OAK RIDGE
National Laboratory

DOCUMENT NUMBER - REV	DISCIPLINE	TYPE
S03020000-DAC10000 - 0	**Design Analysis and Calculation**	**Document**
LEGACY DOCUMENT NUMBER	PUBLISHED ON / REVISION / STATUS	
	06/05/2026 / 0 / Published	

Target Systems Analysis Material Model Definitions DAC

Owner:

Tipton Jr, Joseph (00977600)

Workflow Role	*Name*	*Date*	*Status*
Approver	Tipton Jr, Joseph (00977600)	05/20/2026	Approved
Approver	Lee, Yong Joong (03022410)	05/31/2026	Approved
Approver	Jacques, Aaron (03084903)	06/01/2026	Approved
Approver	Anderson, David (00952845)	06/01/2026	Approved

Change Log

Revision	State	Date	Change Description
0	Published	06/05/2026	

S03020000-DAC10000

Target Systems Analysis: Material Model Definitions

Joseph B. Tipton, Jr.
Justin Mach

May 5, 2026

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

S03020000-DAC10000

Second Target Station

TARGET SYSTEMS ANALYSIS: MATERIAL MODEL DEFINITIONS

Joseph B. Tipton, Jr.
Justin Mach

May 5, 2026

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
ASME/BPVC	Boiler and Pressure Vessel Code
ASTM	American Society for Testing and Materials
CTE	coefficient of thermal expansion
DAC	Design Analysis Calculation
DBTT	ductile-brittle transition temperature
dpa	displacements per atom
ESS	European Spallation Source
FDR	Final Design Review
FEA	finite element analysis
FFOS	fatigue factor of safety
FSRF	Fatigue Strength Reduction Factor
HCF	high cycle fatigue
HIP	hot isostatic pressing
J-C	Johnson-Cook
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
LWR	light water reactor
MLE	maximum likelihood estimation
MPH	Material Properties Handbook
MSTD	Materials Science and Technology Division
MTS	Mechanical Threshold Stress
NUREG	U.S. Nuclear Regulatory Commission
OFHC	Oxygen-free high thermal conductivity
ORNL	Oak Ridge National Laboratory
PH	precipitation hardened
PI	prediction interval
RBF	rotating bending fatigue
SA	solution annealed
SNS	Spallation Neutron Source
STS	Second Target Station
SWT	Smith-Watson-Topper
TS	Target Systems
UTS	Ultimate Tensile Strength
VHCF	very high cycle fatigue
VHP	Vacuum Hot Press
YS	Yield Strength
Z-A	Zerilli-Armstrong

ABSTRACT

The Second Target Station (STS) project at Oak Ridge National Laboratory (ORNL) aims to produce the world's brightest pulsed neutron source. Accordingly, the Target Systems (TS) will be a unique design, and engineers must rely heavily upon detailed analyses and simulations to inform design decisions.

This report serves to document and justify the material models used in thermostructural analyses for the target assembly. Models are presented for tungsten, tantalum, copper, solution annealed Inconel 718, and stainless steel 316L. Effects of spallation-relevent irradiation on these materials is included where available.

The resulting material input decks are included for engineering analysis software including Abaqus and Sierra Multiphysics.

1. INTRODUCTION

The STS project at ORNL aims to produce the world's brightest pulsed neutron source. Accordingly, the TS will be a unique design, and engineers must rely heavily upon detailed analyses and simulations to inform design decisions.

Adding further complexity, the nature of the spallation environment requires both specialized materials and consideration of material degradation/transmutation from irradiation. The current target design utilizes the following engineering materials:

- Tungsten
- Tantalum
- Copper
- Inconel 718 (Solution Annealed)
- Stainless Steel 316L

Engineering analysts in the TS group use a variety of software packages to simulate the thermostructural performance of target components. This currently includes:

- ANSYS
- Abaqus
- FE-SAFE
- Sierra Multiphysics
- STAR-CCM++

This document is intended to document and justify the thermostructural material models used in TS Design Analysis Calculation (DAC)s. The specific material models input decks are listed in the Appendices.

2. TUNGSTEN

2.1 MATERIAL BEHAVIOR

The target material selection is governed by the neutronic performance (spallation of neutrons from an incident proton beam) which necessitates tungsten. Pure, unalloyed tungsten cannot be used by itself as it experiences unacceptable corrosion when in contact with water coolant [91]. Tungsten alloys have been pursued historically, however, ". . . there are only few elements (Ti, V, Nb, Mo, Ta, Re), which are soluble in sufficient concentrations in the tungsten lattice, and unfortunately, all of them – with the exception of rhenium – either increase the DBTT or reduce toughness" [82]. Furthermore, alloying with rhenium is counterproductive under irradiation conditions. Rhenium is indeed a transmutation product of irradiated tungsten which contributes to loss of thermal conductivity and embrittlement [45] [44]. Compared to tungsten, tantalum has superior mechanical properties, however, it suffers from a lower neutron yield (approx. 15%) along with significantly higher decay heat [75]. The current state-of-the-art for solid targets seeks to surround pure, unalloyed tungsten with a thin, tantalum layer for corrosion protection.

Tungsten is a brittle metal with a high density and melting point. Applications of tungsten include high-temperature applications or ballast. The manufacturing process typically has at least one dimension with a high amount of deformation (65%) to improve the strength of the product. Smaller stock sizes (sheet, foil, wire, etc.) that can be heavily deformed have much higher properties than those of dimensionally large products. Accordingly, care must be exercised when comparing Tungsten properties from vendors, other spallation targets, and other processing routes.

2.1.1 Unirradiated Condition

2.1.1.1 Ultimate Tensile Strength

Tungsten tensile strength varies widely with processing route. Table 2 summarizes the best available data from commercial vendors, third party testing, and published literature. This is amenable to design explorations that consider different tungsten geometries. Actual strengths are expected to be stochastic due to the brittle nature of tungsten at spallation temperatures. Sensitivity to lower tungsten fracture strength should be considered in designs.

Table 2. Tungsten tensile strength limits by process type

Description	Direction	UTS [MPa]
60 mm plate	In Plane (rolling)	669[a] @150°C
	Out of Plane (normal)	233[a] @150°C
48 mm forging	In Plane	538
	Out of Plane	315
58 mm forging	In Plane	560[b]
	Out of Plane	174[b]
Rod < 80 mm	Radial	804
	Circumferential	579
10-20 mm plate	In Plane	998[a]
	Out of Plane	677[c]
1 mm sheet	N/A	1200

[a] 3-pt bend test serves as proxy for tensile
[b] Used ratio for tensile/Bending strength from 48mm IMR data (50% reduction)
[c] Ratio of Longitudinal to Transverse for RTP/RLP from Haibany material of the same provenance

2.1.1.2 Fatigue Strength

There are 3 potential sources of fatigue data for unirradiated tungsten below the ductile-brittle transition temperature (DBTT). Schmidt and Ogden [88] reported fatigue data for transverse grain samples of 0.02 inch (0.5 mm) rolled tungsten sheet. The testing was completely reversed sheet-bending at room temperature. The data is summarized in Figure 1.

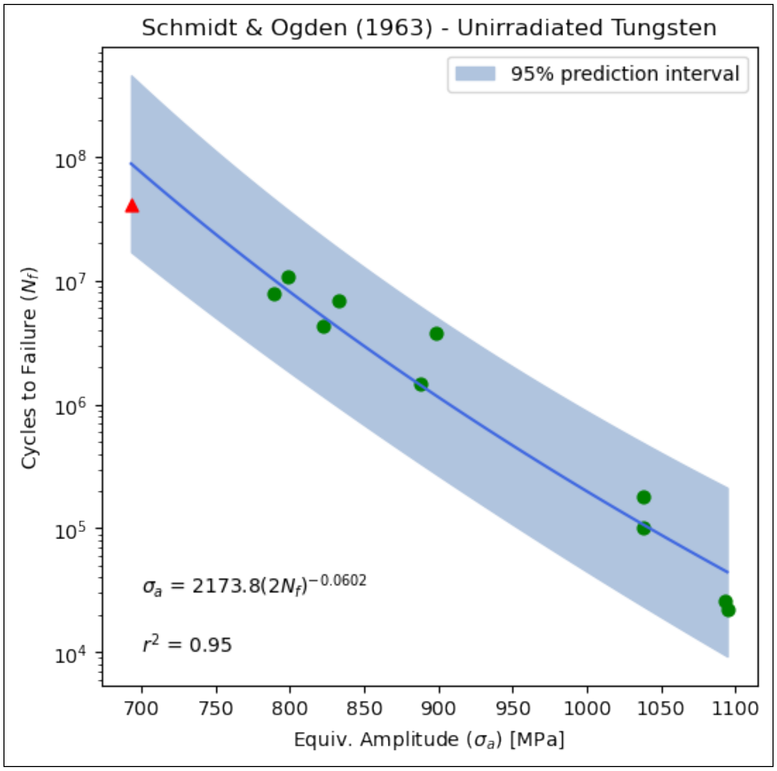


Figure 1. Bending fatigue of rolled tungsten sheet from Schmidt and Ogden [88]. The Basquin model fit parameters are included along with a 95% prediction interval assuming normal statistics. The triangle data are run-outs.

European Spallation Source (ESS) pursued investigations of tungsten fatigue for their target design. Habainy *et al*. [40] [42] first tested commercial samples from Beijing Tian-Long Tungsten & Molybdenum Co. at different temperatures, and only room temperature results are presented here. Samples from rolled 20-mm sheet were tested in the longitudinal (L) direction in both unpolished (U) and polished (P) conditions. Samples from forged 90-mm plate were also tested in the unpolished (U) and (P) polished conditions. Data points were first inferred from a digitized image. Due to the brittle nature of the tungsten, the fatigue tests were performed only in the tensile regime. Figure 2 summarizes the data after using the Goodman linear relationship to adjust to a fully-reversing ($R = -1$) stress amplitude. The data was scaled using the reported mean UTS for each sample type at room temperature.

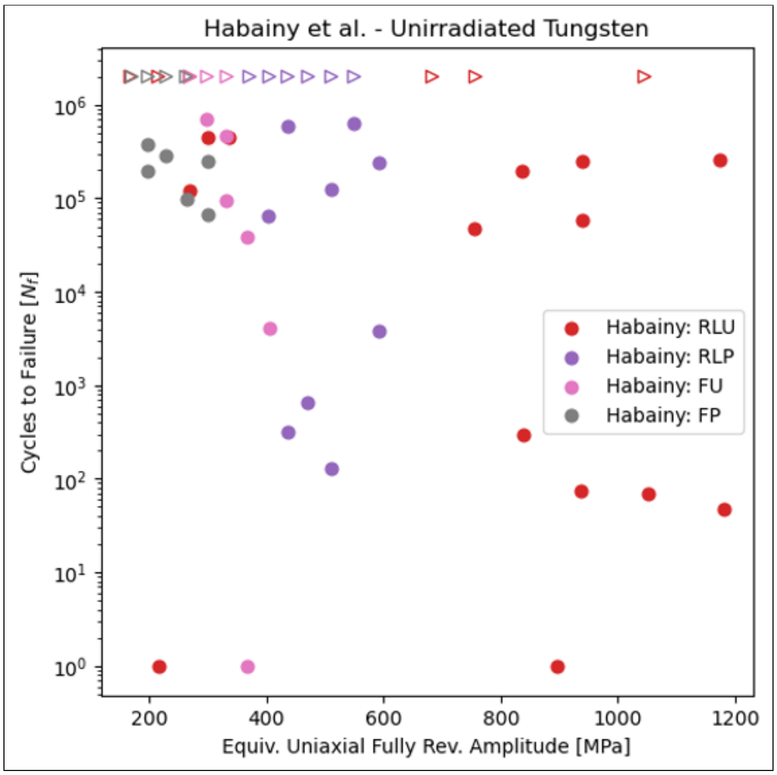


Figure 2. Tensile fatigue tests of tungsten from Habainy *et al.* [40]. The samples represent rolled vs. forged (R/F), longitudinal (L), and unpollished vs. pollished (U/P) conditions. The triangle data are run-outs.

Habainy *et al*. later published fatigue tests of 20-mm tungsten plate from Plansee in both the sintered and HIPed (SH) and rolled and annealed (RA) forms [43] [42]. The samples were electropolished and tested at room temperature. The RA samples were tested in the direction of rolling. Due to the brittle nature of the tungsten, the fatigue tests were performed only in the tensile regime. Figure 3 summarizes the data after using the Goodman linear relationship to adjust to a fully-reversing ($R = -1$) stress amplitude. The data was scaled using the reported static tensile strengths of 560 MPa (SH) and 998 MPa (RA).

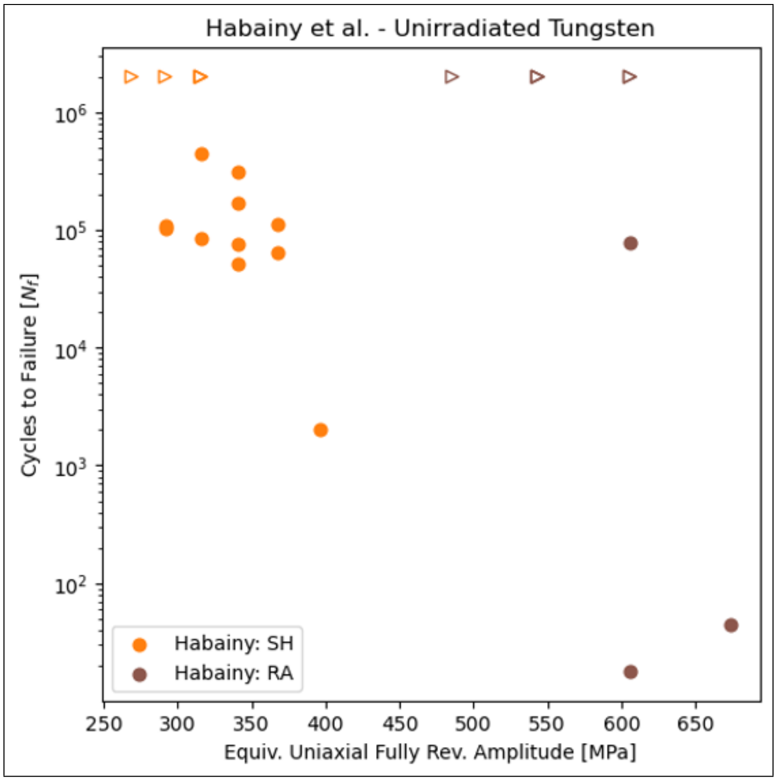


Figure 3. Tensile fatigue tests of sintered and HIPed (SH) and rolled and annealed (RA) tungsten from Habainy *et al*. [43]. The triangle data are run-outs.

In 2021, the Target Systems group at STS contracted with IMR Test Labs to perform RBF tests of tungsten [48]. Samples were cut from 48 mm forged plate from Plansee. The samples were in-plane to the forging, finished with 600 grit sanding, and tested at room temperature. Figure 4 summarizes the data after using a 0.7 knockdown factor to account for the reduced tensile load area of rotating bending tests [46, pg. 13].

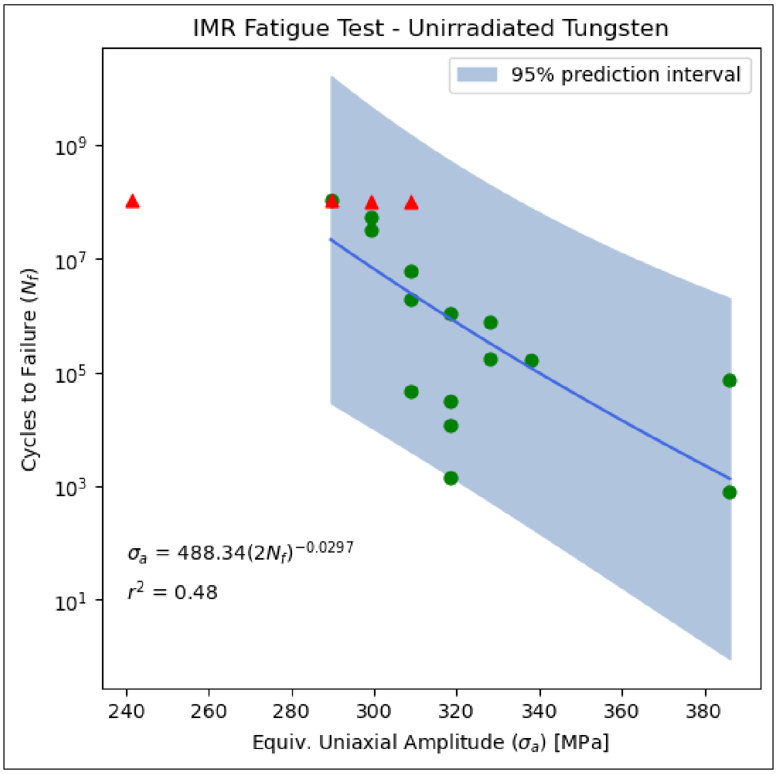


Figure 4. RBF fatigue of thick forged tungsten plate [48]. The Basquin model fit parameters are included along with a 95% prediction interval assuming normal statistics. The triangle data are run-outs.

The available data sets are plotted together and summarized in Figure 5 in the more traditional Wöhler curve format. There is obviously too much scatter to obtain a useful model. In order to arrive at a conservative and applicable S-N curve, the following data sets are excluded:

- Schmidt & Ogden - The Schmidt & Ogden data is for very thin sheet (0.5 mm). It is obvious that this does not represent the potential target block processing routes and should be (conservatively) omitted.
- Unpolished (U) samples - It appears that polished samples have worse fatigue performance than unpolished samples. This may seem counterintuitive as polishing would be expected to remove crack initiation sites on the surface. What appears to be more dominant, however, is that polishing removes compressive residual stresses on the sample surfaces due to machining. We proceed (conservatively) by removing the unpolished sample data.
- Forged plate data (F) from Habainy - Habainy *et al.* reported that the FP specimens had unsatisfactory polishing resulting in a rough surface and also density variations. Furthermore, some of the FP test pieces fractured in the shoulder region. Fracture surface observations of a higher temperature test specimen (280°C) revealed loose grains indicating problems with sintering of the material before processing. Taken together, there is a strong argument to omit the FP data as not representative of the material quality and preparation quality that would be expected in a spallation target.
- Rolled plate data (R) from Habainy - Rolled plate appears to exhibit superior fatigue performance, albeit with high scatter. Lower fatigue performance (but with less scatter) is seen with sintered and HIPed samples along with thick forged samples. Since the conceptual design of the STS target calls for a large block, we make the conservative decision to omit rolled plate (RLP). Any future design choice to utilize rolled plates could reconsider the fatigue dataset to recapture potential fatigue margin.

Figure 6 shows the remaining data sets that comprise the fatigue model baseline. It is rather impressive how well the Habainy *et al.* RA data (with Goodman correction to $R = -1$) matches IMR thick forge testing (with knockdown for RBF). For regression analysis purposes, the Habainy *et al.* RA runouts are excluded as they are too short-lived to inform STS target design. In addition, one IMR sample (20RBF) is omitted as it was an exploratory test at 50 ksi (241 MPa), ended in a runout, and is found to have a high leverage on the statistics.

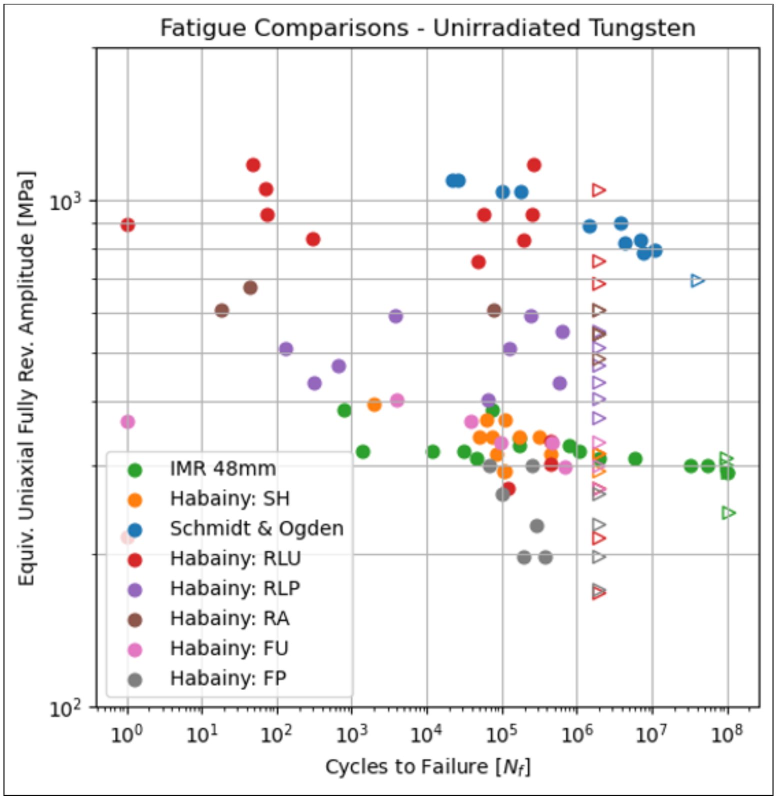


Figure 5. Summary of data used for tungsten fatigue analysis. The encircled data points are excluded.

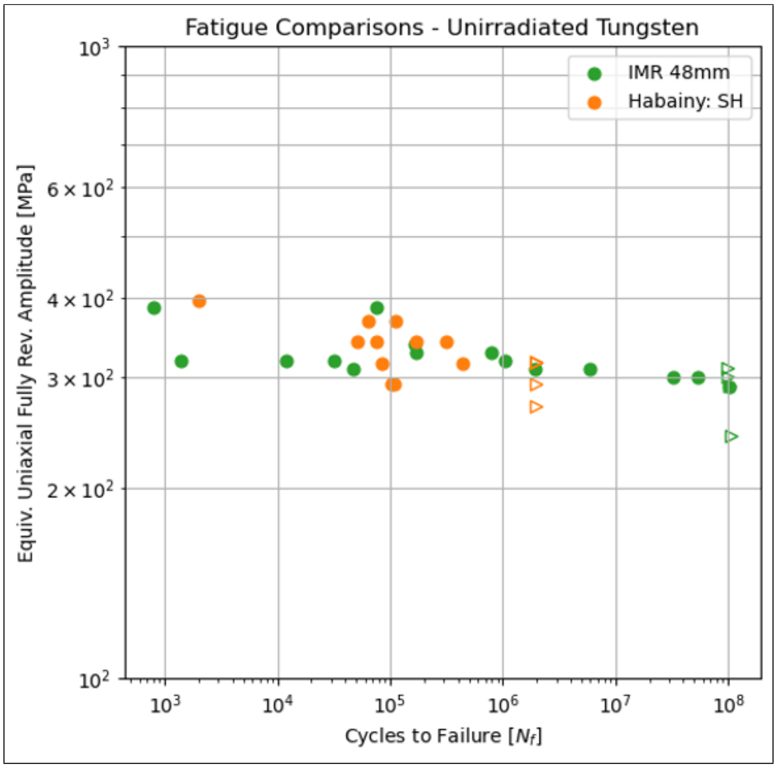
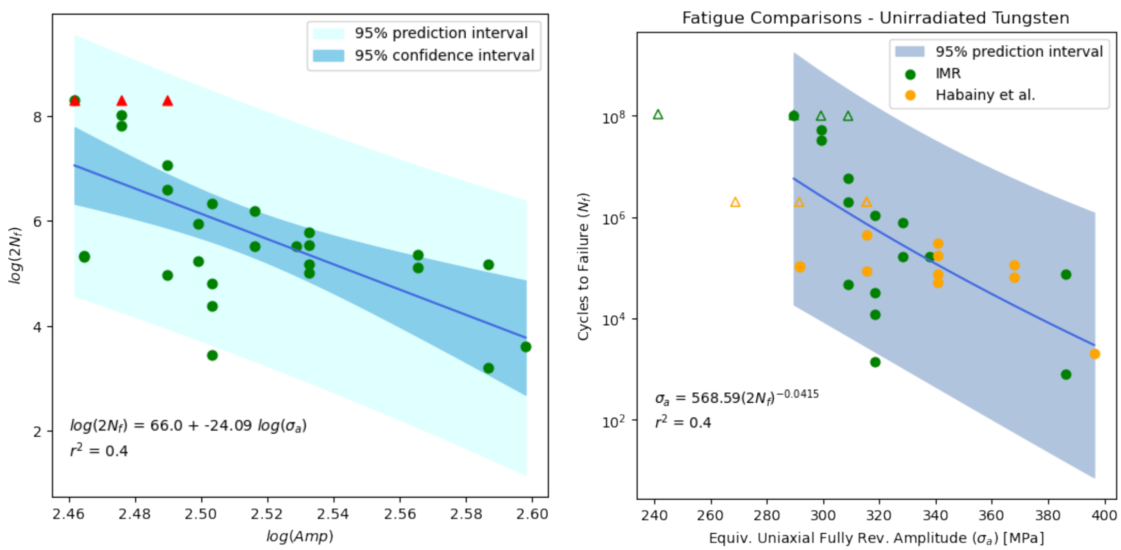


Figure 6. Summary of data used for tungsten fatigue analysis. The encircled data points are excluded.

Figure 7 shows the Basquin model fit of the combined fatigue data. A linear regression analysis is performed on a log-log transformation of the data where the testing amplitude is the independent variable. The data is then replotted without the transformation.



(a) Linear regression analysis.

(b) Basquin model and 95% PI overlaid with complete ESS and IMR data sets.

Figure 7. Basquin model fit for unirradiated tungsten fatigue.

Figure 8 re-plots the fatigue curve in the more traditional S-N format. The Basquin model is extrapolated to the 10 year life requirement for tungsten blocks. The 10 year operational life consists of 135 million beam pulse events on an individual tungsten block (assuming 5,000 operational hours per year). Accordingly, the equivalent uniaxial fully reversing fatigue strength at 135 million cycles to failure is 254 MPa.

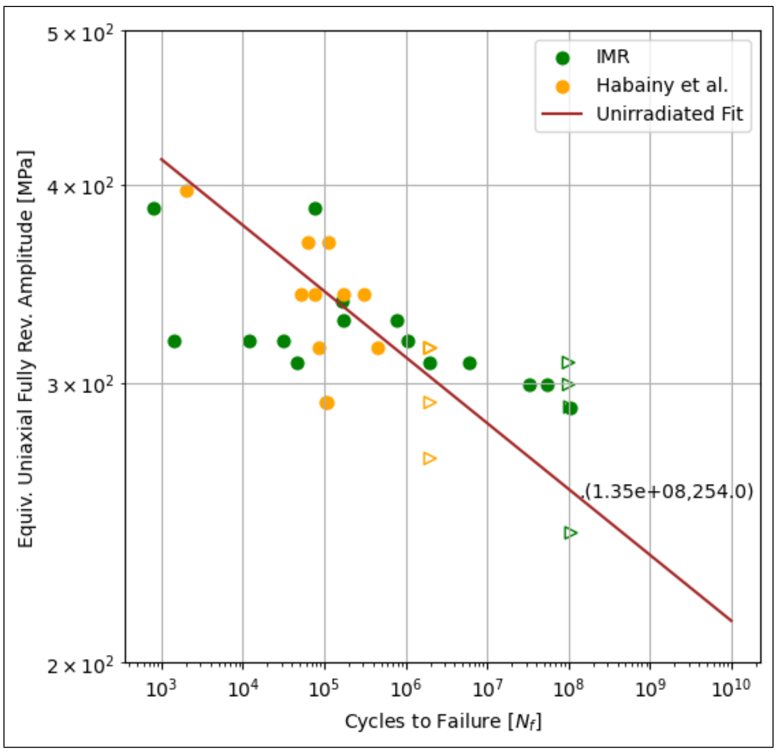
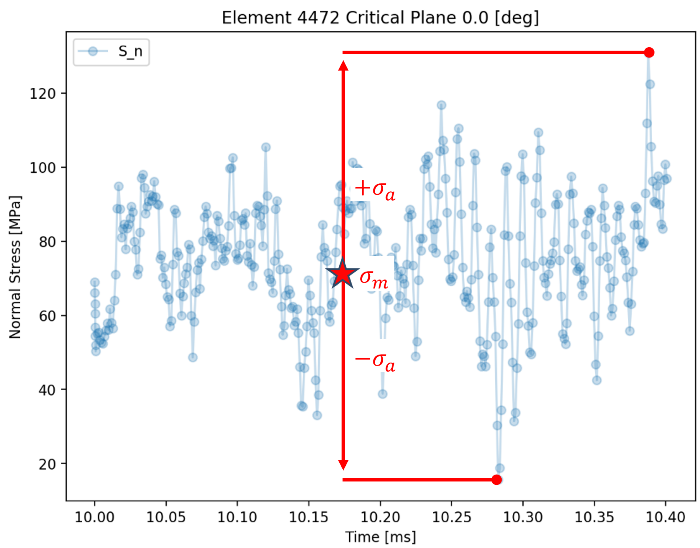


Figure 8. S-N curve for unirradiated tungsten.

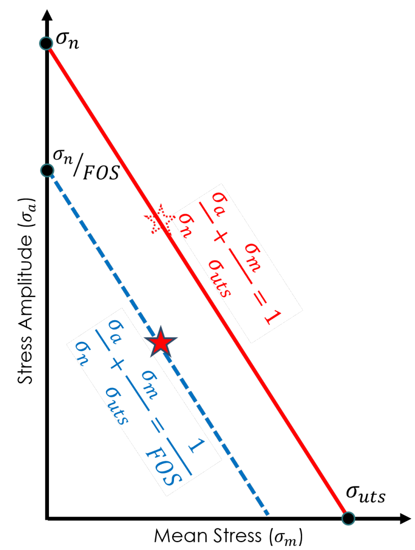
2.1.1.3 Fatigue Model

Tungsten will be well below the DBTT during operation in both unirradiated and irradiated conditions and is then assumed to follow brittle failure theory. A fatigue calculation should then calculate the largest normal stress amplitude. The stress plane in which that occurs, however, is unknown *a priori*. The stress plane orientation must be determined as part of the post-processing analysis (i.e. critical plane analysis).

The conceptual definition of the fatigue factor of safety (FFOS) is shown in Figure 9. The dynamic stress response for a finite-element in a stress plane over time is shown with the mean stress (σ_m) and stress amplitude (σ_a) calculated from the peak stresses. The Goodman diagram assumes a linear relationship between the UTS and the fully reversing stress amplitude (σ_n) to account for mean stress effects. The FFOS is then defined from the ratio of the equivalent fully reversing stress amplitude with design limit.



(a) Example of mean stress and stress amplitude calculation from a dynamic stress response.



(b) Modified Goodman diagram showing mean stress and stress amplitude use in the FFOS calculation.

Figure 9. Fatigue Factor of Safety (FOS) concept definition.

Figure 10 summarizes the 10 year fatigue life design envelope for unirradiated tungsten in the form of the modified Goodman diagram. The compressive strength regime is not an active constraint in practice and is ignored here. Instead, the Goodman equation is used to calculate the FFOS for a given fatigue analysis.

When commercial *fe-safe* software is used for the fatigue analysis, the Normal Stress algorithm is chosen with the Goodman mean stress correction. The Basquin model is input, and all plastic effects are disabled through parameter inputs as shown in Table 3. *fe-safe* will then perform a critical plane analysis using the normal stress components of the stress tensor and using a rainflow cycle counting algorithm. The FFOS will also be calculated in a more formal manner as follows [36, pp. 17–1]:

> The factor of strength (FOS) is the factor which, when applied to either the loading, or to the elastic stresses in the finite element model, will produce the required target life at the node. The FOS is calculated at each node, and the results written as an additional value to the output file. The FOS values can be plotted as contour plots.

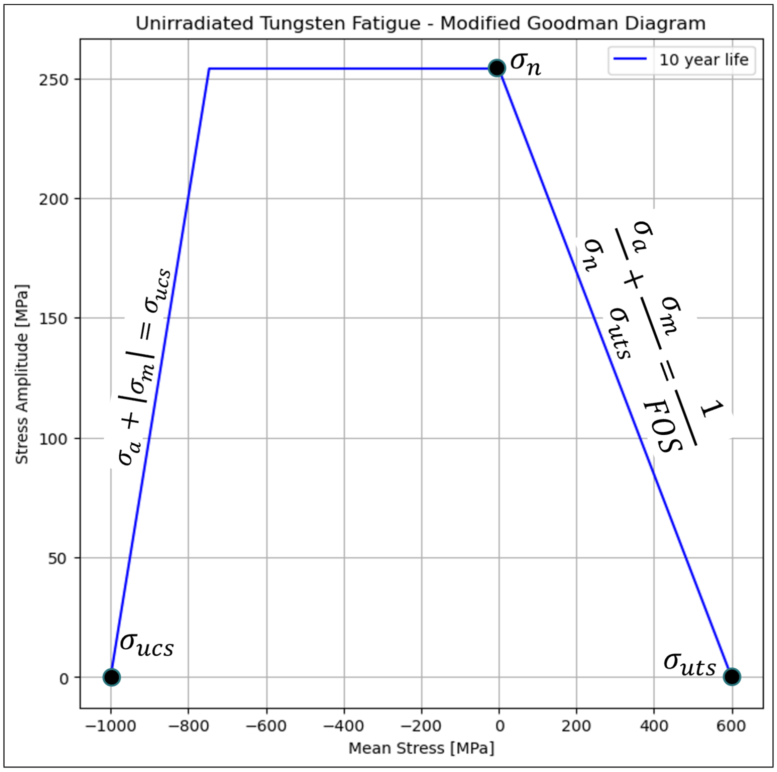


Figure 10. Modified Goodman diagram for unirradiated condition at 10 year design life of 135M cycles.

Table 3. Tungsten fatigue model settings in *fe-safe* software.

Parameter Name	Value	Comment
fatigue strength coefficient (sf’)	σ'_f	see Sec. 2.1.2.2
fatigue strength exponent (b)	-0.0415080	Basquin fit
fatigue ductility coefficient (Ef’)	0	Plasticity disabled
fatigue ductility exponent (c)	0	Plasticity disabled
K’	1E20	Cyclic plasticity disabled
n’	1	Cyclic plasticity disabled
CAEL	1E11	Constant amplitude endurance limit disabled
Young’s modulus	398,000 MPa	
Poisson’s ratio	0.28	
ultimate tensile strength	σ'_f	see Sec. 2.1.2.2
algorithm	NormalStress:-Goodman	Brittle failure mode

2.1.1.4 Density

Knowledge of tungsten density comes from testing Plansee 48 mm and 58 mm plate forgings. Testing was performed by Plansee and independently by IMR, both using the Archimedes method. The results are summarized in Figure 11. The 95% PI is calculated using normal statistics. The result is an average density of 19,197 with a 95% PI of ± 164 kg/m3. The expected range of values for analysis is thus 19,033 to 19,361 kg/m3.

It should be noted that lower density material is usually indicative of increased porosity and correlates with weaker strength. These effects are not captured in this report.

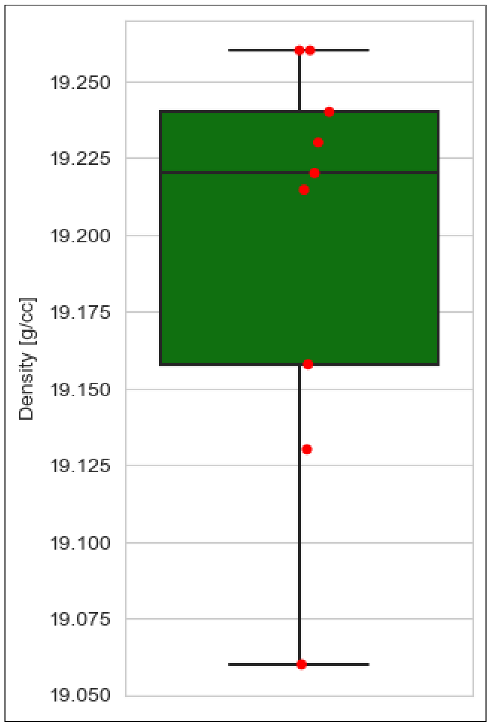


Figure 11. Graphical summary of density measurements for unirradiated tungsten. The data are summarized using a boxplot with individual measurements overlaid in red.

2.1.1.5 Elastic Modulus

The ITER MPH provides a polynomial function for tungsten modulus of elasticity as a function of temperature [30]. Equation 1 is reported to be valid from $0 < T(°C) < 400$ with a 0.9753 correlation coefficient. The elastic modulus is a weak function of temperature over the range of interest. For example, there is only a 5% variation between 20°C (398 GPa) and 200°C (396 GPa).

$$E(GPa) = 397.903 - 2.3066 \times 10^{-3}\, T - 2.7162 \times 10^{-5}\, T^2 \text{ ; where } T(°C) \tag{1}$$

2.1.1.6 Poisson's Ratio

The ITER MPH provides a polynomial function for the Poisson's Ratio of tungsten as a function of temperature [9]. Equation 2 is reported to be valid from $20 < T(^{\circ}C) < 2,000$ with a 0.9796 correlation coefficient. Poisson's Ratio is a weak function of temperature over the range of interest (e.g. a < 2% variation occurs over 500 degrees temperature change).

$$\nu = 0.279 + 1.0893 \times 10^{-5}\ T\ ;\ \text{where}\ T(^{\circ}C) \tag{2}$$

2.1.1.7 Thermal Conductivity

The ITER MPH provides a polynomial function for the thermal conductivity of tungsten as a function of temperature [31]. Equation 3 is reported to be valid from $0 < T(°C) < 3,500$ with a 0.9599 correlation coefficient.

$$K(\text{W/m-K}) = 174.9274 - 0.1067\,T + 5.0067 \times 10^{-5}\,T^2 - 7.8349 \times 10^{-9}\,T^3 \text{ ; where } T(°C) \quad (3)$$

2.1.1.8 Coefficient of Thermal Expansion

The ITER MPH provides tabulated data for the instantaneous CTE of tungsten as a function of temperature [8]. A linear regression of the data over the temperature range of interest is given in Figure 12. The ITER MPH includes a statement from the American Society of Mechanical Engineers (ASME) Code that there is an associated ± 10% uncertainty.

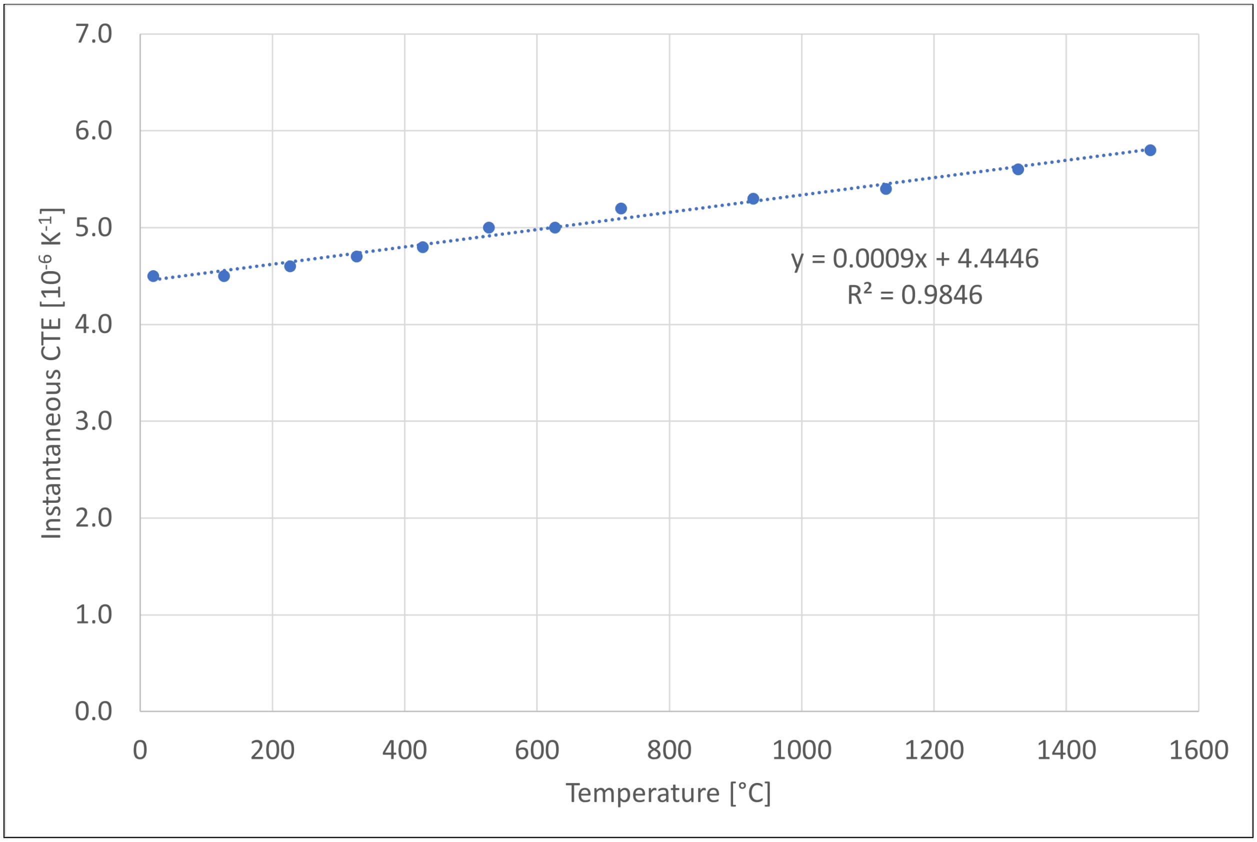


Figure 12. Linear regression of the instantaneous CTE for pure tungsten as a function of temperature. Data sourced from the ITER MPH [8].

2.1.1.9 Specific Heat

The ITER MPH provides a polynomial function for the specific heat of tungsten as a function of temperature [29]. Equation 4 is reported to be valid from $0 < T(^{\circ}C) < 3,000$ with a 0.8224 correlation coefficient.

$$C_p(\text{J/kg-K}) = 128.308 + 3.2797 \times 10^{-2}\, T - 3.4097 \times 10^{-6}\, T^2 \text{ ; where } T(^{\circ}C) \tag{4}$$

2.1.2 Irradiated Condition

2.1.2.1 Ultimate Tensile Strength

The best knowledge of UTS comes from experiments at the ESS by Habainy *et al.* [44]. Pure tungsten samples were irradiated in a spallation-relevant environment followed by 3-point bend tests. The tungsten samples were cut from high-purity, cross-rolled, 10-mm plate. Figure 13 summarizes the results for irradiation at room temperature. The bend strength is used as a substitute for UTS and the 3 data points for irradiated strength are assumed to follow a normal distribution. The 95% prediction interval is calculated using Student's t-statistic. The result is an average irradiated strength of 303 [MPa] with a 95% PI of ± 103 [MPa].

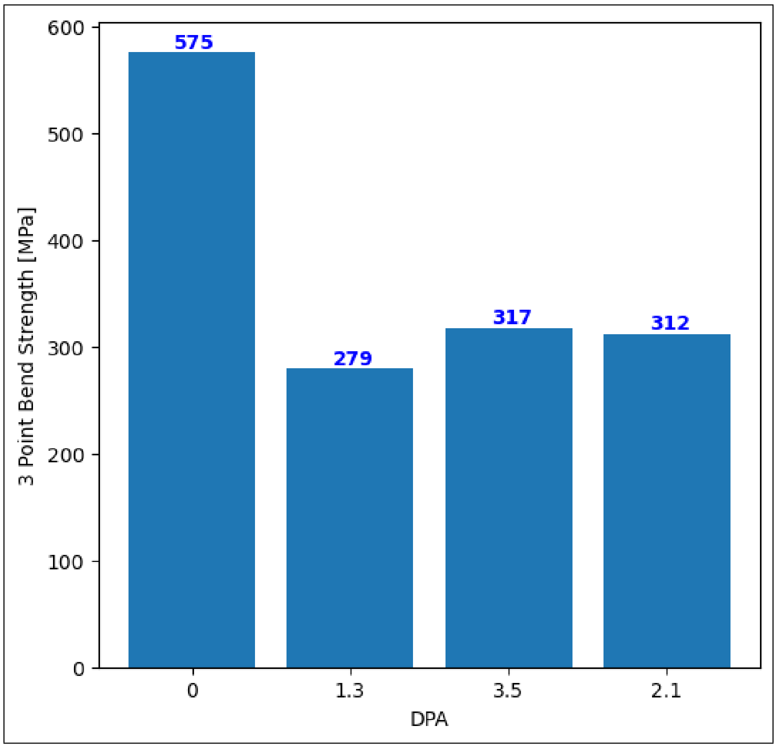


Figure 13. Strength testing of cross-rolled tungsten plate as a function of dpa from room-temperature irradiated in a spallation environment [44].

Given the scarcity of irradiated tungsten data, we take the average irradiated strength and deduce a 0.53 knockdown factor for UTS. This factor is then applied to the unirradiated strength data already presented in Table 2. For further conservatism, the weakest direction strength (i.e. out-of-plane) is taken. Figure 14 then summarizes the irradiated UTS of tungsten across a continuum of plate thicknesses that are available for design solutions.

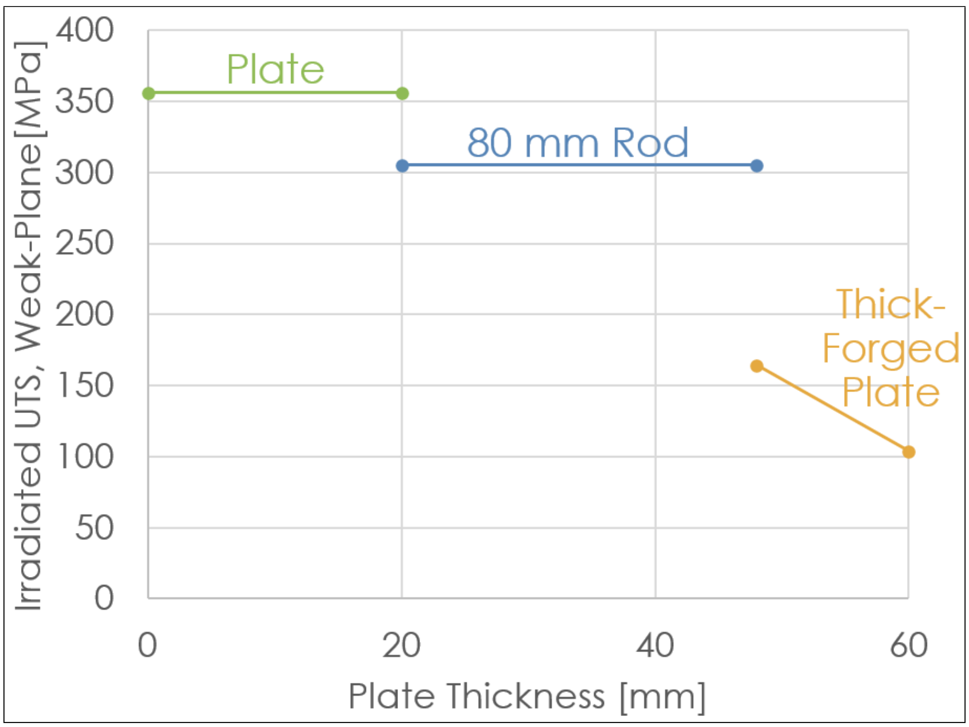


Figure 14. Tungsten irradiated UTS limits, using weakest plane strengths, as a function of plate thicknesses.

2.1.2.2 Fatigue Strength

The present analysis methodology treats the tungsten target as fully irradiated for the entirety of the analysis. A knockdown factor is assumed to account for the effects of irradiation on the fatigue of tungsten. The fatigue strength coefficient (σ'_f = 569 MPa) of the Basquin model fit is the extrapolated strength at one fatigue cycle which is conceptually equal to the static fracture stress of the material. Indeed, this value is within 1% of the reported bend strength of unirradiated tungsten from ESS (see Figure 13). An irradiation knockdown factor (K_{irr}) is thus used to scale the Basquin model such that the effective fatigue strength coefficient is 300 MPa. Figure 15 shows the resulting shifted fatigue curve. This methodology implicitly assumes the slope and scatter (i.e. 95% PI) of the Basquin model does not change. The lower 95% PI is algebraically modeled with a separate Basquin model fit and uses an additional knockdown factor (K_{95}). For uncertainty quantification, the lower bound of K_{95} is thus 0.78 and the upper bound is 1.2 (roughly the upper 95% PI).

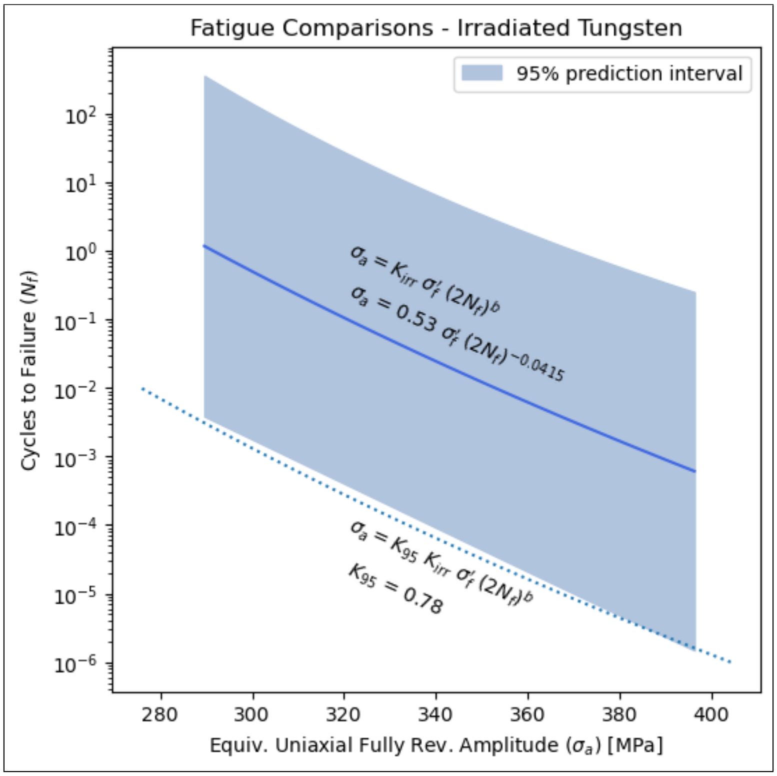


Figure 15. Basquin model fit for irradiated tungsten fatigue using an irradiation knockdown factor. The dotted line represents a separate Basquin model fit to algebraically approximate the lower 95% PI using an additional knockdown factor (K_{95}).

Figure 16 summarizes the best engineering guess for fatigue analysis of the tungsten block stress response in the more traditional S-N format. The figure includes the original Basquin model fit with the unirradiated fatigue data. Also shown is the knocked-down curve for irradiated fatigue with the corresponding lower 95% PI. Two points are indicated on the figure corresponding to a 10 year life requirement for tungsten blocks. The 10 year operational life consists of 135 million beam pulse events on an individual tungsten block (assuming 5,000 operational hours per year). Accordingly, the fatigue strength at 135 million cycles to failure is 134 MPa with a lower 95% PI of 105 MPa.

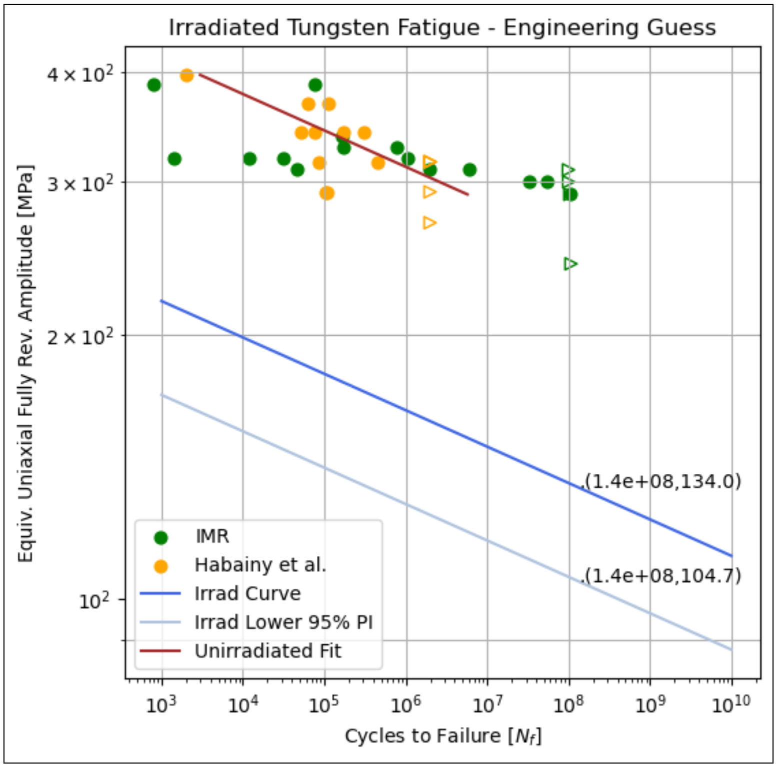


Figure 16. S-N curve for irradiated tungsten using baseline fatigue data.

2.1.2.3 Fatigue Model

Tungsten will remain embrittled during irradiated conditions. The fatigue model thus continues to follow the method presented in Section 2.1.1.3 which is a brittle failure theory with a modified Goodman diagram. The UTS depends on the form of tungsten and uses the worst strength direction given in Table 2. The fatigue strength (σ_n) follows the fatigue curve for irradiated tungsten presented above and is summarized in Equation 5:

$$\sigma_n = K_{95}\ K_{irr}\ \sigma'_f\ (2N_f)^b \tag{5}$$

where the constants are listed in Equation 6 as:

$$\begin{gathered} K_{95} = 1.0 \text{ or } 0.78 \\ K_{irr} = 0.53 \\ \sigma'_f = \sigma_{UTS} \\ b = -0.041508\ . \end{gathered} \tag{6}$$

2.1.2.4 Density

Density is assumed to be unaffected by irradiation. This is supported by experiments finding negligible radiation-induced swelling for tungsten at accelerator relevant conditions. In a spallation environment test, Maloy and Pitcher [66] reported, "Tungsten Removal from Cladding . . . Some discoloration observed but no change in diameter seen from measurements accurate to +/- 5 microns." Similarly, Jones *et al*. [33] reported that "W is resistant to void swelling (as bcc). . . Peak swelling is 1.5% at 800-1000°C." Unfortunately, this report is listed as . . . "not publicly available until copyright issues on all materials data resolved."

2.1.2.5 Elastic Modulus

The current consensus is to assume the elastic modulus of tungsten does not change with irradiation. Earlier in the project, irradiation was assumed to account for a 20% increase in the room temperature elastic modulus to 477 GPa. This came from reported results that initially suggested a 15% increase in stiffness with irradiation [41], and an additional 5% was added for conservatism. These results are now in question, however, as described below [57]:

> In some of previous thermomechanical analyses of a tungsten block for the STS target, an increased modulus of elasticity for irradiated tungsten was used compared to that of unirradiated one. This was mainly motivated by a paper Habainy *et al.* , where it was reported that uranium beam irradiated pure tungsten up to 0.1 dpa showed about 20% increase in stiffness. However, it was found that the reported increase of elastic modulus is questionable. The experimental method that was used to derive an increase in elastic modulus in the Habainy *et al.* paper was critically reviewed by ORNL experts in nuclear materials. It was concluded that the measured increase of elastic modulus might not be solely due to radiation damage effect. The uranium atoms stopped in the damaged region could have formed interstitials which might have made the lattice stiffer, making the radiation damage effect in the shadow. Following the expert's opinion, we decided to remove the redundant conservatism by taking the elastic modulus of unirradiated tungsten for thermomechanical analyses of tungsten blocks for the STS target design.

ORNL R&D staff are measuring the elastic modulus of tungsten rods that were previously irradiated at Los Alamos National Laboratory (LANL). Preliminary results obtained in 2026 via ultrasonic transducer indicate that there is no significant change in elastic modulus up to the proton displacement damage dose of 25 dpa.

Until more information is available, the nominal value of 398 GPa is assumed. Any uncertainty analysis should incorporate an upper bound of 477 GPa.

2.1.2.6 Poisson's Ratio

Poisson's Ratio is assumed to be unaffected by irradiation.

2.1.2.7 Thermal Conductivity

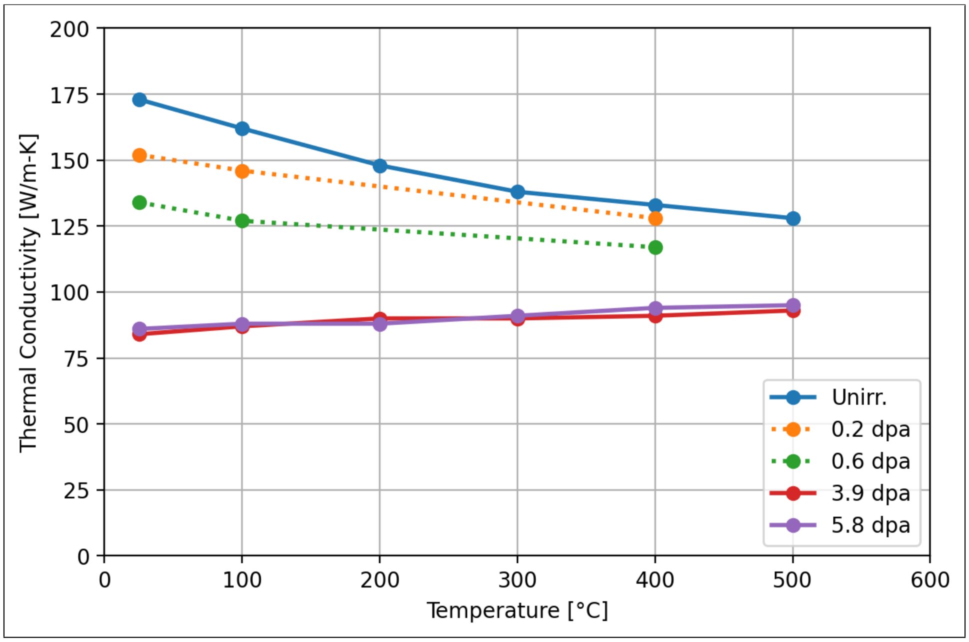


Figure 17. Thermal conductivity variation of tungsten as a function of temperature and dpa damage. Plot produced with data tabulated from Habainy *et al.* [45] and Peacock *et al.* [79].

Habainy *et al.* measured the thermal diffusivity of tungsten samples after irradiation to 3.9 dpa and 5.8 dpa in a target at the Swiss Spallation Neutron Source (SINQ) [45]. Thermal conductivity was calculated using unirradiated density and specific heat values.

Roedig *et al.* also tested irradiated tungsten samples as part of ITER fusion R&D activities [83]. Tungsten samples were irradiated with fast neutrons at 200°C to 0.2 dpa and 0.6 dpa at the High Flux Reactor in Petten, Netherlands. Both thermal diffusivity and heat capacity were measured as functions of temperature. There is a typo in the report, however, it appears that unirradiated density was used as little swelling was observed. Only thermal conductivity was reported, and this data was provided separately in Peacock *et al.* [79].

As seen in Figure 17, the thermal conductivity of tungsten decreases upon irradiation and appears to saturate by at least 3.9 dpa of damage. The temperature dependence also disappears with this level of irradiation. Accordingly, simulations of irradiated tungsten blocks use a constant thermal conductivity of 87 W/m-K. The thermal diffusivity data reported by Habainy is consistent with other published thermal diffusivity experiments on rolled and annealed Tungsten [81].

For the purposes of uncertainty quantification, a lower bound of 78.3 W/m-K is assumed (10% below the nominal 87 W/m-K for irradiated tungsten). The upper bound is 175 W/m-K which corresponds to the unirradiated thermal conductivity at room temperature.

2.1.2.8 Coefficient of Thermal Expansion

The CTE is assumed to be unaffected by irradiation.

2.1.2.9 Specific Heat

Roedig *et al*. tested irradiated tungsten samples as part of ITER fusion R&D activities [83]. Tungsten samples were irradiated with fast neutrons at 200°C to 0.2 dpa and 0.6 dpa at the High Flux Reactor in Petten, Netherlands. Both thermal diffusivity and heat capacity were measured as functions of temperature. Only thermal conductivity results were reported, however, so actual heat capacity values are not available. The authors state that,

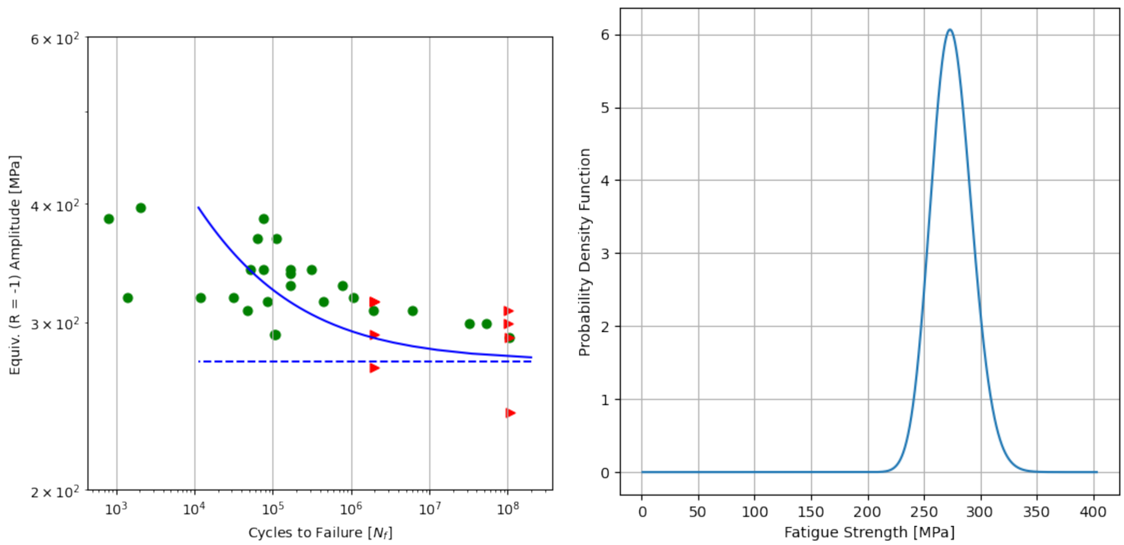
> "The thermal diffusivity is decreased and the heat capacity is increased after neutron irradiation. However the effect on the thermal diffusivity is more distinct, and the latter gives a higher contribution to the degradation of thermal conductivity."

With no other information available, changes to specific heat from irradiation are assumed to be negligible.

2.2 FUTURE WORK

2.2.1 Fatigue Strength

Pascual and Meeker [78] present an alternative method for modeling fatigue called the "Random Fatigue-Limit Model". This attempts to fit a linear-log model to the fatigue data while assuming error follows a normal distribution. An additional parameter, the endurance stress limit, seeks to define a fatigue limit (i.e. a stress below which fatigue failure will not occur). The model also formally incorporates fatigue runouts as censored data. The unknown parameters are found via maximum likelihood estimation (MLE). Figure 18 shows an initial attempt to apply this model to the unirradiated tungsten data. The resulting endurance stress limit is 273 MPa. This is slightly higher than the 10 year design fatigue stress of 254 MPa given in Figure 7 and also has less uncertainty. This model should be investigated further, especially as more irradiated tungsten fatigue data becomes available.



(a) MLE of log-fit model including endurance stress limit prediction and considering censored data.

(b) Endurance stress limit prediction.

Figure 18. Random fatigue limit model applied to unirradiated tungsten.

2.2.2 Fracture Strength

More recently, the STS target design has favored the increased strength of tungsten plate. The team has also become more familiar with better practices for characterizing brittle materials.

At the anticipated operational temperatures of STS, tungsten will be below the DBTT and will behave as a brittle, flaw-controlled material. Its measured strength is therefore not a single intrinsic value. It instead depends on the distribution of critical defects and on the stressed area or volume being sampled. Uniaxial tensile tests can be difficult to interpret under these conditions. They are sensitive to gripping and alignment, they can introduce unintended bending, and they may also cause premature failure at stress concentrations near shoulders or grips. As a result, the measured strength can reflect the test setup as much as the material. Four-point bending is often a better option for brittle tungsten specimens. It provides a well-defined stress state and a constant-moment region. It also avoids single loading contact as well as grip-related failures. Fraction is thus more likely to initiate from the inherent surface/edge flaw population.

