

Target Segment Thermostructural Analysis



Joseph B. Tipton, Jr.

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Second Target Station

**TARGET SEGMENT THERMOSTRUCTURAL
ANALYSIS**

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April 21, 2026

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
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LIST OF ABBREVIATIONS

ASCE	American Society of Civil Engineers
ASME/BPVC	American Society of Mechanical Engineers Boiler & Pressure Vessel Code
BID	beam intercepting device
CAD	computer aided design
CFD	computational fluid dynamics
COTS	commercial-off-the-shelf
CSV	comma-separated value
CTE	coefficient of thermal expansion
DAC	design analysis calculation
DBTT	Ductile-to-Brittle Transition Temperature
DOF	degrees of freedom
EBW	electron beam weld
EOS	equation of state
FDR	final design review
FEA	finite element analysis
FOS	fatigue factor of strength
FSRF	Fatigue Strength Reduction Factor
FTS	the First Target Station
HAZ	heat affected zone
HCF	high cycle fatigue
HIP	hot isostatic pressure
LRFD	Load and Resistance Factor Design
NUREG	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PEEQ	plastic equivalent strain
PLM	product lifecycle management
SEI	Structural Engineering Institute
STS	Second Target Station
UTS	ultimate tensile strength
WOL	worst-of-life

ABSTRACT

The Second Target Station (STS) rotating target assembly design consists of 20 target segments, connected to a central shaft with drive and coolant manifold. The purpose of this report is to document thermostructural analyses of an individual target segment to verify project requirements. Specifically, the American Society of Mechanical Engineers Boiler & Pressure Vessel Code (ASME/BPVC) is followed, where feasible, to analyze the target segment for protection against plastic collapse, local failure, and cyclic failure. The target segment is analyzed under the worst-of-life (WOL) condition which includes manufacturing residual stresses along with irradiated material properties. Simulation of manufacturing steps is important to capture the significant residual stresses due to plastic hardening. Protection against plastic collapse and local failure is demonstrated using the elastic-plastic method. Protection against cyclic loading is found to be the most challenging requirement.

The 10 year lifetime requirement accounts for both beam trips and beam pulses. Five different loading conditions are considered including nominal beam, offset beam, diffuse beam, overfocused beam, and low-coolant flow. Under these conditions, the target segment Inconel shroud and flow cover, tungsten plates, and stainless steel heel meet the 10 year design life using mean fatigue life curves.

Weld fatigue lives are marginal in several locations which highlights the need for high-quality, full-penetration welds along with post-machining surface treatments of flow channel entrances. Attempts to demonstrate mesh convergence were unsuccessful due to limits of machine and software capabilities. If the target segment were to fail in marginal areas, the spallation package integrity appears to be maintained indicating a robust design.

1. INTRODUCTION

1.1 STS TARGET ASSEMBLY

The STS Project overarching goal is to design and build the world's brightest source of cold wavelength neutrons for cutting-edge science. To achieve this goal, the tungsten-tantalum spallation target will receive 1.3 GeV proton pulses at a rate of 15 Hz totaling 700 kW beam power. The focused nature of the proton beam and the decay heat require a target assembly that consists of 20 individual target segments rotating at 45 rpm such that each target segment receives a proton pulse every $1\frac{1}{3}$ seconds. Figure 1 identifies the target assembly within the larger target system and concrete monolith.

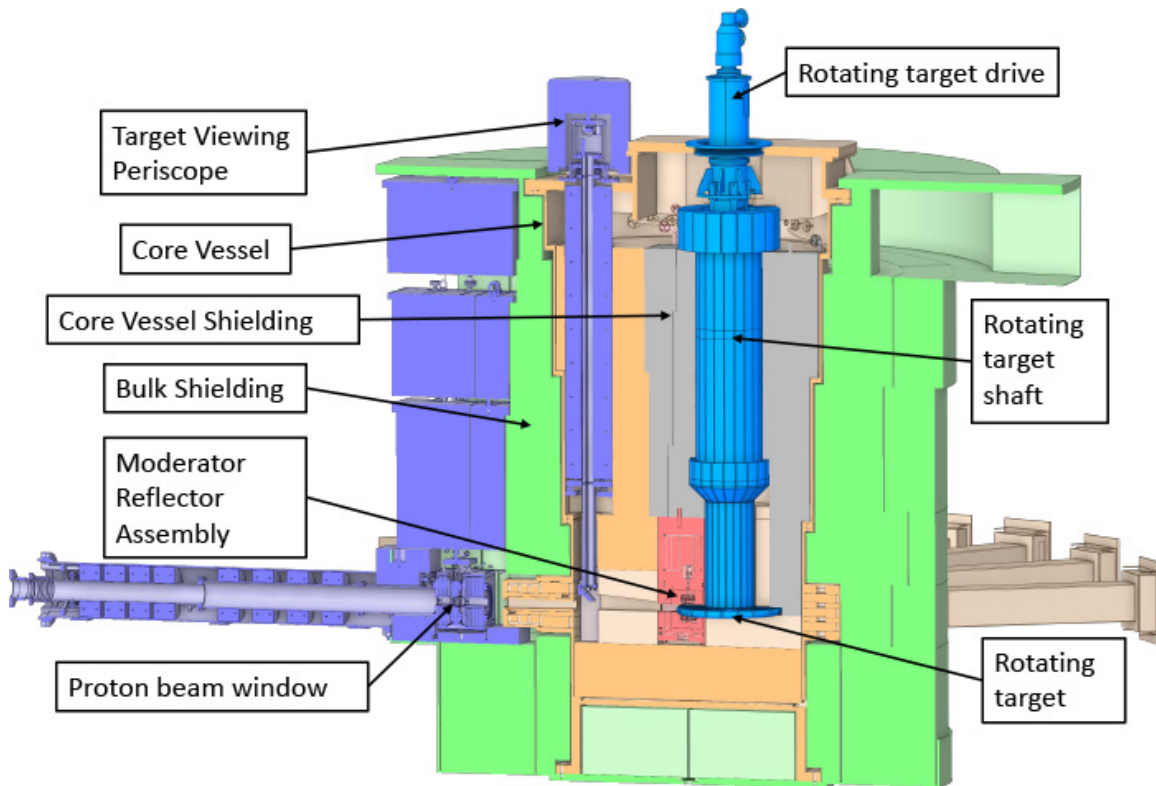


Figure 1. Target Systems hardware within the monolith at the conceptual design state (intended only to connote major components and relationships). The hardware is approximately 7 meters tall and 5 meters in diameter. Taken from <https://neutrons.ornl.gov/sts/sts-target-systems>.

Figure 2 shows the target assembly. The top of the assembly consists of a drive system and coolant distribution system. It is connected to a large shaft around which 20 target segments are held. Also shown is an individual target segment along with a mid-plane cross-section view. The target segment is approximately 5 meters in height. A concentric system of pipes carries coolant water in and out. A large block near the midsection aids with radiation shielding. All materials in the target segment (apart from the foot discussed next) are 316L stainless steel.

The vertical section of the target segment is called the *stave*. The bottom of the stave, or *heel*, connects to the target *foot*. The heel also directs water coolant to a side manifold in the foot. The coolant flows across the foot through machined channels to the other side manifold, back into the heel, and then back up the stave. A pin underneath the heel locates the target into a slot on the shaft that provides radial restraint.

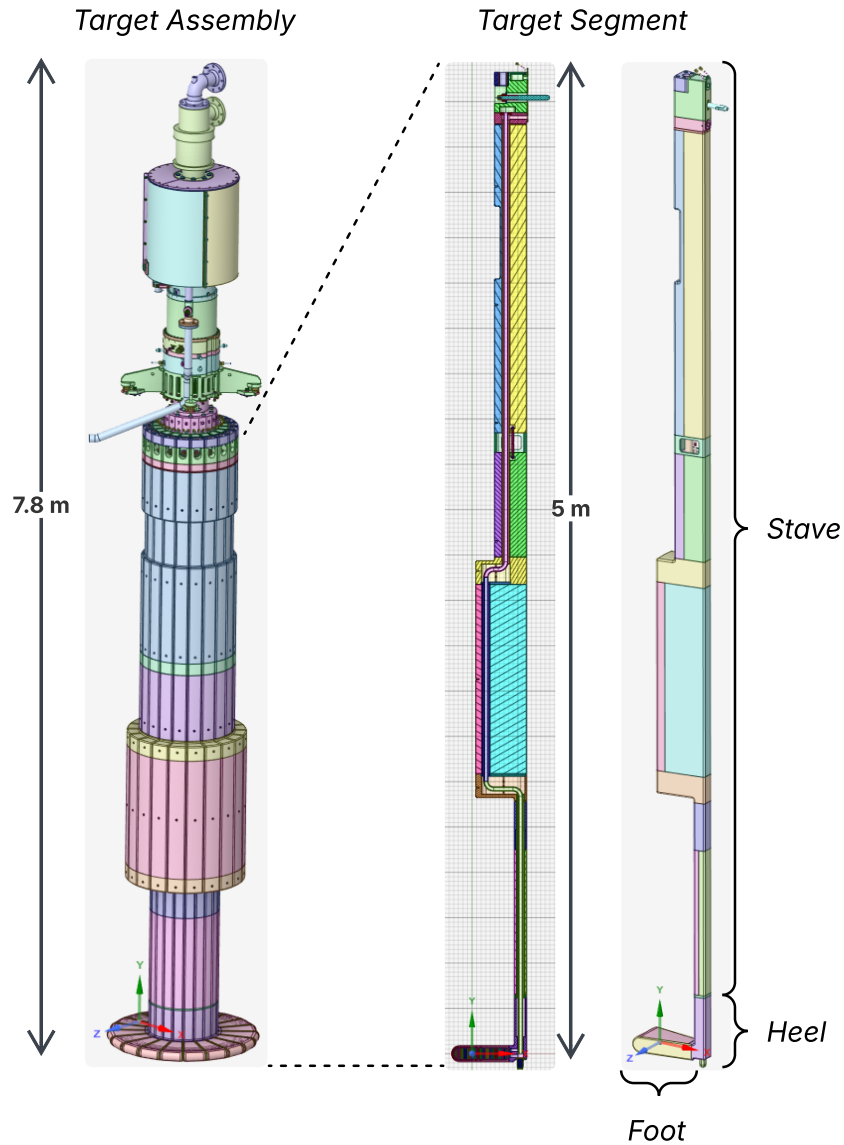


Figure 2. Target Assembly showing manifold, drive, and 20 target segments. An individual segment is shown in detail with cross-section view. Relative heights are denoted along with the *stave*, *heel*, and *foot* regions.

