each selected target inelastic strain, x.

For the creep-fatigue evaluation, the yield stress is set as a temperature dependent "pseudo yield stress" based on the allowable time duration, $T_{d,k}$, for trial k. This "pseudo yield stress" is equal to the lesser of the yield strength and the minimum stress-to-rupture in time $T_{d,k}$, where yield strength is given in Table I-14.5 of Subsection NH as modified by Sub-article NH-2160; and the minimum stress-to-rupture is from Figure I-14.6B of Subsection NH multiplied by the elastic analysis factor from Table T-1411-1 of Subsection NH. For weldments the minimum stress-to-rupture is reduced by the appropriate stress rupture factors in Tables I-14.10B-3 of Subsection NH. Appendix C provides the computations used to develop the temperature dependent base metal and weldment pseudo yield stress data for each trial time $T_{d,k}$.

High temperature service for SA-182 grade F316 is defined as temperatures above the maximum temperature limit, $T_{max} = 800°\text{F}$, listed in Table 2A of Section II Part D [Ref. 2].

3.3 Constraints

The end of the nozzle and the half-symmetry plane of the vessel are constrained to center nodes, one for applying nozzle loads and the other for applying boundary conditions as shown in Figure 3-1. The constraints are defined using kinematic couplings with all degrees of freedom constrained except radially, to allow for thermal expansion.

3.4 Initial Conditions

The entire vessel is assigned an initial condition temperature of 70°F.

3.5 Boundary Conditions

3.5.1 Thermal Boundary Conditions

The heat transfer thermal boundary conditions due to convection inside the vessel are applied, as shown in Figure 3.5.1-1, with the same time dependent sink temperature and with the following different film coefficients.

- Nozzle Internal Film Coefficient = 1,929.01E-06 BTU/s-in^2-°F
- Shell Internal Film Coefficient = 964.506E-06 BTU/s-in^2-°F

The exterior surface of the vessel has insulated boundary conditions.

3.5.2 Mechanical Boundary Conditions

The vessel is fully constrained in all degrees of freedom at the symmetry center node as shown in Figure 3-1.

3.6 Loads

3.6.1 Internal Pressure

The internal pressure is applied to the inside surface of the vessel and nozzle as shown in Figure 3-1. The time dependent reaction, $F_p(t)$, due to pressure at the nozzle end is applied as an additional axial load computed as follows.

$$F_p(t) = P(t)\pi r_i^2 = P(t) \times 113.097 in^2 \qquad \text{(3-1)}$$

where
$P(t)$ = time dependent internal pressure, psi
r_i = internal radius of nozzle, 6 in

3.6.2 Mechanical Loads

The nozzle axial load, shear force and torsional moment are applied to the nozzle end center node as shown in Figure 3-1. These mechanical loads are based on the design loads, listed in Table 3.6.2-1, which are scaled by a time dependent mechanical load factor to obtain time dependent mechanical loads.

3.6.3 Time Histories

The temperature, pressure, and mechanical load time histories for each composite cycle are listed in Table 3.6.3-1 and plotted in Figure 3.6.3-1 and Figure 3.6.3-2.

Temperature is applied to the heat transfer analysis model using a single tabular amplitude as a function of total time.

To facilitate a restart analysis in Abaqus for evaluating multiple cycles, the pressure and mechanical loads are applied to the stress analysis model using individual step tabular amplitudes as a function of step time.

The total time duration of high temperature service, t_d, for all Level A, B and C Service Loadings is determined in Table 3.6.3-2.

4. Analysis

4.1 Methodology

Two types of analyses are run for each set of composite cycles. A transient heat transfer analysis is performed to establish the temperature field in the vessel throughout the composite cycle. Stress analyses are performed with the time dependent temperature field results from the heat transfer analysis to obtain the strains in the vessel due to both mechanical loads and thermal expansion. Note: Each cycle of a stress analysis using a "pseudo yield stress" has no direct correlation to the number of design or fatigue cycles and is hence defined as a "pseudo-cycle".

A pseudo-cyclic analysis is performed using the restart option to analyze multiple pseudo-cycles of a composite cycle. After the initial pseudo-cycle is analyzed, the analysis is restarted at the end of the previous pseudo-cycle to continue with another set of composite cycle loadings. This restart process is repeated until a sufficient number of pseudo-cycles have been reached.

4.1.1 Strain Limits Methodology

The strain limits methodology is developed in accordance with the Strain Limits Code Case in Section 2 of the Design Specification [Ref. 1].

For the strain limits evaluation, stress analyses are performed where the “pseudo yield stress” is adjusted based on the selected target inelastic strains, x. Initially the target inelastic strain is selected as the averaged inelastic strain limit, ϵ_{avg}, (1% for base metal and 0.5% for weld metal).

With the target inelastic strain selected; a pseudo-cyclic analysis is performed where an intermediate check is performed at the end of each pseudo-cycle. If there exists a through thickness region where the total inelastic strain (target inelastic strain plus plastic strains) exceed the averaged inelastic strain limit, $x + \epsilon_p > \epsilon_{avg}$, then the target inelastic strain, x, is reduced. Some effort is made to maximize the region where total inelastic stains are less than the averaged inelastic strain limit before proceeding to the next pseudo-cycle. If further reduction of x decreases this region then the target inelastic strain selection has been optimized. Once optimized, if there still exists a through thickness region where total inelastic strains exceed the averaged inelastic strain limit then it is concluded that the strain limits criteria cannot be met. Otherwise, additional pseudo-cycles are analyzed until ratcheting has ceased.

Ratcheting is evaluated at every location in the model by checking the change in plastic strain, $\Delta\epsilon_p$, between the beginning and end of a single pseudo-cycle. Ratcheting has ceased when there is no change in plastic strain throughout the whole model between the beginning and end of a single pseudo-cycle.

Plastic strains are evaluated as:

$$\epsilon_p = \sqrt{\frac{2}{3}\left(\epsilon_{x.p}^2 + \epsilon_{y.p}^2 + \epsilon_{z.p}^2 + 2\epsilon_{xy.p}^2 + 2\epsilon_{yz.p}^2 + 2\epsilon_{zx.p}^2\right)} \qquad (4\text{-}1)$$

Note: The Abaqus output variable for this value is PEMAG.

The total inelastic strain is defined by adding the target inelastic strain, x, to the computed plastic strains, ϵ_p:

$$\epsilon_{tot} = x + \epsilon_p \qquad (4\text{-}2)$$

The averaged strain limits are evaluated such that there exists at least one point for all through-thickness locations that meets the following criteria:

$$\epsilon_{tot} \le \epsilon_{avg} \qquad (4\text{-}3)$$

where
ϵ_{avg} = 1% for base metal regions or 0.5% for weldment regions

The local strain limits are evaluated such that all locations meet the following criteria:

$$\epsilon_{tot} \leq \epsilon_{local} \tag{4-4}$$

where
ϵ_{local} = 5% for base metal regions or 2.5% for weldment regions

Section 4.1.1 is repeated for different values of x until criteria (4-3) and (4-4) have been meet and ratcheting has ceased. If no value of x meets these requirements then it is concluded that the strain limits criteria cannot be met.

4.1.2 Creep-Fatigue Methodology

The creep-fatigue methodology is developed in accordance with the Creep-Fatigue Code Case in Section 2 of the Design Specification [Ref. 1].

For the creep-fatigue evaluation stress analyses are performed where the "pseudo yield stress" is adjusted based on the allowable time duration, $T_{d,k}$ for the current trial, k. The allowable time duration is determined by selecting a target cyclic creep damage value, $D_{c,k}$, for trial k (initially selected as 1.0) using the following equation:

$$T_{d,k} = t_d / D_{c,k} \tag{4-5}$$

where
t_d = duration of high temperature service

With the target creep damage selected, a pseudo-cyclic analysis is performed for the current trial. If the pseudo-cyclic analysis does not shakedown for the initial trial (with creep damage of 1.0) then the creep-fatigue evaluation fails since longer trial times, $T_{d,k}$, will only make shakedown more difficult.

Shakedown is evaluated at every location in the model by checking the maximum change in plastic strain over every increment of a single pseudo-cycle. Shakedown is achieved when there is no change in plastic strain throughout the whole model during a single pseudo-cycle, i.e. the model is behaving elastic.

Using the strain results from the pseudo-cycle that shakes down, the maximum equivalent strain range, $\Delta\epsilon_{max,kj}$, are computed for each cycle type j of trial k over every point in time, i, for each potential extreme condition point in time, o, at every location in the component:

$$\Delta\epsilon_{max,kj} = \max\left[\frac{\sqrt{2}}{2(1+\nu^*)}\sqrt{\begin{matrix}\left(\Delta\epsilon_{xi} - \Delta\epsilon_{yi}\right)^2 + \\ \left(\Delta\epsilon_{yi} - \Delta\epsilon_{zi}\right)^2 + \\ \left(\Delta\epsilon_{zi} - \Delta\epsilon_{xi}\right)^2 + \\ 6\left(\Delta\epsilon_{xyi}^2 + \Delta\epsilon_{yzi}^2 + \Delta\epsilon_{zxi}^2\right)\end{matrix}}\right] \tag{4-6}$$

where
ν^* = Poisson's ratio
= 0.3 [Ref. 1, Section 5.2 of the Creep-Fatigue Code Case]
$\Delta\boldsymbol{\epsilon}_i = \boldsymbol{\epsilon}_i - \boldsymbol{\epsilon}_o$
= change in strain components from potential extreme condition point in time, o, to point in time, i

The range of potential extreme condition points in time, o, includes every time point up to the current point in time, i, being evaluated. This ensures that every possible combination of the points in time are considered such that the maximum equivalent strain range is obtained.

A point of consideration, p, is selected in the component to evaluate fatigue damage based on the location where the largest strain ranges occur in both the base metal and the weldment.

The number of design allowable cycles, $N_{d,kpj}$, are determined for cycle type j of trial k at point p from the design fatigue curve for 316 SS [Ref. 3, Figure NH-T-1420-1B] where the strain range, ϵ_t, is defined as $\epsilon_t = \Delta\epsilon_{max,kj}$ and the maximum metal temperature is 1175°F for the A & B composite cycle and 1300°F for the A & C composite cycle. Note: for strain ranges within the weld region, the number of design allowable cycles are reduced by 50%.

The total fatigue damage, $D_{f,kp}$, is computed for trial k at point p:

$$D_{f,kp} = \sum_j \frac{n_j}{N_{d,kpj}} \tag{4-7}$$

where

n_j = number of applied cycles for cycle type j

If the total fatigue damage is not less than 1.0 then the creep-fatigue evaluation has failed.

The allowable creep-fatigue damage, D_{kp}, is determined for trial k at point p:

$$D_{kp} = D_{f,kp} + \max \begin{bmatrix} 1 + \frac{D_{ic} - 1}{D_{if}} D_{f,kp} \\ \frac{D_{ic}}{D_{if} - 1}\left(D_{f,kp} - 1\right) \end{bmatrix} \tag{4-8}$$

where

$\left(D_{if}, D_{ic}\right)$ = creep-fatigue damage envelope intersection parameters [Ref. 3, Figure NH-T-1420-2]
= $(0.3, 0.3)$ for 316 stainless steel

The total creep-fatigue damage for trial k is computed and compared to the allowable damage for trial k at point p:

$$D_{f,kp} + D_{c,k} \leq D_{kp} \tag{4-9}$$

Note: The creep damage used in this equation is not necessarily the creep damage at a specific point, but is the "maximum cyclic creep damage over the structure" as specified in Section 4.4 of the Creep Fatigue Code Case.

If the total creep-fatigue damage exceeds the allowable damage then a reduced target creep damage, $D_{c,k+1}$, is selected for the next trial, $k + 1$, based on the following equation:

$$D_{c,k+1} \leq D_{kp} - D_{f,kp} \tag{4-10}$$

Section 4.1.2 is repeated until either the creep-fatigue evaluation passes the criterion of equation (4-9) or fails due to excessive creep or fatigue damage or both.

4.2 Analysis Steps

Each composite cycle is broken up into discrete steps and when necessary limits to maximum time increments are applied to ensure that the analysis deals with all the changes within a cycle. The step names and durations are summarized in Table 4.2-1 and Table 4.2-2 and are plotted with the time history amplitudes in Figure 4.2-1 and Figure 4.2-2.

4.3 Results

4.3.1 Heat Transfer Results

The temperature contour results of the heat transfer analyses are shown in Figure 4.3.1-1 and Figure 4.3.1-2.

4.3.2 Strain Limits Evaluation

The results of the strain limits evaluations for each composite cycle are presented in Table 4.3.2-1 and Figure 4.3.2-1 through Figure 4.3.2-5.

4.3.2.1 Level A & B Composite Cycle Evaluation

The REP-B model strain limits evaluation for the Level A & B Composite Cycle with a target base metal inelastic strain of 1% passes after two pseudo-cycles with a maximum total inelastic strain of 1.0006%.

The REP-W model strain limits evaluation for the Level A & B Composite cycle with a target base metal inelastic strain of 1% and a target weldment inelastic strain of 0.5% passes after three pseudo-cycles with a maximum total inelastic strain of 1.0009% in the base metal at the nozzle to shell transition and 0.5% in the weldment, with no plastic strain in the weldment.

4.3.2.2 Level A & C Composite Cycle Evaluation

The base metal only strain limits evaluation for the Level A & C Composite Cycle does not pass. With an optimized target base metal inelastic strain of 0.60%, the region of total inelastic strains less than the average strain limit is maximized, but after two pseudo-cycles the total inelastic strain near the region of where shakedown would occur is well over the 1.0% limit.

Since the base metal only evaluation did not pass for the Level A & C Composite Cycle it is concluded that the REP with weldment evaluation will not pass either, and is thus not evaluated.

4.3.3 Creep-Fatigue Evaluation

The results of the creep-fatigue evaluations for each composite cycle are presented in Table 4.3.3-1 & Table 4.3.3-2 and Figure 4.3.3-1 through Figure 4.3.3-5.

4.3.3.1 Level A & B Composite Cycle REP-B Model Evaluation

The REP-B model Level A & B Composite Cycle analysis with a target creep damage of 0.90 passes after 3 pseudo-cycles.

Figure 4.3.3-1 shows the maximum change in plastic strain during pseudo-cycle 3 is 0.0% indicating that shakedown has occurred and the model is behaving elastically.

Figure 4.3.3-2 shows the maximum equivalent strain ranges for each cycle type. Based on the location of the largest strain ranges, the point at which fatigue damage is evaluated is selected as element 49099 integration point 1, which is located on the outside surface of the shell-to-nozzle transition at the radius into the nozzle neck.

Table 4.3.3-2 lists a maximum equivalent strain range of 0.110% from the first cycle type of the fatigue evaluation for 90 applied repetitions of Level A & B loadings between increment 10 of the Level A: Ramp Down step to increment 9 of the Level B: Peak Up step.

Table 4.3.3-1 lists the Level A&B cycle type fatigue damage as 0.00045 based on a conservatively selected 2E+5 allowable number of cycles from the 316 SS NH fatigue curve.

Table 4.3.3-2 lists a maximum equivalent strain range of 0.076% from the second cycle type for 692 applied repetitions (782 Level B cycles – 90 previously applied repetitions) of the Level B only loadings between increment 9 of the Level B: Peak Up step to increment 9 of the Level B: Ramp Down 2 step.

Table 4.3.3-1 lists the Level B only cycle type fatigue damage as 0.00346 based on a conservatively selected 2E+5 allowable number of cycles from the 316 SS NH fatigue curve.

Table 4.3.3-1 also lists the total creep-fatigue damage as 0.904 and the allowable creep-fatigue damage as 0.995, which is sufficiently greater than the calculated value. This places the creep-fatigue damage within the NH-T-1420-2 creep-fatigue interaction envelope, thus meeting the criteria for creep-fatigue interaction.

4.3.3.2 Level A & B Composite Cycle REP-W Model Evaluation

The REP-W model Level A & B Composite Cycle analysis with a target creep damage of 0.95 passes after 3 pseudo-cycles.

Figure 4.3.3-3 shows the maximum change in plastic strain during pseudo-cycle 3 is 0.0% indicating that shakedown has occurred and the model is behaving elastically.

Base Metal Evaluation:

Figure 4.3.3-4 shows the maximum equivalent strain ranges for each cycle type. Based on the location of the largest strain ranges, the point at which fatigue damage is evaluated is selected as element 45139 integration point 7, which is located on the outside surface of the shell-to-nozzle transition at the radius into the nozzle neck.

Table 4.3.3-2 lists a maximum equivalent strain range of 0.108% from the first cycle type of the fatigue evaluation for 90 applied repetitions of Level A & B loadings between increment 10 of the Level A: Ramp Down step to increment 9 of the Level B: Peak Up step.

Table 4.3.3-1 lists the Level A&B cycle type fatigue damage as 0.00045 based on a conservatively selected 2E+5 allowable number of cycles from the 316 SS NH fatigue curve.

Table 4.3.3-2 lists a maximum equivalent strain range of 0.077% from the second cycle type for 692 applied repetitions (782 Level B cycles – 90 previously applied repetitions) of the Level B only loadings between increment 9 of the Level B: Peak Up step to increment 9 of the Level B: Ramp Down 2 step.

Table 4.3.3-1 lists the Level B only cycle type fatigue damage as 0.00346 based on a conservatively selected 2E+5 allowable number of cycles from the 316 SS NH fatigue curve.

Table 4.3.3-1 also lists the total creep-fatigue damage as 0.954 and the allowable creep-fatigue damage as 0.995, which is sufficiently greater than the calculated value. This places the creep-fatigue damage within the NH-T-1420-2 creep-fatigue interaction envelope, thus meeting the criteria for creep-fatigue interaction for the base metal.

Weldment Evaluation:

Figure 4.3.3-4 shows the maximum equivalent strain ranges for each cycle type. Based on the location of the largest strain ranges, the point at which fatigue damage is evaluated is selected as element 53273 integration point 3, which is located on the inside surface of the weldment.

Table 4.3.3-2 lists a maximum equivalent strain range of 0.083% from the first cycle type of the fatigue evaluation for 782 applied repetitions of the Level B only loadings between increment 9 of the Level B: Peak Down 2 step to increment 8 of the Peak Up step.

Table 4.3.3-1 lists the Level B only cycle type fatigue damage as 0.00782 based on a conservatively selected 1E+5 allowable number of cycles from the 316 SS NH fatigue curve for weld material.

Table 4.3.3-2 lists a maximum equivalent strain range of 0.037% from the second cycle type for 90 applied repetitions of the Level A only loadings between increment 1 of the Level A: Ramp Down step to increment 2 of the Level A: Ramp Up step.

Table 4.3.3-1 lists the Level A only cycle type fatigue damage as 0.0009 based on a conservatively selected 1E+5 allowable number of cycles from the 316 SS NH fatigue curve for weld material.

Table 4.3.3-1 also lists the total creep-fatigue damage as 0.958 and the allowable creep-fatigue damage as 0.988, which is sufficiently greater than the calculated value. This places the creep-fatigue damage within the NH-T-1420-2 creep-fatigue interaction envelope, thus meeting the criteria for creep-fatigue interaction for the weldment.

4.3.3.3 Level A & C Composite Cycle Evaluation

The base metal only creep-fatigue evaluation for the Level A & C Composite Cycle with a target creep damage of 1.0 does not pass after 20 pseudo-cycles.

As shown in Figure 4.3.3-5, the change in plastic strain after each pseudo-cycle is 0.28% indicating that stable ratcheting continues and shakedown does not occur. Further reduction of the target creep damage will only produce weaker pseudo-yield stresses, resulting in even more severe ratcheting.

Since the base metal only evaluation did not pass for the Level A & C Composite Cycle the REP with weldment evaluation will not pass either.

5. Software

Abaqus 6.13-4 is used to perform the analyses in this report.

The input and output files used to perform the analysis and are listed in Attachment 1.

References

1. 20362-R-001 Rev. 3, Elevated Temperature Code Case Representative Example Problem Specification Report in accordance with Modification 3 of the Subcontract
2. The American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Section II, Part D, ”Materials, Properties”, 2013
3. The American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NH, ”Class 1 Components in Elevated Temperature Service,” 2013

Tables

Table 3.2-1 Poisson's Ratio and Density

Material Parameter	Reference	Temperature Range	Value
Poisson's Ratio	Section II, Part D, Table PRD	70°F to 1,500°F	0.31
Density, lb-s²/in⁴	Section II, Part D, Table PRD	70°F to 1,500°F	7.51E-04

Notes:
(1) Weight is converted to mass by dividing by standard gravity (386.1 in/s²).