Weibull statistics are needed to characterize brittle fracture because failure is controlled by the largest "critical" flaw within the stressed region, consistent with a weakest-link model. In this view, a brittle component behaves like a chain: the probability of failure is governed by the most severe defect among many potential sites, so strength shows inherent scatter even for nominally identical specimens. This also creates a strong volume (or stressed area) effect: a larger stressed volume contains more potential critical flaws, so it is more likely to fail at a lower applied stress. Weibull analysis captures these features by describing strength with a distribution rather than a single value. Weibull analysis also provides a scaling framework to predict the expected strength for a different specimen size or geometry. This enables consistent comparisons and reliability predictions across specimen types.

In light of this, ORNL Materials Science and Technology Division (MSTD) was asked to perform 4-pt bend testing of tungsten plate per American Society for Testing and Materials (ASTM) C1161-18. Samples were taken from different commercial offerings of 12, 16, and 18-mm tungsten plate. In total, 43 samples were tested with roughly half of the samples oriented in the rolling direction and half oriented transverse to the rolling direction. The sample directions were denoted as "X" and "Y". (Microscope examination of the grain direction would be needed to confirm the direction.)

The fracture strength of each test was calculated from the rectangular bar samples using simple beam theory. The Python SciPy library was used to fit a 2-D Weibull distribution to the data, assuming a zero location parameter. Figure 19 shows the data histogram summary with the Weibull fit. The shape and scale are 5.39 and 1056 MPa, respectively. Using the Weibull distribution, the minimal strength of the plate samples is 450 MPa with 99% confidence and 609 MPa with 95% confidence.

Weibull statistics were also used to test for directional dependence. Figure 20 gives a graphical comparison of the two models which shows significant overlap between the "X" and "Y" directions. A Weibull likelihood-ratio test also did not reveal statistical significance between the two models.

Future work should attempt to scale the expected strength in these plate samples to the plate geometries expected in the spallation target. In addition, testing should be performed in the through-thickness direction to better understand the directional dependence of rolled plate. If significantly anisotropy is expected, the fatigue model would need to be modified to account for critical-plane dependence on strength. Or the weakest direction would need to be used if the conservatism can be tolerated.

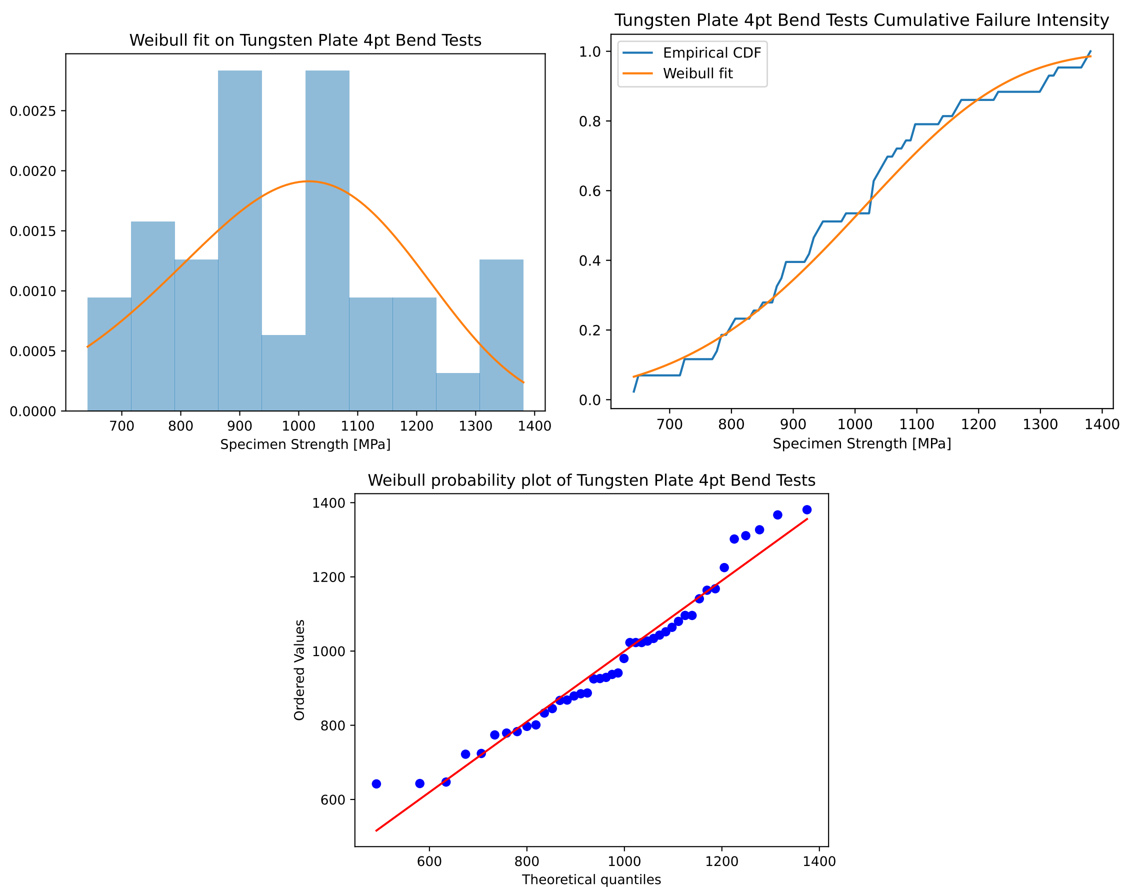


Figure 19. Weibull statistics applied to 4-pt bend fracture tests of commercial tungsten plate.

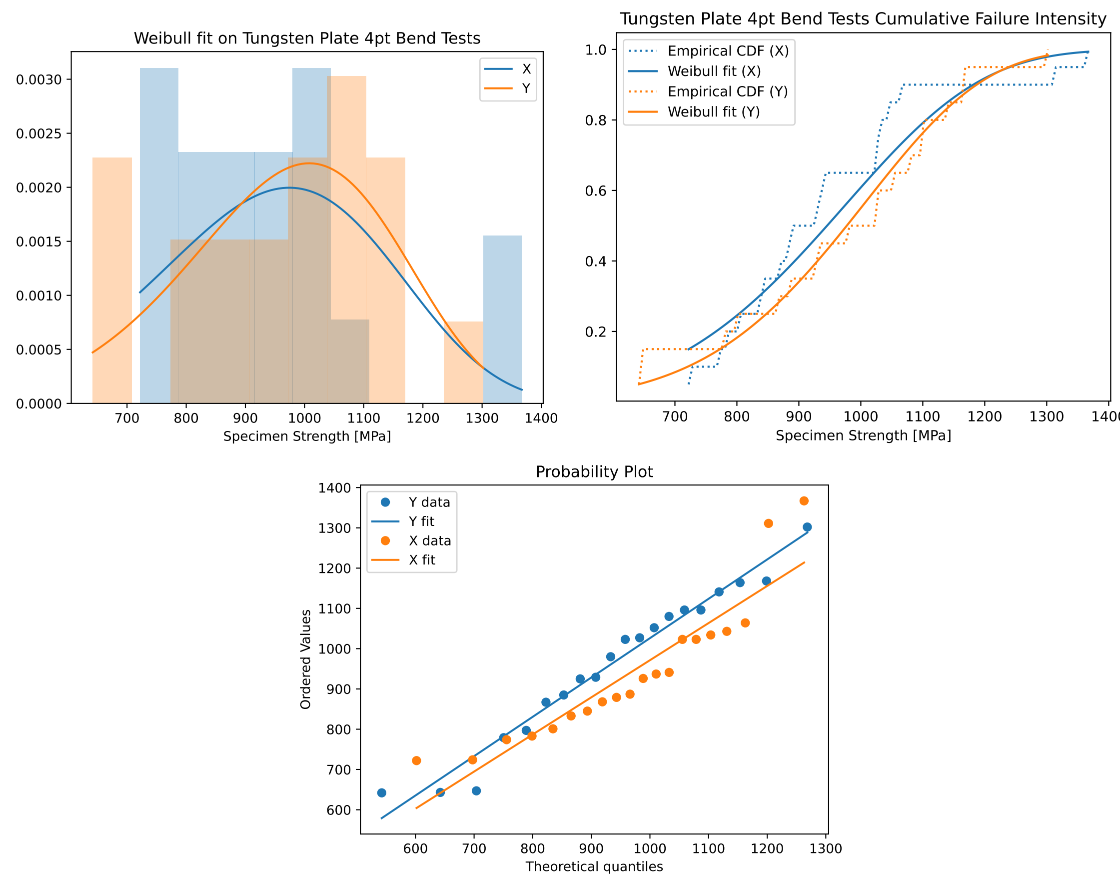


Figure 20. Weibull statistics applied to 4-pt bend fracture tests of commercial tungsten plate. "X" and "Y" models separate the data in the rolling and transverse directions. Statistical significance is not found.

3. INCONEL 718 SOLUTION-ANNEALED

3.1 MATERIAL BEHAVIOR

INCONEL alloy 718 is owned by the Special Metals Corporation which offers the following overview [50]:

> For most applications, INCONEL alloy 718 is specified as: solution annealed and precipitation hardened (precipitation hardening, age hardening, and precipitation heat treatment are synonymous terms). Alloy 718 is hardened by the precipitation of secondary phases (e.g. gamma prime and gamma double-prime) into the metal matrix. The precipitation of these nickel-(aluminum, titanium, niobium) phases is induced by heat treating in the temperature range of 1100 to 1500°F. For this metallurgical reaction to properly take place, the aging constituents (aluminum, titanium, niobium) must be in solution (dissolved in the matrix); if they are precipitated as some other phase or are combined in some other form, they will not precipitate correctly and the full strength of the alloy with not be realized. To perform this function, the material must first be solution heat treated (solution annealed is a synonymous term). . . . If the material is to be machined, formed, or welded, it typically is purchased in the mill annealed or stress relieved condition. The material is then fabricated in its most malleable condition. After fabrication, it can be heat treated as required per the applicable specification.

INCONEL 718 has a history of use in proton beam windows at spallation facilities worldwide including ISIS, Los Alamos Neutron Science Center (LANSCE), and Spallation Neutron Source (SNS). McClintock *et al.* provide a historical account [70]. They report that the precipitation hardened (PH) form experiences a loss of ductility after spallation-relevant irradiation. In contrast, the solution annealed (SA) form of the alloy IN718(SA) appears to demonstrate increased ductility with irradiation. This makes it an appealing structural material for spallation target design. Unfortunately, the majority of the published literature is for the alloy in the PH form.

3.1.1 Unirradiated Condition

3.1.1.1 Tensile Strength

Table 4 summarizes the data available on IN718(SA) tensile properties from Special Metals [50] and is mainly from smooth bar tests. Table 5 summarizes the data available on IN718(SA) tensile strengths for plate stock acquired by ORNL for R&D activities. All materials follow the AMS 5596M/N specification. Figure 21 visually summarizes IN718(SA) strengths in the annealed condition as a function of hardness, anneal temperature, type (round, bar, plate), size, and direction. Marker size scales with the thickness (from 0.125 to 4 inches). Transverse and longitudinal test directions are included. The anneal temperature of 954°C corresponds with AMS-5596 which is specified by the project for manufacturing. A yield stress of 400 MPa appears to be conservative.

Table 4. IN718(SA) tensile strengths for round and bar stock as published by Special Metals [50].

Type	Size	Anneal [°C]	Orientation	UTS [MPa]	YS [MPa]	Elongation [%]	[%] Area Reduction
Bar	2.5in D	954	L	934.2	534.3	45	49
Bar	2.5in D	954	T	892.9	506.8	32	29
Bar	2.5in D	1066	L	786	347.5	62	65
Bar	2.5in D	1066	T	772.2	343.4	53	49
Bar	4in D	954	L	810.1	379.2	53	52
Bar	4in D	954	T	820.5	389.6	50	46
Bar	4in D	1066	L	775.7	330.9	60	63
Bar	4in D	1066	T	786	344.7	61	55
Bar	4in D	954	L	865.3	493	45	49
Bar	4in D	954	T	851.5	461.9	46	43
Bar	4in D	1066	L	792.9	324.1	59	65
Bar	4in D	1066	T	686	327.5	32	31
Bar	4in D	954	L	868.7	493	45	47
Bar	4in D	954	T	786	413.7	26	25
Bar	4in D	1066	L	789.5	365.4	58	61
Bar	4in D	1066	T	723.9	324.1	34	29
Bar	4in D	954	L	841.2	434.4	51	51
Bar	4in D	954	T	751.5	389.6	32	31
Bar	4in D	1066	L	775.7	344.7	62	62
Bar	4in D	1066	T	734.3	341.3	38	33
Bar	4in D	954	L	820.5	389.6	51	54
Bar	4in D	954	T	789.5	372.3	45	38
Bar	4in D	1066	L	761.9	324.1	60	62
Bar	4in D	1066	T	748.1	313.7	58	53
Bar	4in D	954	T	765.3	375.8	41	35
Bar	4in D	1066	T	682.6	317.2	36	36

Table 5. IN718(SA) tensile strengths for plate stock acquired by ORNL for R&D activities. All materials follow the AMS 5596M/N specification.

Source	Heat No.	Thickness	Hardness [in]	YS 0.2% [HRB]	UTS [MPa]	Direction [MPa]	Grain Size	A.L.A. GS [ASTM E112]
ATI	SEY2886-01	0.04	91	433	911	n/a	9	6
ATI	07K3C58-02	0.125	89	405	868	n/a	8.5	5.5
SM	HT9801EK31	0.1875	88.3	378	823	T	7	5
ATI	07K1H98-01	0.25	91.5	396	823	T	6	3
SM	HT0448EK12	0.25	93.5	473	856	T	6	4
SM	HT0925EK12	0.375	94.5	465	854	T	7	5
SM	HT9767EK41	0.52	94.1	470	862	T	6	5
SM	HT0730EK11	0.5	97.5	577	908	T	7	n/a

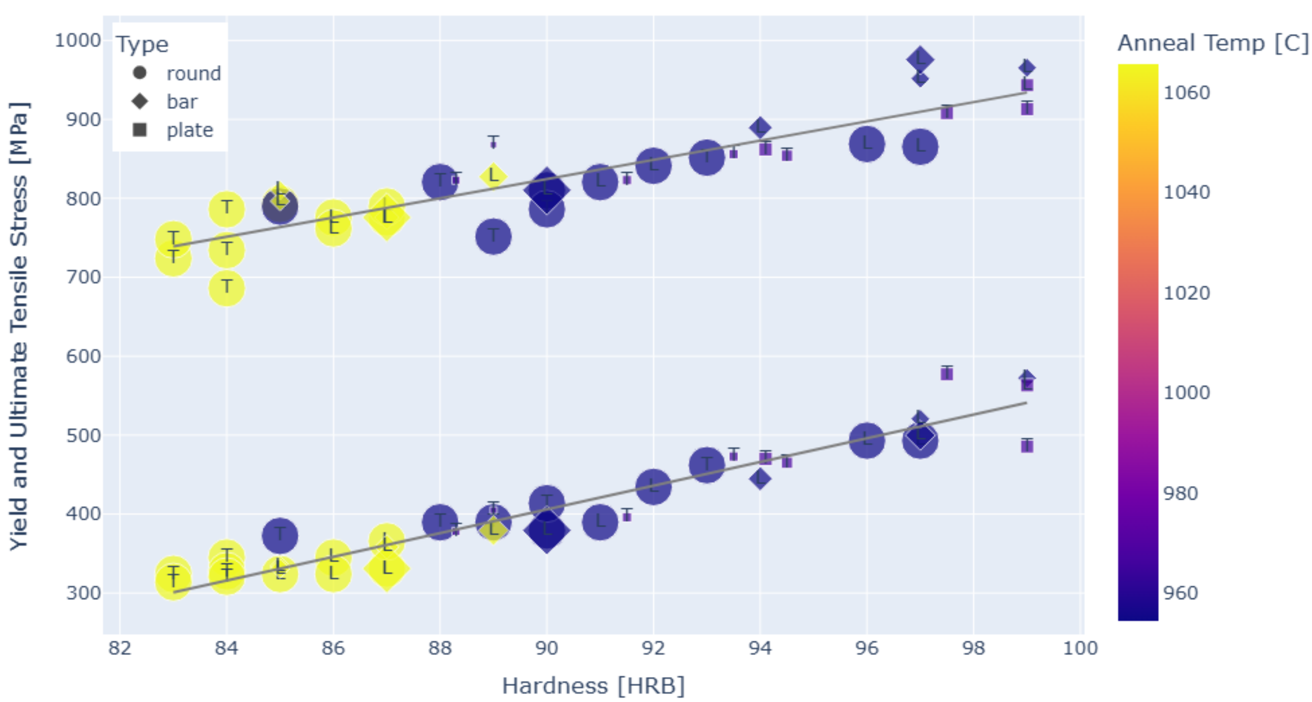


Figure 21. IN718 strengths in the annealed condition as a function of hardness, anneal temperature, type (round, bar, plate), size, and direction. Marker size scales with the thickness (from 0.125 to 4 inches). Transverse and longitudinal test directions are included.

At Final Design Review (FDR), the project expects to use a forging that is solution annealed. The MK5 R&D target used forged Inconel. This material started as a forging that met the SAE AMS 5662 spec, but not the grain size requirement. It went through hot isostatic pressing (HIP) in the MK5 fabrication [93]. Unfortunately, strength data was not documented before manufacturing. After manufacturing, tensile samples were machined from the top and side of the target shroud. Thus, both plastic hardening and a little aging are expected, and it is not possible to separate the two effects. Figure 22 summarizes the tensile testing with 653 MPa Yield Strength (YS) and 960 MPa UTS (conservatively ignoring the top sample which was stronger than the side samples).

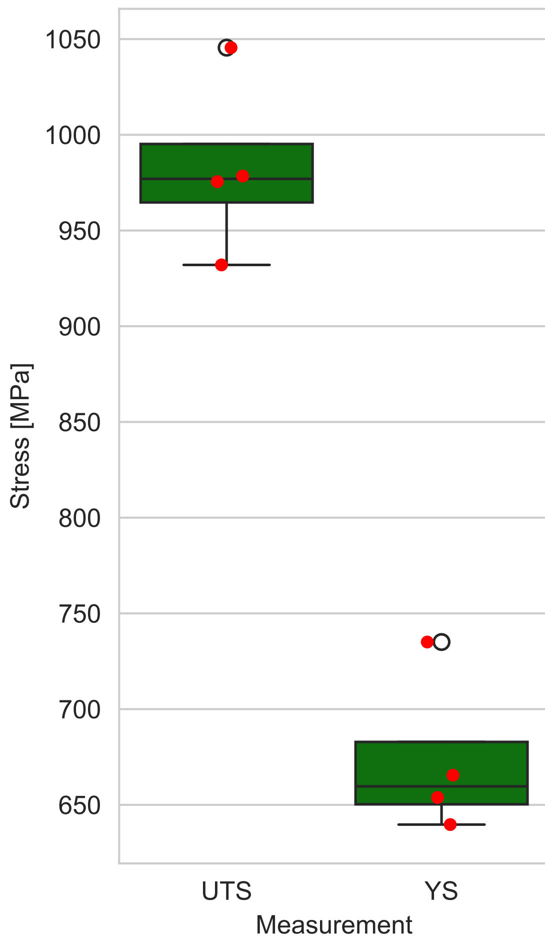


Figure 22. IN718SA samples from MK5

The project also performed tensile testing on half inch plate. Half the samples were tested as received and half were tested after being cycled through HIP-relevant heat treating (i.e. vacuum furnace cycle to mimic HIP temperatures but with a slow cooling rate that might have promoted some precipitation hardening). Figure 23 summarizes the tensile results.

If the same scaling is applied to the MK5 forging material, it would have had 515 MPa YS and 849 MPa UTS before manufacturing. And this is without meeting the grain size requirement.

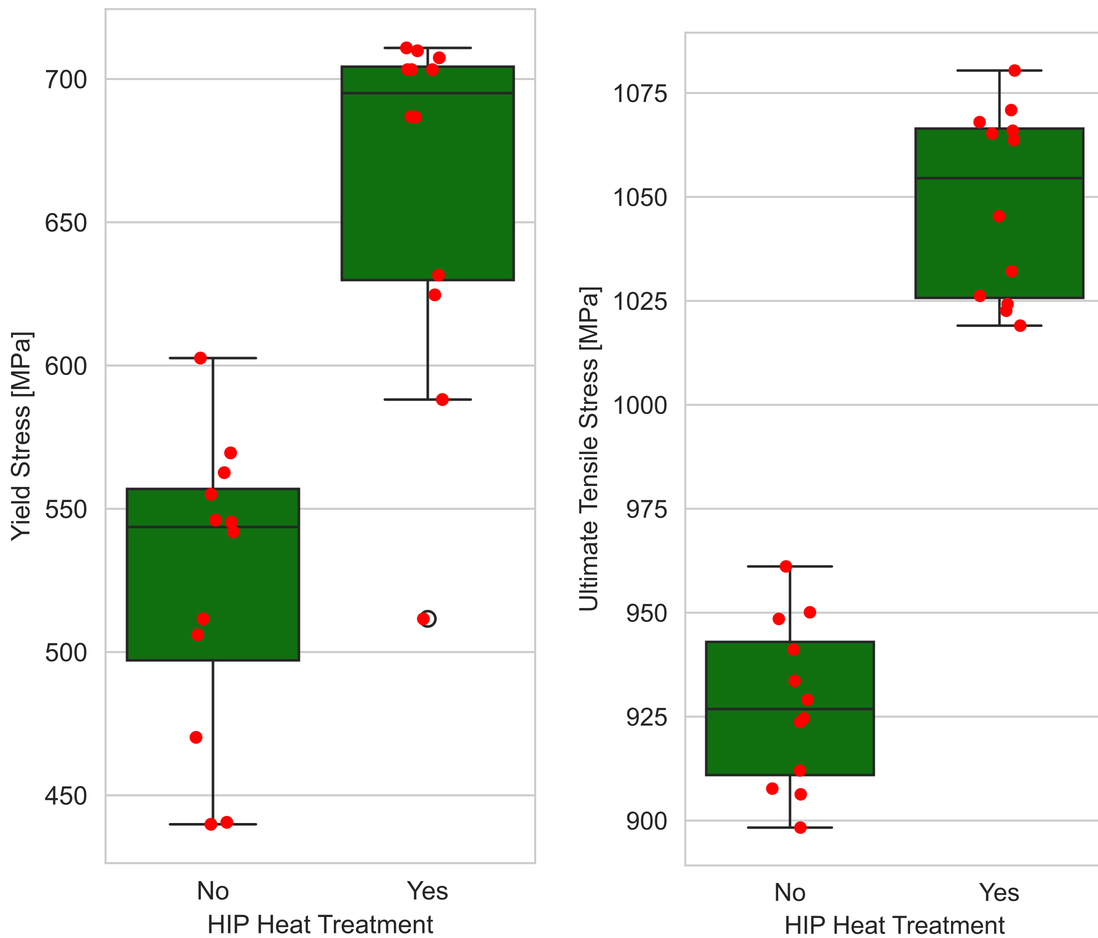


Figure 23. Available tensile strength data for IN718(SA) half inch plate.

At the time of FDR, R&D activities are continuing. A forging has been procured that meets grain size requirements. Half the tensile samples from this forging will be heat treated to 950°C and then air quenched (instead of vacuum cool which promotes aging). In the meantime, the project assumes 930 MPa UTS and a conservative 400 MPa YS, following internal specifications [94] [93].

3.1.1.2 Thermoelastic-Plastic Behavior

The yield stress for SA is based on a grain dislocation physics model communicated by Moretti *et al.* [72]. Equation 7 lists the five contributions to the yield stress σ_Y.

$$\sigma_Y = \sigma_G + \sigma_{HP} + \sigma_{disl} + \sigma_{SS} + \sigma_{drag} \tag{7}$$

The term σ_G is a long-range athermal resistance due to parallel dislocations and is also known as Taylor hardening.

$$\sigma_G = \alpha M G b \sqrt{\rho_{io}} \tag{8}$$

The term σ_{HP} is another long-range resistance that captures the effect of grain size via the Hall-Petch model.

$$\sigma_{HP} = k_{HP} \frac{G}{G_{RT}} \frac{1}{\sqrt{g}} \tag{9}$$

The term σ_{disl} is a short-range resistance due to perpendicular dislocations.

$$\sigma_{disl} = f_{DSA} s_{disl} G \left\{ 1 - \left[\frac{1}{f_{DSA} A_{disl}} \frac{k_B}{b^3} \frac{T}{G} \ln\left(\frac{\dot{\epsilon}_{ref}}{\dot{\epsilon}_P} \right) \right]^{1/q} \right\}^{1/p} \tag{10}$$

The term σ_{SS} is a short-range resistance due to alloy solutes. It is assumed to operate as a simple sum of the contributions of each solute separately.

$$\sigma_{SS} = \left(\sum_i \sigma_{SS,i}{}^{3/2} \right)^{2/3} \tag{11}$$

$$\sigma_{SS,i} = \sigma_{ss0} \exp\left[-\frac{1}{C_1} \frac{k_B T}{H_{sol}} \ln\left(\frac{\dot{\epsilon}_{SS}}{\dot{\epsilon}_P} \right) \right] \tag{12}$$

$$\sigma_{ss0} = A_L M G \left(\frac{1}{4\pi^2 N_{cell}} \right)^{4/3} \left(\frac{W}{b} \right)^{1/3} \left(\epsilon_i^{mis} \right)^{4/3} \left(X_i^{sol} \right)^{2/3} \tag{13}$$

$$\epsilon_i^{mis} = \alpha_S \delta_i + \eta_i'; \quad \eta_i' = \frac{\eta_i}{1 + |\eta_i|/2} \tag{14}$$

$$H_{sol} = 5.55 G b^3 \left(\frac{w}{b} \right)^{3/2} \sqrt{\frac{\sigma_{ss0}}{MG}} \tag{15}$$

The term σ_{drag} is a short-range resistance due to phonon and electron interactions with dislocations. This effect is primarily felt at high strain rate deformation and is considered negligible for the current model.

Table 6 identifies the parameters used in Equations 7 through 15 and references their sources. Figure 24 gives the resulting yield strength as a function of temperature. To produce the figure, the grain size is set to 20 μm, the plastic strain rate is set to $5 \times 10^{-4}\ s^{-1}$, and the initial immobile dislocation density is chosen such that the room temperature yield stress is 400 MPa.

As an aside, these values were initially created when the project was pursuing 1.125-in plate with a grain size of 20 μm that had a corresponding room temperature yield stress of 400 MPa. As previously described, the project is now pursuing a forging with grain size ASTM 6 ($\approx 45\ \mu m$) and a room temperature yield stress of 400 MPa. Changing the grain size in the model to 45 μm and choosing an initial immobile dislocation density of $\rho_{io} = 1.29 \times 10^{13}\ m/m^3$ creates a stress-strain model that is essentially indistinguishable from what is presented in 26.

Table 6. Parameters used for Inconel 718 yield stress model.

Symbol	Name	Value	Units	Source
α	calibration factor	0.5		[72]
M	Taylor lattice factor	3.06		[72]
b	Burgers vector mag.	2.54×10^{-10}	m	[72]
ρ_{io}	initial immobile dislocation density	7.6×10^{12}	m/m^3	fit
G	shear modulus	$f(T)$	MPa	Table 7
G_{RT}	shear modulus at room temp.	$f(T)$	MPa	Table 7
k_{HP}	Hall-Petch parameter	0.35×10^{6}	$MPa\sqrt{m}$	[72]
$\bar{g}$	avg. grain size	20	μm	fit
f_{DSA}	dynamic strain aging	1		Disabled
s_{disl}	obstacle strength calibration parameter	1.5×10^{-3}		[72]
A_{disl}	energy barrier for dislocation	1		[72]
k_B	Boltzmann constant	1.38×10^{-23}	J/K	
$\dot{\epsilon}_{ref}$	reference strain rate	$M \times 10^{6}$	s^{-1}	[72]
q	fitting parameter	1		[72]
p	fitting parameter	1		[72]
C_1	fitting parameter	0.57016		[72]
$\dot{\epsilon}_{SS}$	ref. strain rate	10^{5}	s^{-1}	[72]
A_L	constant	$1/\sqrt{2}$		[72]
N_{cell}	number atoms in unit cell	4		F.C.C.
w/b	range of action of diffuse obstacle	1.7		[72]
X_i^{sol}	atomic fraction of alloying element			Table 8
α_s	screw dislocations	16		[72]
δ_i	size misfit			Table 8
η_i	shear modulus misfit			Table 8
Θ_{II}	stage-two hardening rate	6,500	MPa	Figure 27
$\dot{\epsilon}_{sat,o}$	ref. strain rate for hardening	1×10^{8}	s^{-1}	[37]
$\sigma_{sat,o}$	sat. stress at 0 K			Table 9
$g_{sat,o}$	dynamic recovery activation energy			Table 9

Table 7. Shear moduli [MPa] for Inconel 718 [38] and its base components [72].

T [°C]	T [K]	IN718	Ni	Cr	Mo	Fe	Nb
20	293	80770	79100	126000	134000	81300	44300
100	373	78194	76800	124000	133000	78000	44300
200	473	75880	73800	121000	131000	73900	44300
300	573	72639	70900	118000	129000	69900	44300
400	673	70093	68000	115000	127000	65800	44300
500	773	67546	65100	112000	125000	61700	44300
600	873	64305	62100	109000	123000	57700	44300
700	973	60370	59200	106000	121000	53600	44300
800	1073	55509	56300	104000	119000	49500	44300
900	1173	51343	53400	101000	117000	45400	44300
1000	1273	48102	50400	97700	115000	41400	44300
1250	1523	41010	43100	90400	110000	31200	44300

Table 8. Solute misfit parameters [72] with atomic fraction [64] for Inconel 718.

Solute	Size Misfit δ_i	Shear Modulus Misfit η_i	Atomic Fraction X_i^{sol}
Cr	0.0298	1.7541	0.204853549
Nb	0.1978	-1.3928	0.031154576
Al	0.0513	-0.0952	0.012872791
Ti	0.1193	-1.8261	0.011368083
Mo	0.1349	-0.119	0.018401383
Fe	0.0333	-1.238	0.186376579
Mn	0.0823	-2.0737	0.001159085

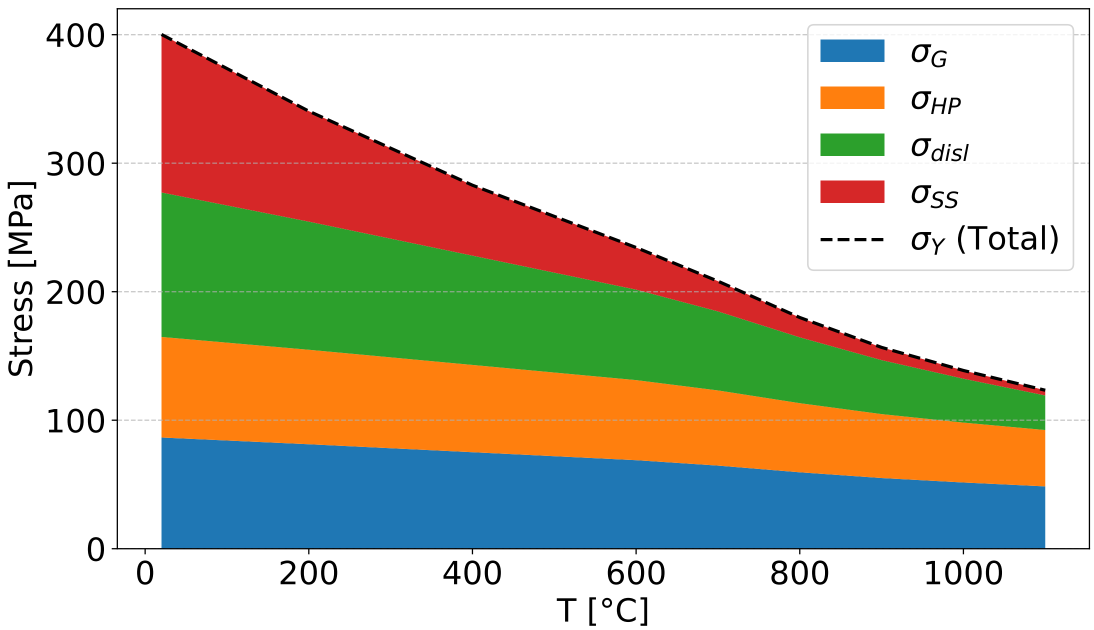


Figure 24. IN718(SA) yield strength as a function of temperature and showing the contributions from short and long range dislocation effects. The data is modeled using Equations 7 through 15.

The flow stress is given in Equation 16 as a combination of yield stress and plastic hardening.

$$\sigma = \sigma_Y + R \tag{16}$$

As part of the Mechanical Threshold Stress (MTS) model, plastic hardening is captured in a modified Voce law that models the interaction of dislocations with stored dislocations during straining [37]. Equation 17 gives the relationship where the term Θ_{II} is the "stage-two hardening rate". In construction of the model, it is used as the final fitting parameter with a value of 6,500 MPa such that that model best matches the experimental data at 0.1 true strain (see Figure 27).

$$R = \sigma_{sat}\left[1 - \exp\left(-\frac{\theta_{II}}{\sigma_{sat}}\epsilon\right)\right] \tag{17}$$

The term σ_{sat} is the saturation stress which varies with temperature and strain rate according to a dynamic recovery equation as shown in Equation 18.

$$\ln(\sigma_{sat}) = \ln(\sigma_{sat,o}) + \frac{kT}{Gb^3 g_{sat,o}}\ln\left(\frac{\dot{\epsilon}}{\dot{\epsilon}_{sat,o}}\right) \tag{18}$$

The fitting parameter $\epsilon_{sat,o}$ is a reference strain rate chosen to be $1 \times 10^8\ s^{-1}$. The fitting parameter $\sigma_{sat,o}$ represents the "saturation stress at 0 K" and $g_{sat,o}$ represents "an activation energy characterizing dynamic recovery" [37]. They are listed in Table 9 which was found by plotting experimental data [64] [72] where the saturation stress is taken as the stress as the highest reported strain. Two trends are clearly visible in Figure 25. At temperatures above 800°C, the source data clearly shows the stress-strain curve to be flat (i.e. zero slope) which is true saturation behavior. At temperatures below 800°C, hardening is still occurring and the last reported stress is not truly indicative of saturation.

Table 9. IN718(SA) plastic hardening curve fit parameters

Parameter	Temperature	Value
$\sigma_{sat,o}$	$\leq 800°C$	1554.6
$g_{sat,o}$	$\leq 800°C$	0.703711
$\sigma_{sat,o}$	$> 800°C$	16946.7
$g_{sat,o}$	$> 800°C$	0.119544

The final constitutive model for IN718(SA) as presented above is shown in Figure 26. The strain rate is fixed at 0.0005 s^{-1} as the high temperature manufacturing processes will experience slow deformation rate (e.g. HIP, casting cooldown, welding). The data points in the figure are input into Abaqus as a thermoelastic-plastic tabulation of true strain, true stress, and temperature. Abaqus then interpolates within this tabular listing. Figure 27 provides a side comparison of the model against the published data of Malmelöv *et al*. [64]. The main discrepancy occurs at 800°C which is most likely due to the discontinuity in the plastic hardening fitting parameters shown in Figure 25. Otherwise, the comparisons show broad agreement and the ability to capture the effects of strain and temperature on the evolving flow stress.

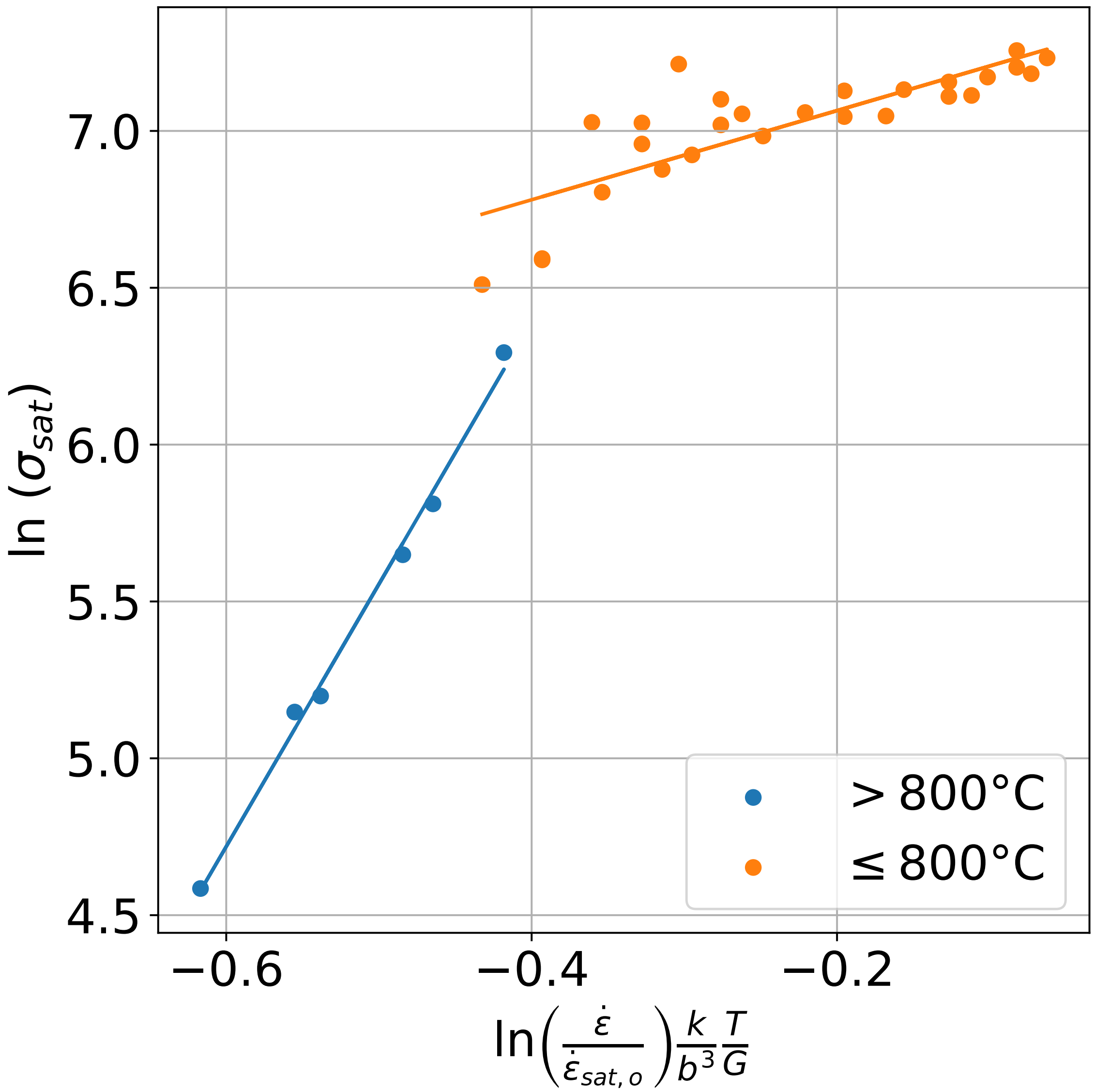


Figure 25. IN718(SA) plastic hardening fitting parameters. Created by plotting experimental data published in [64] and [72] in the form of Equation 18. Two trends in the data are evident, and 2 sets of model parameters are chosen for temperatures below/above 800°C.

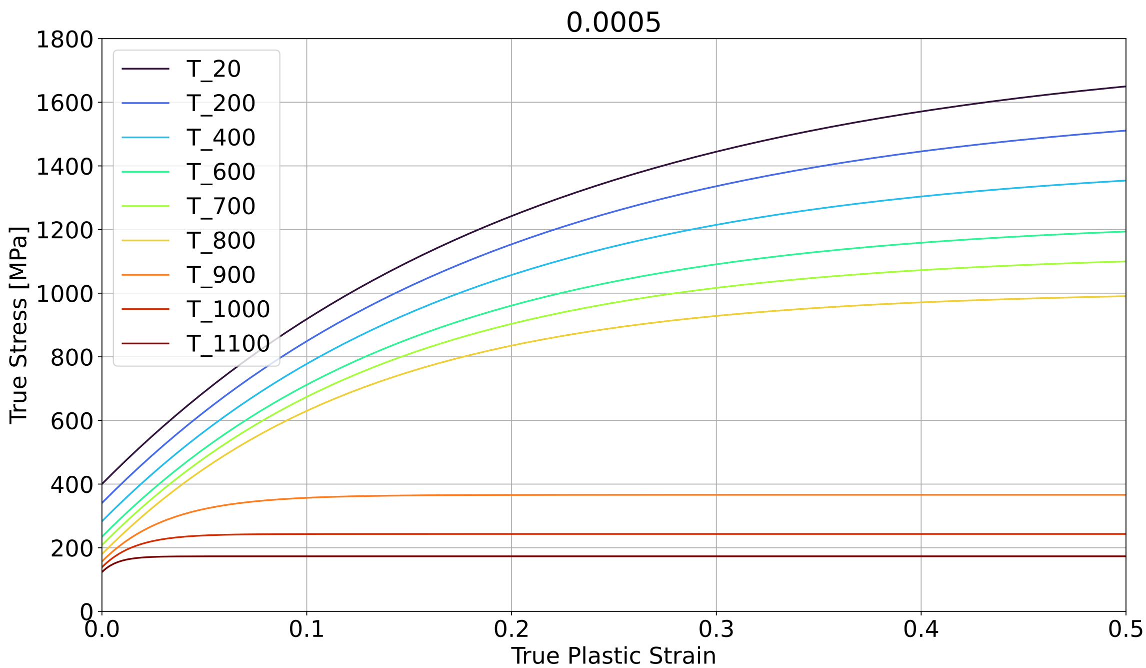


Figure 26. IN718(SA) true stress/strain curve used as the baseline constitutive model for IN718(SA). The data points are generated using Equations 16 through 18. The data points are then input into Abaqus as a thermoelastic-plastic tabulation of true strain, true stress, and temperature.

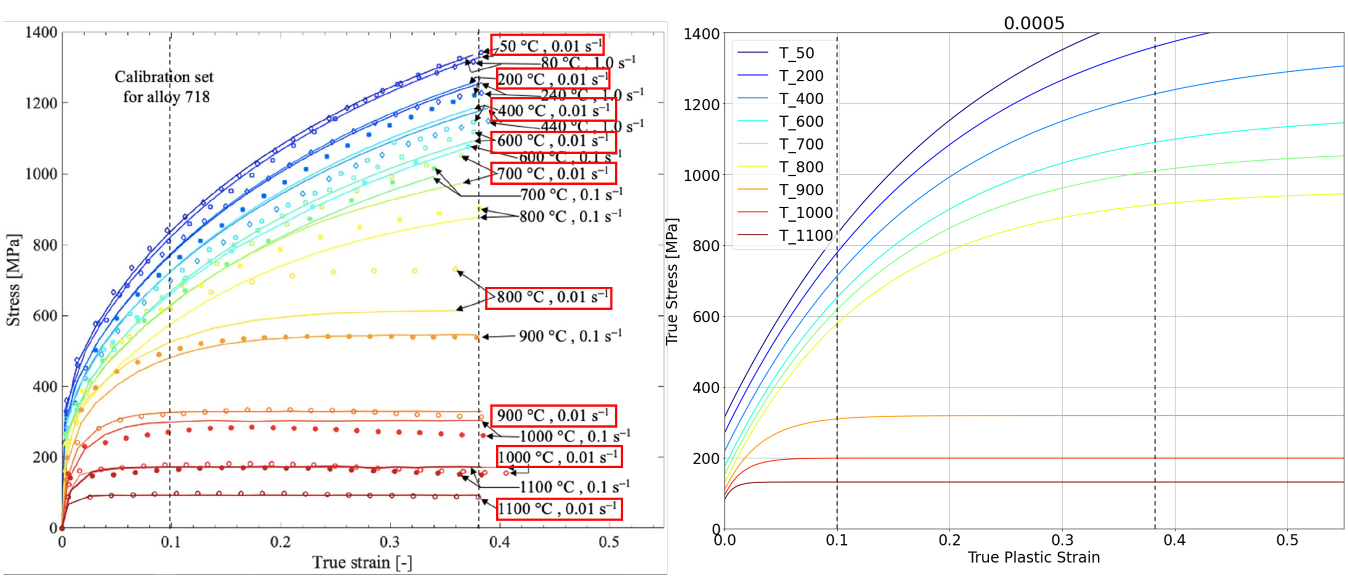


Figure 27. Side-by-side comparison of IN718(SA) true stress/strain curve model (right) compared against experimental results of Malmelöv *et al.* [64] (left). The lower strain rate experimental data is highlighted in red to guide the comparison.

3.1.1.3 Fatigue Strength

Table 10 and Figure 28 summarize a literature review of Inconel 718 cyclic fatigue under room temperature conditions. It should be noted that the Military Handbook (MIL-HDBK-5H) itself references 2 sets of room temperature data which are already included here: Korth 1978 and Ruff 1986. Also, the work of Belan [16] is excluded from the data summary as the reported data is suspect for several reasons including: no mention of surface preparation, ultrasonic testing on a custom built machine, reported stress amplitudes are abnormally low, microscopic examination of one sample shows failure initiated from a massive surface flaw.

The data summary varies by grain size, fatigue stress ratio, fatigue test method, material heat treatment, and cyclic regime. The modified Goodman method is first used to adjust all data to an equivalent fully-reversing stress amplitude. Some reported data use RBF test methods. Bannantine *et al*. suggest a conservative knockdown factor of 0.7 for RBF data with the following reasoning: [46]

> When relating the fatigue data from rotating bending and axial loading for a similar specimen, the volume idea discussed in the preceding section can be used. Since the axial specimen has no gradient, it has a greater volume of material subjected to the high stress. The ratio of endurance limits for a material found using axial and rotating bending tests ranges from 0.6 to 0.9. These test data may include some error due to eccentricity in axial loading.

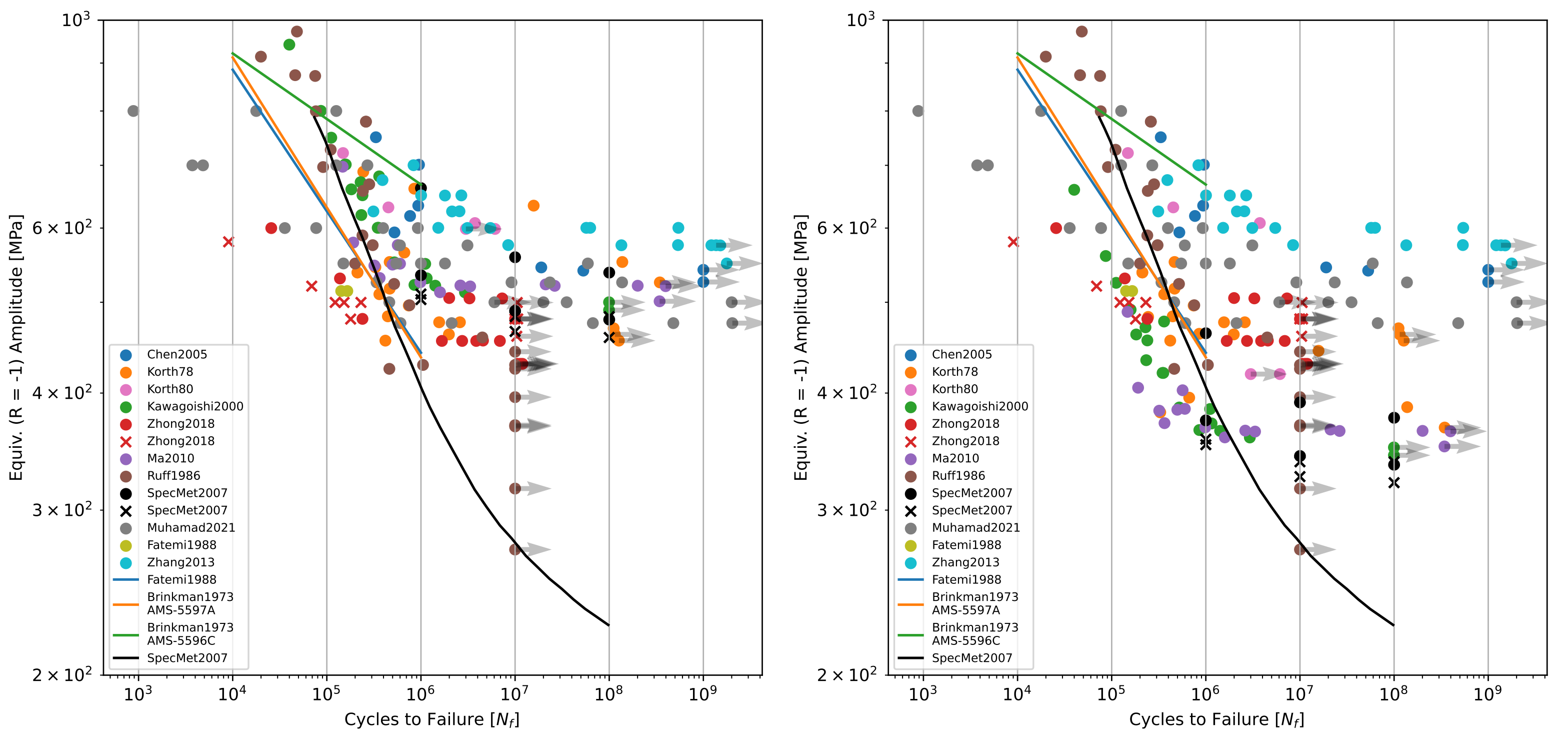
The figure plots the data summary both with a $K_{RBF} = 0.7$ knockdown for RBF test data and without the knockdown. It is apparent that the knockdown adds more spread to the data and is too conservative. This has implications of increasing the fatigue margin. This also makes the data more consistent with the statement from Special Metals that, "If fatigue strength is of prime importance, INCONEL alloy 718 forgings can be used in the annealed rather than the annealed and aged condition; aging raises fatigue strength only slightly (less than 4 ksi in Table 31). [50]"

Reported data using ultrasonic test methods also show a clear trend of increased fatigue strength. Chen *et al*. [25] and Tsutsumi *et al*. [97] both call into question fatigue results from ultrasonic testing. It is therefore conservative to omit this data as is shown in Figure 29.

Figure 30 further parses the data by heat treatment. Two sets of reported data are available for solution annealed IN718 and show good consistency when the RBF knockdown is omitted. The Basquin fatigue model is applied to the HCF data to arrive at a mean cyclic SN curve for IN718(SA). At the STS design goal of 10 years, 135M pulses, the mean fatigue strength is 449 MPa when the RBF knockdown is omitted or 317 MPa with the 0.7 RBF knockdown.

Table 10. Available fatigue data for IN718 at room temperature.

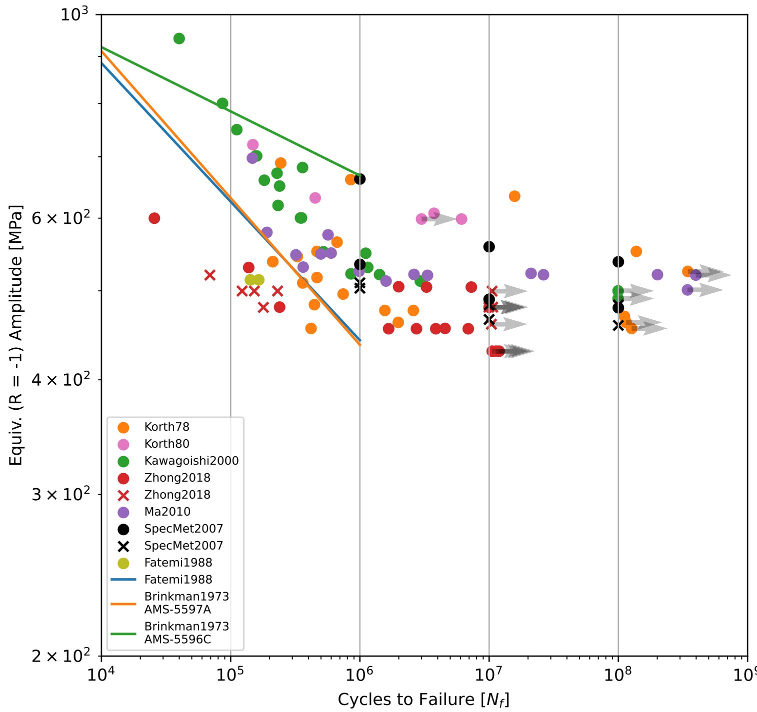
Authors	Year	Treatment	Freq. [Hz]	Test	R	Grain [μm]	Ref.
Chen *et al*.	2005	PH	20k	Ultrasonic	-1	9	[25]
Korth & Smolik	1978	PH	30	Push/Pull	-1	26-45	[56]
Korth & Smolik	1978	PH	167	RBF	-1	26-45	[56]
Kawagoishi *et al*.	2000	PH	50	RBF	-1	9	[51]
Zhong *et al*.	2018	PH	130	Push/Pull	-1	15	[102]
Zhong *et al*.	2018	SA	130	Push/Pull	-1	15	[102]
Ma *et al*.	2010	PH	52.5	RBF	-1	10	[61]
Ruff	1986	PH	n/a	Push/Pull	-0.5,0.1,0.5	n/a	[84]
Special Metals	2007	PH	n/a	RBF	-1	13-58	[50]
Special Metals	2007	SA	n/a	RBF	-1	13-58	[50]
Fatemi & Kurath	1988	PH	n/a	Push/Pull	-1	10-200	[34]
Muhammad *et al*.	2021	PH	5	Push/Pull	-1	10-30	[74]
Muhammad *et al*.	2021	PH	20k	Ultrasonic	-1	10-30	[74]
Brinkman & Korth	1973	PH	n/a	Push/Pull	-1	n/a	[18]
Korth	1980	PH	10	Push/Pull	-0.1, 0.1, 0.2	n/a	[55]
Korth	1980	PH	30	RBF	-0.1, 0.1, 0.2	n/a	[55]
Zhang *et al*.	2013	PH	20k	Ultrasonic	-1	10	[100]



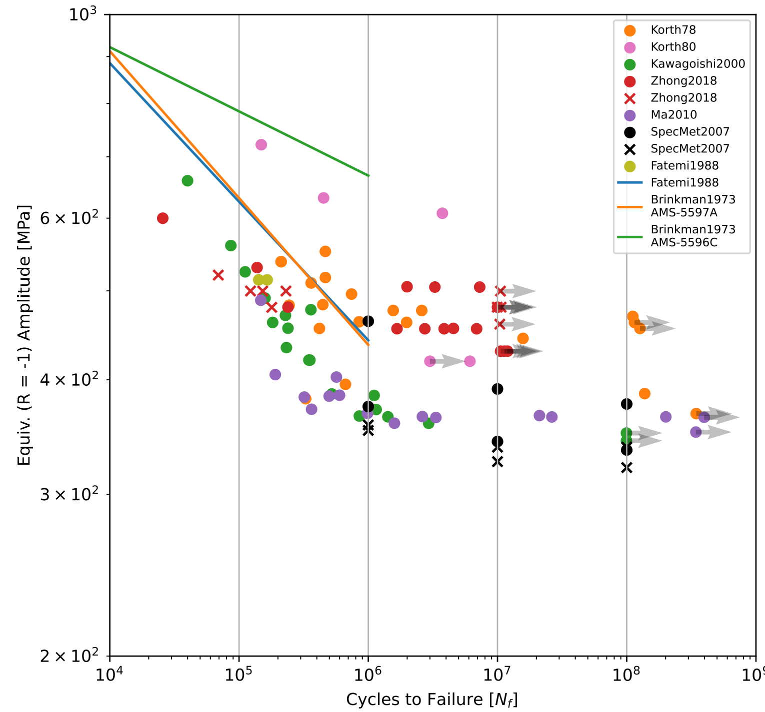
(a) No knockdown for rotating bending fatigue data.

(b) K_{RBF} = 0.7

Figure 28. Available fatigue data for IN718 (x = Solution Annealed, o = Precipitation Hardened)

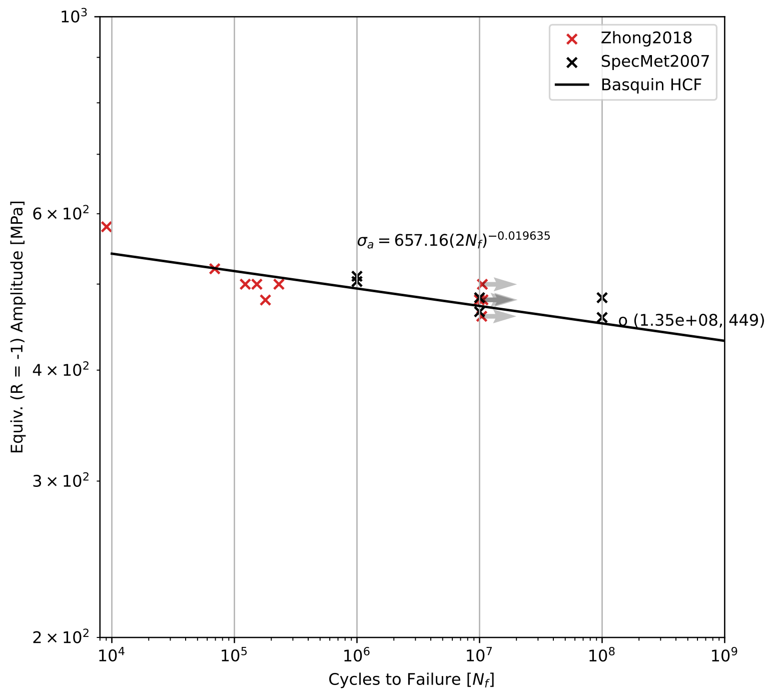


(a) No knockdown for rotating bending fatigue data.

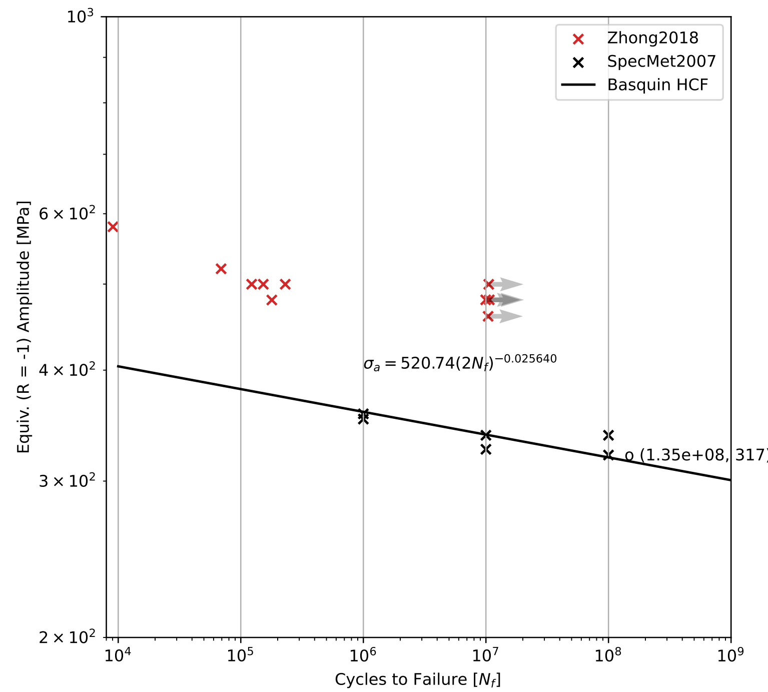


(b) $K_{RBF} = 0.7$

Figure 29. Available fatigue data for IN718. Focusing on HCF regime and with ultrasonic data removed. (x = Solution Annealed, o = Precipitation Hardened)



(a) No knockdown for rotating bending fatigue data.



(b) K_{RBF} = 0.7

Figure 30. Available fatigue data for IN718(SA). Data above 10^4 cycles is then used to establish the Basquin HCF model. The fatigue strength at 10 years (135M cycles) is indicated on the trendline.

GRAIN SIZE EFFECT ON FATIGUE STRENGTH

Grain size effects on fatigue strength can be inferred from the Special Metals handbook. Figure 4 from their handbook is "Effect of grain size on endurance limit (10^8 cycles) of plate annealed and aged in accordance with AMS 5596" and gives a band of values [50]. The lower edge of the band is digitized and curve fit with a 5th order polynomial in Figure 31. (The choice of the lower band is commensurate with the Special Metals statement that "If fatigue strength is of prime importance, INCONEL alloy 718 forgings can be used in the annealed rather than the annealed and aged condition; aging raises fatigue strength only slightly (less than 4 ksi in Table 31). [50]") The curve is then transformed from average grain size in inches to ASTM grain size using Equation 19. Figure 31 also shows the transformed plot with a 2nd order polynomial curve fit.

$$\text{ASTM} = \ln\left(\frac{2 \cdot 0.01^2}{\text{AvgSize}^2}\right)/\ln(2) \tag{19}$$

The STS project has specified an ASTM No. 6 or finer grain size for the target segment Inconel [94]. This would correspond to a 10^8 cycle endurance stress of 325 MPa as indicated on Figure 31.

The Basquin model presented in Figure 30 (without knockdown for RBF) comes from Zhong(2018) and Special Metals(2007). Table 10 indicates this source data was built on grain sizes varying from 13-58 μm. This Basquin model created from this data predicts 451.5 MPa at 10^8 cycles.

Assuming the grain size effect is constant throughout the HCF regime, the knockdown for ASTM 6 grain size would then be $K_{grain} = 325/451.5 = 0.72$.

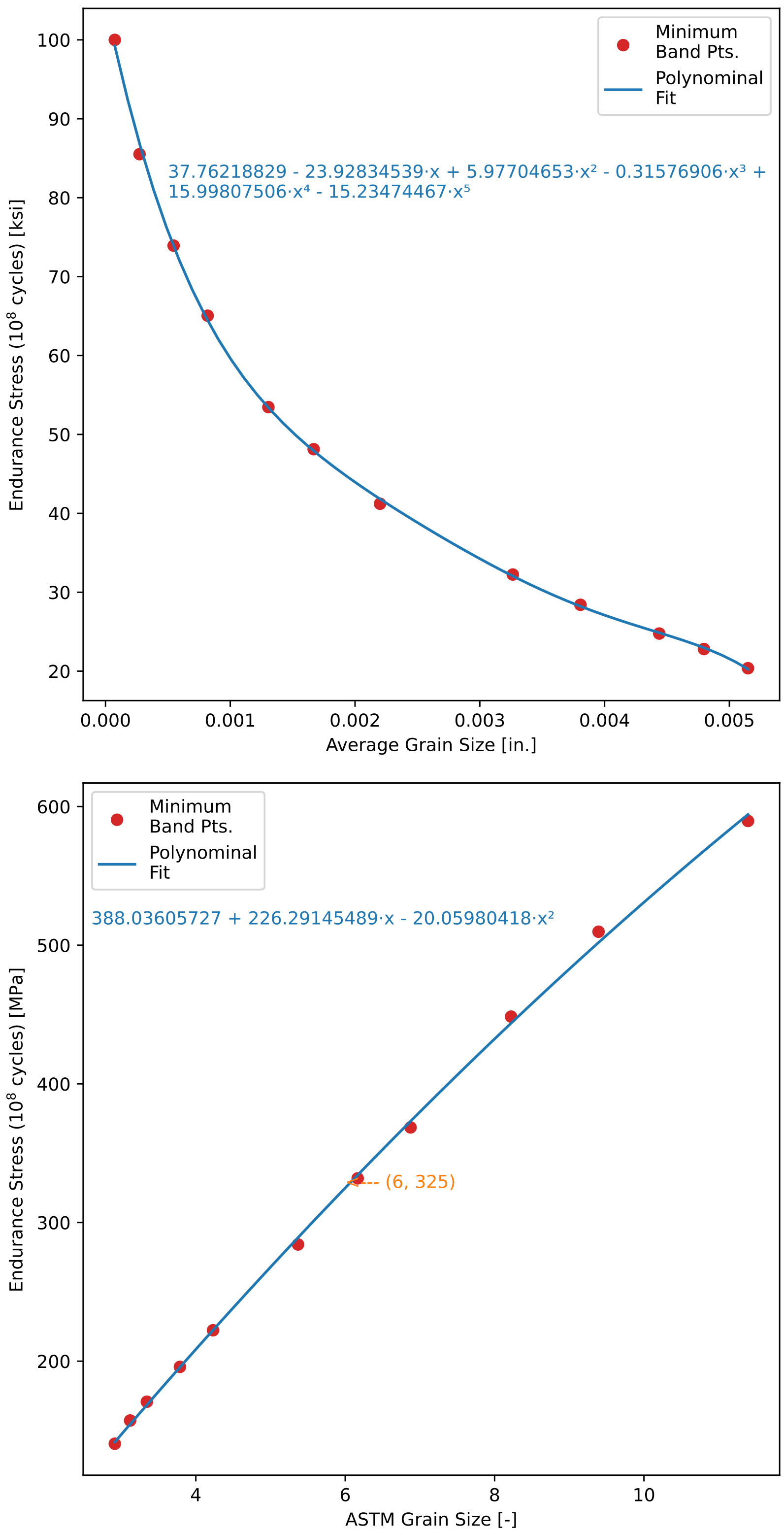


Figure 31. Effect of grain size on endurance limit (10^8 cycles) of plate annealed and aged in accordance with AMS 5596. Data taken from [50].