1.2 TARGET HEEL & FOOT

The target core consists of a laminate of 15 thick tungsten plates diffusion bonded with thin tantalum sheets. The laminate is then surrounded with a tantalum cladding and inserted into an Inconel shell. An Inconel side plate is welded to the shell. This core package then goes through a hot isostatic pressure (HIP) process before the Inconel shell is machined to create coolant flow passages. After the Inconel shroud is welded to the stainless steel heel, the Inconel flow covers are welded to the shroud and heel.

Figures 3 through 10 provide various views of the target segment.

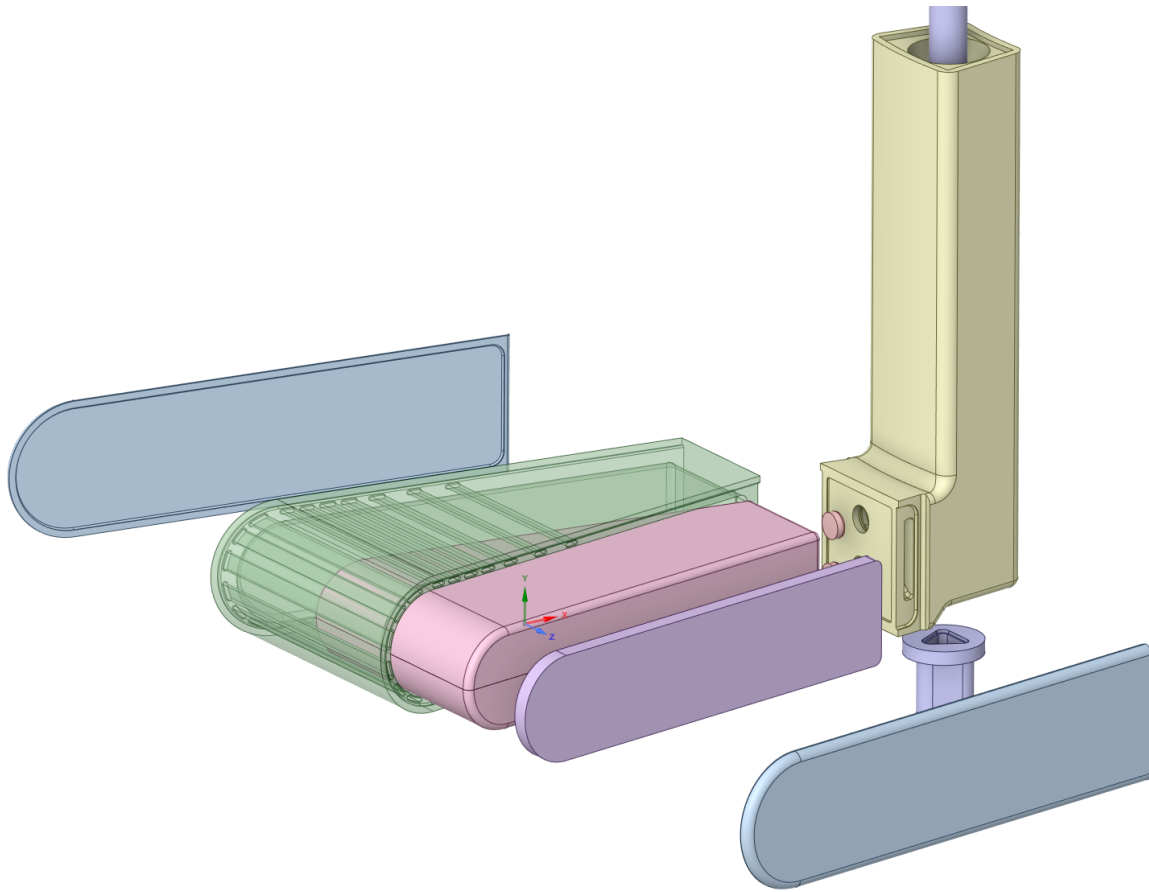


Figure 3. Exploded view of lower target segment showing (L to R): Inconel flow cover, Inconel shroud with cooling channels, target core package, Inconel side plate, stainless steel heel with weld plugs, Inconel pin with CuCrZr insert, and Inconel flow cover.

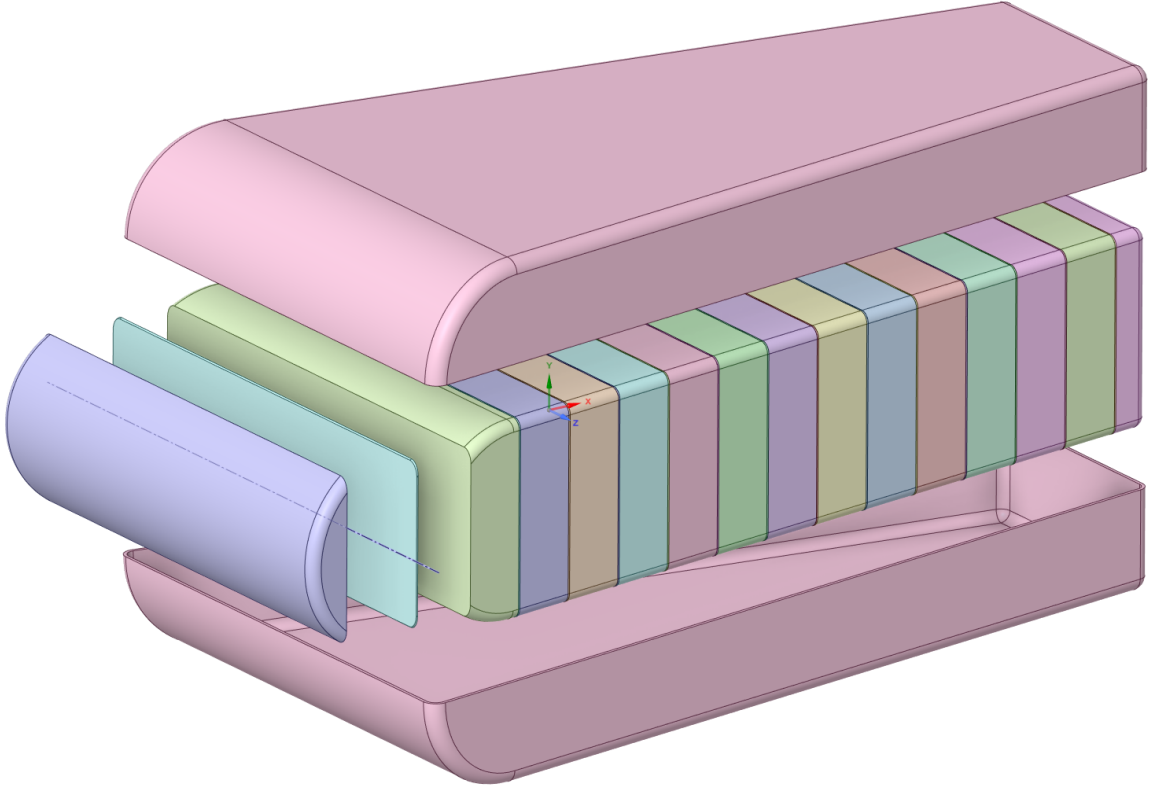


Figure 4. Exploded view of target core showing a laminate of 15 tungsten plates (≈ 18 mm) joined with tantalum foils (0.5 mm) and surrounded with a tantalum cladding (1 mm).

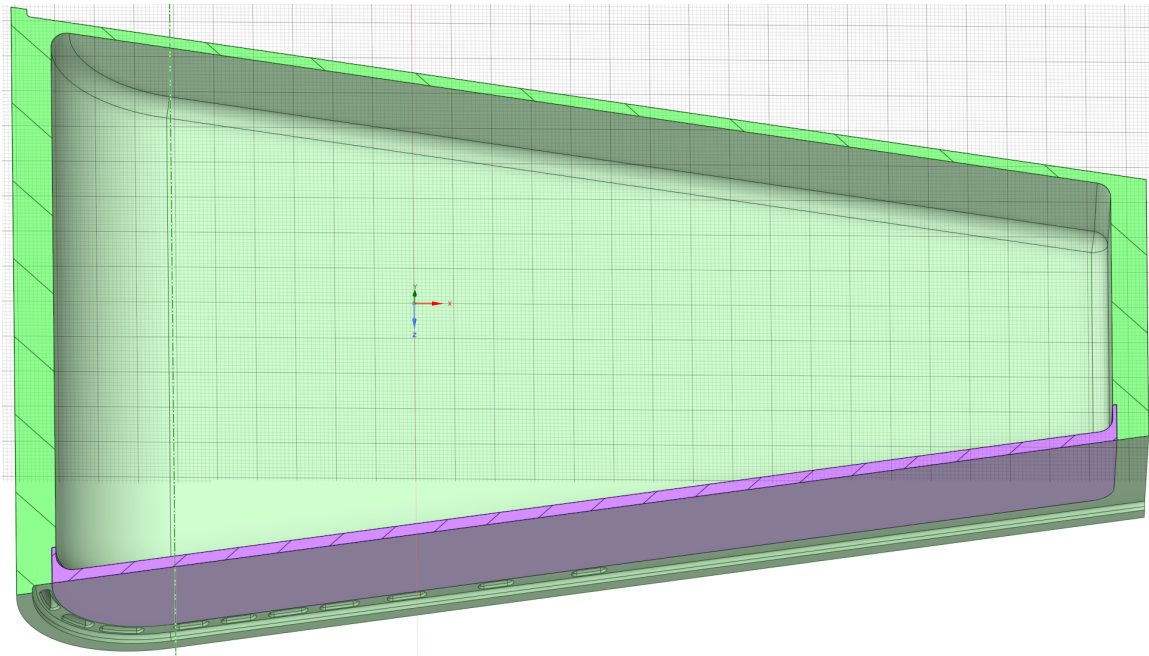


Figure 5. Cut plane view of Inconel shroud and side plate which are welded together after the target core package is inserted. The shroud is 10 mm thick and the sides are 3 mm thick.