Table 3.2-2 Mechanical Properties

Temperature, °F	Modulus of Elasticity, psi	Temperature, °F	Yield Stress, psi
70	28.3 E+6	70	30.0 E+3
200	27.5 E+6	100	30.0 E+3
300	27.0 E+6	200	25.9 E+3
400	26.4 E+6	300	23.4 E+3
500	25.9 E+6	400	21.4 E+3
600	25.3 E+6	500	20.0 E+3
700	24.8 E+6	600	18.9 E+3
800	24.1 E+6	650	18.5 E+3
900	23.5 E+6	700	18.2 E+3
1000	22.8 E+6	750	17.9 E+3
1100	22.0 E+6	800	17.7 E+3
1200	21.2 E+6	850	17.5 E+3
1300	20.3 E+6	900	17.3 E+3
1400	19.2 E+6	950	17.1 E+3
1500	18.1 E+6	1000	17.0 E+3
		1050	16.8 E+3
		1100	16.6 E+3
		1150	16.3 E+3
		1200	16.0 E+3
		1250	15.5 E+3
		1300	14.9 E+3
		1350	14.2 E+3
		1400	13.3 E+3
		1450	12.3 E+3
		1500	10.9 E+3

Table 3.2-3 Thermal Properties

Temperature, °F	Mean Thermal Expansion Coefficient, in/in-°F	Conductivity, BTU/s-in-°F	Specific Heat, BTU-in/s²-lb-°F
70	8.50E-06	1.90E-04	42.94
100	8.60E-06	1.92E-04	43.55
150	8.80E-06	1.99E-04	44.52
200	8.90E-06	2.04E-04	45.41
250	9.10E-06	2.11E-04	46.24
300	9.20E-06	2.15E-04	47.00
350	9.40E-06	2.20E-04	47.70
400	9.50E-06	2.27E-04	48.35
450	9.60E-06	2.31E-04	48.94
500	9.70E-06	2.36E-04	49.49
550	9.80E-06	2.43E-04	49.99
600	9.80E-06	2.48E-04	50.45
650	9.90E-06	2.52E-04	50.88
700	1.00E-05	2.59E-04	51.28
750	1.00E-05	2.64E-04	51.65
800	1.01E-05	2.69E-04	52.00
850	1.02E-05	2.75E-04	52.34
900	1.02E-05	2.80E-04	52.65
950	1.03E-05	2.85E-04	52.96
1000	1.03E-05	2.89E-04	53.26
1050	1.04E-05	2.96E-04	53.56
1100	1.04E-05	3.01E-04	53.86
1150	1.05E-05	3.06E-04	54.17
1200	1.06E-05	3.10E-04	54.49
1250	1.06E-05	3.15E-04	54.83
1300	1.07E-05	3.19E-04	55.18
1350	1.07E-05	3.26E-04	55.56
1400	1.08E-05	3.31E-04	55.97
1450	1.08E-05	3.36E-04	56.41
1500	1.08E-05	3.40E-04	56.88

Table 3.6.2-1 Mechanical Design Loads

Load	Value
Nozzle Axial Load	30,000 lbf
Nozzle Shear Force	4,000 lbf
Nozzle Torsional Moment	20,000 lbf-in

Table 3.6.3-1 Time Histories

Level A & B Composite Cycle				Level A & C Composite Cycle			
Time, sec	Temperature, °F	Pressure, psi	Mechanical Load Factor	Time, sec	Temperature, °F	Pressure, psi	Mechanical Load Factor
0	70.0	0.0	0.000	**0**	70.0	0.0	0.000
180000	1100.0	675.0	1.000	**180000**	1100.0	675.0	1.000
1620000	1100.0	675.0	1.000	**1620000**	1100.0	675.0	1.000
1621100	1170.0	743.8	1.229	**1620060**	1100.0	675.0	2.000
1621120	1171.0	745.0	1.233	**1620120**	1100.0	675.0	-1.500
1621140	1172.0	746.3	1.238	**1620180**	1100.0	675.0	1.000
1621160	1173.0	747.5	1.242	**1621620**	1290.0	771.0	0.863
1621170	1174.0	748.1	1.244	**1621630**	1292.0	771.7	0.862
1621180	1174.5	748.8	1.246	**1621640**	1294.0	772.3	0.861
1621190	1175.0	749.4	1.248	**1621650**	1296.0	773.0	0.860
1621200	1175.0	750.0	1.250	**1621660**	1298.0	773.7	0.859
1621210	1174.8	750.0	1.250	**1621670**	1299.0	774.3	0.858
1621220	1174.5	750.0	1.250	**1621680**	1300.0	775.0	0.857
1621230	1174.3	749.9	1.250	**1621690**	1299.0	774.1	0.856
1621240	1174.0	749.9	1.250	**1621700**	1298.0	773.3	0.855
1621300	1172.6	749.8	1.249	**1621710**	1296.0	772.4	0.854
1623000	1131.9	745.8	1.236	**1621720**	1294.0	771.6	0.853
1630000	850.0	729.6	1.182	**1621730**	1292.0	770.7	0.852
1650000	425.0	683.3	1.028	**1621740**	1290.0	769.8	0.851
1653600	400.0	675.0	1.000	**1621780**	1280.0	766.4	0.848
1740000	400.0	675.0	1.000	**1622180**	1150.0	731.9	0.810
1862400	1100.0	675.0	1.000	**1625180**	700.0	473.6	0.524
3302400	1100.0	675.0	1.000	**1630680**	70.0	0.0	0.000
3572400	70.0	0.0	0.000	**3070680**	70.0	0.0	0.000
5012400	70.0	0.0	0.000				

Table 3.6.3-2 Total Time Druation of High Temperature Service

Step Name	Duration, sec	Temperature, °F	Duration Above 800F, sec	No. Cycles	Total Time, sec	Total Time Above 800F, sec
Level A: Initial State		70				
Level A: Ramp Up	180,000	1100	52,427	90	16,200,000	4,718,447
Level A: Steady State	1,440,000	1100	1,440,000	90	129,600,000	129,600,000
Level A: Ramp Down	270,000	70	78,641	90	24,300,000	7,077,670
Level B: Initial State		1100				
Level B: Ramp Up	1,100	1170	1,100	782	860,200	860,200
Level B: Peak Up	100	1175	100	782	78,200	78,200
Level B: Peak Down	100	1172.6	100	782	78,200	78,200
Level B: Ramp Down 1	1,700	1131.9	1,700	782	1,329,400	1,329,400
Level B: Ramp Down 2	7,000	850	7,000	782	5,474,000	5,474,000
Level B: Ramp Down 3	20,000	425	2,353	782	15,640,000	1,840,000
Level B: Ramp Down 4	3,600	400	0	782	2,815,200	0
Level B: Hold State	86,400	400	0	782	67,564,800	0
Level B: Recover	122,400	1100	52,457	782	95,716,800	41,021,486
Level C: Initial State		1100				
Level C: SSE Up	60	1100	60	25	1,500	1,500
Level C: SSE Down	60	1100	60	25	1,500	1,500
Level C: SSE Recover	60	1100	60	25	1,500	1,500
Level C: Ramp Up	1,440	1290	1,440	25	36,000	36,000
Level C: Peak Up	60	1300	60	25	1,500	1,500
Level C: Peak Down	100	1280	100	25	2,500	2,500
Level C: Ramp Down 1	400	11450	400	25	10,000	10,000
Level C: Ramp Down 2	3,000	700	2,972	25	75,000	74,302
Level C: Ramp Down 3	5,500	70	0	25	137,500	0
Total:					**359,923,800**	**192,206,405**

Table 4.2-1 Level A & B Composite Cycle Analysis Steps

Step Name	Duration, sec	Step End Time, sec	Maximum Time Increment, sec	Maximum Temperature Change, °F
Level A: Ramp Up	180,000	180,000	auto	50
Level A: Steady State 1	1,440,000	1,620,000	auto	50
Level B: Ramp Up	1,100	1,621,100	auto	5
Level B: Peak Up	100	1,621,200	10	1
Level B: Peak Down	100	1,621,300	10	1
Level B: Ramp Down 1	1,700	1,623,000	auto	1
Level B: Ramp Down 2	7,000	1,630,000	auto	10
Level B: Ramp Down 3	20,000	1,650,000	auto	50
Level B: Ramp Down 4	3,600	1,653,600	auto	5
Level B: Hold State	86,400	1,740,000	auto	5
Level B: Recover	122,400	1,862,400	auto	50
Level A: Steady State 2	1,440,000	3,302,400	auto	50
Level A: Ramp Down	270,000	3,572,400	auto	50
Shutdown: Steady State	1,440,000	5,012,400	auto	50

Table 4.2-2 Level A & C Composite Cycle Analysis Steps

Step Name	Duration, sec	Step End Time, sec	Maximum Time Increment, sec	Maximum Temperature Change, °F
Level A: Ramp Up	180,000	180,000	auto	50
Level A: Steady State 1	1,440,000	1,620,000	auto	50
Level C: SSE Up	60	1,620,060	auto	50
Level C: SSE Down	60	1,620,120	auto	50
Level C: SSE Recover	60	1,620,180	auto	50
Level C: Ramp Up	1,440	1,621,620	auto	10
Level C: Peak Up	60	1,621,680	10	1
Level C: Peak Down	100	1,621,780	10	1
Level C: Ramp Down 1	400	1,622,180	auto	5
Level C: Ramp Down 2	300	1,625,180	auto	10
Level C: Ramp Down 3	5,500	1,630,680	auto	50
Shutdown: Steady State	1,440,000	3,070,680	auto	50

Table 4.3.2-1 Strain Limits Evaluation Results

Cycle	Model	Target Creep Strain x: Base Metal	Target Creep Strain x: Weld	Pseudo-Cycle	Ratcheting Check $(\max\lvert\Delta\epsilon_p\rvert)$	Average Strain Check, Min. Thickness(1) x Max. Length(2) Region Not Exceeding Limit: $\epsilon_{tot} \leq \epsilon_{avg}$: Base Metal (1.0% limit)	Average Strain Check: Weld (0.5% limit)	Local Strain Check $\max(\epsilon_{tot})$: Base Metal (5.0% limit)	Local Strain Check: Weld (2.5% limit)	Status
Composite Cycle A & B	REP-B	1.00%	n/a	1	Yes (0.0006%)	~99% x 100%	n/a	1.0006%	n/a	Optimized and Cycle
				2	No (0%)	~99% x 100%	n/a	1.0006%	n/a	**PASS**
	REP-W	1.00%	0.50%	1	Yes (0.0009%)	~99% x 100%	100% x 100%	1.0009%	n/a	Optimized and Cycle
				2	Yes (0.00003%)	~99% x 100%	100% x 100%	1.0009%	n/a	Cycle
				3	No (0%)	~99% x 100%	100% x 100%	1.0009%	0.50%	**PASS**
Composite Cycle A & C	REP-B(3)	1.00%	n/a	1	Yes	0% x 0%	n/a		n/a	Reduce
		0.65%	n/a	1	Yes	0% x ~98%	n/a		n/a	Reduce
		0.60%	n/a	1	Yes (1.0%)	0% x ~98%	n/a	1.6%	n/a	Optimized and Cycle
				2	Yes (1.1%)	0% x ~88%	n/a	2.7%	n/a	**FAIL**
		0.55%	n/a	1	Yes	0% x ~96%	n/a		n/a	Increase

Notes:

(1) The average strain limit is satisfied when the minimum distance through the thickness where $\epsilon_{tot} \leq \epsilon_{avg}$ (measured in percentage of wall thickness) is greater than 0%.

(2) The maximum lateral length where $\epsilon_{tot} \leq \epsilon_{avg}$ is measured in percentage of total lateral length of the region being evaluated.

(3) The Composite Cycle A&C REP-B model is the model used in 20362-R-002 Rev. 1.

Table 4.3.3-1 Creep-Fatigue Evaluation Results

Cycle	Model	Location	Target Creep Damage	Shakedown (Pseudo-Cycle)	Cycle Type (Applied Repetitions)	Maximum Equivalent Strain Range	Allowable Cycles(1)	Fatigue Damage	Total Damage	Allowable Damage	Status
Composite Cycle A&B	REP-B	Base Metal	1.00	Yes (3)	Level A & B (90)	0.110%	2.0E+5	0.00045	1.004	0.995	Reduce
					Level B (692)	0.076%	2.0E+5	0.00346			
			0.90	Yes (3)	Level A & B (90)	0.110%(2)	2.0E+5	0.00045	0.904	0.995	**PASS**
					Level B (692)	0.076%(2)	2.0E+5	0.00346			
	REP-W	Base Metal	1.00	Yes (3)	Level A & B (90)	0.108%	2.0E+5	0.00045	1.004	0.995	Reduce
					Level B (692)	0.077%	2.0E+5	0.00346			
			0.95	Yes (3)	Level A & B (90)	0.108%(2)	2.0E+5	0.00045	0.954	0.995	**PASS**
					Level B (692)	0.077%(2)	2.0E+5	0.00346			
			0.90	No (20)							Increase
		Weldment	0.95	Yes (3)	Level B (782)	0.083%(2)	1.0E+5	0.00782	0.958	0.988	**PASS**
					Level A (90)	0.037%(2)	1.0E+5	0.00090			
Composite Cycle A&C	REP-B(3)	Base Metal	1.00	No (20)	n/a	n/a	n/a	n/a	>1	n/a	**FAIL**

Notes:

(1) Allowable Cycles are conservatively taken at the next highest strain range in the Table for Figure NH-T-1420-1B.
(2) See Table 4.3.3-2 for maximum equivalent strain range evaluations.
(3) The Composite Cycle A&C REP-B model is based on the model used in 20362-R-002 Rev. 1.

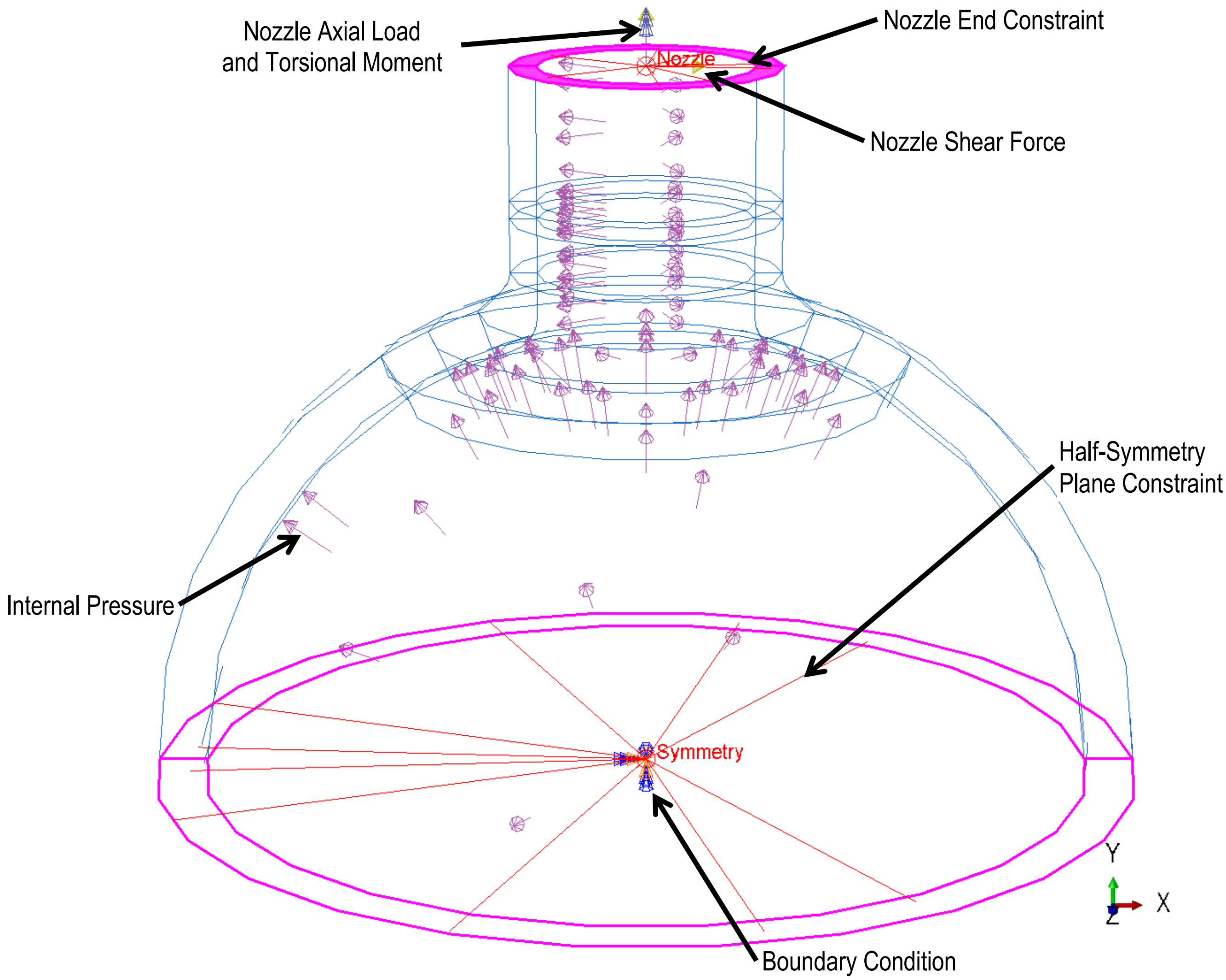
Table 4.3.3-2 Creep-Fatigue Final Maximum Equivalent Strain Range Evaluations for Composite Cycle A&B

Model	Location	Cycle Type	Extreme Condition and Point in Time of Max. Equivalent Strain Range		E11 ϵ_x	E22 ϵ_y	E33 ϵ_z	E12 ϵ_{xy}	E13 ϵ_{xz}	E23 ϵ_{yz}	DEMAX $\Delta\epsilon_{max}$ eq. (4-6)
REP-B	Base Metal El. 49099(1) int. pt. 1	Level A & B	Level A: Ramp Down, Increment 10	ϵ_o	0.0007%	0.0001%	0.0007%	0.0019%	0.0003%	0.0016%	0.1073%
			Level B: Peak Up Increment 9	ϵ_i	1.1639%	1.1797%	1.1655%	0.0449%	-0.0511%	0.0453%	
		Level B	Level B: Ramp Down 2 Increment 9	ϵ_o	1.0042%	0.9991%	1.0050%	0.0126%	-0.0220%	0.0104%	0.0760%
			Level B: Peak Up Increment 9	ϵ_i	1.1639%	1.1797%	1.1655%	0.0449%	-0.0511%	0.0453%	
REP-W	Base Metal El. 45139(2) int. pt. 7	Level A & B	Level A: Ramp Down, Increment 10	ϵ_o	0.0008%	0.0001%	0.0007%	0.0015%	0.0005%	0.0013%	0.1077%
			Level B: Peak Up Increment 9	ϵ_i	1.1639%	1.1799%	1.1656%	0.0448%	-0.0511%	0.0451%	
		Level B	Level B: Ramp Down 2 Increment 9	ϵ_o	1.0043%	0.9990%	1.0050%	0.0121%	-0.0218%	0.0100%	0.0765%
			Level B: Peak Up Increment 9	ϵ_i	1.1639%	1.1799%	1.1656%	0.0448%	-0.0511%	0.0451%	
	Weldment El. 53273(3) int. pt. 3	Level B	Level B: Ramp Down 2, Increment 9	ϵ_o	1.0127%	0.9781%	1.0128%	-0.0321%	-0.0181%	-0.0311%	0.0830%
			Level B: Peak Up, Increment 9	ϵ_i	1.1618%	1.1687%	1.1613%	0.0064%	0.0046%	0.0050%	
		Level A	Level A: Ramp Down, Increment 1	ϵ_o	1.0803%	1.0638%	1.0802%	-0.0153%	-0.0085%	-0.0153%	0.0370%
			Level A: Ramp Up, Increment 2	ϵ_i	0.0347%	0.0365%	0.0346%	0.0017%	0.0010%	0.0015%	

Notes:
(1) Element 49099 is located on the outside surface of the shell to nozzle transition as shown in Figure 4.3.3-2.
(2) Element 45139 is located on the outside surface of the shell to nozzle transition as shown in Figure 4.3.3-4.
(3) Element 53273 is located on the inside surface of the weldment as shown in Figure 4.3.3-4.

Figures

Figure 3-1 REP General Model



Note: The weldment is not shown in this generalization the two REP vessels.