INCONEL 718(SA) FATIGUE DESIGN CURVE

Figure 32 shows the resulting modified Goodman diagram for IN718(SA) for the 10 year fatigue design life. The nominal UTS is 930 MPa as was previously discussed in the section on Tensile Strength. The design envelope includes the possibility of a 15% reduction. The fully-reversing fatigue stress amplitude is given by Equation 20. The reduced value uses the separate curve fit from Figure 30 that includes data knockdowns for RBF.

$$\begin{aligned} \sigma_a &= K_{grain}\sigma'_f\left(2N_f\right)^b \\ where\ \ K_{grain} &= 0.72 \\ \sigma'_f &= 657.16\text{ MPa} \\ N_f &= 135\times10^6 \\ b &= -0.019635 \end{aligned} \tag{20}$$

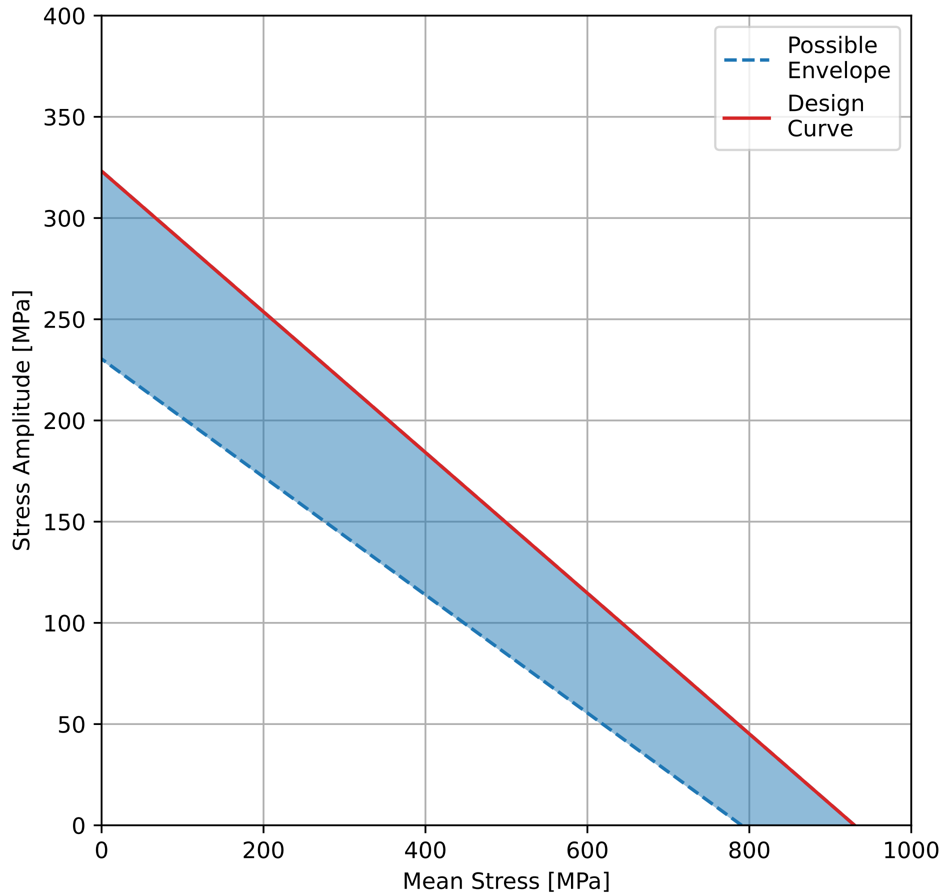


Figure 32. IN718(SA) Goodman diagram showing 10 year fatigue design limit. The band includes uncertainties from ultimate tensile strength and fully-reversing fatigue strength.

ASIDE - INFINITE LIFE THRESHOLD

As previously mentioned, if the RBF knockdown factor is not applied, then the data is more consistent with the statement from Special Metals that precipitation hardening has a small effect on fatigue life. If that is true, then the experimental findings from Korth [55] with IN718(PH) would also apply to IN718(SA):

> The stress-strain parameter also indicates a stress amplitude threshold below which no failure will occur regardless of the mean stress value. A limiting value of mean stress will be reached, of course, when the sum of the stress amplitude and mean stress is equal to the ultimate tensile strength. This threshold phenomenon also appears to be confirmed by the experimental data. No failures were experienced at the 427°C test temperature when the stress amplitude was below approximately 260 MPa, even though some peak stresses were near or just below the ultimate tensile strength. Figure 12 gives evidence of the stress amplitude threshold effect where the stress amplitude reduction factor due to mean stress, Sa/Seq, is plotted against Smax. A lower-bound envelope drawn through the data shows that the reduction factor decreases in an essentially linear fashion until a value of approximately 0.5 is reached and then levels off, showing no further decrease even though the maximum stress continues to increase right up to the ultimate tensile strength.

Figure 33 reproduces the graph presented by Korth which shows an infinite life threshold for stress amplitudes below 50% of the endurance stress, even for mean stresses near ultimate. Applying this to logic to the IN718(SA) fatigue strength would indicate a design stress amplitude of 225 MPa, irrespective of mean stress.

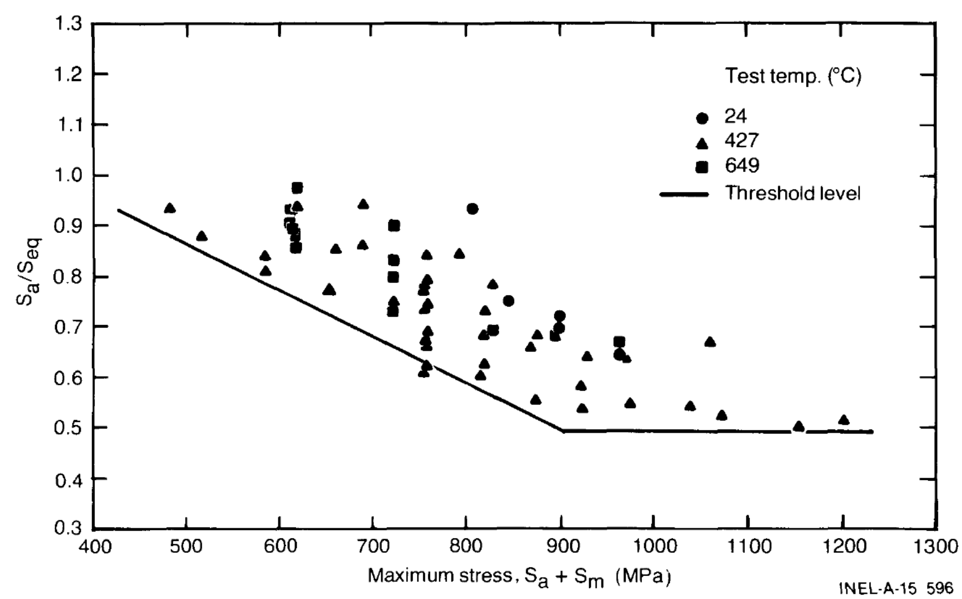


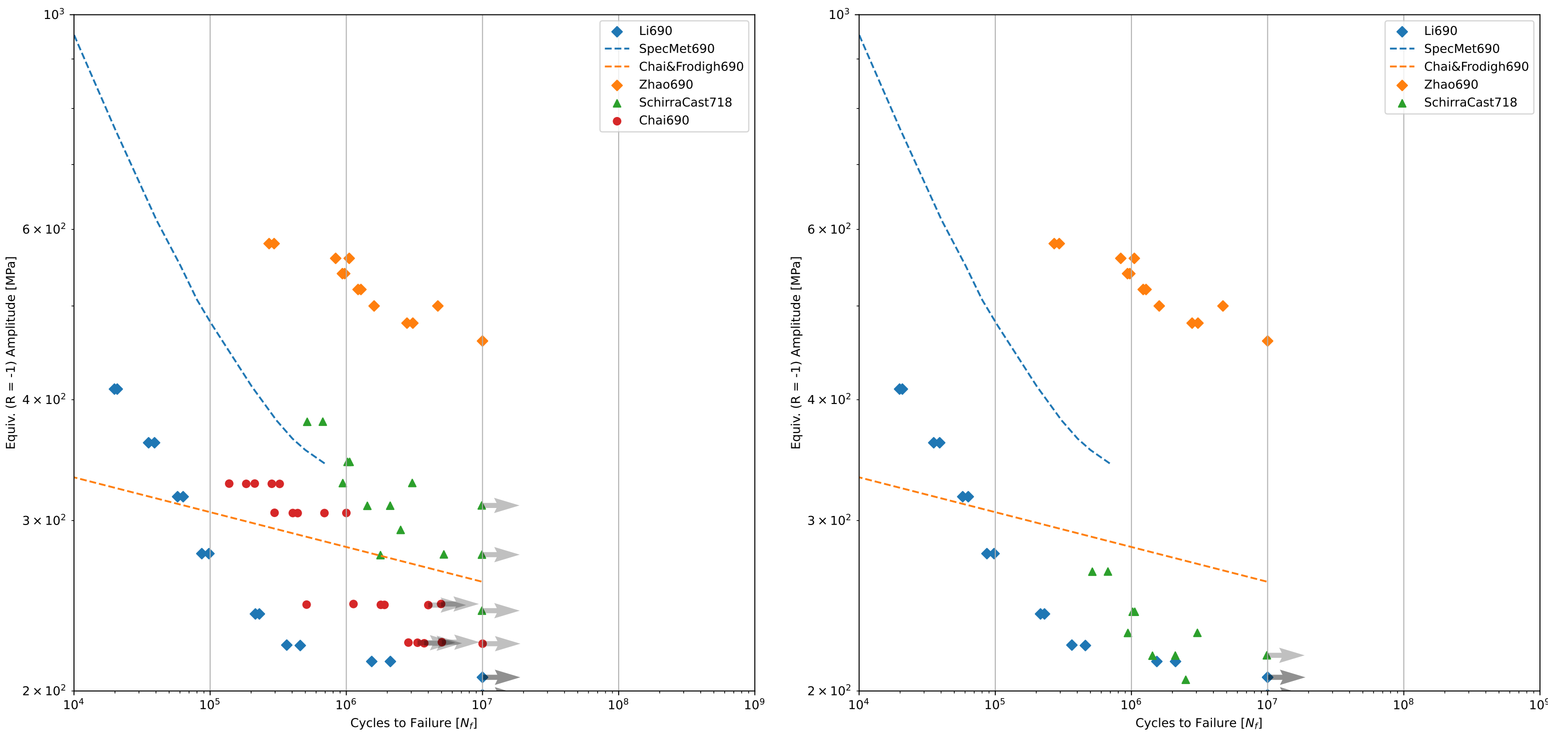
Figure 33. Stress amplitude reduction versus maximum stress for IN718(PH) mean stress tests. Reproduced from Korth [55].

ASIDE - OTHER FORMS OF INCONEL

As an aside, Table 11 and Figure 34 summarize fatigue data available in the literature for other forms of Inconel including 690 and investment cast 718. Both are attractive engineering materials for target manufacturing. Figure 35 compares the data against IN718(SA) and shows consistently worse performance. This supplies further reason for the choice of IN718(SA).

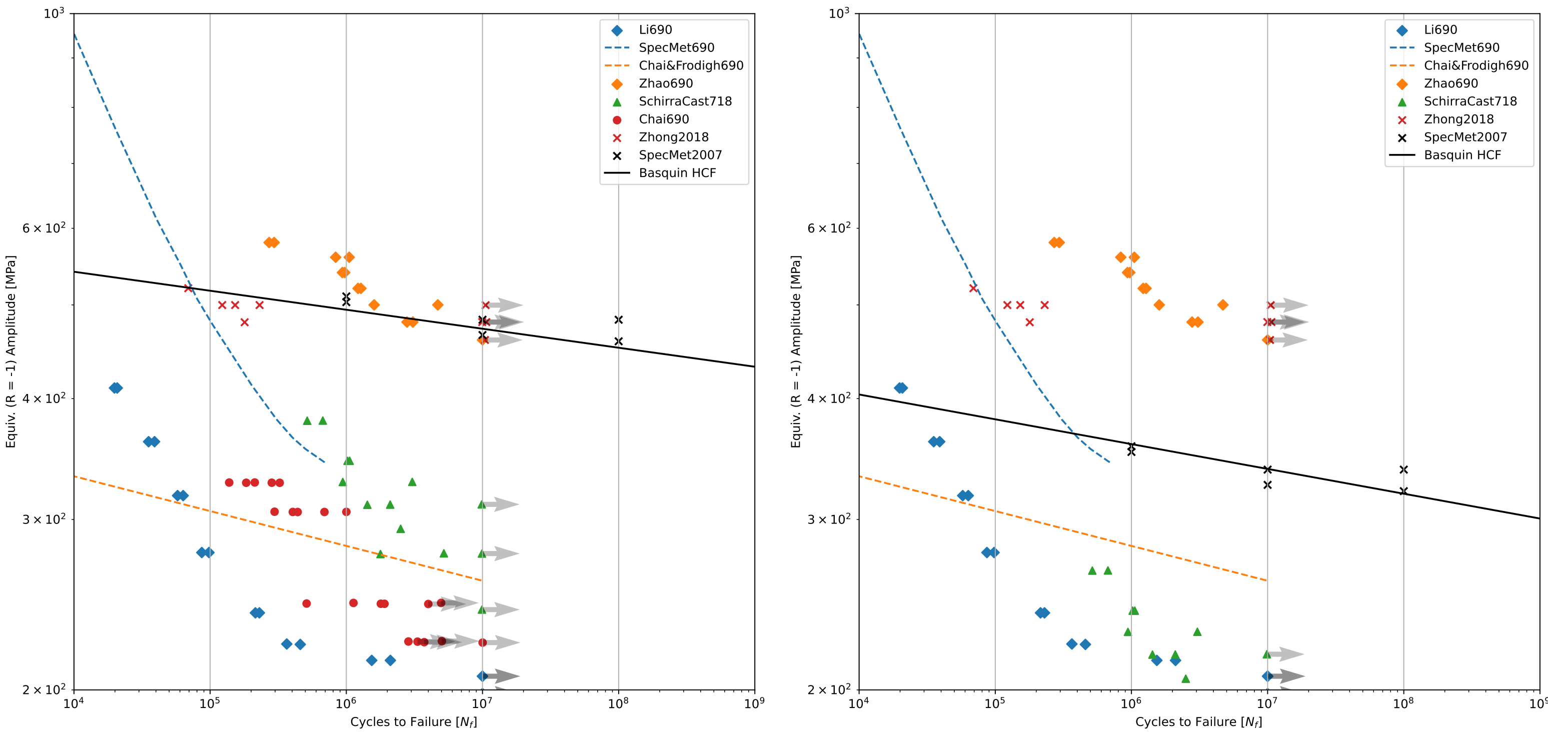
Table 11. Available fatigue data for other possible Inconel alloys at room temperature.

Authors	**Year**	**Treatment**	**Freq. [Hz]**	**Test**	**R**	**Ref.**
Li *et al*.	2020	690	30	Tensile/Tensile	0.1	[60]
Chai *et al*.	2007	690	140	Tensile/Tensile	0.1	[22]
Special Metals	2009	690	n/a	Push/Pull	-1	[49]
Chai & Frodigh	2002	690	0.15	Push/Pull	-1	[21]
Zhao *et al*.	2017	690	n/a	Push/Pull	-1	[101]
Schirra	1997	718 Cast	30	Krouse	-1	[86]



(a) No knockdown for RBF data. **(b)** $K_{RBF} = 0.7$

Figure 34. Available fatigue data for IN690 and cast IN718(PH).



(a) No knockdown for RBF data. **(b)** $K_{RBF} = 0.7$

Figure 35. Available fatigue data for IN690 and cast IN718 with overlay of IN718(SA) fatigue data. Both IN690 and cast IN718 perform worse than IN718(SA).

3.1.1.4 Weld Tensile and Fatigue Strength

Tensile Strength

To ascertain the tensile strength of the weld, tensile tests of as-welded Inconel Filler Metal 718 are compared against annealed bar/round stock of Inconel 718. Figure 36 shows the comparison of the mean UTS which is a 10% reduction from 944 MPa to 854 MPa. Special Metals also tested the effects of post-weld annealing temperatures followed by aging (precipitation hardening). Aging aside, they found that "re-annealing after welding prior to aging" produced better properties [50]. The UTS reduction presented would be conservative as any welds would be expected to go through re-annealing during the HIP manufacturing process.

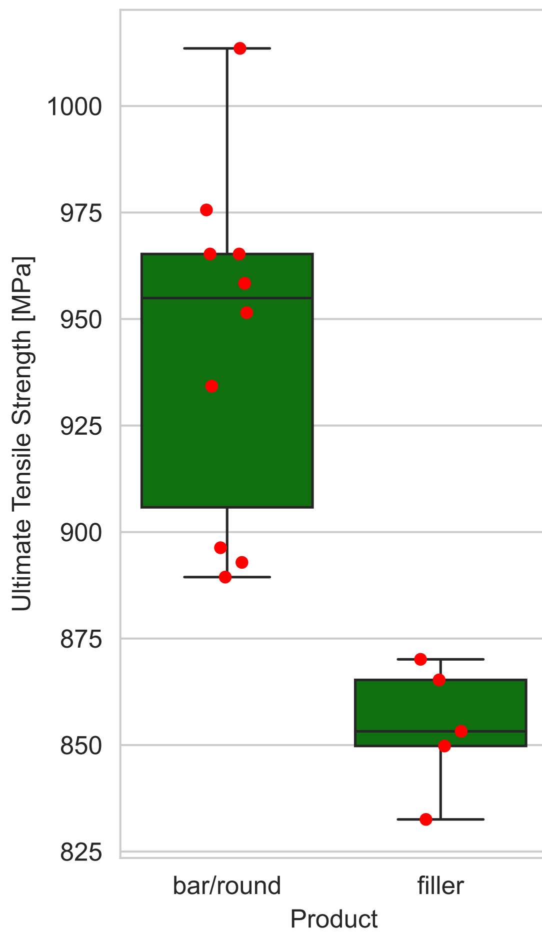


Figure 36. UTS of as-welded filler material compared to annealed bar/round stock. Data from Tables 8 and 35 of Special Metals [50].

Fatigue Strength

With the previously discussed assumption that IN718(PH) and IN718(SA) fatigue behavior is comparable, Special Metals provides a statement on weld fatigue [50]:

> Weldments were found to have a room-temperature fatigue strength (10^8 cycles) of approximately 62.5 ksi (tested in R.R. Moore rotating-beam apparatus). They were made from hot-rolled , annealed (per AMS 5596) 0.500-in. plate, joined with 0.125-in.-diameter INCONEL Filler Metal 718 by the gas tungsten-arc process. Samples were aged 1325°F/8 hr, F.C. to 1150°F, hold at

1150°F for total aging time of 18 hours and tested as polished specimens. In comparable tests, alloy 718 bar had a fatigue strength (10^8 cycles) of 89.0 ksi.

This would indicate a weld fatigue strength reduction factor (FSRF) of 1.424 (89.0 ksi / 62.5 ksi).

Weld Modified Goodman Diagram

Figure 37 shows the Goodman diagram for the 10 year pulse lifetime with a modification for welds. The UTS is reduced by 10% and the fatigue strength at 135M cycles is reduced by a 1.424 Fatigue Strength Reduction Factor (FSRF). Any further debits (i.e. due to weld inspectability) should be considered in respective component DACs.

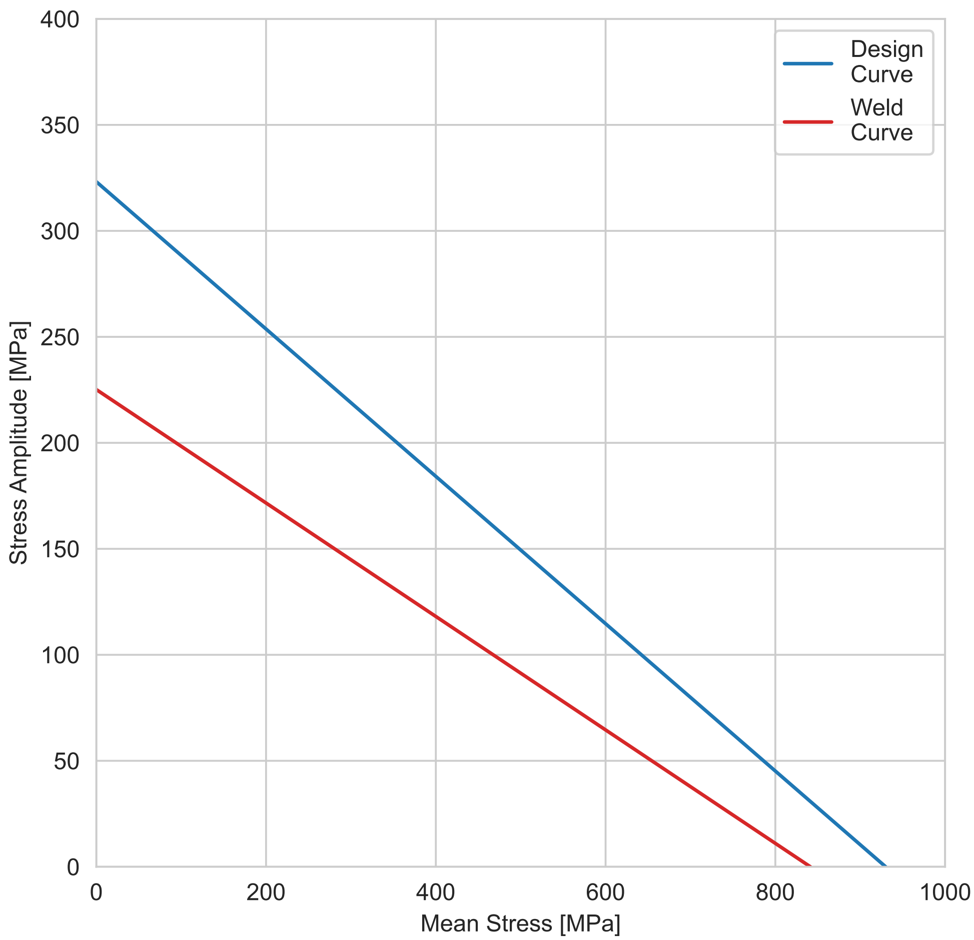


Figure 37. Reduced fatigue lifetime design envelope for Inconel weld materials.

3.1.1.5 Fatigue Model

There does not appear to be a clear consensus in the literature on a fatigue failure mode for Inconel. In recent years, SNS has used *fe-safe* commercial fatigue software to perform fatigue life analysis on target finite element analysis (FEA) simulations. One benefit of the software is that it provides an extensive material library which includes IN718(PH). The default material model, somewhat surprisingly, is a normal stress mode with a custom mean stress correction. This seems to be in conflict with the theory reference manual which states [35, pp. 7–16]:

> It has been shown over the past 20 years that principal stresses should only be used for fatigue analysis of 'brittle' metals, for example cast irons and very high strength steels. *A fatigue analysis using principal stresses gives very unsafe fatigue life predictions for more ductile metals including most commonly used steels.*

The brittle failure mode may be connected to the PH treatment of the alloy. Zhong *et al.* performed HCF tests of both SA and PH treatments, however, they only went up to 10^7 cycles. As they reported, "From the perspective of the fatigue source area as the fracture mode, the [SA] state had an obvious plastic fracture mode . . . , and the small facet of the cleavage for the fatigue fracture area of the [PH] state . . . illustrated a cleavage fracture mode . . ." [102]. They accordingly found that the fatigue limit of the SA state was lower than that of the PH state. This is in conflict, however, with Special Metals which reported, "If fatigue strength is of prime importance, INCONEL alloy 718 forgings can be used in the annealed rather than the annealed and aged condition; aging raises fatigue strength only slightly (less than 4 ksi in Table 31)" [50].

Another confounding issue is the very high cycle fatigue (VHCF) regime (loosely defined as > 10^7 cycles). For steels, the VHCF regime corresponds to a change in failure mode from surface crack initiation to volumetric crack initiation [90] [80]. Song *et al.* performed HCF and VHCF tests on selective laser melted Inconel 718. In their paper, they compared results to equivalent fatigue tests of wrought specimens at 650°C. They found: [92]

> In the regime above $10^7 - 10^8$ cycles, however, all fatigue cracks were initiated from the internal defects (e.g., lack of fusion defects and inclusion) and the microstructure discontinuities (e.g., Laves phase and phase, or crystallographic facets), regardless of the fabrication processes and the test temperatures, indicating the defect and microstructure dominant failure in the VHCF regime. The transition of the two fatigue crack initiation modes was located at about 10^8 cycles for the SLM alloy and at 10^7 cycles for the wrought alloy.

Chen *et al.* reported IN718(PH) ultrasonic fatigue tests in the VHCF regime. They found [25]:

> ". . . that fatigue strength increases as frequency is raised up to 19.5 kHz and the most of fatigue life is consumed in nucleating and propagating small cracks up to 100 μm. Transition of fracture mode from transgranular ductile fracture to transgranular ductile fracture to cleavage-dominated fracture occurs beyond a critical stress intensity factor range of approximately 21 $MPa\sqrt{m}$ leading to the catastrophic failure under ultrasonic fatigue."

The brittle failure mode, however, could be a function of the testing frequency (and not the quantity of cycles itself). They later point out [25]:

> . . . it is possible that the plastic deformation per cycle is reduced due to less time available for dislocations to glide along favored slip systems . . . , implying that more cycles or higher stress is needed to cause the same degree of fatigue damage as at low frequency. . . . On the other hand, more dislocation sources will be activated in the vicinity of crack tip during the subsequent crack extension. Because the activated dislocations have insufficient time to glide away from the neighborhood of crack tip, some of them will be pinned nearby and more will accumulate at

> grain boundaries, interfaces of precipitations, and specific weaker slip systems to largely absorb ultrasonic energy . . . The former promotes the formation of brittle stress field near crack tip . . . and the latter reduces the necessary stress for potential cleavage cracking.

At this time, we assume a ductile fatigue failure mode for IN718(SA) in the VHCF regime while recognizing the conflicting nature of:

- SA versus PH fatigue behavior
- potential change in crack initiation in transition from HCF to VHCF
- confounding effect of testing frequency versus quantity of cycles

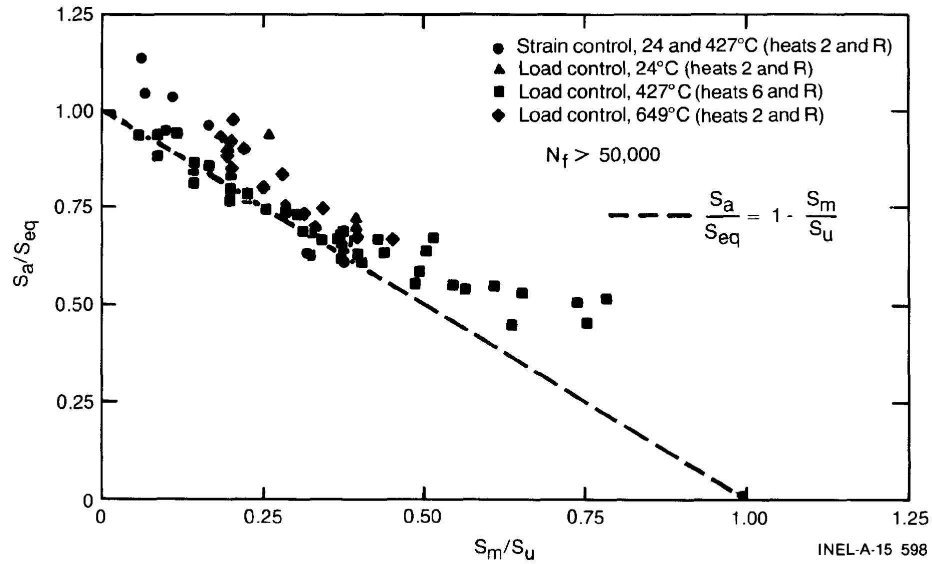
In *fe-safe* software, the most appropriate model is the Brown-Miller fatigue model. This fatigue model is the " . . . preferred algorithm for most ductile metals at room temperature and is the default algorithm for most materials in the fe-safe material database." [36, p. 14-16] The Brown-Miller model ". . . proposes that the maximum fatigue damage occurs on the plane which experiences the maximum shear strain amplitude, and that the damage is a function of both this shear strain and the strain normal to this plane." [35, p. 7-19] In particular, the FEA stress results are used with the stress-based Brown-Miller model, and plasticity effects are disabled since these are already accounted for in the simulations.

Finally, Figure 38 shows the effects of mean stress on IN718(PH) fatigue tests. The Smith-Watson-Topper (SWT) mean stress method is found to be more accurate and has an additional benefit of not requiring UTS knowledge. It does so at the expense of additional model complexity and also makes graphical summary more difficult. The modified Goodman method is shown to be increasingly conservative at high mean stress. This is beneficial and will continue to be used.

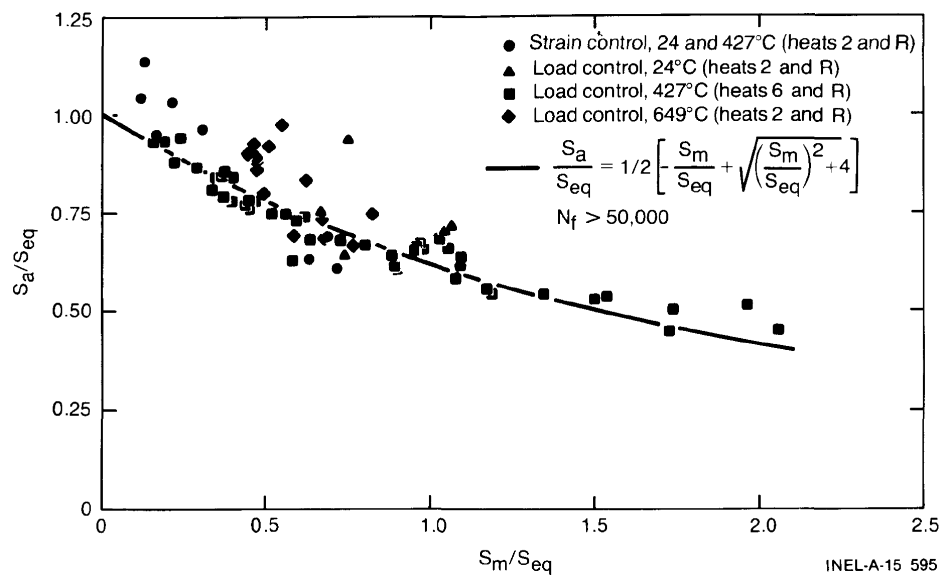
Table 12 lists the important fatigue parameters in the *fe-safe* material definition.

Table 12. IN718SA fatigue model settings in *fe-safe* software.

Parameter Name	Value	Comment
fatigue strength coefficient (sf’)	473.16 MPa	$K_{grain} \cdot \sigma'_f$ for ASTM 6
fatigue strength exponent (b)	-0.019635	Basquin fit
fatigue ductility coefficient (Ef’)	0	Plasticity disabled
fatigue ductility exponent (c)	0	Plasticity disabled
K’	1E20	Cyclic plasticity disabled
n’	1	Cyclic plasticity disabled
CAEL	1E11	Constant amplitude endurance limit disabled
Young’s modulus	209,628 MPa	
Poisson’s ratio	0.3	
ultimate tensile strength	930 MPa	
ultimate compressive strength	930 MPa	Assume same as UTS
algorithm	(shear+ direct)Stress: - Goodman	Stress based Brown-Miller



(a) IN718(PH) fatigue data fit with Goodman model.



(b) IN718(PH) fatigue data fit with Smith-Watson-Topper (SWT) model.

Figure 38. Mean stress effects on fatigue strength of IN718(PH). Reproduced from [55].

3.1.1.6 Density

A constant density of $8,190\ kg/m^3$ is reported by Special Metals [50].

3.1.1.7 Elastic Modulus

Figure 39 shows the modulus of elasticity as a function of temperature for IN690 [17]. This is applied to IN718(SA).

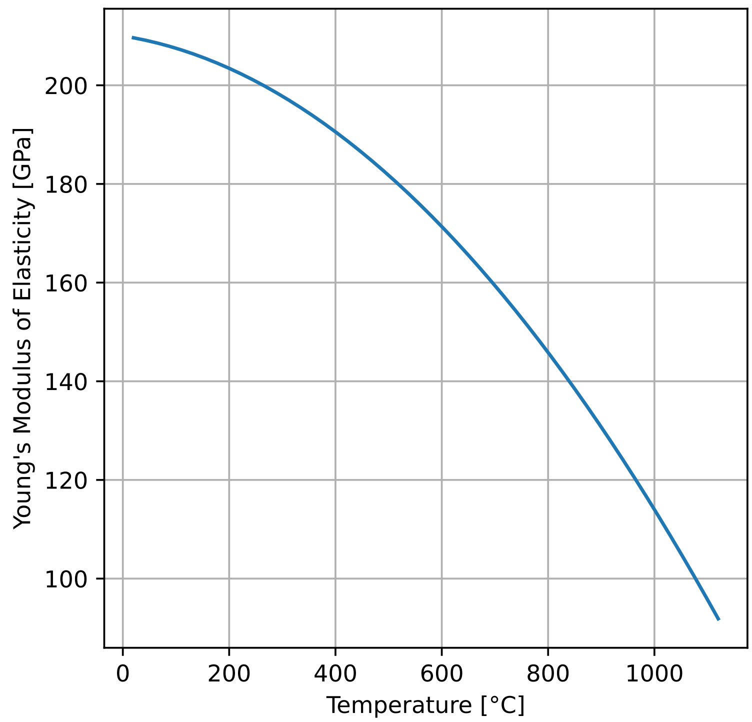


Figure 39. IN718(SA) modulus of elasticity as a function of temperature, as inferred from IN690.

3.1.1.8 Poisson's Ratio

Figure 40 shows the Poisson's Ratio as a function of temperature for IN690 [17]. A constant value of 0.3 is used for IN718(SA).

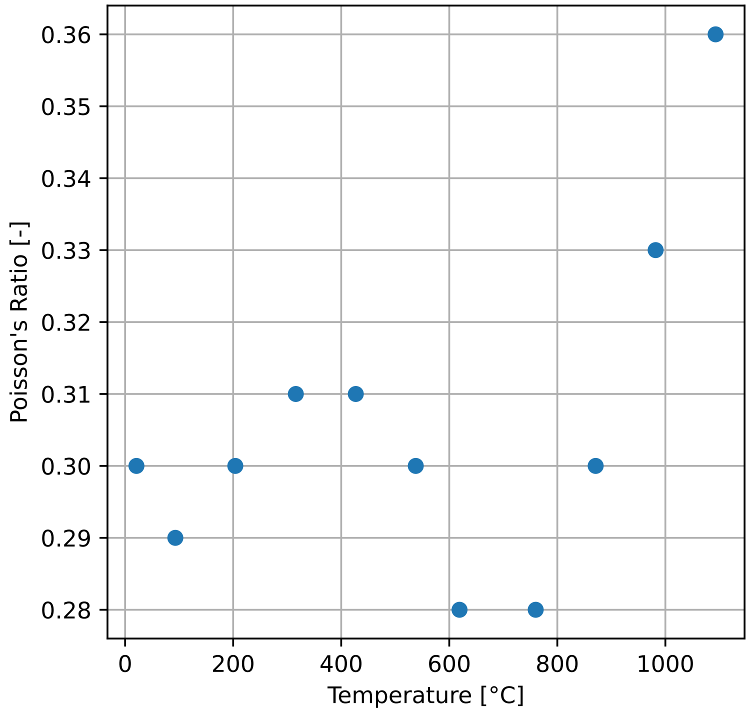


Figure 40. IN718(SA) Poisson's ratio as a function of temperature, as inferred from IN690.

3.1.1.9 Thermal Conductivity

Figure 41 shows the thermal conductivity as a function of temperature for IN718. The Boiler and Pressure Vessel Code (ASME/BPVC) data is reported for IN718(PH) [1] while the Special Metals data is reported for IN718(SA) [50]. The difference between the two data sets is considered negligible.

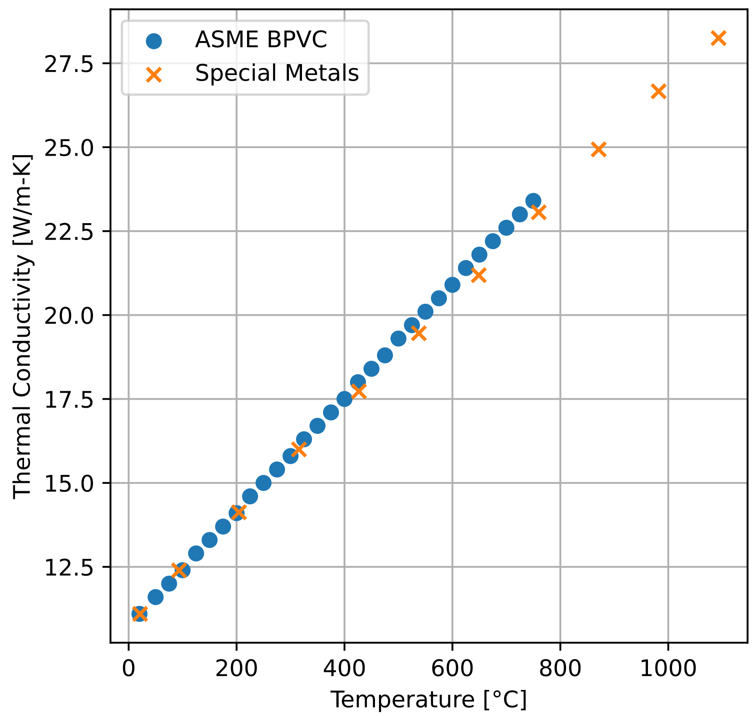


Figure 41. IN718(SA) thermal conductivity as a function of temperature.

3.1.1.10 Coefficient of Thermal Expansion

Figure 42 shows the CTE as a function of temperature for IN690 reported by Special Metals [49], and this is used for IN718SA. The CTE is an average from a 24°C reference temperature. To accommodate Sierra, which calculates the CTE from the slope of a thermal strain function, the data is curve-fit with the polynomial shown in Equation 21. This can then be simply integrated for use in Sierra.

$$CTE_{avg} = -3.270911 \times 10^{-9}\, T^3 + 6.924748 \times 10^{-6}\, T^2 - 2.807229 \times 10^{-4}\, T + 1.405871 \times 10^{1} \qquad (21)$$

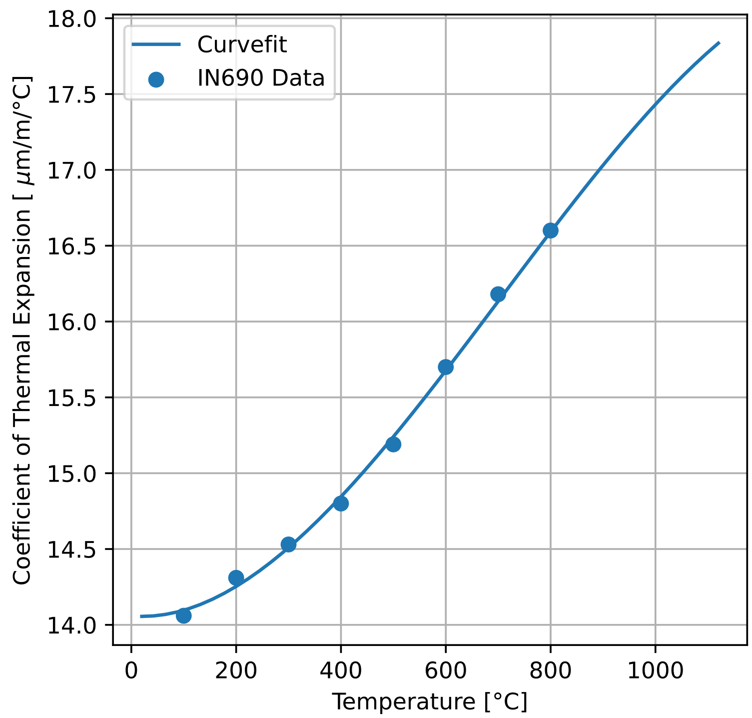


Figure 42. IN718(SA) CTE as a function of temperature, as inferred from IN690.

3.1.1.11 Specific Heat

Figure 43 shows the thermal conductivity as a function of temperature for IN718(PH). The ASME/BPVC data was calculated from thermal diffusivity, thermal conductivity, and density [2]. Special Metals reports a room temperature value which matches within expected tolerance [50]. These data sets are assumed to apply to IN718SA.

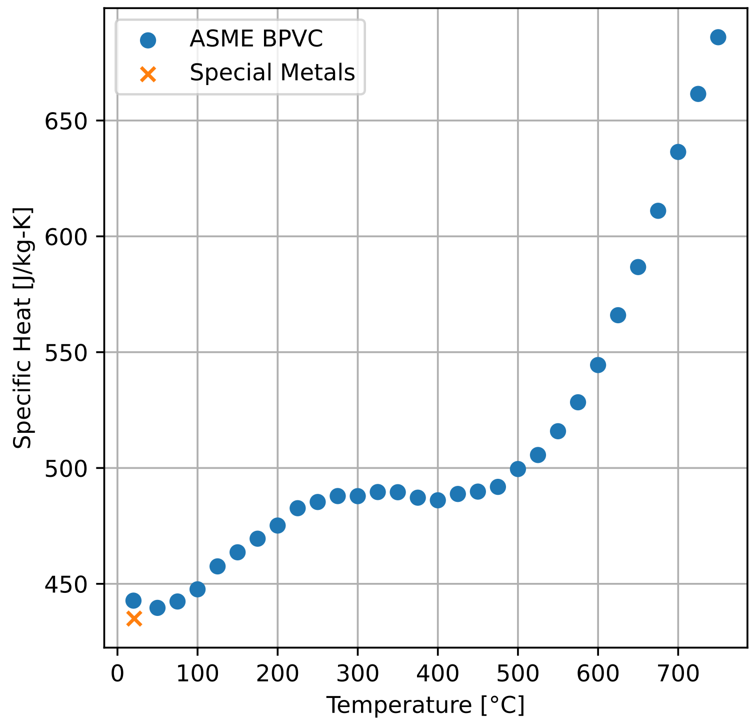


Figure 43. IN718(SA) specific heat as a function of temperature.

3.1.1.12 Creep

A creep model for IN718(SA) can be constructed from the experiments of Thomas *et al.* [95]. The Inconel samples used in the experiments were maintained in the annealed condition:

> This material was received in annealed state (1 h at 1010°C), with a hardness HRB= 102. The as-received grain size was evaluated by conventional metallographic preparation, resulting in an average size of 85 μm. . . . Cylindrical samples, 7.4mm in diameter and 11mm in length, were machined for this purpose. They were isothermically upset at the following temperatures: 1080, 1050, 1000, 950 and 900 °C, at four different strain rates: 0.1, 0.01, 0.001 and 0.0005 s. The heating and cooling rates were fast enough to avoid precipitation while achieving the testing temperature. In both studies, and in order to homogenize the microstructure, samples were previously pre-heated at 1080°C during 1 h.

Thomas *et al.* chose to use a normalized the hyperbolic-sine law model (Equation 22) with the temperature dependent Young's modulus and self-diffusion coefficient (Equation 23), both for pure nickel. For small values of the stress argument, they recovered a linear relationship (Equation 24) that could be fit with experimental data to determine the material constants. The creep exponent was closer to 6 which appeared to be due to precipitation hardening effects so the theoretical value of 5 was used by the authors in their fitting. They made an error in the reported value for A, however, as the slope from Equation 24 is actually $A^{1/n}\alpha$. The correct value $A = 1.03323 \times 10^{25}\ m^{-2}$ was obtained instead by manually digitizing the data and performing a linear regression.

$$\frac{\dot{\epsilon}}{D(T)} = A\left[\sinh \alpha \frac{\sigma}{E(T)}\right]^n \tag{22}$$

$$D(T) = D_0 \exp\left(-\frac{Q_{sd}}{RT}\right) \tag{23}$$

$$\left[\frac{\dot{\epsilon}}{D(T)}\right]^{1/n} \approx A^{1/n}\alpha\left[\frac{\sigma}{E(T)}\right]; \quad \text{for } \alpha\frac{\sigma}{E(T)} \ll 1 \tag{24}$$

The closest comparable creep model in Abaqus software is the hyperbolic-sine law model, shown in Equation 25. The parameter values are then found as shown in Equation 26. Since the Abaqus simulation models require constant parameters, the elastic modulus value is set to the HIP manufacturing dwell temperature of 954°C.

$$\dot{\epsilon} = C_1\,[\sinh(C_2\sigma)]^n \exp\left(-\frac{\Delta H}{RT}\right) \tag{25}$$

$$\begin{aligned}
C_1 = A \cdot D_0 = 1.03323 \times 10^{25}\ m^{-2} \cdot 1.6 \times 10^{-4}\ m^2/s = 1.6532 \times 10^{21}\ s^{-1} \\
C_2 = \alpha/E(T) = 5.03/160.472\ \text{GPa} = 3.1345 \times 10^{-11}\ \text{Pa}^{-1} \\
n = 5 \\
\Delta H = Q_{sd} = 285\ \text{KJ/mol} \\
R = 8.314\ \text{J/K-mol}
\end{aligned} \tag{26}$$

Appendix E contains an unpublished validation of this creep model. Vacuum Hot Press (VHP) samples of IN718(SA), tantalum, and tungsten were made at ORNL. Gross deformation was measured and compared against FEA simulations where creep was the dominant deformation mechanism. The model was able to match global deformation measurements within 5% error.

3.1.2 Irradiated Condition

Quite impressively, IN718(SA) appears to demonstrate increased ductility with irradiation [70]. Without further information, we assume no changes to material properties in the irradiated condition.

3.2 FUTURE WORK

Tom McManamy provided a new reference for thermal conductivity, specific heat, and CTE as functions of temperature. A perusal of the reported results appears to match the Special Metals and ASME/BPVC data already provided. This could be analyzed in more detail in the future.

- A. S. Agazhanov, D. A. Samoshkin, and Y. M. Kozlovskii, "Thermophysical properties of Inconel 718 alloy," Journal of Physics: Conference Series, vol. 1382, no. 1, p. 012175, Nov. 2019, doi: 10.1088/1742-6596/1382/1/012175.

Tom McManamy has also provided a reference for emissivity of IN718 as a function of temperature. This should be incorporated into the Abaqus material properties for radiation heat transfer studies.

- Greene, G A. 1999. "DEPENDENCE OF TOTAL HEMISPHERICAL EMISSIVITY OF INCONEL-718 ON SURFACE OXIDATION AND TEMPERATURE.". United States. https://doi.org/10.2172/750781. https://www.osti.gov/servlets/purl/750781.

The following tensile data is available and could be used to better tune and validate the IN718(SA) constitutive model:

- Thomas *et al*. [95] report flow stresses over a range of plastic strains (0-80%), temperatures (900, 950, 1000, 1050°C), and strain rates (0.0005, 0.001, 0.01, 0.1 s^{-1})
- Malmelöv *et al*. [64] report flow stresses over a range of plastic strains (0-40%), temperatures (50, 200, 400, 600, 700, 800, 900, 1000, 1100°C), and strain rates (0.01, 0.1 s^{-1})
- Moretti *et al*. [72] report flow stresses over a range of plastic strains (0-70%), temperatures (RT, 200, 400, 600, 700, 800°C), and strain rates (0.001, 0.01, 0.1, 1400, 2000 s^{-1})

4. COPPER

4.1 MATERIAL BEHAVIOR

4.1.1 Unirradiated Condition

4.1.1.1 ThermoElastic-Plastic Behavior

Table 13. Copper constitutive model physical properties and adjustable parameters.

Parameter	Name	Value	Units	Ref.
k/b^3	Boltzman's constant divided by cube of the Burgers vector	0.823	[MPa/K]	[54]
$\dot{\epsilon}_0$	Reference strain rate	10^{-7}	[1/s]	[54]
g_0	Normalized activation energy	0.8464		[53, Fig.26]
σ_{V0}	Voce (saturation) stress	774	[MPa]	[53, Fig.26]
p	MTS model fitting constant (glide resistance profile shape)	0.5		[53]
q	MTS model fitting constant (glide resistance profile shape)	2		[53]
μ_0	Reference shear modulus	45780	[MPa]	[54]
T_0	Reference temperature for shear modulus	180	[K]	[54]
D_0	Shear modulus equation fitting constant	3000	[MPa]	[54]
κ	Modified Voce hardening law exponent	1.3		[53, Fig.22]
Θ_0/μ	Normalized characteristic strain hardening value	0.045		[53, Fig.22]

Kocks and Mecking present a modified Voce law that is shown to describe copper well [53]

$$\frac{\Theta}{\Theta_0} = \left(1 - \frac{\sigma}{\kappa\sigma_V}\right)^{\kappa} \text{ ; where } \Theta = \frac{d\sigma}{d\epsilon} \tag{27}$$

Here, Θ is the net hardening rate and is the derivative of the true plastic stress with respect to the true plastic strain. This can be integrated to recover an equation for the plastic stress as a function of strain

$$\sigma = \kappa\sigma_V \left[1 - \left(\frac{\theta_0\epsilon(\kappa - 1)}{\sigma_V\kappa} + 1\right)^{\frac{1}{1-\kappa}}\right] \tag{28}$$

The scaling stress, or Voce saturation stress, is described by

$$\sigma_V = \frac{\mu}{\mu_0}\sigma_{V_0}\left[1 - \left(\frac{k/b^3 T \ln\frac{\dot{\epsilon}_0}{\dot{\epsilon}}}{\mu g_0}\right)^p\right]^q \tag{29}$$

Finally, the temperature dependence of the shear modulus is described by

$$\mu = \mu_0 - \frac{D_0}{\exp\left[\frac{T_0}{T}\right] - 1} \tag{30}$$

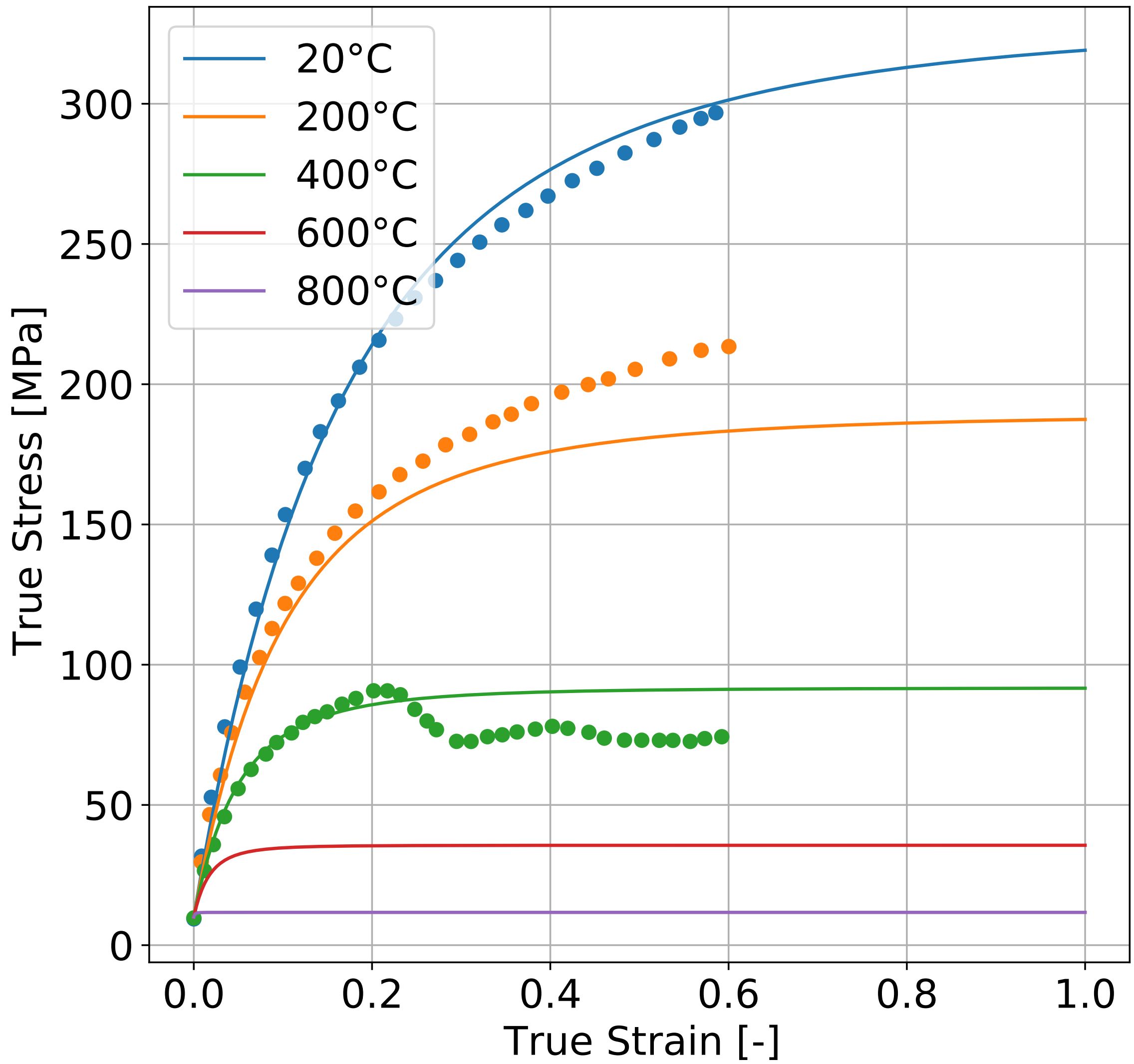


Figure 44. Copper thermoelastic-plastic response. Symbols are compression measurements of copper polycrystals at $10^{-4}s^{-1}$ by Chen & Kocks [27]. Lines are functions of the modified Voce law.

Table 13 summarizes the parameters and properties used in the model. Figure 44 compares the modified Voce law against copper polycrystal compression measurements by Chen & Kocks [27] for a 0.0001/s strain rate. Equation 27 is shifted by 10 MPa to account for the yield stress shown in the Chen & Kocks paper. Good agreement is seen for strains below 20%. At 400°C, measured data shows the effects of dynamic recrystallization. The response is essentially perfectly plastic by 800°C.

The analytical curves can then be implemented in FEA software such as Sierra Multiphysics as a ThermoElastic-Plastic material model. Strain rate effects are ignored since the dominant physics to model are the slow manufacturing process. The yield stress is fixed at 10 MPa to avoid numerical instabilities in the FEA software.

4.1.1.2 Fatigue Strength & Model

A fatigue strength and model have not been developed at this time. The current target design uses as a heat transfer material only and not as a structural material. Furthermore, it is fully contained between the Inconel shroud and the W/Ta laminate.

4.1.1.3 Density

A room temperature density of $8,940\ kg/m^3$ is reported by the ITER MPH [11]. A curve fit of density as a function of temperature was also created by ITER using the thermal expansion function. Equation 31 is reported to be valid from $20 < T(°C) < 900$

$$\rho(kg/m^3) = 8940\left[1 - 3.0 \times 10^{-6}\,(T - 20)\left(-2.49 \times 10^{-9}\,T^3 + 8.18 \times 10^{-6}\,T^2 + 3.16 \times 10^{-3}\,T + 16.8\right)\right] \tag{31}$$

4.1.1.4 Elastic Modulus

The ITER MPH provides a polynomial function for pure copper modulus of elasticity as a function of temperature [15]. Equation 32 is reported to be valid from $20 < T(°C) < 400$ with a 1.00 correlation coefficient. The elastic modulus is a weak function of temperature over the range of interest.

$$E(GPa) = 117.0 - 2.17 \times 10^{-2}\, T - 6.29 \times 10^{-5}\, T^2 \text{ ; where } T(°C) \tag{32}$$

4.1.1.5 Poisson's Ratio

The ITER MPH recommends a value of $\nu = 0.33$ over the entire temperature range with an expected uncertainty of 10% [12].

4.1.1.6 Thermal Conductivity

The ITER MPH provides a polynomial function for the thermal conductivity of pure copper as a function of temperature [14]. Equation 33 is reported to be valid from $20 < T(^{\circ}C) < 1,000$.

$$K(\text{W/m-K}) = 402.0 - 7.08 \times 10^{-2}\ T + 2.46 \times 10^{-6}\ T^2 \text{ ; where } T(^{\circ}C) \tag{33}$$

4.1.1.7 Coefficient of Thermal Expansion

The ITER MPH provides tabulated data for the instantaneous CTE of pure copper as a function of temperature [10]. A fourth order polynomial fit of the data over the temperature range of interest is given in Figure 45 and Equation 34.

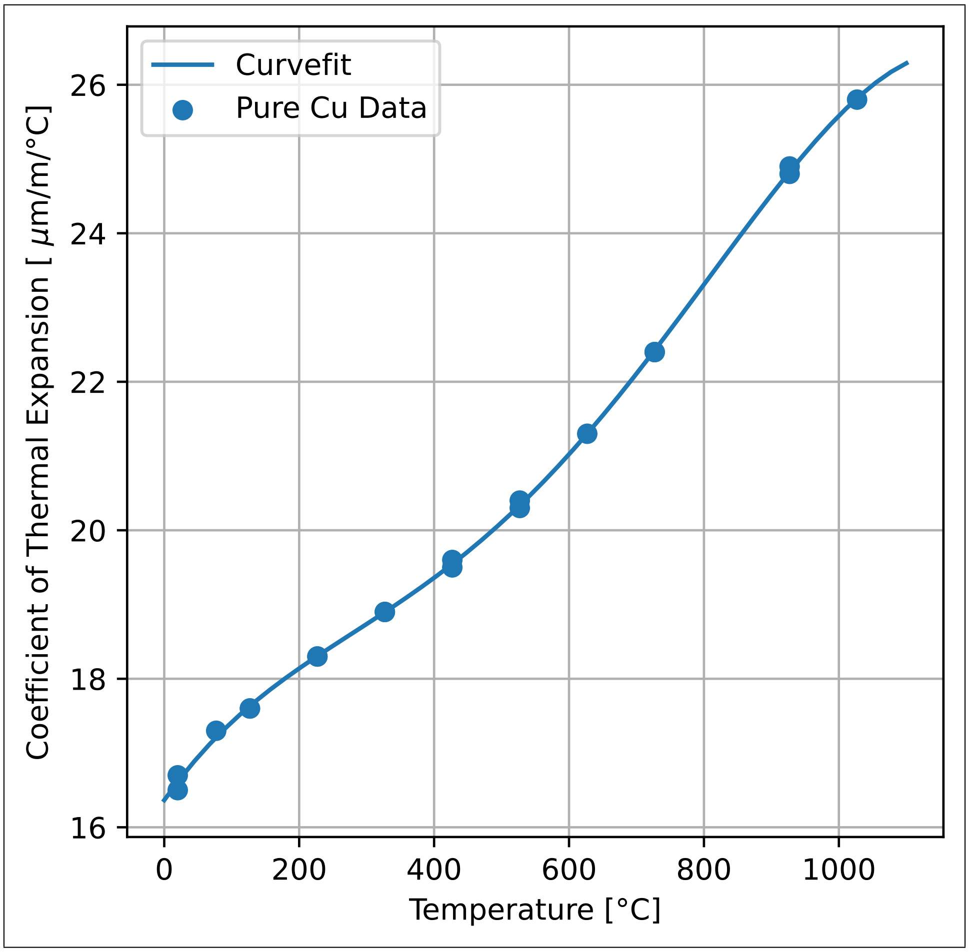


Figure 45. Instantaneous CTE for pure copper as a function of temperature. Data sourced from the ITER MPH [10].

$$
\begin{aligned}
CTE_{inst} = -2.12982695 \times 10^{-11}\, T^4 + 4.63435502 \times 10^{-8}\, T^3 \\
-2.87696224 \times 10^{-5}\, T^2 + 1.29411722 \times 10^{-2}\, T \\
+1.63651568 \times 10^{1}
\end{aligned}
\tag{34}
$$

4.1.1.8 Specific Heat

The ITER MPH provides a polynomial function for the specific heat of pure copper as a function of temperature [13]. Equation 35 is reported to be valid from $20 < T(^{\circ}C) < 1,000$.

$$C_P(\text{J/kg-K}) = 387.0 + 6.35 \times 10^{-2}\ T + 4.36 \times 10^{-5}\ T^2\ ;\ \text{where}\ T(^{\circ}C) \tag{35}$$

4.1.2 Irradiated Condition

4.1.2.1 Stress-Strain Behavior

Li and Zinkle provide summaries of experiments with OFHC copper under fission-relevant, neutron irradiations [59]. Figure 46 indicates the yield stress of copper saturated with dpa at approximately 300 MPa. Figure 47 indicates reduced elongation and reduced strain hardening. Even so, it appears that several percent of strain is achievable. Using this information, an elastic-plastic model for irradiated copper is chosen with a yield stress of 300 MPa and a plastic modulus of 13 MPa.

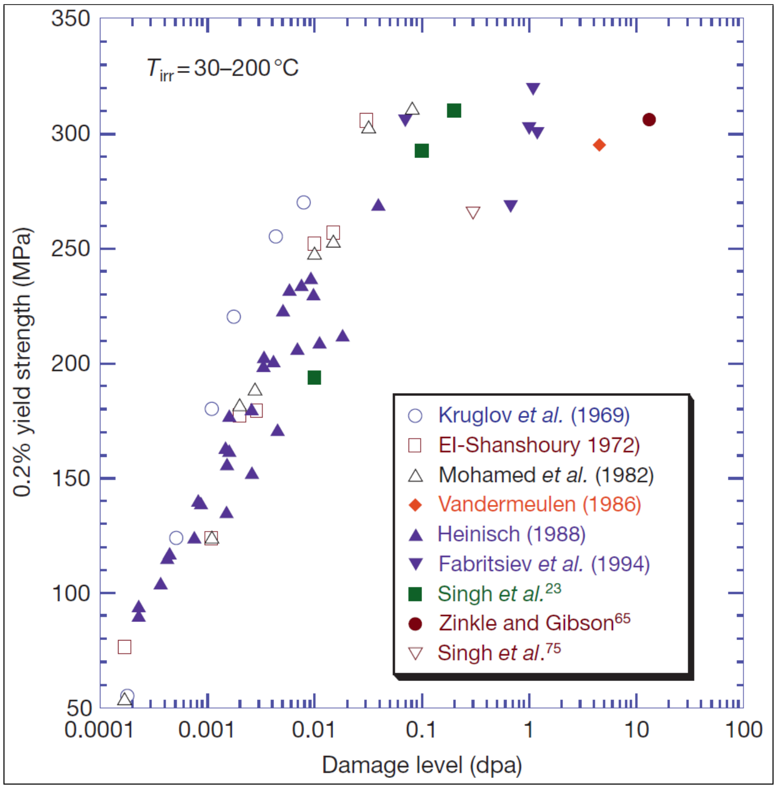


Figure 46. Summary data of radiation hardening in copper under fission-relevant, neutron irradiation. Reproduced from [59].