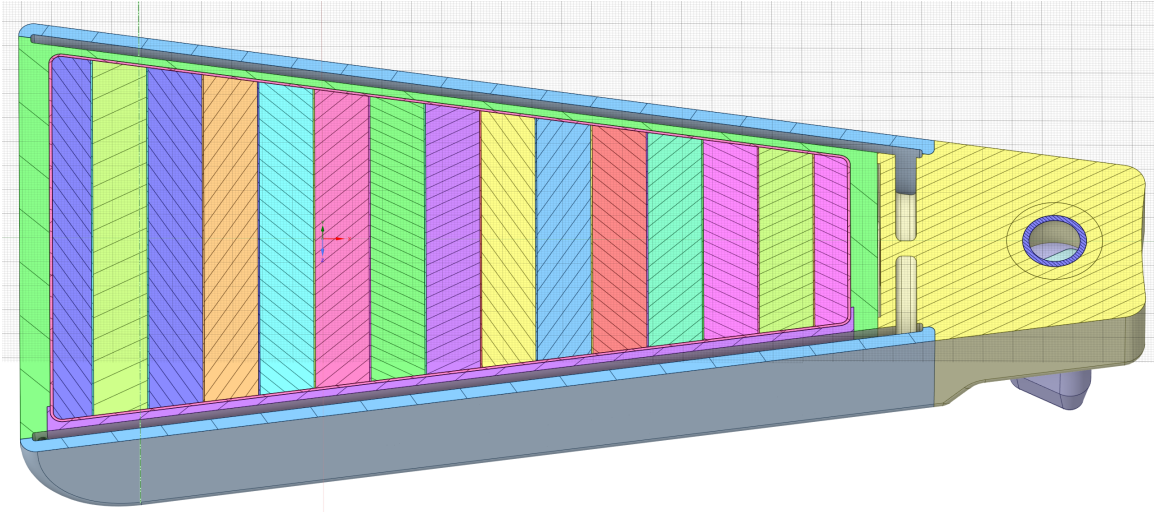


Figure 6. Cut plane view of the assembled target foot. The Inconel side flow covers are 4.5 mm thick.

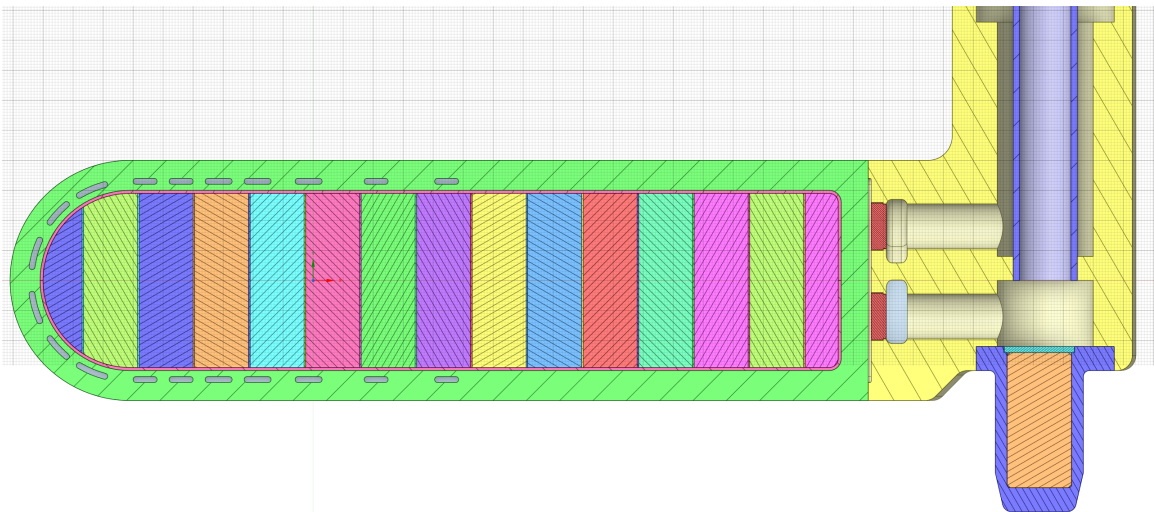


Figure 7. Cut plan view of the assembled target foot.

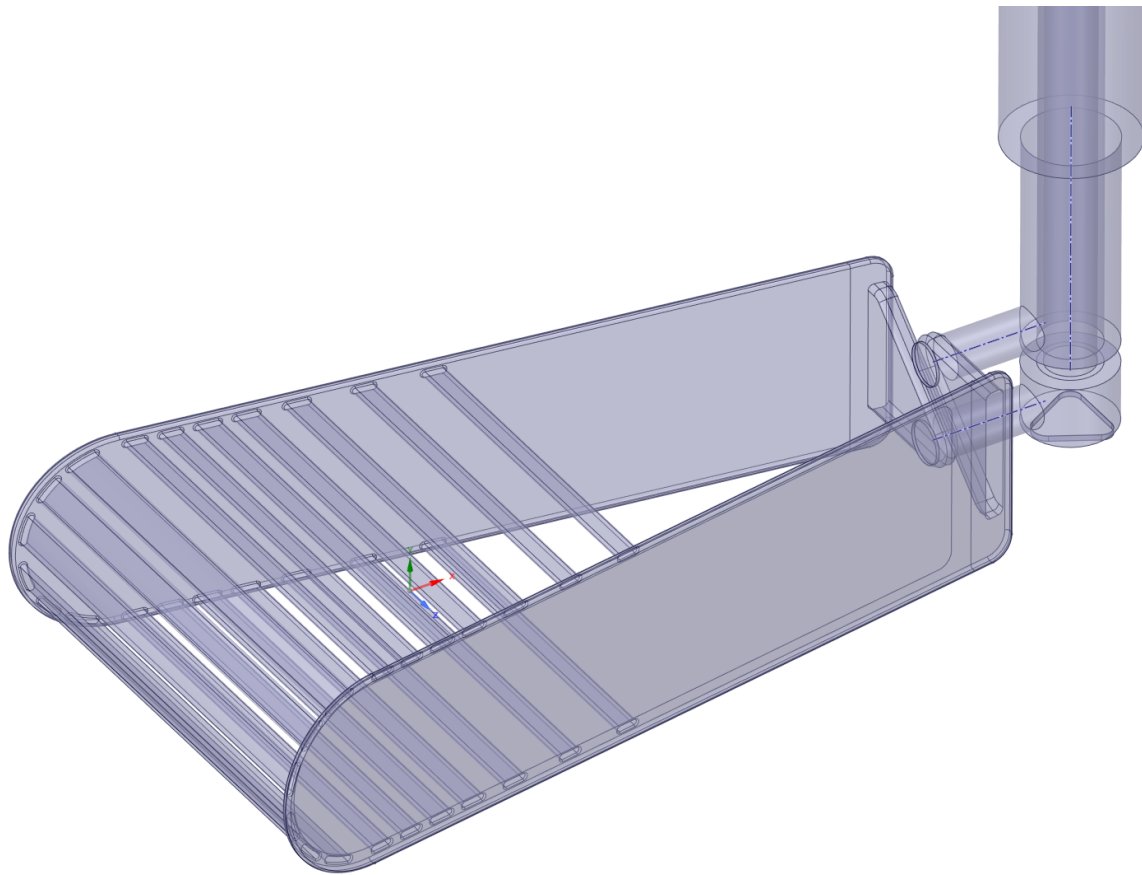


Figure 8. Target water volume extraction. Coolant flow through one of the annular passageways in the heel, through a side manifold, across the cooling channels, through the other side manifold, and back up the heel.

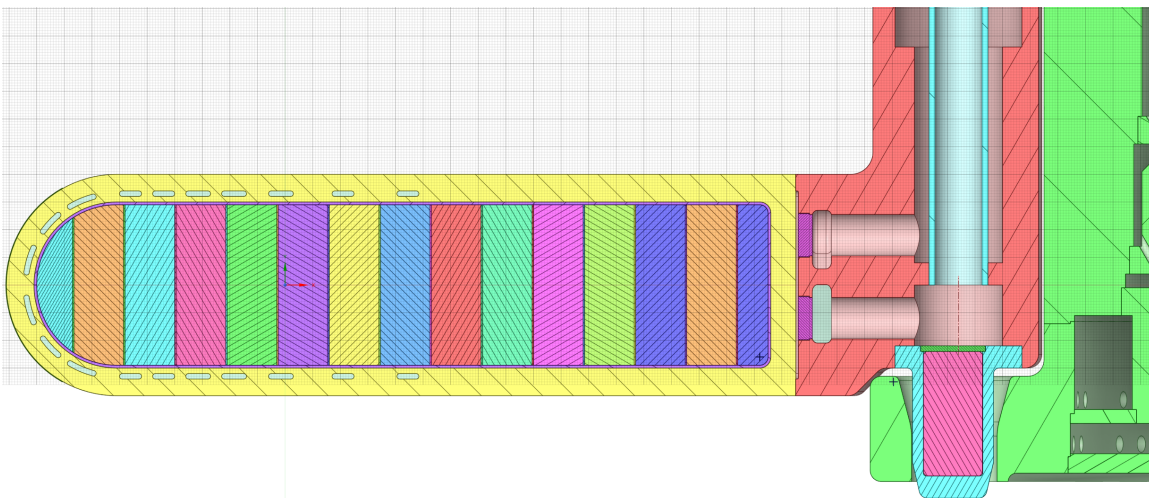


Figure 9. Cut plan view of the assembled target foot showing pin positioning in the shaft assembly.

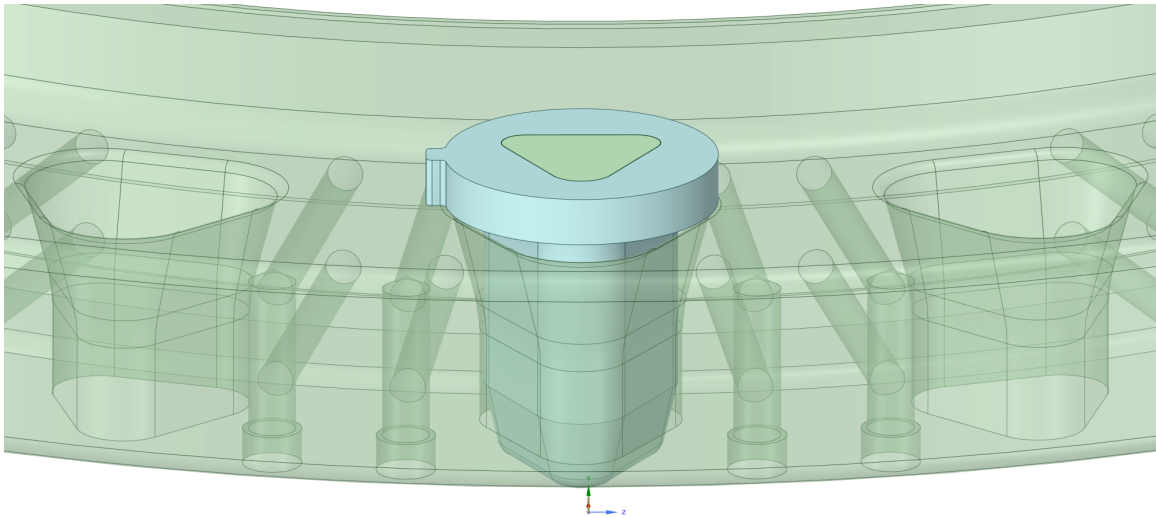


Figure 10. Close-up view of the pin-to-slot interface between the target foot and the shaft assembly. Cross-drilled cooling channels are shown but are part of the shaft assembly analysis scope.