Figure 3.1-1 REP Vessel Profile

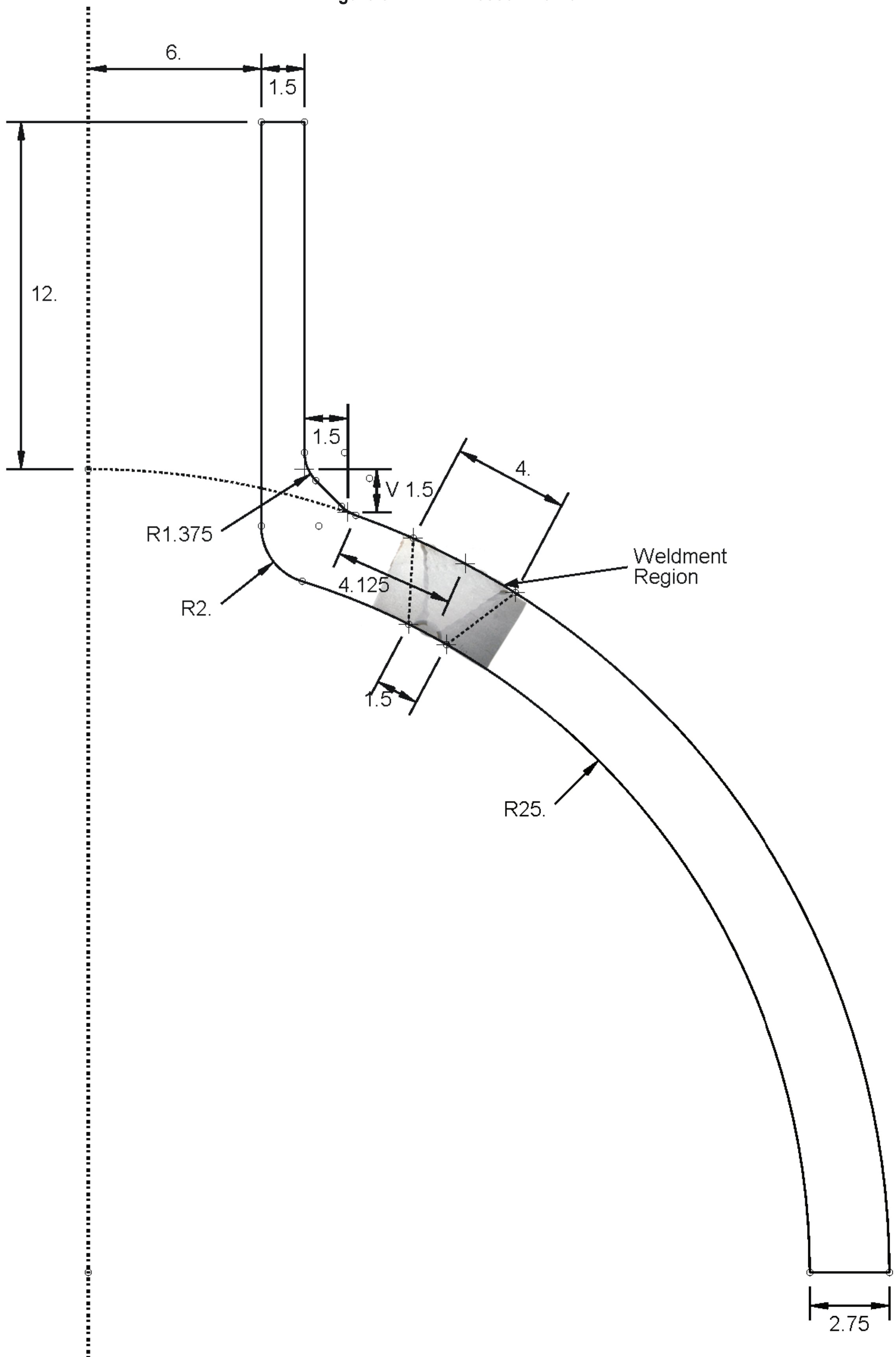


Figure 3.1-2 REP Base Metal Only Vessel (REP-B) Mesh

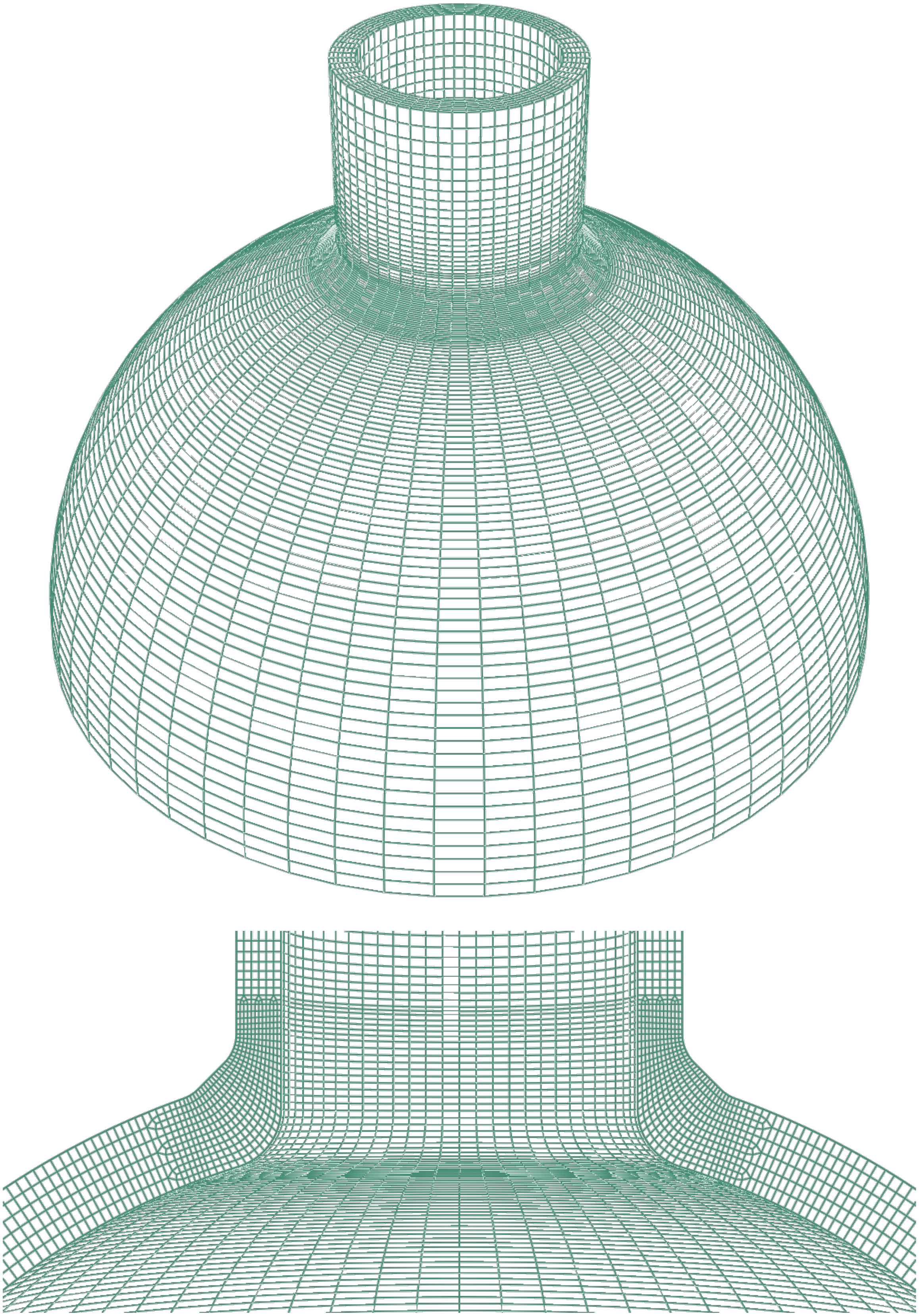


Figure 3.1-3 REP Vessel with Weldment (REP-W) Mesh

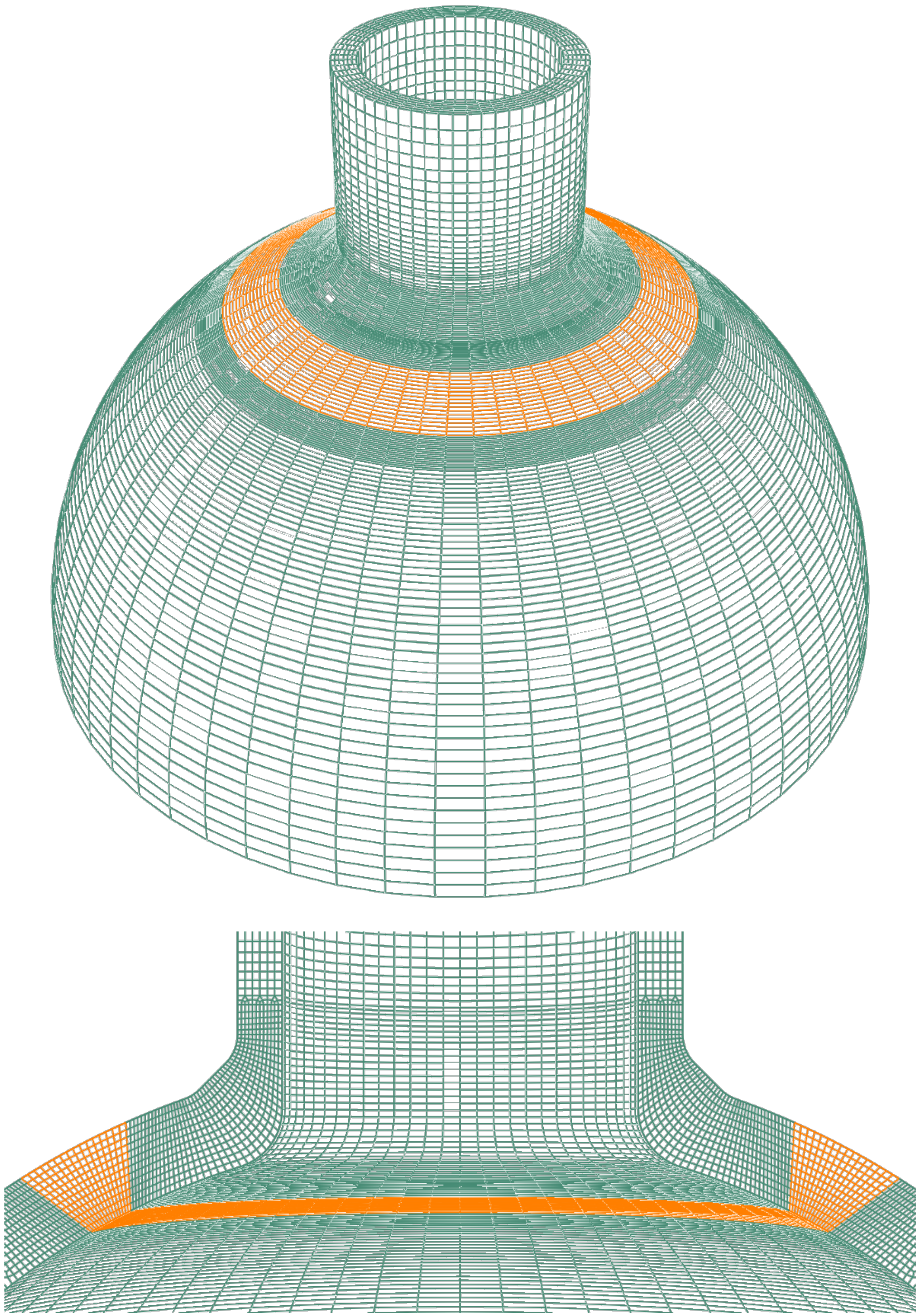


Figure 3.5.1-1 Thermal Boundary Conditions

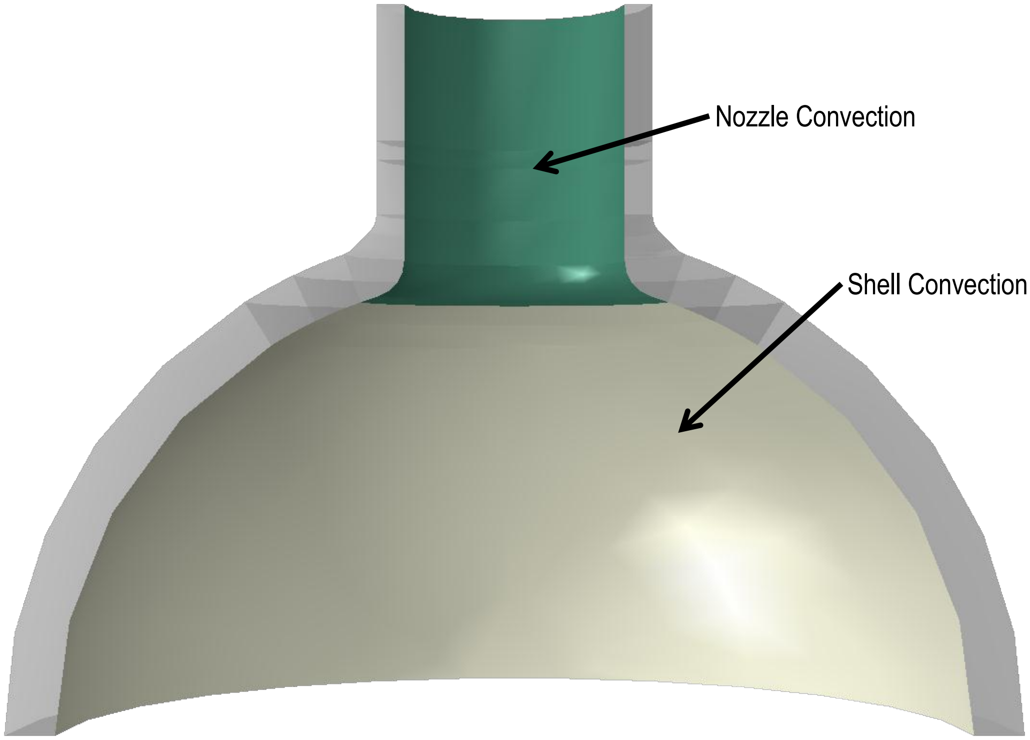


Figure 3.6.3-1 Level A & B Composite Cycle Time History Plot

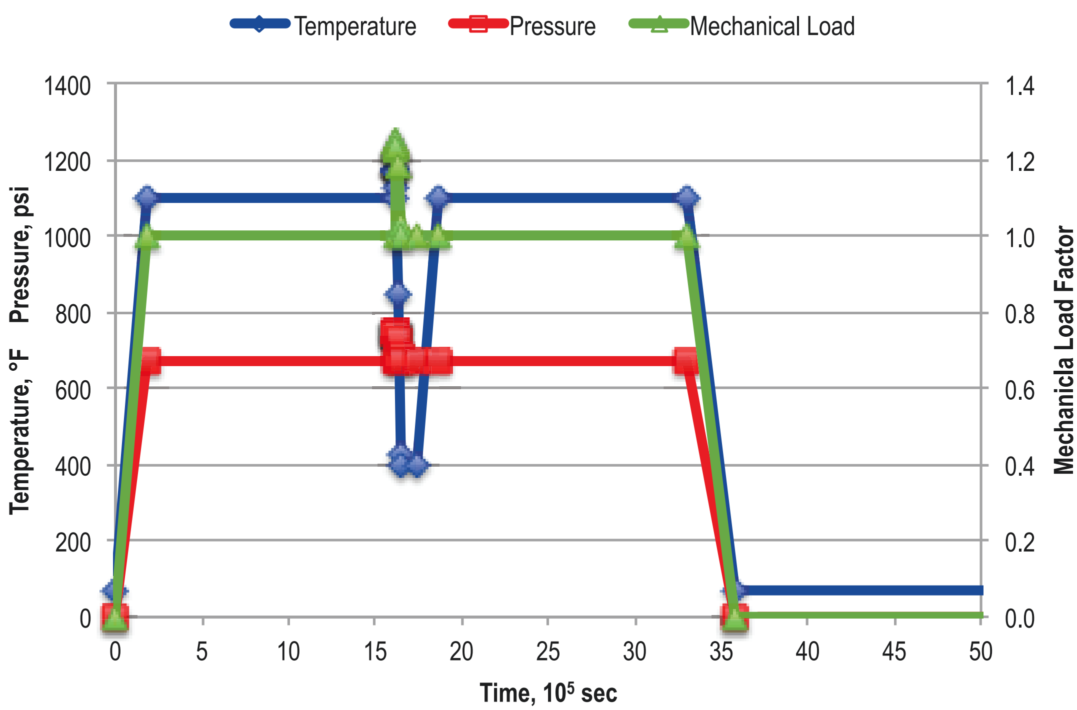


Figure 3.6.3-2 Level A & C Composite Cycle Time History Plot

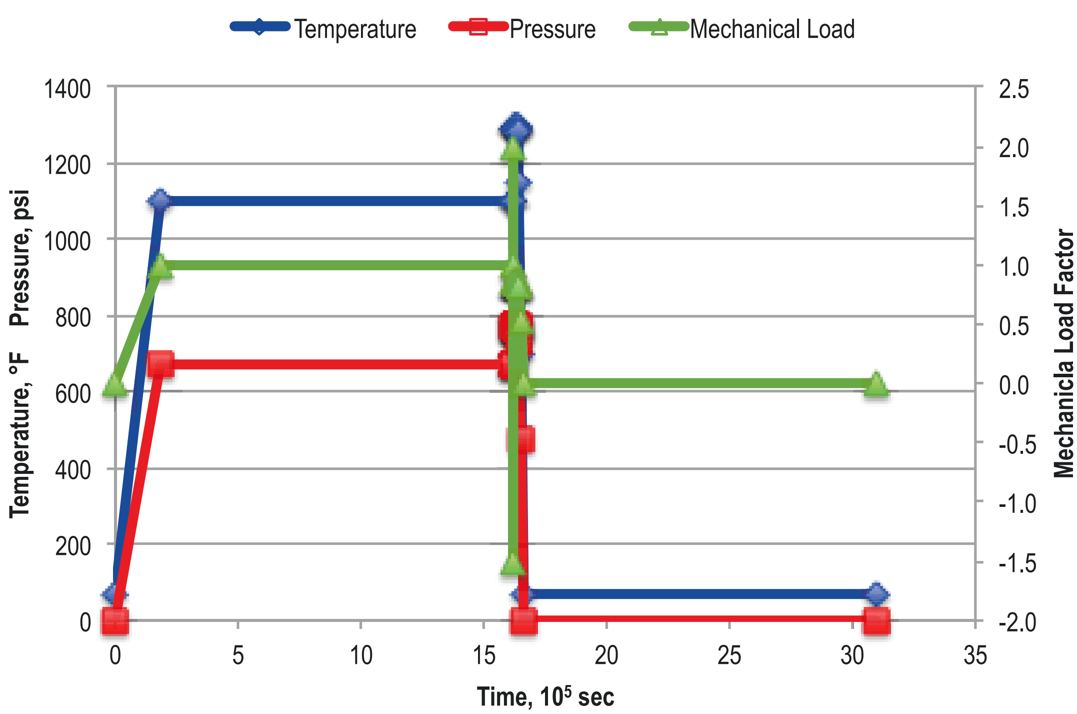


Figure 4.2-1 Level A & B Composite Cycle Steps Plot

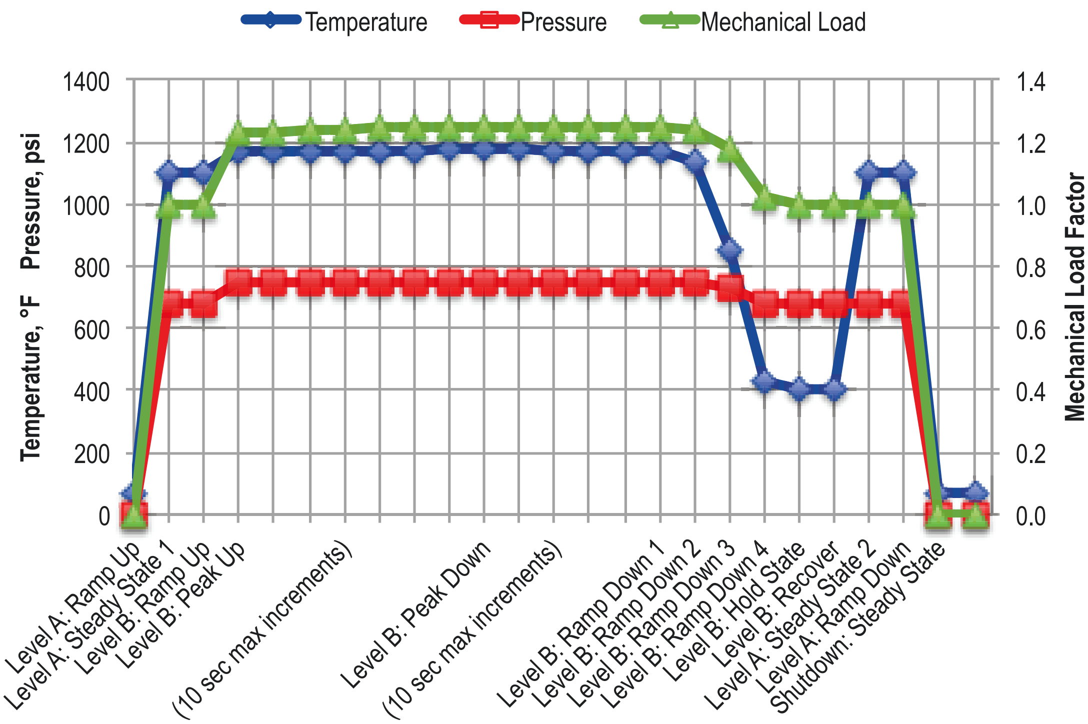


Figure 4.2-2 Level A & C Composite Cycle Steps Plot

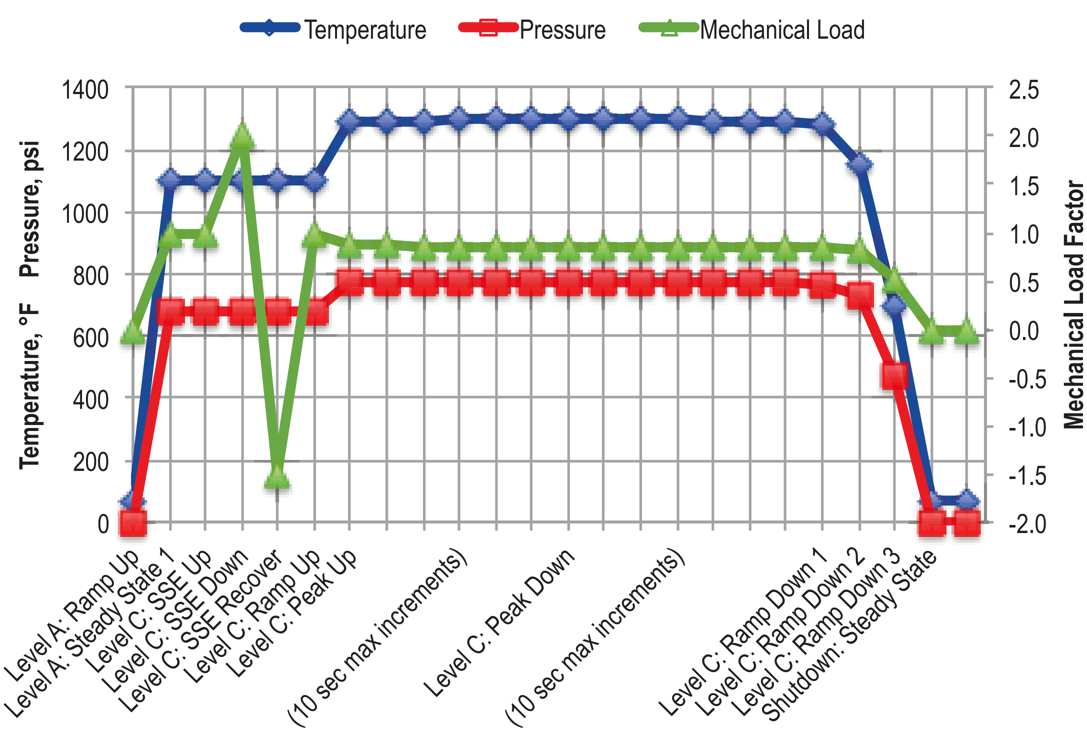
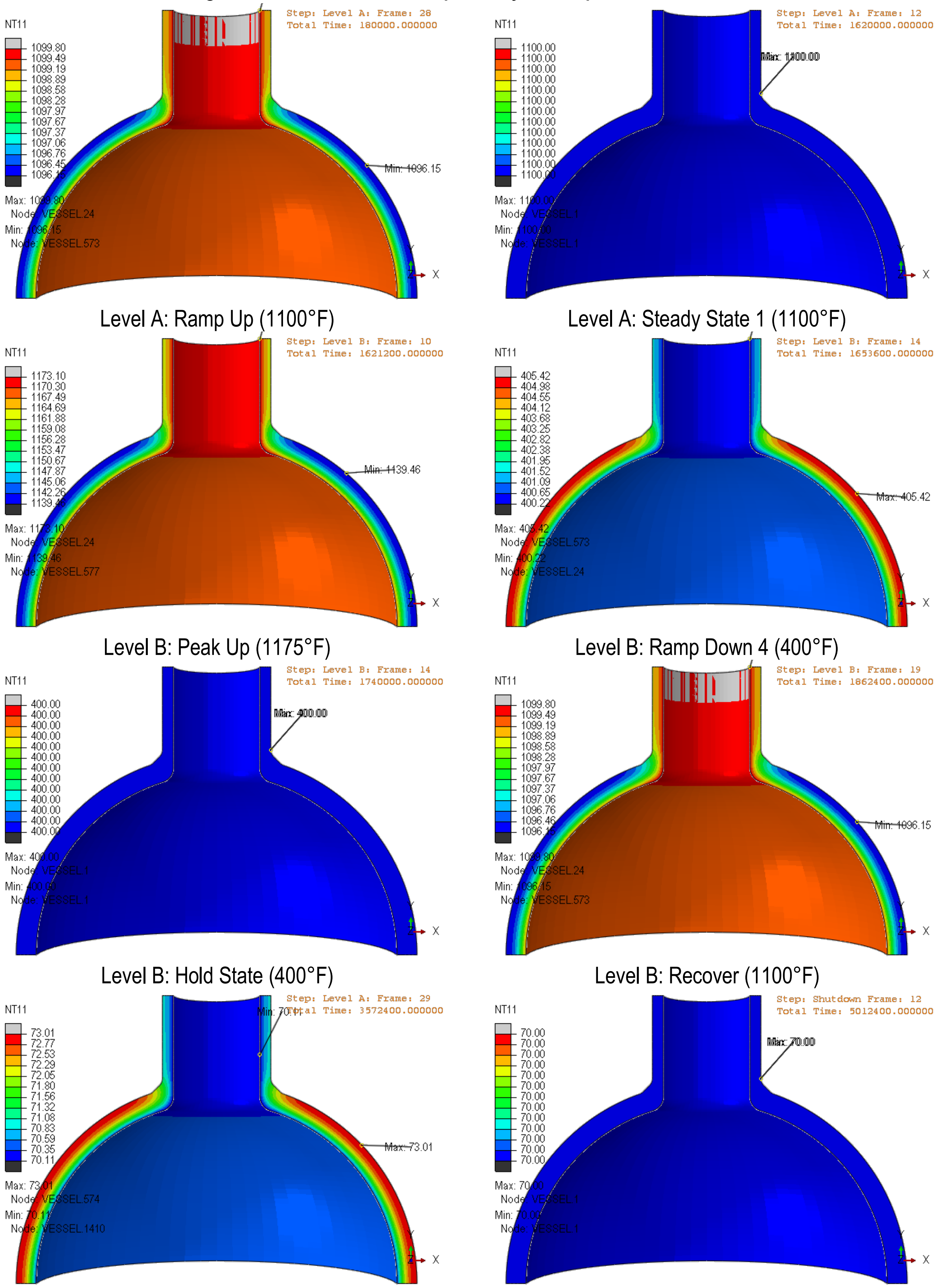