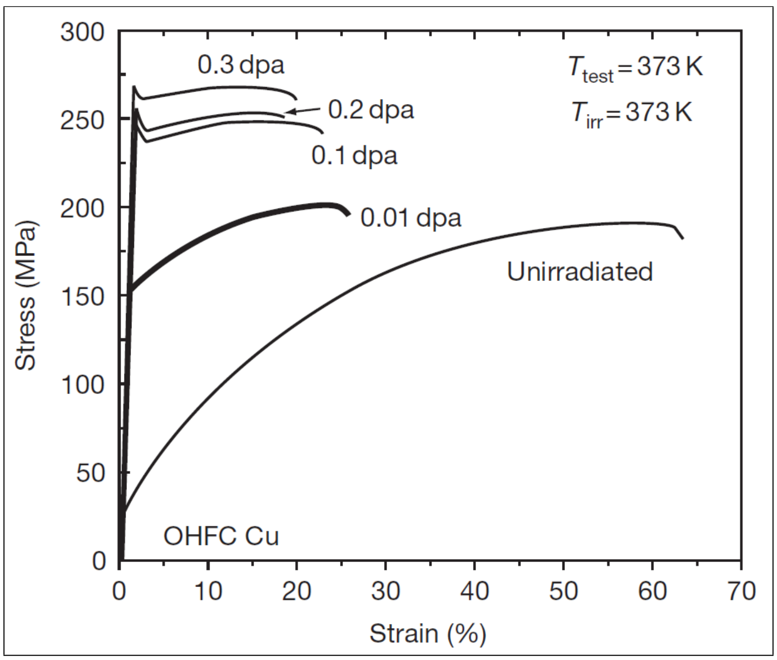


Figure 47. Engineering stress-strain curves for OFHC copper under low temperature, fission-relevant, neutron irradiation. Reproduced from [59].

4.1.2.2 Thermal Conductivity

As shown in Figure 48, the ITER MPH reports a 6% reduction in thermal conductivity for pure copper due to radiation defects that is present for even small dpa levels. For conservatism, we apply this 6% reduction to Equation 33 at beginning of life simulations (i.e. unirradiated condition).

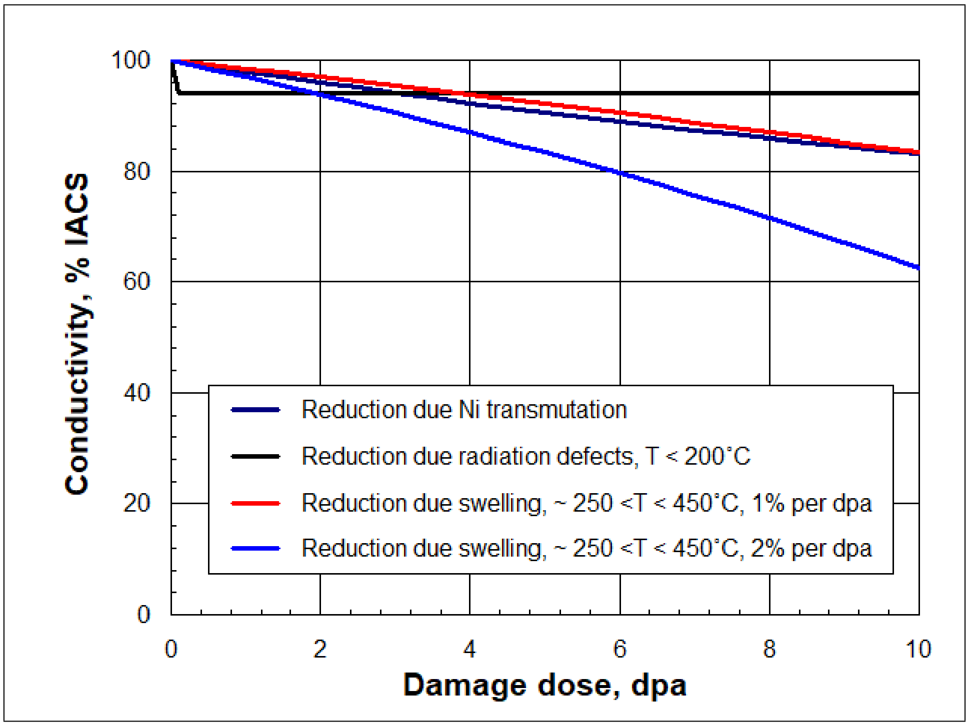


Figure 48. Calculated reduction of conductivity verus damage dose for copper in ITER. Reproduced from the ITER MPH [14].

For the irradiated condition, we assume a 20% reduction in thermal conductivity. This is also based upon the ITER MPH which states [14]:

> The combined effect, based on the contributions of the solid transmutation, displacement damage (mainly at temperatures less than 200°C) and possible swelling (in the temperature range 250 - 450°C) will be not larger than 15-20% at the ITER lifetime fluence goal of 5 dpa.

4.1.2.3 Swelling

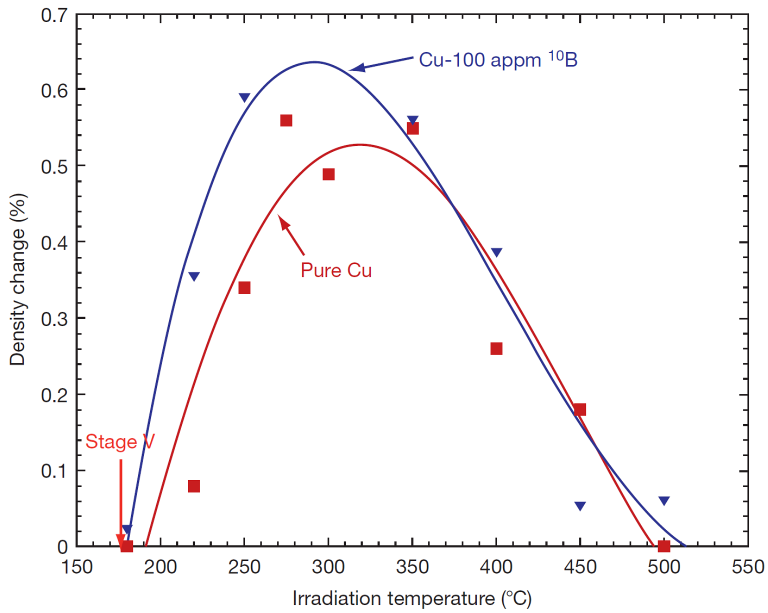


Figure 49. Swelling in pure copper as a function of irradiation temperature for fission-relevant, neutron irradiation. Reproduced from [59].

From Li and Zinkle provide a summary of radiation swelling in copper as shown in Figure 49. They provide the following details [59]:

> Radiation-induced void swelling in copper and copper alloys has been studied extensively. Zinkle and Farrell . . . measured the temperature dependence of void swelling in pure copper and a dilute Cu–B alloy neutron irradiated to ~1.1-1.3 dpa at a damage rate of 2×10^{-7}dpa s^{-1} at temperatures of 180-500°C . . . Maximum swelling occurs at ~300–325°C in pure copper under fission neutron irradiation conditions. The lower temperature limit for void swelling is ~180°C, and the higher temperature limit ~500°C. Low-dose irradiation (<0.2 dpa) often leads to inhomogeneous void formation and nonlinear swelling behavior. . . . A steady-state swelling rate of ~0.5%/dpa is observed in copper at high doses, and the swelling level can be as high as 60%. . . . Variations in displacement damage rate can shift the peak swelling temperature. An order of magnitude decrease in neutron flux can lower the peak swelling temperature by ~20°C. The peak swelling temperature shift can be as high as ~165°C between neutron irradiation (10^{-7}dpa s^{-1}) and ion irradiation (10^{-3}dpa s^{-1}).

We can then deduce the following to model copper swelling in a spallation-relevant environment:

- Treat the pure copper trendline as percent swelling **per dpa** irradiation
- The neutron flux reported (2×10^{-7}dpa s^{-1}) is approximately an order of magnitude higher than the peak flux predicted for the STS target (6.8×10^{-8}dpa s^{-1}). (This value was calculated for a preliminary target design with copper between tungsten plates and would receive a higher peak dose than current designs.) Accordingly, the swelling curve should be shifted down 20°C. The lowest data point shown is 0 density change at 180°C irradiation temperature, so the spallation-relevant swelling curve should start at 160°C.

The density change must be implemented in FEA simulations as an artificial strain. Consider a cube of dimensions a, b, and c. For a constant mass, the percent density change equals the percent volume change. The percent volume change can be manipulated to strain as follows:

$$\begin{aligned}\frac{\Delta V}{V} &= \frac{(a+\Delta a)(b+\Delta b)(c+\Delta c)-abc}{abc}\\ \frac{\Delta V}{V} &= \left(\frac{a+\Delta a}{a}\right)\left(\frac{b+\Delta b}{b}\right)\left(\frac{c+\Delta c}{c}\right)-1\\ \frac{\Delta V}{V} &= (1+\epsilon_{xx})\left(1+\epsilon_{yy}\right)(1+\epsilon_{zz})-1\end{aligned} \tag{36}$$

Let the strain be due to isotropic thermal expansion. Then $\epsilon_{xx} = \epsilon_{yy} = \epsilon_{zz} = \epsilon_T =$, and

$$\begin{aligned}\frac{\Delta V}{V} &= (1+\epsilon_T)^3-1\\ \frac{\Delta V}{V} &= 1+2\epsilon_T+\epsilon_T^2+\epsilon_T+2\epsilon_T^2+\epsilon_T^3-1\\ \frac{\Delta V}{V} &= 3\epsilon_T+\left(3\epsilon_T^2+\epsilon_T^3\right)\\ \frac{\Delta V}{V} &\approx 3\epsilon_T\end{aligned} \tag{37}$$

As shown, the higher order terms are ignored, and the thermal swelling strain is one-third of the volume change fraction. As an example, neglecting the higher order terms associated with a 0.007 thermal strain creates a $< 1\%$ error.

To create the swelling model for FEA:

- The pure copper swelling trendline in Figure 49 is digitized.
- The fraction density change is divided by 3 to yield isotropic strain.
- The strain data is fit with a fourth-order polynomial, and the roots of the polynominal show a y-intercept at 195°C.
- The polynominal is then shifted down by 35°C resulting in Equation 38 as shown in Figure 50.
- The strain equation is then used in FEA software such as Sierra to implement an artificial strain in the copper as a function of temperature and dpa.

$$\begin{aligned}\epsilon_T(\mu\epsilon/\text{dpa}) = 4.373373\times10^{-7}\,(T+35)^4 - 4.063910\times10^{-4}\,(T+35)^3\\ +2.491789\times10^{-2}\,(T+35)^2 + 5.130007\times10^{1}\,(T+35)\\ -8.570303\times10^{3}\ \ ;\text{ where } T(^\circ C)\end{aligned} \tag{38}$$

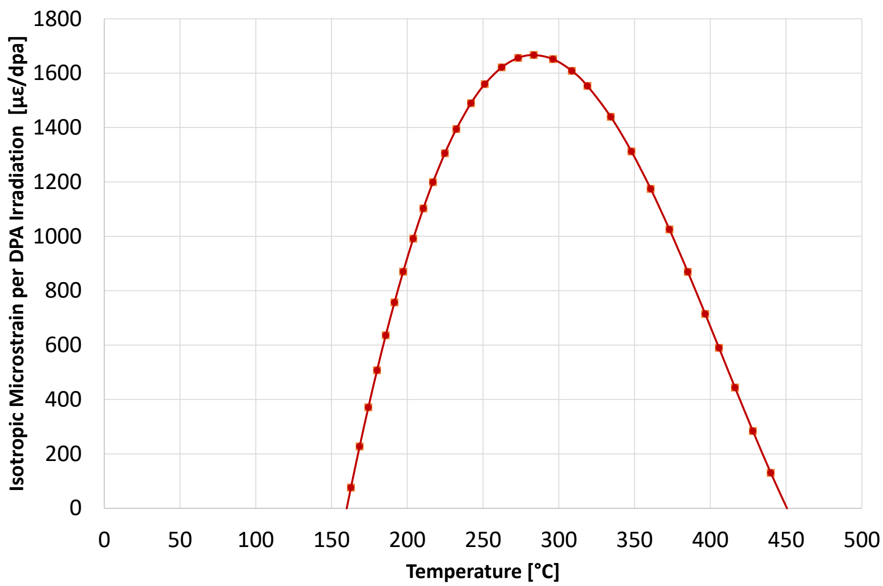


Figure 50. Isotropic swelling strain per dpa of irradiation. Curve has been shifted to account for increased helium production in the spallation environment.

4.2 FUTURE WORK

Yong-Joong Lee has identified work related to DEMO fusion reactors that treats copper as fully brittle with irradiation. In contrast, recent work by Garrison *et al.* on W/Cu laminates reported the copper remained ductile after irradiation [39]. This included high-temperature (410-780°C), fission-relevant, neutron irradiation to a maximum of 1.76 dpa.

R&D activities are ongoing to explore the fundamental mechanisms of irradiation hardening and irradiation swelling. The final target design uses tantalum instead of copper due to these risks. Copper could be considered for future target design iterations should more favorable results be published.

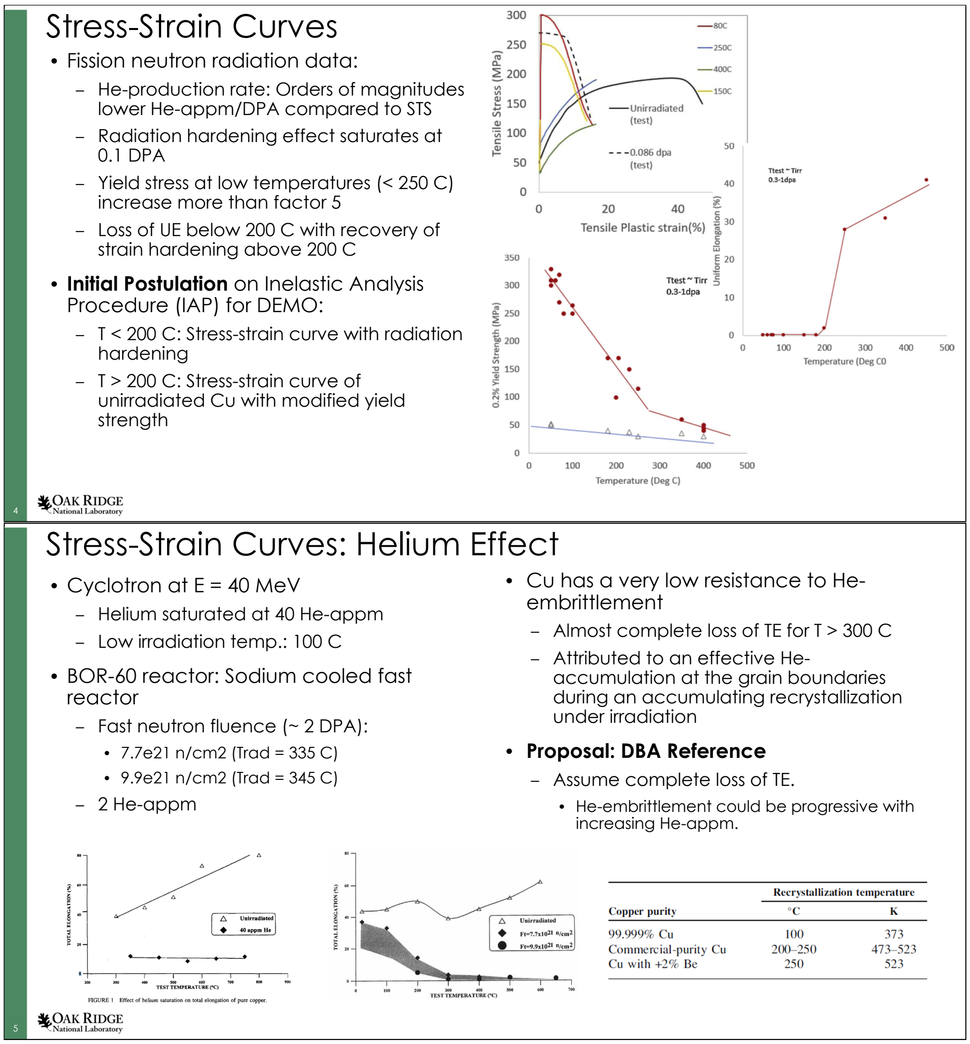


Figure 51. Slides from Yong-Joong Lee presentation "Copper in STS Target Environment" 19 June 2023.

5. 316L STAINLESS STEEL

5.1 MATERIAL BEHAVIOR

5.1.1 Unirradiated Condition

5.1.1.1 Thermoelastic-Plastic Behavior

Figure 52 shows tensile strengths as a function of temperature for 16Cr-12Ni-2Mo steel reported by the ASME/BPVC [3] [4].

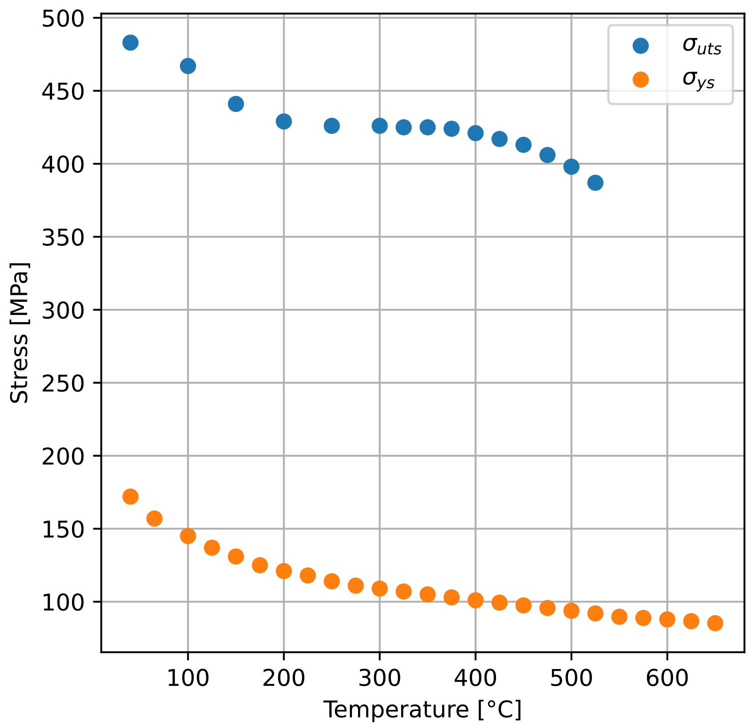


Figure 52. SS316L tensile strengths as a function of temperature [3] [4].

The ASME/BPVC also provides an empirical elastic-plastic stress-strain model for use in elastic-plastic analyses [7]. Equation 39 defines the true strain to be a summation of the elastic strain and two plastic strain contributions.

$$\epsilon_t = \frac{\sigma_t}{E_y} + \gamma_1 + \gamma_2 \tag{39}$$

The term γ_1 is the true strain in the micro-strain region of the stress-strain curve while γ_2 defines the macro-strain region. Equation 40 gives these as

$$\begin{aligned} \gamma_1 &= \frac{\epsilon_1}{2}\left(1.0 - \tanh[H]\right) \\ \gamma_2 &= \frac{\epsilon_2}{2}\left(1.0 + \tanh[H]\right) \end{aligned} \tag{40}$$

The term H is a stress-strain curve fitting parameter that is a function of the yield stress σ_{ys}, ultimate tensile stress σ_{uts}, and their ratio R as shown in Equation 41.

$$
\begin{aligned}
H &= \frac{2\left[\sigma_t - \left(\sigma_{ys} + K\{\sigma_{uts} - \sigma_{ys}\}\right)\right]}{K\left(\sigma_{uts} - \sigma_{ys}\right)} \\
K &= 1.5R^{1.5} - 0.5R^{2.5} - R^{3.5} \\
R &= \frac{\sigma_{ys}}{\sigma_{uts}}
\end{aligned}
\tag{41}
$$

The terms ϵ_1 and ϵ_2 define the true plastic strain in the micro- and macro-strain regions of the stress-strain curve, respectfully. Equation 42 shows these are defined akin to the Ramberg-Osgood relationship.

$$
\begin{aligned}
\epsilon_1 &= \left(\frac{\sigma_t}{A_1}\right)^{\frac{1}{m_1}} \\
\epsilon_2 &= \left(\frac{\sigma_t}{A_2}\right)^{\frac{1}{m_2}}
\end{aligned}
\tag{42}
$$

The strain hardening parameters are given in Equation 43

$$
\begin{aligned}
A_1 &= \frac{\sigma_{ys}\left(1 + \epsilon_{ys}\right)}{\left(\ln\left[1 + \epsilon_{ys}\right]\right)^{m_1}} \\
m_1 &= \frac{\ln[R] + \left(\epsilon_p - \epsilon_{ys}\right)}{\ln\left[\frac{\ln\left[1+\epsilon_p\right]}{\ln\left[1+\epsilon_{ys}\right]}\right]} \\
A_2 &= \frac{\sigma_{uts}\exp[m_2]}{{m_2}^{m_2}} \\
m_2 &= 0.75(1 - R)
\end{aligned}
\tag{43}
$$

where

- A_1 is the curve fitting constant for the elastic region of the stress-strain curve
- A_2 is the curve fitting constant for the plastic region of the stress-strain curve
- m_1 is the curve fitting exponent for the stress-strain curve equal to the true strain at the proportional limit and the strain hardening coefficient in the large strain region.
- m_2 is the curve fitting exponent for the stress-strain curve equal to the true strain at the true ultimate stress
- $\epsilon_{ys} = 0.2\%$ which is the engineering offset strain
- $\epsilon_p = 2.0 \times 10^{-5}$ which is the stress-strain curve fitting parameter

Values for m_2 and ϵ_p are taken from Table 3-D.1 for "Stainless Steel and Nickel Base Alloys" up to 480°C.

Equations 39 through 43 are combined to produce the SS316L stress-strain curves presented in Figure 53. This data is also used to generate the Abaqus plastic stress-strain material data for SS316L archived in Appendix A. For each temperature of interest, an array of true stress values is created that goes from the true stress at ϵ_p (found via iteration or root finding) to the true ultimate tensile stress ($\sigma_{uts}\exp[m_2]$). These values are then used to calculate the corresponding true plastic strain ($\gamma_1 + \gamma_2$). As a nuance, Abaqus requires the first data line to have zero plastic strain so this strain value is overwritten as zero. Additionally, Abaqus assumes perfectly-plastic behavior past the last tabulated data point which is the true ultimate stress.

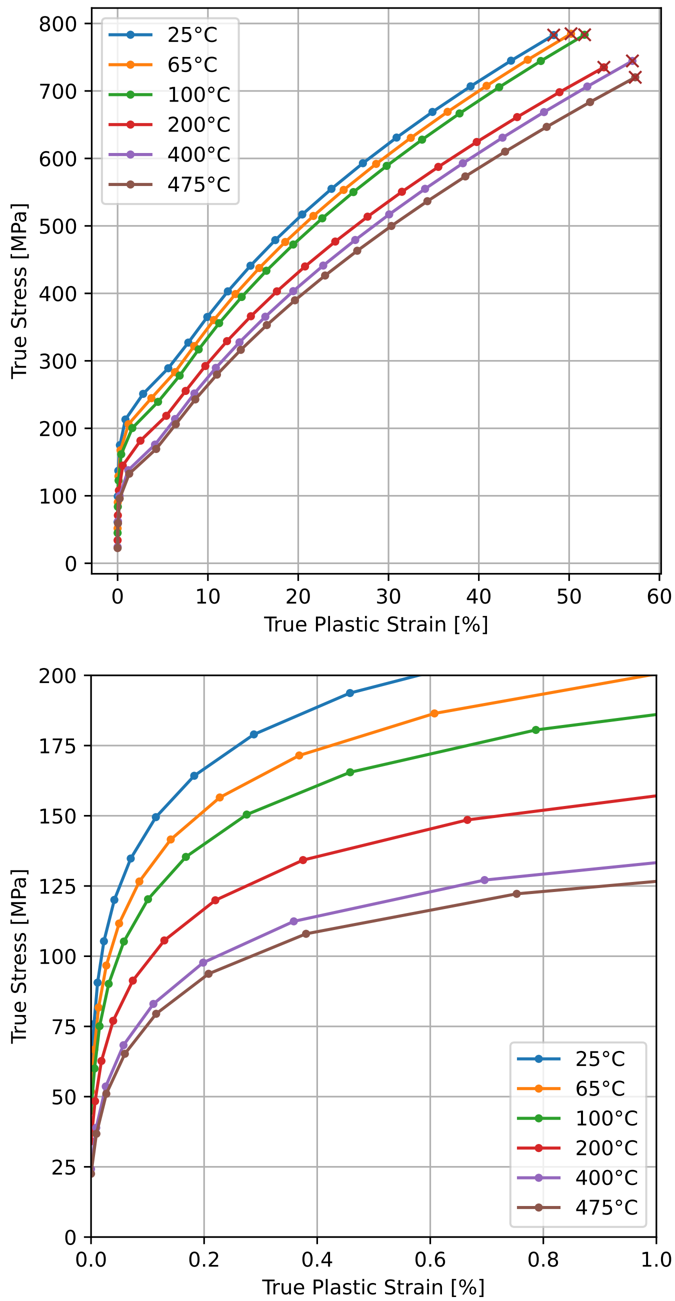


Figure 53. ASME/BPVC thermoelastic-plastic stress-strain curves for stainless steel [7].

5.1.1.2 Fatigue Strength & Model

Mach *et al*. [63] performed fatigue analysis for the SNS liquid mercury target and compared the available fatigue curves for 316L as shown in Figure 54. They chose to use the *fe-safe* built-in material library for stainless steel. This material library has a fatigue curve with temperature dependence and uses the Brown-Miller fatigue model with Morrow mean stress correction. Discussions with *fe-safe* support staff have since revealed a lack of documentation as to the origin of this material library.

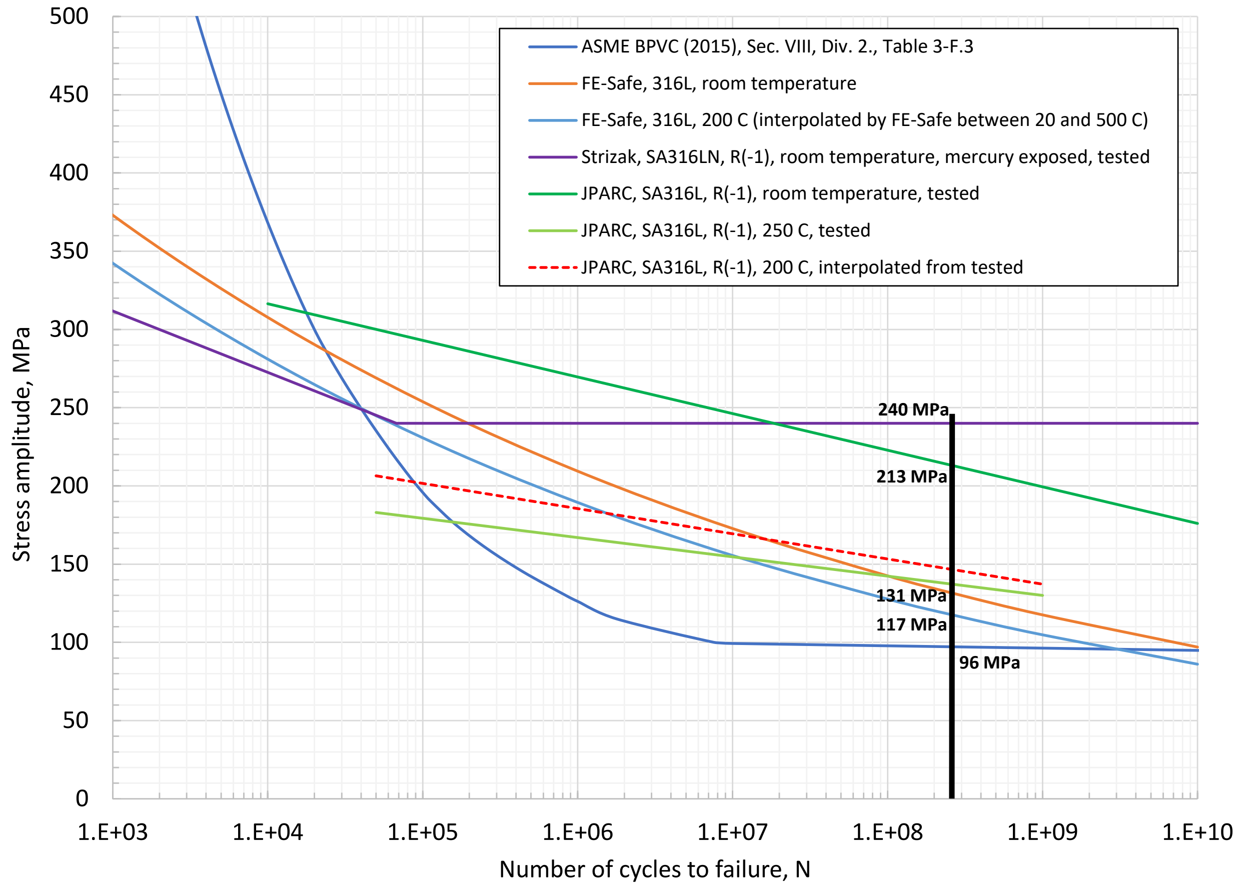


Figure 54. SS316L stress-life curve comparisons (reproduced from Mach *et al*. [63])

A more comprehensive and better documented source of fatigue data comes from a U.S. Nuclear Regulatory Commission (NUREG) study completed through Argonne National Laboratory (ANL) that sought to update the ASME/BPVC to better account for light water reactor (LWR) coolant environments. Morley and McLennan [73] provide an excellent summary in their abstract:

> In the 2009 addendum to the ASME BPV Code . . ., new design fatigue curves were adopted for austenitic stainless steel and nickel-based alloys. These changes followed publication of NUREG/CR-6909 . . . which, in addition to describing a methodology to account for environmental effects on fatigue, challenged both the mean air curve underlying the design fatigue curve and factors used to define the design position from this mean behaviour.
>
> The methodology to build the design curve starts with the mean air curve obtained by laboratory testing, a correction is made for mean stress effects and then the resulting curve is translated by coefficients, referred to within this paper as design factors, applied on stress or on cycles, with

the lower of the two translated curves defining the design curve. The translation by these design factors is to account for factors present in service applications but not present in the laboratory testing and also to provide a conservative position accounting for scatter in fatigue behaviour.

Following a detailed review of the appropriate factor on cycles in NUREG/CR-6909 . . ., the revised ASME design curve replaced the historic design factor of 20 on cycles with a factor of 12, although a later revision of NUREG/CR-6909 . . . further refined this to below 10, the factor of 12 remains. The historic design factor of 2 on stress was not reviewed in any detail NUREG/CR-6909 and was not changed at this time. However, a number of reviews previously and since . . . have suggested that a design factor of 2 is excessive compared to the aim of describing a 95% bounding curve position.

Figure 55 shows the previous ASME/BPVC mean fatigue curve compared against ANL test fatigue data in air over a range of applicable temperatures. In air, at temperatures up to 400°C, the fatigue data for type 316L is best represented by:

$$ln(N) = 6.891 - 1.920 ln\left(\epsilon_a - 0.112\right) \tag{44}$$

where ϵ_a is the percent applied strain amplitude. The authors then used this mean curve to recommend a new fatigue design curve by (a) correcting for mean stress effects using the modified Goodman relationship and then (b) lowering the mean-stress-adjusted curve by the more conservative factor of 2 on stress or 12 on cycles. Figure 56 shows the curve with margins and also documents the elastic modulus and tensile strengths.

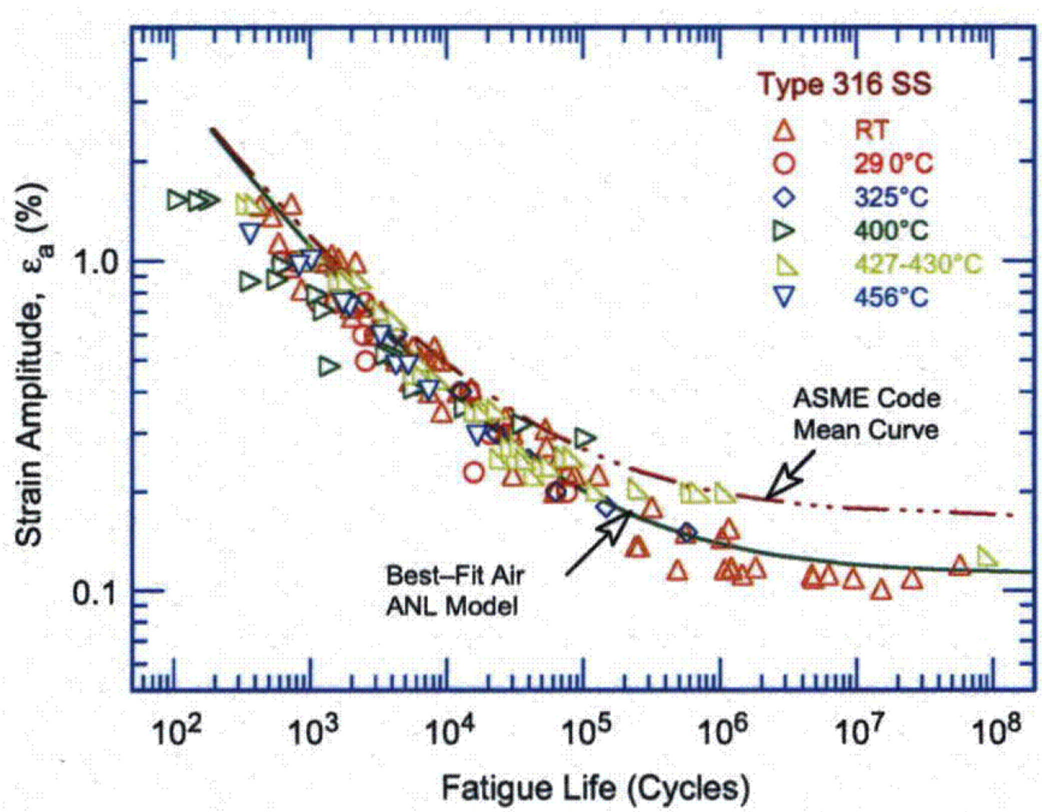


Figure 55. SS316L stress-life curve comparisons (reproduced from [28]).

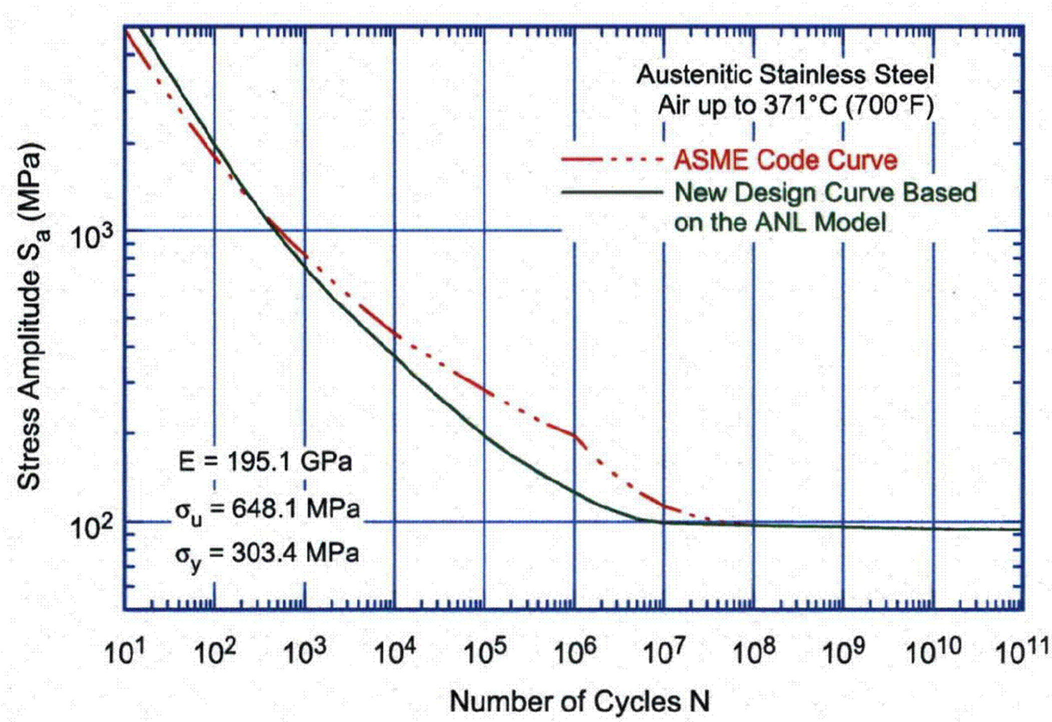


Figure 56. ASME BPVC stress-life curve for SS316L, showing the changes made in 2009 based on ANL testing (reproduced from [28]).

Morley and McLennan [73] also provide an informative statistical analysis on the scatter present in the ANL fatigue data. Figure 57 shows a summary. They reported:

> It has been shown that the current design factor of 2 on stress is excessively conservative to describe data scatter at a 95% bound, which is described instead by a factor of 1.4. If scatter is taken to be the dominant aggravating factor, in line with the general consensus, the design curve could be revised to be less onerous, while maintaining the intended conservatism. A practical and simple development of the current design curve construction is proposed. An additional margin is proposed, through use of a factor of 1.6 rather than 1.4, to account for a number of simplifications in the current construction that have been described qualitatively in the literature and appear to have some basis. Further work to quantify and codify these would be of benefit and may allow this blanket additional margin to be revised at a later date.

For the present study, we seek to design around the mean life curves and thus use the mean fatigue curve given in Equation 44. The 10 year design life of 1.35M cycles dictates a HCF regime that must be predominantly elastic. Accordingly, the applied strain amplitude term in Equation 44 is replaced with σ_a/E which assumes an elastic stress-strain regime. In *fe-safe* software, the FEA stress results are used with the stress-based Brown-Miller model, and plasticity effects are disabled. This fatigue model is the " . . . preferred algorithm for most ductile metals at room temperature and is the default algorithm for most materials in the fe-safe material database." [36, p. 14-16] The Brown-Miller model ". . . proposes that the maximum fatigue damage occurs on the plane which experiences the maximum shear strain amplitude, and that the damage is a function of both this shear strain and the strain normal to this plane." [35, p. 7-19] Table 14 lists the important fatigue parameters in the *fe-safe* material definition. Since the fatigue curve equation is non-standard, the curve is input as an array of stress-cycle data points.

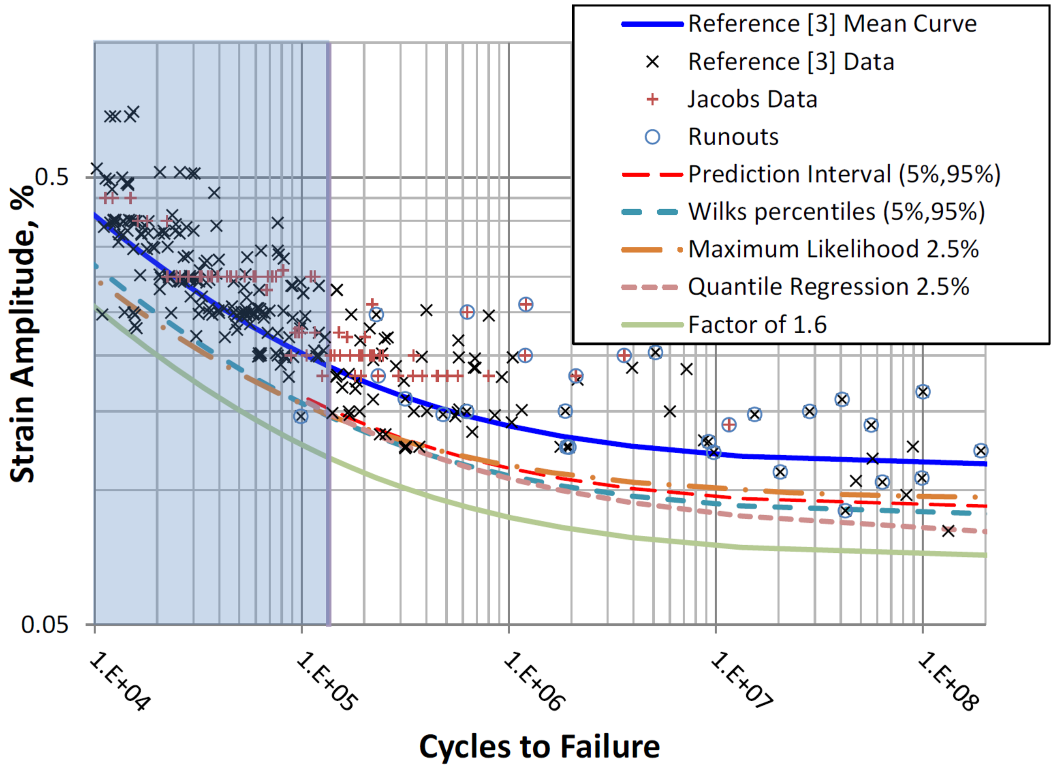


Figure 57. SS316L stress-life data with statistical treatment (reproduced from [73]).

Table 14. Type 316L stainless steel fatigue model settings in *fe-safe* software.

Parameter Name	Value	Comment
stress -life table enabled	`true`	
sample series	*varies*	22 points logspaced from 1.0E+6 to 1.0E+11
control series	*varies*	Equation 44 solved for σ_a
K'	1E20	Cyclic plasticity disabled
n'	1	Cyclic plasticity disabled
CAEL	1E11	Constant amplitude endurance limit disabled
Young's modulus	398,000 MPa	
Poisson's ratio	0.31	
ultimate tensile strength	648.1 MPa	
ultimate compressive strength	648.1 MPa	Assume same as UTS
algorithm	(shear+ direct)Stress: - Goodman	Stress based Brown-Miller

5.1.1.3 Density

TheASME/BPVC recommends a constant value of ρ = 8030 (kg/m-°C) for the Poisson's Ratio of SS316L [5].

5.1.1.4 Elastic Modulus

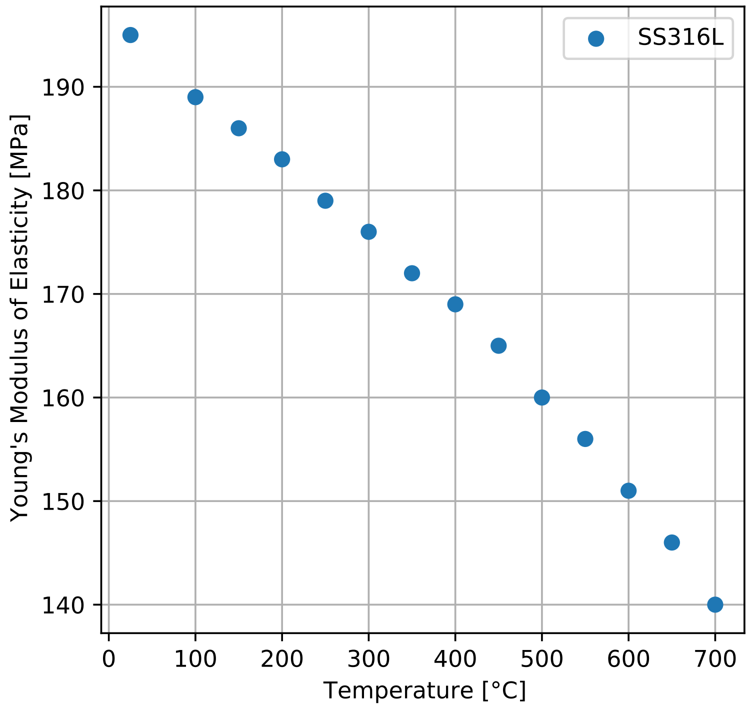


Figure 58. SS316L modulus of elasticity as a function of temperature [6].

5.1.1.5 Poisson's Ratio

The ASME/BPVC recommends a constant value of $\nu = 0.31$ for the Poisson's Ratio of SS316L [5].

5.1.1.6 Thermal Conductivity

Figure 59 shows the thermal conductivity as a function of temperature for 16Cr-12Ni-2Mo high-alloy steel reported by the ASME/BPVC [2], and this is used for SS316L. The standard also states that

> "Values of thermal conductivity and thermal diffusivity should be used with the understanding that there is an associated ±10% uncertainty. This uncertainty results from compositional variations and variables associated with original data acquisition and analysis."

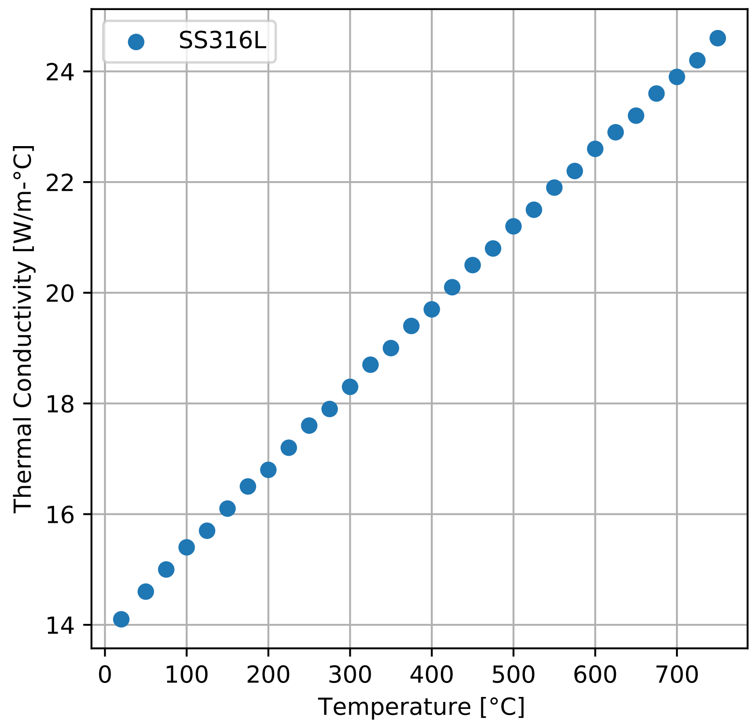


Figure 59. SS316L Thermal conductivity as a function of temperature [2].

5.1.1.7 Coefficient of Thermal Expansion

Figure 60 shows the CTE as a function of temperature for austenitic steels reported by the ASME/BPVC [2], and this is used for SS316L. To accommodate Sierra, which calculates the CTE from the slope of a thermal strain function, the data is curve-fit with the polynomial shown in Equation 45, where temperature is given in Celsius. This can then be simply integrated for use in Sierra.

$$CTE_{inst} = -3.66463841 \times 10^{-13}\, T^4 - 2.45978068 \times 10^{-7}\, T^3 + 4.23285227 \times 10^{-6}\, T^2 + 2.27205870 \times 10^{-2}\, T + 1.48614082 \times 10^{1} \quad (45)$$

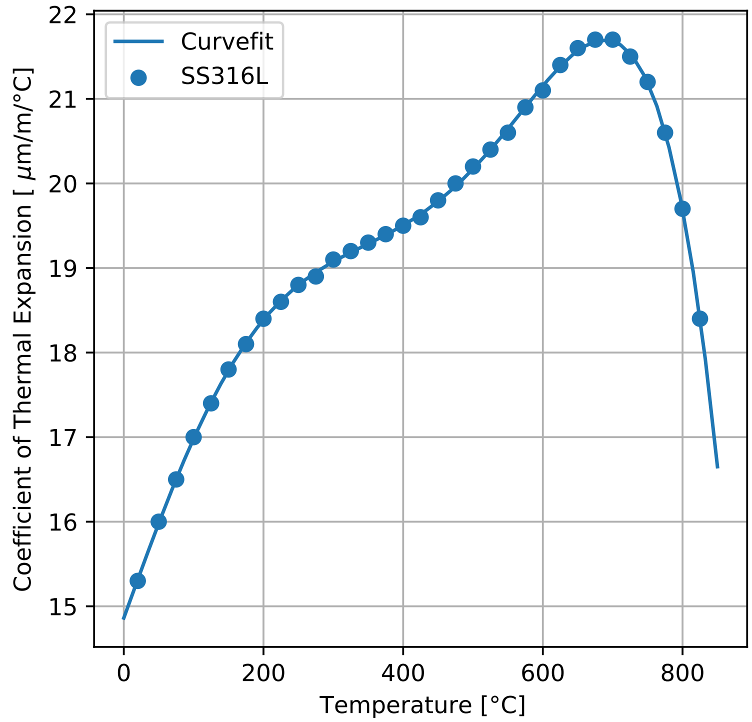


Figure 60. SS316L Instantaneous CTE as a function of temperature [2].

5.1.1.8 Specific Heat

Figure 61 shows the specific heat as a function of temperature for 16Cr-12Ni-2Mo high-alloy steel, and this is used for SS316L. It is calculated from the ASME/BPVC values for density, thermal conductivity, and thermal diffusivity.

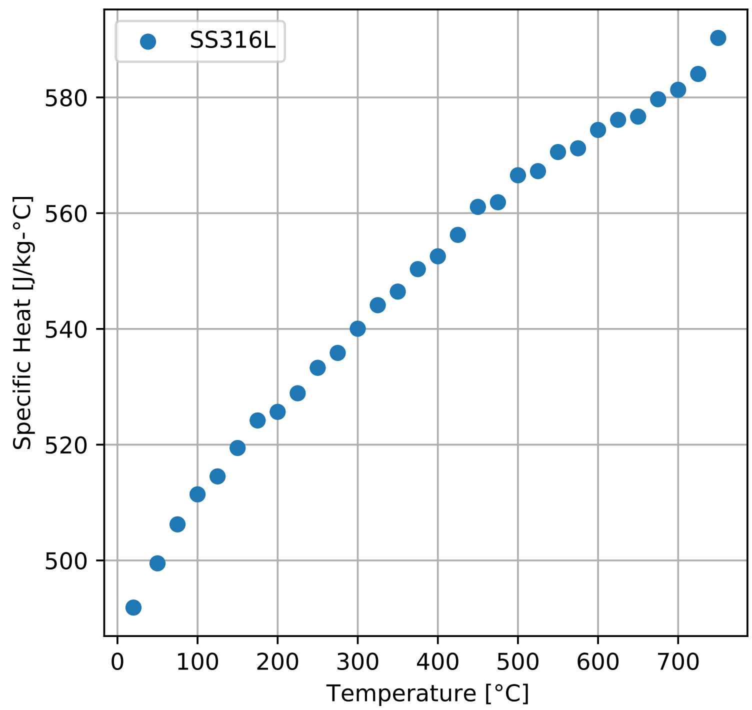


Figure 61. SS316L Specific heat as a function of temperature, as calculated from density, thermal conductivity, and thermal diffusivity [2].

5.1.2 Irradiated Condition

There are currently no model modifications for SS316L in the irradiated condition. Irradiation hardening and reduction in ductility are expected. At this time, however, the SS316L used in the target design is not expected to experience plastic deformation under normal operation.

5.2 FUTURE WORK

The SS316L material model currently implemented in Abaqus and Sierra codes is bilinear with a constant hardening modulus. This could be further refined to follow the ASME/BPVC elastic-plastic stress-strain model.

David McClintock has performed work on irradiated SS316L, and this could be incorporated into material models.

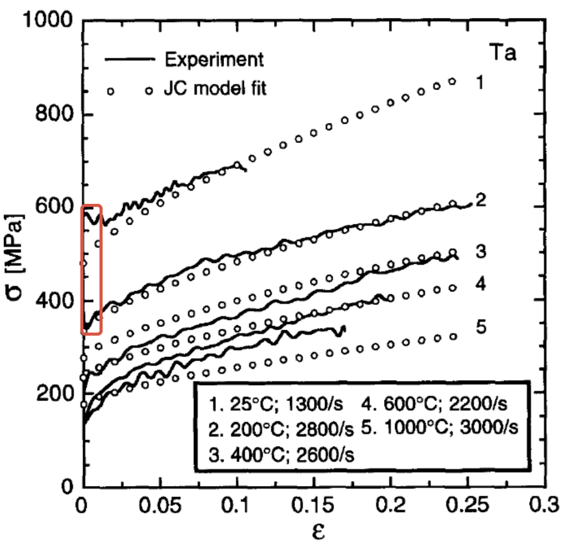
6. TANTALUM

6.1 MATERIAL BEHAVIOR

6.1.1 Unirradiated Condition

6.1.1.1 Thermostructural Constitutive Models

A fair amount of literature exists for tantalum elasto-viscoplastic constitutive modeling at temperatures and strain rates compatible with impact ballistics. Research also exists for the lower temperatures and strain rates that are expected in spallation targets. Chen & Gray [26] fitted data for Ta over strain rates from 10^{-3} to 5000 s^{-1} and over temperatures from 25 to 1000°C. They found the Zerilli-Armstrong (Z-A) model provided better description of unalloyed Ta behavior than the Johnson-Cook (J-C) model. Both models would supposedly capture the effects of temperature, creep, strain, and strain rate. Figure 62 summarizes the J-C model and indicates the data range of most interest for the STS environment.



A. *JC Model*[15]

$$\sigma = (A + B \cdot \varepsilon_p^{\,n})(1 + C \cdot \ln \dot{\varepsilon}^*)(1 - T^{*m}) \qquad [3]$$

where $\dot{\varepsilon}^*$ is a nondimensional strain-rate value, ε_p is the plastic strain, and T^* is $(T - T_{room})/(T_{melt} - T_{room})$. The value of T is in degrees kelvin, and A, B, n, C, and m are constants for this model.

Table III. Fitting Parameters for JC Model

	A (MPa)	B (MPa)	n	C	m	T_m (K)
Ta	340	750	0.7	0.0575	0.400	3250

Figure 62. Tantalum Johnson-Cook constitutive model showing comparisons with experiment [26].

Figures 63 and 64 compare all available data for strength as a function of temperature. The values used by ISIS for their Ta clad W target modeling are also given by Wilcox [99]. Table 15 gives the sample types and preparations used by the authors where available. All were tensile tests except for Chen & Gray who performed compression tests over a wide range of strain rates and temperatures. For target systems analysis, we currently use the Chen & Gray model as it covers the temperature range including manufacturing, however, the effect of lower strengths should also be considered.

The ORNL MSTD also performed monotonic tensile tests of 1mm tantalum sheet specimens at room temperature under varying strain rages. Figure 65 summarizes the results and clearly shows the effect of strain rate hardening. Furthermore, the Chen & Gray model shows excellent agreement with the 0.2% yield strength from these tests.

Helebrant & Stephens [47] also report monotonic tensile tests of tantalum specimens at 3 different strain rates, as shown in Figure 66. The response qualitatively matches that of the ORNL MSTD testing and illustrates the sensitivity of yield strength to strain rate, including low strain rates. (This might furthermore explain the

Table 15. Literature review of tantalum strength testing.

Reference	Name	Sample Type	Preparation
[20]	Cardonne(1995)	Sheet (1mm)	Fully-Recrystallized
[87]	Schmidt(1963)	Sheet (1mm)	Cold rolled 75% and recrystallized 1 hour @ 1200°C
[98]	Wiffen(1973)	Hourglass (3.175mm)	Annealed 1 hr in vacuum @ 1250°C
[71]	Miller(1959)Ref.Pugh	Sheet	N/A
[71]	Miller(1959)Ref.Bechtold	N/A	Annealed 1 hr in vacuum @ 1700°C
[26]	Chen(1996)	Billet (6.35mm)	Annealed, Cross-Rolled, Cut

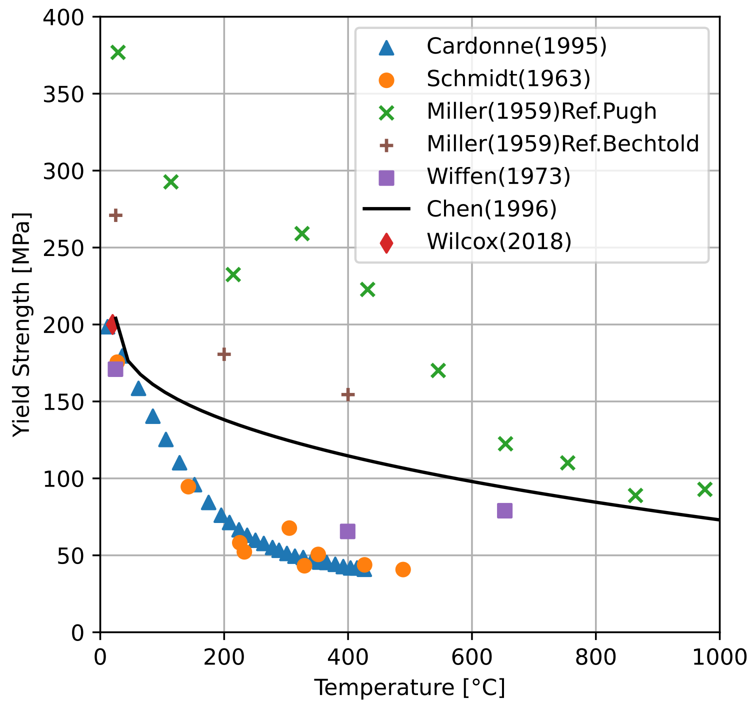


Figure 63. Tantalum yield strength as a function of temperature.

scatter seen in Figure 63.) Also shown is the bilinear constitutive model used by Wilcox and the Chen & Gray J-C model at room temperature and 0.001/s strain rate.

The target systems simulations presently choose a thermoelastic-plastic model for tantalum that conservatively sets a fixed 0.001/s strain rate. During HIP manufacturing, the tantalum strength will be predominantly driven by temperature effects. And during proton beam pulse response, the tantalum will not take credit for any increased strength at temporarily high strain rates.

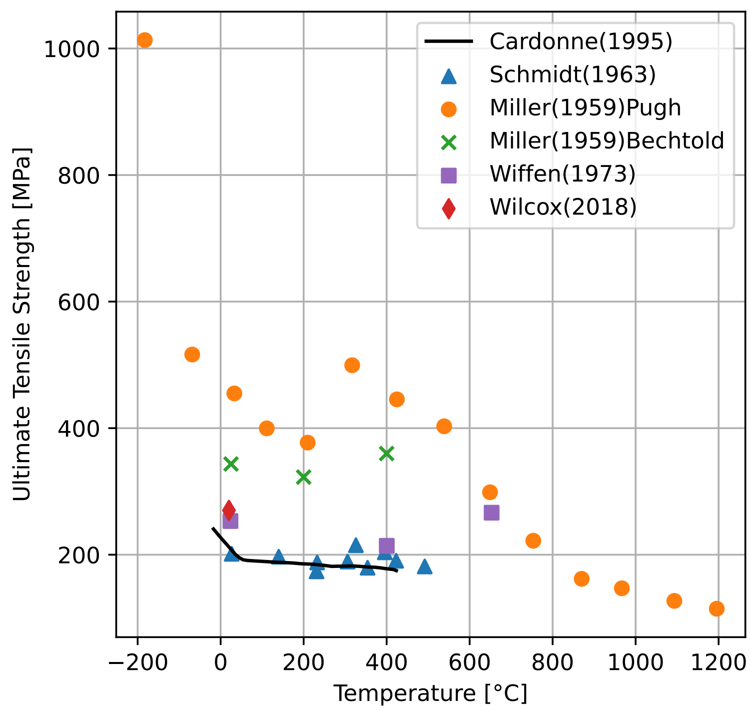


Figure 64. Tantalum ultimate tensile strength as a function of temperature.

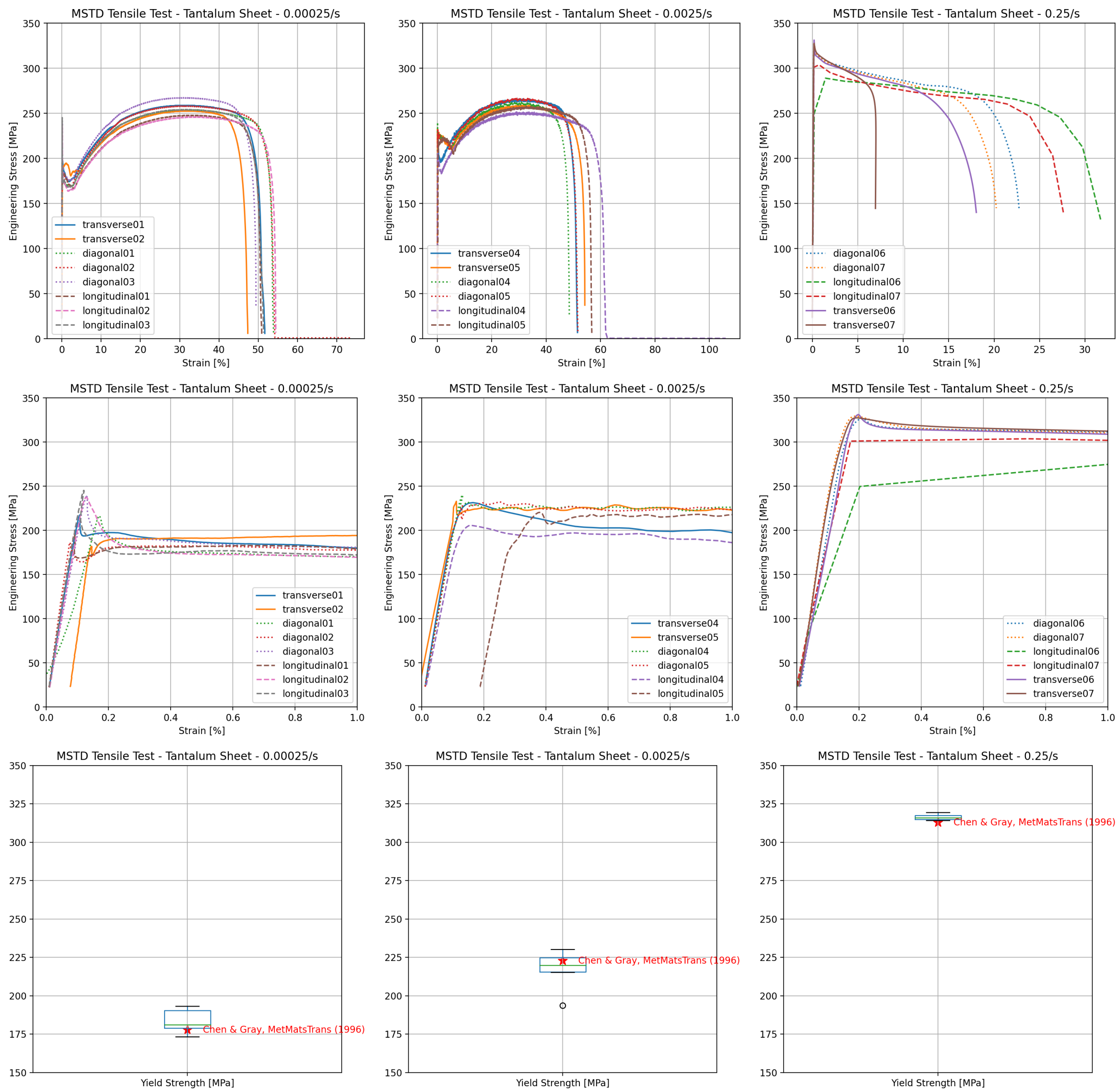


Figure 65. Tantalum monotonic tensile tests as a function of strain rates. Columns L-R are strain rates of 0.00025/s, 0.0025/s, and 0.25/s. Rows T-B are full stress-strain response, zoom view of yield behavior, and comparison against the Chen & Gray model.