The target segment experiences minor structural loads including dead weight, rotation, and fluid pressure. The major structural loads are due to proton pulses on the target. Each pulse delivers 27 kJ of energy that is volumetrically deposited in the tungsten/tantalum target block over a 700 ns timespan. Figure 11 summarizes the three timescales of effects on the target segment. The longest timescale is on the order of 1 min. for bulk heat diffusion through the target segment until the rate of energy deposition balances with the rate of energy transport through the coolant. The resulting quasi-steady temperature gradient induces significant thermal stresses (e.g. a peak tensile stress of approximately 170 MPa on the tungsten). The second timescale occurs between successive beam pulses on an individual target segment, $1\frac{1}{3}$ s, and represents the thermal stresses caused by energy deposited from a single beam pulse. This is relatively minor (e.g. a 16°C peak temperature rise for tungsten associated with approximately 5 MPa stress increase). The shortest timescale is on the order of $400\text{ }\mu\text{s}$ and is caused by the inertial effects of the rapid energy deposition of a proton pulse. The near-instantaneous temperature rise in the core of the target block creates a compressive stress field, the expansion of which generates elastic stress waves that propagate throughout the target. These stress waves are significant (e.g. roughly half of the quasi-static stress) and are the dominant source of cyclic loading in the target segment.

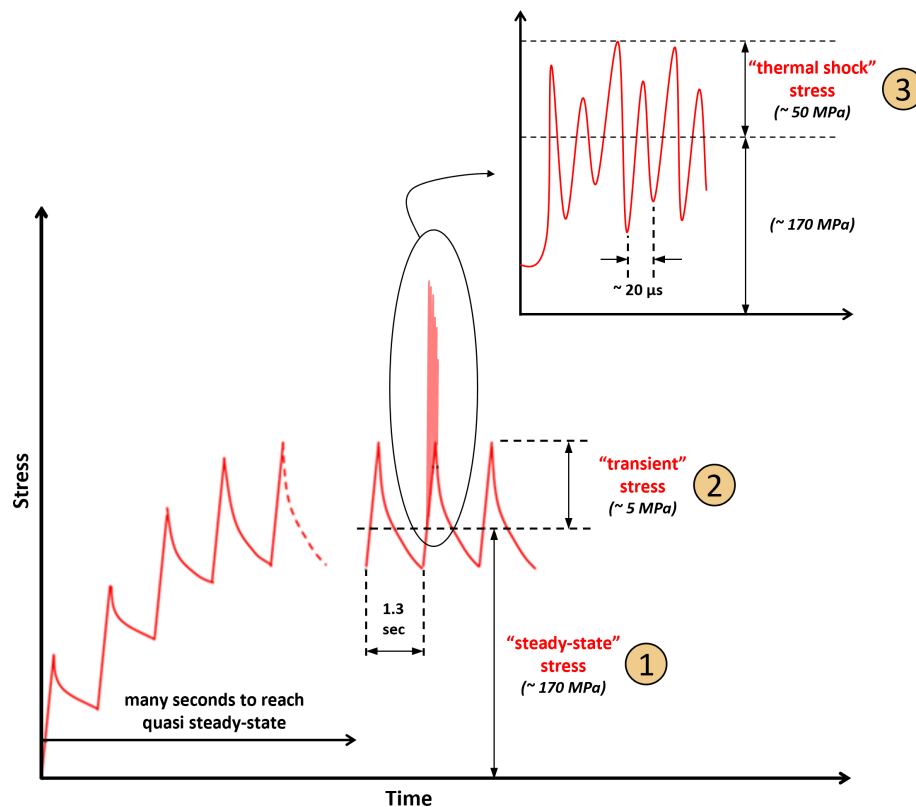


Figure 11. Spallation target thermal loading timescales. Image adapted from original by Peter Loveridge, High Power Targets Group, ISIS Spallation Source.

1.3 DESIGN REQUIREMENTS

STS requirements for the target segment are reported in controlled document S03020400-SRD10000 [11]. The purpose of this report is to document thermostructural fatigue analyses of the lower target segment for the final design review (FDR). This includes the target foot, heel, and a short portion of the stave as shown in Figures 3 through 10. This report does not address design requirements for the full stave structure with the bolted connection to the shaft. Another design analysis calculation (DAC) addresses these structures as part of the target assembly [14].

The following requirements from the controlled document [11] apply in part to this DAC:

1.3.1 REQMT: 1600 - Design Loads and Acceptance Criteria

The target segment shall be designed so that limit states (structural integrity) are maintained under all load combinations (including seismic). Loads and limit states are defined by:

Table 1. Failure Mode Acceptance Criterion

Failure Mode ^a	ASME ^a	ASCE 7	AISC 360	NASA	Judgment	Datasheet
Seismic Interactions		X				
General Stress	X	X				
Weld Stresses	X					
Residual Stress	X					
Buckling	X					
Resonance					X	
Cyclic Loading	X ^b					
Bolt Pullout				X		
Bolt Failure	X					
Slip Critical Joints			X			
COTS components						X ^c

^a Limit states and methods of evaluation only. Target Assembly is not a pressure vessel and does not require fabrication methods, stamping, material sourcing, and allowable materials.

^b Ref (*Sec VIII, D2, ASME Boiler and Pressure Vessel Code, Rules for Construction of Pressure Vessels*) limit states are followed for the segment leg, shaft, and drive where possible but the nature and materials of the Target Segment foot do not adhere to the Boiler and Pressure Vessel Code (BPVC). The code provides conservative lifetimes to prevent failures, whereas the project acknowledges failure will occur and is interested in an accurate lifetime assessment.

^c Manufacturer Data Sheets may not include complete data on all load scenarios. The engineer must use good judgment or a conservative approach to failure modes or loadings beyond the manufacturer's published data.

Note: This specifically includes the segment attachment pin during a seismic event

1.3.2 REQMT: 1574 - Segment Lifetime

Segment Fatigue margin shall be equal to or greater than 1 for a 10-year operational life for all materials with the following load combinations:

Case		Beam Loads						Body Loads			Water			State	Criteria
ID	Case	Power kW	Focus ^a 10 ¹¹	Profile Name	Offset v/h, mm	Pulses 10 ⁸	Trips 10 ⁵	Grav	Rot	Accel	Temp °C	Flow gpm	Press psi	State	Criteria
A	Nominal	700	6.24	60cm ²	0/0	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL ^b	Req 1574 ^c
B	Nominal-corner	700	6.24	60cm ²	8.5/12	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL ^b	Req 1574 ^d
C	Nominal-low flow	700	6.24	60cm ²	0/0	1.35	1.25	Y	Y	N	32.2	5.71	36	WOL ^b	Req 1574 ^d
D	Overfocused	714	6.6	57cm ²	0/0	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL ^b	Req 1574 ^c
E	Diffuse	700	4.61	94.5cm ²	0/0	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL ^b	Req 1574 ^d

^a protons/mm²/sec

^b Worst of Life material conditions (irradiated elastic modulus and thermal conductivity, but not strength)

^c Fatigue methodology (weld reduction factors, etc.) determined in accordance with ASME ASME BPVC Sec. VIII.2, Part 5; allowable stresses are determined from best-in class irradiated material limits and not ASME fatigue curves.

^d Fatigue lifetime criteria to be evaluated; minor deviations in life are acceptable for edge, corner, and worst case conditions

Figure 12. Target segment lifetime availability requirement (#1574).

1.4 APPROACH/METHODOLOGIES

Figure 13 shows how the requirements given in Section 1.3 are interpreted and combined into specific design analyses. The lower target segment does not have any commercial-off-the-shelf (COTS) components, bolts, or slip critical joints, so those design requirements are not considered. Furthermore, this DAC does not consider resonance as the segment is analyzed in isolation from the rest of the target assembly. This leaves Requirement #1600 to focus on analysis via the ASME/BPVC which natively specifies the American Society of Civil Engineers (ASCE) Structural Engineering Institute (SEI) to define seismic loads. Residual stresses are considered by directly simulating the manufacturing of the target foot (as will be developed in Sections 3.3.1 and 4.4). The beam cases listed in Requirement #1574 are considered as part of the ASME/BPVC fatigue assessment. Fatigue assessment is also where weld stresses are directly assessed. The sections that follow further develop the methodology for each analysis type.

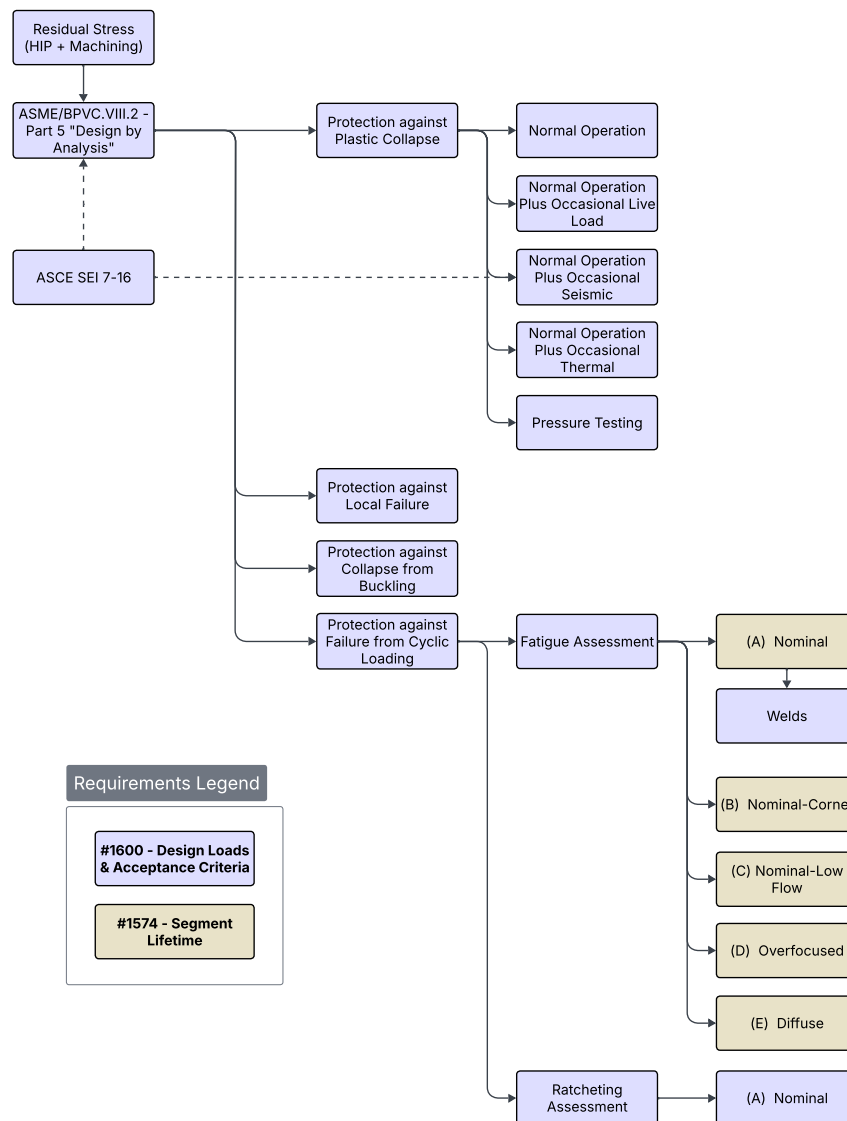


Figure 13. Target segment foot design requirement cases.