Figure 4.3.1-1 Level A & B Composite Cycle Temperature Contours



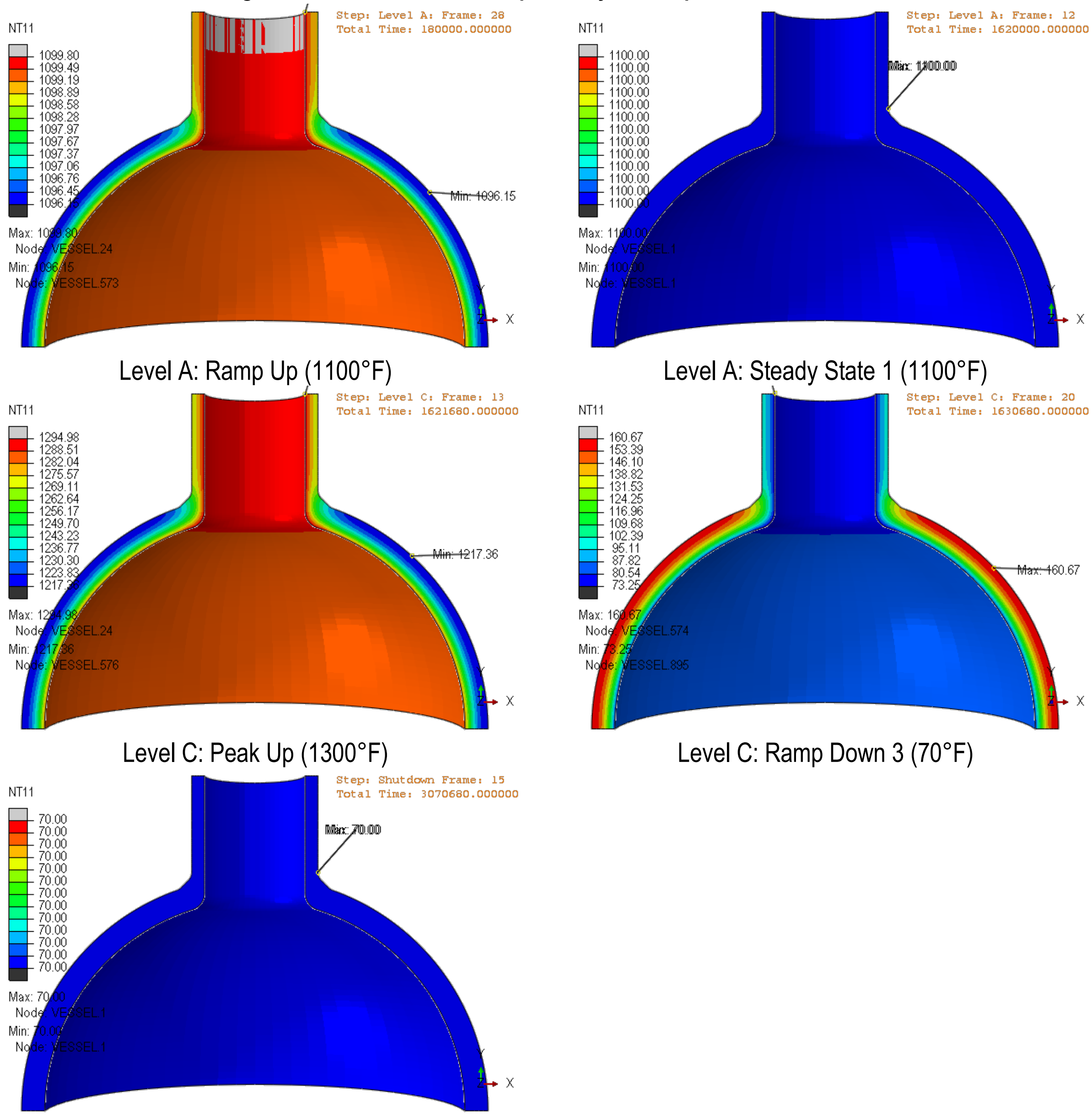
Level A: Ramp Up (1100°F) | Level A: Steady State 1 (1100°F)

Level B: Peak Up (1175°F) | Level B: Ramp Down 4 (400°F)

Level B: Hold State (400°F) | Level B: Recover (1100°F)

Level A: Ramp Down (70°F) | Shutdown: Steady State (70°F)

Figure 4.3.1-2 Level A & C Composite Cycle Temperature Contours



Shutdown: Steady State (70°F)

Figure 4.3.2-1 Level A & B Composite Cycle REP-B Strain Limits Ratcheting Check
Change in Plasitc Inelastic Strain Magnitude
1.00% Base Metal Target Inelastic Strain, Pseudo Cycle 2

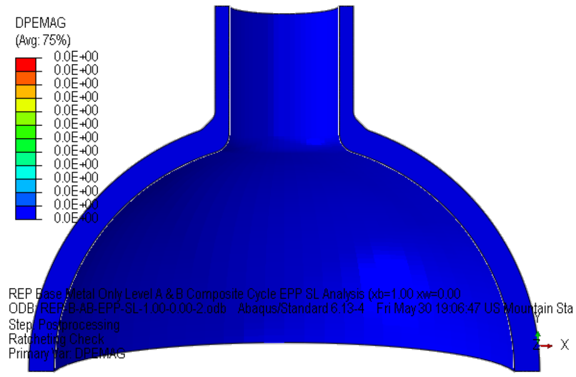


Figure 4.3.2-2 Level A & B Composite Cycle REP-B Strain Limits Evaluation
Total Inelastic Strain
1.00% Base Metal Target Inelastic Strain, Pseudo Cycle 2

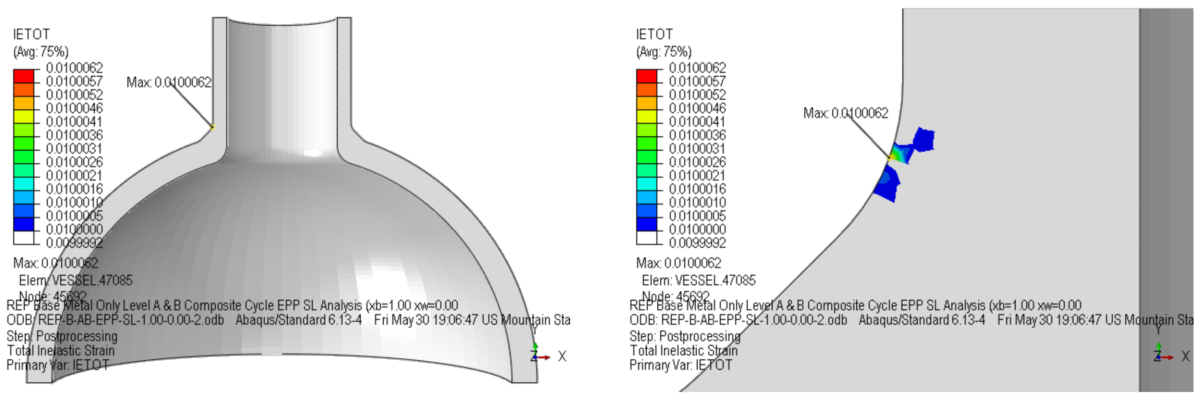
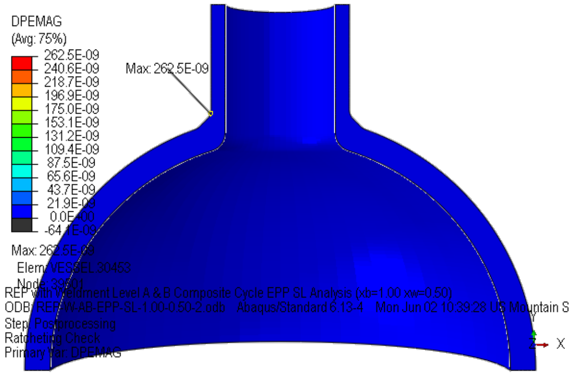
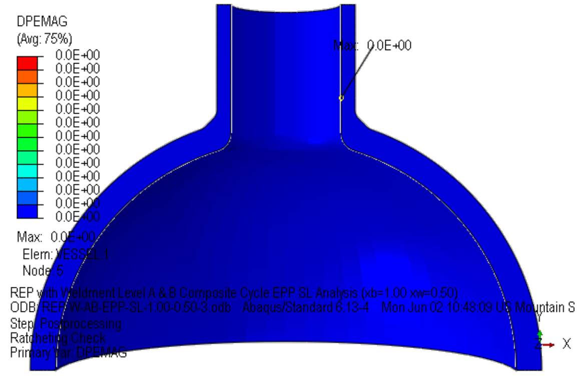


Figure 4.3.2-3 Level A & B Composite Cycle REP-W Strain Limits Ratcheting Check
Change in Plasitc Inelastic Strain Magnitude
1.00% Base Metal Target Inelastic Strain and 0.50% Weldment Target Inelastic Strain

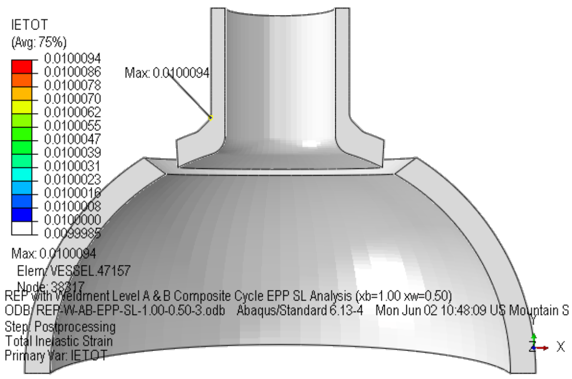


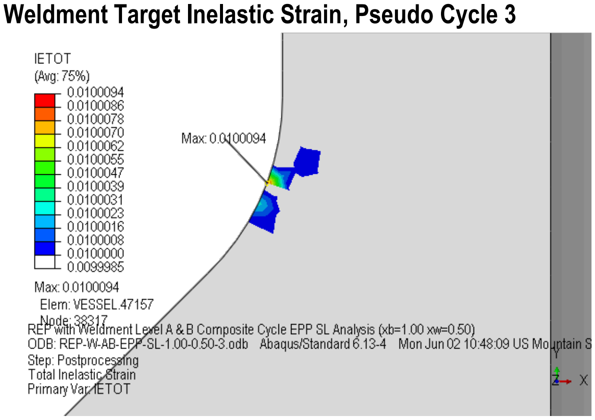
Pseudo Cycle 2



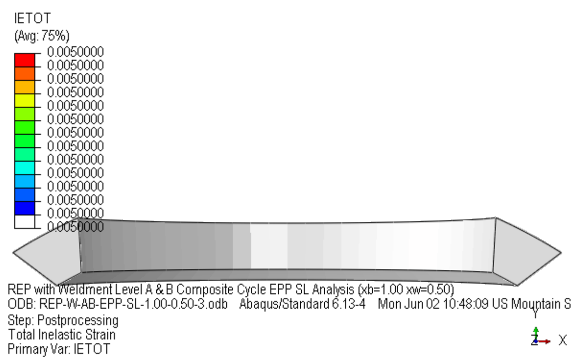
Pseudo Cycle 3

Figure 4.3.2-4 Level A & B Composite Cycle REP-W Strain Limits Evaluation
Total Inelastic Strain
1.00% Base Metal Target Inelastic Strain and 0.50% Weldment Target Inelastic Strain, Pseudo Cycle 3



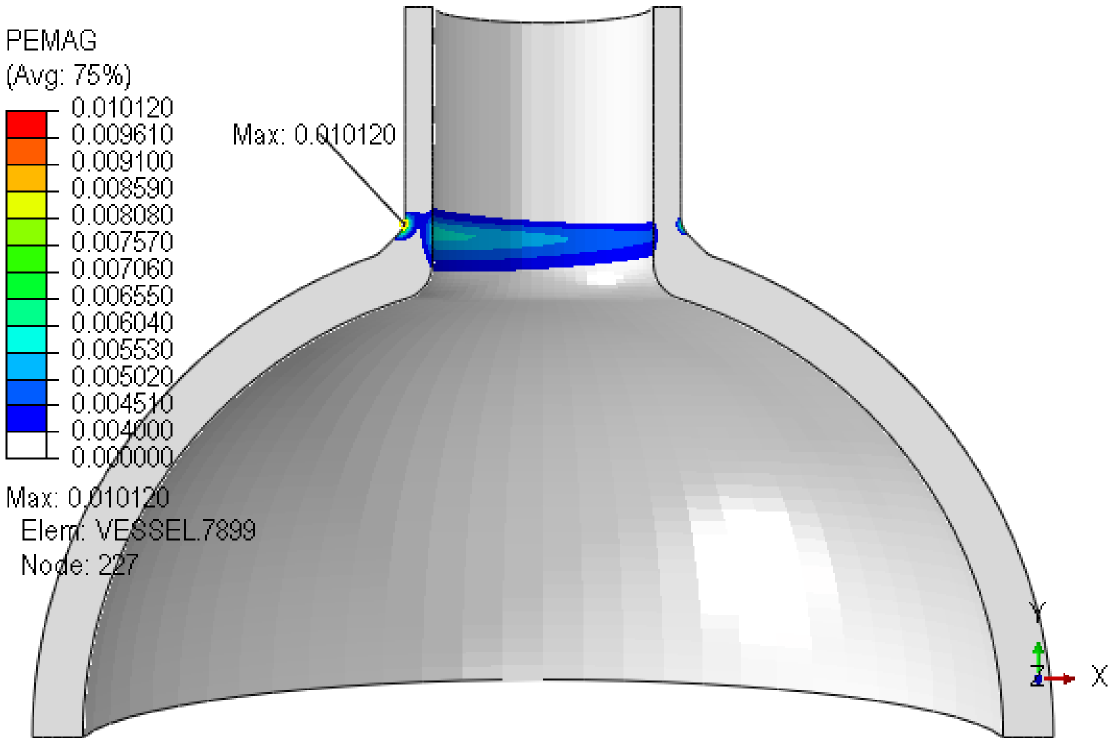


Base Metal

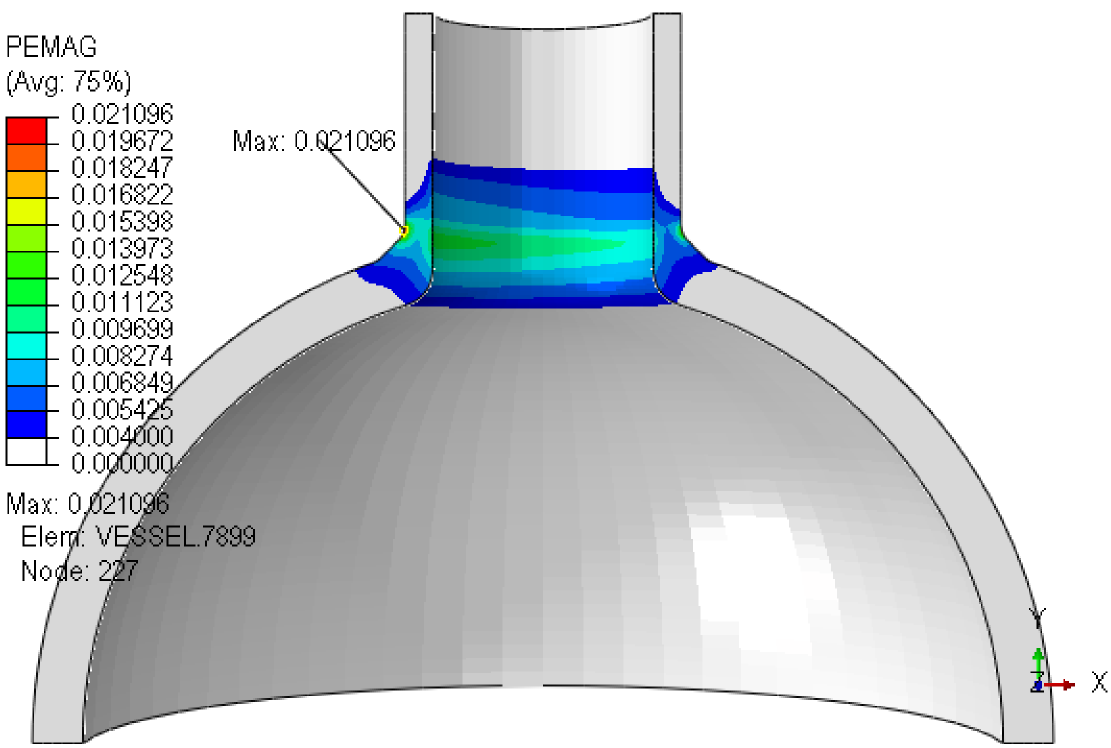


Weldment

Figure 4.3.2-5 Level A & C Composite Cycle Base Metal Only Strain Limits Evaluation
Plastic Strain Magnitude
0.60% Target Inelastic Strain



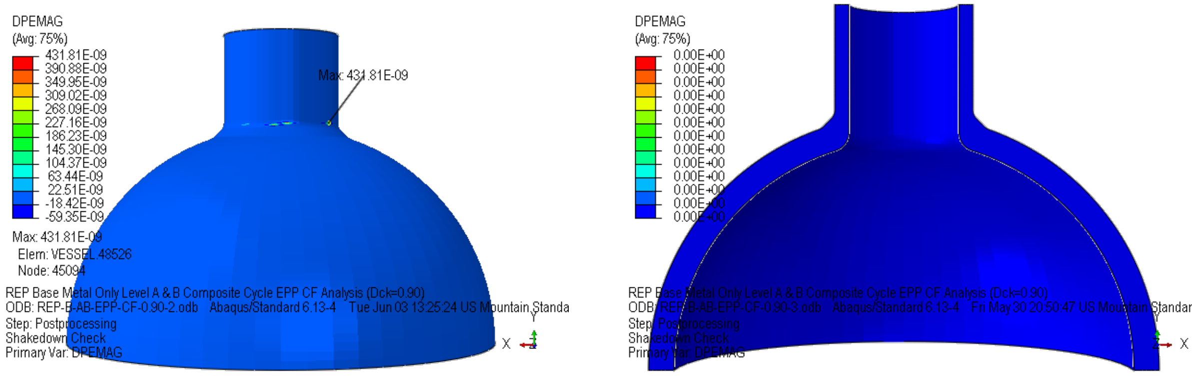
Pseudo Cycle 1



Pseudo Cycle 2

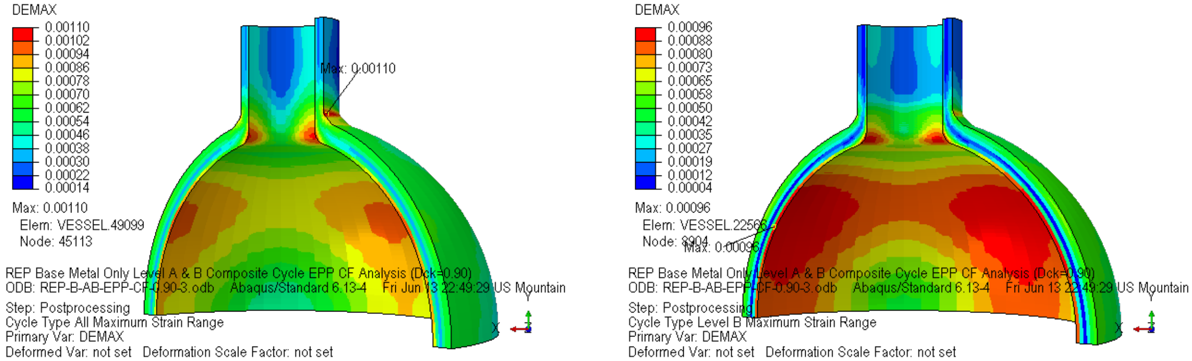
Notes:
(1) The Composite Cycle A&C base metal only results are from 20362-R-002 Rev. 1.

Figure 4.3.3-1 Level A & B Composite Cycle REP-B Creep-Fatigue Shakedown Check
Change in Plastic Strain Magnitude
0.90 Target Creep Damage



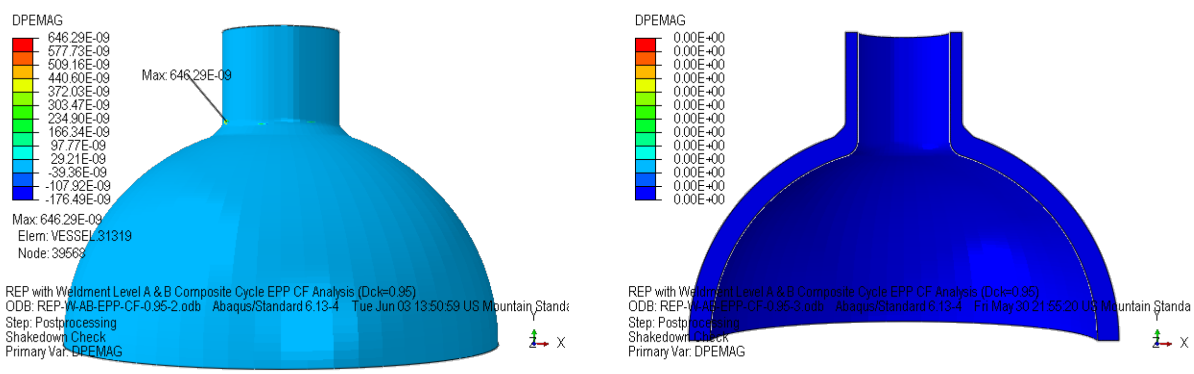
Pseudo Cycles 2 | Pseudo Cycle 3

Figure 4.3.3-2 Level A & B Composite Cycle REP-B Creep-Fatigue Evaluation
Maximum Equivalent Strain Range
0.90 Target Creep Damage



Level A & B Cycle Type | Level B Cycle Type

Figure 4.3.3-3 Level A & B Composite Cycle REP-W Creep-Fatigue Shakedown Check
Change in Plastic Strain Magnitude
0.95 Target Creep Damage



Change in Plastic Strain Magnitude for Shakedown Check (pseudo cycles 2 and 3)

Figure 4.3.3-4 Level A & B Composite Cycle REP-W Creep-Fatigue Evaluation
Maximum Equivalent Strain Range
0.95 Target Creep Damage