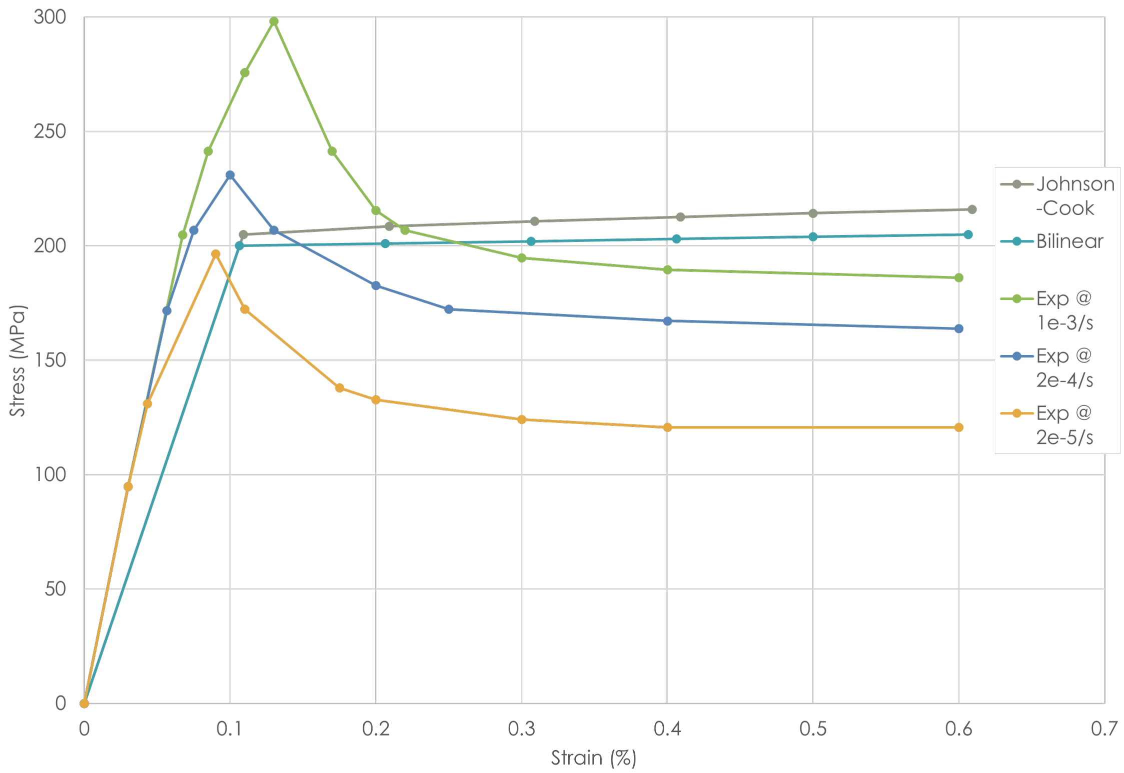
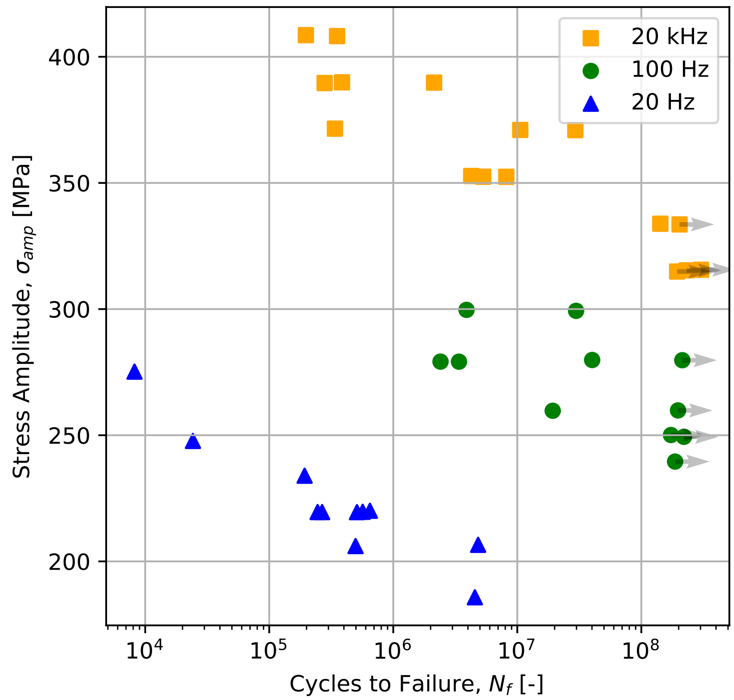


Figure 66. Tantalum room-temperature monotonic stress-strain comparisons showing 3 tests at varying stress rates [47] and the Johnson-Cook model [26] at 0.001/s strain rate.

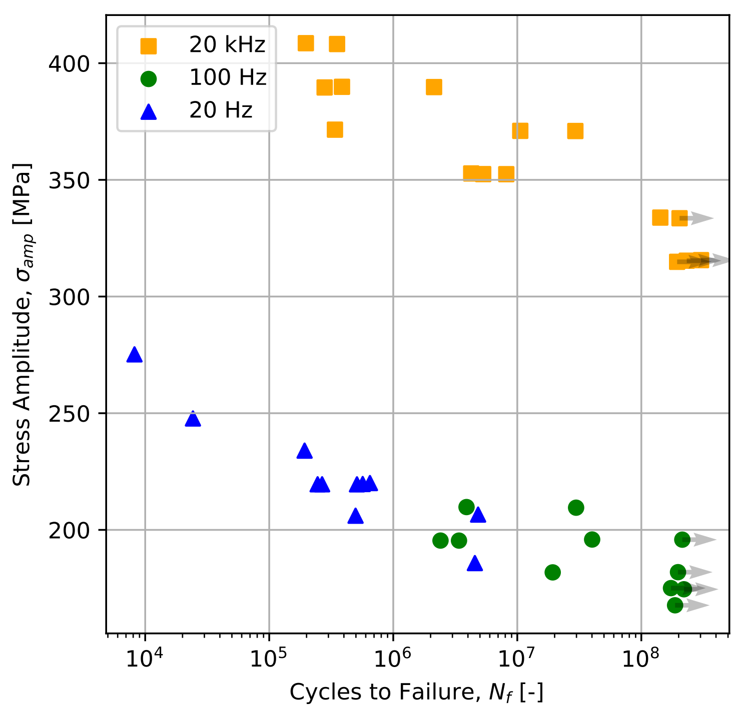
6.1.1.2 Fatigue Strength & Model

Figure 67 summarizes the fatigue data available for tantalum. At room temperatures, tantalum demonstrates strong strain rate dependence with differences seen at 1Hz, 20-100Hz, and 20kHz cycling frequencies. At 1Hz testing, researchers at ISIS and elsewhere found creep was dominant [75] [68]. At testing in the range of 20-100Hz, Marechal reported no influence in loading frequency but high influence of mean stresses causing a creep-fatigue interaction including strong nonlinearities in damage predictions that invalidated the Palmgren-Miner linear damage rule [67]. At 20kHz testing, fatigue strength was found to be greater than monotonic yield strength [77], although this appears to combine the effects of strain hardening and strain rate [76]. Also, at 20kHz testing, brittle failure modes were reported.

At this time, tantalum fatigue lifetime predictions are not being modeled as the tantalum is not a structural boundary.



(a) No knockdown for rotating bending fatigue data.



(b) $K_{RBF} = 0.7$

Figure 67. Available fatigue data for tantalum including: 20 Hz large grain tests [47], 100 Hz RBF tests [77], and 20 kHz ultrasonic fatigue tests [77]. The effect of a knockdown for RBF is also shown.

6.1.1.3 Density

The available literature (Table 16) consistently indicates a tantalum density of $16,600\ kg/m^3$.

Table 16. Literature review of tantalum density.

Reference	Name	Density (kg/m3)
[87]	Schmidt(1963)	16,607.9
[89]	Schussler(1990)	16,600
[52]	Köck(1989)	16,600
[20]	Cardonne(1995)	16,600

6.1.1.4 Elastic Modulus

Figure 68 summarizes reported tantalum data for the modulus of elasticity as a function of temperature. The data of Schmidt, Reference 20 is chosen for engineering simulations.

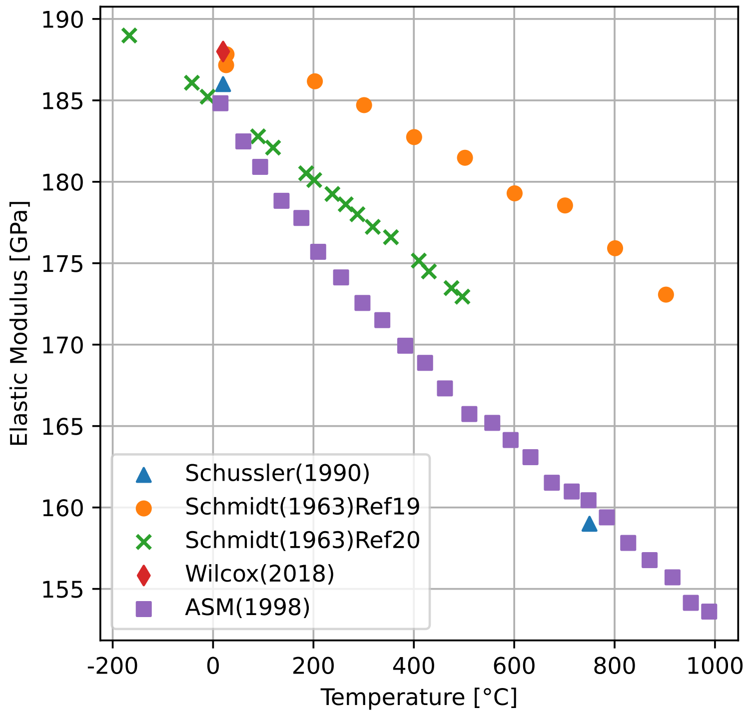


Figure 68. Tantalum modulus of elasticity as a function of temperature. Data sources include Schussler [89], Schmidt [87], and Davis/ASM [32].

6.1.1.5 Poisson's Ratio

The data available for Poisson's Ratio is sparse, with Schussler & Droegkamp [89] reporting a value of 0.35 at room temperature (20°C).

6.1.1.6 Thermal Conductivity

Figure 69 summarizes reported data for the thermal conductivity of tantalum as a function of temperature. The data of Schmidt is chosen for engineering simulations.

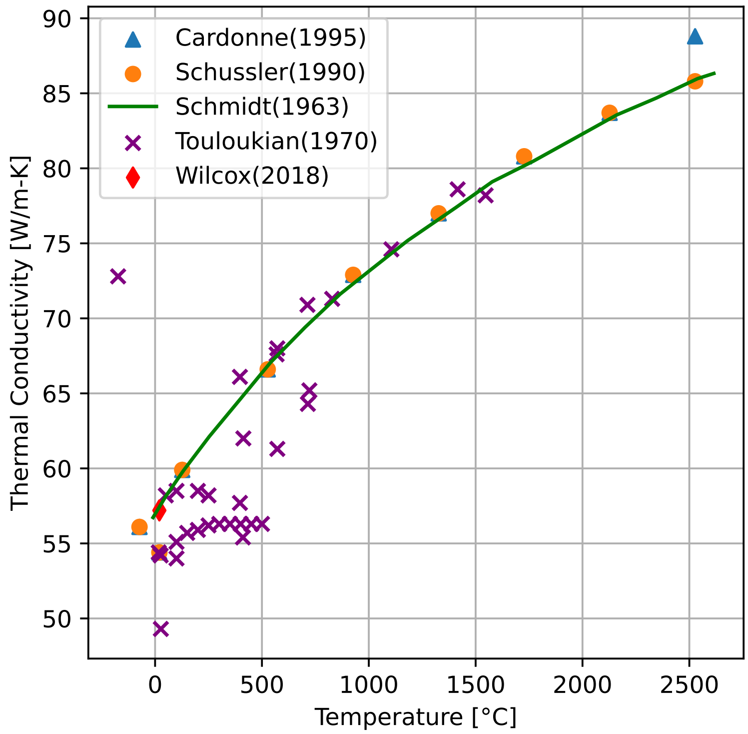


Figure 69. Tantalum thermal conductivity as a function of temperature. Experimental data sources include Cardonne *et al*. [20], Schussler & Droegkamp [89], Schmidt & Ogden [87], and Touloukian *et al*. [96].

6.1.1.7 Coefficient of Thermal Expansion

Figure 70 summarizes reported data for the linear CTE of tantalum as a function of temperature. The data appears to reflect an average CTE except for Touloukian *et al.* . The Touloukian *et al.* data is a recommended polynomial trend for thermal strain. The curve shown has been differentiated to show the instantaneous CTE. This function is chosen for engineering simulations as listed in Equation 46 where temperature is in Celsius.

$$\text{CTE } [\mu m/m \cdot K] = 6.308 + 2 \cdot 9.706 \times 10^{-4} \cdot (T - 20) - 3 \cdot 2.545 \times 10^{-7} \cdot (T - 20)^2 \tag{46}$$

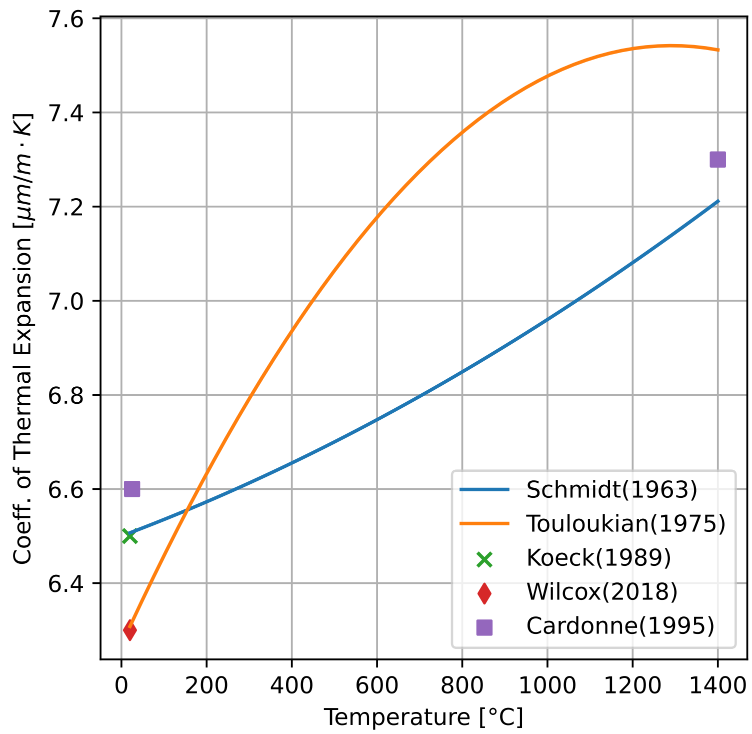


Figure 70. Tantalum CTE as a function of temperature. Experimental data sources include Cardonne *et al.* [20], Schmidt & Ogden [87], Köck & Paschen [52], and Touloukian *et al.* [96].

6.1.1.8 Specific Heat

Figure 71 summarizes reported data for the specific heat capacity of tantalum as a function of temperature. The data of Schussler & Droegkamp is chosen for engineering simulations as listed in Equation 47 where temperature is in Celsius.

$$c_p\ [J/kg \cdot K] = 139.04 + 1.757 \times 10^{-2} \cdot T + 1.375 \times 10^{-6} \cdot T^2 \tag{47}$$

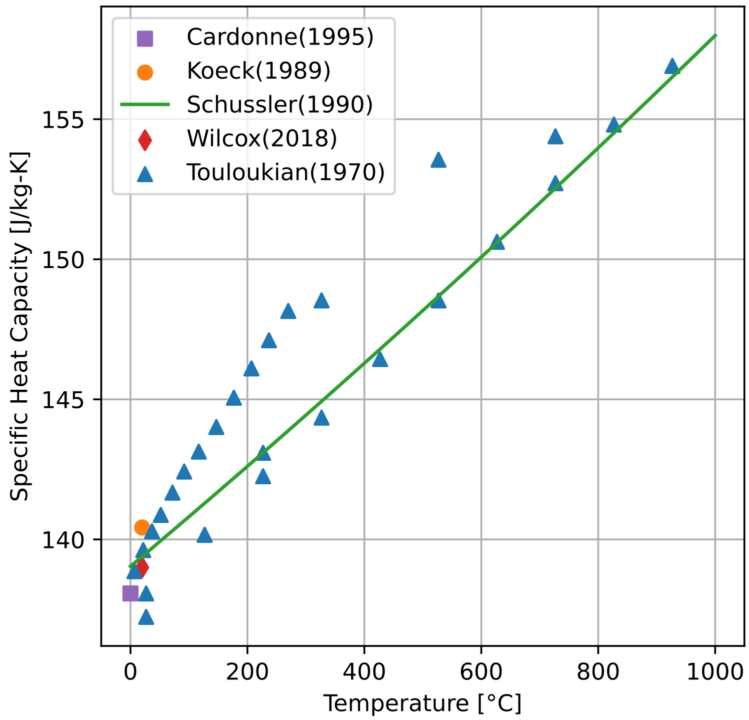


Figure 71. Tantalum specific heat capacity as a function of temperature. Experimental data sources include Cardonne *et al.* [20], Schussler & Droegkamp [89], Köck & Paschen [52], and Touloukian *et al.* [96].

6.1.1.9 Creep

Maag and Mattson produced creep models for potential fission cladding materials including tantalum [62]. Their experiments used thin wall tubes under temperatures and pressures relevant to fission reactors. They combined their biaxial results with other reported uniaxial data and fit to an empirical power law creep relationship. The uniaxial and biaxial combined fit, shown in Figure 72 is re-expressed in Equation 48 and Equation 49 with SI units.

$$\dot{\epsilon} = A\sigma^n \exp\left(-\frac{\Delta H}{RT}\right) \tag{48}$$

$$\begin{aligned} A &= 3.7700 \times 10^{-29}\ s^{-1} \\ n &= 4.7 \\ \Delta H/R &= 43786.0\ K \end{aligned} \tag{49}$$

According to Maag and Mattson, ". . . A is a constant that includes such structural effects as grain size, dislocation density, and other microstructural features; n is the stress exponent that normally has a value of about 5 for pure metals and about 3 for alloys; and ΔH is the activation energy for the controlling creep mechanism, which at high temperatures is similar to the energy required for self-diffusion." [62]

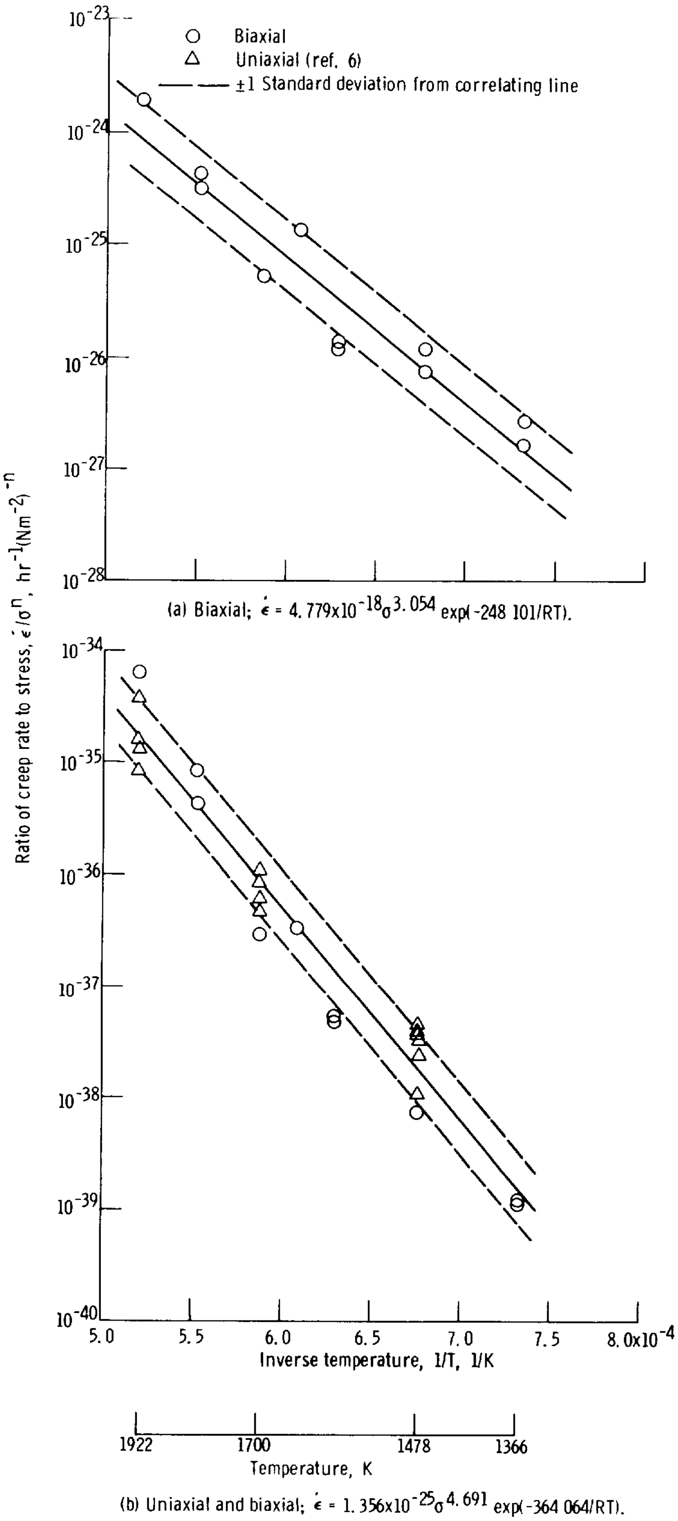


Figure 72. Tantalum creep experimental results reproduced from Maag and Mattson [62].

6.1.2 Irradiated Condition

6.1.2.1 Tensile Strength

Tantalum has been studied in fission and spallation-relevant irradiation environments. Leonard provides a research summary [58]. Chen *et al.* tested tantalum that had been irradiated at LANSCE and found high ductility, even after 10 dpa [23] [24]. It is possible, however, that the Ta sample's decay heat caused post-irradiation self-annealing which recovered ductility. Nonetheless, previous experiments by Wiffen in lower-temperature fission environments found a drop in uniform elongation (attributed to dislocation channeling) but with total elongation still around 5-10% [98]. It does also appear that controlling impurities including oxygen concentrations is key [19] [85].

Considering these research efforts, Maloy *et al.* provide a summary of the irradiation effects in tantalum as follows [65]:

- High Ductility and low yield stress observed in tantalum at room temperature.
- Mechanical testing after irradiation at ISIS showed retention of ductility to doses up to 10 dpa.
- Stronger embrittlement observed for Ta-W alloys over high purity tantalum.
- Oxygen additions to tantalum result in a strong increase in yield stress and a stronger hardening increase with irradiation.
- Tantalum easily picks up oxygen at temperatures above 400°C resulting in strong hardening, embrittlement and oxide formation.
- Very low corrosion rate observed under irradiation.

For simulation purposes, we conservatively assume tantalum's yield strength stays the same. We also expect ductility to remain up to 10%.

6.1.2.2 Fatigue

No information is currently available.

6.1.2.3 Density

The density is assumed to be unaffected by irradiation. Massey *et al*. provide a introductory summary of irradiation-induced void swelling in pure tantalum [69]. The temperatures at which void swelling is a concern (> 600°C) are well above operation temperatures for the spallation target.

6.1.2.4 Elastic Modulus

The elastic modulus is assumed to be unaffected by irradiation.

6.1.2.5 Poisson's Ratio

Poisson's Ratio is assumed to be unaffected by irradiation.

6.1.2.6 Thermal Conductivity

The thermal conductivity is assumed to be unaffected by irradiation.

6.1.2.7 Coefficient of Thermal Expansion

The CTE is assumed to be unaffected by irradiation.

6.1.2.8 Specific Heat

The specific heat is assumed to be unaffected by irradiation.

6.1.2.9 Creep

Creep is only included in simulations during the HIP manufacturing process. Accordingly, irradiation effects are not considered.

7. REFERENCES

[1] ASME BPVC.II.D.M-2021. *Table TE-4 – Thermal Expansion for Nickel Alloys – N07718*. Standard. Two Park Avenue, New York, NY: American Society of Mechanical Engineers, 2021.

[2] ASME BPVC.II.D.M-2021. *Table TCD – Nominal Coefficients of Thermal Conductivity (TC) and Thermal Diffusivity (TD) – High Alloy Steels, Material Group K, 16Cr-12Ni-2Mo*. Standard. Two Park Avenue, New York, NY: American Society of Mechanical Engineers, 2021.

[3] ASME BPVC.II.D.M-2021. *Table Y-1 – Yield Strength Values, Sy, for Ferrous and Nonferrous Materials – 16Cr-12Ni-2Mo*. Standard. Two Park Avenue, New York, NY: American Society of Mechanical Engineers, 2021.

[4] ASME BPVC.II.D.M-2021. *Table U – Tensile Strength Values, Su, for Ferrous and Nonferrous Materials – 16Cr-12Ni-2Mo*. Standard. Two Park Avenue, New York, NY: American Society of Mechanical Engineers, 2021.

[5] ASME BPVC.II.D.M-2021. *Table PRD – Poisson's Ratio and Density of Materials – High Alloy Steels (300 series)*. Standard. Two Park Avenue, New York, NY: American Society of Mechanical Engineers, 2021.

[6] ASME BPVC.II.D.M-2021. *Table TM-1 – Moduli of Elasticity E of Ferrous Materials for Given Temperatures – Material Group G (Austenitic Steels)*. Standard. Two Park Avenue, New York, NY: American Society of Mechanical Engineers, 2021.

[7] ASME BPVC.VIII.2-2021. *Annex 3-D – Strength Parameters*. Standard. Two Park Avenue, New York, NY: American Society of Mechanical Engineers, 2021.

[8] V. Barabash. *Pure Tungsten - Thermal Expansion 2237TK v2.0*. Tech. rep. ITER-AM01-3114. ITER Material Properties Handbook, 2009.

[9] V. Barabash and J.W. Davis. *Pure Tungsten - Poisson's Ratio 2237DS v1.0*. Tech. rep. ITER-AM01-2110. ITER Material Properties Handbook, 2009.

[10] V. Barabash et al. *Pure Cu - Coefficient of Thermal Expansion 24L786 v1.1*. Tech. rep. ITER-AK01-3114. ITER Material Properties Handbook, 2009.

[11] V. Barabash et al. *Pure Cu - Density 24L7A5 v1.0*. Tech. rep. ITER-AK01-3304. ITER Material Properties Handbook, 2009.

[12] V. Barabash et al. *Pure Cu - Poisson's Ratio 24L6Y2 v1.0*. Tech. rep. ITER-AK01-2110. ITER Material Properties Handbook, 2009.

[13] V. Barabash et al. *Pure Cu - Specific Heat 24L767 v1.0*. Tech. rep. ITER-AK01-3108. ITER Material Properties Handbook, 2009.

[14] V. Barabash et al. *Pure Cu - Thermal Conductivity 24L77P v1.0*. Tech. rep. ITER-AK01-3112. ITER Material Properties Handbook, 2009.

[15] V. Barabash et al. *Pure Cu - Young's Modulus 24L6ZJ v1.0*. Tech. rep. ITER-AK01-2111. ITER Material Properties Handbook, 2009.

[16] Juraj Belan. "The Fractography Analysis of IN 718 Alloy after Fatigue Test". In: *Key Engineering Materials* 635 (Dec. 2014), pp. 9–12. ISSN: 1662-9795. DOI: 10.4028/www.scientific.net/kem.635.9. URL: http://dx.doi.org/10.4028/www.scientific.net/kem.635.9.

[17] Jérôme Blaizot et al. "Constitutive model for nickel alloy 690 (Inconel 690) at various strain rates and temperatures". In: *International Journal of Plasticity* 80 (May 2016), pp. 139–153. ISSN: 0749-6419. DOI: 10.1016/j.ijplas.2015.08.010. URL: http://dx.doi.org/10.1016/j.ijplas.2015.08.010.

[18] C. R. Brinkman and G. E. Korth. "Strain fatigue and tensile behavior of Inconel 718 from room temperature to 650*sup*0C". In: (Aug. 1973). DOI: 10.2172/4405742. URL: https://www.osti.gov/biblio/4405742.

[19] Thak Sang Byun and Stuart A. Maloy. “Dose dependence of mechanical properties in tantalum and tantalum alloys after low temperature irradiation”. In: *Journal of Nuclear Materials* 377.1 (June 2008), pp. 72–79. ISSN: 0022-3115. DOI: 10.1016/j.jnucmat.2008.02.034. URL: http://dx.doi.org/10.1016/j.jnucmat.2008.02.034.

[20] S.M. Cardonne et al. “Tantalum and its alloys”. In: *International Journal of Refractory Metals and Hard Materials* 13.4 (Jan. 1995), pp. 187–194. ISSN: 0263-4368. DOI: 10.1016/0263-4368(95)94023-r. URL: http://dx.doi.org/10.1016/0263-4368(95)94023-r.

[21] G Chai and J Frodigh. “Influence of temperature on the fatigue properties of alloy 690”. In: July 2002.

[22] Guocai Chai, Johan Frodigh, and Hans Törnblom. “Fatigue Behavior of Alloy 690 and Alloy 800 SG Tubing at Temperatures Up to 330 C in Very High Cycle Fatigue Regime”. In: *13th International Conference on Environmental Degradation of Materials in Nuclear Power Systems* (Whistler, British Columbia, Canada). Canadian Nuclear Society. Curran Associates, Inc., Apr. 2007, pp. 1115–1126. ISBN: 9781605600598.

[23] J Chen et al. “Mechanical properties of pure tantalum after 800 MeV proton irradiation”. In: *Journal of Nuclear Materials* 298.3 (Oct. 2001), pp. 248–254. ISSN: 0022-3115. DOI: 10.1016/s0022-3115(01)00654-7. URL: http://dx.doi.org/10.1016/s0022-3115(01)00654-7.

[24] J Chen et al. “Summary of the results from post-irradiation examination of spent targets at the FZ-Juelich”. In: *Journal of Nuclear Materials* 318 (May 2003), pp. 56–69. ISSN: 0022-3115. DOI: 10.1016/s0022-3115(03)00007-2. URL: http://dx.doi.org/10.1016/s0022-3115(03)00007-2.

[25] Q Chen et al. “Small crack behavior and fracture of nickel-based superalloy under ultrasonic fatigue”. In: *International Journal of Fatigue* 27.10-12 (Oct. 2005), pp. 1227–1232. DOI: 10.1016/j.ijfatigue.2005.07.022.

[26] Shuh Rong Chen and George T. Gray. “Constitutive behavior of tantalum and tantalum-tungsten alloys”. In: *Metallurgical and Materials Transactions A* 27.10 (Oct. 1996), pp. 2994–3006. ISSN: 1543-1940. DOI: 10.1007/bf02663849. URL: http://dx.doi.org/10.1007/bf02663849.

[27] Shuh Rong Chen and U.F. Kocks. “High-temperature plasticity in copper polycrystals”. In: *High Temperature Constitutive Modeling–Theory and Application* (Toronto, Ontario, Canada). Ed. by Alan David Freed and Kevin P. Walker. Applied Mechanics Division (AMD). American Society of Mechanical Engineers, Dec. 1991. ISBN: 0791808351. URL: https://www.osti.gov/biblio/5238950.

[28] O. K. Chopra and W. J. Shack. *Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials (NUREG/CR-6909, ANL-06/08)*. Tech. rep. U.S. Nuclear Regulatory Commission, Feb. 2007. URL: https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6909/index.html.

[29] J.W. Davis. *Pure Tungsten - Specific Heat Capacity 2237KP v1.0*. Tech. rep. ITER-AM01-3108. ITER Material Properties Handbook, 2009.

[30] J.W. Davis. *Pure Tungsten - Young’s Modulus 2237ED v1.0*. Tech. rep. ITER-AM01-2111. ITER Material Properties Handbook, 2009.

[31] J.W. Davis, V. Barabash, and S. Fabritsiev. *Pure Tungsten - Thermal Conductivity 2237RQ v1.0*. Tech. rep. ITER-AM01-3112. ITER Material Properties Handbook, 2009.

[32] “Refractory Metals and Alloys”. In: *Metals Handbook Desk Edition*. Ed. by Joseph R. Davis. 2nd. ASM International, Dec. 1998, pp. 629–633. DOI: 10.31399/asm.hb.mhde2.a0003151. URL: http://dx.doi.org/10.31399/asm.hb.mhde2.a0003151.

[33] R.B. Jones; G. Hall; B. Marsden; C.A. English. “On The Irradiation Response Of Be, W And Graphite for Proton Accelerator Applications”. National Nuclear Laboratory Literature Review, UK. Nov. 2013.

[34] Ali Fatemi and Peter Kurath. “Multiaxial Fatigue Life Predictions Under the Influence of Mean-Stresses”. In: *Journal of Engineering Materials and Technology* 110.4 (Oct. 1988), pp. 380–388. DOI: 10.1115/1.3226066.

[35] *fe-safe 2025 Fatigue Theory Reference*. Dassault Systemes Americas Corp. Vol. 2, Issue 1, 2024.

[36] *fe-safe 2025 fe-safe User Guide*. Dassault Systemes Americas Corp. Vol. 1, Issue 25.2, 2024.

[37] Paul S. Follansbee. “Analysis of Deformation in Inconel 718 When the Stress Anomaly and Dynamic Strain Aging Coexist”. In: *Metallurgical and Materials Transactions A* 47.9 (June 2016), pp. 4455–4466. ISSN: 1543-1940. DOI: 10.1007/s11661-016-3609-1. URL: http://dx.doi.org/10.1007/s11661-016-3609-1.

[38] M. Fukuhara and A. Sanpei. “Elastic moduli and internal frictions of Inconel 718 and Ti-6Al-4V as a function of temperature”. In: *Journal of Materials Science Letters* 12.14 (1993), pp. 1122–1124. ISSN: 1573-4811. DOI: 10.1007/bf00420541. URL: http://dx.doi.org/10.1007/bf00420541.

[39] L.M. Garrison et al. “Irradiation effects in tungsten-copper laminate composite”. In: *Journal of Nuclear Materials* 481 (Dec. 2016), pp. 134–146. ISSN: 0022-3115. DOI: 10.1016/j.jnucmat.2016.09.020. URL: http://dx.doi.org/10.1016/j.jnucmat.2016.09.020.

[40] J. Habainy et al. “Fatigue behavior of rolled and forged tungsten at 25°, 280° and 480 °C”. In: *Journal of Nuclear Materials* 465 (Oct. 2015), pp. 438–447. ISSN: 0022-3115. DOI: 10.1016/j.jnucmat.2015.06.032. URL: http://dx.doi.org/10.1016/j.jnucmat.2015.06.032.

[41] J. Habainy et al. “Study of heavy ion beam induced damage in tungsten for high power target applications”. In: *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 439 (Jan. 2019), pp. 7–16. DOI: 10.1016/j.nimb.2018.11.017. URL: https://doi.org/10.1016%2Fj.nimb.2018.11.017.

[42] Jemila Habainy. “Characterisation of mechanical and thermal properties of tungsten for high power spallation target applications”. English. Doctoral Thesis (compilation). Materials Engineering, Oct. 2018. ISBN: 978-91-7753-844-8. URL: https://portal.research.lu.se/en/publications/characterisation-of-mechanical-and-thermal-properties-of-tungsten.

[43] Jemila Habainy et al. “Fatigue properties of tungsten from two different processing routes”. In: *Journal of Nuclear Materials* 506 (Aug. 2018), pp. 83–91. DOI: 10.1016/j.jnucmat.2017.10.061. URL: https://doi.org/10.1016%2Fj.jnucmat.2017.10.061.

[44] Jemila Habainy et al. “Mechanical properties of tungsten irradiated with high-energy protons and spallation neutrons”. In: *Journal of Nuclear Materials* 514 (Feb. 2019), pp. 189–195. DOI: 10.1016/j.jnucmat.2018.12.003. URL: https://doi.org/10.1016/j.jnucmat.2018.12.003.

[45] Jemila Habainy et al. “Thermal diffusivity of tungsten irradiated with protons up to 5.8 dpa”. In: *Journal of Nuclear Materials* 509 (Oct. 2018), pp. 152–157. DOI: 10.1016/j.jnucmat.2018.06.041. URL: https://doi.org/10.1016/j.jnucmat.2018.06.041.

[46] J.A. Bannantine; J.J. Comer; J.L. Handrock. *Fundamentals of Metal Fatigue Analysis*. Englewood Cliffs, New Jersey: Prentice Hall, 1990.

[47] D. R. Helebrant and R. I. Stephens. “Cyclic Yield Behavior of Tantalum”. In: *Journal of Materials, JMLSA* 7.4 (Dec. 1972), pp. 536–541.

[48] IMR. *IMR Report Number 202103793 Preliminary*. Tech. rep. 202103793. IMR Test Labs, Lansing, NY, 2021.

[49] *Inconel Alloy 690*. Tech. rep. SMC-079. Special Metals Corporation, Oct. 2009. URL: https://www.specialmetals.com/documents/technical-bulletins/inconel/inconel-alloy-690.pdf.

[50] *Inconel Alloy 718*. Tech. rep. SMC-045. Special Metals Corporation, Sept. 2007. URL: https://www.specialmetals.com/documents/technical-bulletins/inconel/inconel-alloy-718.pdf.

[51] Kawagoishi, Chen, and Nisitani. "Fatigue strength of Inconel 718 at elevated temperatures". In: *Fatigue & Fracture of Engineering Materials & Structures* 23.3 (Mar. 2000), pp. 209–216. DOI: 10.1046/j.1460-2695.2000.00263.x.

[52] W. Köck and P. Paschen. "Tantalum—processing, properties and applications". In: *JOM* 41.10 (Oct. 1989), pp. 33–39. ISSN: 1543-1851. DOI: 10.1007/bf03220360. URL: http://dx.doi.org/10.1007/bf03220360.

[53] U.F. Kocks and H. Mecking. "Physics and phenomenology of strain hardening: the FCC case". In: *Progress in Materials Science* 48.3 (2003), pp. 171–273. ISSN: 0079-6425. DOI: https://doi.org/10.1016/S0079-6425(02)00003-8. URL: https://www.sciencedirect.com/science/article/pii/S0079642502000038.

[54] S. Kok, A.J. Beaudoin, and D.A. Tortorelli. "On the development of stage IV hardening using a model based on the mechanical threshold". In: *Acta Materialia* 50.7 (Apr. 2002), pp. 1653–1667. ISSN: 1359-6454. DOI: 10.1016/s1359-6454(02)00002-2. URL: http://dx.doi.org/10.1016/s1359-6454(02)00002-2.

[55] G E Korth. "Mean stress effects on high-cycle fatigue of Alloy 718". In: (July 1980). DOI: 10.2172/5493726. URL: https://www.osti.gov/biblio/5493726.

[56] G E Korth and G R Smolik. "Status report of physical and mechanical test data of Alloy 718". In: (Sept. 1978). DOI: 10.2172/6807751. URL: https://www.osti.gov/biblio/6807751.

[57] Y.J. Lee. Personal Communication. Jan. 7, 2022.

[58] K.J. Leonard. "Radiation Effects in Refractory Metals and Alloys". In: *Comprehensive Nuclear Materials*. Ed. by Rudy J.M. Konings. Vol. 4. Materials Science and Materials Engineering 6. Amsterdam, Netherlands: Elsevier, Mar. 2012, pp. 181–213. DOI: 10.1016/b978-0-08-056033-5.00088-4. URL: http://dx.doi.org/10.1016/b978-0-08-056033-5.00088-4.

[59] Meimei Li and Steven Zinkle. "Physical and Mechanical Properties of Copper and Copper Alloys". In: *Comprehensive Nuclear Materials*. Ed. by Rudy J.M. Konings. Vol. 4. Materials Science and Materials Engineering 20. Amsterdam, Netherlands: Elsevier, Mar. 2012, pp. 667–690. DOI: 10.1016/b978-0-08-056033-5.00122-1. URL: http://dx.doi.org/10.1016/b978-0-08-056033-5.00122-1.

[60] Zhenhua Li et al. "High cycle fatigue behavior and numerical evaluation of Alloy 690TT steam generator tube". In: *International Journal of Fatigue* 137 (Aug. 2020), p. 105662. DOI: 10.1016/j.ijfatigue.2020.105662.

[61] Xian-feng Ma et al. "Fatigue and fracture behavior of nickel-based superalloy Inconel 718 up to the very high cycle regime". In: *Journal of Zhejiang University-SCIENCE A* 11.10 (Oct. 2010), pp. 727–737. DOI: 10.1631/jzus.a1000171.

[62] William L. Maag and William F. Mattson. *Experimental biaxial creep data for tantalum, molybdenum, and alloys T-111, TZM, and TZC*. Technical Note NASA/TN D-6149. Lewis Research Center, Cleveland OH, USA: NASA, Feb. 1971. URL: https://ntrs.nasa.gov/citations/19710007023.

[63] Justin Mach et al. "Fatigue analysis of the Spallation Neutron Source 2 MW target design". In: *Nuclear Instruments and Methods in Physics Research Section A - Accelerators, Spectrometers, Detectors and Associated Equipment* 1010 (Sept. 2021), p. 165481. ISSN: 0168-9002. DOI: 10.1016/j.nima.2021.165481. URL: http://dx.doi.org/10.1016/j.nima.2021.165481.

[64] Andreas Malmelöv et al. "Mechanism Based Flow Stress Model for Alloy 625 and Alloy 718". In: *Materials* 13.24 (Dec. 2020), p. 5620. ISSN: 1996-1944. DOI: 10.3390/ma13245620. URL: http://dx.doi.org/10.3390/ma13245620.

[65] S. Maloy, P. Hosemann, and D. Byler. *Irradiation effects in tungsten and tantalum*. 3rd High-Power Targetry Workshop, September 10-14, 2007, Bad Zurzach, Switzerland. Sept. 2007.

[66] Stuart A Maloy and Eric J. Pitcher. "Materials issues associated with the design of the materials test station". In: (Nov. 2008). URL: https://www.osti.gov/biblio/1254944.

[67] David Marechal et al. "High-Cycle Fatigue Behaviour of Pure Tantalum under Multiaxial and Variable Amplitude Loadings". In: *Advanced Materials Research* 891–892 (Mar. 2014), pp. 1341–1346. ISSN: 1662-8985. DOI: 10.4028/www.scientific.net/amr.891-892.1341. URL: http://dx.doi.org/10.4028/www.scientific.net/amr.891-892.1341.

[68] David MARÉCHAL et al. *Creep-fatigue interactions in pure Tantalum under constant and variable amplitude*. Tech. rep. Institut de Mécanique et d'Ingénierie de Bordeaux (I2M), 2015. URL: http://hdl.handle.net/10985/9596.

[69] Caleb P. Massey et al. "Post-irradiation examination of commercial tantalum alloys following neutron irradiation". In: *Journal of Nuclear Materials* 591 (2024), p. 154906. ISSN: 0022-3115. DOI: https://doi.org/10.1016/j.jnucmat.2024.154906. URL: https://www.sciencedirect.com/science/article/pii/S0022311524000114.

[70] David A. McClintock et al. "Observations of radiation-enhanced ductility in irradiated Inconel 718: Tensile properties, deformation behavior, and microstructure". In: *Acta Materialia* 231 (June 2022), p. 117889. DOI: 10.1016/j.actamat.2022.117889. URL: https://doi.org/10.1016%2Fj.actamat.2022.117889.

[71] G. L. Miller. *Tantalum and Niobium*. New York: Academic Press Inc., 1959. URL: https://hdl.handle.net/2027/mdp.39015002045915.

[72] Marie Anna Moretti, Lars-Erik Lindgren, and Paul Åkerström. "Physics-Based Flow Stress Model for Alloy 718". In: *Metallurgical and Materials Transactions A* 54.5 (Sept. 2022), pp. 1985–1997. ISSN: 1543-1940. DOI: 10.1007/s11661-022-06819-7. URL: http://dx.doi.org/10.1007/s11661-022-06819-7.

[73] *Statistical Analyses of Austenitic Stainless Steel High Cycle Fatigue Data to Support a Revised Design Factor for Design Fatigue Curve Development*. Vol. Volume 1: Codes and Standards. Pressure Vessels and Piping Conference. July 2022, V001T01A012. DOI: 10.1115/PVP2022-84249. eprint: https://asmedigitalcollection.asme.org/PVP/proceedings-pdf/PVP2022/86144/V001T01A012/6939414/v001t01a012-pvp2022-84249.pdf. URL: https://doi.org/10.1115/PVP2022-84249.

[74] Muztahid Muhammad et al. "An investigation into the effects of cyclic strain rate on the high cycle and very high cycle fatigue behaviors of wrought and additively manufactured Inconel 718". In: *International Journal of Fatigue* 144 (Mar. 2021), p. 106038. ISSN: 0142-1123. DOI: 10.1016/j.ijfatigue.2020.106038. URL: http://dx.doi.org/10.1016/j.ijfatigue.2020.106038.

[75] A.T. Nelson et al. "Fabrication of a tantalum-clad tungsten target for LANSCE". In: *Journal of Nuclear Materials* 431.1-3 (Dec. 2012), pp. 172–184. DOI: 10.1016/j.jnucmat.2011.11.041. URL: https://doi.org/10.1016/j.jnucmat.2011.11.041.

[76] M Papakyriacou et al. "Cyclic plastic deformation of tantalum and niobium at very high numbers of cycles". In: *Materials Science and Engineering: A* 325.1–2 (Feb. 2002), pp. 520–524. ISSN: 0921-5093. DOI: 10.1016/s0921-5093(01)01446-0. URL: http://dx.doi.org/10.1016/s0921-5093(01)01446-0.

[77] M Papakyriacou et al. "Influence of loading frequency on high cycle fatigue properties of b.c.c. and h.c.p. metals". In: *Materials Science and Engineering: A* 308.1–2 (June 2001), pp. 143–152. ISSN: 0921-5093. DOI: 10.1016/s0921-5093(00)01978-x. URL: http://dx.doi.org/10.1016/s0921-5093(00)01978-x.

[78] Francis G. Pascual and William Q. Meeker. "Estimating Fatigue Curves With the Random Fatigue-Limit Model". In: *Technometrics* 41.4 (Nov. 1999), pp. 277–289. DOI: 10.1080/00401706.1999.10485925.

[79] A.T Peacock et al. "Overview of recent European materials R&D activities related to ITER". In: *Journal of Nuclear Materials* 329-333 (Aug. 2004), pp. 173–177. ISSN: 0022-3115. DOI: 10.1016/j.jnucmat.2004.04.008. URL: http://dx.doi.org/10.1016/j.jnucmat.2004.04.008.

[80] B. Pyttel, D. Schwerdt, and C. Berger. "Very high cycle fatigue – Is there a fatigue limit?" In: *International Journal of Fatigue* 33.1 (Jan. 2011), pp. 49–58. DOI: 10.1016/j.ijfatigue.2010.05.009.

[81] Abdallah Reza et al. "Thermal diffusivity degradation and point defect density in self-ion implanted tungsten". In: *Acta Materialia* 193 (July 2020), pp. 270–279. DOI: 10.1016/j.actamat.2020.03.034. URL: https://doi.org/10.1016%2Fj.actamat.2020.03.034.

[82] Michael Rieth et al. "Behavior of tungsten under irradiation and plasma interaction". In: *Journal of Nuclear Materials* 519 (June 2019), pp. 334–368. DOI: 10.1016/j.jnucmat.2019.03.035. URL: https://doi.org/10.1016/j.jnucmat.2019.03.035.

[83] M Roedig et al. "Post irradiation testing of samples from the irradiation experiments PARIDE 3 and PARIDE 4". In: *Journal of Nuclear Materials* 329-333 (Aug. 2004), pp. 766–770. ISSN: 0022-3115. DOI: 10.1016/j.jnucmat.2004.04.176. URL: http://dx.doi.org/10.1016/j.jnucmat.2004.04.176.

[84] Paul E. Ruff. *Effect of Manufacturing Processes on Structural Allowables Phase 2*. Tech. rep. AFWAL-TR-86-4120. Battelle Columbus Division, Nov. 1986. URL: https://apps.dtic.mil/sti/citations/ADA176232.

[85] Shigeru Saito et al. "Mechanical properties of pure tungsten and tantalum irradiated by protons and neutrons at the Swiss spallation-neutron source". In: *Nuclear Materials and Energy* 34 (Mar. 2023), p. 101338. ISSN: 2352-1791. DOI: 10.1016/j.nme.2022.101338. URL: http://dx.doi.org/10.1016/j.nme.2022.101338.

[86] J.J. Schirra. "Development of a Improved Heat Treatment for Investment Cast Inconel 718 (PWA 649)". In: *Proceedings of the Fourth International Symposium on Superalloys 718, 625, 706 and Derivatives* (Pittsburgh, Pennsylvania). Ed. by E. A. Loria. The Minerals, Metals & Materials Society, June 1997, pp. 439–446. URL: http://www.tms.org/superalloys/10.7449/1997/Superalloys_1997_439_446.pdf.

[87] F. F. Schmidt and Horace R Ogden. *The Engineering Properties of Tantalum and Tantalum Alloys*. Tech. rep. 189. Defense Metals Information Center (DMIC), Battelle Memorial Institute, Sept. 1963. URL: https://apps.dtic.mil/sti/citations/AD0426344.

[88] F.F. Schmidt and H.R. Ogden. *The Engineering Properties of Tungsten adn Tungsten Alloys*. DMIC Report 191 AD0425547. Battelle Memorial Inst., Defense Metals Information Center, Columbus, Ohio, 1963. URL: https://apps.dtic.mil/sti/citations/AD0425547.

[89] Mortimer Schussler and R.E. Droegkamp. "Properties of Pure Metals". In: *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*. Vol. 2. ASM Handbook. ASM International, Jan. 1990. Chap. Tantalum (Ta), pp. 1099–1201. ISBN: 978-1-62708-162-7. DOI: 10.31399/asm.hb.v02.a0001117. eprint: https://dl.asminternational.org/book/chapter-pdf/452316/a0001117.pdf. URL: https://doi.org/10.31399/asm.hb.v02.a0001117.

[90] Ashutosh Sharma, Min Chul Oh, and Byungmin Ahn. "Recent Advances in Very High Cycle Fatigue Behavior of Metals and Alloys—A Review". In: *Metals* 10.9 (Sept. 2020), p. 1200. DOI: 10.3390/met10091200.

[91] Walter Sommer et al. "Materials Selection and Qualification Processes at a High-Power Spallation Neutron Source". In: *Materials Characterization* 43.2-3 (Aug. 1999), pp. 97–123. DOI: 10.1016/s1044-5803(99)00041-8. URL: https://doi.org/10.1016/S1044-5803(99)00041-8.

[92] Zongxian Song et al. "Very-High-Cycle Fatigue Behavior of Inconel 718 Alloy Fabricated by Selective Laser Melting at Elevated Temperature". In: *Materials* 14.4 (Feb. 2021), p. 1001. DOI: 10.3390/ma14041001.

[93] *Specification for Hot Isostatic Pressing of Second Target Station Target Materials*. Windchill Doc. No. S07030100-TSP10001-A.14. ORNL STS Second Target Station. Jan. 2026. URL: https://windchill-prod.ornl.gov:8443/Windchill/app/#ptc1/tcomp/infoPage?ContainerOid=

OR%3Awt.pdmlink.PDMLinkProduct%3A1228746141&oid=VR%3Awt.doc.WTDocument%3A455766615&u8=1.

[94] *Specification, Inconel, Target Segment*. Windchill Doc. No. S03020000-TSP10000-A.15. ORNL STS Second Target Station. Jan. 2026. URL: https://windchill-prod.ornl.gov:8443/Windchill/app/#ptc1/tcomp/infoPage?ContainerOid=OR%3Awt.pdmlink.PDMLinkProduct%3A1228746141&oid=VR%3Awt.doc.WTDocument%3A851312504&u8=1.

[95] A. Thomas et al. "High temperature deformation of Inconel 718". In: *Journal of Materials Processing Technology* 177.1–3 (July 2006), pp. 469–472. ISSN: 0924-0136. DOI: 10.1016/j.jmatprotec.2006.04.072. URL: http://dx.doi.org/10.1016/j.jmatprotec.2006.04.072.

[96] Y. S. Touloukian et al. *Thermal Conductivity - Metallic Elements and Alloys*. Ed. by Y. S. Touloukian and C. Y. Ho. Vol. 1. Thermophysical Properties of Matter - The TPRC Data Series. New York, N.Y.: IFI/Plenum Data Company, 1970. URL: https://apps.dtic.mil/sti/citations/ADA951935.

[97] N. TSUTSUMI, Y. MURAKAMI, and V. DOQUET. "Effect of test frequency on fatigue strength of low carbon steel". In: *Fatigue & Fracture of Engineering Materials & Structures* 32.6 (June 2009), pp. 473–483. DOI: 10.1111/j.1460-2695.2009.01350.x.

[98] F. W. Wiffen. "Tensile properties of fast-reactor neutron-irradiated bcc metals and alloys". In: *Conference on defects and defect clusters in bcc metals and their alloys, Gaithersburg, Maryland, USA, 14 Aug 1973* (Aug. 1973). DOI: 10.2172/4445536. URL: https://doi.org/10.2172/4445536.

[99] Dan Wilcox et al. "Stress levels and failure modes of tantalum-clad tungsten targets at ISIS". In: *Journal of Nuclear Materials* 506 (Aug. 2018), pp. 76–82. ISSN: 0022-3115. DOI: 10.1016/j.jnucmat.2017.10.075. URL: http://dx.doi.org/10.1016/j.jnucmat.2017.10.075.

[100] YangYang Zhang, Zheng Duan, and HuiJi Shi. "Comparison of the very high cycle fatigue behaviors of INCONEL 718 with different loading frequencies". In: *Science China Physics, Mechanics and Astronomy* 56.3 (Feb. 2013), pp. 617–623. ISSN: 1869-1927. DOI: 10.1007/s11433-013-5013-9. URL: http://dx.doi.org/10.1007/s11433-013-5013-9.

[101] Yuxiang Zhao et al. "Study on high-cycle fatigue behavior for TA16 and 690 tube". In: *Nuclear Power Engineering* 38.5 (2017), pp. 129–131. DOI: 10.13832/j.jnpe.2017.05.0129.

[102] Liqiong Zhong et al. "High Cycle Fatigue Performance of Inconel 718 Alloys with Different Strengths at Room Temperature". In: *Metals* 9.1 (Dec. 2018), p. 13. DOI: 10.3390/met9010013.