The STS target assembly is a highly-custom proton beam intercepting device (BID) and does not clearly fall under a mechanical engineering design code. The target segment has been designed for robustness with coolant flow through the stave inside stainless tubing and through the target inside Inconel channels. In the heel region of the target, the coolant passes through a custom manifold. While it is perhaps feasible to categorize this as a process piping system, there is historical precedence at the First Target Station (FTS) to design under the ASME/BPVC.

The design of the target segment under the ASME/BPVC comes with several caveats, including:

- *Training* - Design and analysis are performed by non-licensed engineers.
- *Functional Requirements* - Part 1.2.4.2 specifically excludes rotating equipment and equipment below a certain size:

Part 1.2 Scope

1.2.4 Classifications Outside the Scope of this Division

1.2.4.2 The following vessels are not included in the scope of this Division. . .

(c) Pressure containers that are integral parts or components of rotating or reciprocating mechanical devices, such as pumps, compressors, turbines, generators, engines, and hydraulic or pneumatic cylinders where the primary design considerations and/or stresses are derived from the functional requirements of the device.

(i) Vessels with an inside diameter, width, height, or cross section diagonal not exceeding 150 mm (6 in.), with no limitation on length of vessel or pressure.

- *Materials* - The target segment is comprised of materials (e.g. brittle tungsten, solution annealed Inconel 718) that are outside the traditional applications of the Code.
- *Manufacturing* - The HIP bonding manufacturing method places the structural material in a state of yield with significant plastic hardening and residual stress before service life.

Accordingly, application of the Code to the target segment design requires significant deviations.

The design requirements specify ASME/BPVC Sec. VIII.2, Part 5 for the Code analysis. Mach and Johns [1] provide a good overview of the ASME/BPVC Section VIII Divisions including justification for the selection of Division 2 (Alternative Rules - Rules for Construction of Pressure Vessels), Part 5 (Design by Analysis) for the liquid mercury target. This section of the Code relies upon design-by-analysis to qualify the design of a component against the following failure modes:

- Protection Against Plastic Collapse
- Protection Against Local Failure
- Protection Against Collapse from Buckling
- Protection Against Failure from Cyclic Loading (including Ratcheting)

The following sections will address each of these failure modes. The background to the Code requirement is first discussed. Then, the application to the target segment will be discussed along with any modifications/deviations.

A Code analysis of the full target segment *stave*, including its attachment bolts, is amenable to a traditional Code analysis as part of the full target assembly. The stave is not subject to significant beam pulse thermal shock loading, is comprised of 316L stainless steel, and follows more traditional manufacturing methods. Accordingly, design calculations of the full target assembly including the stave will be documented in a separate DAC [14].

1.4.1 Plastic Collapse

Plastic Collapse Assessment Background

Figure 14 outlines the 3 options for demonstrating protection against plastic collapse. The Elastic Stress Analysis Method applies specified loading combinations to an analysis using elastic material properties. Stress fields must be decomposed into primary effects (i.e. membrane, bending) and secondary effects (e.g. thermal) and combinations are compared against allowable limits. This can be difficult for non-standard geometries and applications such as spallation targets. The Limit-Load Analysis Method utilizes elastic-perfectly plastic material models and establishes minimum load factors for which stable solutions (i.e. numerical convergence) are achievable. The Elastic-Plastic Stress Analysis Method utilizes thermoelastic-plastic material curves with plastic hardening. A Load and Resistance Factor Design (LRFD) methodology is incorporated with origins from the ASCE SEI whereby statistical reasoning establishes safety factors to apply to loads. A converged solution then indicates acceptance for protection against plastic collapse.

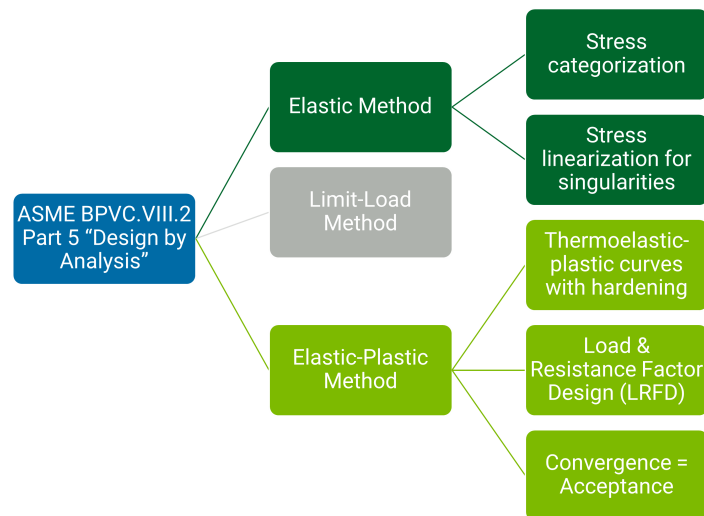


Figure 14. ASME BPVC analysis options for demonstrating protection against plastic collapse.

Application to STS Target Segment Foot

The Elastic-Plastic Stress Analysis Method is chosen as it natively includes thermoelastic-plastic material properties with hardening. This allows for simulations of the target manufacturing process, which generates significant residual stresses, to be imported for use.

Figure 15 reproduces the load case combinations and load factors. Figure 16 reproduces the load parameters. The load factor parameter β is defined in Figure 17. Part 4 of the Code, Section 4.1.1.2 defines this as a Class 2 vessel as it is designed by analysis (instead of design by rule).

The intent of the load case combinations is to capture scenarios including the following:

- Pressure testing
- Normal operation
- Normal operation plus occasional
- Abnormal or startup operation plus occasional

With this in mind, the following 5 load cases are defined for the target segment foot analysis. (Note that wind and snow loads do not apply and have been removed.)

Criteria	Required Factored Load Combinations
Design Conditions	
Global	$(1) \beta(P + P_s + D)$ $(2) 0.88\beta(P + P_s + D + T) + 1.13\beta L + 0.36\beta S_s$ $(3) 0.88\beta(P + P_s + D) + 1.13\beta S_s + 0.71\beta L$ or $0.36\beta W$ $(4) 0.88\beta(P + P_s + D) + 0.71\beta W + 0.71\beta L + 0.36\beta S_s$ $(5) 0.88\beta(P + P_s + D) + 0.71\beta E + 0.71\beta L + 0.14\beta S_s$
Local	$1.7(P + P_s + D)$
Serviceability	Per User's Design Specification, if applicable; see 5.2.4.3(b)
Test Condition	
Global	$\frac{\beta}{1.5} \times \frac{1}{\beta_T} (P_T + P_s + D + 0.6W_{pt})$
Serviceability	Per User's Design Specification, if applicable

GENERAL NOTES:

(a) The parameters used in the Design Load Combination column are defined in Table 5.2.

(b) See 5.2.4.3 for descriptions of global and serviceability criteria.

(c) S is the allowable membrane stress at the design temperature.

(d) S_T is the allowable membrane stress at the pressure test temperature.

(e) Loads listed herein shall be considered to act in the combinations described above; whichever produces the most unfavorable effect in the component being considered. Effects of one or more loads not acting shall be considered.

Figure 15. ASME/BPVC.VIII.2-2021 Table 5.5 Load Case Combinations and Load Factors for an Elastic-Plastic Analysis

Design Load Parameter	Operating Load Parameter [Note (1)]	Description
P	P_o	Internal and external specified design or operating pressure
P_s	P_{so}	Design or operating static head from liquid or bulk materials (e.g., catalyst)
P_T	...	Selected hydrostatic or pneumatic test pressure [see 8.2.1(d) or 8.3.1]. Used only in the pressure test load combinations.
D	D_o	Deadweight of the vessel, contents, and appurtenances at the location of interest, including the following: - weight of vessel including internals, supports (e.g., skirts, lugs, saddles, and legs), and appurtenances (e.g., platforms, ladders, etc.) - weight of vessel contents design, operating, and test conditions - refractory linings, insulation - static reactions from the weight of attached equipment, such as motors, machinery, other vessels, and piping - transportation loads (the static forces obtained as equivalent to the dynamic loads experienced during normal operation of a transport vessel [see 1.2.1.3(b)])
L	L_o	- Appurtenance live loading - Effects of fluid momentum, steady state, and transient - Loads resulting from wave action
E	Same as design parameter	Earthquake loads (see 5.1.3.2)
W		Wind loads (see 5.1.3.2)
W_{pt}		The pressure test wind load case. The design wind speed for this case shall be specified by the Owner-User. Used only in the pressure test load combinations.
S_s		Snow loads
T	T_o	The self-restraining load case (i.e., thermal loads, applied displacements). This load case does not typically affect the collapse load, but should be considered in cases where elastic follow-up causes stresses that do not relax sufficiently to redistribute the load without excessive deformation.

NOTE:

(1) The operating load parameters do not necessarily represent single quantities, but rather each operating load parameter may represent multiple operating conditions as specified in the User's Design Specification [see 2.2.1.1(e) and 2.2.1.1(f)].