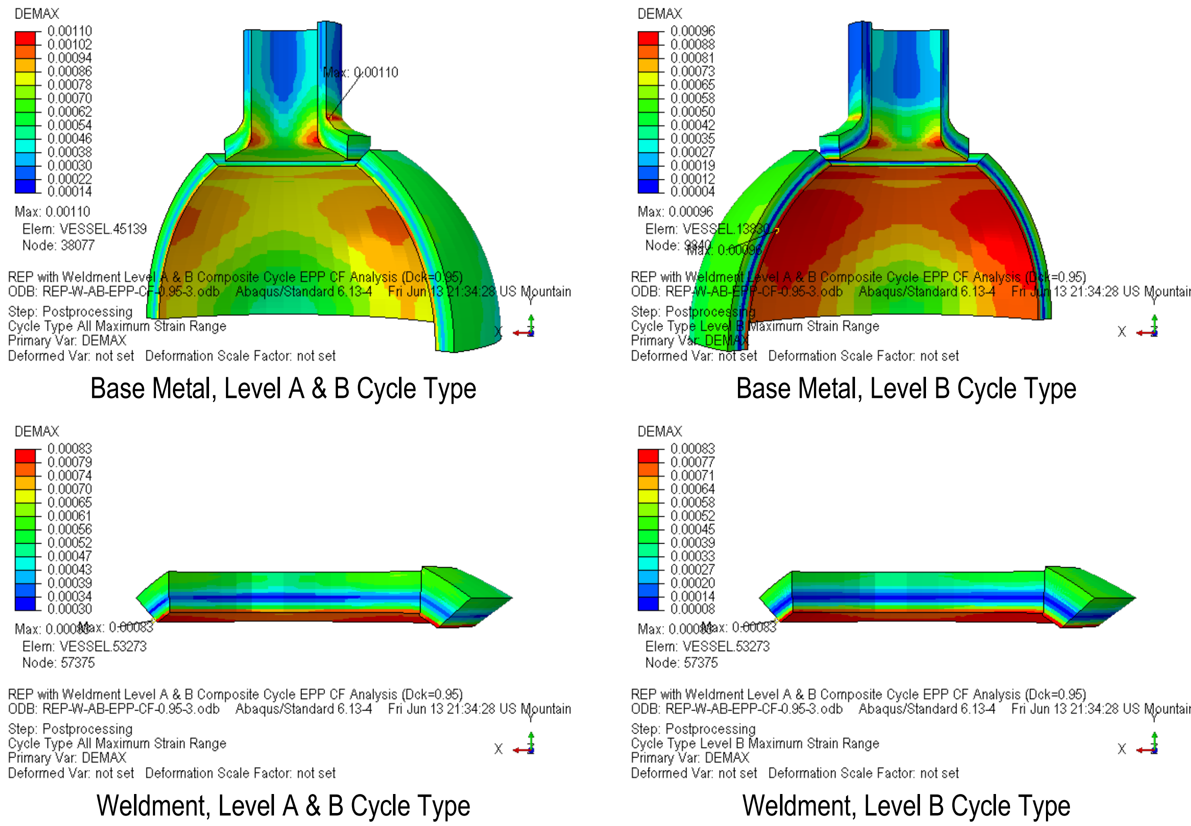
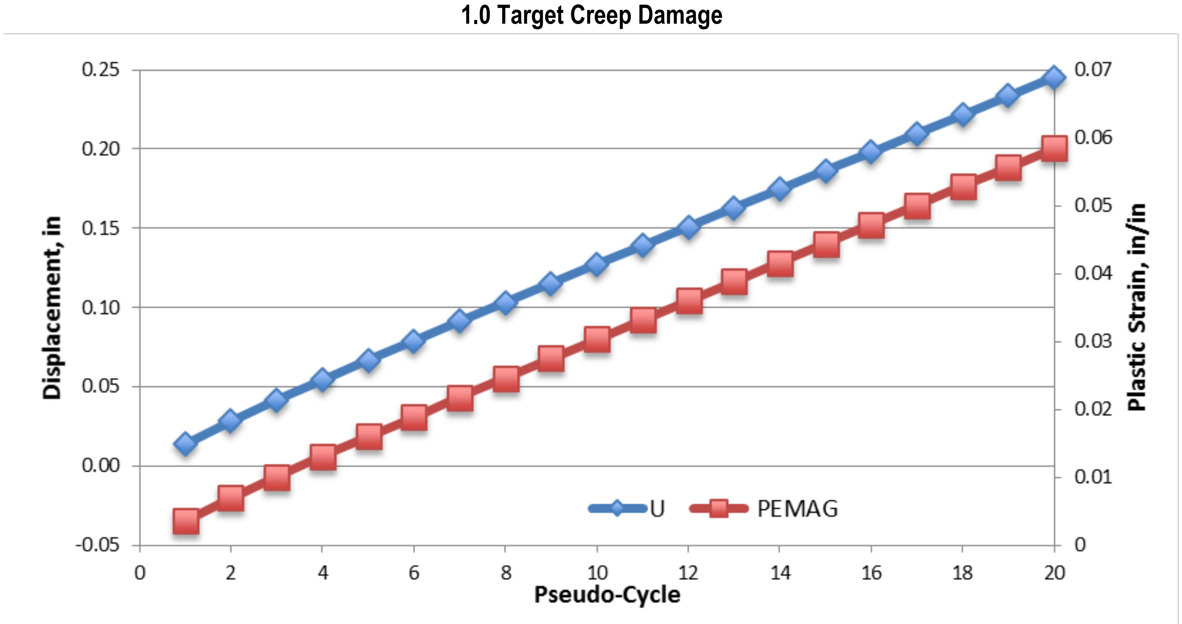


Figure 4.3.3-5 Level A & C Composite Cycle Base Metal Only Creep-Fatigue Shakedown Check
1.0 Target Creep Damage



Notes:
(1) The Composite Cycle A&C base metal only results are based on the model used in 20362-R-002 Rev. 1.
(2) The Composite Cycle A&C exhibits signs of stable ratcheting of 0.28% plastic strain per cycle, therefore shakedown does not occur.

Appendix A — Mesh Study

This mesh study provides the basis for selecting the appropriate mesh density of the REP vessel to obtain accurate results near the shell to nozzle junction where high stress and strains are expected.

A.1 Mesh Study Model

The model used to perform the mesh study is based on the REP vessel described in Section 0, applying isothermal static design loads on various models with different mesh densities.

A.1.1 Mesh Densities

The different mesh densities selected are listed in Table A-1.

Table A-1 Mesh Densities

Model Name	Approximate Size of Elements
REP-1	1”
REP-05	1/2"
REP-025	1/4”
REP-0125	1/8”

A.1.2 Design Loads

The design loads specified in the design specification [Ref. 1] are used for the mesh study as listed in Table A-2.

Table A-2 Design Loads

Load	Value
Design Pressure	700 psi
Design Temperature	1200 F
Nozzle Axial Load	30,000 lbf
Nozzle Shear Force	4,000 lbf
Nozzle Torsional Moment	20,000 lbf-in

A.2 Mesh Study Analysis

Isothermal static stress analyses are run for each of the models listed in Table A-1. The results are compared in Table A-3 and Figure A-1 and Figure A-2. Based on these results all the models provide results with in 1%. Therefore, model REP-025 is selected as a conservatively adequate mesh density.

Table A-3 Maximum Tresca Stress Results, ksi

Model Name	Design Pressure Only	All Design Loads
REP-1	7.62	8.42
REP-05	7.62	8.42
REP-025	7.60	8.38
REP-0125	7.59	8.37

Figure A-1 Design Pressure Only Tresca Stress Contours

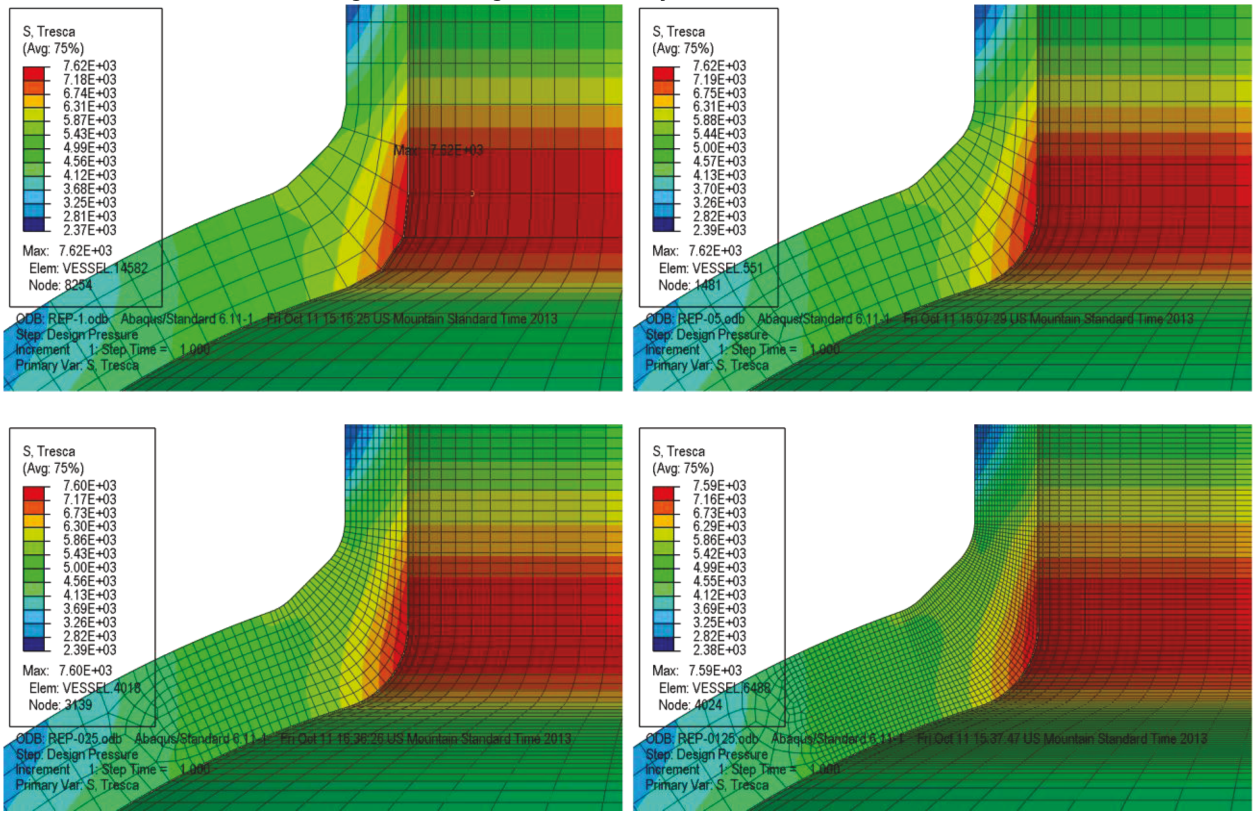
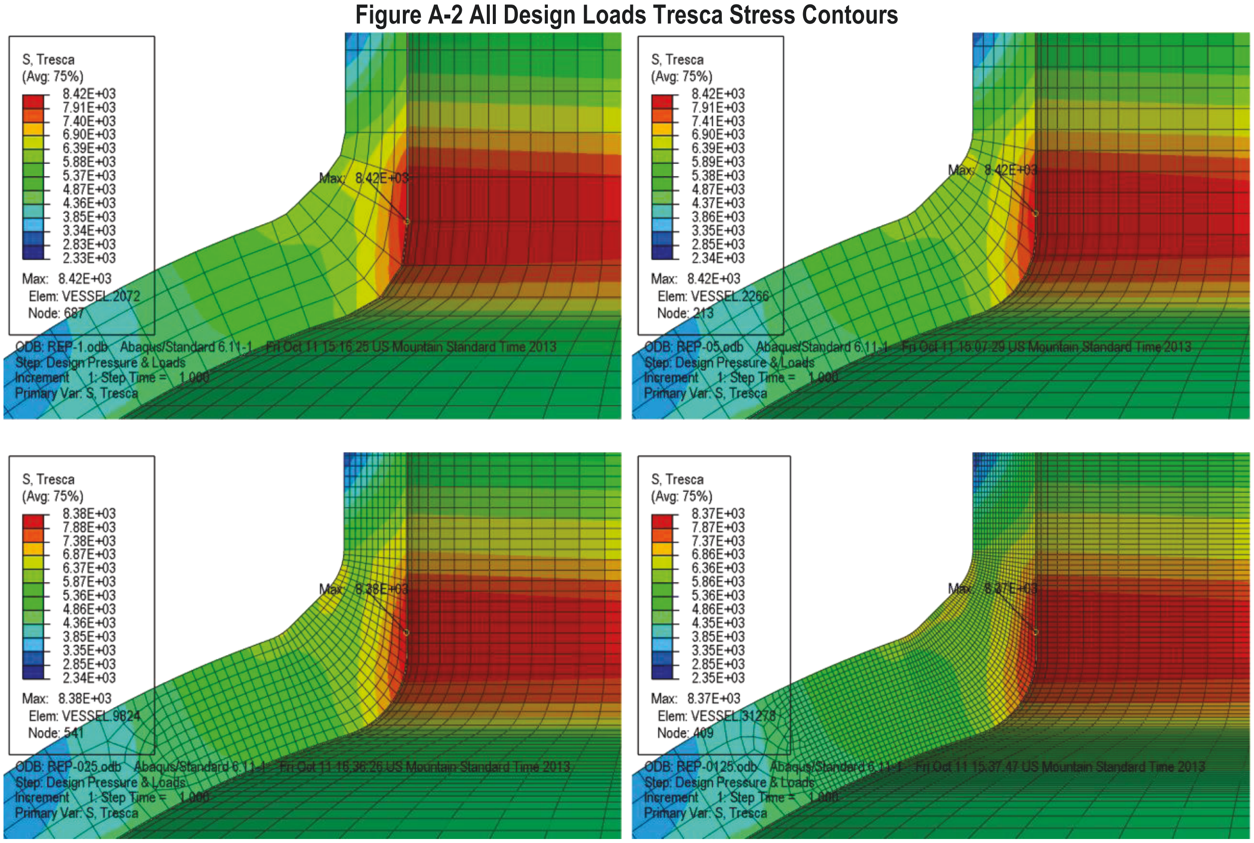


Figure A-2 All Design Loads Tresca Stress Contours



Appendix B — Pseudo Yield Stress for Strain Limits Analysis

This appendix defines the equations used to compute the temperature dependent Pseudo Yield Stress for the strain limits analysis at various target inelastic strain values.

B.1 316H Yield Stress

The equation for yield stress as a function of temperature is defined below.

$a_0 := 1.10298556$

$a_1 := -1.47430259\text{e-}3$

$a_2 := 1.52887261\text{e-}6$

$a_3 := -7.8404955\text{e-}10$

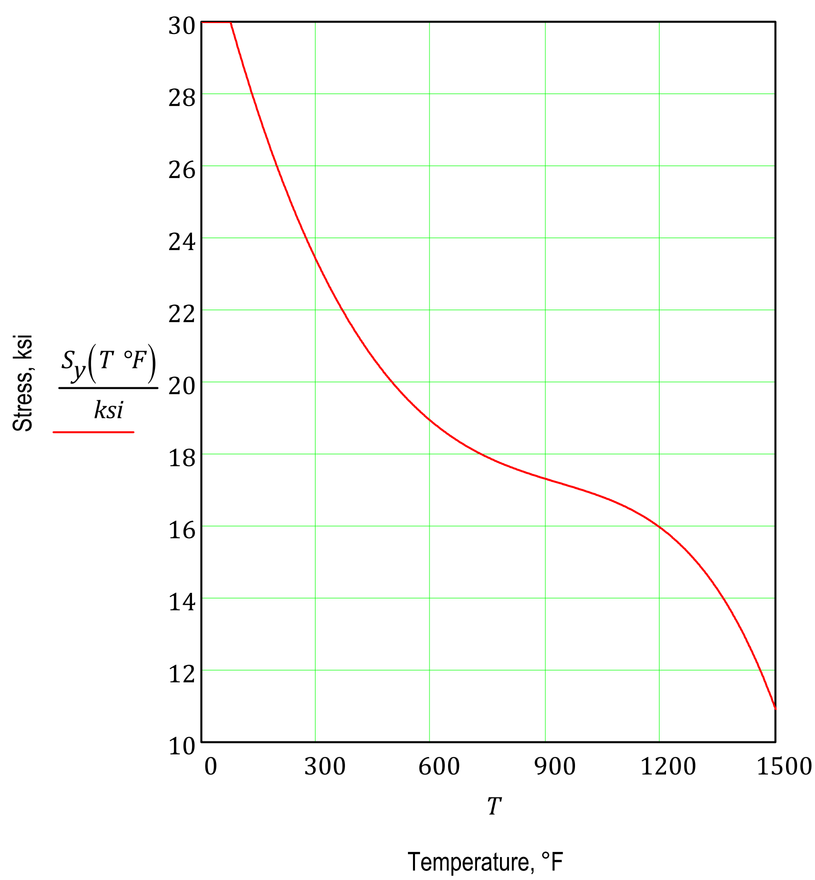
$a_4 := 3.10394363\text{e-}13$

$a_5 := -1.17555515\text{e-}16$

$$S_y(T) := min\left[\sum_{n=0}^{5}\left[a_n\left(T\ /°F\right)^n\right],\ 1\right]30\ \ ksi$$

$T =$ (·°F) and $\overrightarrow{S_y(T)} =$ (·ksi)

T (°F)	$S_y(T)$ (ksi)
75	30.0
100	29.1
200	25.9
300	23.4
400	21.4
500	20.0
600	18.9
650	18.5
700	18.2
750	17.9
800	17.7
850	17.5
900	17.3
950	17.2
1000	17.0
1050	16.8
1100	16.6
1150	16.3
1200	16.0
1250	15.5
1300	14.9
1350	14.2
1400	13.3
1450	12.2
1500	10.9



B.2 316H Hot Tensile Plastic Strain

The hot tensile plastic strain parameters as a function of temperature are defined below.

$$\sigma_y(T) := 1.0\left(23402.6 \cdot psi - 8.04798 \cdot T \cdot \frac{psi}{K}\right)$$

$$\sigma_p(T) := \sigma_y(T) - 8188.8 \cdot psi + 3.51356 \cdot T \cdot \frac{psi}{K}$$

$$K_1(T) := 60786.5 \cdot psi - 13.7959 \cdot T \cdot \frac{psi}{K}$$

$$m_1(T) := 0.309503 + 6.13279 \cdot 10^{-5} \cdot T \cdot \frac{1}{K}$$

$$K_2(T) := \begin{cases} 203100 psi & \text{if} \quad 600\ °F \le T \le 1000\ °F \\ 664859 psi - 569.369 \cdot T \frac{psi}{K} & \text{if} \quad 1000\ °F < T < 1200\ °F \\ NaN & otherwise \end{cases}$$

$$m_2(T) := \begin{cases} 0.7315 & \text{if} \quad 600\ °F \le T < 1000\ °F \\ 1.65136 - 1.13423 \cdot 10^{-3} \cdot T \cdot \frac{1}{K} & \text{if} \quad 1000\ °F \le T \le 1200\ °F \\ NaN & otherwise \end{cases}$$

$$\varepsilon_p(\sigma, T) := \begin{cases} 0 & \text{if} \quad \sigma < \sigma_p(T) \\ otherwise & \\ \quad \begin{cases} min\left[\left(\frac{\sigma - \sigma_p(T)}{K_1(T)}\right)^{1 \div m_1(T)}, \left(\frac{\sigma - \sigma_p(T)}{K_2(T)}\right)^{1 \div m_2(T)}\right] & \text{if} \quad 600\ °F \le T \le 1200\ °F \\ \left(\frac{\sigma - \sigma_p(T)}{K_1(T)}\right)^{1 \div m_1(T)} & \text{if} \quad 1200\ °F \le T \le 1400\ °F \\ NaN & otherwise \end{cases} \end{cases}$$

B.3 316H Creep Strain

The creep strain parameters as a function of temperature are defined below.

$$G(T) := \begin{cases} 0 \quad \text{if} \quad 800\ °F \le T < 1000\ °F \\ 1.28221\% - 1.58103 \cdot 10^{-3}\, T \dfrac{\%}{K} \quad \text{if} \quad 1000\ °F \le T < 1100\ °F \\ -0.271855\% + 2.13509 \cdot 10^{-4}\, T \dfrac{\%}{K} \quad \text{if} \quad 1100\ °F \le T \le 1200\ °F \\ -0.692411\% + 6.69643 \cdot 10^{-4}\, T \dfrac{\%}{K} \quad \text{if} \quad 1200\ °F < T < 1300\ °F \\ -0.704318\% + 6.81818 \cdot 10^{-4}\, T \dfrac{\%}{K} \quad \text{if} \quad 1300\ °F \le T \le 1400\ °F \\ NaN \quad \text{otherwise} \end{cases}$$

$$H(T) := \begin{cases} 0 \quad \text{if} \quad 800\ °F \le T < 1000\ °F \\ -3.20553 \cdot 10^{-4} \dfrac{\%}{psi} + 3.95256 \cdot 10^{-7}\, T \dfrac{\%}{psi \cdot K} \quad \text{if} \quad 1000\ °F \le T < 1100\ °F \\ 6.79633 \cdot 10^{-5} \dfrac{\%}{psi} - 5.33767 \cdot 10^{-8}\, T \dfrac{\%}{psi \cdot K} \quad \text{if} \quad 1100\ °F \le T \le 1200\ °F \\ 1.73103 \cdot 10^{-4} \dfrac{\%}{psi} - 1.67411 \cdot 10^{-7}\, T \dfrac{\%}{psi \cdot K} \quad \text{if} \quad 1200\ °F < T < 1300\ °F \\ 1.7608 \cdot 10^{-4} \dfrac{\%}{psi} - 1.70455 \cdot 10^{-7}\, T \dfrac{\%}{psi \cdot K} \quad \text{if} \quad 1300\ °F \le T \le 1400\ °F \\ NaN \quad \text{otherwise} \end{cases}$$

$$D(T) := \begin{cases} 5.7078 \cdot 10^{13} \dfrac{1}{hr} \quad \text{if} \quad 800\ °F \le T < 1000\ °F \\ -4.4986 \cdot 10^{17} \dfrac{1}{hr} + 5.54768 \cdot 10^{14}\, T \dfrac{1}{hr \cdot K} \quad \text{if} \quad 1000\ °F \le T \le 1075.5\ °F \\ 2.86941 \cdot 10^{17} \dfrac{1}{hr} - 3.09286 \cdot 10^{14}\, T \dfrac{1}{hr \cdot K} \quad \text{if} \quad 1075.5\ °F < T \le 1200\ °F \\ 1.3369 \cdot 10^{10} e^{-\frac{10878.5\ K}{T}} \dfrac{1}{hr} \quad \text{if} \quad 1200\ °F < T \le 1400\ °F \\ NaN \quad \text{otherwise} \end{cases}$$

$$\beta(T) := \begin{cases} -4.257 \cdot 10^{-4} \dfrac{1}{psi} + 7.733 \cdot 10^{-7}\, T \dfrac{1}{psi \cdot K} \quad \text{if} \quad 800\ °F \le T \le 1400\ °F \\ NaN \quad \text{otherwise} \end{cases}$$

$$n(T) := \begin{cases} 4.6 & \text{if} \quad 800\ °F \le T < 1000\ °F \\ -80.9236 + 0.105455\, T \dfrac{1}{K} & \text{if} \quad 1000\ °F \le T \le 1075.5\ °F \\ 50.1136 - 0.0482143\, T \dfrac{1}{K} & \text{if} \quad 1075.5\ °F < T \le 1200\ °F \\ 14.4647 - 9.54954 \cdot 10^{-3} T \dfrac{1}{K} & \text{if} \quad 1200\ °F < T \le 1400\ °F \\ NaN & \text{otherwise} \end{cases}$$

$$C(T) := \begin{cases} 7.1 & \text{if} \quad 800\ °F \le T < 1000\ °F \\ 25.5318 - 0.0227273\, T \dfrac{1}{K} & \text{if} \quad 1000\ °F \le T < 1100\ °F \\ 54.5625 - 0.05625\, T \dfrac{1}{K} & \text{if} \quad 1100\ °F \le T \le 1200\ °F \\ 7.68378 - 5.4054 \cdot 10^{-3} T \dfrac{1}{K} & \text{if} \quad 1200\ °F < T \le 1400\ °F \\ NaN & \text{otherwise} \end{cases}$$

$$B(T) := \begin{cases} 5.7078 \cdot 10^{13} \dfrac{1}{hr} & \text{if} \quad 800\ °F \le T < 1000\ °F \\ -3.92183 \cdot 10^{16} \dfrac{1}{hr} + 4.84416 \cdot 10^{13}\, T \dfrac{1}{hr \cdot K} & \text{if} \quad 1000\ °F \le T \le 1075.5\ °F \\ 1.44225 \cdot 10^{-8} \cdot e^{\frac{45475.8\ K}{T}} \dfrac{1}{hr} & \text{if} \quad 1075.5\ °F < T \le 1200\ °F \\ 2.85517 \cdot 10^{8} \cdot e^{\frac{10878.5\ K}{T}} \dfrac{1}{hr} & \text{if} \quad 1200\ °F < T \le 1400\ °F \\ NaN & \text{otherwise} \end{cases}$$

$$L(T) := \left| \begin{array}{l} M \leftarrow 43.1255 - \dfrac{49995.0\ K}{T} \quad if \quad 800\ °F \le T < 1000\ °F \\ if \quad 1000\ °F \le T \le 1075.5\ °F \\ \quad \left| \begin{array}{l} z \leftarrow T\dfrac{1}{K} - 610 \\ M \leftarrow -1153.38 + 16.4457z - 0.0754331z^2 + 0.000107956z^3 \end{array} \right. \\ if \quad 1075.5\ °F < T < 1100\ °F \\ \quad \left| \begin{array}{l} z \leftarrow T\dfrac{1}{K} - 610 \\ M \leftarrow -274.235 + 1.15596z - 0.00115945z^2 \end{array} \right. \\ if \quad 1100\ °F \le T \le 1200\ °F \\ \quad \left| \begin{array}{l} z \leftarrow T\dfrac{1}{K} - 610 \\ M \leftarrow -274.235 + 1.15598z - 0.00115945z^2 \end{array} \right. \\ if \quad 1200\ °F < T \le 1400\ °F \\ \quad \left| \begin{array}{l} w \leftarrow T\dfrac{1}{K} - 680 \\ M \leftarrow -54.6029 + 0.118486w - 8.63568 \cdot 10^{-6} w^2 \end{array} \right. \\ M \leftarrow NaN \quad otherwise \\ e^M \dfrac{1}{hr} \end{array} \right.$$

$$A(T) := \left| \begin{array}{l} 5.6229 \cdot 10^{12} \dfrac{\%}{hr} \quad if \quad 800\ °F \le T < 1000\ °F \\ -7.85348 \cdot 10^{15} \dfrac{\%}{hr} + 9.69329 \cdot 10^{12} T \dfrac{\%}{hr \cdot K} \quad if \quad 1000\ °F \le T \le 1075.5\ °F \\ 5.28787 \cdot 10^{-6} e^{\frac{39057.1\ K}{T}} \dfrac{\%}{hr} \quad if \quad 1075.5\ °F < T \le 1200\ °F \\ 6.03371 \cdot 10^{10} e^{\frac{4967.76\ K}{T}} \dfrac{\%}{hr} \quad if \quad 1200\ °F < T \le 1400\ °F \\ NaN \quad otherwise \end{array} \right.$$

$$Q := 67000 \cdot \frac{cal}{mol} \qquad R := 1.987 \frac{cal}{mol \cdot K}$$

The steady-state creep strain equation as a function of stress, temperature and time is defined below.