APPENDIX A. ABAQUS MATERIAL MODELS

A.0.1 abq_FDR_matls.inp

```
**
********************************** M A T E R I A L S ************************************
**
**
** CU OFE ---------------------------------------
**
*Material, name=Cu_OFE
*Density
8940.,
*Elastic
 1.16541e+11, 0.33,  20.
 1.14201e+11, 0.33, 100.
 1.10144e+11, 0.33, 200.
 1.04829e+11, 0.33, 300.
  9.8256e+10, 0.33, 400.
  9.0425e+10, 0.33, 500.
  8.1336e+10, 0.33, 600.
  7.0989e+10, 0.33, 700.
*Expansion
 1.66128e-05, 20.
 1.74158e-05,100.
 1.81393e-05,200.
  1.8737e-05,300.
 1.93592e-05,400.
 2.01051e-05,500.
 2.10227e-05,600.
  2.2109e-05,700.
*Plastic, hardening=MULTILINEAR KINEMATIC
       1e+07,         0.,        20.
 1.18937e+07,      0.001,        20.
 1.27193e+07, 0.00143845,        20.
 1.39021e+07, 0.00206914,        20.
 1.55935e+07, 0.00297635,        20.
 1.80058e+07, 0.00428133,        20.
 2.14338e+07, 0.00615848,        20.
 2.62792e+07, 0.00885867,        20.
 3.30769e+07,  0.0127428,        20.
 4.25118e+07,  0.0183298,        20.
 5.54104e+07,  0.0263665,        20.
 7.26743e+07,  0.0379269,        20.
 9.51104e+07,  0.0545559,        20.
 1.23118e+08,   0.078476,        20.
 1.56241e+08,   0.112884,        20.
 1.92745e+08,   0.162378,        20.
 2.29539e+08,   0.233572,        20.
  2.6282e+08,   0.335982,        20.
 2.89385e+08,   0.483293,        20.
 3.07882e+08,   0.695193,        20.
 3.19074e+08,         1.,        20.
       1e+07,         0.,       100.
 1.18336e+07,      0.001,       100.
  1.2632e+07, 0.00143845,       100.
 1.37747e+07, 0.00206914,       100.
 1.54063e+07, 0.00297635,       100.
 1.77286e+07, 0.00428133,       100.
 2.10189e+07, 0.00615848,       100.
 2.56505e+07, 0.00885867,       100.
 3.21096e+07,  0.0127428,       100.
 4.09996e+07,  0.0183298,       100.
 5.30105e+07,  0.0263665,       100.
 6.88241e+07,  0.0379269,       100.
 8.89168e+07,  0.0545559,       100.
 1.13247e+08,   0.078476,       100.
 1.40893e+08,   0.112884,       100.
 1.69846e+08,   0.162378,       100.
 1.97262e+08,   0.233572,       100.
 2.20315e+08,   0.335982,       100.
```

```
  2.3729e+08,   0.483293,       100.
 2.48158e+08,   0.695193,       100.
 2.54216e+08,         1.,       100.
       1e+07,         0.,       200.
 1.17573e+07,      0.001,       200.
 1.25207e+07, 0.00143845,       200.
 1.36114e+07, 0.00206914,       200.
  1.5165e+07, 0.00297635,       200.
 1.73686e+07, 0.00428133,       200.
 2.04752e+07, 0.00615848,       200.
 2.48171e+07, 0.00885867,       200.
 3.08116e+07,  0.0127428,       200.
 3.89458e+07,  0.0183298,       200.
   4.972e+07,  0.0263665,       200.
  6.3523e+07,  0.0379269,       200.
 8.04234e+07,  0.0545559,       200.
 9.99073e+07,   0.078476,       200.
  1.2069e+08,   0.112884,       200.
 1.40813e+08,   0.162378,       200.
 1.58175e+08,   0.233572,       200.
 1.71325e+08,   0.335982,       200.
 1.79991e+08,   0.483293,       200.
 1.84959e+08,   0.695193,       200.
 1.87455e+08,         1.,       200.
       1e+07,         0.,       300.
 1.16794e+07,      0.001,       300.
 1.24065e+07, 0.00143845,       300.
 1.34425e+07, 0.00206914,       300.
 1.49129e+07, 0.00297635,       300.
 1.69874e+07, 0.00428133,       300.
 1.98902e+07, 0.00615848,       300.
 2.39043e+07, 0.00885867,       300.
 2.93636e+07,  0.0127428,       300.
 3.66177e+07,  0.0183298,       300.
 4.59516e+07,  0.0263665,       300.
 5.74469e+07,  0.0379269,       300.
 7.08019e+07,  0.0545559,       300.
 8.51872e+07,   0.078476,       300.
 9.92837e+07,   0.112884,       300.
 1.11618e+08,   0.162378,       300.
 1.21104e+08,   0.233572,       300.
 1.27457e+08,   0.335982,       300.
 1.31156e+08,   0.483293,       300.
 1.33042e+08,   0.695193,       300.
 1.33895e+08,         1.,       300.
       1e+07,         0.,       400.
 1.15992e+07,      0.001,       400.
 1.22875e+07, 0.00143845,       400.
 1.32643e+07, 0.00206914,       400.
  1.4642e+07, 0.00297635,       400.
 1.65693e+07, 0.00428133,       400.
 1.92331e+07, 0.00615848,       400.
 2.28537e+07, 0.00885867,       400.
 2.76604e+07,  0.0127428,       400.
 3.38375e+07,  0.0183298,       400.
 4.14326e+07,  0.0263665,       400.
 5.02373e+07,  0.0379269,       400.
 5.96951e+07,  0.0545559,       400.
 6.89317e+07,   0.078476,       400.
 7.69814e+07,   0.112884,       400.
 8.31457e+07,   0.162378,       400.
 8.72551e+07,   0.233572,       400.
 8.96372e+07,   0.335982,       400.
 9.08466e+07,   0.483293,       400.
  9.1392e+07,   0.695193,       400.
 9.16145e+07,         1.,       400.
       1e+07,         0.,       500.
 1.15142e+07,      0.001,       500.
 1.21591e+07, 0.00143845,       500.
 1.30669e+07, 0.00206914,       500.
 1.43332e+07, 0.00297635,       500.
 1.60768e+07, 0.00428133,       500.
```

```
 1.84335e+07, 0.00615848,       500.
 2.15386e+07, 0.00885867,       500.
 2.54875e+07,  0.0127428,       500.
 3.02753e+07,  0.0183298,       500.
 3.57244e+07,  0.0263665,       500.
 4.14427e+07,  0.0379269,       500.
 4.68708e+07,  0.0545559,       500.
 5.14482e+07,   0.078476,       500.
 5.48292e+07,   0.112884,       500.
 5.70007e+07,   0.162378,       500.
 5.82148e+07,   0.233572,       500.
 5.88112e+07,   0.335982,       500.
 5.90727e+07,   0.483293,       500.
 5.91769e+07,   0.695193,       500.
 5.92153e+07,         1.,       500.
       1e+07,         0.,       600.
 1.14173e+07,      0.001,       600.
 1.20066e+07, 0.00143845,       600.
 1.28219e+07, 0.00206914,       600.
 1.39317e+07, 0.00297635,       600.
 1.54081e+07, 0.00428133,       600.
 1.73108e+07, 0.00615848,       600.
 1.96591e+07, 0.00885867,       600.
 2.23949e+07,  0.0127428,       600.
 2.53524e+07,  0.0183298,       600.
 2.82633e+07,  0.0263665,       600.
 3.08234e+07,  0.0379269,       600.
 3.28038e+07,  0.0545559,       600.
 3.41379e+07,   0.078476,       600.
 3.49193e+07,   0.112884,       600.
 3.53198e+07,   0.162378,       600.
 3.55019e+07,   0.233572,       600.
 3.55767e+07,   0.335982,       600.
  3.5605e+07,   0.483293,       600.
  3.5615e+07,   0.695193,       600.
 3.56184e+07,         1.,       600.
    7.68e+06,         0.,       700.
 8.95783e+06,      0.001,       700.
 9.45104e+06, 0.00143845,       700.
 1.00987e+07, 0.00206914,       700.
 1.09187e+07, 0.00297635,       700.
 1.19068e+07, 0.00428133,       700.
 1.30226e+07, 0.00615848,       700.
  1.4182e+07, 0.00885867,       700.
 1.52694e+07,  0.0127428,       700.
 1.61738e+07,  0.0183298,       700.
  1.6832e+07,  0.0263665,       700.
 1.72483e+07,  0.0379269,       700.
 1.74777e+07,  0.0545559,       700.
  1.7589e+07,   0.078476,       700.
 1.76372e+07,   0.112884,       700.
 1.76562e+07,   0.162378,       700.
 1.76632e+07,   0.233572,       700.
 1.76656e+07,   0.335982,       700.
 1.76664e+07,   0.483293,       700.
 1.76667e+07,   0.695193,       700.
 1.76667e+07,         1.,       700.
**
** TUNGSTEN ----------------------------------------
**
*MATERIAL, NAME=W
*DENSITY
19250.0    ,0.0
*ELASTIC, TYPE = ISOTROPIC
3.9800E+11,0.279     ,20.0
3.9700E+11,0.28      ,100.0
3.9600E+11,0.281     ,200.0
3.9500E+11,0.282     ,300.0
3.9300E+11,0.283     ,400.0
3.9000E+11,0.284     ,500.0
3.8700E+11,0.286     ,600.0
3.8300E+11,0.287     ,700.0
```

```
3.7900E+11,0.288     ,800.0
3.7400E+11,0.289     ,900.0
3.6800E+11,0.29      ,1000.0
3.6200E+11,0.291     ,1100.0
3.5600E+11,0.292     ,1200.0
3.4900E+11,0.293     ,1300.0
3.4100E+11,0.294     ,1400.0
3.3300E+11,0.295     ,1500.0
*EXPANSION, ZERO = 20.0      , TYPE = ISO
4.5000E-06,20.0
4.5000E-06,100.0
4.5300E-06,200.0
4.5800E-06,300.0
4.6300E-06,400.0
4.6800E-06,500.0
4.7200E-06,600.0
4.7600E-06,700.0
4.8100E-06,800.0
4.8500E-06,900.0
4.8900E-06,1000.0
4.9800E-06,1200.0
5.0800E-06,1400.0
5.1800E-06,1600.0
**
** TANTALUM ---------------------------------------
**
*MATERIAL, NAME=tantalum
*DENSITY
16600.0   ,0.0
*ELASTIC, TYPE = ISOTROPIC
1.8439E+11,0.35      ,25.0
1.8279E+11,0.35      ,89.7548
1.8210E+11,0.35      ,119.514
1.8052E+11,0.35      ,185.469
1.8011E+11,0.35      ,201.558
1.7925E+11,0.35      ,237.752
1.7862E+11,0.35      ,264.295
1.7801E+11,0.35      ,287.624
1.7723E+11,0.35      ,318.191
1.7660E+11,0.35      ,354.373
1.7516E+11,0.35      ,409.878
1.7450E+11,0.35      ,429.997
1.7347E+11,0.35      ,475.037
1.7295E+11,0.35      ,496.754
1.7047E+11,0.35      ,600.0
1.6805E+11,0.35      ,700.0
1.6563E+11,0.35      ,800.0
1.6321E+11,0.35      ,900.0
1.6079E+11,0.35      ,1000.0
*EXPANSION, ZERO = 20.0      , TYPE = ISO
6.3560E-06,25.0
6.4761E-06,89.7548
6.5291E-06,119.514
6.6418E-06,185.469
6.6683E-06,201.558
6.7264E-06,237.752
6.7677E-06,264.295
6.8032E-06,287.624
6.8484E-06,318.191
6.9000E-06,354.373
6.9754E-06,409.878
7.0015E-06,429.997
7.0578E-06,475.037
7.0839E-06,496.754
7.1979E-06,600.0
7.2927E-06,700.0
7.3723E-06,800.0
7.4367E-06,900.0
7.4857E-06,1000.0
*PLASTIC
204000000.,0.0       ,25.0
207574000.,1.0000E-03,25.0
```

```
208610000.,0.00143845,25.0
209947000.,0.00206914,25.0
211670000.,0.00297635,25.0
213893000.,0.00428133,25.0
216760000.,0.00615848,25.0
220458000.,0.00885867,25.0
225227000.,0.0127428 ,25.0
231379000.,0.0183298 ,25.0
239314000.,0.0263665 ,25.0
249549000.,0.0379269 ,25.0
262749000.,0.0545559 ,25.0
279775000.,0.078476  ,25.0
301736000.,0.112884  ,25.0
330061000.,0.162378  ,25.0
366595000.,0.233572  ,25.0
413717000.,0.335982  ,25.0
474495000.,0.483293  ,25.0
552888000.,0.695193  ,25.0
654000000.,1.0       ,25.0
157052000.,0.0       ,100.0
159804000.,1.0000E-03,100.0
160601000.,0.00143845,100.0
161630000.,0.00206914,100.0
162957000.,0.00297635,100.0
164668000.,0.00428133,100.0
166875000.,0.00615848,100.0
169722000.,0.00885867,100.0
173394000.,0.0127428 ,100.0
178130000.,0.0183298 ,100.0
184239000.,0.0263665 ,100.0
192118000.,0.0379269 ,100.0
202281000.,0.0545559 ,100.0
215389000.,0.078476  ,100.0
232295000.,0.112884  ,100.0
254102000.,0.162378  ,100.0
282228000.,0.233572  ,100.0
318505000.,0.335982  ,100.0
365296000.,0.483293  ,100.0
425648000.,0.695193  ,100.0
503490000.,1.0       ,100.0
138112000.,0.0       ,200.0
140532000.,1.0000E-03,200.0
141233000.,0.00143845,200.0
142138000.,0.00206914,200.0
143304000.,0.00297635,200.0
144809000.,0.00428133,200.0
146750000.,0.00615848,200.0
149254000.,0.00885867,200.0
152483000.,0.0127428 ,200.0
156648000.,0.0183298 ,200.0
162020000.,0.0263665 ,200.0
168949000.,0.0379269 ,200.0
177886000.,0.0545559 ,200.0
189413000.,0.078476  ,200.0
204281000.,0.112884  ,200.0
223457000.,0.162378  ,200.0
248192000.,0.233572  ,200.0
280094000.,0.335982  ,200.0
321242000.,0.483293  ,200.0
374316000.,0.695193  ,200.0
442770000.,1.0       ,200.0
125055000.,0.0       ,300.0
127246000.,1.0000E-03,300.0
127881000.,0.00143845,300.0
128700000.,0.00206914,300.0
129757000.,0.00297635,300.0
131119000.,0.00428133,300.0
132877000.,0.00615848,300.0
135144000.,0.00885867,300.0
138068000.,0.0127428 ,300.0
141839000.,0.0183298 ,300.0
146703000.,0.0263665 ,300.0
```

```
152977000.,0.0379269 ,300.0
161069000.,0.0545559 ,300.0
171506000.,0.078476  ,300.0
184968000.,0.112884  ,300.0
202332000.,0.162378  ,300.0
224728000.,0.233572  ,300.0
253614000.,0.335982  ,300.0
290872000.,0.483293  ,300.0
338928000.,0.695193  ,300.0
400911000.,1.0       ,300.0
114627000.,0.0       ,400.0
116636000.,1.0000E-03,400.0
117218000.,0.00143845,400.0
117969000.,0.00206914,400.0
118937000.,0.00297635,400.0
120186000.,0.00428133,400.0
121797000.,0.00615848,400.0
123875000.,0.00885867,400.0
126555000.,0.0127428 ,400.0
130012000.,0.0183298 ,400.0
134470000.,0.0263665 ,400.0
140221000.,0.0379269 ,400.0
147638000.,0.0545559 ,400.0
157205000.,0.078476  ,400.0
169545000.,0.112884  ,400.0
185461000.,0.162378  ,400.0
205989000.,0.233572  ,400.0
232467000.,0.335982  ,400.0
266618000.,0.483293  ,400.0
310667000.,0.695193  ,400.0
367482000.,1.0       ,400.0
105764000.,0.0       ,500.0
107617000.,1.0000E-03,500.0
108154000.,0.00143845,500.0
108847000.,0.00206914,500.0
109741000.,0.00297635,500.0
110893000.,0.00428133,500.0
112380000.,0.00615848,500.0
114297000.,0.00885867,500.0
116770000.,0.0127428 ,500.0
119959000.,0.0183298 ,500.0
124073000.,0.0263665 ,500.0
129379000.,0.0379269 ,500.0
136223000.,0.0545559 ,500.0
145050000.,0.078476  ,500.0
156436000.,0.112884  ,500.0
171121000.,0.162378  ,500.0
190062000.,0.233572  ,500.0
214492000.,0.335982  ,500.0
246003000.,0.483293  ,500.0
286646000.,0.695193  ,500.0
339068000.,1.0       ,500.0
97962500.0,0.0       ,600.0
99679000.0,1.0000E-03,600.0
100176000.,0.00143845,600.0
100818000.,0.00206914,600.0
101646000.,0.00297635,600.0
102713000.,0.00428133,600.0
104090000.,0.00615848,600.0
105866000.,0.00885867,600.0
108156000.,0.0127428 ,600.0
111110000.,0.0183298 ,600.0
114921000.,0.0263665 ,600.0
119835000.,0.0379269 ,600.0
126174000.,0.0545559 ,600.0
134350000.,0.078476  ,600.0
144896000.,0.112884  ,600.0
158498000.,0.162378  ,600.0
176042000.,0.233572  ,600.0
198670000.,0.335982  ,600.0
227857000.,0.483293  ,600.0
265501000.,0.695193  ,600.0
```

```
314056000.,1.0       ,600.0
90938700.0,0.0       ,700.0
92532100.0,1.0000E-03,700.0
92993900.0,0.00143845,700.0
93589500.0,0.00206914,700.0
94357800.0,0.00297635,700.0
95348700.0,0.00428133,700.0
96626700.0,0.00615848,700.0
98275200.0,0.00885867,700.0
100401000.,0.0127428 ,700.0
103144000.,0.0183298 ,700.0
106681000.,0.0263665 ,700.0
111243000.,0.0379269 ,700.0
117128000.,0.0545559 ,700.0
124718000.,0.078476  ,700.0
134507000.,0.112884  ,700.0
147134000.,0.162378  ,700.0
163420000.,0.233572  ,700.0
184426000.,0.335982  ,700.0
211520000.,0.483293  ,700.0
246465000.,0.695193  ,700.0
291539000.,1.0       ,700.0
84515100.0,0.0       ,800.0
85995900.0,1.0000E-03,800.0
86425100.0,0.00143845,800.0
86978700.0,0.00206914,800.0
87692600.0,0.00297635,800.0
88613500.0,0.00428133,800.0
89801300.0,0.00615848,800.0
91333300.0,0.00885867,800.0
93309400.0,0.0127428 ,800.0
95858000.0,0.0183298 ,800.0
99145400.0,0.0263665 ,800.0
103385000.,0.0379269 ,800.0
108854000.,0.0545559 ,800.0
115908000.,0.078476  ,800.0
125006000.,0.112884  ,800.0
136741000.,0.162378  ,800.0
151876000.,0.233572  ,800.0
171399000.,0.335982  ,800.0
196578000.,0.483293  ,800.0
229056000.,0.695193  ,800.0
270945000.,1.0       ,800.0
78571700.0,0.0       ,900.0
79948400.0,1.0000E-03,900.0
80347400.0,0.00143845,900.0
80862000.0,0.00206914,900.0
81525800.0,0.00297635,900.0
82381900.0,0.00428133,900.0
83486200.0,0.00615848,900.0
84910400.0,0.00885867,900.0
86747500.0,0.0127428 ,900.0
89117000.0,0.0183298 ,900.0
92173100.0,0.0263665 ,900.0
96115000.0,0.0379269 ,900.0
101199000.,0.0545559 ,900.0
107757000.,0.078476  ,900.0
116215000.,0.112884  ,900.0
127125000.,0.162378  ,900.0
141196000.,0.233572  ,900.0
159345000.,0.335982  ,900.0
182754000.,0.483293  ,900.0
212948000.,0.695193  ,900.0
251891000.,1.0       ,900.0
73023200.0,0.0       ,1000.0
74302700.0,1.0000E-03,1000.0
74673500.0,0.00143845,1000.0
75151800.0,0.00206914,1000.0
75768700.0,0.00297635,1000.0
76564400.0,0.00428133,1000.0
77590700.0,0.00615848,1000.0
78914400.0,0.00885867,1000.0
```

```
80621700.0,0.0127428 ,1000.0
82823900.0,0.0183298 ,1000.0
85664200.0,0.0263665 ,1000.0
89327700.0,0.0379269 ,1000.0
94052900.0,0.0545559 ,1000.0
100148000.,0.078476  ,1000.0
108009000.,0.112884  ,1000.0
118148000.,0.162378  ,1000.0
131225000.,0.233572  ,1000.0
148093000.,0.335982  ,1000.0
169849000.,0.483293  ,1000.0
197910000.,0.695193  ,1000.0
234104000.,1.0       ,1000.0
67806700.0,0.0       ,1100.0
68994800.0,1.0000E-03,1100.0
69339100.0,0.00143845,1100.0
69783200.0,0.00206914,1100.0
70356000.0,0.00297635,1100.0
71094900.0,0.00428133,1100.0
72047800.0,0.00615848,1100.0
73277000.0,0.00885867,1100.0
74862400.0,0.0127428 ,1100.0
76907200.0,0.0183298 ,1100.0
79544600.0,0.0263665 ,1100.0
82946400.0,0.0379269 ,1100.0
87334100.0,0.0545559 ,1100.0
92993300.0,0.078476  ,1100.0
100293000.,0.112884  ,1100.0
109708000.,0.162378  ,1100.0
121851000.,0.233572  ,1100.0
137514000.,0.335982  ,1100.0
157715000.,0.483293  ,1100.0
183772000.,0.695193  ,1100.0
217380000.,1.0       ,1100.0
62873800.0,0.0       ,1200.0
63975500.0,1.0000E-03,1200.0
64294800.0,0.00143845,1200.0
64706600.0,0.00206914,1200.0
65237700.0,0.00297635,1200.0
65922800.0,0.00428133,1200.0
66806500.0,0.00615848,1200.0
67946200.0,0.00885867,1200.0
69416200.0,0.0127428 ,1200.0
71312300.0,0.0183298 ,1200.0
73757800.0,0.0263665 ,1200.0
76912100.0,0.0379269 ,1200.0
80980600.0,0.0545559 ,1200.0
86228200.0,0.078476  ,1200.0
92996500.0,0.112884  ,1200.0
101726000.,0.162378  ,1200.0
112986000.,0.233572  ,1200.0
127510000.,0.335982  ,1200.0
146242000.,0.483293  ,1200.0
170403000.,0.695193  ,1200.0
201566000.,1.0       ,1200.0
*CREEP, LAW=DOUBLE POWER
3.7700E-29, 43786.0   , 4.7       , 0.0       , 0.0       , 0.0       , 1.0
**
** INCONEL 718 SOLUTION ANNEALED ----------------------------------------
**
*MATERIAL, NAME=IN718SA
*DENSITY
8190.0    ,0.0
*ELASTIC, TYPE = ISOTROPIC
2.1000E+11,0.3       ,20.0
2.0800E+11,0.3       ,100.0
2.0300E+11,0.3       ,200.0
1.9800E+11,0.3       ,300.0
1.9100E+11,0.3       ,400.0
1.8200E+11,0.3       ,500.0
1.7100E+11,0.3       ,600.0
1.5900E+11,0.3       ,700.0
```

```
1.4600E+11,0.3       ,800.0
1.3100E+11,0.3       ,900.0
1.1400E+11,0.3       ,1000.0
9.5700E+10,0.3       ,1100.0
*EXPANSION, ZERO = 20.0      , TYPE = ISO
1.4060E-05,25.0
1.4060E-05,100.0
1.4310E-05,200.0
1.4530E-05,300.0
1.4800E-05,400.0
1.5190E-05,500.0
1.5700E-05,600.0
1.6180E-05,700.0
1.6600E-05,800.0
1.7010E-05,900.0
1.7410E-05,1000.0
1.7790E-05,1100.0
*PLASTIC
400171000.,0.0       ,20.0
406656000.,1.0000E-03,20.0
409490000.,0.00143845,20.0
413556000.,0.00206914,20.0
419383000.,0.00297635,20.0
427722000.,0.00428133,20.0
439627000.,0.00615848,20.0
456569000.,0.00885867,20.0
480564000.,0.0127428 ,20.0
514320000.,0.0183298 ,20.0
561345000.,0.0263665 ,20.0
625944000.,0.0379269 ,20.0
712913000.,0.0545559 ,20.0
826657000.,0.078476  ,20.0
969366000.,0.112884  ,20.0
1.1381E+09,0.162378  ,20.0
1.3212E+09,0.233572  ,20.0
1.4971E+09,0.335982  ,20.0
1.6391E+09,0.483293  ,20.0
1.7287E+09,0.695193  ,20.0
1.7686E+09,1.0       ,20.0
340502000.,0.0       ,200.0
346985000.,1.0000E-03,200.0
349817000.,0.00143845,200.0
353880000.,0.00206914,200.0
359701000.,0.00297635,200.0
368027000.,0.00428133,200.0
379907000.,0.00615848,200.0
396796000.,0.00885867,200.0
420683000.,0.0127428 ,200.0
454220000.,0.0183298 ,200.0
500809000.,0.0263665 ,200.0
564547000.,0.0379269 ,200.0
649854000.,0.0545559 ,200.0
760489000.,0.078476  ,200.0
897629000.,0.112884  ,200.0
1.0570E+09,0.162378  ,200.0
1.2256E+09,0.233572  ,200.0
1.3821E+09,0.335982  ,200.0
1.5022E+09,0.483293  ,200.0
1.5728E+09,0.695193  ,200.0
1.6012E+09,1.0       ,200.0
282862000.,0.0       ,400.0
289344000.,1.0000E-03,400.0
292174000.,0.00143845,400.0
296232000.,0.00206914,400.0
302045000.,0.00297635,400.0
310353000.,0.00428133,400.0
322195000.,0.00615848,400.0
339009000.,0.00885867,400.0
362743000.,0.0127428 ,400.0
395972000.,0.0183298 ,400.0
441945000.,0.0263665 ,400.0
504475000.,0.0379269 ,400.0
```

```
587470000.,0.0545559 ,400.0
693822000.,0.078476  ,400.0
823403000.,0.112884  ,400.0
970279000.,0.162378  ,400.0
1.1204E+09,0.233572  ,400.0
1.2528E+09,0.335982  ,400.0
1.3475E+09,0.483293  ,400.0
1.3977E+09,0.695193  ,400.0
1.4153E+09,1.0       ,400.0
234372000.,0.0       ,600.0
240851000.,1.0000E-03,600.0
243679000.,0.00143845,600.0
247732000.,0.00206914,600.0
253532000.,0.00297635,600.0
261817000.,0.00428133,600.0
273610000.,0.00615848,600.0
290324000.,0.00885867,600.0
313856000.,0.0127428 ,600.0
346678000.,0.0183298 ,600.0
391845000.,0.0263665 ,600.0
452805000.,0.0379269 ,600.0
532821000.,0.0545559 ,600.0
633732000.,0.078476  ,600.0
753903000.,0.112884  ,600.0
885724000.,0.162378  ,600.0
1.0143E+09,0.233572  ,600.0
1.1204E+09,0.335982  ,600.0
1.1894E+09,0.483293  ,600.0
1.2214E+09,0.695193  ,600.0
1.2307E+09,1.0       ,600.0
208183000.,0.0       ,700.0
214660000.,1.0000E-03,700.0
217486000.,0.00143845,700.0
221534000.,0.00206914,700.0
227327000.,0.00297635,700.0
235594000.,0.00428133,700.0
247353000.,0.00615848,700.0
263996000.,0.00885867,700.0
287386000.,0.0127428 ,700.0
319922000.,0.0183298 ,700.0
364524000.,0.0263665 ,700.0
424392000.,0.0379269 ,700.0
502356000.,0.0545559 ,700.0
599571000.,0.078476  ,700.0
713475000.,0.112884  ,700.0
835551000.,0.162378  ,700.0
950738000.,0.233572  ,700.0
1.0414E+09,0.335982  ,700.0
1.0965E+09,0.483293  ,700.0
1.1198E+09,0.695193  ,700.0
1.1258E+09,1.0       ,700.0
179914000.,0.0       ,800.0
186389000.,1.0000E-03,800.0
189212000.,0.00143845,800.0
193255000.,0.00206914,800.0
199036000.,0.00297635,800.0
207280000.,0.00428133,800.0
218991000.,0.00615848,800.0
235536000.,0.00885867,800.0
258729000.,0.0127428 ,800.0
290872000.,0.0183298 ,800.0
334702000.,0.0263665 ,800.0
393086000.,0.0379269 ,800.0
468287000.,0.0545559 ,800.0
560595000.,0.078476  ,800.0
666338000.,0.112884  ,800.0
776072000.,0.162378  ,800.0
874961000.,0.233572  ,800.0
947860000.,0.335982  ,800.0
988289000.,0.483293  ,800.0
1.0033E+09,0.695193  ,800.0
1.0065E+09,1.0       ,800.0
```

```
156659000.,0.0       ,900.0
163060000.,1.0000E-03,900.0
165804000.,0.00143845,900.0
169686000.,0.00206914,900.0
175140000.,0.00297635,900.0
182720000.,0.00428133,900.0
193100000.,0.00615848,900.0
207011000.,0.00885867,900.0
225085000.,0.0127428 ,900.0
247549000.,0.0183298 ,900.0
273746000.,0.0263665 ,900.0
301636000.,0.0379269 ,900.0
327701000.,0.0545559 ,900.0
347936000.,0.078476  ,900.0
360011000.,0.112884  ,900.0
364982000.,0.162378  ,900.0
366198000.,0.233572  ,900.0
366342000.,0.335982  ,900.0
366348000.,0.483293  ,900.0
366348000.,0.695193  ,900.0
366348000.,1.0       ,900.0
138690000.,0.0       ,1000.0
144993000.,1.0000E-03,1000.0
147635000.,0.00143845,1000.0
151311000.,0.00206914,1000.0
156353000.,0.00297635,1000.0
163124000.,0.00428133,1000.0
171951000.,0.00615848,1000.0
182970000.,0.00885867,1000.0
195904000.,0.0127428 ,1000.0
209801000.,0.0183298 ,1000.0
222962000.,0.0263665 ,1000.0
233374000.,0.0379269 ,1000.0
239754000.,0.0545559 ,1000.0
242481000.,0.078476  ,1000.0
243184000.,0.112884  ,1000.0
243273000.,0.162378  ,1000.0
243277000.,0.233572  ,1000.0
243277000.,0.335982  ,1000.0
243277000.,0.483293  ,1000.0
243277000.,0.695193  ,1000.0
243277000.,1.0       ,1000.0
123321000.,0.0       ,1100.0
129414000.,1.0000E-03,1100.0
131845000.,0.00143845,1100.0
135105000.,0.00206914,1100.0
139348000.,0.00297635,1100.0
144633000.,0.00428133,1100.0
150815000.,0.00615848,1100.0
157426000.,0.00885867,1100.0
163644000.,0.0127428 ,1100.0
168515000.,0.0183298 ,1100.0
171460000.,0.0263665 ,1100.0
172694000.,0.0379269 ,1100.0
173003000.,0.0545559 ,1100.0
173041000.,0.078476  ,1100.0
173043000.,0.112884  ,1100.0
173043000.,0.162378  ,1100.0
173043000.,0.233572  ,1100.0
173043000.,0.335982  ,1100.0
173043000.,0.483293  ,1100.0
173043000.,0.695193  ,1100.0
173043000.,1.0       ,1100.0
*CREEP, LAW=HYPERB
1.6532E+21,3.1345E-11,5.0       ,285000.0  ,8.3145
**
** STAINLESS STEEL 316L ----------------------------------------
**
*MATERIAL, NAME=SS316L
*DENSITY
8030.0    ,0.0
*ELASTIC, TYPE = ISOTROPIC
```

```
1.9500E+11,0.31      ,25.0
1.8900E+11,0.31      ,100.0
1.8600E+11,0.31      ,150.0
1.8300E+11,0.31      ,200.0
1.7900E+11,0.31      ,250.0
1.7600E+11,0.31      ,300.0
1.7200E+11,0.31      ,350.0
1.6900E+11,0.31      ,400.0
1.6500E+11,0.31      ,450.0
1.6000E+11,0.31      ,500.0
1.5600E+11,0.31      ,550.0
1.5100E+11,0.31      ,600.0
1.4600E+11,0.31      ,650.0
1.4000E+11,0.31      ,700.0
*EXPANSION, ZERO = 20.0      , TYPE = ISO
1.5316E-05,20.0
1.5428E-05,25.0
1.5981E-05,50.0
1.6502E-05,75.0
1.6982E-05,100.0
1.7413E-05,125.0
1.7791E-05,150.0
1.8115E-05,175.0
1.8388E-05,200.0
1.8614E-05,225.0
1.8798E-05,250.0
1.8949E-05,275.0
1.9074E-05,300.0
1.9184E-05,325.0
1.9286E-05,350.0
1.9391E-05,375.0
1.9505E-05,400.0
1.9636E-05,425.0
1.9789E-05,450.0
1.9967E-05,475.0
2.0171E-05,500.0
2.0400E-05,525.0
2.0646E-05,550.0
2.0902E-05,575.0
2.1154E-05,600.0
2.1384E-05,625.0
2.1569E-05,650.0
2.1680E-05,675.0
2.1683E-05,700.0
2.1537E-05,725.0
2.1194E-05,750.0
2.0601E-05,775.0
1.9694E-05,800.0
1.8404E-05,825.0
*PLASTIC
61139316.222086355,0.0,25.0
99123874.86338061,0.00017338117534924802,25.0
137108433.50467488,0.0007605481312342939,25.0
175092992.14596915,0.002554550349249083,25.0
213077550.7872634,0.008652823068906555,25.0
251062109.4285577,0.02827886374269912,25.0
289046668.06985193,0.05609593923576345,25.0
327031226.7111462,0.07829947356086803,25.0
365015785.3524405,0.09933947255240311,25.0
403000343.9937347,0.12208937705530296,25.0
440984902.635029,0.14714115308999157,25.0
478969461.27632326,0.174600035692718,25.0
516954019.9176175,0.20449229540782932,25.0
554938578.5589118,0.23683239095623862,25.0
592923137.200206,0.27163268775726307,25.0
630907695.8415003,0.3089047173135107,25.0
668892254.4827945,0.3486593564861336,25.0
706876813.1240888,0.3909068962705142,25.0
744861371.765383,0.43565709985968654,25.0
782845930.4066772,0.4829192546607921,25.0
61139316.222086355,0.0,40.0
99123874.86338061,0.00017338117534924802,40.0
```

```
137108433.50467488,0.0007605481312342939,40.0
175092992.14596915,0.002554550349249083,40.0
213077550.7872634,0.008652823068906555,40.0
251062109.4285577,0.02827886374269912,40.0
289046668.06985193,0.05609593923576345,40.0
327031226.7111462,0.07829947356086803,40.0
365015785.3524405,0.09933947255240311,40.0
403000343.9937347,0.12208937705530296,40.0
440984902.635029,0.14714115308999157,40.0
478969461.27632326,0.174600035692718,40.0
516954019.9176175,0.20449229540782932,40.0
554938578.5589118,0.23683239095623862,40.0
592923137.200206,0.27163268775726307,40.0
630907695.8415003,0.3089047173135107,40.0
668892254.4827945,0.3486593564861336,40.0
706876813.1240888,0.3909068962705142,40.0
744861371.765383,0.43565709985968654,40.0
782845930.4066772,0.4829192546607921,40.0
51806945.09565362,0.0,65.0
90385161.75208598,0.00020349684873331093,65.0
128963378.40851836,0.000927346343976116,65.0
167541595.06495073,0.003240599552372871,65.0
206119811.7213831,0.012097619491873862,65.0
244698028.37781546,0.03738682154614684,65.0
283276245.0342479,0.06356261352885366,65.0
321854461.69068015,0.08474538402056186,65.0
360432678.34711254,0.10656158640339262,65.0
399010895.0035449,0.13052808473809135,65.0
437589111.6599773,0.15687154213243026,65.0
476167328.3164097,0.18561940380049924,65.0
514745544.9728421,0.21677322419230372,65.0
553323761.6292744,0.2503317092608195,65.0
591901978.2857068,0.28629340706534767,65.0
630480194.9421391,0.32465695395311883,65.0
669058411.5985715,0.36542107609130997,65.0
707636628.2550039,0.4085845771533278,65.0
746214844.9114363,0.4541463287879294,65.0
784793061.5678686,0.5021052631580049,65.0
44954405.659465395,0.0,100.0
83812396.20050764,0.00023354845734688913,100.0
122670386.74154988,0.0010946289478958643,100.0
161528377.28259215,0.003997601633814875,100.0
200386367.8236344,0.01627078655191519,100.0
239244358.36467662,0.0447967333162267,100.0
278102348.90571886,0.06870901400603395,100.0
316960339.4467611,0.08978536272700892,100.0
355818329.98780334,0.11243485486187166,100.0
394676320.5288456,0.1374016713775266,100.0
433534311.0698878,0.16476248020601206,100.0
472392301.6109301,0.19451240900880257,100.0
511250292.15197235,0.22663883103288635,100.0
550108282.6930146,0.2611293857833871,100.0
588966273.2340568,0.29797261700624966,100.0
627824263.7750992,0.3371579002279687,100.0
666682254.3161414,0.3786753351356535,100.0
705540244.8571836,0.4225156552829504,100.0
744398235.3982259,0.4686701537234528,100.0
783256225.9392681,0.5171306209850168,100.0
41283123.37946807,0.0,125.0
79450049.08506969,0.00024890773767328057,125.0
117616974.79067132,0.0011804494922546178,125.0
155783900.49627292,0.004419819057653056,125.0
193950826.20187455,0.01863449517733809,125.0
232117751.9074762,0.04783123593849767,125.0
270284677.6130778,0.07080566963804066,125.0
308451603.31867945,0.09200931467814248,125.0
346618529.0242811,0.1150620207671285,125.0
384785454.7298827,0.14047214444374542,125.0
422952380.43548435,0.1682764765657828,125.0
461119306.141086,0.19846047024448574,125.0
499286231.84668756,0.23100608936655403,125.0
537453157.5522891,0.26589642548639203,125.0
```

```
575620083.2578908,0.3031158965637698,125.0
613787008.9634925,0.34265008432355026,125.0
651953934.6690941,0.3844855790394153,125.0
690120860.3746957,0.42860985218099523,125.0
728287786.0802974,0.475011151581477,125.0
766454711.7858989,0.523678414096918,125.0
38860675.93685849,0.0,150.0
76138659.98453552,0.0002578595759783052,150.0
113416644.03221254,0.0012305847688565215,150.0
150694628.07988957,0.004678753824295303,150.0
187972612.12756658,0.020061324386880512,150.0
225250596.17524362,0.04938594617230351,150.0
262528580.22292066,0.07191090076112362,150.0
299806564.27059764,0.09321985153505694,150.0
337084548.3182747,0.1164973286197901,150.0
374362532.3659517,0.142147845160743 7,150.0
411640516.41362876,0.17019133599723726,150.0
448918500.46130574,0.20060875972660858,150.0
486196484.5089828,0.23337929640697452,150.0
523474468.5566598,0.2684836487261596,150.0
560752452.6043369,0.3059040694778811,150.0
598030436.6520139,0.34562415592612866,150.0
635308420.6996909,0.38762866847204047,150.0
672586404.747368,0.43190338268153605,150.0
709864388.795045,0.47843496758066734,150.0
747142372.842722,0.5272108843537421,150.0
35873820.272110485,0.0,175.0
73057088.09277683,0.00027792942993893076,175.0
110240355.91344318,0.0013433558121280595,175.0
147423623.73410955,0.005297905675007308,175.0
184606891.5547759,0.0233270510326924 8,175.0
221790159.37544224,0.052378793677771006,175.0
258973427.1961086,0.07414622745324553,175.0
296156695.01677495,0.09574015531963602,175.0
333339962.83744127,0.11949277856467226,175.0
370523230.65810764,0.14564016978980854,175.0
407706498.47877395,0.17417552452744 3,175.0
444889766.2994403,0.20507172024288134,175.0
482073034.1201067,0.2383024465039795,175.0
519256301.940773,0.2738436288430255,175.0
556439569.7614394,0.3116731991497274,175.0
593622837.5821058,0.35177080834240293,175.0
630806105.4027721,0.39411759011119135,175.0
667989373.2234384,0.4386959693230179,175.0
705172641.0441048,0.4854895047793349,175.0
742355908.8647711,0.5344827586206896,175.0
34086549.819447696,0.0,200.0
70978586.67658976,0.000289940675023686,200.0
107870623.53373182,0.001411133091966976,200.0
144762660.39087388,0.0056966244921471555,200.0
181654697.24801594,0.02528339879378341,200.0
218546734.105158,0.05389448442674857,200.0
255438770.96230006,0.07535451893283478,200.0
292330807.81944215,0.09713715657296705,200.0
329222844.6765842,0.12115539444056486,200.0
366114881.5337263,0.14757551093654933,200.0
403006918.3908683,0.17637963471579934,200.0
439898955.24801034,0.20753672690239044,200.0
476790992.1051524,0.24101759079733442,200.0
513683028.9622945,0.2767956180123375,200.0
550575065.8194366,0.31484645499891156,200.0
587467102.6765785,0.3551476731129585,200.0
624359139.5337207,0.39767850163426416,200.0
661251176.3908627,0.4424196117274592,200.0
698143213.2480049,0.48935293936855073,200.0
735035250.1051469,0.5384615384615385,200.0
32532968.980058886,0.0,225.0
69546186.83638555,0.00030456965726573677,225.0
106559404.69271222,0.0014940298750709873,225.0
143572622.54903886,0.006213724971566102,225.0
180585840.40536553,0.02762092690648073 5,225.0
217599058.2616922,0.05551569696629224,225.0
```

```
254612276.11801884,0.07672149384306735,225.0
291625493.9743455,0.09874144492187545,225.0
328638711.8306722,0.12306522309502026,225.0
365651929.68699884,0.1497957538883304,225.0
402665147.54332554,0.17890489159789977,225.0
439678365.3996522,0.21035746581955977,225.0
476691583.2559788,0.2441210894550173,225.0
513704801.1123055,0.28016634385022815,225.0
550718018.9686321,0.3184663471083037,225.0
587731236.8249588,0.35899637647246213,225.0
624744454.6812855,0.40173356588968717,225.0
661757672.5376122,0.44665666178408464,225.0
698770890.3939388,0.49374582318057697,225.0
735784108.2502655,0.5429824561403508,225.0
30474245.3042713,0.0,250.0
67704337.27527209,0.0003269290561736591,250.0
104934429.24627288,0.001621619798096787,250.0
142164521.21727368,0.007077211977874352,250.0
179394613.18827447,0.031009097884582414,250.0
216624705.15927526,0.0576162159868944l,250.0
253854797.13027605,0.0786296790346664,250.0
291084889.1012768,0.10101390369062821,250.0
328314981.0722776,0.1257695333557385,250.0
365545073.0432784,0.1529342056500769,250.0
402775165.0142792,0.1824685004274746,250.0
440005256.98528,0.21433190554194698,250.0
477235348.95628077,0.2484877250801584,250.0
514465440.92728156,0.2849027398062465,250.0
551695532.8982824,0.32354666034372986,250.0
588925624.8692832,0.3643916832677458,250.0
626155716.840284,0.40741213828520784,250.0
663385808.8112848,0.45258420403991345,250.0
700615900.7822856,0.49988567601418565,250.0
737845992.7532864,0.5492957746478874,250.0
28893517.37013135,0.0,275.0
66412457.31749254,0.00034756525024566255,275.0
103931397.26485372,0.0017405409061940441,275.0
141450337.21221492,0.007959701177558998,275.0
178969277.1595761,0.03385754147439006,275.0
216488217.10693726,0.05924906905115153,275.0
254007157.05429846,0.08023363386851569,275.0
291526097.0016597,0.10294535751328258,275.0
329045036.94902086,0.12806576634171157,275.0
366563976.89638203,0.15559400241004628,275.0
404082916.8437432,0.18548317306186662,275.0
441601856.79110444,0.21768858310578829,275.0
479120796.7384656,0.2521700561275576,275.0
516639736.6858268,0.2888913056799498,275.0
554158676.633188,0.32781930323717273,275.0
591677616.5805491,0.36892377856439057,275.0
629196556.5279104,0.4121768240896253,275.0
666715496.4752716,0.457552576852261,275.0
704234436.4226327,0.5050269592049541,275.0
741753376.3699939,0.5545774647887324,275.0
27863024.524040263,0.0,300.0
65573906.7958256,0.00036240759859948967,300.0
103284789.06761093,0.0018269046573937187,300.0
140995671.33939627,0.008648566513358904,300.0
178706553.6111816,0.03571395351230033,300.0
216417435.8829669,0.06028657478734695,300.0
254128318.15475225,0.08131006210808772,300.0
291839200.42653763,0.10424894543583572,300.0
329550082.69832295,0.12961388715292274,300.0
367260964.9701083,0.15738459364292778,300.0
404971847.2418936,0.18750989115631642,300.0
442682729.51367897,0.2199424085115235,300.0
480393611.7854643,0.25463971020410753,300.0
518104494.0572496,0.2915635225723224,300.0
555815376.3290349,0.33067904791158625,300.0
593526258.6008202,0.3719544274505705,300.0
631237140.8726056,0.4153603169153053,300.0
668948023.144391,0.46086954575107575,300.0
```

```
706658905.4161762,0.5084568396129101,300.0
744369787.6879616,0.5580985915492958,300.0
26914209.212513264,0.0,325.0
64703548.937204674,0.0003761544529135295,325.0
102492888.6618961,0.001907611730147354,325.0
140282228.3865875,0.009328396312463636,325.0
178071568.11127892,0.037284695906023686,325.0
215860907.83597034,0.06116635363148816,325.0
253650247.56066173,0.08225706397714383,325.0
291439587.2853531,0.10539914218400129,325.0
329228927.0100446,0.13097854735912545,325.0
367018266.73473597,0.15896122403741939,325.0
404807606.4594274,0.18929260074081558,325.0
442596946.1841188,0.2219230298345594,325.0
480386285.9088102,0.25680814093880855,325.0
518175625.63350165,0.29390796145392795,325.0
555964965.358193,0.33318618471104666,325.0
593754305.0828844,0.3746096000874173,325.0
631543644.8075758,0.41814764324732245,325.0
669332984.5322672,0.46377203542498985,325.0
707122324.2569586,0.5114564899674793,325.0
744911663.98165,0.5611764705882354,325.0
25918708.784199595,0.0,350.0
63899061.42837597,0.00039287210661904834,350.0
101879414.07255234,0.002006815746160732,350.0
139859766.71672872,0.010209933597231878,350.0
177840119.36090508,0.03900633378355582,350.0
215820472.00508144,0.06215009377644839,350.0
253800824.64925784,0.0833511293711001,350.0
291781177.2934342,0.10673058055796338,350.0
329761529.93761057,0.13255659673180917,350.0
367741882.58178693,0.16078233142580556,350.0
405722235.2259633,0.19134962524054072,350.0
443702587.87013966,0.22420628448857322,350.0
481682940.5143161,0.25930576581121895,350.0
519663293.15849245,0.29660619256358545,350.0
557643645.8026688,0.33606957097915846,350.0
595623998.4468452,0.3776611824125002,350.0
633604351.0910215,0.42134910441348744,350.0
671584703.7351979,0.46710382708971915,350.0
709565056.3793743,0.5148979413511141,350.0
747545409.0235506,0.5647058823529413,350.0
25000594.472077496,0.0,375.0
63058591.79667712,0.000408461525115262,375.0
101116589.12127674,0.002100503334499109,375.0
139174586.44587636,0.011085609269153897,375.0
177232583.77047598,0.040435916813088925,375.0
215290581.0950756,0.06299704298668506,375.0
253348578.41967523,0.08432031380945114,375.0
291406575.74427485,0.10791147888455148,375.0
329464573.0688745,0.13395466312441373,375.0
367522570.3934741,0.1623938987459206,375.0
405580567.7180737,0.1931680876965446,375.0
443638565.04267335,0.22622285167676037,375.0
481696562.367273,0.2615097787715254,375.0
519754559.6918726,0.2989853587576607,375.0
557812557.0164722,0.33861015393035826,375.0
595870554.3410718,0.38034815792339355,375.0
633928551.6656715,0.424166291075226,375.0
671986548.9902711,0.4700339966282502,375.0
710044546.3148707,0.517922912905999,375.0
748102543.6394703,0.567806603773585,375.0
24211153.21122934,0.0,400.0
62120749.28196791,0.000420416535716603,400.0
100030345.35270648,0.002173209838234534,400.0
137939941.42344505,0.011791072685885515,400.0
175849537.4941836,0.04142631738117091,400.0
213759133.56492215,0.06360783304637645,400.0
251668729.63566077,0.08503329086601231,400.0
289578325.7063993,0.10878064682019663,400.0
327487921.7771379,0.13498270249592523,400.0
365397517.8478764,0.1635778372072904,400.0
```

```
403307113.918615,0.19450290769682768,400.0
441216709.9893536,0.22770196921250715,400.0
479126306.06009215,0.2631252691781496,400.0
517035902.1308307,0.3007281275810699,400.0
554945498.2015693,0.3404700747753884,400.0
592855094.2723079,0.38231418581679516,400.0
630764690.3430464,0.4262265570184437,400.0
668674286.413785,0.47217588742040517,400.0
706583882.4845235,0.5201331392464598,400.0
744493478.5552621,0.5700712589073634,400.0
23675445.14232901,0.0,425.0
61285670.573749766,0.0004266899633106766,425.0
98895896.00517052,0.002211686773018328,425.0
136506121.4365913,0.0121725600132526,425.0
174116346.86801204,0.0419119768365352,425.0
211726572.29943278,0.06391648400082998,425.0
249336797.73085356,0.08539763634061823,425.0
286947023.16227436,0.10922487012102582,425.0
324557248.5936951,0.1355078003743658,425.0
362167474.02511585,0.1641822083074879,425.0
399777699.4565366,0.1951839384057777,425.0
437387924.8879574,0.22845625837857547,425.0
474998150.31937814,0.2639487416459269,425.0
512608375.7507989,0.3016161208461224,425.0
550218601.1822196,0.3414174088564044,425.0
587828826.6136403,0.383315220654147,425.0
625439052.0450611,0.4272752403003133,425.0
663049277.4764819,0.4732657949167501,425.0
700659502.9079026,0.5212575091918817,425.0
738269728.3393234,0.5712230215827339,425.0
23000137.860976502,0.0,450.0
60339388.50266704,0.00043630413718612936,450.0
97678639.14435758,0.002271115149630025,450.0
135017889.7860481,0.012771554395655195,450.0
172357140.42773867,0.04261387925813332,450.0
209696391.06942922,0.06437511354541173,450.0
247035641.7111197,0.08594362847046884,450.0
284374892.35281026,0.109890568641805,450.0
321714142.9945008,0.13629428143950104,450.0
359053393.63619137,0.16508697424371307,450.0
396392644.2778819,0.1962030118556701,450.0
433731894.9195724,0.22958449791194036,450.0
471071145.56126297,0.2651800098268421,450.0
508410396.2029535,0.302943413233761,450.0
545749646.844644,0.34283295796422986,450.0
583088897.4863346,0.38481058127282763,450.0
620428148.128025,0.4288413605262002,450.0
657767398.7697155,0.47489307601102965,450.0
695106649.4114062,0.5229358565627755,450.0
732445900.0530967,0.5729418886198547,450.0
22540868.815972496,0.0,475.0
59261229.61435905,0.00043785608173279873,475.0
95981590.41274561,0.0022807627045051742,475.0
132701951.21113217,0.01286981352026725,475.0
169422312.00951874,0.04272259535842779,475.0
206142672.80790532,0.06444760718897011,475.0
242863033.60629186,0.08603040625007138,475.0
279583394.4046784,0.10999636820104952,475.0
316303755.203065,0.1364192310738886,475.0
353024116.00145155,0.16523066655587493,475.0
389744476.7998381,0.19636480812441073,475.0
426464837.59822464,0.22976357616314178,475.0
463185198.3966112,0.2653753913318623,475.0
499905559.1949978,0.3031539829166211,475.0
536625919.9933843,0.34305748084026283,475.0
573346280.7917708,0.3850477159318091,475.0
610066641.5901574,0.4290896703500392,475.0
646787002.388544,0.4751510386217333,475.0
683507363.1869305,0.5232018718654253,475.0
720227723.9853171,0.5732142857142857,475.0
**
** HIP DUMMY ----------------------------------------
```

```
**
*MATERIAL, NAME=SS316L_dummy
*DENSITY
8030.0    ,0.0
*ELASTIC, TYPE = ISOTROPIC
1.9500E+09,0.31      ,25.0
**
** WATER EOS ---------------------------------------
**
*MATERIAL, NAME=water_elastic
*DENSITY
1000.0    ,0.0
*ELASTIC, TYPE = ISOTROPIC
68856750.0,0.495     ,0.0
*PHYSICAL CONSTANTS,ABSOLUTE ZERO = -273.15
*****
```

APPENDIX B. FE-SAFE MATERIAL FATIGUE MODELS

B.0.1 FESAFE_Fatigue_W.stlx

```
<!DOCTYPE settings>
<root>
    <!--fe-safe Settings File-->
    <meta version="3"/>
    <data>
        <group name="project">
            <group name="interfaces">
                <boolean name="load␣all␣groups">true</boolean>
                <boolean name="add␣surface␣groups">true</boolean>
            </group>
            <directory name="generated␣results␣directory">./results</directory>
            <integer name="diagnostic␣level">0</integer>
            <group name="model">
                <file name="mesh␣source␣file">abq_half_pulse.odb</file>
                <file name="source␣file">abq_half_pulse.odb</file>
                <group name="stress␣units">
                    <string name="description">Pa</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="strain␣units">
                    <string name="description">strain</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="temperature␣units">
                    <string name="description">degC</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="force␣units">
                    <string name="description">N</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="distance␣units">
                    <string name="description">m</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <boolean name="surface␣as␣nodal">true</boolean>
                <enumerator name="extract␣strain␣type">Total</enumerator>
                <boolean name="extract␣forces">false</boolean>
                <boolean name="extract␣strains">false</boolean>
                <boolean name="extract␣groups">true</boolean>
                <string name="debug␣items">None</string>
            </group>
            <group name="job">
                <enumerator name="type">general</enumerator>
                <group name="material␣databases">
                    <array name="materials" size="2">
                        <entry index="1">
                            <group name="material">
                                <file name="database">/</file>
                                <string name="fatigue␣strength␣coefficient␣(sf')">356.0</string>
                                <string name="fatigue␣ductility␣coefficient␣(Ef')">0</string>
                                <string name="fatigue␣strength␣exponent␣(b)">-0.0415080</string>
                                <string name="fatigue␣ductility␣exponent␣(c)">0</string>
                                <string name="K'">1E20</string>
                                <string name="Young's␣modulus">398000</string>
                                <string name="ultimate␣tensile␣strength">356.0</string>
                                <string name="n'">1</string>
                                <string name="CAEL">1E11</string>
                                <string name="material␣name">IrradiatedTungsten</string>
                                <string name="temperature␣list">0</string>
                                <group name="stress-life␣curve">
                                    <string name="control␣series">0</string>
```

```
                        <string name="sample␣series">0</string>
                    </group>
                    <group name="torsion-life␣curve">
                        <string name="control␣series">0</string>
                    </group>
                    <string name="Poisson's␣ratio">0.28</string>
                    <string name="algorithm">NormalStress:-Goodman</string>
                    <string name="class">Other</string>
                    <string name="units">Use system default</string>
                    <string name="quality">Caution_Approximate!!</string>
                    <string name="comment␣1">approximated for tungsten</string>
                    <string name="revision␣number">98</string>
                    <string name="revision␣date">25 Feb. 2022</string>
                    <string name="default␣MSC">"C:\SIMULIA\EstProducts\2020\win_b64\
                         Durability_resources\data\goodman.msc"</string>
                    <string name="grey␣iron␣index">None</string>
                    <string name="Convert␣SN␣To␣TN">1</string>
                </group>
            </entry>
        </array>
        <boolean name="nodal␣property␣mapping␣enabled">true</boolean>
        <boolean name="material␣diagnostics">true</boolean>
        <boolean name="stress-life␣table␣enabled">false</boolean>
        <boolean name="abort␣if␣no␣stress␣life␣data">true</boolean>
        <boolean name="correct␣elastic␣stress">false</boolean>
        <enumerator name="temperature␣interpolation">linear</enumerator>
        <boolean name="temperature␣clamp␣warning">false</boolean>
        <boolean name="material␣extrapolation␣warning">false</boolean>
        <boolean name="R-ratio␣clamp␣warning">false</boolean>
        <real name="Downing␣coefficient">2.55</real>
        <real name="Downing␣exponent">-0.8</real>
    </group>
    <array name="groups" size="2">
        <entry index="0">
            <group name="group">
                <string name="number">0</string>
                <string name="group␣name">Default</string>
                <string name="display␣name">Default</string>
                <string name="algorithm">NoAnalysis</string>
                <string name="mean␣stress␣correction">Unknown MSC</string>
                <integer name="subgroup">1</integer>
                <file name="user␣MSC␣file"/>
                <string name="frf␣life">Infinite</string>
            </group>
        </entry>
        <entry index="1">
            <group name="group">
                <string name="number">1</string>
                <string name="group␣name">PART-1-1_TUNGSTEN</string>
                <string name="display␣name">PART-1-1_TUNGSTEN</string>
                <string name="algorithm">NormalStress</string>
                <string name="mean␣stress␣correction">Goodman</string>
                <integer name="subgroup">0</integer>
                <file name="user␣MSC␣file"/>
                <string name="frf␣life">Infinite</string>
            </group>
        </entry>
    </array>
    <group name="gating">
        <real name="tensor␣gate">5</real>
        <real name="load␣history␣gate">5</real>
        <real name="near␣zero␣stress">10</real>
        <real name="near␣zero␣strain">10</real>
        <boolean name="tensor␣gate␣enabled">true</boolean>
        <boolean name="load␣history␣gate␣enabled">false</boolean>
        <boolean name="CAEL␣gate␣enabled">true</boolean>
        <boolean name="trigonometric␣look-up␣tables">true</boolean>
    </group>
    <group name="probability">
        <string name="target␣lives">1000</string>
    </group>
    <group name="exports">
```

```
<group name="results">
    <file name="FER␣file">./fesafe.fer</file>
    <integer name="contour␣policy">0</integer>
</group>
<boolean name="logarithmic␣lives">true</boolean>
<group name="plots">
    <group name="worst␣node">
        <boolean name="Haigh␣critical␣plane">true</boolean>
        <boolean name="Smith␣critical␣plane">false</boolean>
        <boolean name="Von␣Mises␣stress">false</boolean>
        <boolean name="ignore␣overflows">true</boolean>
    </group>
    <group name="worst␣cycle">
        <boolean name="Haigh">true</boolean>
        <boolean name="Smith">false</boolean>
    </group>
    <boolean name="Haigh">true</boolean>
    <boolean name="Smith">false</boolean>
    <boolean name="Von␣Mises␣stress">false</boolean>
    <boolean name="stress␣tensors">false</boolean>
    <boolean name="stress␣tensors␣after␣gating">false</boolean>
    <boolean name="principals">false</boolean>
    <boolean name="critical␣plane␣normals">false</boolean>
    <boolean name="plasticity␣corrected␣critical␣plane␣normals">false</boolean>
    <boolean name="all␣plane␣normals">false</boolean>
    <boolean name="Dang␣Van">false</boolean>
    <boolean name="damage">false</boolean>
    <boolean name="TURBOlife">false</boolean>
    <boolean name="modal">false</boolean>
    <boolean name="critical␣distance␣plots">false</boolean>
    <boolean name="critical␣distance␣tensor␣histories">false</boolean>
    <boolean name="PSD␣Frequency␣Response␣Function␣plots">false</boolean>
</group>
<group name="contours">
    <boolean name="life">true</boolean>
    <boolean name="damage">false</boolean>
    <boolean name="block␣damage">false</boolean>
    <boolean name="FRF␣horizontal">false</boolean>
    <boolean name="FRF␣vertical">false</boolean>
    <boolean name="FRF␣radial">false</boolean>
    <boolean name="FRF␣worst">false</boolean>
    <boolean name="largest␣loading␣stress">true</boolean>
    <boolean name="SMAXYS">false</boolean>
    <boolean name="SMAXUTS">false</boolean>
    <boolean name="SM">true</boolean>
    <boolean name="SMPreNeuber">false</boolean>
    <boolean name="SRP␣nodal␣temperatures">false</boolean>
    <boolean name="critical␣planes␣all">false</boolean>
    <boolean name="critical␣planes␣worst">false</boolean>
    <boolean name="critical␣distance␣success">false</boolean>
    <boolean name="critical␣distance␣diagnostics">false</boolean>
    <boolean name="critical␣distance␣cycle">false</boolean>
    <boolean name="turbolife␣accumulated␣stress␣strain">false</boolean>
    <boolean name="NASA␣life2">false</boolean>
    <boolean name="temperature-dependent␣UTS␣and␣FS">false</boolean>
    <boolean name="maximum␣temperature">false</boolean>
</group>
<group name="logs">
    <boolean name="load_sensitivity">false</boolean>
    <boolean name="worst␣n␣lives">false</boolean>
    <integer name="n">100</integer>
    <boolean name="ranked␣elimination␣table">false</boolean>
    <boolean name="nodal␣information">false</boolean>
    <boolean name="block␣life␣table">false</boolean>
    <boolean name="plane␣life␣table">false</boolean>
    <boolean name="critical␣plane␣life␣table">false</boolean>
    <boolean name="all␣planes␣life␣table">false</boolean>
    <boolean name="fos␣planes">false</boolean>
    <boolean name="grey␣iron␣damage">false</boolean>
    <boolean name="dataset␣stresses">false</boolean>
    <boolean name="ep␣residuals">false</boolean>
    <boolean name="stress␣and␣strain␣tensors">false</boolean>
```

```
                <boolean name="principals">false</boolean>
                <boolean name="TURBOlife">false</boolean>
                <boolean name="critical␣distance␣items">false</boolean>
                <boolean name="critical␣distance␣summary">false</boolean>
                <boolean name="PSD␣items">false</boolean>
                <enumerator name="history␣indexing">One</enumerator>
            </group>
            <boolean name="only␣analyse␣listed␣items">false</boolean>
            <boolean name="traffic␣lights">false</boolean>
            <real name="traffic␣lights␣lower">1e+06</real>
            <real name="traffic␣lights␣upper">1e+07</real>
            <enumerator name="unit␣system">Metric</enumerator>
        </group>
        <group name="fos">
            <real name="design␣life">1.0</real>
            <boolean name="infinite␣design␣life">false</boolean>
            <real name="maximum">5</real>
            <real name="fine␣maximum">1.5</real>
            <real name="fine␣minimum">0.8</real>
            <real name="minimum">0.5</real>
            <integer name="maximum␣coarse␣iterations">20</integer>
            <integer name="maximum␣fine␣iterations">16</integer>
        </group>
        <group name="critical␣distance">
            <boolean name="apply␣corrections">false</boolean>
            <enumerator name="method">point</enumerator>
            <boolean name="use␣safety-factor␣thresholds">true</boolean>
            <real name="safety-factor␣ceiling">10</real>
            <real name="safety-factor␣floor">0</real>
            <boolean name="allow␣quadratic␣interpolation">true</boolean>
        </group>
        <group name="welds">
            <real name="proportional␣variance␣threshold">0.8</real>
            <boolean name="use␣modified␣wang␣brown">true</boolean>
            <boolean name="use␣nonlinear␣shear␣correction">true</boolean>
            <enumerator name="structural␣stress␣calculation␣mode">Basic Nodal Force</enumerator>
            <boolean name="automatically␣bound␣plate␣thickness">false</boolean>
            <real name="plate␣bound␣median␣margin">0.25</real>
            <boolean name="split␣incomplete␣toes">false</boolean>
            <real name="min␣line␣length␣post␣split">0.75</real>
            <boolean name="reject␣no␣through␣nodes">false</boolean>
            <boolean name="auto-detect␣toe␣failures">true</boolean>
            <boolean name="auto-detect␣fusion␣failures">true</boolean>
            <boolean name="auto-detect␣throat␣failures">false</boolean>
            <boolean name="auto-detect␣root␣failures">false</boolean>
            <boolean name="use␣compact␣contour␣mode">true</boolean>
            <real name="co-planarity␣tolerance">5</real>
            <real name="cone␣tolerance">0.05</real>
            <enumerator name="Ir␣function">IrDisplacement</enumerator>
            <integer name="smoothing␣iterations">0</integer>
            <enumerator name="weld␣end␣correction">VirtualNode</enumerator>
            <enumerator name="throat/fusion␣failure␣sense">FromSurface</enumerator>
            <real name="wrap␣angle">90</real>
            <real name="blunt␣root␣threshold">0.25</real>
        </group>
        <group name="planes">
            <integer name="critical␣plane␣search␣count">18</integer>
        </group>
        <group name="psd">
            <enumerator name="PSD␣response">Von Mises</enumerator>
            <boolean name="Apply␣nodal␣filtering">false</boolean>
            <integer name="Number␣of␣stress␣range␣intervals">1000</integer>
            <real name="RMS␣stress␣cut-off␣multiple">10</real>
            <real name="Combined␣shear-normal␣K">0.25</real>
            <boolean name="Bound␣Dirlik␣at␣UTS">false</boolean>
            <enumerator name="Weld␣SS␣response">Normal</enumerator>
        </group>
        <file name="loading␣file">./FESAFE_Fatigue.ldf</file>
        <file name="output␣file">./abq_half_pulse_FESAFE_Tungsten.odb</file>
        <string name="loading␣mode">LDF</string>
        <real name="scale␣factor">1</real>
        <real name="overflow␣value">0</real>
```

```
                <real name="infinite␣life␣value">-1</real>
                <integer name="modal␣samples␣per␣cycle">10</integer>
                <real name="modal␣gate␣percentage">0.1</real>
                <boolean name="disable␣temperature␣analysis">false</boolean>
                <string name="life␣units␣description">Repeats</string>
                <real name="life␣units␣factor">1</real>
                <boolean name="disable␣triaxiality">false</boolean>
                <boolean name="disable␣failed␣directional␣cosine␣to␣XYZ">false</boolean>
                <boolean name="Von␣Mises␣signed">false</boolean>
                <boolean name="ignore␣compressive␣cycles">false</boolean>
                <boolean name="enforce␣thread␣affinity">false</boolean>
                <integer name="max␣overflows">1000</integer>
            </group>
        </group>
    </data>
</root>
```

B.0.2 FESAFE_Fatigue_IN718SA.stlx

```xml
<!DOCTYPE settings>
<root>
    <!--fe-safe Settings File-->
    <meta version="3"/>
    <data>
        <group name="project">
            <group name="interfaces">
                <boolean name="load␣all␣groups">true</boolean>
                <boolean name="add␣surface␣groups">true</boolean>
            </group>
            <directory name="generated␣results␣directory">./results</directory>
            <integer name="diagnostic␣level">0</integer>
            <group name="model">
                <file name="mesh␣source␣file">abq_half_pulse.odb</file>
                <file name="source␣file">abq_half_pulse.odb</file>
                <group name="stress␣units">
                    <string name="description">Pa</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="strain␣units">
                    <string name="description">strain</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="temperature␣units">
                    <string name="description">degC</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="force␣units">
                    <string name="description">N</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="distance␣units">
                    <string name="description">m</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <boolean name="surface␣as␣nodal">true</boolean>
                <enumerator name="extract␣strain␣type">Total</enumerator>
                <boolean name="extract␣forces">false</boolean>
                <boolean name="extract␣strains">false</boolean>
                <boolean name="extract␣groups">true</boolean>
                <string name="debug␣items">None</string>
            </group>
            <group name="job">
                <enumerator name="type">general</enumerator>
                <group name="material␣databases">
                    <array name="materials" size="2">
                        <entry index="1">
                            <group name="material">
                                <file name="database">/</file>
                                <string name="fatigue␣strength␣coefficient␣(sf')">473.16</string>
                                <string name="fatigue␣ductility␣coefficient␣(Ef')">0</string>
                                <string name="fatigue␣strength␣exponent␣(b)">-0.019635</string>
                                <string name="fatigue␣ductility␣exponent␣(c)">0</string>
                                <string name="K'">1E20</string>
                                <string name="Young's␣modulus">209628</string>
                                <string name="ultimate␣tensile␣strength">930.0</string>
                                <string name="n'">1</string>
                                <string name="CAEL">1E11</string>
                                <string name="0.2%␣Buch␣proof␣stress">-9999</string>
                                <string name="material␣name">IN718SA_BM_Goodman</string>
                                <string name="temperature␣list">0</string>
                                <group name="stress-life␣curve">
                                    <string name="control␣series">-9999</string>
                                    <string name="sample␣series">0</string>
                                </group>
```

```
<group name="torsion-life␣curve">
    <string name="control␣series">0</string>
    <string name="sample␣series">-9999</string>
</group>
<string name="R␣ratio␣list">-9999</string>
<group name="strain-life␣curve">
    <string name="control␣series">-9999</string>
    <string name="sample␣series">-9999</string>
</group>
<group name="stress-strain␣curve">
    <string name="control␣series">-9999</string>
    <string name="sample␣series">-9999</string>
</group>
<string name="strain␣rate␣list">-9999</string>
<string name="hours␣list">-9999</string>
<string name="initial␣compressive␣stresses">-9999</string>
<string name="initial␣tensile␣stresses">-9999</string>
<string name="pre-soak␣factor">-9999</string>
<string name="Weibull␣slope">-9999</string>
<string name="Weibull␣minimum">-9999</string>
<string name="ultimate␣compressive␣strength">930.0</string>
<string name="tensile␣secant␣slope">-9999</string>
<string name="compressive␣K'">-9999</string>
<string name="compressive␣n'">-9999</string>
<string name="compressive␣secant␣slope">-9999</string>
<string name="modulus␣of␣unloading">-9999</string>
<string name="SWT␣coefficient">-9999</string>
<string name="SWT␣exponent">-9999</string>
<string name="fatigue␣strength␣exponent␣above␣knee␣(b2)">-9999</string>
<string name="life␣curve␣knee">-9999</string>
<string name="in-phase␣loading␣factor">-9999</string>
<string name="out-of-phase␣loading␣factor">-9999</string>
<string name="compressive␣relaxed␣stresses">-9999</string>
<string name="tensile␣relaxed␣stresses">-9999</string>
<string name="Dang␣Van␣endurance␣limit␣stress">-9999</string>
<string name="Dang␣Van␣stress␣ratio">-9999</string>
<string name="Poisson's␣ratio">0.3</string>
<string name="algorithm">(shear+direct)Stress:-Goodman</string>
<string name="class">Other</string>
<string name="units">Use system default</string>
<group name="creep">
    <string name="monotonic␣K'">-9999</string>
    <string name="monotonic␣n'">-9999</string>
    <string name="damage␣to␣harden">-9999</string>
    <string name="strain␣rates">-9999</string>
    <string name="ductility␣values">-9999</string>
    <string name="strain␣list">-9999</string>
    <string name="stress␣list">-9999</string>
    <string name="strain␣table">-9999</string>
    <string name="stress␣table">-9999</string>
    <string name="temperature␣threshold">-9999</string>
    <string name="fatigue␣percentage␣values">-9999</string>
    <string name="creep␣percentage␣values">-9999</string>
</group>
<string name="quality">Caution_Approximate!!</string>
<string name="source">-9999</string>
<string name="comment␣1">Ductile failure mode</string>
<string name="revision␣number">3</string>
<string name="revision␣date">4 December 2023</string>
<string name="revision␣history">-9999</string>
<string name="default␣MSC">"/SIMULIA/EstProducts/2020/win_b64/
     Durability_resources/data/goodman.msc"</string>
<string name="threshold␣stress␣intensity␣factor">-9999</string>
<string name="critical␣distance">-9999</string>
<string name="alternating␣shear␣stress">-9999</string>
<string name="alternating␣bending␣fatigue␣strength">-9999</string>
<group name="fully␣reversed">
    <string name="fatigue␣ductility␣coefficient␣(Ef')">-9999</string>
    <string name="fatigue␣ductility␣exponent␣(c)">-9999</string>
</group>
<group name="plastic␣reversed␣by␣creep">
    <string name="fatigue␣ductility␣coefficient␣(Ef')">-9999</string>
```

```
                            <string name="fatigue␣ductility␣exponent␣(c)">-9999</string>
                        </group>
                        <group name="creep␣reversed␣by␣plastic">
                            <string name="fatigue␣ductility␣coefficient␣(Ef')">-9999</string>
                            <string name="fatigue␣ductility␣exponent␣(c)">-9999</string>
                        </group>
                        <string name="Walker␣gamma␣(r␣is␣positive)">-9999</string>
                        <string name="Walker␣gamma␣(r␣is␣negative)">-9999</string>
                        <string name="Default␣knock-down␣curve">-9999</string>
                        <string name="static␣fatigue␣strength␣coefficient␣(sf)">-9999</string>
                        <string name="fkm␣material">-9999</string>
                        <string name="elongation">-9999</string>
                        <string name="grey␣iron␣index">None</string>
                        <string name="softening␣factor">-9999</string>
                        <string name="Convert␣SN␣To␣TN">1</string>
                    </group>
                </entry>
            </array>
            <boolean name="nodal␣property␣mapping␣enabled">true</boolean>
            <boolean name="material␣diagnostics">true</boolean>
            <boolean name="stress-life␣table␣enabled">false</boolean>
            <boolean name="abort␣if␣no␣stress␣life␣data">true</boolean>
            <boolean name="correct␣elastic␣stress">false</boolean>
            <enumerator name="temperature␣interpolation">linear</enumerator>
            <boolean name="temperature␣clamp␣warning">false</boolean>
            <boolean name="material␣extrapolation␣warning">false</boolean>
            <boolean name="R-ratio␣clamp␣warning">false</boolean>
            <real name="Downing␣coefficient">2.55</real>
            <real name="Downing␣exponent">-0.8</real>
        </group>
        <array name="groups" size="2">
            <entry index="0">
                <group name="group">
                    <string name="number">0</string>
                    <string name="group␣name">Default</string>
                    <string name="display␣name">Default</string>
                    <string name="algorithm">NoAnalysis</string>
                    <string name="mean␣stress␣correction">Unknown MSC</string>
                    <integer name="subgroup">1</integer>
                    <file name="user␣MSC␣file"/>
                    <string name="frf␣life">Infinite</string>
                </group>
            </entry>
            <entry index="1">
                <group name="group">
                    <string name="number">1</string>
                    <string name="group␣name">IN718SA</string>
                    <string name="display␣name">IN718SA</string>
                    <string name="algorithm">DefaultMaterial</string>
                    <string name="mean␣stress␣correction">Goodman</string>
                    <integer name="subgroup">1</integer>
                    <string name="frf␣life">Infinite</string>
                </group>
            </entry>
        </array>
        <group name="gating">
            <real name="tensor␣gate">5</real>
            <real name="load␣history␣gate">5</real>
            <real name="near␣zero␣stress">10</real>
            <real name="near␣zero␣strain">10</real>
            <boolean name="tensor␣gate␣enabled">true</boolean>
            <boolean name="load␣history␣gate␣enabled">false</boolean>
            <boolean name="CAEL␣gate␣enabled">true</boolean>
            <boolean name="trigonometric␣look-up␣tables">true</boolean>
        </group>
        <group name="probability">
            <string name="target␣lives">1000</string>
        </group>
        <group name="exports">
            <group name="results">
                <file name="FER␣file">./fesafe.fer</file>
                <integer name="contour␣policy">0</integer>
```

```
</group>
<boolean name="logarithmic␣lives">true</boolean>
<group name="plots">
    <group name="worst␣node">
        <boolean name="Haigh␣critical␣plane">true</boolean>
        <boolean name="Smith␣critical␣plane">false</boolean>
        <boolean name="Von␣Mises␣stress">false</boolean>
        <boolean name="ignore␣overflows">true</boolean>
    </group>
    <group name="worst␣cycle">
        <boolean name="Haigh">true</boolean>
        <boolean name="Smith">false</boolean>
    </group>
    <boolean name="Haigh">true</boolean>
    <boolean name="Smith">false</boolean>
    <boolean name="Von␣Mises␣stress">false</boolean>
    <boolean name="stress␣tensors">false</boolean>
    <boolean name="stress␣tensors␣after␣gating">false</boolean>
    <boolean name="principals">false</boolean>
    <boolean name="critical␣plane␣normals">false</boolean>
    <boolean name="plasticity␣corrected␣critical␣plane␣normals">false</boolean>
    <boolean name="all␣plane␣normals">false</boolean>
    <boolean name="Dang␣Van">false</boolean>
    <boolean name="damage">false</boolean>
    <boolean name="TURBOlife">false</boolean>
    <boolean name="modal">false</boolean>
    <boolean name="critical␣distance␣plots">false</boolean>
    <boolean name="critical␣distance␣tensor␣histories">false</boolean>
    <boolean name="PSD␣Frequency␣Response␣Function␣plots">false</boolean>
</group>
<group name="contours">
    <boolean name="life">true</boolean>
    <boolean name="damage">false</boolean>
    <boolean name="block␣damage">false</boolean>
    <boolean name="FRF␣horizontal">false</boolean>
    <boolean name="FRF␣vertical">false</boolean>
    <boolean name="FRF␣radial">false</boolean>
    <boolean name="FRF␣worst">false</boolean>
    <boolean name="largest␣loading␣stress">true</boolean>
    <boolean name="SMAXYS">false</boolean>
    <boolean name="SMAXUTS">false</boolean>
    <boolean name="SM">true</boolean>
    <boolean name="SMPreNeuber">true</boolean>
    <boolean name="SRP␣nodal␣temperatures">false</boolean>
    <boolean name="critical␣planes␣all">false</boolean>
    <boolean name="critical␣planes␣worst">false</boolean>
    <boolean name="critical␣distance␣success">false</boolean>
    <boolean name="critical␣distance␣diagnostics">false</boolean>
    <boolean name="critical␣distance␣cycle">false</boolean>
    <boolean name="turbolife␣accumulated␣stress␣strain">false</boolean>
    <boolean name="NASA␣life2">false</boolean>
    <boolean name="temperature-dependent␣UTS␣and␣FS">false</boolean>
    <boolean name="maximum␣temperature">false</boolean>
</group>
<group name="logs">
    <boolean name="load_sensitivity">false</boolean>
    <boolean name="worst␣n␣lives">false</boolean>
    <integer name="n">100</integer>
    <boolean name="ranked␣elimination␣table">false</boolean>
    <boolean name="nodal␣information">false</boolean>
    <boolean name="block␣life␣table">false</boolean>
    <boolean name="plane␣life␣table">false</boolean>
    <boolean name="critical␣plane␣life␣table">false</boolean>
    <boolean name="all␣planes␣life␣table">false</boolean>
    <boolean name="fos␣planes">false</boolean>
    <boolean name="grey␣iron␣damage">false</boolean>
    <boolean name="dataset␣stresses">false</boolean>
    <boolean name="ep␣residuals">false</boolean>
    <boolean name="stress␣and␣strain␣tensors">false</boolean>
    <boolean name="principals">false</boolean>
    <boolean name="TURBOlife">false</boolean>
    <boolean name="critical␣distance␣items">false</boolean>
```

```
        <boolean name="critical␣distance␣summary">false</boolean>
        <boolean name="PSD␣items">false</boolean>
        <enumerator name="history␣indexing">One</enumerator>
    </group>
    <boolean name="only␣analyse␣listed␣items">false</boolean>
    <boolean name="traffic␣lights">false</boolean>
    <real name="traffic␣lights␣lower">1e+06</real>
    <real name="traffic␣lights␣upper">1e+07</real>
    <enumerator name="unit␣system">Metric</enumerator>
</group>
<group name="fos">
    <real name="design␣life">1.0</real>
    <boolean name="infinite␣design␣life">false</boolean>
    <real name="maximum">5</real>
    <real name="fine␣maximum">1.5</real>
    <real name="fine␣minimum">0.8</real>
    <real name="minimum">0.5</real>
    <integer name="maximum␣coarse␣iterations">20</integer>
    <integer name="maximum␣fine␣iterations">16</integer>
</group>
<group name="critical␣distance">
    <boolean name="apply␣corrections">false</boolean>
    <enumerator name="method">point</enumerator>
    <boolean name="use␣safety-factor␣thresholds">true</boolean>
    <real name="safety-factor␣ceiling">10</real>
    <real name="safety-factor␣floor">0</real>
    <boolean name="allow␣quadratic␣interpolation">true</boolean>
</group>
<group name="welds">
    <real name="proportional␣variance␣threshold">0.8</real>
    <boolean name="use␣modified␣wang_brown">true</boolean>
    <boolean name="use␣nonlinear␣shear␣correction">true</boolean>
    <enumerator name="structural␣stress␣calculation␣mode">Basic Nodal Force</enumerator>
    <boolean name="automatically␣bound␣plate␣thickness">false</boolean>
    <real name="plate␣bound␣median␣margin">0.25</real>
    <boolean name="split␣incomplete␣toes">false</boolean>
    <real name="min␣line␣length␣post␣split">0.75</real>
    <boolean name="reject␣no␣through␣nodes">false</boolean>
    <boolean name="auto-detect␣toe␣failures">true</boolean>
    <boolean name="auto-detect␣fusion␣failures">true</boolean>
    <boolean name="auto-detect␣throat␣failures">false</boolean>
    <boolean name="auto-detect␣root␣failures">false</boolean>
    <boolean name="use␣compact␣contour␣mode">true</boolean>
    <real name="co-planarity␣tolerance">5</real>
    <real name="cone␣tolerance">0.05</real>
    <enumerator name="Ir␣function">IrDisplacement</enumerator>
    <integer name="smoothing␣iterations">0</integer>
    <enumerator name="weld␣end␣correction">VirtualNode</enumerator>
    <enumerator name="throat/fusion␣failure␣sense">FromSurface</enumerator>
    <real name="wrap␣angle">90</real>
    <real name="blunt␣root␣threshold">0.25</real>
</group>
<group name="planes">
    <integer name="critical␣plane␣search␣count">18</integer>
</group>
<group name="psd">
    <enumerator name="PSD␣response">Von Mises</enumerator>
    <boolean name="Apply␣nodal␣filtering">false</boolean>
    <integer name="Number␣of␣stress␣range␣intervals">1000</integer>
    <real name="RMS␣stress␣cut-off␣multiple">10</real>
    <real name="Combined␣shear-normal␣K">0.25</real>
    <boolean name="Bound␣Dirlik␣at␣UTS">false</boolean>
    <enumerator name="Weld␣SS␣response">Normal</enumerator>
</group>
<file name="loading␣file">./FESAFE_Fatigue.ldf</file>
<file name="output␣file">./abq_half_pulse_FESAFE_Inconel.odb</file>
<string name="loading␣mode">LDF</string>
<real name="scale␣factor">1</real>
<real name="overflow␣value">0</real>
<real name="infinite␣life␣value">-1</real>
<integer name="modal␣samples␣per␣cycle">10</integer>
<real name="modal␣gate␣percentage">0.1</real>
```

```
                <boolean name="disable␣temperature␣analysis">false</boolean>
                <string name="life␣units␣description">Repeats</string>
                <real name="life␣units␣factor">1</real>
                <boolean name="disable␣triaxiality">false</boolean>
                <boolean name="disable␣failed␣directional␣cosine␣to␣XYZ">false</boolean>
                <boolean name="Von␣Mises␣signed">false</boolean>
                <boolean name="ignore␣compressive␣cycles">false</boolean>
                <boolean name="enforce␣thread␣affinity">false</boolean>
                <integer name="max␣overflows">1000</integer>
            </group>
        </group>
    </data>
</root>
```