Figure 16. ASME/BPVC.VIII.2-2021 Table 5.2 Load Combination Parameters

Class	β	β_T		γ_{min}		$\gamma_{St/s}$	
		Hydrostatic	Pneumatic	Hydrostatic	Pneumatic	Hydrostatic	Pneumatic
1	3.0	0.95	0.8	$1.5\beta_T$	$1.5\beta_T$	1.25	1.15
2	2.4	0.95	0.8	$1.5\beta_T$	$1.5\beta_T$	1.25	1.15

Figure 17. ASME/BPVC.VIII.2-2021 Table 4.1.3 Load Factor and Pressure Test Factors for Class 1 and Class 2 Construction and Hydrostatic or Pneumatic Testing

- **Normal operation** - The Code was not intended for rotating machinery. In the target analysis, the rotational loads are live loads and are not variable or transient. They are part of normal operation and are thus included. Additionally, the thermal loads caused by time averaged proton beam energy deposition is part of normal operation and is included.

$$2.4(P + P_S + D + L + T) \quad (1)$$

- **Normal operation plus occasional live load** - This represents the situation with a combination of normal operation combined with a temporary and abnormal live loading.

$$2.112(P + P_S + D + T) + 2.712L \quad (2)$$

- **Normal operation plus occasional seismic** - This represents an earthquake situation during normal operation.

$$2.112(P + P_S + D + L + T) + 1.704E \quad (3)$$

- **Normal operation plus occasional thermal** - This represents the situation with a combination of normal operation combined with a temporary and abnormal thermal loading.

$$2.112(P + P_S + D + L) + 2.712T \quad (4)$$

- **Pressure testing** - This represents the pressure test condition where the segment is being blown down with compressed gas.

$$2.0(P_T + P_S + D) \quad (5)$$

1.4.2 Local Failure

Local Failure Assessment Background

Local failure is a possible brittle failure mode in an otherwise ductile material. It can occur when a material is in a state of high hydrostatic tension which does not affect the von Mises equivalent stress but nonetheless reduces the fracture strain limit of the material. The Elastic Stress Analysis Method provides a triaxial stress limit test condition. The Elastic-Plastic Stress Analysis Method instead identifies a local strain limit test condition as shown in Equation 6 where ϵ_L is the limiting triaxial strain. The uniaxial strain limit ϵ_{Lu} and material coefficients m_2 and α_{sl} are reproduced in Figure 18.

Uniaxial Strain Limit, ϵ_{Lu} [Note (1)], [Note (2)], [Note (3)]					
Material	Maximum Temperature	m_2 (Column 3)	Elongation Specified (Column 4)	Reduction of Area Specified (Column 5)	α_{sl}
Ferritic steel [Note (4)]	480°C (900°F)	0.60(1.00 - R)	$2 \cdot \ln \left[1 + \frac{E}{100} \right]$	$\ln \left[\frac{100}{100 - RA} \right]$	2.2
Stainless steel and nickel base alloys	480°C (900°F)	0.75(1.00 - R)	$3 \cdot \ln \left[1 + \frac{E}{100} \right]$	$\ln \left[\frac{100}{100 - RA} \right]$	0.6
Duplex stainless steel	480°C (900°F)	0.70(0.95 - R)	$2 \cdot \ln \left[1 + \frac{E}{100} \right]$	$\ln \left[\frac{100}{100 - RA} \right]$	2.2
Precipitation-hardening nickel-based austenitic alloys	540°C (1,000°F)	1.09(0.93 - R)	$\ln \left[1 + \frac{E}{100} \right]$	$\ln \left[\frac{100}{100 - RA} \right]$	2.2
Aluminum	120°C (250°F)	0.52(0.98 - R)	$1.3 \cdot \ln \left[1 + \frac{E}{100} \right]$	$\ln \left[\frac{100}{100 - RA} \right]$	2.2
Copper	65°C (150°F)	0.50(1.00 - R)	$2 \cdot \ln \left[1 + \frac{E}{100} \right]$	$\ln \left[\frac{100}{100 - RA} \right]$	2.2
Titanium and zirconium	260°C (500°F)	0.50(0.98 - R)	$1.3 \cdot \ln \left[1 + \frac{E}{100} \right]$	$\ln \left[\frac{100}{100 - RA} \right]$	2.2

NOTES:
(1) If the elongation and reduction in area are not specified, then $\epsilon_{Lu} = m_2$. If the elongation or reduction in area is specified, then ϵ_{Lu} is the maximum number computed from columns 3, 4, or 5, as applicable.
(2) R is represented by eq. (3-D.11).
(3) E is the % elongation and RA is the % reduction in area determined from the applicable material specification.
(4) Ferritic steel includes carbon, low alloy, and alloy steels, and ferritic, martensitic, and iron-based age-hardening stainless steels.

Figure 18. ASME/BPVC.VIII.2-2025 Table 5.7 Uniaxial Strain Limit for Use in Multiaxial Strain Limit Criterion

$$\epsilon_L = \epsilon_{Lu} \cdot \exp \left[- \left(\frac{\alpha_{sl}}{1 + m_2} \right) \left(\sigma_{tri} - \frac{1}{3} \right) \right] \quad (6)$$

Equation 7 defines the triaxial stress σ_{tri} as a function of the 3 principal stresses and the von Mises equivalent stress.

$$\sigma_{tri} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3\sigma_e} \quad (7)$$

Each point in the component to analyze must then satisfy the condition shown in Equation 8,

$$\epsilon_{peq} + \epsilon_{cf} \leq \epsilon_L \quad (8)$$

where ϵ_{peq} is the plastic equivalent strain from the analysis and ϵ_{cf} is any additional strain from forming or manufacturing the part.

Application to STS Target Segment Foot

The local failure case listed in Figure 15 is interpreted to represent normal operation. For the target segment foot, this then includes live rotational loading and thermal loading as shown in Equation 9.

$$1.7 (P + P_S + D + L + T) \quad (9)$$

For the Inconel shroud and flow cover, the uniaxial strain limit values are taken from the "Precipitation-hardened nickel-based austenitic alloys" category in Figure 18 ($\epsilon_{Lu} = m_2 = 1.09[0.93 - R]$ and $\alpha_{sl} = 2.2$). The target uses solution annealed Inconel 718. The lack of precipitation hardening should increase ductility, however, so the uniaxial strain limit should be conservative. For the stainless steel heel, the uniaxial strain limit values are taken from the "Stainless steel and nickel base alloys" category in Figure 18 ($\epsilon_{Lu} = m_2 = 0.75[1.00 - R]$ and $\alpha_{sl} = 0.6$). In both cases, the uniaxial strain limit accounts for temperature through the variable R which is the ratio of the yield strength to the ultimate tensile strength.

The triaxial strain limit will be post-processed for each nodal stress result and compared against the accumulated plastic strain. As will be explained, this report includes simulation of the manufacturing of the target foot package. Thus, the nodal plastic equivalent strain will include the forming strain ϵ_{cf} . The stainless steel heel and Inconel flow cover are assumed to be fully stress relieved with zero residual strain.

A local failure analysis for the tungsten is not needed as the tungsten is fully brittle in all scenarios. The appropriate failure mode for tungsten will be when the normal stresses approach the failure stress.

1.4.3 Collapse from Buckling

Buckling (plastic collapse by instability) is characterized by a sudden loss of load-carrying capacity when a structure experiences destabilizing compressive stresses, typically from external pressure, internal vacuum, and/or compressive bending. For the target segment, thick-walled construction substantially reduces susceptibility to shell-type buckling because the relevant diameter-to-thickness ratios are low and local wall instability is not expected.

Moreover, there are no credible in-scope operational scenarios that would impose significant compressive bending on the target segment/foot sufficient to trigger an instability. Potential compressive bending loads could arise during installation or handling—for example, if the segment were inadvertently supported on the foot or alignment pin—but these temporary conditions are outside the scope of this report and are better addressed through handling fixtures and procedural controls. Accordingly, given the thick-walled nature of the pressure boundary and the absence of credible operational compressive load cases, collapse by buckling is not considered a credible failure mode for the target segment for the purposes of this design report.

1.4.4 Cyclic Fatigue

The Code provides detailed procedures but does not explain the history or theory behind them. As a World Nuclear Associate report states, "The code would also benefit from having specific validation and theoretical background of all the original methods proposed in the Code" [17]. This section relies heavily upon presentation slides by Hinnant [5] to understand the logic behind the code and better inform application to the STS target segment design and analysis.

Cyclic Fatigue Assessment Background

The Code provides 3 methodologies to analyze cyclic fatigue :

- 5.5.3 Fatigue Assessment - Elastic Stress Analysis and Equivalent Stresses
- 5.5.4 Fatigue Assessment - Elastic-Plastic Stress Analysis and Equivalent Strains
- 5.5.5 Fatigue Assessment of Welds - Elastic Analysis and Structural Stress

Sections 5.5.3 and 5.5.4 are "notch stress" methods which are built upon knowing the peak stress at the location of failure. They are designed for use with smooth bar fatigue curves. The Code provides these fatigue curves for each common engineering material. The curves are created by taking the best fit curve on experiments using smooth bar fatigue specimens and then incorporating a fixed design margin for conservatism. The margin is defined as the worst of either a 2x reduction on stress or a 20x reduction on cycles. The 20x reduction on cycles reportedly consists of a factor of 2 to account for data scatter, a factor of 2.5 to account for specimen size effects, and a factor of 4 to account for surface finish/environment effects [5]. Mean stress corrections are also included in the fatigue curves. This appears to be done in a conservative manner by using the Goodman method along with the highest possible sustainable mean stress (the cyclic yield stress) [18]. As a consulting group observes, [10]

"These ASME curves are not useful for predicting the cycle life of equipment. They are used to specify a permissible design life which includes a large factor of safety."

For Sections 5.5.3 and 5.5.4, the goal is to determine the load cycle histogram, find the alternating peak stress (a.k.a. alternating notch stress) for each cycle, use the smooth bar fatigue curve to find the number of permissible cycles, and calculate a cumulative damage parameter via Miner's Rule. Section 5.5.3 uses an elastic stress analysis and defines the alternating peak stress (for the k^{th} cycle) as:

$$S_{alt,k} = \frac{K_f \cdot K_{e,k} \cdot \Delta S_{P,k}}{2} \quad (10)$$

$\Delta S_{P,k}$ is the von Mises equivalent stress range. $K_{e,k}$ is a "Fatigue Penalty Factor" that is a simplified elastic plastic correction term to correct for "under predicted strains and elastic follow-up" [5]. It can be defined as the ratio of total elastic-plastic strain range to elastic strain range.