$$\varepsilon'_m(\sigma, T) := A(T) \cdot sinh\left(\frac{\beta(T) \cdot \sigma}{n(T)}\right)^{n(T)} e^{\frac{-Q}{R \cdot T}}$$

$$\varepsilon_{cr.ss}(\sigma, T, t) := \varepsilon'_m(\sigma, T) \cdot t$$ steady-state creep strain

The short-time transient creep strain equation as a function of stress, temperature and time is defined below.

$$s(\sigma, T) := max\left(D(T) \cdot sinh\left(\frac{\beta(T) \cdot \sigma}{n(T)}\right)^{n(T)} e^{\frac{-Q}{R \cdot T}}, 2.5 \cdot 10^{-2} \frac{1}{hr}\right)$$

$$\varepsilon_x(\sigma, T) := \begin{vmatrix} 0 \quad if \quad \sigma \le 4000 \ psi \\ G(T) + H(T)\sigma \quad if \quad \sigma > 4000 \ psi \end{vmatrix}$$

$$\varepsilon_{cr.s}(\sigma, T, t) := \varepsilon_x(\sigma, T) \cdot \left(1 - e^{-s(\sigma, T) \cdot t}\right)$$ short-time transient creep strain

The long-time transient creep strain equation as a function of stress, temperature and time is defined below.

$$r(\sigma, T) := max\left[B(T) \cdot sinh\left(\frac{\beta(T) \cdot \sigma}{n(T)}\right)^{n(T)} e^{\frac{-Q}{R \cdot T}}, L(T)\left(\frac{\sigma}{psi}\right)^{n(T)-3.6}\right]$$

$$\varepsilon_t(\sigma, T) := C(T) \frac{\varepsilon'_m(\sigma, T)}{r(\sigma, T)}$$

$$\varepsilon_{cr.l}(\sigma, T, t) := \varepsilon_t(\sigma, T) \cdot \left(1 - e^{-r(\sigma, T) \cdot t}\right)$$ long-time transient creep strain

The total creep strain equation as a function of stress, temperature and time is defined below.

$$\varepsilon_{cr}(\sigma, T, t) := \varepsilon_{cr.s}(\sigma, T, t) + \varepsilon_{cr.l}(\sigma, T, t) + \varepsilon_{cr.ss}(\sigma, T, t)$$ creep strain

B.4 316H Total Inelastic Strain and Stress

The total inelastic strain equation as a function of target creep strain, temperature and time is defined below.

$$\varepsilon_{in}(\sigma, T, t) := \varepsilon_p(\sigma, T) + \varepsilon_{cr}(\sigma, T, t)$$ inelastic strain

The total inelastic stress is solved for by finding the root as defined below.

$$\sigma_{in}(\varepsilon, T, t) := \begin{vmatrix} \sigma \leftarrow 30ksi \\ root\left(\varepsilon_{in}(\sigma, T, t) - \varepsilon, \sigma\right) \end{vmatrix}$$ inelastic stress

B.5 Pseudo Yield Stress

The Pseudo Yield Stress equation as a function of target inelastic strain, temperature and time is defined below.

$$S_{xT}(x, T, t) := \left| \begin{array}{l} S_y(T) \quad if \quad \left| \begin{array}{l} 1 \quad if \quad IsNaN\left(\varepsilon_{in}\left(S_y(T), T, t\right)\right) \\ x \geq \varepsilon_{in}\left(S_y(T), T, t\right) \quad otherwise \end{array} \right. \\ \sigma_{in}(x, T, t) \quad otherwise \end{array} \right.$$

pseudo yield stress

The function used to select temperature data points between temperatures T_0 and T_N with a resolution of T_{inc} where linear interpolation between data points do not exceed a standard deviation of dev is defined below:

$$T_{xT}\left(x, t, T_0, T_N, T_{inc}, dev\right) := \left| \begin{array}{l} N \leftarrow trunc\left(\dfrac{T_N - T_0}{T_{inc}}\right) \\ for \quad i \in 0..N \\ \quad \left| \begin{array}{l} T_i \leftarrow T_0 + i \cdot T_{inc} \\ S_i \leftarrow S_{xT}\left(x, T_i, t\right) \end{array} \right. \\ T^*_0 \leftarrow T_0 \\ j \leftarrow 0 \\ i^* \leftarrow 0 \\ for \quad i \in 2..N \\ \quad \left| \begin{array}{l} T_{sub} \leftarrow submatrix(T, i^*, i, 0, 0) \\ S_{sub} \leftarrow submatrix(S, i^*, i, 0, 0) \\ if \quad stderr\left(\dfrac{T_{sub}}{K}, \dfrac{S_{sub}}{psi}\right) > dev \\ \quad \left| \begin{array}{l} i^* \leftarrow i - 1 \\ j \leftarrow j + 1 \\ T^*_j \leftarrow T_{i-1} \end{array} \right. \end{array} \right. \\ T^*_{j+1} \leftarrow T_N \\ T^* \end{array} \right.$$

The following pages list the pseudo yield stress data compared to the analytical functions for the various target inelastic strains used in the strain limit analyses based on these input parameters:

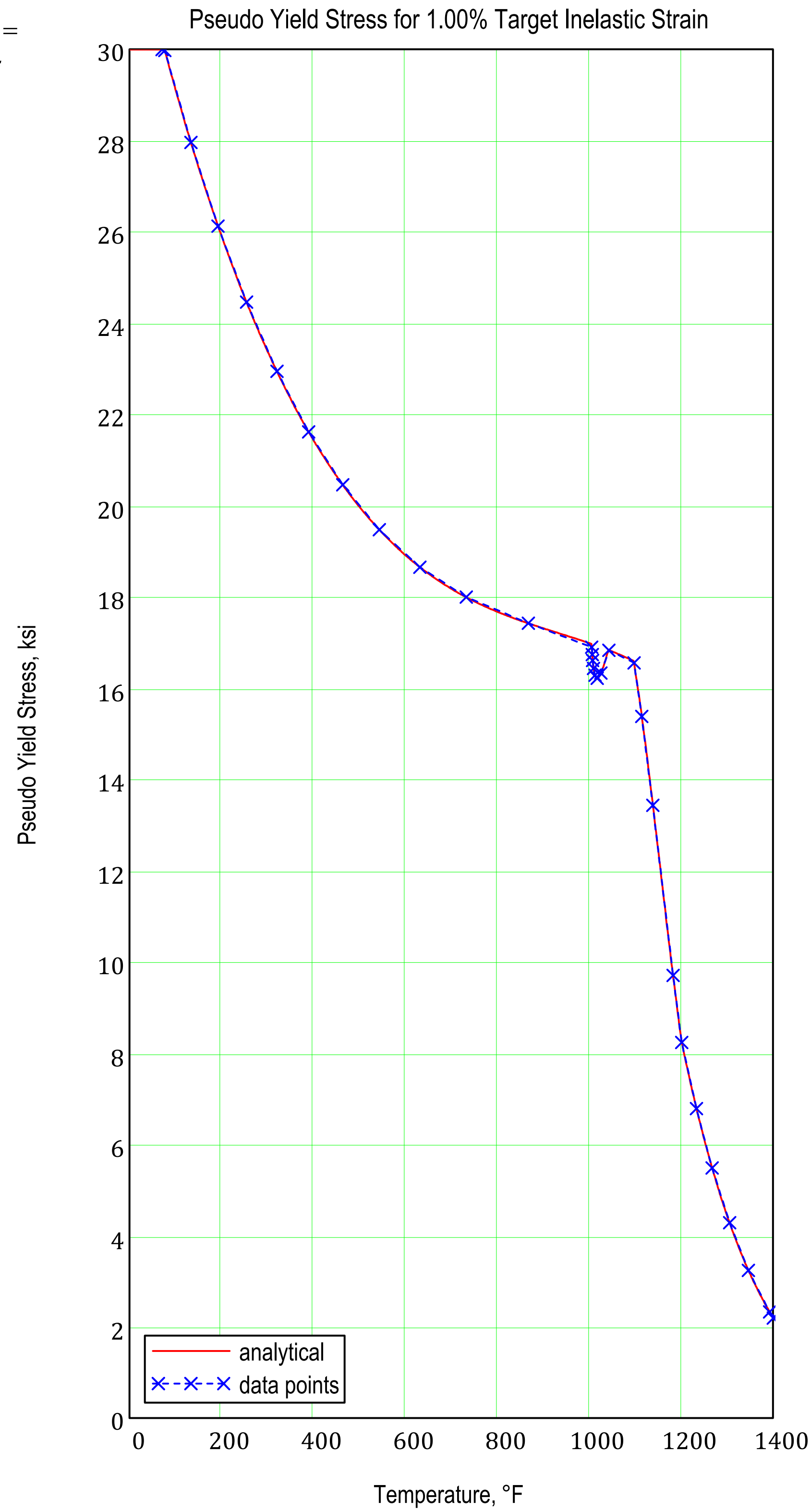
$t_d := 192206405sec = 5.339 \times 10^4 \cdot hr$ — total time duration of high temperature service, see Table 3.6.3-2

$T_0 := 70\ °F \qquad T_N := 1400\ °F$ — start and end temperature

$T_{inc} := 1\Delta°F \qquad dev := 10$ — temperature resolution and maximum allowed deviation

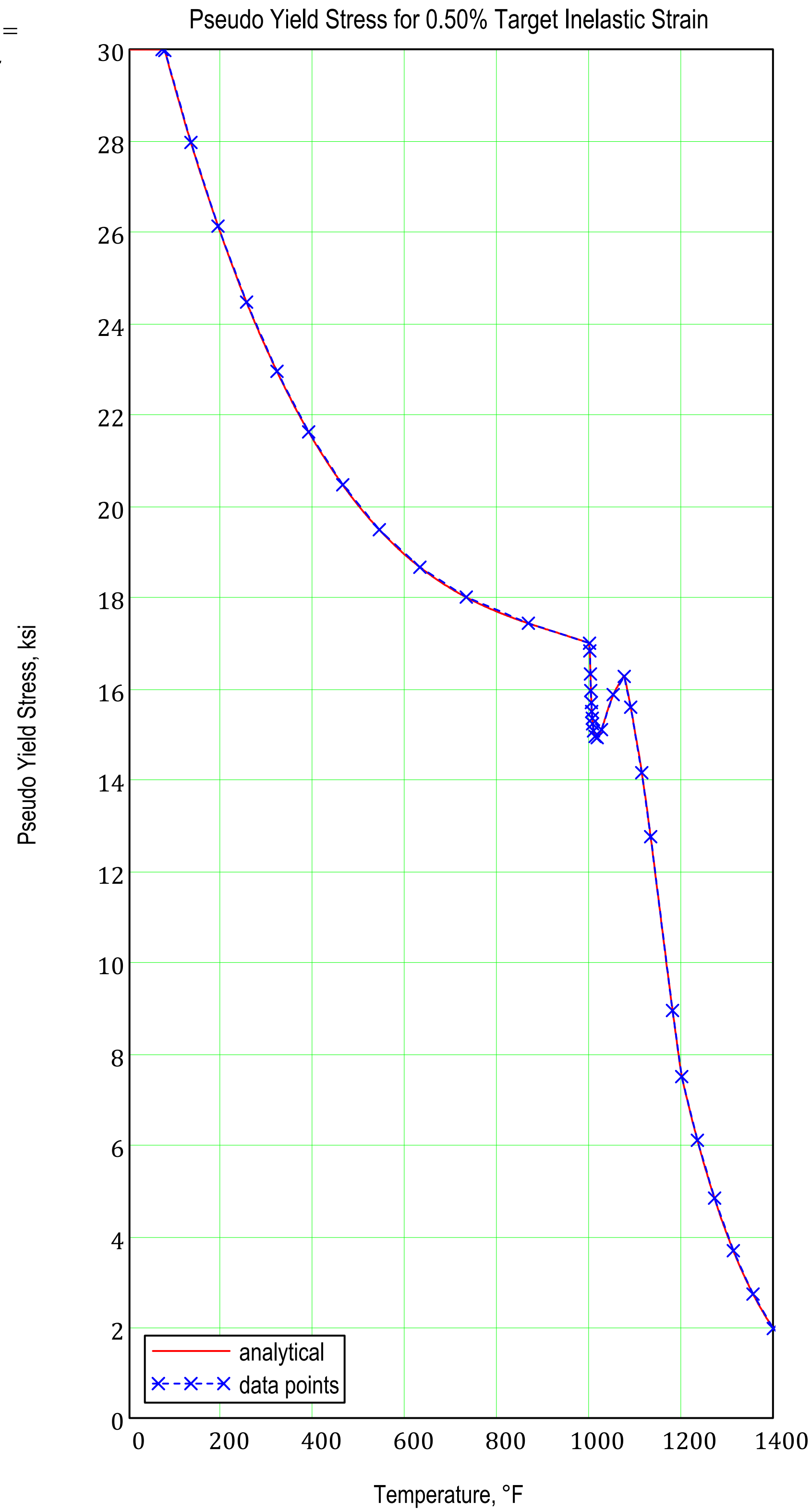
$x := 1.00\%$ $\quad T := T_{xT}(x, t_d, T_0, T_N, T_{inc}, dev)$

$T =$ (°F)	$\overrightarrow{S_{xT}(x, T, t_d)} =$ (ksi)
70	30.00
76	29.98
133	27.97
192	26.13
254	24.46
320	22.95
389	21.62
463	20.46
543	19.47
631	18.66
732	18.00
867	17.42
1005	16.90
1006	16.74
1007	16.61
1009	16.44
1012	16.29
1017	16.22
1025	16.33
1042	16.84
1097	16.56
1114	15.38
1138	13.43
1182	9.71
1201	8.24
1233	6.79
1267	5.48
1305	4.29
1346	3.24
1392	2.33
1400	2.20



$x := 0.60\%$ $\quad T := T_{xT}(x, t_d, T_0, T_N, T_{inc}, dev)$

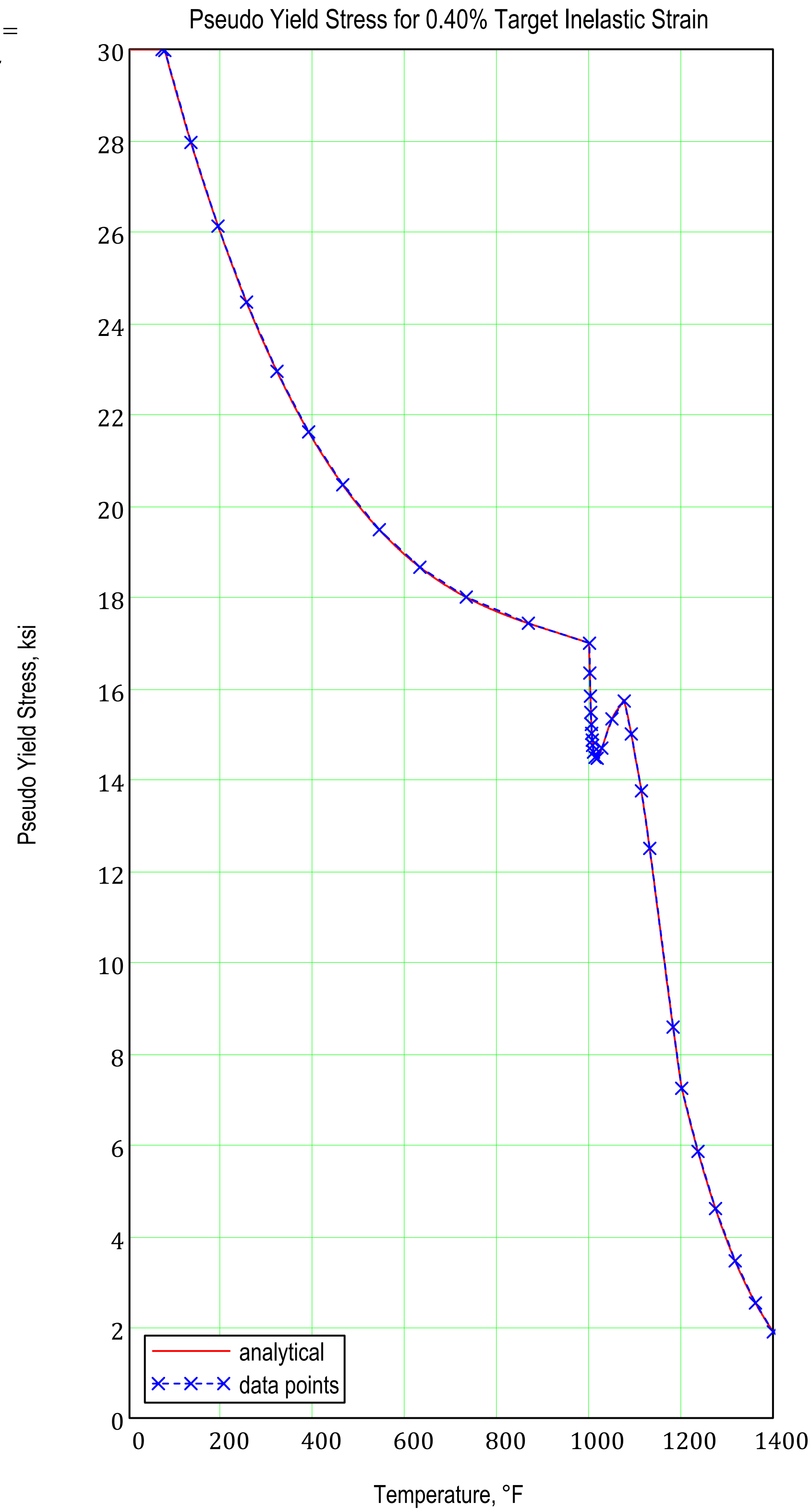
$T =$ (°F)	$\overrightarrow{S_{xT}(x, T, t_d)} =$ (ksi)
70	30.00
76	29.98
133	27.97
192	26.13
254	24.46
320	22.95
389	21.62
463	20.46
543	19.47
631	18.66
732	18.00
867	17.42
1000	16.99
1001	16.82
1002	16.31
1003	15.95
1004	15.69
1005	15.49
1006	15.34
1007	15.23
1009	15.07
1012	14.95
1017	14.92
1026	15.10
1052	15.86
1076	16.26
1090	15.59
1114	14.15
1133	12.75
1181	8.94
1201	7.49
1235	6.09
1272	4.82
1313	3.68
1356	2.72
1400	1.97