B.0.3 FESAFE_Fatigue_SS316.stlx


```
<!DOCTYPE settings>
<root>
    <!--fe-safe Settings File-->
    <meta version="3"/>
    <data>
        <group name="project">
            <group name="interfaces">
                <boolean name="load␣all␣groups">true</boolean>
                <boolean name="add␣surface␣groups">true</boolean>
            </group>
            <directory name="generated␣results␣directory">./results</directory>
            <integer name="diagnostic␣level">0</integer>
            <group name="model">
                <file name="mesh␣source␣file">abq_half_pulse.odb</file>
                <file name="source␣file">abq_half_pulse.odb</file>
                <group name="stress␣units">
                    <string name="description">Pa</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="strain␣units">
                    <string name="description">strain</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="temperature␣units">
                    <string name="description">degC</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="force␣units">
                    <string name="description">N</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <group name="distance␣units">
                    <string name="description">m</string>
                    <real name="scale">1</real>
                    <real name="offset">0</real>
                </group>
                <boolean name="surface␣as␣nodal">true</boolean>
                <enumerator name="extract␣strain␣type">Total</enumerator>
                <boolean name="extract␣forces">false</boolean>
                <boolean name="extract␣strains">false</boolean>
                <boolean name="extract␣groups">true</boolean>
                <string name="debug␣items">None</string>
            </group>
            <group name="job">
                <enumerator name="type">general</enumerator>
                <group name="material␣databases">
                    <array name="materials" size="2">
                        <entry index="1">
                            <group name="material">
                                <file name="database">/</file>
                                <string name="fatigue␣strength␣coefficient␣(sf')">648.1</string>
                                <string name="fatigue␣ductility␣coefficient␣(Ef')">1E-12</string>
                                <string name="fatigue␣strength␣exponent␣(b)">-0.02</string>
                                <string name="fatigue␣ductility␣exponent␣(c)">-1</string>
                                <string name="K'">1E20</string>
                                <string name="Young's␣modulus">195100</string>
                                <string name="ultimate␣tensile␣strength">648.1</string>
                                <string name="n'">1</string>
                                <string name="CAEL">1E11</string>
                                <string name="0.2%␣Buch␣proof␣stress">-9999</string>
                                <string name="material␣name">SS316_BM_Goodman</string>
                                <string name="temperature␣list">0</string>
                                <group name="stress-life␣curve">
                                    <string name="control␣series">271.47, 262.35, 254.78, 248.52, 243.35,
                                         239.06, 235.52, 232.58, 230.16, 228.15, 226.48, 225.11, 223.97, 223.03,
                                          222.25, 221.61, 221.07, 220.63, 220.26, 219.96, 218.95, 218.64</string
```

```
    >
<string name="sample␣series">1.0e+06, 1.438e+06, 2.069e+06, 2.976e+06,
    4.281e+06, 6.158e+06, 8.859e+06, 1.274e+07, 1.833e+07, 2.637e+07, 3.793
    e+07, 5.456e+07, 7.848e+07, 1.129e+08, 1.624e+08, 2.336e+08, 3.360e+08,
     4.833e+08, 6.952e+08, 1.0e+09, 1.0e+10, 1.0e+11</string>
</group>
<group name="torsion-life␣curve">
    <string name="control␣series">0</string>
    <string name="sample␣series">-9999</string>
</group>
<string name="R␣ratio␣list">-9999</string>
<group name="strain-life␣curve">
    <string name="control␣series">-9999</string>
    <string name="sample␣series">-9999</string>
</group>
<group name="stress-strain␣curve">
    <string name="control␣series">-9999</string>
    <string name="sample␣series">-9999</string>
</group>
<string name="strain␣rate␣list">-9999</string>
<string name="hours␣list">-9999</string>
<string name="initial␣compressive␣stresses">-9999</string>
<string name="initial␣tensile␣stresses">-9999</string>
<string name="pre-soak␣factor">-9999</string>
<string name="Weibull␣slope">-9999</string>
<string name="Weibull␣minimum">-9999</string>
<string name="ultimate␣compressive␣strength">648.1</string>
<string name="tensile␣secant␣slope">-9999</string>
<string name="compressive␣K'">-9999</string>
<string name="compressive␣n'">-9999</string>
<string name="compressive␣secant␣slope">-9999</string>
<string name="modulus␣of␣unloading">-9999</string>
<string name="SWT␣coefficient">-9999</string>
<string name="SWT␣exponent">-9999</string>
<string name="fatigue␣strength␣exponent␣above␣knee␣(b2)">-9999</string>
<string name="life␣curve␣knee">-9999</string>
<string name="in-phase␣loading␣factor">-9999</string>
<string name="out-of-phase␣loading␣factor">-9999</string>
<string name="compressive␣relaxed␣stresses">-9999</string>
<string name="tensile␣relaxed␣stresses">-9999</string>
<string name="Dang␣Van␣endurance␣limit␣stress">-9999</string>
<string name="Dang␣Van␣stress␣ratio">-9999</string>
<string name="Poisson's␣ratio">0.31</string>
<string name="algorithm">(shear+direct)Stress:-Goodman</string>
<string name="class">Other</string>
<string name="units">Use system default</string>
<group name="creep">
    <string name="monotonic␣K'">-9999</string>
    <string name="monotonic␣n'">-9999</string>
    <string name="damage␣to␣harden">-9999</string>
    <string name="strain␣rates">-9999</string>
    <string name="ductility␣values">-9999</string>
    <string name="strain␣list">-9999</string>
    <string name="stress␣list">-9999</string>
    <string name="strain␣table">-9999</string>
    <string name="stress␣table">-9999</string>
    <string name="temperature␣threshold">-9999</string>
    <string name="fatigue␣percentage␣values">-9999</string>
    <string name="creep␣percentage␣values">-9999</string>
</group>
<string name="quality">Mean fatigue life</string>
<string name="source">NUREG_CR 6909</string>
<string name="comment␣1">Figure 30, Equation 32</string>
<string name="revision␣number">1</string>
<string name="revision␣date">5 March 2024</string>
<string name="revision␣history">-9999</string>
<string name="default␣MSC">"/SIMULIA/EstProducts/2020/win_b64/
    Durability_resources/data/goodman.msc"</string>
<string name="threshold␣stress␣intensity␣factor">-9999</string>
<string name="critical␣distance">-9999</string>
<string name="alternating␣shear␣stress">-9999</string>
<string name="alternating␣bending␣fatigue␣strength">-9999</string>
```

```
                <group name="fully␣reversed">
                    <string name="fatigue␣ductility␣coefficient␣(Ef')">-9999</string>
                    <string name="fatigue␣ductility␣exponent␣(c)">-9999</string>
                </group>
                <group name="plastic␣reversed␣by␣creep">
                    <string name="fatigue␣ductility␣coefficient␣(Ef')">-9999</string>
                    <string name="fatigue␣ductility␣exponent␣(c)">-9999</string>
                </group>
                <group name="creep␣reversed␣by␣plastic">
                    <string name="fatigue␣ductility␣coefficient␣(Ef')">-9999</string>
                    <string name="fatigue␣ductility␣exponent␣(c)">-9999</string>
                </group>
                <string name="Walker␣gamma␣(r␣is␣positive)">-9999</string>
                <string name="Walker␣gamma␣(r␣is␣negative)">-9999</string>
                <string name="Default␣knock-down␣curve">-9999</string>
                <string name="static␣fatigue␣strength␣coefficient␣(sf)">-9999</string>
                <string name="fkm␣material">-9999</string>
                <string name="elongation">-9999</string>
                <string name="grey␣iron␣index">None</string>
                <string name="softening␣factor">-9999</string>
                <string name="Convert␣SN␣To␣TN">1</string>
            </group>
        </entry>
    </array>
    <boolean name="nodal␣property␣mapping␣enabled">true</boolean>
    <boolean name="material␣diagnostics">true</boolean>
    <boolean name="stress-life␣table␣enabled">true</boolean>
    <boolean name="abort␣if␣no␣stress␣life␣data">true</boolean>
    <boolean name="correct␣elastic␣stress">false</boolean>
    <enumerator name="temperature␣interpolation">linear</enumerator>
    <boolean name="temperature␣clamp␣warning">false</boolean>
    <boolean name="material␣extrapolation␣warning">false</boolean>
    <boolean name="R-ratio␣clamp␣warning">false</boolean>
    <real name="Downing␣coefficient">2.55</real>
    <real name="Downing␣exponent">-0.8</real>
</group>
<array name="groups" size="2">
    <entry index="0">
        <group name="group">
            <string name="number">0</string>
            <string name="group␣name">Default</string>
            <string name="display␣name">Default</string>
            <string name="algorithm">NoAnalysis</string>
            <string name="mean␣stress␣correction">Unknown MSC</string>
            <integer name="subgroup">1</integer>
            <file name="user␣MSC␣file"/>
            <string name="frf␣life">Infinite</string>
        </group>
    </entry>
    <entry index="1">
        <group name="group">
            <string name="number">1</string>
            <string name="group␣name">SS316L</string>
            <string name="display␣name">SS316L</string>
            <string name="algorithm">DefaultMaterial</string>
            <string name="mean␣stress␣correction">Goodman</string>
            <integer name="subgroup">1</integer>
            <string name="frf␣life">Infinite</string>
        </group>
    </entry>
</array>
<group name="gating">
    <real name="tensor␣gate">5</real>
    <real name="load␣history␣gate">5</real>
    <real name="near␣zero␣stress">10</real>
    <real name="near␣zero␣strain">10</real>
    <boolean name="tensor␣gate␣enabled">true</boolean>
    <boolean name="load␣history␣gate␣enabled">false</boolean>
    <boolean name="CAEL␣gate␣enabled">true</boolean>
    <boolean name="trigonometric␣look-up␣tables">true</boolean>
</group>
<group name="probability">
```

```
                    <string name="target␣lives">1000</string>
                </group>
                <group name="exports">
                    <group name="results">
                        <file name="FER␣file">./fesafe.fer</file>
                        <integer name="contour␣policy">0</integer>
                    </group>
                    <boolean name="logarithmic␣lives">true</boolean>
                    <group name="plots">
                        <group name="worst␣node">
                            <boolean name="Haigh␣critical␣plane">true</boolean>
                            <boolean name="Smith␣critical␣plane">false</boolean>
                            <boolean name="Von␣Mises␣stress">false</boolean>
                            <boolean name="ignore␣overflows">true</boolean>
                        </group>
                        <group name="worst␣cycle">
                            <boolean name="Haigh">true</boolean>
                            <boolean name="Smith">false</boolean>
                        </group>
                        <boolean name="Haigh">true</boolean>
                        <boolean name="Smith">false</boolean>
                        <boolean name="Von␣Mises␣stress">false</boolean>
                        <boolean name="stress␣tensors">false</boolean>
                        <boolean name="stress␣tensors␣after␣gating">false</boolean>
                        <boolean name="principals">false</boolean>
                        <boolean name="critical␣plane␣normals">false</boolean>
                        <boolean name="plasticity␣corrected␣critical␣plane␣normals">false</boolean>
                        <boolean name="all␣plane␣normals">false</boolean>
                        <boolean name="Dang␣Van">false</boolean>
                        <boolean name="damage">false</boolean>
                        <boolean name="TURBOlife">false</boolean>
                        <boolean name="modal">false</boolean>
                        <boolean name="critical␣distance␣plots">false</boolean>
                        <boolean name="critical␣distance␣tensor␣histories">false</boolean>
                        <boolean name="PSD␣Frequency␣Response␣Function␣plots">false</boolean>
                    </group>
                    <group name="contours">
                        <boolean name="life">true</boolean>
                        <boolean name="damage">false</boolean>
                        <boolean name="block␣damage">false</boolean>
                        <boolean name="FRF␣horizontal">false</boolean>
                        <boolean name="FRF␣vertical">false</boolean>
                        <boolean name="FRF␣radial">false</boolean>
                        <boolean name="FRF␣worst">false</boolean>
                        <boolean name="largest␣loading␣stress">true</boolean>
                        <boolean name="SMAXYS">false</boolean>
                        <boolean name="SMAXUTS">false</boolean>
                        <boolean name="SM">true</boolean>
                        <boolean name="SMPreNeuber">true</boolean>
                        <boolean name="SRP␣nodal␣temperatures">false</boolean>
                        <boolean name="critical␣planes␣all">false</boolean>
                        <boolean name="critical␣planes␣worst">false</boolean>
                        <boolean name="critical␣distance␣success">false</boolean>
                        <boolean name="critical␣distance␣diagnostics">false</boolean>
                        <boolean name="critical␣distance␣cycle">false</boolean>
                        <boolean name="turbolife␣accumulated␣stress␣strain">false</boolean>
                        <boolean name="NASA␣life2">false</boolean>
                        <boolean name="temperature-dependent␣UTS␣and␣FS">false</boolean>
                        <boolean name="maximum␣temperature">false</boolean>
                    </group>
                    <group name="logs">
                        <boolean name="load_sensitivity">false</boolean>
                        <boolean name="worst␣n␣lives">false</boolean>
                        <integer name="n">100</integer>
                        <boolean name="ranked␣elimination␣table">false</boolean>
                        <boolean name="nodal␣information">false</boolean>
                        <boolean name="block␣life␣table">false</boolean>
                        <boolean name="plane␣life␣table">false</boolean>
                        <boolean name="critical␣plane␣life␣table">false</boolean>
                        <boolean name="all␣planes␣life␣table">false</boolean>
                        <boolean name="fos␣planes">false</boolean>
                        <boolean name="grey␣iron␣damage">false</boolean>
```

```
                <boolean name="dataset␣stresses">false</boolean>
                <boolean name="ep␣residuals">false</boolean>
                <boolean name="stress␣and␣strain␣tensors">false</boolean>
                <boolean name="principals">false</boolean>
                <boolean name="TURBOlife">false</boolean>
                <boolean name="critical␣distance␣items">false</boolean>
                <boolean name="critical␣distance␣summary">false</boolean>
                <boolean name="PSD␣items">false</boolean>
                <enumerator name="history␣indexing">One</enumerator>
            </group>
            <boolean name="only␣analyse␣listed␣items">false</boolean>
            <boolean name="traffic␣lights">false</boolean>
            <real name="traffic␣lights␣lower">1e+06</real>
            <real name="traffic␣lights␣upper">1e+07</real>
            <enumerator name="unit␣system">Metric</enumerator>
        </group>
        <group name="fos">
            <real name="design␣life">1.0</real>
            <boolean name="infinite␣design␣life">false</boolean>
            <real name="maximum">5</real>
            <real name="fine␣maximum">1.5</real>
            <real name="fine␣minimum">0.8</real>
            <real name="minimum">0.5</real>
            <integer name="maximum␣coarse␣iterations">20</integer>
            <integer name="maximum␣fine␣iterations">16</integer>
        </group>
        <group name="critical␣distance">
            <boolean name="apply␣corrections">false</boolean>
            <enumerator name="method">point</enumerator>
            <boolean name="use␣safety-factor␣thresholds">true</boolean>
            <real name="safety-factor␣ceiling">10</real>
            <real name="safety-factor␣floor">0</real>
            <boolean name="allow␣quadratic␣interpolation">true</boolean>
        </group>
        <group name="welds">
            <real name="proportional␣variance␣threshold">0.8</real>
            <boolean name="use␣modified␣wang␣brown">true</boolean>
            <boolean name="use␣nonlinear␣shear␣correction">true</boolean>
            <enumerator name="structural␣stress␣calculation␣mode">Basic Nodal Force</enumerator>
            <boolean name="automatically␣bound␣plate␣thickness">false</boolean>
            <real name="plate␣bound␣median␣margin">0.25</real>
            <boolean name="split␣incomplete␣toes">false</boolean>
            <real name="min␣line␣length␣post␣split">0.75</real>
            <boolean name="reject␣no␣through␣nodes">false</boolean>
            <boolean name="auto-detect␣toe␣failures">true</boolean>
            <boolean name="auto-detect␣fusion␣failures">true</boolean>
            <boolean name="auto-detect␣throat␣failures">false</boolean>
            <boolean name="auto-detect␣root␣failures">false</boolean>
            <boolean name="use␣compact␣contour␣mode">true</boolean>
            <real name="co-planarity␣tolerance">5</real>
            <real name="cone␣tolerance">0.05</real>
            <enumerator name="Ir␣function">IrDisplacement</enumerator>
            <integer name="smoothing␣iterations">0</integer>
            <enumerator name="weld␣end␣correction">VirtualNode</enumerator>
            <enumerator name="throat/fusion␣failure␣sense">FromSurface</enumerator>
            <real name="wrap␣angle">90</real>
            <real name="blunt␣root␣threshold">0.25</real>
        </group>
        <group name="planes">
            <integer name="critical␣plane␣search␣count">18</integer>
        </group>
        <group name="psd">
            <enumerator name="PSD␣response">Von Mises</enumerator>
            <boolean name="Apply␣nodal␣filtering">false</boolean>
            <integer name="Number␣of␣stress␣range␣intervals">1000</integer>
            <real name="RMS␣stress␣cut-off␣multiple">10</real>
            <real name="Combined␣shear-normal␣K">0.25</real>
            <boolean name="Bound␣Dirlik␣at␣UTS">false</boolean>
            <enumerator name="Weld␣SS␣response">Normal</enumerator>
        </group>
        <file name="loading␣file">./FESAFE_Fatigue.ldf</file>
        <file name="output␣file">./abq_half_pulse_FESAFE_SS316.odb</file>
```

```xml
                <string name="loading mode">LDF</string>
                <real name="scale factor">1</real>
                <real name="overflow value">0</real>
                <real name="infinite life value">-1</real>
                <integer name="modal samples per cycle">10</integer>
                <real name="modal gate percentage">0.1</real>
                <boolean name="disable temperature analysis">false</boolean>
                <string name="life units description">Repeats</string>
                <real name="life units factor">1</real>
                <boolean name="disable triaxiality">false</boolean>
                <boolean name="disable failed directional cosine to XYZ">false</boolean>
                <boolean name="Von Mises signed">false</boolean>
                <boolean name="ignore compressive cycles">false</boolean>
                <boolean name="enforce thread affinity">false</boolean>
                <integer name="max overflows">1000</integer>
            </group>
        </group>
    </data>
</root>
```

APPENDIX C. SIERRA MULTIPHYSICS MATERIAL MODELS

C.0.1 MatlProps_Thermal.i

```
######################################################################
##
## SIERRA ARIA THERMAL MATERIAL DATABASE
##
## Authors:  Joseph Tipton
##
## Change Log:
##
##    --> 2023-06-30 Per analysis by Yongjoong Lee, assume 6% loss of
##                   thermal conductivity at BOL and 20% loss at EOL
##    --> 2023-11-14 Changed tunsten specific heat to polynomial
##    --> 2024-01-19 Updated and changed SS316L props to match ASME BPVC
##    --> 2024-02-26 Updated Ta model to a function of temperature
######################################################################




##--------------------------------------------------------------------
## GENERAL
##--------------------------------------------------------------------
begin aria material Nb
  density = constant RHO = 8600.0
  heat conduction = Basic
  specific heat = constant CP = 272.0
  thermal conductivity = constant K = 54.4
end




##--------------------------------------------------------------------
## MATERIALS - Tantalum
## Source: Specific Heat - Schussler(1990)
##         Thermal Conductivity - Schmidt(1963)
##--------------------------------------------------------------------

begin aria material Ta
  density = constant RHO = 16600.0
  heat conduction = Basic
  specific heat = polynomial variable = temperature order = 2 C0 = 139.04 C1 = 1.757e-2 C2 = 1.375e-6
  thermal conductivity = user_function name = K_Ta   x = Temperature
end

begin definition for function K_Ta
  type = piecewise linear
  begin values
    #T(C)         K(W/m-C)
    9.657716      56.728741
    50.931667     58.161772
    132.618853    59.849650
    253.853453    62.130346
    401.466291    64.666882
    538.534214    67.034183
    702.004305    69.406452
    865.490348    71.611472
    1007.910493   73.227152
    1181.981332   75.183288
    1408.832575   77.400232
    1577.646910   79.104503
    1770.255101   80.478750
    1954.934666   81.935130
    2160.720011   83.562732
    2345.431481   84.684617
    2538.047649   85.975239
    2614.582026   86.324141
  end
```

```
end



##---------------------------------------------------------------------
## MATERIALS - Tungsten
## Source: ITER MPH
##         Irradiated thermal conductivity from Habainy
##---------------------------------------------------------------------

begin aria material W_Irrad
  density = constant RHO = 19250.0
  heat conduction = Basic
  specific heat = polynomial variable = temperature order = 2 C0 = 128.308 C1 = 3.2797e-2 C2 = 3.4097e-6
  thermal conductivity = constant K = 87.0
  #shell thickness = constant T = 5.0e-7
end

begin aria material W
  density = constant RHO = 19250.0
  heat conduction = Basic
  specific heat = polynomial variable = temperature order = 2 C0 = 128.308 C1 = 3.2797e-2 C2 = 3.4097e-6
  thermal conductivity = thermal a = 174.9274 b = -0.1067 c = 5.0067e-5 d = -7.8349e-9
end



##---------------------------------------------------------------------
## MATERIALS - Copper
## Source: ITER MPH
##---------------------------------------------------------------------

begin aria material Cu_Irrad
  density = scalar_string_function f = "8940*(1-0.000003*(1.68e+1␣+␣3.16e-3*Temperature␣+␣8.18e-6*Temperature
       ^2␣-␣2.49e-9*Temperature^3)*(Temperature-20))"
  heat conduction = Basic
  specific heat = scalar_string_function f = "3.87e+2␣+␣6.35e-2*Temperature␣+␣4.36e-5*Temperature^2"
  thermal conductivity = scalar_string_function f = "0.8*(4.02e+2␣-␣7.08e-2*Temperature␣+␣2.46e-6*Temperature
       ^2)"
end

begin aria material Cu_OFHC
  density = scalar_string_function f = "8940*(1-0.000003*(1.68e+1␣+␣3.16e-3*Temperature␣+␣8.18e-6*Temperature
       ^2␣-␣2.49e-9*Temperature^3)*(Temperature-20))"
  heat conduction = Basic
  specific heat = scalar_string_function f = "3.87e+2␣+␣6.35e-2*Temperature␣+␣4.36e-5*Temperature^2"
  thermal conductivity = scalar_string_function f = "0.94*(4.02e+2␣-␣7.08e-2*Temperature␣+␣2.46e-6*
       Temperature^2)"
end



##---------------------------------------------------------------------
## MATERIALS - Inconel 718 (UNS N07718)
## solution + precipitation hardened
## ASME BPVC.II.B-2021
##---------------------------------------------------------------------

begin aria material IN718
  density              = constant rho = 8220.0
  thermal conductivity = user_function name = K_IN718   x = Temperature
  specific heat        = user_function name = Cp_IN718  x = Temperature
  heat conduction      = basic
end

begin definition for function K_IN718
  type = piecewise linear
  begin values
    #T(C) K(W/m-C)
```

```
    20    11.1
    50    11.6
    75    12.0
    100   12.4
    125   12.9
    150   13.3
    175   13.7
    200   14.1
    225   14.6
    250   15.0
    275   15.4
    300   15.8
    325   16.3
    350   16.7
    375   17.1
    400   17.5
    425   18.0
    450   18.4
    475   18.8
    500   19.3
    525   19.7
    550   20.1
    575   20.5
    600   20.9
    625   21.4
    650   21.8
    675   22.2
    700   22.6
    725   23.0
    750   23.4
  end
end

begin definition for function Cp_IN718
  # calculated using density, thermal conductivity, and thermal diffusivity
  type = piecewise linear
  begin values
    #T(C)  Cp (J/kg-K)
    20     442.742611
    50     439.6237427
    75     442.3800044
    100    447.6308057
    125    457.5344215
    150    463.6117095
    175    469.4835681
    200    475.1602402
    225    482.6510103
    250    485.323808
    275    487.8852393
    300    487.8530759
    325    489.6218197
    350    489.5494386
    375    487.1878152
    400    486.0625049
    425    488.7904067
    450    489.8124338
    475    491.8504565
    500    499.5599731
    525    505.6104797
    550    515.8766824
    575    528.372304
    600    544.4494808
    625    565.957897
    650    586.740736
    675    611.0248704
    700    636.4332703
    725    661.4783754
    750    685.9555008
  end
end
```

```
##--------------------------------------------------------------------
## MATERIALS - Stainless Steel 316L
## ASME BPVC.II Part D Metric (2021)
##--------------------------------------------------------------------

begin aria material SS316L
  density              = constant rho = 8030.0
  thermal conductivity = user_function name = K_SS316L   x = Temperature
  specific heat        = user_function name = Cp_SS316L  x = Temperature
  heat conduction      = basic
end

begin definition for function K_SS316L
# ASME BPVC.II.D.M-2021 (Table TCD)
# Nominal Coefficients of Thermal Conductivity (TC) and Thermal Diffusivity (TD)
# High Alloy Steels, Material Group K, 16Cr-12Ni-2Mo
  type = piecewise linear
  begin values
    #T(C) K(W/m-C)
    20    14.1
    50    14.6
    75    15.0
    100   15.4
    125   15.7
    150   16.1
    175   16.5
    200   16.8
    225   17.2
    250   17.6
    275   17.9
    300   18.3
    325   18.7
    350   19.0
    375   19.4
    400   19.7
    425   20.1
    450   20.5
    475   20.8
    500   21.2
    525   21.5
    550   21.9
    575   22.2
    600   22.6
    625   22.9
    650   23.2
    675   23.6
    700   23.9
    725   24.2
    750   24.6
  end
end

begin definition for function Cp_SS316L
  # ASME BPVC.II.D.M-2021 (Table TCD)
  # Nominal Coefficients of Thermal Conductivity (TC) and Thermal Diffusivity (TD)
  # High Alloy Steels, Material Group K, 16Cr-12Ni-2Mo
  # calculated using density, thermal conductivity, and thermal diffusivity
  type = piecewise linear
  begin values
    #T(C)  Cp (J/kg-K)
     20.0   491.85303013
     50.0   499.5004995
     75.0   506.23171238
    100.0   511.41552511
    125.0   514.5179262
    150.0   519.42521245
    175.0   524.18227565
    200.0   525.66693993
    225.0   528.88089418
    250.0   533.28000533
```

```
        275.0    535.85113517
        300.0    540.03647459
        325.0    544.10446806
        350.0    546.44965904
        375.0    550.32806928
        400.0    552.54507309
        425.0    556.24740556
        450.0    561.08275286
        475.0    561.88425725
        500.0    566.54498421
        525.0    567.25837432
        550.0    570.55914797
        575.0    571.20508836
        600.0    574.37669962
        625.0    576.1223694
        650.0    576.67976625
        675.0    579.68024248
        700.0    581.31615816
        725.0    584.05012212
        750.0    590.27202902
    end
  end
```

C.0.2 MatlProps_Structural.i

```
#######################################################################
##
## SIERRA ADAGIO STRUCTURAL MATERIAL DATABASE
##
## Authors:  Justin Mach, Joseph Tipton
##
## Available Models:
##
##    --> Niobium (Nb):
##            * ELASTIC
##
##    --> Inconel 690 (IN690):
##            * THERMOELASTIC_PLASTIC
##
##    --> Inconel 718 SA (IN718SA):
##            * THERMOELASTIC_PLASTIC
##
##    --> Inconel 718 SA Plate(IN718SA_P):
##            * THERMOELASTIC_PLASTIC
##
##    --> Inconel 718 SA Forging(IN718SA_F):
##            * THERMOELASTIC_PLASTIC
##
##    --> Inconel 718 SA Forging(IN718SA_B):
##            * THERMOELASTIC_PLASTIC
##
##    --> Inconel 718 SA+PH (IN718_ASME):
##            * THERMOELASTIC
##            * THERMOELASTIC_PLASTIC
##
##    --> Copper Irradiated (Cu_Irrad):
##            * THERMOELASTIC
##            * THERMOELASTIC_PLASTIC
##
##    --> Copper OFE (Cu_OFE):
##            * THERMOELASTIC_PLASTIC
##
##    --> Stainless 316L (SS316L):
##            * THERMOELASTIC_PLASTIC
##
##    --> Tungsten (W):
##            * THERMOELASTIC
##
##    --> Tantalum (Ta):
##            * ELASTIC_PLASTIC
##            * THERMOELASTIC_PLASTIC
##
## Change Log:
##
##    --> 2023-05-19 Integration of our separate libraries
##    --> 2023-05-23 Piecewise analytic CTE functions produced slope
##        (CTE) discontinuities.  Replaced with analytic curve fits.
##    --> 2023-05-25 Change irradiated Cu CTE with swelling to be a
##        cumulative effect s.t. the slope (CTE) always is positive.
##    --> 2023-06-01 Added IN718SA model by shifting YS of IN690
##    --> 2023-06-14 Added Cu_1dpa_Swell function
##    --> 2023-06-16 Combined 2 separate Ta models into 1 with 2 options
##    --> 2023-06-30 Removed Cu radiation swelling as CTE functions
##                   (these are now handled in the input deck with fields)
##    --> 2023-11-02 Added temperature dependence for Tantalum E & CTE
##    --> 2023-11-14 Changed W CTE to match ITER MPH Inst. CTE curve
##                   Added table of contents
##    --> 2024-01-11 Changed Cu CTE from mean to instantaneous
##    --> 2024-01-19 Disabled Cu plastic data past 700 C  as it was too
##                   soft for solution stability.  Use 700 C  props as ceiling
##    --> 2024-01-19 Expanded E table for SS316L and changed plastic modulus
##    --> 2024-02-26 Updated Tantalum CTE and Modulus
##    --> 2025-04-15 Added new material model for Inconel 718(SA) for
##                   plate and forging as IN718SA_P, IN718SA_F, IN718SA_B
#######################################################################
```

```
##--------------------------------------------------------------------
## MATERIALS - Niobium
##--------------------------------------------------------------------

begin function CTE_Nb
  type is analytic
  # Initial Temp is the Reference Temp
  evaluate expression is "7.1e-06␣*␣x"
end

begin property specification for material Nb
  density = 8600.0
  THERMAL LOG STRAIN FUNCTION = CTE_Nb
  begin parameters for model ELASTIC
    youngs modulus = 1.03e+11
    poissons ratio = 0.38
  end
end




##--------------------------------------------------------------------
## MATERIALS - Inconel 690
## solution annealed
##--------------------------------------------------------------------

begin function CTE_690
  # Curvefit from Special Metals table
  type is analytic
  # slope is CTE
  evaluate expression is "␣\#
␣␣␣␣␣␣(-3.270911e-09␣*␣pow(x,4)␣/␣4␣\#
␣␣␣␣␣␣+␣6.924748e-06␣*␣pow(x,3)␣/␣3␣\#
␣␣␣␣␣␣-␣2.807229e-04␣*␣pow(x,2)␣/␣2␣\#
␣␣␣␣␣␣+␣1.405871e+01␣*␣x)␣*␣1.0e-6"
  evaluate from 20 to 1120 by 100
end

begin function E_690
  type is analytic
  # Source is J. Blaizot et al. IJP 80 (2016) 139-153
  evaluate expression is "␣\#
␣␣␣␣␣␣(210.0␣␣␣␣␣␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣-␣0.017␣*␣x␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣-␣7.9e-05␣*␣pow(x,2)\#
␣␣␣␣␣␣)␣*␣1.0e+9"
  evaluate from 20 to 1120 by 100
end

begin function Nu_690
  # Source is Special Metals
  type is piecewise linear
  y scale = 3.33333
  begin values
  # T(C)   Poissons ratio
    21    0.3
    93    0.29
    204   0.3
    316   0.31
    427   0.31
    538   0.30
    619   0.28
    760   0.28
    871   0.30
    982   0.33
    1093  0.36
  end
end

```

```
begin function YS_690
  type is piecewise linear
  # Source is J. Blaizot et al. IJP 80 (2016) 139-153
  y scale = 1.0e+6
  begin values
  # T(C)  Yield (MPa)
     20    320
     100   271
     200   234
     300   211
     400   193
     500   179
     600   167
     650   162
     800   142
     900   80
     987   51
     1100  30
  end values
end

begin property specification for material IN690
  # Source: Special Metals
  # Source is J. Blaizot et al. IJP 80 (2016) 139-153
  density = 8190
  THERMAL LOG STRAIN FUNCTION = CTE_690
  begin parameters for model THERMOELASTIC_PLASTIC
    youngs modulus = 1.0
    poissons ratio = 0.3
    #
    # Hardening Behavior
    #
    beta = 0.0
    yield stress = 1.0
    youngs modulus function = E_690
    poissons ratio function = Nu_690
    yield stress function = YS_690
    temperatures = 20.0 100.0 200.0 300.0 400.0 500.0 \#
                    600.0 650.0 800.0 900.0 987.0 1100.0
    hardening functions = HARD_690_20 HARD_690_100 HARD_690_200 \#
                          HARD_690_300 HARD_690_400 HARD_690_500 \#
                          HARD_690_600 HARD_690_650 HARD_690_800 \#
                          HARD_690_900 HARD_690_987 HARD_690_1100
  end
end

begin function HARD_690_20
  type is analytic
  evaluate expression is "1970.0e+6␣*␣x"
end

begin function HARD_690_100
  type is analytic
  evaluate expression is "1917.0e+6␣*␣x"
end

begin function HARD_690_200
  type is analytic
  evaluate expression is "1852.0e+6␣*␣x"
end

begin function HARD_690_300
  type is analytic
  evaluate expression is "1787.0e+6␣*␣x"
end

begin function HARD_690_400
  type is analytic
  evaluate expression is "1721.0e+6␣*␣x"
end

begin function HARD_690_500
```

```
  type is analytic
  evaluate expression is "1656.0e+6␣*␣x"
end

begin function HARD_690_600
  type is analytic
  evaluate expression is "1591.0e+6␣*␣x"
end

begin function HARD_690_650
  type is analytic
  evaluate expression is "1558.0e+6␣*␣x"
end

begin function HARD_690_800
  type is analytic
  evaluate expression is "54.0e+6␣*␣x"
end

begin function HARD_690_900
  type is analytic
  evaluate expression is "1.0e+6␣*␣x"
end

begin function HARD_690_987
  type is analytic
  evaluate expression is "1.0e+6␣*␣x"
end

begin function HARD_690_1100
  type is analytic
  evaluate expression is "1.0e+6␣*␣x"
end



##--------------------------------------------------------------------
## MATERIALS - Inconel 718
## solution annealed
##
##--------------------------------------------------------------------

begin function YS_718SA
  type is piecewise linear
  # This is the YS_690 data with the y scale changed such that
  # RT yield is 400 MPa to match Special Metals Inconel 718
  # Table 32 for 1.125-in. Hot-Rolled Plate in annealed condition.
  y scale = 1.25e+6
  begin values
  # T(C)  Yield (MPa)
     20    320
     100   271
     200   234
     300   211
     400   193
     500   179
     600   167
     650   162
     800   142
     900   80
     987   51
     1100  30
  end values
end

begin property specification for material IN718SA
  # In absence of other data, we use the IN690 model and simply
  # shift the yield stress function upward to match the room-temperature
  # yield of IN718SA
  density = 8190
  THERMAL LOG STRAIN FUNCTION = CTE_690
```

```
    begin parameters for model THERMOELASTIC_PLASTIC
      youngs modulus = 1.0
      poissons ratio = 0.3
      #
      # Hardening Behavior
      #
      beta = 0.0
      yield stress = 1.0
      youngs modulus function = E_690
      poissons ratio function = Nu_690
      yield stress function = YS_718SA
      temperatures = 20.0 100.0 200.0 300.0 400.0 500.0 \#
                     600.0 650.0 800.0 900.0 987.0 1100.0
      hardening functions = HARD_690_20 HARD_690_100 HARD_690_200 \#
                            HARD_690_300 HARD_690_400 HARD_690_500 \#
                            HARD_690_600 HARD_690_650 HARD_690_800 \#
                            HARD_690_900 HARD_690_987 HARD_690_1100
    end
  end

  begin function YS_718SA_P
    type is piecewise linear
    # This a hybrid model based on yield stress modeling from
        # Moretti et al.(2023), Malmelov et al.(2020)
        # and Voce strain hardening with MTS like scaling of saturation stress
        # based on Follasbee(2014,2016) 718 modeling
    # RT yield is 400 MPa to match Special Metals Inconel 718
    # Table 32 for 1.125-in. Hot-Rolled Plate in annealed condition.
    y scale = 1.0e+6
    begin values
    # T(C)  Yield (MPa)
      20    400
      200   340
      400   282
      600   234
      700   208
      800   179
      900   156
      1000  138
      1100  123
    end values
  end

  begin function YS_718SA_F
    type is piecewise linear
    # This a hybrid model based on yield stress modeling from
        # Moretti et al.(2023), Malmelov et al.(2020)
        # and Voce strain hardening with MTS like scaling of saturation stress
        # based on Follasbee(2014,2016) 718 modeling
    # RT yield is 690 MPa to match Special Metals Inconel 718
    # Table 31 for 6-by-9-in. Forging in annealed condition.
    y scale = 1.0e+6
    begin values
    # T(C)  Yield (MPa)
      20    690
      200   613
      400   534
      600   465
      700   425
      800   379
      900   341
      1000  311
      1100  286
    end values
  end

  begin function YS_718SA_B
    type is piecewise linear
    # This a hybrid model based on yield stress modeling from
        # Moretti et al.(2023), Malmelov et al.(2020)
        # and Voce strain hardening with MTS like scaling of saturation stress
        # based on Follasbee(2014,2016) 718 modeling
```

```
  # RT yield is 540 MPa to match Special Metals Inconel 718
  # Table 8 for 98 HRB hot-rolled bar
  y scale = 1.0e+6
  begin values
  # T(C)  Yield (MPa)
     20    541
     200   473
     400   405
     600   346
     700   313
     800   277
     900   246
     1000  223
     1100  202
  end values
end

  begin property specification for material IN718SA_P
  density = 8190
  THERMAL LOG STRAIN FUNCTION = CTE_690
  begin parameters for model THERMOELASTIC_PLASTIC
    youngs modulus = 1.0
    poissons ratio = 0.3
    #
    # Hardening Behavior
    #
    beta = 0.0
    yield stress = 1.0
    youngs modulus function = E_690
    poissons ratio function = Nu_690
    yield stress function = YS_718SA_P
    temperatures = 20.0 200.0 400.0 600.0 700.0\#
                    800.0 900.0 1000.0 1100.0
    hardening functions = HARD_718SA_20 HARD_718SA_200 \#
                          HARD_718SA_400 HARD_718SA_600 \#
                          HARD_718SA_700 HARD_718SA_800\#
                          HARD_718SA_900 HARD_718SA_1000 HARD_718SA_1100
  end
end

begin property specification for material IN718SA_F
  density = 8190
  THERMAL LOG STRAIN FUNCTION = CTE_690
  begin parameters for model THERMOELASTIC_PLASTIC
    youngs modulus = 1.0
    poissons ratio = 0.3
    #
    # Hardening Behavior
    #
    beta = 0.0
    yield stress = 1.0
    youngs modulus function = E_690
    poissons ratio function = Nu_690
    yield stress function = YS_718SA_F
    temperatures = 20.0 200.0 400.0 600.0 700.0\#
                    800.0 900.0 1000.0 1100.0
    hardening functions = HARD_718SA_20 HARD_718SA_200 \#
                          HARD_718SA_400 HARD_718SA_600 \#
                          HARD_718SA_700 HARD_718SA_800\#
                          HARD_718SA_900 HARD_718SA_1000 HARD_718SA_1100
  end
end

begin property specification for material IN718SA_B
  density = 8190
  THERMAL LOG STRAIN FUNCTION = CTE_690
  begin parameters for model THERMOELASTIC_PLASTIC
    youngs modulus = 1.0
    poissons ratio = 0.3
    #
    # Hardening Behavior
    #
```

```
    beta = 0.0
    yield stress = 1.0
    youngs modulus function = E_690
    poissons ratio function = Nu_690
    yield stress function = YS_718SA_B
    temperatures = 20.0 200.0 400.0 600.0 700.0\#
                    800.0 900.0 1000.0 1100.0
    hardening functions = HARD_718SA_20 HARD_718SA_200 \#
                          HARD_718SA_400 HARD_718SA_600 \#
                          HARD_718SA_700 HARD_718SA_800\#
                          HARD_718SA_900 HARD_718SA_1000 HARD_718SA_1100
  end
end

begin function HARD_718SA_20
  type is analytic
  evaluate expression is "1380e+6*(1-exp(-6500e+6␣*␣x␣/␣1380e+6))"
end

begin function HARD_718SA_200
  type is analytic
  evaluate expression is "1268e+6*(1-exp(-6500e+6␣*␣x␣/␣1268e+6))"
end

begin function HARD_718SA_400
  type is analytic
  evaluate expression is "1136e+6*(1-exp(-6500e+6␣*␣x␣/␣1136e+6))"
end

begin function HARD_718SA_600
  type is analytic
  evaluate expression is "997e+6*(1-exp(-6500e+6␣*␣x␣/␣997e+6))"
end

begin function HARD_718SA_700
  type is analytic
  evaluate expression is "918e+6*(1-exp(-6500e+6␣*␣x␣/␣918e+6))"
end

begin function HARD_718SA_800
  type is analytic
  evaluate expression is "826e+6*(1-exp(-6500e+6␣*␣x␣/␣826e+6))"
end

begin function HARD_718SA_900
  type is analytic
  evaluate expression is "209e+6*(1-exp(-6500e+6␣*␣x␣/␣209e+6))"
end

begin function HARD_718SA_1000
  type is analytic
  evaluate expression is "104e+6*(1-exp(-6500e+6␣*␣x␣/␣104e+6))"
end

begin function HARD_718SA_1100
  type is analytic
  evaluate expression is "50e+6*(1-exp(-6500e+6␣*␣x␣/␣50e+6))"
end



##-------------------------------------------------------------------
## MATERIALS - Inconel 718 (UNS N07718)
## solution + precipitation hardened
## ASME BPVC.II.B-2021
##-------------------------------------------------------------------

begin function CTE_IN718_ASME
  type is analytic
  # Initial Temp is the Reference Temp
  # Slope is the CTE
```

```
    # Linear CTE curve was regression fit from table data from 20C to 550C
    evaluate expression is "␣␣␣␣␣␣␣\#
␣␣␣␣␣␣(12.664541␣*␣x␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣+␣6.706e-3␣*␣pow(x,2)␣/␣2.0)␣\#
␣␣␣␣␣␣*␣1.0e-6"
    evaluate from 20 to 1120 by 100
    debug = ON
  end

  begin function E_IN718_ASME
    type is piecewise linear
    y scale = 1.0e+9
    begin values
    # T(C)  E(GPa)
      25    199
      100   195
      150   192
      200   190
      250   188
      300   185
      350   183
      400   180
      450   176
      500   173
      550   169
    end values
  end

  begin function YS_IN718_ASME
    type is piecewise linear
    y scale = 1.0e+6
    begin values
    # T(C)  Yield(MPa)
      20    1034
      50    1016
      100    989
      150    970
      200    955
      250    945
      300    937
      350    929
      375    925
      400    922
      425    918
      450    914
      475    909
      500    902
      525    896
      550    888
      566    883
    end values
  end

  begin function HARD_IN718_21C
    type is analytic
    # ANSYS Engineering Data, Additive Manufacturing Metals, 2021 R2
    evaluate expression is "3.0e+9␣*␣x"
  end

  begin function HARD_IN718_538C
    type is analytic
    # ANSYS Engineering Data, Additive Manufacturing Metals, 2021 R2
    evaluate expression is "2.76e+9␣*␣x"
  end

  begin function HARD_IN718_816C
    type is analytic
    # ANSYS Engineering Data, Additive Manufacturing Metals, 2021 R2
    evaluate expression is "1.0e+7␣*␣x"
  end

  begin function HARD_IN718_982C
```

```
    type is analytic
    # ANSYS Engineering Data, Additive Manufacturing Metals, 2021 R2
    evaluate expression is "1.0e+7␣*␣x"
  end

  begin function HARD_IN718_1093C
    type is analytic
    # ANSYS Engineering Data, Additive Manufacturing Metals, 2021 R2
    evaluate expression is "1.0e+7␣*␣x"
  end

  begin property specification for material IN718_ASME
    density = 8220.0
    THERMAL LOG STRAIN FUNCTION = CTE_IN718_ASME
    begin parameters for model THERMOELASTIC
      youngs modulus = 1.0
      poissons ratio = 0.31
      youngs modulus function = E_IN718_ASME
      poissons ratio function = SIERRA_CONSTANT_FUNCTION_ONE
    end
    begin parameters for model THERMOELASTIC_PLASTIC
      youngs modulus = 1.0
      poissons ratio = 0.31
      beta = 0.0
      yield stress = 1.0
      youngs modulus function = E_IN718_ASME
      poissons ratio function = SIERRA_CONSTANT_FUNCTION_ONE
      yield stress function = YS_IN718_ASME
      temperatures = 21.0 538.0 816.0 982.0 1093.0
      hardening functions = HARD_IN718_21C HARD_IN718_538C HARD_IN718_816C HARD_IN718_982C HARD_IN718_1093C
    end
  end




  ##---------------------------------------------------------------------
  ## MATERIALS - Copper
  ##---------------------------------------------------------------------

  begin function CTE_Cu
  # Source: ITER MPH
    type is analytic
    # Initial Temp is the Reference Temp
    # Slope is the CTE
    evaluate expression is "␣␣␣␣␣␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣(16.3651568␣*␣x␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣+␣1.29411722e-2␣*␣pow(x,2)␣/␣2.0␣␣␣\#
␣␣␣␣␣␣-␣2.87696224e-5␣*␣pow(x,3)␣/␣3.0␣␣␣\#
␣␣␣␣␣␣+␣4.63435502e-8␣*␣pow(x,4)␣/␣4.0␣␣␣\#
␣␣␣␣␣␣-2.12982695e-11␣*␣pow(x,5)␣/␣5.0)␣␣\#
␣␣␣␣␣␣*␣1.0e-6"
  end

  begin function E_Cu
  # Source: ITER MPH
    type is analytic
    evaluate expression is "␣␣␣␣␣␣␣\#
␣␣␣␣␣␣(1.17e+2␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣-␣2.17e-2␣*␣x␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣-␣6.29e-5␣*␣pow(x,2))␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣*␣1.0e+9"
  end

  begin function HARD_Cu_Irrad
  # Source: Li & Zinkle 2012 (Fig. 8)
    type is analytic
    evaluate expression is "1.3e+7␣*␣x"
  end

  begin property specification for material Cu_Irrad
    density = 8940.0
```

```
    THERMAL LOG STRAIN FUNCTION = CTE_Cu
    begin parameters for model THERMOELASTIC
      youngs modulus = 1.0
      poissons ratio = 0.33
      youngs modulus function = E_Cu
      poissons ratio function = SIERRA_CONSTANT_FUNCTION_ONE
    end
    begin parameters for model THERMOELASTIC_PLASTIC
      youngs modulus = 1.0
      poissons ratio = 0.33
      #
      # Hardening Behavior
      #
      beta = 0.0
      yield stress = 300.0e+6  # Li & Zinkle 2012 (Fig. 9)
      youngs modulus function = E_Cu
      poissons ratio function = SIERRA_CONSTANT_FUNCTION_ONE
      yield stress function = SIERRA_CONSTANT_FUNCTION_ONE
      temperatures = 20.0
      hardening functions = HARD_Cu_Irrad
    end
  end


  begin function HARD_Cu_20
    type is analytic
    evaluate expression is "1.3*246e+6*(1-pow((1901e+6*x*(1.3-1)/1.3/246e+6)+1.0,(1.0/(1.0-1.3))))"
  end

  begin function HARD_Cu_100
    type is analytic
    evaluate expression is "1.3*192e+6*(1-pow((1842e+6*x*(1.3-1)/1.3/192e+6)+1.0,(1.0/(1.0-1.3))))"
  end

  begin function HARD_Cu_200
    type is analytic
    evaluate expression is "1.3*138e+6*(1-pow((1769e+6*x*(1.3-1)/1.3/138e+6)+1.0,(1.0/(1.0-1.3))))"
  end

  begin function HARD_Cu_300
    type is analytic
    evaluate expression is "1.3*95.7e+6*(1-pow((1694e+6*x*(1.3-1)/1.3/95.7e+6)+1.0,(1.0/(1.0-1.3))))"
  end

  begin function HARD_Cu_400
    type is analytic
    evaluate expression is "1.3*62.9e+6*(1-pow((1620e+6*x*(1.3-1)/1.3/62.9e+6)+1.0,(1.0/(1.0-1.3))))"
  end

  begin function HARD_Cu_500
    type is analytic
    evaluate expression is "1.3*37.9e+6*(1-pow((1545e+6*x*(1.3-1)/1.3/37.9e+6)+1.0,(1.0/(1.0-1.3))))"
  end

  begin function HARD_Cu_600
    type is analytic
    evaluate expression is "1.3*19.7e+6*(1-pow((1471e+6*x*(1.3-1)/1.3/19.7e+6)+1.0,(1.0/(1.0-1.3))))"
  end

  begin function HARD_Cu_700
    type is analytic
#                                11mpa                                       11mpa
    evaluate expression is "1.3*7.68e+6*(1-pow((1396e+6*x*(1.3-1)/1.3/7.68e+6)+1.0,(1.0/(1.0-1.3))))"
  end

#  begin function HARD_Cu_800
#    type is analytic
#    evaluate expression is "1.3*1.30e+6*(1-pow((1321e+6*x*(1.3-1)/1.3/1.30e+6)+1.0,(1.0/(1.0-1.3))))"
#  end

#  begin function HARD_Cu_900
#    type is analytic
```

```
#     evaluate expression is "1.3*0.214e+6*(1-pow((1246e+6*x*(1.3-1)/1.3/0.214e+6)+1.0,(1.0/(1.0-1.3))))"
#   end

#   begin function HARD_Cu_1100
#     type is analytic
#     evaluate expression is "1.3*0.0214e+6*(1-pow((124.6e+6*x*(1.3-1)/1.3/0.0214e+6)+1.0,(1.0/(1.0-1.3))))"
#   end

  begin function YS_Cu
    type is piecewise linear
    y scale = 1.0e+6
    begin values
    # T(C)  Yield(MPa)
      20    10
      100   10
      200   10
      300   10
      400   10
      500   10
      600   10
      700   7.68
#       800   1.30
#       900   0.214
#       1100  0.0214
    end values
  end

  begin property specification for material Cu_OFE
  # Source: Chen & Kocks (1991) and Kocks & Mecking (2003)
  # Assumed strain rate = 1.0E-04
    density = 8940.0
    THERMAL LOG STRAIN FUNCTION = CTE_Cu
    begin parameters for model THERMOELASTIC_PLASTIC
      youngs modulus = 1.0
      poissons ratio = 0.33
      #
      # Hardening Behavior
      BETA = 0.0
      YIELD STRESS = 1.0
      YOUNGS MODULUS FUNCTION = E_Cu
      POISSONS RATIO FUNCTION = SIERRA_CONSTANT_FUNCTION_ONE
      YIELD STRESS FUNCTION = YS_Cu
      TEMPERATURES = 20.0 100.0 200.0 300.0 400.0 500.0 600.0 700.0 #800.0 900.0 1100.0
      HARDENING FUNCTIONS = HARD_Cu_20 HARD_Cu_100 HARD_Cu_200 \#
                            HARD_Cu_300 HARD_Cu_400 HARD_Cu_500 \#
                            HARD_Cu_600 HARD_Cu_700 #HARD_Cu_800 HARD_Cu_900 Hard_Cu_1100
    end
  end




  ##-------------------------------------------------------------------
  ## MATERIALS - SS316L
  ## ASME BPVC.II Part D (Tables TE-1, TCD, TM-1, Y-1)
  ##-------------------------------------------------------------------

  begin function CTE_SS316L
    # Curvefit from ASME BPVC.II.D.M-2021
    # Table TE-1 Coefficients for Austenitic Stainless Steels (Group 3)
    type is analytic
    # slope is CTE
    evaluate expression is "␣\#
␣␣␣␣␣␣(-3.664638e-13␣*␣pow(x,6)␣/␣6␣\#
␣␣␣␣␣␣+␣5.614524e-10␣*␣pow(x,5)␣/␣5␣\#
␣␣␣␣␣␣-␣2.459781e-07␣*␣pow(x,4)␣/␣4␣\#
␣␣␣␣␣␣+␣4.232852e-06␣*␣pow(x,3)␣/␣3␣\#
␣␣␣␣␣␣+␣2.272059e-02␣*␣pow(x,2)␣/␣2␣\#
␣␣␣␣␣␣+␣1.486141e+01␣*␣x)␣*␣1.0e-6"
    evaluate from 20 to 825 by 25
  end

```

```
begin function E_SS316L
  # ASME BPVC.II.D.M-2021 (Table TM-1)
  # Moduli of Elasticity E of Ferrous Materials for Given Temperatures
  # Material Group G (Austenitic Steels)
  type is piecewise linear
  y scale = 1.0e+9
  begin values
  # T(C)  E(GPa)
    25    195
    100   189
    150   186
    200   183
    250   179
    300   176
    350   172
    400   169
    450   165
    500   160
    550   156
    600   151
    650   146
    700   140
  end values
end

begin function YS_SS316L
  # ASME BPVC.II.D.M-2021 (Table Y-1)
  # Yield Strength Values, Sy, for Ferrous and Nonferrous Materials
  # 16Cr-12Ni-2Mo
  type is piecewise linear
  y scale = 1.0e+6
  begin values
  # T(C)  Yield(MPa)
     40    172
     65    157
    100    145
    125    137
    150    131
    175    125
    200    121
    225    118
    250    114
    275    111
    300    109
    325    107
    350    105
    375    103
    400    101
    425     99.4
    450     97.5
    475     95.7
    500     93.8
    525     92.0
    550     89.7
    575     88.9
    600     87.9
    625     86.7
    650     85.3
  end values
end


begin function HARD_SS316L
  type is analytic
  # Iteka and Adibi (2019)
  evaluate expression is "186.3e+7␣*␣x"
end

begin property specification for material SS316L
  # ASME BPVC.II.D.M-2021 (Table PRD)
  # Poissons Ratio and Density of Materials
  # High Alloy Steels (300 series)
```

```
    density = 8030.0
    THERMAL LOG STRAIN FUNCTION = CTE_SS316L
    begin parameters for model THERMOELASTIC_PLASTIC
      youngs modulus = 1.0
      poissons ratio = 0.31
      beta = 0.0
      yield stress = 1.0
      youngs modulus function = E_SS316L
      poissons ratio function = SIERRA_CONSTANT_FUNCTION_ONE
      yield stress function = YS_SS316L
      temperatures = 25.0
      hardening functions = HARD_SS316L
    end
  end



  ##-----------------------------------------------------------------
  ## MATERIALS - Tungsten
  ##-----------------------------------------------------------------

  begin function CTE_W
    # Curvefit from ITER MPH
    type is analytic
    # slope is CTE
    evaluate expression is "␣\#
␣␣␣␣␣␣(9.0e-04␣*␣pow(x,2)␣/␣2␣\#
␣␣␣␣␣␣+␣4.4446␣*␣x)␣*␣1.0e-6"
    evaluate from 20 to 1600 by 100
  end


  begin function Nu_W
    # Source is ITER MPH ref. eqn.
    type is piecewise linear
    # Scale by 1/nu nominal
    y scale = 3.58423
    begin values
    # T(C)  Poissons ratio
      20    0.279
      100   0.280
      200   0.281
      300   0.282
      400   0.283
      500   0.284
      600   0.286
      700   0.287
      800   0.288
      900   0.289
      1000  0.290
      1100  0.291
      1200  0.292
      1300  0.293
      1400  0.294
      1500  0.295
    end
  end

  begin function E_W
    # Source is ITER MPH ref. eqn.
    type is piecewise linear
    y scale = 1.0e+9
    begin values
    # T(C)  E(GPa)
      20    398
      100   397
      200   396
      300   395
      400   393
      500   390
```

```
      600   387
      700   383
      800   379
      900   374
      1000  368
      1100  362
      1200  356
      1300  349
      1400  341
      1500  333
    end values
  end

  begin property specification for material W
    density = 19250.0
    THERMAL LOG STRAIN FUNCTION = CTE_W
    begin parameters for model THERMOELASTIC
      youngs modulus = 1.0
      poissons ratio = 0.279
      youngs modulus function = E_W
      poissons ratio function = Nu_W
    end
  end



  ##-------------------------------------------------------------------
  ## MATERIALS - Tantalum
  ##-------------------------------------------------------------------

  begin function CTE_Ta
    # Source is Touloukian(1975) Figure 51R
    type is analytic
    # slope is CTE
    evaluate expression is "␣␣␣␣␣␣␣\#
␣␣␣␣␣␣(6.308*x␣+␣9.706e-4*pow(x,2)␣\#
␣␣␣␣␣␣␣-␣2.545e-7*pow(x,3))␣*␣1.0e-6"
    evaluate from 20 to 1600 by 100
  end

  begin function Yield_Ta
    type is analytic
    evaluate expression is "1.0␣-␣((x␣-␣25.0)/(2976.85␣-␣25.0))^0.4"
  end

  begin function Hard200
    type is analytic
    evaluate expression is "␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣(1␣-␣((200.0␣-␣25.0)/(2976.85␣-␣25.0))^0.4)␣*␣␣\#
␣␣␣␣␣␣0.6␣*␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣1.0e+6␣*␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣(340.0␣+␣750.0*x^0.7)␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣\#
␣␣␣␣␣␣"
  end

  begin function E_Ta
    # Schmidt(1963) Reference 20
    type is piecewise linear
    y scale = 1.0e+9
    begin values
      # T(C)        E(GPa)
      -166.830844   188.983902
      -42.163751    186.080789
      -10.788514    185.223491
      89.754823     182.790268
      119.513960    182.099053
      185.469215    180.523018
      201.557633    180.108228
      237.752138    179.251097
      264.295204    178.615150
      287.623813    178.006782
```

```
      318.191001   177.232525
      354.372602   176.596912
      409.878047   175.158964
      429.997036   174.495105
      475.036542   173.472142
      496.753890   172.946787
      600.0        170.47
      700.0        168.05
      800.0        165.63
      900.0        163.21
      1000.0       160.79
    end values
  end

  begin property specification for material Ta
    density = 16600.
    THERMAL LOG STRAIN FUNCTION = CTE_Ta
    begin parameters for model ELASTIC_PLASTIC
      youngs modulus = 1.88e+11
      poissons ratio = 0.35
      #
      #Hardening Behavior
      #
      YIELD STRESS = 2.0e+8
      BETA = 0.0
      HARDENING MODULUS = 1.0e+9
    end
    begin parameters for model THERMOELASTIC_PLASTIC
      youngs modulus = 1.0
      poissons ratio = 0.35
      #
      # Hardening Behavior
      #
      BETA = 0.0
      YIELD STRESS = 204.0E+6
      YOUNGS MODULUS FUNCTION = E_Ta
      POISSONS RATIO FUNCTION = SIERRA_CONSTANT_FUNCTION_ONE
      YIELD STRESS FUNCTION = Yield_Ta
      TEMPERATURES = 200.0
      HARDENING FUNCTIONS = Hard200
    end
  end
```