The term K_f is a Fatigue Strength Reduction Factor (FSRF). If the actual weld geometry is included in the analysis (e.g. such as a fillet weld being directly modeled and meshed), then peak stresses are automatically resolved. The downside is the high demand on mesh resolution. A preferred alternative is to use a coarser mesh that does not resolve the weld geometry and instead apply the FSRF which is essentially a downward shift in the fatigue curve. The FSRF is based on weld joint type (i.e. partial penetration, full penetration, fillet) and inspection level. The tables provided by the Code are reproduced in Figure 19. As Hinnant points out, the FSRF factors essentially require a stress linearization to analyze [5]:

Table 5.11 Weld Surface Fatigue-Strength-Reduction Factors								
Weld Condition	Surface Condition	Quality Levels (See Table 5.12)						
		1	2	3	4	5	6	7
Full penetration	Machined	1.0	1.5	1.5	2.0	2.5	3.0	4.0
	As-welded	1.2	1.6	1.7	2.0	2.5	3.0	4.0
Partial penetration	Final surface machined	NA	1.5	1.5	2.0	2.5	3.0	4.0
	Final surface as-welded	NA	1.6	1.7	2.0	2.5	3.0	4.0
	Root	NA	NA	NA	NA	NA	NA	4.0
Fillet	Toe machined	NA	NA	1.5	NA	2.5	3.0	4.0
	Toe as-welded	NA	NA	1.7	NA	2.5	3.0	4.0
	Root	NA	NA	NA	NA	NA	NA	4.0

Table 5.12		
Weld Surface Fatigue-Strength-Reduction Factors		
Fatigue-Strength-Reduction Factor	Quality Level	Definition
1.0	1	Machined or ground weld that receives a full volumetric examination, and a surface that receives MT/PT examination and a VT examination
1.2	1	As-welded weld that receives a full volumetric examination, and a surface that receives MT/PT and VT examination
1.5	2	Machined or ground weld that receives a partial volumetric examination, and a surface that receives MT/PT examination and VT examination
1.6	2	As-welded weld that receives a partial volumetric examination, and a surface that receives MT/PT and VT examination
1.5	3	Machined or ground weld surface that receives MT/PT examination and a VT examination (visual), but the weld receives no volumetric examination inspection
1.7	3	As-welded surface that receives MT/PT examination and a VT examination (visual), but the weld receives no volumetric examination inspection
2.0	4	Weld has received a partial or full volumetric examination, and the surface has received VT examination, but no MT/PT examination
2.5	5	VT examination only of the surface; no volumetric examination nor MT/PT examination
3.0	6	Volumetric examination only
4.0	7	Weld backsides that are nondefinable and/or receive no examination

GENERAL NOTES:

(a) Volumetric examination is RT or UT in accordance with [Part 7](#).

(b) MT/PT examination is magnetic particle or liquid penetrant examination in accordance with [Part 7](#).

(c) VT examination is visual examination in accordance with [Part 7](#).

(d) See [WRC Bulletin 432](#) for further information.

Figure 19. ASME BPVC Tables 5.11 and 5.12 for weld strength reduction factors.

"For unwelded regions with manufactured notches (radii, fillets, holes, etc), the alternating peak stress may be taken directly from the FEA solution. For as-welded regions, the peak stress can not be taken directly from the FEA solution due to singularities in the model. The peak stress for these areas is calculated using the secondary stress or M+B stress normal to the weld toe."

Section 5.5.4 uses an elastic-plastic stress analysis. The cycle-by-cycle analysis requires a cyclic plasticity algorithm with kinematic hardening. The Twice Yield Method applies a single loading step. Both methods require a cyclic stress-strain curve for the material. The alternating peak stress (for the k^{th} cycle) is calculated via

$$S_{alt,k} = \frac{1}{2} E_{ya,k} \cdot \left(\frac{\Delta S_{p,k}}{E_{ya,k}} + \Delta \epsilon_{peq,k} \right) \quad (11)$$

where $\Delta \epsilon_{peq,k}$ is the equivalent plastic strain range and $\Delta S_{p,k}$ is the von Mises equivalent stress range. A FSRF parameter is not included for this section of the code. A possible reason could be that there is no

experimental history of cyclic stress-strain curves for welded specimens.

Section 5.5.5 uses a modified membrane plus bending stress method called the "Equivalent Structural Stress". It is insensitive to finite element analysis (FEA) mesh as it calculates only on nodal forces and moments on weld lines. It furthermore uses a derivative of the Battelle Master SN Method which uses a single fatigue curve built on tests of welded specimens. The user defines the margin on the weld fatigue curves and a statistical lower margin of 3 standard deviations is recommended. One key difference is that the single fatigue curve is material agnostic and therefore shows no difference between carbon steel and stainless steel (nor Inconel). Another key difference is that the Master SN curve does not have an endurance limit in the high cycle fatigue (HCF) regime (as opposed to smooth bar fatigue data which does show an endurance limit for many materials).

Application to STS Target Segment Foot

A cyclic fatigue analysis of the foot of the target segment does not clearly fall into these methodologies for the following reasons:

- *5.5.3 Fatigue Assessment - Elastic Stress Analysis and Equivalent Stresses* - The foot of the target segment experiences plastic strains during manufacturing that leave significant residual stresses. The component then begins its service life in this state (i.e. yielded and with significant plastic hardening). The tungsten core is a fully brittle material, and a von Mises equivalent stress analysis does not apply.
- *5.5.4 Fatigue Assessment - Elastic-Plastic Stress Analysis and Equivalent Strains* - Cyclic stress-strain curves are not available for the target materials.
- *5.5.5 Fatigue Assessment of Welds - Elastic Analysis and Structural Stress* - Gives no credit to the higher quality materials (e.g. stainless steel, Inconel) and methods (e.g. electron beam weld (EBW)) used by the STS team to strive for a robust, HCF design.

In light of this, the STS team chooses to use a combination of Sections 5.5.3 and 5.5.4 and to perform a bounding analysis of the target segment foot under WOL conditions. The analyses will assume the full lifetime of pulses occurs at WOL conditions which includes irradiated material properties and residual stresses from manufacturing.

Structural simulations will use elastic-plastic material constitutive models where available. Cycle counting, peak stress calculation, and damage summation will be performed by *fe-safe* commercial software. (FTS has previously pursued an equivalent fatigue analysis method using commercial software for an elastic-plastic analysis that models the full transient response [1]. The same methodology will be applied here.) While the Code appears to use a von Mises equivalent stress, the *fe-safe* theory manual cautions against the von Mises equivalent stress for fatigue analysis [3, Sec. 7.4.8]:

"A major problem with the practical application of von Mises criteria to measured signals is that the von Mises stress or strain is always positive, even for negative values of stress or strain, and so Rainflow cycle counting cannot be applied directly. Some approximations have been proposed, such as assigning the sign of the largest stress or strain to the von Mises stress or strain, or alternatively to assign the sign of the hydrostatic stress or strain to the von Mises stress or strain. These are termed 'signed von Mises' criteria. The different methods of determining the sign can give significantly different life estimates. . . von Mises criteria correlate poorly with test data, particularly for biaxial stresses when the two in-plane principal stresses change their orientation during the fatigue loading."

Instead, the target segment foot will be analyzed using the recommended critical plane methods including normal stress for brittle failure modes (e.g. tungsten) and stress-based (Kandil) Brown-Miller for ductile

failure modes (e.g. stainless steel and Inconel). Further discussions and development of these models are found in the "Target Systems Materials Library" [16]. Best available fatigue curves are used but do not incorporate the "2 and 20" margins that are built into Code curves. Also, mean stresses will be corrected directly using the modified Goodman method.

The welds used in the target foot are all specified as full-penetration EBW [12]. The geometry is assumed to be clean (i.e. no fillets or beads) and well-represented by the computer aided design (CAD) models. Weld regions will be approximated by a heat affected zone (HAZ) of 2-3mm on each side of the weld line. These regions will go through fatigue analysis with a custom Inconel 718(SA) weld filler material fatigue curve as defined in the "Target Systems Materials Library" [16]. These weld regions will also incorporate the FSRF in a qualitative manner whereby the fatigue factor of strength (FOS) contour plots will be explored for margin against applicable FSRF values.

1.4.5 Plastic Ratcheting

Plastic Ratcheting Assessment Background

The goal of a plastic ratcheting analysis is to ensure any initial plastic deformation ends in elastic shakedown. Put another way, continued cycles of loading should not cause continued plastic deformation. Section 5.5.7 "Ratcheting Assessment - Elastic-Plastic Stress Analysis" of the Code gives an assessment procedure that is interpreted as follows:

1. Create an appropriate numerical model of the component.
2. Define all relevant loads and applicable load cases.
3. Use elastic perfectly plastic material models and include the effects of non-linear geometry.
4. Perform an elastic-plastic analysis for the applicable loading.
5. Use at least 3 complete load repetitions to demonstrate convergence and satisfy one of the criteria:
 - (a) no plastic strains develop in the component
 - (b) an elastic core remains in load bearing structures of the component
 - (c) no permanent change in the overall dimensions of the component

Application to STS Target Segment Foot

The analysis for the target segment foot makes 2 major modifications. First, since the manufacturing of the target produces significant residual stresses, an elastic perfectly-plastic material model cannot be used for the Inconel shroud. This component must continue to use its native thermoelastic-plastic model with hardening. The other components (i.e. flow cover and heel) can use elastic-perfectly plastic material models. Second, the nature of the target connections (suspended from a stave and engaged with a pin/slot feature) make determining overall dimension changes difficult. Instead, this criteria will be replaced by a demonstration of elastic shakedown through showing a reduction in plastic equivalent strain (PEEQ) with each beam pulse event.

2. ASSUMPTIONS

The following major assumptions apply to the analyses herein:

2.1 NUMERICAL DISCRETIZATION

- mesh assumed to be sufficiently converged

2.2 STRUCTURAL ANALYSES

- all interfaces assumed to be perfectly flat and smooth
- perfect bonds
- machining operation simulated via model subtraction (i.e. no compressive surface residual stresses from tooling)
- CuCrZr is not a structural material and is modeled instead as OFE Cu
- stave structure is replaced by a beam element (i.e. accurate deflection of the stave is not required as long as the stave holds the target and allows it to engage with the pin/slot feature)
- negligible thermal loads generated by the "long" transient effect of one pulse per target wheel rotation (see Figure 11)
- negligible thermal diffusion during the "thermal shock" beam pulse response (see Figure 11)
- water volume effect on structural solution is neglected except for static pressure on wetted surfaces (see Section 5.11.2)
- tungsten/tantalum laminate residual stresses are negligible compared to residual stresses generated from target foot HIP and machining residual stresses
- flow cover and heel structures have no residual stresses/strains from manufacturing

2.3 FATIGUE ANALYSES

- analysis does not consider initial defects or crack propagation
- tantalum fatigue is neglected
- beam trips do not interact with beam pulses in fatigue lifing
- fatigue cycles are elastic

3. PHYSICAL MODEL DEFINITION

The physical model definition includes CAD geometry, material properties, and loads. Figure 20 uses a flowchart to identify the flow of information and upstream analyses that are used in this DAC. The sections below provide further details.