$x := 0.50\%$ $\quad T := T_{xT}(x, t_d, T_0, T_N, T_{inc}, dev)$

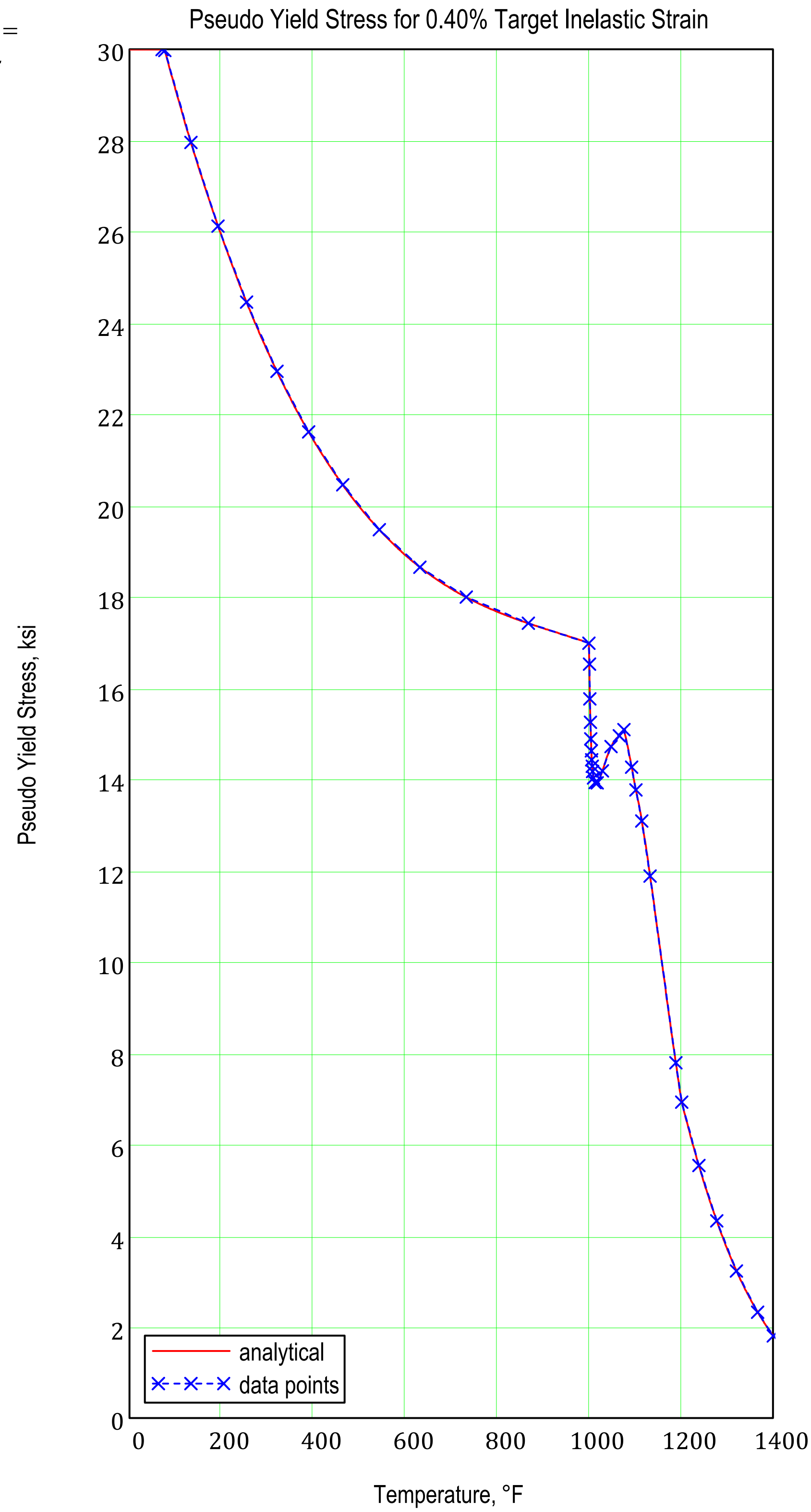
$T =$ (°F) $\quad \overrightarrow{S_{xT}(x, T, t_d)} =$ (ksi)

T (°F)	S_{xT} (ksi)
70	30.00
76	29.98
133	27.97
192	26.13
254	24.46
320	22.95
389	21.62
463	20.46
543	19.47
631	18.66
732	18.00
867	17.42
1000	16.99
1001	16.34
1002	15.83
1003	15.47
1004	15.21
1005	15.01
1006	14.86
1007	14.75
1009	14.60
1012	14.49
1017	14.47
1027	14.69
1049	15.33
1076	15.72
1091	15.00
1113	13.75
1131	12.49
1182	8.57
1201	7.24
1236	5.85
1274	4.60
1317	3.45
1361	2.53
1400	1.89



$x := 0.40\%$ $\quad T := T_{xT}(x, t_d, T_0, T_N, T_{inc}, dev)$

$T =$ (·°F)	$\overrightarrow{S_{xT}(x, T, t_d)} =$ (·ksi)
70	30.00
76	29.98
133	27.97
192	26.13
254	24.46
320	22.95
389	21.62
463	20.46
543	19.47
631	18.66
732	18.00
867	17.42
999	16.99
1000	16.53
1001	15.77
1002	15.25
1003	14.89
1004	14.63
1005	14.44
1006	14.29
1007	14.18
1009	14.03
1012	13.93
1017	13.93
1028	14.19
1047	14.72
1065	14.96
1075	15.09
1092	14.27
1101	13.77
1114	13.09
1132	11.89
1188	7.80
1201	6.93
1238	5.54
1277	4.33
...	...



Appendix C — Pseudo Yield Stress for Creep-Fatigue Analysis

This appendix defines the equations used to compute the temperature dependent Pseudo Yield Stress for the creep-fatigue analysis at various selected trial time values.

C.1 316H Yield Stress

The equation for yield stress as a function of temperature is defined below.

$a_0 := 1.10298556$

$a_1 := -1.47430259\text{e-}03$

$a_2 := 1.52887261\text{e-}06$

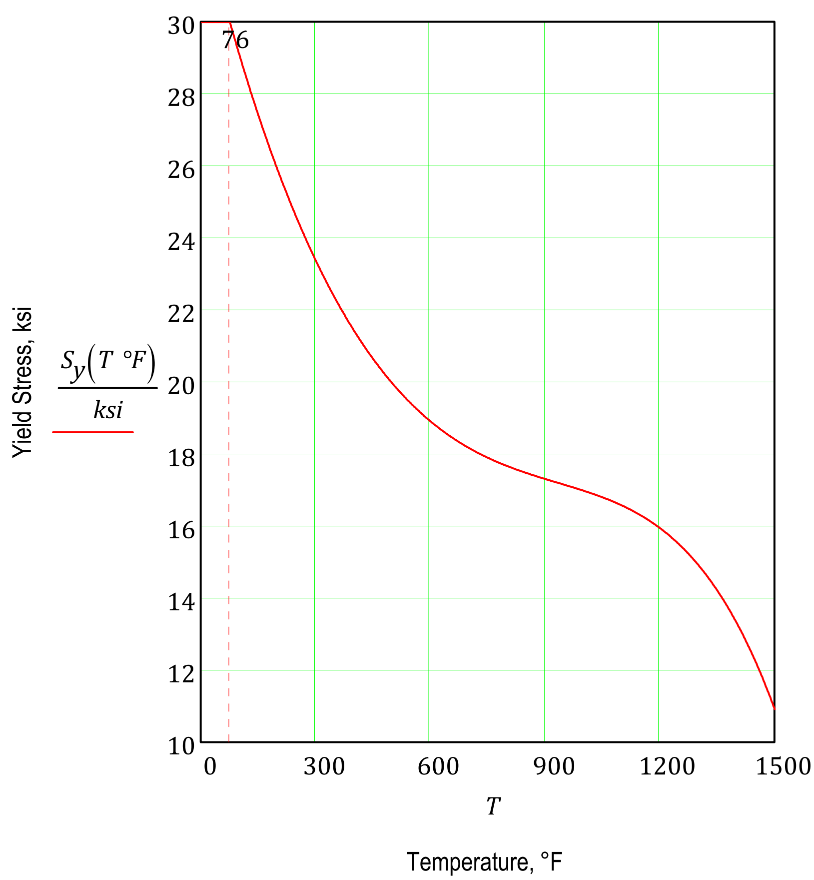
$a_3 := -7.8404955\text{e-}10$

$a_4 := 3.10394363\text{e-}13$

$a_5 := -1.17555515\text{e-}16$

$$S_y(T) := min\left[\sum_{n=0}^{5}\left[a_n\,(T/°F)^n\right], 1\right] 30\ ksi$$

$T =$ (°F)	$\overrightarrow{S_y(T)} =$ (ksi)
75	30.0
100	29.1
200	25.9
300	23.4
400	21.4
500	20.0
600	18.9
650	18.5
700	18.2
750	17.9
800	17.7
850	17.5
900	17.3
950	17.2
1000	17.0
1050	16.8
1100	16.6
1150	16.3
1200	16.0
1250	15.5
1300	14.9
1350	14.2
1400	13.3
1450	12.2
1500	10.9



C.2 316H Tensile Strength

The equation for tensile strength as a function of temperature is defined below.

$b_0 := 1.08437074$

$b_1 := -1.25566465\text{e-}03$

$b_2 := 2.41683284\text{e-}06$

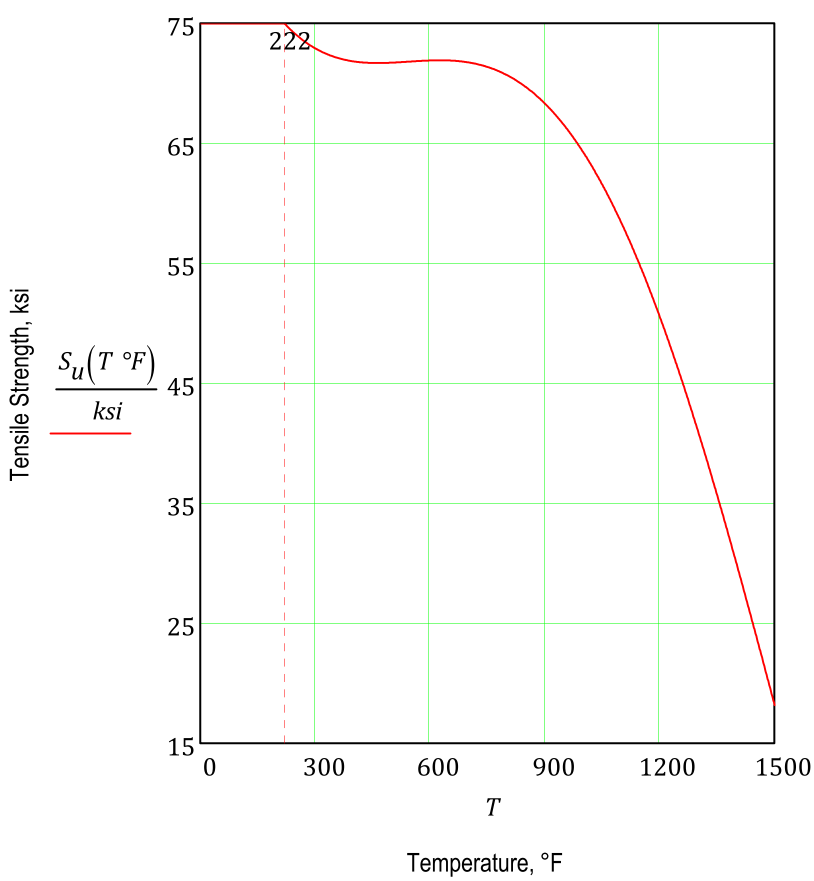
$b_3 := -1.49661353\text{e-}09$

$b_4 := -1.59739404\text{e-}13$

$b_5 := 1.89846445\text{e-}16$

$$S_u(T) := \min\left[\sum_{n=0}^{5}\left[1.1\, b_n \left(T / {}^\circ F\right)^n\right],\, 1\right] 75\ \ ksi$$

$T =$ ($\cdot {}^\circ F$)	$\overrightarrow{S_u(T)} =$ ($\cdot ksi$)
75	75.0
100	75.0
200	75.0
300	72.9
400	71.8
500	71.7
600	71.9
650	71.9
700	71.8
750	71.4
800	70.7
850	69.7
900	68.3
950	66.5
1000	64.3
1050	61.6
1100	58.4
1150	54.7
1200	50.6
1250	46.0
1300	41.0
1350	35.7
1400	30.0
1450	24.2
1500	18.2



C.3 316H Minimum Stress-to-Rupture

The minimum stress-to-rupture equation as a function of time to rupture and temperature is defined below.

$a_0 := 26377.99$

$a_1 := -1982.62$

$a_2 := -866.40$

$C_{LMC} := 16.282$

$SEE := 0.35$

$ksi = 6.89476 \cdot MPa$

$$a'_0(t, T) := a_0 - \left(log\left(\frac{t}{hr}\right) + C_{LMC} + 1.65SEE\right) \cdot \left(\frac{T}{K}\right)$$

$$S_r(t, T) := min\left(10^{\frac{-a_1 - \sqrt{a_1^2 - 4a_2 \cdot a'_0(t, T)}}{2a_2}} \cdot MPa, \frac{S_u(T)}{1.1}\right)$$

$t =$ [1, 10, 30, $1 \cdot 10^2$, $3 \cdot 10^2$, $1 \cdot 10^3$, $3 \cdot 10^3$, $1 \cdot 10^4$, $3 \cdot 10^4$, $1 \cdot 10^5$, $3 \cdot 10^5$] $\cdot hr$

$T =$ (°F); $S =$ ($\cdot ksi$)

T (°F)	1	10	30	$1 \cdot 10^2$	$3 \cdot 10^2$	$1 \cdot 10^3$	$3 \cdot 10^3$	$1 \cdot 10^4$	$3 \cdot 10^4$	$1 \cdot 10^5$	$3 \cdot 10^5$
800	64.3	64.3	64.3	64.3	64.3	64.3	64.3	64.3	64.3	59.2	52.5
850	63.4	63.4	63.4	63.4	63.4	63.4	63.4	61.7	54.6	47.6	41.9
900	62.1	62.1	62.1	62.1	62.1	62.1	57.8	50.2	44.0	38.1	33.2
950	60.5	60.5	60.5	60.5	60.5	54.0	47.2	40.6	35.3	30.3	26.2
1000	58.4	58.4	58.4	58.4	51.6	44.2	38.4	32.7	28.2	23.9	20.5
1050	56.0	56.0	56.0	49.1	42.4	36.1	31.0	26.2	22.3	18.7	15.9
1100	53.1	53.1	47.9	40.6	34.8	29.2	24.9	20.8	17.6	14.5	12.2
1150	49.7	46.5	39.7	33.3	28.3	23.6	19.9	16.4	13.7	11.2	9.3
1200	46.0	38.7	32.8	27.3	22.9	18.9	15.7	12.8	10.6	8.5	7.0
1250	41.8	32.1	27.0	22.2	18.5	15.0	12.4	10.0	8.1	6.4	5.2
1300	37.3	26.5	22.1	17.9	14.8	11.9	9.7	7.7	6.1	4.8	3.8
1350	32.3	21.8	18.0	14.4	11.7	9.3	7.5	5.8	4.6	3.5	2.7
1400	27.0	17.8	14.5	11.5	9.3	7.2	5.7	4.4	3.4	2.5	1.9
1450	22.0	14.5	11.7	9.1	7.2	5.5	4.3	3.2	2.5	1.8	1.3
1500	16.5	11.7	9.3	7.2	5.6	4.2	3.2	2.4	1.7	1.2	0.9
1050	56.0	56.0	56.0	49.1	42.4	36.1	31.0	26.2	22.3	18.7	15.9
1100	53.1	53.1	47.9	40.6	34.8	29.2	24.9	20.8	17.6	14.5	12.2
1150	49.7	46.5	39.7	33.3	28.3	23.6	19.9	16.4	13.7	11.2	9.3
1200	46.0	38.7	32.8	27.3	22.9	18.9	15.7	12.8	10.6	8.5	7.0
1250	41.8	32.1	27.0	22.2	18.5	15.0	12.4	10.0	8.1	6.4	5.2
1300	37.3	26.5	22.1	17.9	14.8	11.9	9.7	7.7	6.1	4.8	3.8
1350	32.3	21.8	18.0	14.4	11.7	9.3	7.5	5.8	4.6	3.5	2.7
1400	27.0	17.8	14.5	11.5	9.3	7.2	5.7	4.4	3.4	2.5	1.9
1450	22.0	14.5	11.7	9.1	7.2	5.5	4.3	3.2	2.5	1.8	1.3
1500	16.5	11.7	9.3	7.2	5.6	4.2	3.2	2.4	1.7	1.2	0.9

The stress rupture factors for SS 316 welds is interpolated from Table NH-I-14.10B-3 below.

$SRF :=$

0	10	30	100	300	1000	3000	$1\cdot10^4$	$3\cdot10^4$	$1\cdot10^5$	$3\cdot10^5$
800	1	1	0.99	0.98	0.97	0.96	0.95	0.94	0.92	0.88
850	1	1	0.99	0.98	0.97	0.96	0.95	0.94	0.92	0.88
900	1	1	0.97	0.94	0.91	0.89	0.88	0.86	0.82	0.78
950	1	1	0.95	0.9	0.87	0.84	0.81	0.78	0.72	0.68
1000	1	1	0.88	0.86	0.83	0.79	0.74	0.7	0.62	0.58
1050	1	1	0.92	0.89	0.87	0.83	0.78	0.74	0.66	0.56
1100	1	1	0.96	0.94	0.9	0.87	0.81	0.75	0.68	0.61
1150	1	1	1	0.96	0.91	0.87	0.81	0.75	0.66	0.59
1200	1	1	0.96	0.95	0.9	0.87	0.81	0.72	0.64	0.55
1250	1	1	0.96	0.93	0.89	0.84	0.77	0.69	0.6	0.51
1300	1	0.98	0.93	0.89	0.83	0.79	0.72	0.65	0.56	0.48
1350	0.99	0.96	0.89	0.84	0.77	0.72	0.65	0.59	0.52	0.45
1400	0.95	0.9	0.82	0.77	0.71	0.66	0.6	0.55	0.47	0.42

$SRF_T := submatrix(SRF, 1, rows(SRF) - 1, 0, 0)\ °F$ temperatures

$SRF_t := submatrix(SRF, 0, 0, 1, cols(SRF) - 1)^T \cdot hr$ time

$SRF_F := submatrix(SRF, 1, rows(SRF) - 1, 1, cols(SRF) - 1)$ factors

Define 2D linear interpolation function:

$$linterp2D(vx, vy, Z, p, q) := \left| \begin{array}{l} for \quad i \in 0 .. rows(Z) - 1 \\ \quad vp_i \leftarrow linterp\left(vy, submatrix(Z, i, i, 0, cols(Z) - 1)^T, q\right) \\ return\ \ linterp(vx, vp, p) \end{array} \right.$$

Define stress rupture factor for welds function:

$$F_r(t, T) := linterp2D\left(SRF_T, SRF_t, SRF_F, T, t\right)$$

C.4 Pseudo Yield Stress

The Pseudo Yield Stress equation for base metal and weld as a function of trial allowable time duration and temperature for creep-fatigue analyses is defined below.

$$S_{ctb}(t, T, K') := min\left(S_y(T), S_r(t, T) \cdot K'\right)$$ psyedo yield stress for base metal

$$S_{ctw}(t, T, K') := min\left(S_y(T), S_r(t, T) \cdot K' \cdot F_r(t, T)\right)$$ psyedo yield stress for weldments

The function used to select temperature data points between temperatures T_0 and T_N with a resolution of T_{inc} where linear interpolation between data points do not exceed a standard deviation of dev is defined below:

$$T_{ct}\left(t, T_0, T_N, T_{inc}, K', S_{ct}, dev\right) := \left|\begin{array}{l}
N \leftarrow trunc\left(\dfrac{T_N - T_0}{T_{inc}}\right) \\
for \quad i \in 0..N \\
\quad \left|\begin{array}{l} T_i \leftarrow T_0 + i \cdot T_{inc} \\ S_i \leftarrow S_{ct}\left(t, T_i, K'\right) \end{array}\right. \\
T^*_0 \leftarrow T_0 \\
j \leftarrow 0 \\
i^* \leftarrow 0 \\
for \quad i \in 2..N \\
\quad \left|\begin{array}{l} T_{sub} \leftarrow submatrix(T, i^*, i, 0, 0) \\ S_{sub} \leftarrow submatrix(S, i^*, i, 0, 0) \\ if \quad stderr\left(\dfrac{T_{sub}}{K}, \dfrac{S_{sub}}{psi}\right) > dev \\ \quad \left|\begin{array}{l} i^* \leftarrow i - 1 \\ j \leftarrow j + 1 \\ T^*_j \leftarrow T_{i-1} \end{array}\right. \end{array}\right. \\
T^*_{j+1} \leftarrow T_N \\
T^*
\end{array}\right.$$

The following pages list the pseudo yield stress data compared to the analytical functions for the various trial times used in the creep-fatigue analyses based on these input parameters:

$t_d := 192206405sec = 5.339 \times 10^4 \cdot hr$ total time duration of high temperature service, see Table 3.6.3-2

$T_0 := 70\ °F \qquad T_N := 1400\ °F$ start and end temperature

$T_{inc} := 1\Delta°F \qquad dev := 10$ temperature resolution and maximum allowed deviation

Pseudo Yield Stress for 1.00 target creep damage.

$D_{c,k} := 1.00 \qquad K' := 0.9$

$$T_{d,k} := \frac{t_d}{D_{c,k}} = 5.339 \times 10^4 \cdot hr$$

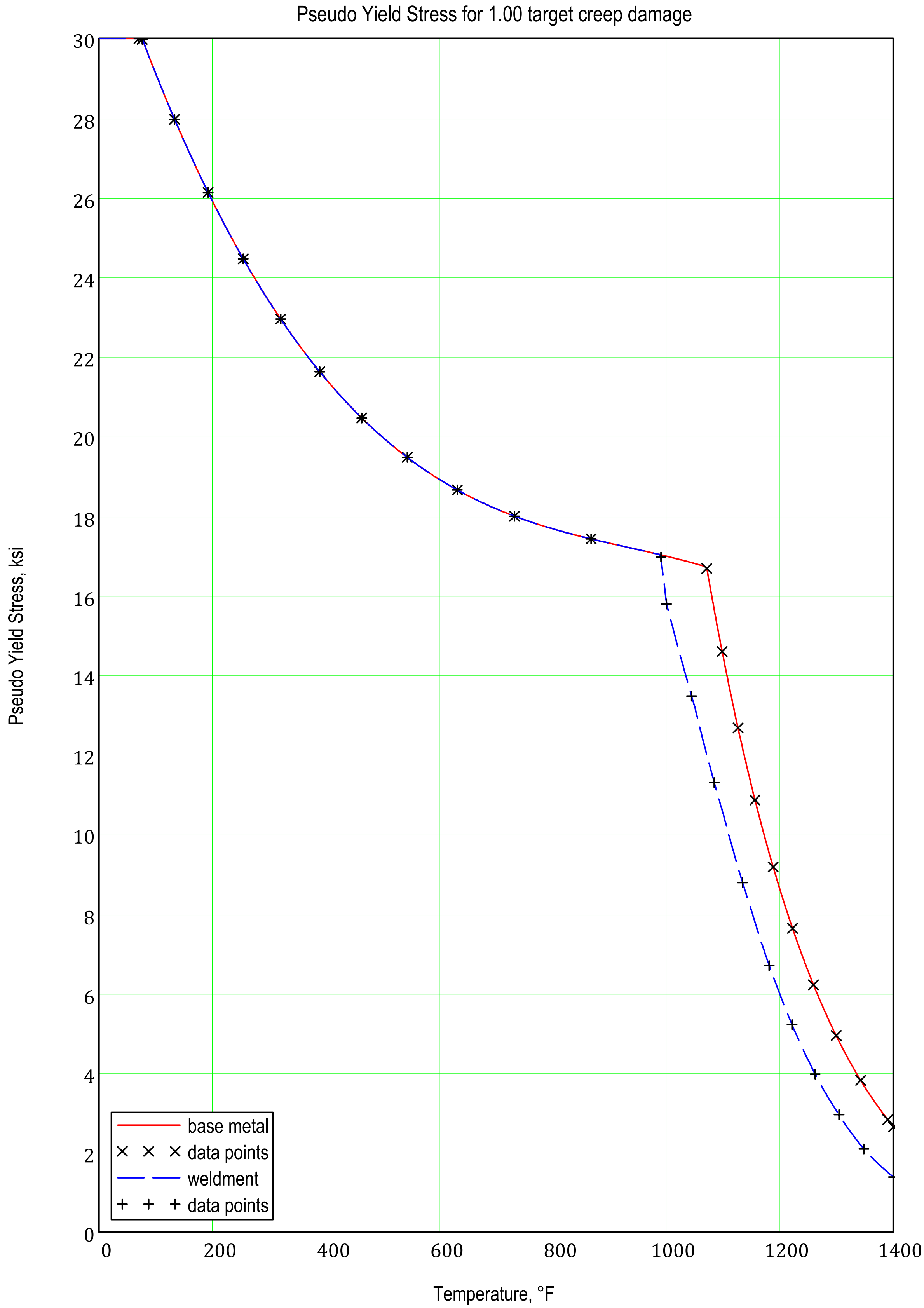
Base Metal Pseudo Yield Stress:

$T_b := T_{ct}\left(T_{d,k}, T_0, T_N, T_{inc}, K', S_{ctb}, dev\right)$

Weldment Pseudo Yield Stress:

$T_w := T_{ct}\left(T_{d,k}, T_0, T_N, T_{inc}, K', S_{ctw}, dev\right)$

$T_b =$ (·°F)	$\overrightarrow{S_{ctb}\left(T_{d,k}, T_b, K'\right)} =$ (·ksi)	$T_w =$ (·°F)	$\overrightarrow{S_{ctw}\left(T_{d,k}, T_w, K'\right)} =$ (·ksi)
70	30.00	70	30.00
76	29.98	76	29.98
133	27.97	133	27.97
192	26.13	192	26.13
254	24.46	254	24.46
320	22.95	320	22.95
389	21.62	389	21.62
463	20.46	463	20.46
543	19.47	543	19.47
631	18.66	631	18.66
732	18.00	732	18.00
867	17.42	867	17.42
1071	16.68	990	16.97
1098	14.60	1000	15.78
1126	12.68	1044	13.48
1156	10.86	1084	11.30
1188	9.18	1134	8.79
1222	7.64	1181	6.70
1259	6.22	1221	5.22
1299	4.94	1262	3.98
1342	3.82	1304	2.95
1390	2.83	1348	2.10
1400	2.65	1400	1.39


Pseudo Yield Stress for 1.00 target creep damage
Pseudo Yield Stress, ksi
Temperature, °F
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0
200
400
600
800
1000
1200
1400
base metal
data points
weldment
data points

Pseudo Yield Stress for 0.95 target creep damage.