APPENDIX D. CUSTOM PYTHON MATERIAL MODELS

APPENDIX D. CUSTOM PYTHON MATERIAL MODELS

D.0.1 MatlProps_Pulse.py

```
import numpy as np
from exodus import exodus, copyTransfer, copy_mesh, add_variables
#import exodusCalcs
import pandas as pd

##
##--------------------------------------------------------------------
## CHANGE LOG
##--------------------------------------------------------------------
## 2024-10-17
##  --> Renamed functions
##  --> Changed all fatigue functions to read all results before
##      computation
##  --> (Saved old functions with 'OLD' appended to name)
## 2024-10-18
##  --> Fixed Mean stress calculation misname
##  --> Removed old ei.close()
## 2025-03-05
##  --> Removed time array halving in fatigueDuctSurf
##  --> Changed `ei.get_elem_blk_ids()[0][0]` to `ei.get_elem_blk_ids()[0].item()`
## 2025-03-13
##  --> fatigueNormAvg()
##  --> Changed dynamic response file to output element ID as variable
##  --> Added new variable to copy as `globEleID`
##  --> fatigueDuctSurf()
##  --> Changed dynamic response file to output nodal ID as variable
##  --> Added new variable to copy as `globNodeID`
## 2025-03-28
##  --> fatigueNormAvg()
##  --> Changed critical plane output to radians to be consistent
##  --> fatigueDuctSurf()
##  --> Added output of critical plane for postprocessing
## 2025-07-21
##  --> Added life calculation for transient events



"""
MATERIAL PROPERTIES for NEUTRONICS CALCULATIONS
==============================================================================
"""
NbDensity = 8600.0       # [kg/m^3]
NbSpecHeat = 272.0       # [J/kg-K]

WDensity = 19250.0       # [kg/m^3]
WSpecHeat = 128.3        # [J/kg-K]

In718Density = 8220.0    # [kg/m^3]
In718SpecHeat = 435.0    # [J/kg-K]

CuDensity = 8940.0       # [kg/m^3]
CuSpecHeat = 385.0       # [J/kg-K]

TaDensity = 16600.0      # [kg/m^3]
TaSpecHeat = 139.0       # [J/kg-K]

SS316LDensity = 8030.0   # [kg/m^3]
SS316LSpecHeat = 492.0   # [J/kg-K]




"""
BEAM PULSES over TARGET DESIGN LIFE
==============================================================================
"""
# Calculate proton beam pulses over design life
```

```
Life = 10.0 # years
Year_to_Sec = 365.0*24.0*3600.0 # sec in a year
Uptime = 5000.0 / (365.0*24.0) # hours operation / year
PulseFreq = 15.0 # pulses / sec
NumTarget = 20.0
Pulses = Life * Year_to_Sec * Uptime * PulseFreq / NumTarget

transEvents = 125000.0




"""
UNIRRADATED TUNGSTEN STRENGTH AND LIFE LIMITS
================================================================================
"""
SultC = 1000.E+6  # Ultimate compressive strength of unirradiated tungsten [Pa]
SultT = 600.E+6   # Ultimate tensile strength of unirradiated tungsten [Pa]

Sfprime = 568.592632E+6
b = -0.04150804
K_irr = 1.0
K_95 = 1.0

Slife = K_95 * K_irr * Sfprime * (2 * Pulses)**b

# store results as dictionary
fatigueWunirr = {}
fatigueWunirr['SultC'] = SultC
fatigueWunirr['SultT'] = SultT
fatigueWunirr['Slife'] = Slife
fatigueWunirr['Stran'] = K_95 * K_irr * Sfprime * (2 * transEvents)**b




"""
IRRADIATED TUNGSTEN STRENGTH AND LIFE LIMITS
================================================================================
"""
SultC = 1000.E+6  # Ultimate compressive strength of irradiated tungsten [Pa]

# Get ultimate tensile strength (irradiated) as a function of plate thickness
t = 0.01 # Tungsten plate thickness

if t <= 0.0:
  raise ValueError('Negative␣plate␣thickness.')
elif t > 0.0 and t <= 0.020:
  SultT = 356.E+6
elif t > 0.020 and t <= 0.048:
  SultT = 305.E+6
elif t > 0.048 and t <= 0.060:
  SultT = (406.06 - 5040.5*t)*1.E+6
else:
  raise ValueError('Plate␣thickness␣larger␣than␣60mm')

Sfprime = 568.592632E+6
b = -0.04150804
K_irr = SultT / Sfprime
K_95 = 1.0

Slife = K_95 * K_irr * Sfprime * (2 * Pulses)**b

# store results as dictionary
fatigueWirr = {}
fatigueWirr['SultC'] = SultC
fatigueWirr['SultT'] = SultT
fatigueWirr['Slife'] = Slife
fatigueWirr['Stran'] = K_95 * K_irr * Sfprime * (2 * transEvents)**b
```

```
"""
INCONEL STRENGTH AND LIFE LIMITS
================================================================================
"""
SultT = 930.E+6   # Ultimate tensile strength [Pa]
SultC = SultT     # Ultimate compressive strength [Pa]
E = 209628*1.0e+6 # Young's Modulus of Elasticity [Pa]
nu = 0.30          # Poisson's Ratio
G = E/2./(1.+nu)   # Shear Modulus [Pa]

Sfprime = 657.16E+6
b = -0.019635
K_astm = 0.72
K_95 = 1.0

Slife = K_95 * K_astm * Sfprime * (2 * Pulses)**b

# store results as dictionary
fatigue718 = {}
fatigue718['SultC'] = SultC
fatigue718['SultT'] = SultT
fatigue718['Slife'] = Slife
fatigue718['E'] = E
fatigue718['nu'] = nu
fatigue718['G'] = G
fatigue718['Stran'] = K_95 * K_astm * Sfprime * (2 * transEvents)**b



"""
STAINLESS STEEL STRENGTH AND LIFE LIMITS
================================================================================
"""
SultT = 648.1E+6   # Ultimate tensile strength [Pa]
SultC = SultT      # Ultimate compressive strength [Pa]
E = 1.951E+11      # Modulus of Elasticity [Pa]
nu = 0.31          # Poisson's Ratio
G = E/2./(1.+nu)   # Shear Modulus [Pa]

#---------------------------------------------------------------
# Calculate fatigue strength of SS316L
# (from Chopra2007 mean ASME curve)
#---------------------------------------------------------------
Slife = 0.01*E*(0.112 + np.exp((6.891-np.log(Pulses))/1.92))

# store results as dictionary
fatigue316 = {}
fatigue316['SultC'] = SultC
fatigue316['SultT'] = SultT
fatigue316['Slife'] = Slife
fatigue316['E'] = E
fatigue316['nu'] = nu
fatigue316['G'] = G
fatigue316['Stran'] = 0.01*E*(0.112 + np.exp((6.891-np.log(transEvents))/1.92))



"""
FATIGUE FAILURE MODELS
================================================================================
"""
def fatigueNormAvg(Matl,fileName,meshName,outName,procTot,procNum):
  """
  *fatigueNormAvg* performs a critical plane fatigue analysis on finite elements assuming
  a brittle normal stress failure mode.  Instead of rainflow counting, it takes
  the peak stresses over time as a conservative proxy.  The algorithm is also
  currently hard-coded to work with element averaged stresses.
  .
```

```
:param Matl:     material dictionary
:param fileName: base name of the decomposed results file
:param meshName: base name of the decomposed mesh file
:param outName:  base name of the desired output file
:param procTot:  total number of processors (or file partitions)
:param procNum:  partition number of interest
.
As output, the function will save a pandas dataframe pickle and an ExodusII
file that each contain
.
:output globEleID:      ExodusII global element ID number
:output CritPlaneFOS:   minimum fatigue factor-of-safety
:output CritPlaneMax:   peak normal stress over time
:output CritPlaneMean:  mean stress at minimum FOS
:output CritPlaneAmp:   stress amplitude at minimum FOS
:output StressStatic:   static stress before beam pulse
:output CritPlanePhi:   3D critical stress plane angle (rad)
:output CritPlaneTheta: 3D critical stress plane angle (rad)
.
Requires packages numpy, exodus, exodusCalcs, pandas
"""
fileName = fileName+'.e.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))
pickleName = outName+'.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))+'.pkl'
meshName = meshName+'.g.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))
outName = outName+'.e.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))
"""
ACCESS STRESS RESULTS
==============================================================================
"""
#read stress data from sierra output .e file
ei = exodus(fileName, mode='r', array_type='numpy')
#confirm block ID and name (assumes there is only 1 block to analyze)
ei.get_elem_blk_ids()
ei.get_elem_blk_names()
blkID = ei.get_elem_blk_ids()[0].item()
# Lists the times saved in seconds
# The exodus time_step index starts at 1 (not zero)
timeArray = ei.get_times()
numTimes = len(timeArray)
#element IDs and Indices
eleIDs = ei.get_elem_id_map()
eleIndex = eleIDs - 1
# get global element IDs
globEleID = ei.get_element_variable_values(blkID, 'IDele', 1)
"""
READ FULL STRESS FIELD FOR ALL TIMES
==============================================================================
References:
https://stackoverflow.com/17394882/how-can-i-add-new-dimensinos-to-a-numpy-array
https://stackoverflow.com/60855200/how-can-i-append0a-multidimensional-array-to-a-new-dimension-with-numpy
https://web.mit.edu/16.20/homepage/3_Constitutive/Constitutive_files/module_3_with_solutions.pdf
"""
StressAll = []
StrainAll = []
for jj in range(0,numTimes):
  # get stress tensor
  S_xx = ei.get_element_variable_values(blkID, 'Savg_xx', jj+1)
  S_yy = ei.get_element_variable_values(blkID, 'Savg_yy', jj+1)
  S_zz = ei.get_element_variable_values(blkID, 'Savg_zz', jj+1)
  S_xy = ei.get_element_variable_values(blkID, 'Savg_xy', jj+1)
  S_yz = ei.get_element_variable_values(blkID, 'Savg_yz', jj+1)
  S_zx = ei.get_element_variable_values(blkID, 'Savg_zx', jj+1)
  #
  Stress = np.array([(S_xx,S_xy,S_zx),(S_xy,S_yy,S_yz),(S_zx,S_yz,S_zz)])
  StressAll.append(Stress.transpose(2,0,1))
  # zero-out unneeded variables to save on memory usage
  Stress=0.0
  S_xx = 0.0
  S_yy = 0.0
  S_zz = 0.0
  S_xy = 0.0
  S_yz = 0.0
```

```
  S_zx = 0.0
ei.close()
ei = 0.0
Stress = np.array(StressAll)
StressAll = 0.0
Strain = np.array(StrainAll)
StrainAll = 0.0
#print("Stress")
#print(Stress.nbytes)
#print("Strain")
#print(Strain.nbytes)
"""
CALCULATE STATIC PRINCIPAL STRESSES
==============================================================================
References:
https://csmbrannon.net/2011/04/25/stress-state-analysis-python-script/
https://csm.mech.utah.edu/content/wp-content/uploads/2011/04/stress.py
https://stackoverflow.com/a/51415122
"""
SS = Stress[0]
#
Sprin = np.linalg.eigvals(SS)
Sprin = np.sort(Sprin)
#
maxPrin = Sprin[:,2]
minPrin = Sprin[:,0]
#
StressStatic = np.where(np.absolute(maxPrin) >= np.absolute(minPrin), maxPrin, minPrin)
"""
CALCULATE FOS BASED ON CRITICAL NORMAL PLANE THEORY
==============================================================================
"""
# initialize stress vectors
CritPlanePhi = np.ones([len(eleIDs)])*1.0e+100
CritPlaneTheta = np.ones([len(eleIDs)])*1.0e+100
CritPlaneFOS = np.ones([len(eleIDs)])*1.0e+100
CritPlaneMean = np.ones([len(eleIDs)])*1.0e+100
CritPlaneAmp = np.ones([len(eleIDs)])*1.0e+100
# rotate through possible stress planes
for phi in np.linspace(0, np.pi/2, num=6):
  print("ProcNum, Phi")
  print(procNum,phi)
  for theta in np.linspace(0, 2*np.pi, num=24):
    # calculate stress normal to plane
    unitVector = np.array([np.sin(phi)*np.cos(theta), np.sin(phi)*np.sin(theta), np.cos(phi)])
    traction = np.dot(Stress,unitVector)
    S_n = np.dot(traction,unitVector)
    # keep the peak normal stresses
    StressNormalMax = np.max(S_n, axis=0)
    StressNormalMin = np.min(S_n, axis=0)
    #
    Smean = (StressNormalMax + StressNormalMin) / 2.0
    Samp = (StressNormalMax - StressNormalMin) / 2.0
    # check for tensile or compressive mean stress
    FOS = np.where(Smean < 0.0, 1.0 / (Samp/Matl['Slife']), 1.0 / (Samp/Matl['Slife'] + abs(Smean)/Matl['SultT']))
    # keep lowest FOS results
    CritPlanePhi = np.where(FOS < CritPlaneFOS, phi, CritPlanePhi)
    CritPlaneTheta = np.where(FOS < CritPlaneFOS, theta, CritPlaneTheta)
    CritPlaneMean = np.where(FOS < CritPlaneFOS, Smean, CritPlaneMean)
    CritPlaneAmp = np.where(FOS < CritPlaneFOS, Samp, CritPlaneAmp)
    # finally, overwrite the test condition
    CritPlaneFOS = np.where(FOS < CritPlaneFOS, FOS, CritPlaneFOS)
# gather results and save to file
resultElems = np.column_stack([eleIDs, CritPlaneFOS, CritPlaneMean+CritPlaneAmp, CritPlaneMean, CritPlaneAmp, StressStatic, CritPlanePhi, CritPlaneTheta, globEleID])
result = pd.DataFrame(resultElems)
result.columns = ['eleIDs','CritPlaneFOS','CritPlaneMax','CritPlaneMean','CritPlaneAmp','StressStatic','CritPlanePhi','CritPlaneTheta','globEleID']
result['procNum'] = procNum
result = result.astype({'eleIDs':'int'})
result = result.astype({'globEleID':'int'})
```

```
    #result = result.set_index('eleIDs')
    result.to_pickle(pickleName)
    result = 0.0
    """
    OUTPUT FOR VISUALIZATION IN PARAVIEW
    ==============================================================================
    .
    The structure of mesh *.g files is such that the elements are arranged in
    sequential order
    .
    EX:  eo.get_elem_id_map() = [      1,       2,       3, ..., 120442, 120443, 120444]
    .
    eleIDs = np.array(ei.get_elem_id_map()) = [1, 2, 3, ..., 120444]
    eleIndex = eleIDs - 1 = [0, 1, 2, ... 120443]
    .
    The processing done on the results *.e file is arranged in a different order,
    and for only a subset of the mesh.  So we need to sort before writing out.
    """
    # gather results and sort on element IDs
    #resultElems = resultElems[resultElems[:,0].argsort()]
    # place in Exodus file as new results
    addGlobalVariables = []
    addNodeVariables = []
    addElementVariables = ["FOS", "Smax", "Sm", "Samp", "Sstatic", "CritPlanePhi", "CritPlaneTheta", "globEleID"]
    exo = copy_mesh(fileName,outName,array_type='ctype')
    add_variables(exo,element_vars=addElementVariables)
    #exo = copyTransfer(meshName,outName,'ctype',addGlobalVariables,addNodeVariables,addElementVariables)
    exo.put_element_variable_values(blkID,'FOS',1,resultElems[:,1])
    exo.put_element_variable_values(blkID,'Smax',1,resultElems[:,2])
    exo.put_element_variable_values(blkID,'Sm',1,resultElems[:,3])
    exo.put_element_variable_values(blkID,'Samp',1,resultElems[:,4])
    exo.put_element_variable_values(blkID,'Sstatic',1,resultElems[:,5])
    exo.put_element_variable_values(blkID,'CritPlanePhi',1,resultElems[:,6])
    exo.put_element_variable_values(blkID,'CritPlaneTheta',1,resultElems[:,7])
    exo.put_element_variable_values(blkID,'globEleID',1,resultElems[:,8])
    exo.close()



def fatigueNormSurf(Matl,fileName,meshName,outName,procTot,procNum):
    """
    *fatigueNormSurf* performs a critical plane fatigue analysis on finite elements assuming
    a brittle normal stress failure mode.  Instead of rainflow counting, it takes
    the peak stresses over time as a conservative proxy.  This version works with
    nodal stress extrapolations.
    .
    :param Matl:     material dictionary
    :param fileName: base name of the decomposed results file
    :param meshName: base name of the decomposed mesh file
    :param outName:  base name of the desired output file
    :param procTot:  total number of processors (or file partitions)
    :param procNum:  partition number of interest
    .
    As output, the function will save a pandas dataframe pickle and an ExodusII
    file that each contain
    .
    :output nodeIDs:        ExodusII global node ID number
    :output CritPlaneFOS:   minimum fatigue factor-of-safety
    :output CritPlaneMax:   peak normal stress over time
    :output CritPlaneMean:  mean stress at minimum FOS
    :output CritPlaneAmp:   stress amplitude at minimum FOS
    :output StressStatic:   static stress before beam pulse
    :output CritPlanePhi:   3D critical stress plane angle
    :output CritPlaneTheta: 3D critical stress plane angle
    .
    Requires packages numpy, exodus, exodusCalcs, pandas
    """
    fileName = fileName+'.e.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))
    pickleName = outName+'.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))+'.pkl'
    meshName = meshName+'.g.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))
    outName = outName+'.e.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))
```

```
"""
ACCESS STRESS RESULTS
================================================================================
"""
#read stress data from sierra output .e file
ei = exodus(fileName, mode='r', array_type='numpy')
# Lists the times saved in seconds
# The exodus time_step index starts at 1 (not zero)
timeArray = ei.get_times()
numTimes = len(timeArray)
#node IDs
nodeIDs = ei.get_node_id_map()
"""
READ FULL STRESS FIELD FOR ALL TIMES
================================================================================
References:
https://stackoverflow.com/17394882/how-can-i-add-new-dimensinos-to-a-numpy-array
https://stackoverflow.com/60855200/how-can-i-append0a-multidimensional-array-to-a-new-dimension-with-numpy
https://web.mit.edu/16.20/homepage/3_Constitutive/Constitutive_files/module_3_with_solutions.pdf
"""
StressAll = []
StrainAll = []
for jj in range(0,numTimes):
  # get stress tensor
  S_xx = ei.get_node_variable_values('Snode_xx', jj+1)
  S_yy = ei.get_node_variable_values('Snode_yy', jj+1)
  S_zz = ei.get_node_variable_values('Snode_zz', jj+1)
  S_xy = ei.get_node_variable_values('Snode_xy', jj+1)
  S_yz = ei.get_node_variable_values('Snode_yz', jj+1)
  S_zx = ei.get_node_variable_values('Snode_zx', jj+1)
  #
  Stress = np.array([(S_xx,S_xy,S_zx),(S_xy,S_yy,S_yz),(S_zx,S_yz,S_zz)])
  StressAll.append(Stress.transpose(2,0,1))
  # zero-out unneeded variables to save on memory usage
  Stress=0.0
  S_xx = 0.0
  S_yy = 0.0
  S_zz = 0.0
  S_xy = 0.0
  S_yz = 0.0
  S_zx = 0.0
ei.close()
ei = 0.0
Stress = np.array(StressAll)
StressAll = 0.0
print("Stress")
print(Stress.nbytes)
"""
CALCULATE STATIC PRINCIPAL STRESSES
================================================================================
References:
https://csmbrannon.net/2011/04/25/stress-state-analysis-python-script/
https://csm.mech.utah.edu/content/wp-content/uploads/2011/04/stress.py
https://stackoverflow.com/a/51415122
"""
SS = Stress[0]
#
Sprin = np.linalg.eigvals(SS)
Sprin = np.sort(Sprin)
#
maxPrin = Sprin[:,2]
minPrin = Sprin[:,0]
#
StressStatic = np.where(np.absolute(maxPrin) >= np.absolute(minPrin), maxPrin, minPrin)
"""
CALCULATE FOS BASED ON CRITICAL NORMAL PLANE THEORY
================================================================================
"""
# initialize stress vectors
CritPlanePhi = np.ones([len(nodeIDs)])*1.0e+100
CritPlaneTheta = np.ones([len(nodeIDs)])*1.0e+100
CritPlaneFOS = np.ones([len(nodeIDs)])*1.0e+100
```

```
  CritPlaneMean = np.ones([len(nodeIDs)])*1.0e+100
  CritPlaneAmp = np.ones([len(nodeIDs)])*1.0e+100
  # rotate through possible stress planes
  for phi in np.linspace(0, np.pi/2, num=6):
    print("ProcNum,␣Phi")
    print(procNum,phi)
    for theta in np.linspace(0, 2*np.pi, num=24):
      # calculate stress normal to plane
      unitVector = np.array([np.sin(phi)*np.cos(theta), np.sin(phi)*np.sin(theta), np.cos(phi)])
      traction = np.dot(Stress,unitVector)
      S_n = np.dot(traction,unitVector)
      # keep the peak normal stresses
      StressNormalMax = np.max(S_n, axis=0)
      StressNormalMin = np.min(S_n, axis=0)
      #
      Smean = (StressNormalMax + StressNormalMin) / 2.0
      Samp = (StressNormalMax - StressNormalMin) / 2.0
      # check for tensile or compressive mean stress
      FOS = np.where(Smean < 0.0, 1.0 / (Samp/Matl['Slife']), 1.0 / (Samp/Matl['Slife'] + abs(Smean)/Matl['SultT']))
      # keep lowest FOS results
      CritPlanePhi = np.where(FOS < CritPlaneFOS, phi/np.pi*180.0, CritPlanePhi)
      CritPlaneTheta = np.where(FOS < CritPlaneFOS, theta/np.pi*180.0, CritPlaneTheta)
      CritPlaneMean = np.where(FOS < CritPlaneFOS, Smean, CritPlaneMean)
      CritPlaneAmp = np.where(FOS < CritPlaneFOS, Samp, CritPlaneAmp)
      # finally, overwrite the test condition
      CritPlaneFOS = np.where(FOS < CritPlaneFOS, FOS, CritPlaneFOS)
  # gather results and save to file
  resultNodes = np.column_stack([nodeIDs, CritPlaneFOS, CritPlaneMean+CritPlaneAmp, CritPlaneMean, CritPlaneAmp, StressStatic, CritPlanePhi, CritPlaneTheta])
  result = pd.DataFrame(resultNodes)
  result.columns = ['nodeIDs','CritPlaneFOS','CritPlaneMax','CritPlaneMean','CritPlaneAmp','StressStatic','CritPlanePhi','CritPlaneTheta']
  result['procNum'] = procNum
  result = result.astype({'nodeIDs':'int'})
  result.to_pickle(pickleName)
  result = 0.0
  """
  OUTPUT FOR VISUALIZATION IN PARAVIEW
  ==============================================================================
  """
  # place in Exodus file as new results
  addGlobalVariables = []
  addNodeVariables = ["FOS", "Smax", "Sm", "Samp", "Sstatic", "CritPlanePhi", "CritPlaneTheta"]
  addElementVariables = []
  exo = copy_mesh(fileName,outName,array_type='ctype')
  add_variables(exo,nodal_vars=addNodeVariables)
  exo.put_node_variable_values('FOS',1,resultNodes[:,1])
  exo.put_node_variable_values('Smax',1,resultNodes[:,2])
  exo.put_node_variable_values('Sm',1,resultNodes[:,3])
  exo.put_node_variable_values('Samp',1,resultNodes[:,4])
  exo.put_node_variable_values('Sstatic',1,resultNodes[:,5])
  exo.put_node_variable_values('CritPlanePhi',1,resultNodes[:,6])
  exo.put_node_variable_values('CritPlaneTheta',1,resultNodes[:,7])
  exo.close()



def fatigueDuctSurf(Matl,fileName,meshName,outName,procTot,procNum):
  """
  *fatigueDuctSurf* performs a critical plane fatigue analysis on finite elements assuming
  a ductile Brown-Miller failure mode.  Instead of rainflow counting, it takes
  the peak stresses over time as a conservative proxy.  This version works with
  nodal stress extrapolations.
  .
  :param Matl:      material dictionary
  :param fileName:  base name of the decomposed results file
  :param meshName:  base name of the decomposed mesh file
  :param outName:   base name of the desired output file
  :param procTot:   total number of processors (or file partitions)
  :param procNum:   partition number of interest
```

```
.
As output, the function will save a pandas dataframe pickle and an ExodusII
file that each contain
.
:output globNodeID:      ExodusII global node ID number
:output CritPlaneFOS:    minimum fatigue factor-of-safety
:output CritPlaneMax:    peak normal stress over time
:output CritPlaneMean:   mean stress at minimum FOS
:output CritPlaneAmp:    stress amplitude at minimum FOS
:output StressStatic:    static stress before beam pulse
:output CritPlaneAlpha:  critical plane angle at min FOS (rad)
:output CritPlaneBeta:   critical plane angle at min FOS (rad)
:output CritPlaneGamma:  critical plane angle at min FOS (rad)
.
Requires packages numpy, exodus, exodusCalcs, pandas
"""
fileName = fileName+'.e.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))
pickleName = outName+'.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))+'.pkl'
meshName = meshName+'.g.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))
outName = outName+'.e.'+str(procTot)+'.'+str(procNum).zfill(len(str(procTot)))
"""
ACCESS STRESS RESULTS
==============================================================================
"""
#read stress data from sierra output .e file
ei = exodus(fileName, mode='r', array_type='numpy')
#confirm block ID and name (assumes there is only 1 block to analyze)
ei.get_elem_blk_ids()
ei.get_elem_blk_names()
blkID = ei.get_elem_blk_ids()[0].item()
# Lists the times saved in seconds
# The exodus time_step index starts at 1 (not zero)
timeArray = ei.get_times()
numTimes = len(timeArray)
#node IDs
nodeIDs = ei.get_node_id_map()
# get global node IDs
globNodeID = ei.get_node_variable_values('IDnode', 1)
"""
READ FULL STRESS FIELD FOR ALL TIMES
==============================================================================
References:
https://stackoverflow.com/17394882/how-can-i-add-new-dimensinos-to-a-numpy-array
https://stackoverflow.com/60855200/how-can-i-append0a-multidimensional-array-to-a-new-dimension-with-numpy
https://web.mit.edu/16.20/homepage/3_Constitutive/Constitutive_files/module_3_with_solutions.pdf
"""
StressAll = []
StrainAll = []
for jj in range(0,numTimes):
  # get stress tensor
  S_xx = ei.get_node_variable_values('Snode_xx', jj+1)
  S_yy = ei.get_node_variable_values('Snode_yy', jj+1)
  S_zz = ei.get_node_variable_values('Snode_zz', jj+1)
  S_xy = ei.get_node_variable_values('Snode_xy', jj+1)
  S_yz = ei.get_node_variable_values('Snode_yz', jj+1)
  S_zx = ei.get_node_variable_values('Snode_zx', jj+1)
  #
  Stress = np.array([(S_xx,S_xy,S_zx),(S_xy,S_yy,S_yz),(S_zx,S_yz,S_zz)])
  StressAll.append(Stress.transpose(2,0,1))
  Stress=0.0
  #
  EPS_xx = (S_xx - Matl['nu']*(S_yy+S_zz))/Matl['E']
  EPS_yy = (S_yy - Matl['nu']*(S_xx+S_zz))/Matl['E']
  EPS_zz = (S_zz - Matl['nu']*(S_xx+S_yy))/Matl['E']
  EPS_yz = S_yz/Matl['G']/2.
  EPS_zx = S_zx/Matl['G']/2.
  EPS_xy = S_xy/Matl['G']/2.
  EPS = np.array([(EPS_xx,EPS_xy,EPS_zx),(EPS_xy,EPS_yy,EPS_yz),(EPS_zx,EPS_yz,EPS_zz)])
  StrainAll.append(EPS.transpose(2,0,1))
  # zero-out unneeded variables to save on memory usage
  S_xx = 0.0
  S_yy = 0.0
```

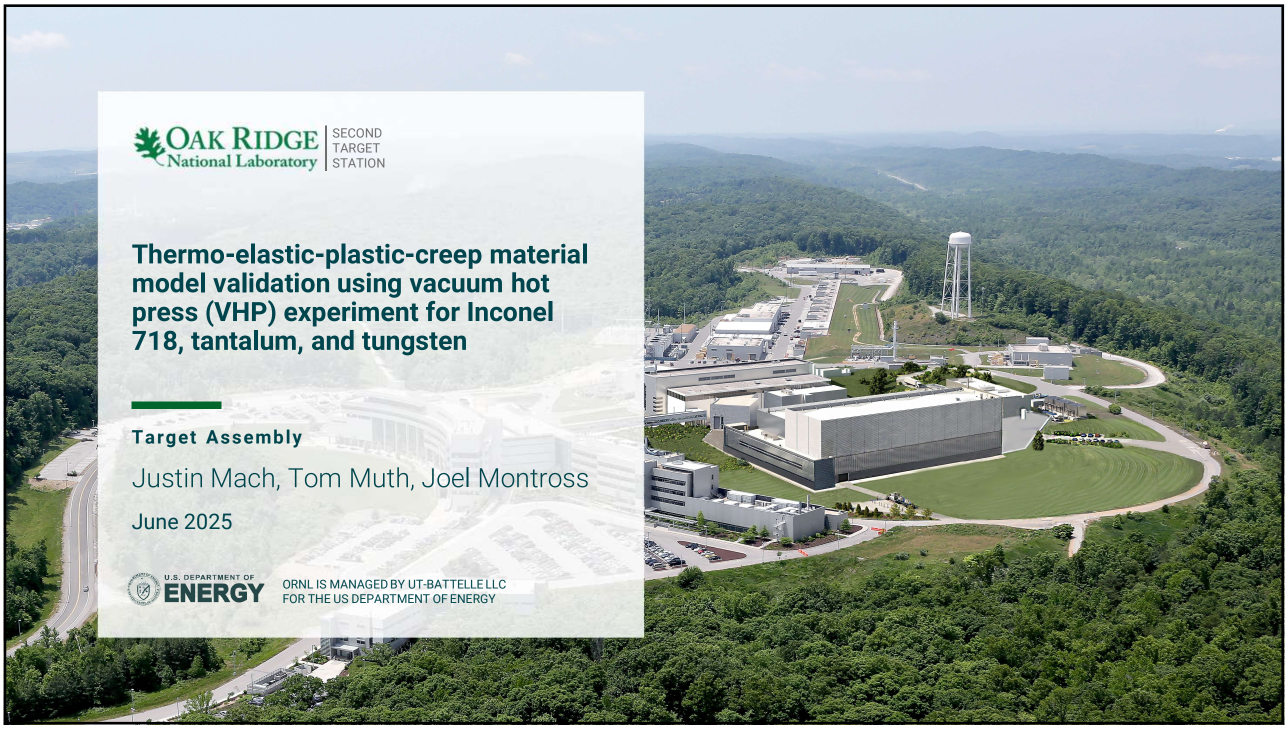
```
  S_zz = 0.0
  S_xy = 0.0
  S_yz = 0.0
  S_zx = 0.0
  EPS_xx = 0.0
  EPS_yy = 0.0
  EPS_zz = 0.0
  EPS_yz = 0.0
  EPS_zx = 0.0
  EPS_xy = 0.0
  EPS = 0.0
ei.close()
ei = 0.0
Stress = np.array(StressAll)
StressAll = 0.0
Strain = np.array(StrainAll)
StrainAll = 0.0
print("Stress")
print(Stress.nbytes)
print("Strain")
print(Strain.nbytes)
"""
CALCULATE STATIC PRINCIPAL STRESSES
==============================================================================
References:
https://csmbrannon.net/2011/04/25/stress-state-analysis-python-script/
https://csm.mech.utah.edu/content/wp-content/uploads/2011/04/stress.py
https://stackoverflow.com/a/51415122
"""
SS = Stress[0]
#
Sprin = np.linalg.eigvals(SS)
Sprin = np.sort(Sprin)
#
maxPrin = Sprin[:,2]
minPrin = Sprin[:,0]
#
StressStatic = np.where(np.absolute(maxPrin) >= np.absolute(minPrin), maxPrin, minPrin)
"""
CALCULATE FOS BASED ON CRITICAL PLANE Brown Miller THEORY
==============================================================================
"""
# initialize stress vectors
CritPlaneFOS = np.ones([len(nodeIDs)])*1.0e+100
CritPlaneMean = np.ones([len(nodeIDs)])*1.0e+100
CritPlaneAmp = np.ones([len(nodeIDs)])*1.0e+100
CritPlaneAlpha = np.ones([len(nodeIDs)])*1.0e+100
CritPlaneBeta = np.ones([len(nodeIDs)])*1.0e+100
CritPlaneGamma = np.ones([len(nodeIDs)])*1.0e+100
# rotate through possible stress planes
for gamma in np.linspace(0, np.pi/2, num=10):
  print("ProcNum,␣Gamma")
  print(procNum,gamma)
  for beta in np.linspace(0, np.pi/2, num=10):
    for alpha in np.linspace(0, np.pi, num=19):
      # choose stress plane
      # https://en.wikipedia.org/wiki/Rotation_matrix
      # where:  alpha = rotation about x-axis
      #         beta = rotation about y-axis
      #         gamma = rotation about z-axis
      #
      R = np.array([(np.cos(beta)*np.cos(gamma), np.sin(alpha)*np.sin(beta)*np.cos(gamma)-np.cos(alpha)*np.
           sin(gamma), np.cos(alpha)*np.sin(beta)*np.cos(gamma)+np.sin(alpha)*np.sin(gamma)),
                    (np.cos(beta)*np.sin(gamma), np.sin(alpha)*np.sin(beta)*np.sin(gamma)+np.cos(alpha)*np.
                         cos(gamma), np.cos(alpha)*np.sin(beta)*np.sin(gamma)-np.sin(alpha)*np.cos(gamma)),
                    (-np.sin(beta),              np.sin(alpha)*np.cos(beta),
                                                                   np.cos(alpha)*np.cos(beta))])
      # original cartesian coordinate system
      e_x = np.array([1., 0., 0.])
      e_y = np.array([0., 1., 0.])
      e_z = np.array([0., 0., 1.])
      # let the x axis define the new normal direction
```

```
        # let the y axis define the new shear direction
        e_n = np.matmul(R,e_x)
        e_s = np.matmul(R,e_y)
        # calculate the normal stress
        traction = np.dot(Stress,e_n)
        S_n = np.dot(traction,e_n)
        # calculate the normal & shear strain
        traction = np.dot(Strain,e_n)
        E_n = np.dot(traction,e_n)
        E_s = 2.*np.dot(traction,e_s)
        # keep the peak normal stresses
        StressNormalMax = np.max(S_n, axis=0)
        StressNormalMin = np.min(S_n, axis=0)
        Smean = (StressNormalMax + StressNormalMin) / 2.0
        # keep the peak normal strains
        StrainNormalMax = np.max(E_n, axis=0)
        StrainNormalMin = np.min(E_n, axis=0)
        # keep the peak shear strains
        StrainShearMax = np.max(E_s, axis=0)
        StrainShearMin = np.min(E_s, axis=0)
        # calculate Kandil-Brown-Miller Parameter
        KBM = np.abs(StrainShearMax-StrainShearMin) + np.abs(StrainNormalMax-StrainNormalMin)
        Samp = Matl['E'] * KBM / 2. / 1.65
        # check for tensile or compressive mean stress
        FOS = np.where(Smean < 0.0, 1.0 / (Samp/Matl['Slife']), 1.0 / (Samp/Matl['Slife'] + abs(Smean)/Matl['SultT']))
        # keep lowest FOS results
        CritPlaneMean = np.where(FOS < CritPlaneFOS, Smean, CritPlaneMean)
        CritPlaneAmp = np.where(FOS < CritPlaneFOS, Samp, CritPlaneAmp)
        CritPlaneAlpha = np.where(FOS < CritPlaneFOS, alpha, CritPlaneAlpha)
        CritPlaneBeta = np.where(FOS < CritPlaneFOS, beta, CritPlaneBeta)
        CritPlaneGamma = np.where(FOS < CritPlaneFOS, gamma, CritPlaneGamma)
        # finally, overwrite the test condition
        CritPlaneFOS = np.where(FOS < CritPlaneFOS, FOS, CritPlaneFOS)
# gather results and save to file
resultNodes = np.column_stack([nodeIDs, CritPlaneFOS, CritPlaneMean+CritPlaneAmp, CritPlaneMean, CritPlaneAmp, StressStatic, globNodeID, CritPlaneAlpha, CritPlaneBeta, CritPlaneGamma])
result = pd.DataFrame(resultNodes)
result.columns = ['nodeIDs','CritPlaneFOS','CritPlaneMax','CritPlaneMean','CritPlaneAmp','StressStatic','globNodeID', 'CritPlaneAlpha', 'CritPlaneBeta', 'CritPlaneGamma']
result['procNum'] = procNum
result = result.astype({'nodeIDs':'int'})
result = result.astype({'globNodeID':'int'})
result.to_pickle(pickleName)
result = 0.0
"""
OUTPUT FOR VISUALIZATION IN PARAVIEW
==============================================================================
"""
# place in Exodus file as new results
addGlobalVariables = []
addNodeVariables = ["FOS", "Smax", "Sm", "Samp", "Sstatic", "globNodeID", "CritPlaneAlpha", "CritPlaneBeta", "CritPlaneGamma"]
addElementVariables = []
exo = copy_mesh(fileName,outName,array_type='ctype')
add_variables(exo,nodal_vars=addNodeVariables)
exo.put_node_variable_values('FOS',1,resultNodes[:,1])
exo.put_node_variable_values('Smax',1,resultNodes[:,2])
exo.put_node_variable_values('Sm',1,resultNodes[:,3])
exo.put_node_variable_values('Samp',1,resultNodes[:,4])
exo.put_node_variable_values('Sstatic',1,resultNodes[:,5])
exo.put_node_variable_values('globNodeID',1,resultNodes[:,6])
exo.put_node_variable_values('CritPlaneAlpha',1,resultNodes[:,7])
exo.put_node_variable_values('CritPlaneBeta',1,resultNodes[:,8])
exo.put_node_variable_values('CritPlaneGamma',1,resultNodes[:,9])
exo.close()
```

APPENDIX E. TARGET MATERIAL CREEP VALIDATION

APPENDIX E. TARGET MATERIAL CREEP VALIDATION

E.0.1 Thermo-elastic-plastic-creep material model validation using vacuum hot press (VHP) experiment for Inconel 718, tantalum, and tungsten



SECOND TARGET STATION

Thermo-elastic-plastic-creep material model validation using vacuum hot press (VHP) experiment for Inconel 718, tantalum, and tungsten

Target Assembly

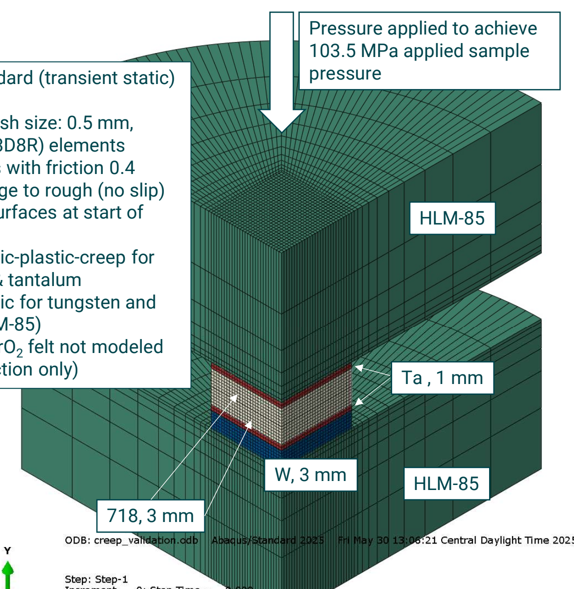
Justin Mach, Tom Muth, Joel Montross

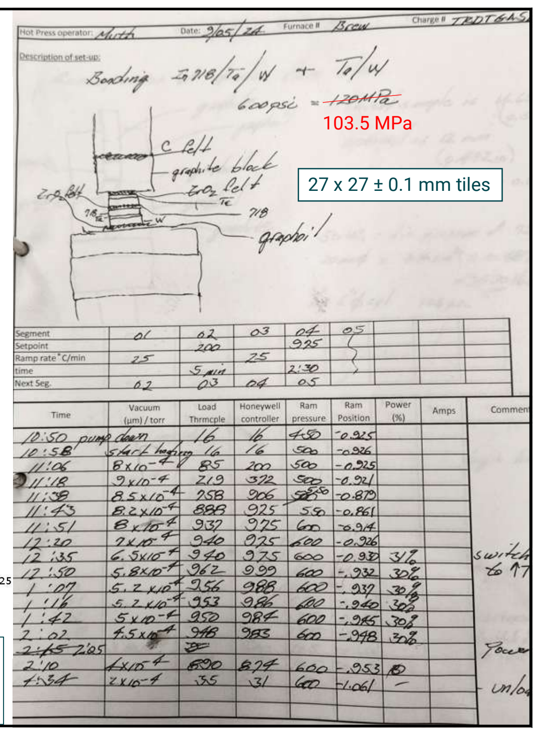
June 2025

1

Model

- Abaqus Standard (transient static)
- ¼ symmetry
- Minimum mesh size: 0.5 mm, linear hex (C3D8R) elements
- Contact pairs with friction 0.4
- Friction change to rough (no slip) for bonded surfaces at start of cooldown
- Thermo-elastic-plastic-creep for Inconel 718 & tantalum
- Thermo-elastic for tungsten and graphite (HLM-85)
- Grafoil and ZrO_2 felt not modeled (interface friction only)





Hot Press operator: Muth Date: 9/05/24 Furnace # Brew Charge # TRDT6AS

Description of set-up:
Bonding In718/Ta/W + Ta/W
600psi ≈ ~~120MPa~~
C felt, graphite block, ZrO_2 felt, TC, 718, W, graphoil

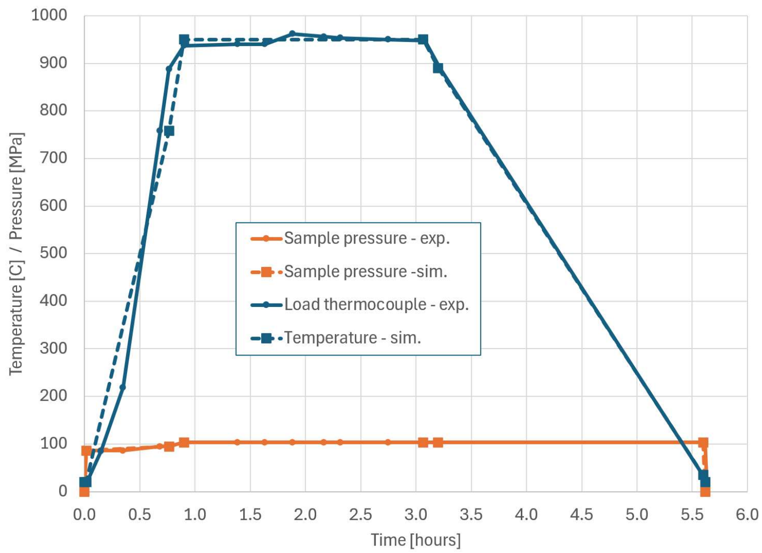
Segment	01	02	03	04	05
Setpoint		200		925	
Ramp rate °C/min	25		25		
time		5 min		2:30	
Next Seg.	02	03	04	05	

Time	Vacuum (µm) / torr	Load Thrmcple	Honeywell controller	Ram pressure	Ram Position	Power (%)	Amps	Comments
10:50	pump down	16	16	450	-0.925			
10:58	start heating	16	16	500	-0.926			
11:06	8x10-4	85	200	500	-0.925			
11:18	9x10-4	219	372	500	-0.921			
11:38	8.5x10-4	758	906	~~500~~ 550	-0.879			
11:43	8.2x10-4	888	925	550	-0.861			
11:51	8x10-4	937	975	600	-0.914			
12:20	7x10-4	940	925	600	-0.926			
12:35	6.5x10-4	940	975	600	-0.930	31%		switch to ↑
12:50	5.8x10-4	962	999	600	-.932	30%		
1:07	5.2x10-4	956	988	600	-.937	30%		
1:16	5.2x10-4	953	986	600	-.940	30%		
1:42	5x10-4	950	984	600	-.945	30%		
2:02	4.5x10-4	948	983	600	-.948	30%		
~~2:15~~ 2:05		~~[illegible]~~						Power
2:10	4x10-4	690	874	600	-.953	0		
4:34	2x10-4	35	31	600	-1.061	–		unload

Creep Models:
- Tantalum – W. Maag and W. Mattson, "Experimental biaxial creep data for tantalum, molybdenum, and alloys T-111, TZM, and TZC", NASA TN D-6149, 1971.
- Inconel – A. Thomas et al., "High temperature deformation of Inconel 718", JMPT, 2006.

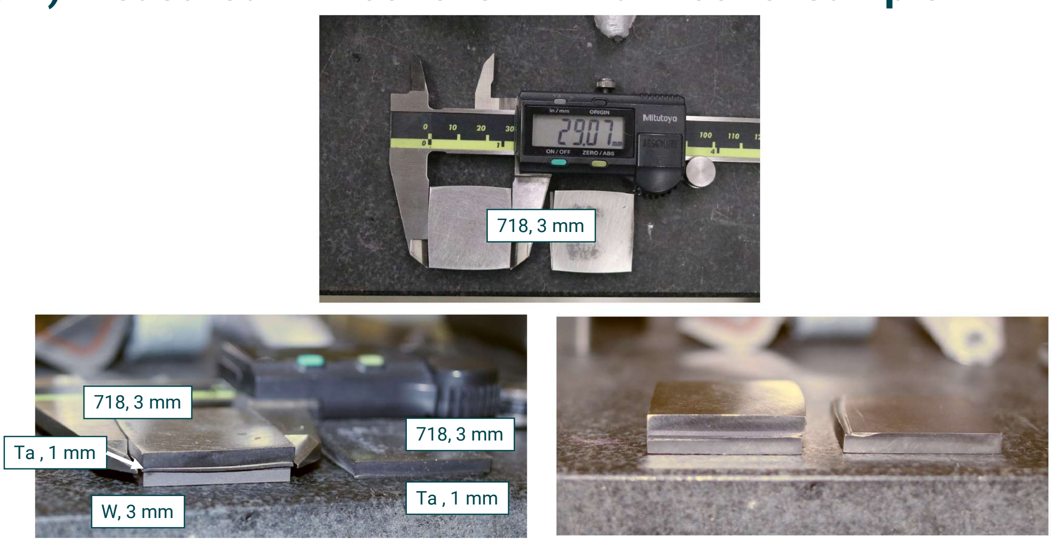
2

Experiment temperature-pressure history and prescribed history in simulation



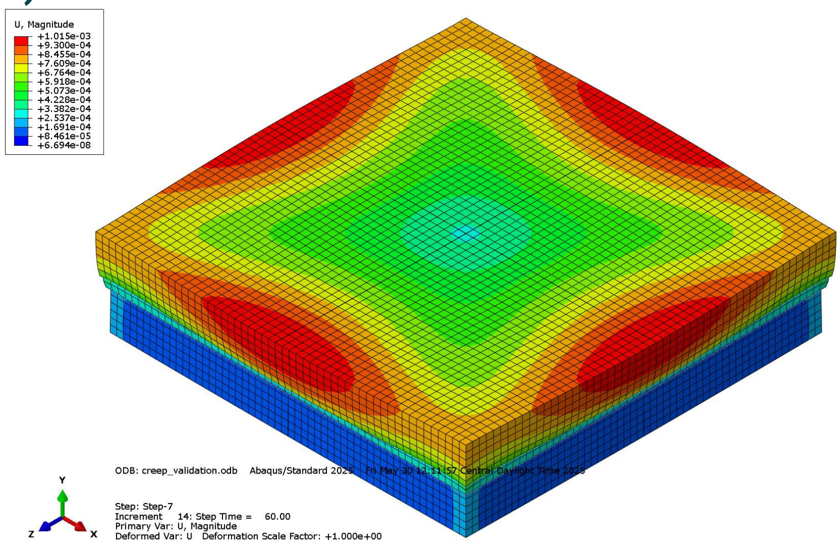
3

Experiment result – lateral expansion of 2.07 mm (~7% true strain) measured in Inconel on W-Ta-Inconel sample

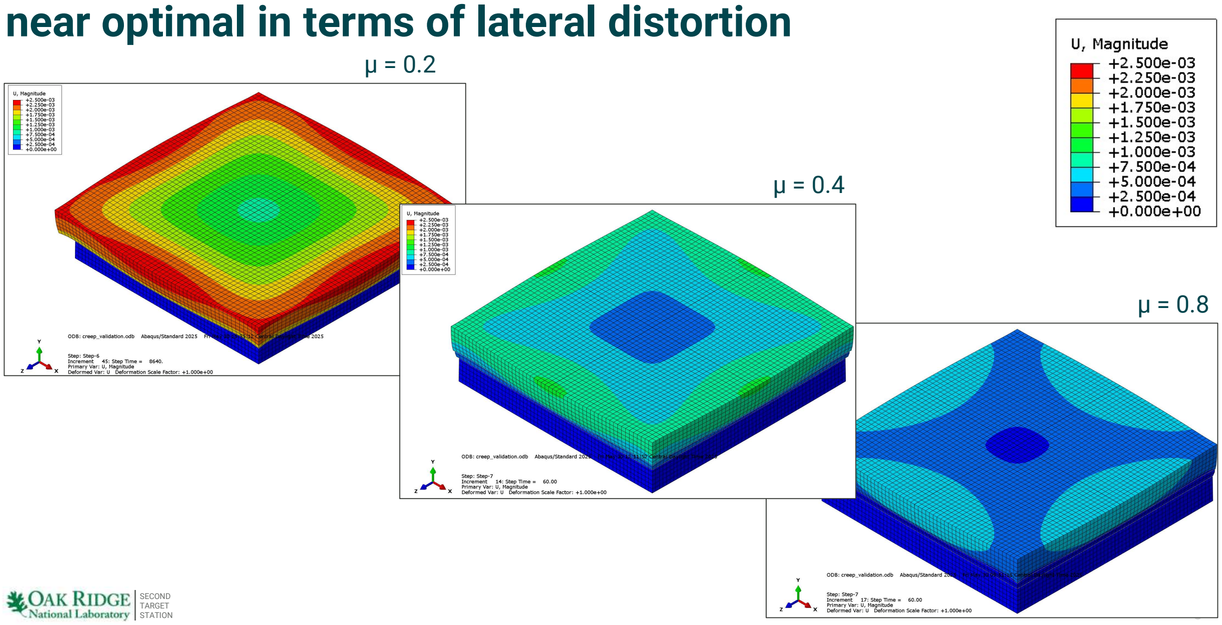


4

Predicted lateral expansion of 1.96 mm vs. 2.07 mm (measured) ~ 5% error → difference of 0.11 mm / 0.004 in.



Sensitivity to assumed friction coefficient → 0.4 seems to be near optimal in terms of lateral distortion



Distortion vs. friction coefficient from previous HIP simulations (without creep) confirmed μ~0.4 is limiting solution in plane strain indentation and compression as per analytical solution

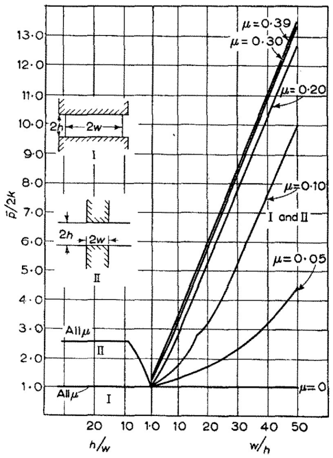
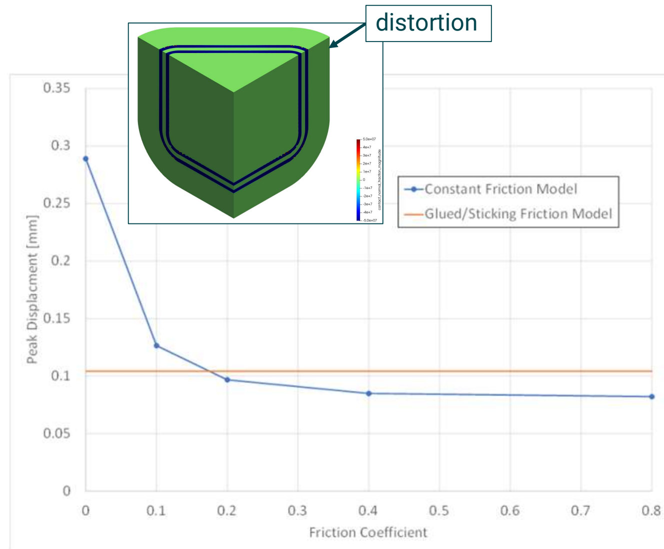


Fig. 12. Mean pressures for indentation and compression in plane strain.

J. Bishop, On the effect of friction on compression and indentation between flat dies, Journal of the Mechanics and Physics of Solids, 6 (1958) 132-144.



OAK RIDGE National Laboratory | SECOND TARGET STATION

Analytical solution supports conclusion that creep is primary mechanism for distortion of sample in this experiment

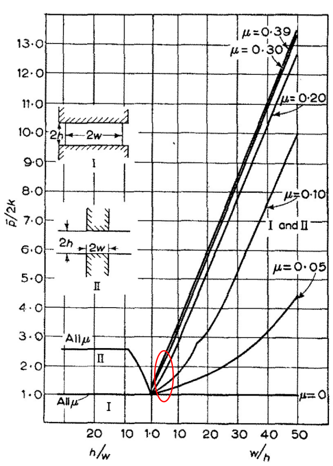


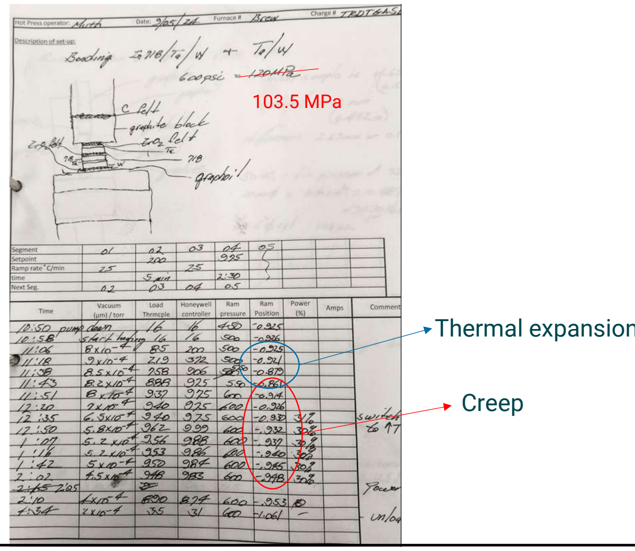
Fig. 12. Mean pressures for indentation and compression in plane strain.

J. Bishop, On the effect of friction on compression and indentation between flat dies, Journal of the Mechanics and Physics of Solids, 6 (1958) 132-144.

- Sample is not in pure plane strain compression, but chart is useful to gain perspective on pressure required to deform material
- Multiple deforming materials (Inconel 718 and tantalum) but 75% is Inconel, so using Inconel properties
- k (shear yield strength) for 718 at 950 C is ~ 85 Mpa
- For w/h ~ 4 (27 mm / 8 mm) → mean pressure required for deformation is between 1 and 2 times greater (depending on friction assumed) than 2k (~170 MPa), which is 170 – 340 MPa
- VHP applied pressure was 103.5 MPa, so to achieve ~ 7% true strain lateral expansion, the analytical solution suggests the distortion was creep driven

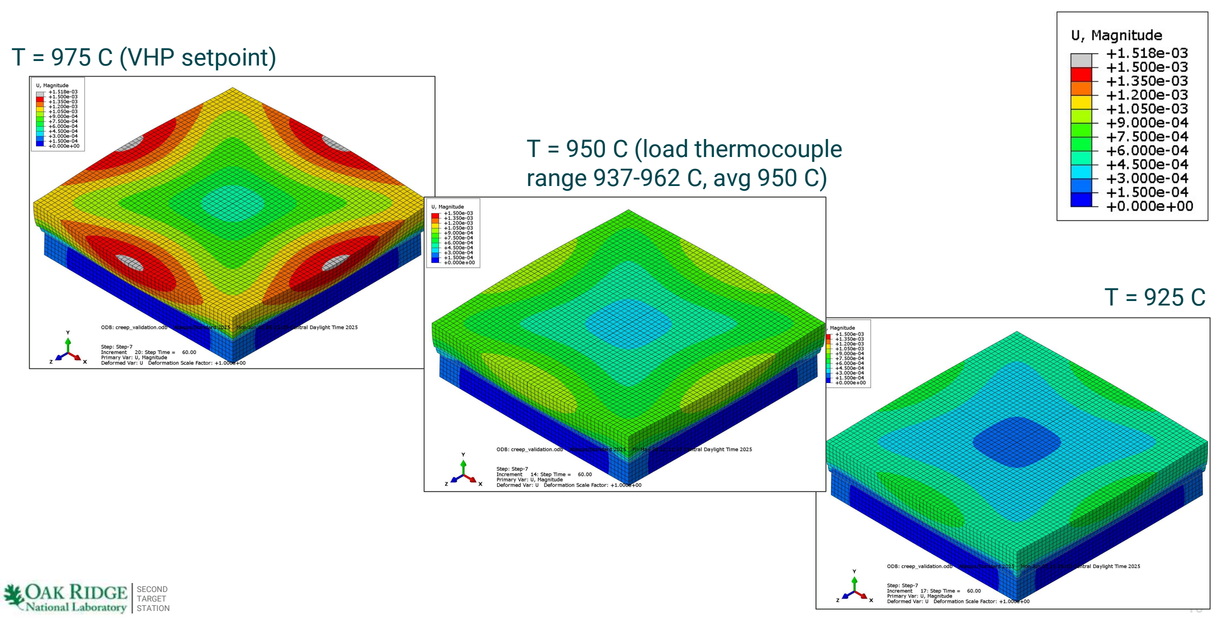
OAK RIDGE National Laboratory | SECOND TARGET STATION

Test log supports creep as primary deformation mechanism → nearly all of ram position downward displacement occurs during peak temperature and pressure hold period



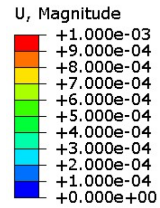
9

Sensitivity to peak temperature for μ = 0.4

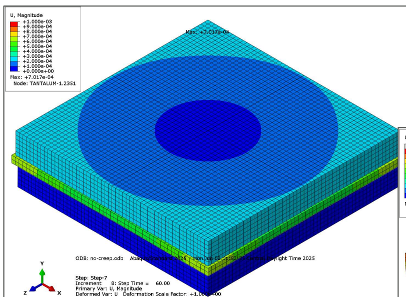


10

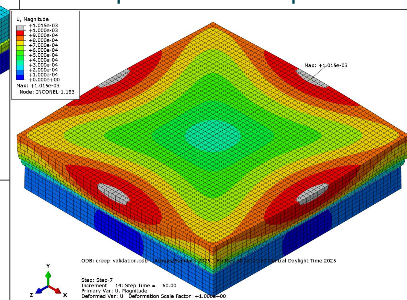
Solution without creep for μ = 0, 0.4 at peak T = 950 C



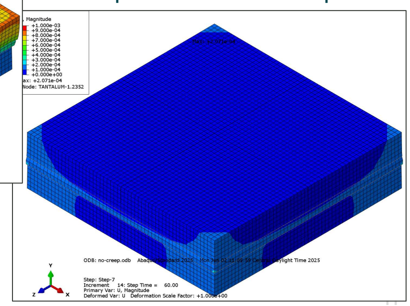
μ = 0 without creep



μ = 0.4 with creep



μ = 0.4 without creep

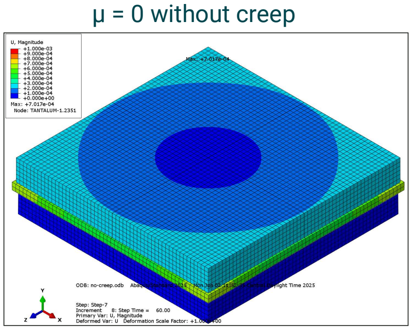


OAK RIDGE National Laboratory | SECOND TARGET STATION

11

Theoretical zero friction requires p~2k (twice shear yield strength, ~170 MPa) in plane strain compression to deform part → applied pressure is still insufficient without creep

μ = 0 without creep



Part deformed shape

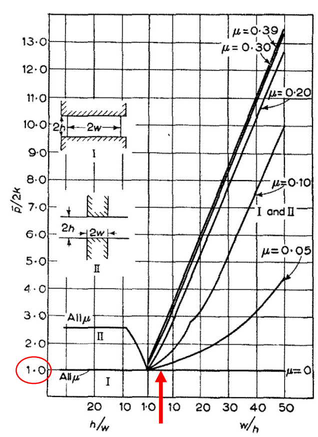


Fig. 12. Mean pressures for indentation and compression in plane strain.

J. Bishop, On the effect of friction on compression and indentation between flat dies, Journal of the Mechanics and Physics of Solids, 6 (1958) 132-144.

OAK RIDGE National Laboratory | SECOND TARGET STATION

12

12

Conclusions

- VHP experiment log indicates creep is primary deformation mechanism for this experiment
- Analytical solution for plane strain compression indicates applied pressure is insufficient to cause ~7% true strain lateral expansion, supporting creep as primary deformation mechanism
- Solution is temperature dependent, but agrees best for peak temperature of 950 C, which is the average of load thermocouple range [937 – 962 C]
- Solution is friction dependent, but agrees best for μ = 0.4, which is supported by analytical solution and prior HIP simulation
- Thermo-elastic-plastic-creep material models for Inconel 718, tantalum, and tungsten (thermo-elastic only) used in this simulation of VHP predict the lateral expansion (distortion) within 5%
- There is a remaining possibility that the friction should be lower/higher and the creep rate correspondingly lower/higher to achieve the same result; independent high temperature creep testing of the Inconel 718 material would be required to investigate further and isolate the creep model from the effect of friction.