$D_{c,k} := 0.95 \qquad K' = 0.9$

$$T_{d,k} := \frac{t_d}{D_{c,k}} = 56201 \cdot hr$$

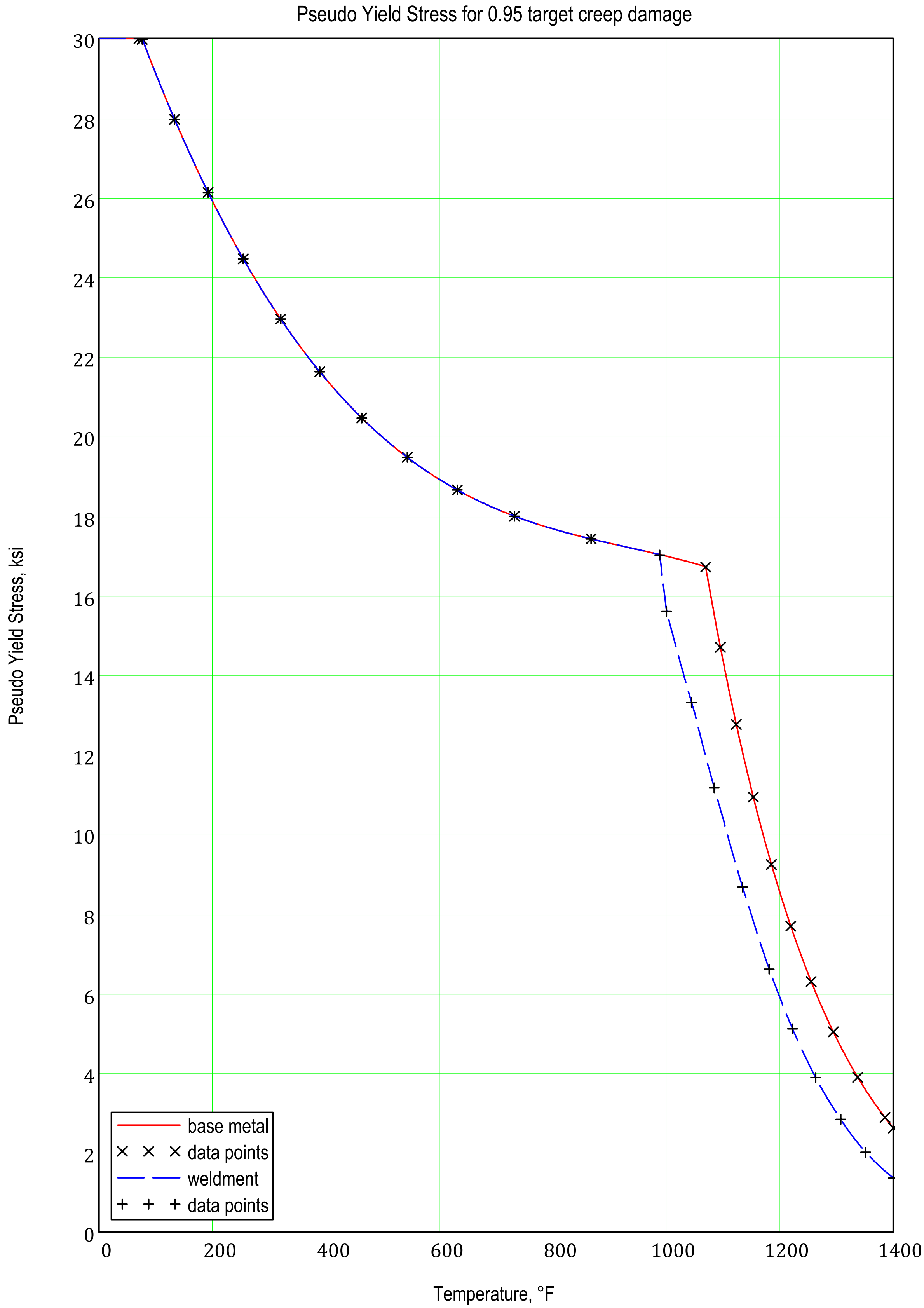
Base Metal Pseudo Yield Stress:

$T_b := T_{ct}\left(T_{d,k}, T_0, T_N, T_{inc}, K', S_{ctb}, dev\right)$

Weldment Pseudo Yield Stress:

$T_w := T_{ct}\left(T_{d,k}, T_0, T_N, T_{inc}, K', S_{ctw}, dev\right)$

$T_b =$ (°F)	$\overrightarrow{S_{ctb}\left(T_{d,k}, T_b, K'\right)} =$ (ksi)	$T_w =$ (°F)	$\overrightarrow{S_{ctw}\left(T_{d,k}, T_w, K'\right)} =$ (ksi)
70	30.00	70	30.00
76	29.98	76	29.98
133	27.97	133	27.97
192	26.13	192	26.13
254	24.46	254	24.46
320	22.95	320	22.95
389	21.62	389	21.62
463	20.46	463	20.46
543	19.47	543	19.47
631	18.66	631	18.66
732	18.00	732	18.00
867	17.42	867	17.42
1069	16.72	988	17.02
1095	14.70	1000	15.60
1123	12.76	1044	13.31
1153	10.94	1084	11.17
1185	9.24	1134	8.67
1219	7.69	1181	6.61
1255	6.30	1222	5.11
1294	5.03	1263	3.89
1337	3.90	1307	2.84
1385	2.89	1351	2.01
1400	2.62	1400	1.36


Pseudo Yield Stress for 0.95 target creep damage
Pseudo Yield Stress, ksi
Temperature, °F
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0
200
400
600
800
1000
1200
1400
base metal
data points
weldment
data points

Pseudo Yield Stress for 0.90 target creep damage.

$D_{c,k} := 0.9 \qquad K' = 0.9$

$$T_{d,k} := \frac{t_d}{D_{c,k}} = 5.932 \times 10^4 \cdot hr$$

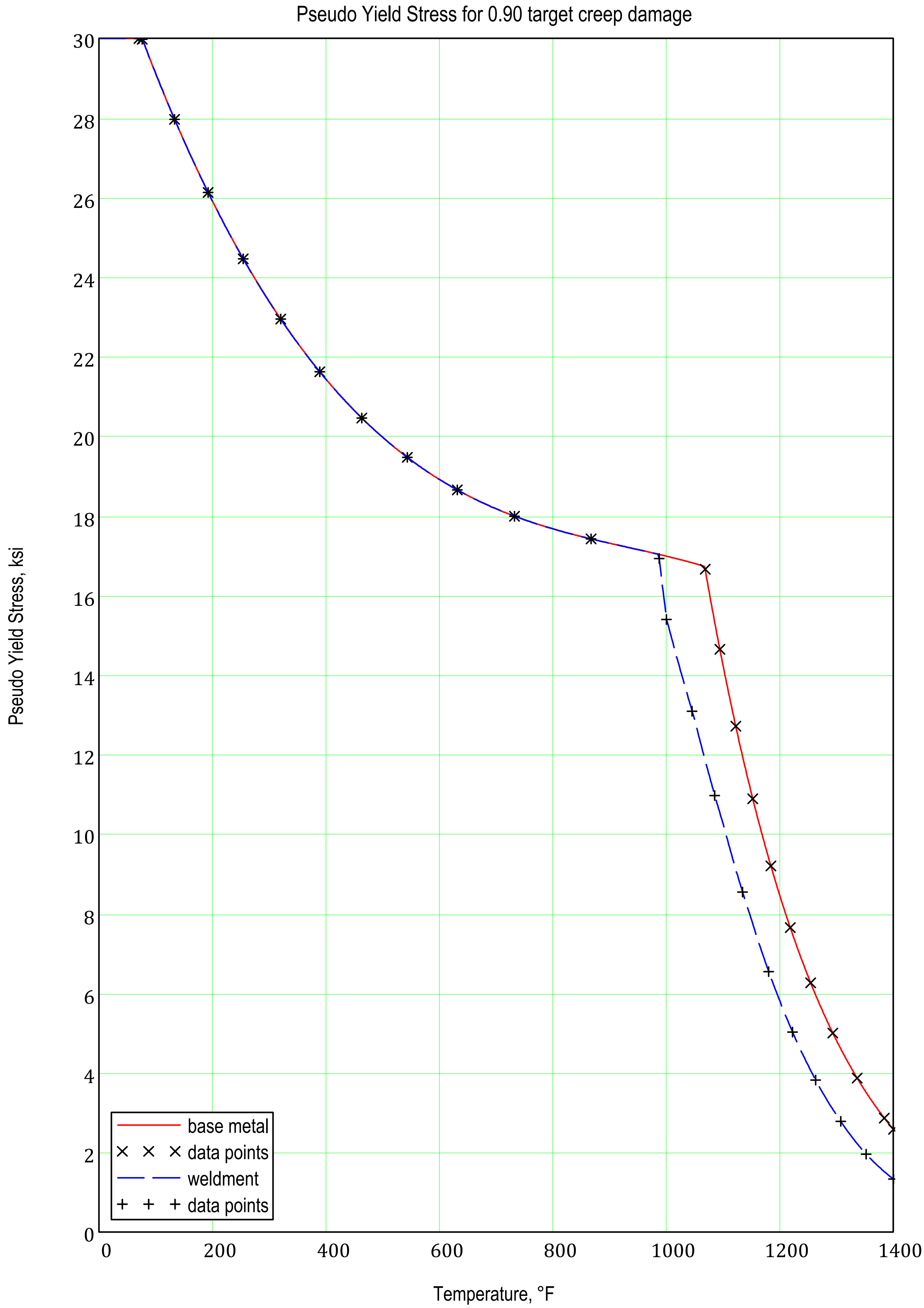
Base Metal Pseudo Yield Stress:

$T_b := T_{ct}\left(T_{d,k}, T_0, T_N, T_{inc}, K', S_{ctb}, dev\right)$

Weldment Pseudo Yield Stress:

$T_w := T_{ct}\left(T_{d,k}, T_0, T_N, T_{inc}, K', S_{ctw}, dev\right)$

$T_b =$ (°F)	$\overrightarrow{S_{ctb}\left(T_{d,k}, T_b, K'\right)} =$ (ksi)	$T_w =$ (°F)	$\overrightarrow{S_{ctw}\left(T_{d,k}, T_w, K'\right)} =$ (ksi)
70	30.00	70	30.00
76	29.98	76	29.98
133	27.97	133	27.97
192	26.13	192	26.13
254	24.46	254	24.46
320	22.95	320	22.95
389	21.62	389	21.62
463	20.46	463	20.46
543	19.47	543	19.47
631	18.66	631	18.66
732	18.00	732	18.00
867	17.42	867	17.42
1068	16.66	987	16.93
1094	14.65	1000	15.40
1122	12.72	1045	13.09
1152	10.90	1085	10.98
1184	9.20	1134	8.55
1218	7.66	1180	6.55
1254	6.27	1222	5.03
1293	5.01	1263	3.82
1336	3.87	1307	2.79
1384	2.87	1352	1.96
1400	2.59	1400	1.34


Pseudo Yield Stress for 0.90 target creep damage
Pseudo Yield Stress, ksi
Temperature, °F
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0
200
400
600
800
1000
1200
1400
base metal
data points
weldment
data points

Attachment 1 — Computer Files

Input Files

Input File Name	Description
REP-B-AB-THM.inp	REP Base Metal Only Level A & B Composite Cycle Heat Transfer Analysis
REP-W-AB-THM.inp	REP with Weldment Level A & B Composite Cycle Heat Transfer Analysis
REP-B-AB-EPP.inp	REP Base Metal Only Level A & B Composite Cycle Elastic-Perfectly Plastic Model
REP-W-AB-EPP.inp	REP with Weldment Level A & B Composite Cycle Elastic-Perfectly Plastic Model
REP-B-AB-EPP-RST.inp	REP Base Metal Only Level A & B Composite Cycle Restart File for multiple pseudo-cycles
REP-W-AB-EPP-RST.inp	REP with Weldment Level A & B Composite Cycle Restart File for multiple pseudo-cycles
REP-B-AB-EPP-SL-#.##-0.00.inp	REP Base Metal Only Level A & B Composite Cycle Strain Limit Analysis for target base metal inelastic strain #.##%
REP-W-AB-EPP-SL-#.##-#.##.inp	REP with Weldment Level A & B Composite Cycle Strain Limit Analysis for target base metal inelastic strain #.##% and weldment inelastic strain #.##%
REP-B-AB-EPP-CF-#.##.inp	REP Base Metal Only Level A & B Composite Cycle Creep-Fatigue Analysis for target creep damage #.##
REP-W-AB-EPP-CF-#.##.inp	REP with Weldment Level A & B Composite Cycle Creep-Fatigue Analysis for target creep damage #.##
REP-thermal-AC.inp	REP Level A & C Composite Cycle Heat Transfer Analysis
REP-EPP-AC.inp	REP Level A & C Composite Cycle Elastic-Perfectly Plastic Model
REP-EPP-AC-N.inp	REP Level A & C Composite Cycle Restart File for multiple pseudo-cycles
REP-EPP-AC-#.##.inp	REP Level A & C Composite Cycle Strain Limit Analysis for target inelastic strain #.##%
REP-EPP-AC-Sctb-Dck=#.##.inp	REP Level A & C Composite Cycle Creep-Fatigue Analysis for target creep damage #.##
SxT-#.##.csv	Strain Limit Pseudo Yield Stress for target inelastic strain #.##% from Appendix B
Sctb-#.##.csv	Creep-Fatigue Pseudo Yield Stress in base metal for target creep damage #.## from Appendix C
Sctw-#.##.csv	Creep-Fatigue Pseudo Yield Stress in weldment for target creep damage #.## from Appendix C

Output Files

Output File Name	Description
REP-B-AB-THM.odb	REP Base Metal Only Level A & B Composite Cycle Heat Transfer Analysis Results
REP-W-AB-THM.odb	REP with Weldment Level A & B Composite Cycle Heat Transfer Analysis Results
REP-B-AB-EPP-SL-#.##-0.00-*.odb	REP Base Metal Only Level A & B Composite Cycle Strain Limit Analysis Results for target base metal inelastic strain #.##% at pseudo cycle *
REP-W-AB-EPP-SL-#.##-#.##-*.odb	REP with Weldment Level A & B Composite Cycle Strain Limit Analysis Results for target base metal inelastic strain #.##% and weldment inelastic strain #.##% at pseudo cycle *
REP-B-AB-EPP-CF-#.##.inp	REP Base Metal Only Level A & B Composite Cycle Creep-Fatigue Analysis Results for target creep damage #.## at pseudo cycle *
REP-WB-AB-EPP-CF-#.##.inp	REP with Weldment Level A & B Composite Cycle Creep-Fatigue Analysis Results for target creep damage #.## at pseudo cycle *
REP-thermal-AC.odb	REP Level A & C Composite Cycle Heat Transfer Analysis Results
REP-EPP-AC-#.##-*.odb	REP Level A & C Composite Cycle Strain Limit Analysis Results for target inelastic strain #.##% at pseudo-cycle *
REP-EPP-AC-Sctb-Dck=#.##-*.odb	REP Level A & C Composite Cycle Creep-Fatigue Analysis Results for target creep damage #.## at pseudo-cycle *

The following computer files directory listing lists the input/output files used in the analyses.

Computer Files Directory Listing

Date	Time	Size	File Name
05/12/2014	04:02 PM	121	REP-B-AB-EPP-CF-0.90.inp
05/09/2014	11:17 PM	121	REP-B-AB-EPP-CF-1.00.inp
05/09/2014	08:54 PM	16,056	REP-B-AB-EPP-RST.inp
05/27/2014	11:19 AM	126	REP-B-AB-EPP-SL-1.00-0.00.inp
05/09/2014	11:15 PM	6,672,158	REP-B-AB-EPP.inp
05/09/2014	09:53 PM	6,775,510	REP-B-AB-THM.inp
02/07/2014	04:46 PM	83	REP-EPP-AC-0.40.inp
02/07/2014	04:46 PM	83	REP-EPP-AC-0.60.inp
02/07/2014	04:46 PM	83	REP-EPP-AC-1.00.inp
01/30/2014	04:32 PM	13,501	REP-EPP-AC-N.inp
01/31/2014	06:40 PM	90	REP-EPP-AC-Sctb-Dck=1.00.inp
01/30/2014	03:56 PM	5,784,459	REP-EPP-AC.inp
10/29/2013	03:42 PM	5,873,427	REP-thermal-AC.inp
05/15/2014	08:34 PM	121	REP-W-AB-EPP-CF-0.90.inp
05/15/2014	02:43 PM	121	REP-W-AB-EPP-CF-1.00.inp
05/09/2014	08:54 PM	16,056	REP-W-AB-EPP-RST.inp
05/27/2014	01:12 PM	126	REP-W-AB-EPP-SL-1.00-0.50.inp
05/10/2014	07:45 AM	11,177,192	REP-W-AB-EPP.inp
05/09/2014	09:53 PM	11,351,188	REP-W-AB-THM.inp
05/15/2014	02:02 PM	547	Sctb-0.90.csv
05/15/2014	02:02 PM	550	Sctb-0.95.csv
05/15/2014	02:02 PM	548	Sctb-1.00.csv
05/15/2014	02:02 PM	547	Sctw-0.90.csv
05/15/2014	02:02 PM	546	Sctw-0.95.csv
05/15/2014	02:02 PM	549	Sctw-1.00.csv
12/23/2013	08:43 AM	917	SxT-0.40.csv
05/27/2014	10:46 AM	868	SxT-0.50.csv
12/23/2013	08:52 AM	823	SxT-0.60.csv
05/27/2014	10:46 AM	748	SxT-1.00.csv
06/02/2014	06:55 PM	6,138,226,708	REP-B-AB-EPP-CF-0.90-3.odb
06/02/2014	05:13 PM	5,055,790,768	REP-B-AB-EPP-SL-1.00-0.00-2.odb
05/09/2014	10:37 PM	81,595,600	REP-B-AB-THM.odb
06/03/2014	02:00 PM	9,357,198,168	REP-W-AB-EPP-CF-0.95-3.odb
06/02/2014	05:13 PM	7,705,960,772	REP-W-AB-EPP-SL-1.00-0.50-3.odb
05/09/2014	10:49 PM	121,749,696	REP-W-AB-THM.odb

Calculation Verification

Verifier: n/a

Verification Method	Verification Scope
☐ Line-by-Line Review	Entire calculation.
☐ Alternate Calculations	

Line-by-Line Review Checklist

	Verification Attribute	Yes	N/A	No(1)
1	Coversheet complete and page count correct?			
2	Revision is alpha if there are open items?			
3	Calculation headers complete?			
4	Attachments are listed and included?			
5	Calculation objective clearly stated?			
6	Scope (boundaries) of calculation clearly stated?			
7	Open items clearly stated?			
8	Design criteria clear and complete?			
9	Input drawings and specifications listed in references with revision or edition number?			
10	Applicable codes, standards listed in references with revision or edition number?			
11	Input parameters are in accordance with references, reasonable or conservative?			
12	Geometry, sizes, properties are in accordance with references or conservative?			
13	Input loads and load combinations in accordance with references or conservatives?			
14	Formulas and software used appropriate and within their range of applicability?			
15	References include the computer program verification document?			
16	Software version is consistent with V&V, and valid for the computer used?			
17	Results clearly stated, and reasonable?			

Notes:
(1) If “No” is selected then an explanation is provided in the following verifier comments.

Verifier Comments (If Necessary)

#	Location	Comment

Record of Revisions

Revision	Date	Description of Changes
0	10/30/2013	Initial issue.
1	1/8/2014	Updated section 2 Summary. Added Strain Limit Pseudo Yield Stress to Section 3.2. Split pressure and mechanical load time history amplitudes into step-based amplitudes in Section 3.6.3. Added methodology for evaluating multiple cycles to Section 4.1. Added Strain Limit Methodology to new Section 4.1.1 Added Strain Limit Evaluation to new Section 4.3.2 Fixed time value typos in Table 3.6.3-1. Added new Table 3.6.3-2 to determine total time duration of high temperature service. Added step end time and maximum temperature change to Table 4.2-1 and 4.2-20 Added state descriptions to Figure 4.3.1-1 and 4.3.1-2. Added new Figures 4.3.2-1 through 4.3.2-4 Added new Appendix B Pseudo Yield Stress for Strain Limit Analysis
2	6/5/2014	Complete revision to include two models, one without a weldment including only base metal and one with a weldment explicitly modeled. Added Creep-Fatigue evaluation. Updated for latest Code Cases in the Design Specification [Ref. 1].
3	6/23/2014	Updated fatigue evaluation. Removed references to deliverable items.