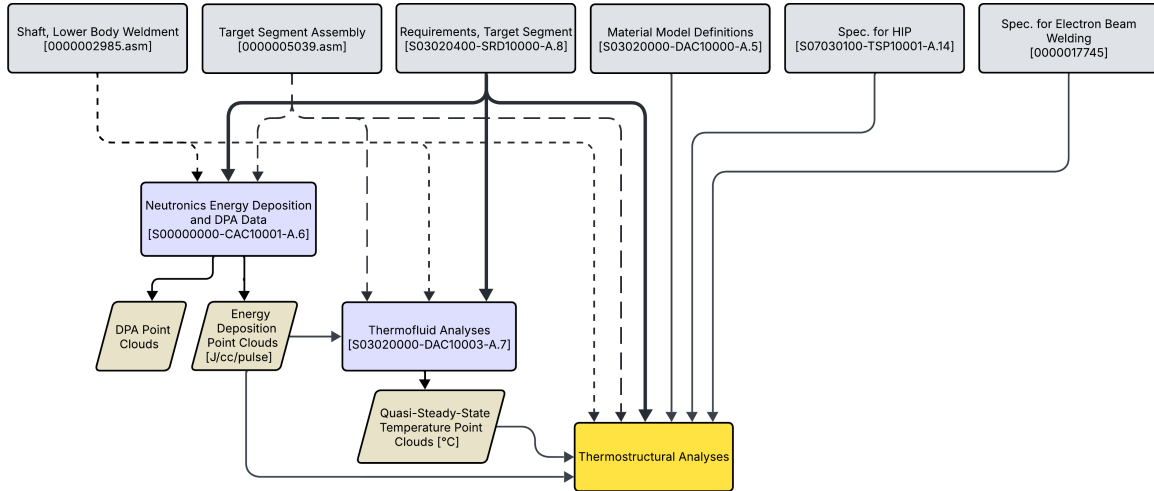


Figure 20. Flowchart of FDR information and analysis flow for model definition. (Larger version available in Appendix A.)

3.1 GEOMETRY

Table 2. Windchill CAD configuration used for analyses. Downloaded on 22 August 2025 from master assembly 0000005039.asm "TARGET SEGMENT ASSEMBLY".

File Name	Number	Version
0000005039.asm	0000005039	0.18
s03020000-m8u-8800-a10003_skel.prt	S03020000-M8U-8800-A10003_SKEL.PRT	0.2
0000006871.asm	0000006871	0.11
0000006871-sk.prt	0000006871-SK.PRT	0.2
0000011300.asm	0000011300.ASM	0.9
0000011300-1a.prt	0000011300-1A.PRT	0.2
0000011300-3.prt	0000011300-3.PRT	0.1
0000006870.prt	0000006870.PRT	0.7
0000006869.prt	0000006869.PRT	0.6
0000006867.prt	0000006867.PRT	0.8
0000006868.prt	0000006868.PRT	0.4
0000006994.prt	0000006994.PRT	0.4
s03020000-m8u-8800-a10003-c_.prt	S03020000-M8U-8800-A10003-C_.PRT	0.1
0000005999.asm	0000005999.ASM	1.8
0000009218.prt	0000009218.PRT	0.4
0000009217.prt	0000009217.PRT	0.5

Continued on next page

Table 2 – Continued from previous page

File Name	Number	Version
0000009219.prt	0000009219.PRT	0.4
0000015843.prt	0000015843	0.5
0000009216.prt	0000009216.PRT	0.6
0000011772.prt	0000011772	0.2
0000010854.prt	0000010854.PRT	0.4
0000010937.prt	0000010937.PRT	0.6
0000010498.prt	0000010498.PRT	0.5
0000011781.prt	0000011781.PRT	0.2
0000011782.prt	0000011782.PRT	0.4
0000011783.prt	0000011783.PRT	0.2
0000010497.prt	0000010497.PRT	0.3
0000010279.prt	0000010279.PRT	1.3
0000010856.prt	0000010856.PRT	0.1
0000010853.prt	0000010853.PRT	0.1
0000010518.prt	0000010518.PRT	0.4
0000011778.prt	0000011778.PRT	0.1
0000010520.prt	0000010520.PRT	0.2
0000010855.prt	0000010855.PRT	0.4
0000011779.prt	0000011779.PRT	0.2
0000006000.prt	0000006000	0.4
0000011774.prt	0000011774.PRT	0.1
0000010496.prt	0000010496.PRT	0.1
0000010499.prt	0000010499.PRT	0.1
0000010500.prt	0000010500.PRT	0.3
0000011775.prt	0000011775.PRT	0.2
0000010519.prt	0000010519.PRT	1.4
0000010507.prt	0000010507.PRT	1.1
0000010506.prt	0000010506.PRT	1.1
swagelok_ss-2-ut-a-4bt.prt	SWAGELOK_SS-2-UT-A-4BT.PRT	0.1
0000008542.asm	0000008542	0.5
0000008543.prt	0000008543	0.4
0000008540.prt	0000008540	0.3
0000008541.prt	0000008541	0.3
0000011171.asm	0000011171.ASM	0.6
0000011173.prt	0000011173	0.7
0000011175.prt	0000011175	0.2
0000011202.prt	0000011202	0.2
0000011201.prt	0000011201	0.2
0000014764.prt	0000014764	0.4
0000011780.prt	0000011780	0.4
shcs_m10_1_5_80l_ti_5.prt	SHCS_M10_1_5_80L_TI_5	1.2
0000011294.asm	0000011294.ASM	0.8
0000011292.prt	0000011292.PRT	0.4
0000011293.prt	0000011293.PRT	0.3
0000011290.prt	0000011290.PRT	0.3
Continued on next page		

Table 2 – Continued from previous page

File Name	Number	Version
0000011243.prt	0000011243.PRT	0.6
0000011245.prt	0000011245.PRT	0.5
0000011619.prt	0000011619.PRT	0.5
0000011621.prt	0000011621.PRT	0.5
0000011246.prt	0000011246.PRT	0.6
np_tail_inner.prt	NP_TAIL_INNER	0.7
0000011237.prt	0000011237.PRT	0.4
0000011302.prt	0000011302.PRT	0.5
0000011308.prt	0000011308.PRT	0.3
0000011620.prt	0000011620.PRT	0.4
0000011624.prt	0000011624.PRT	0.2
0000011638.prt	0000011638.PRT	0.3
0000011618.prt	0000011618.PRT	0.2
0000011648.prt	0000011648.PRT	0.2
0000011633.prt	0000011633.PRT	0.2

Table 3. Windchill CAD configuration used for analyses. Downloaded on 30 September 2025 from master assembly 0000002985.asm "SHAFT, LOWER BODY WELDMENT".

File Name	Number	Version
0000002985.asm	0000002985.ASM	0.5
0000005126.prt	0000005126.PRT	0.2
0000004931.prt	0000004931.PRT	0.1
0000004933.prt	0000004933.PRT	0.1
0000017290.prt	0000017290.PRT	0.1
0000017312.prt	0000017312.PRT	0.1
0000002982.prt	0000002982.PRT	0.1
0000002981.prt	0000002981.PRT	0.2
0000002850.prt	0000002850.PRT	0.2
0000017319.prt	0000017319.PRT	0.1
0000002983.prt	0000002983.PRT	0.4
0000002984.prt	0000002984.PRT	0.6
0000004934.prt	0000004934.PRT	0.1
0000004932.prt	0000004932.PRT	0.1
0000004935.prt	0000004935.PRT	0.1
0000005038.prt	0000005038.PRT	0.3
0000010842.prt	0000010842.PRT	0.4
0000010845.prt	0000010845.PRT	0.4
0000014226.prt	0000014226	0.4
0000019397.prt	0000019397.PRT	0.2

The CAD geometry of the target segment used for these analyses was downloaded from the Windchill product lifecycle management (PLM) on 22 August 2025 with the version control as listed in Table 2. The CAD geometry of the shaft assembly used for these analyses was downloaded from the Windchill PLM on 30 September 2025 with the version control as listed in Table 3. The following gross modifications were made:

- Z-plane slice, keeping the negative-z half
- cut stave at 100 mm above target
- combine all tantalum volumes
- pin body joined with pin cap and keyway removed
- shaft ring feature sliced to 1/20 and cooling channels filled
- cooling pipe joined to heel structure
- heel flow manifold region cut as separate volume (to aid meshing)
- heel flow channel weld caps joined to heel
- entire shaft assembly removed except for one ring slot

Figure 2 shows the STS_WORLD_CENTER origin (located conceptually at the peak neutron production location). Figure 21 shows the analysis CAD model with the origin located at the center of shaft rotation. The center of shaft rotation is defined as a 483-mm shift from STS_WORLD_CENTER in the +x direction. Figure 22 shows the analysis CAD model in more detail. Figure 23 and Figure 24 show the quarter symmetry CAD model used for manufacturing simulations of the target foot package.

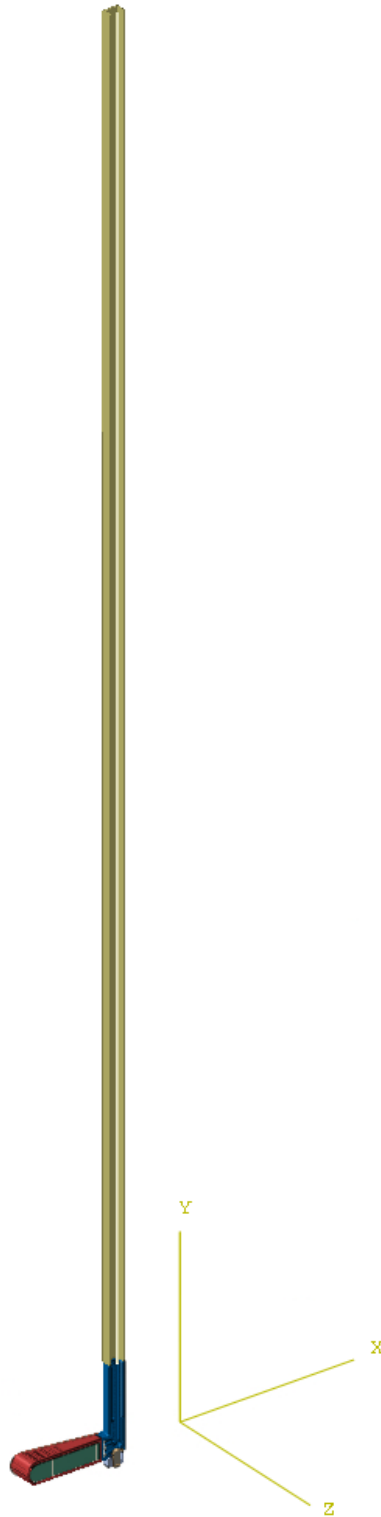


Figure 21. CAD model of analyzed domain in half symmetry. The model origin is located at the center of the rotating shaft. Only the bottom 100-mm of the stave, called the heel, is modeled directly. The remainder of the stave is approximated as a beam element with matching cross section as shown.

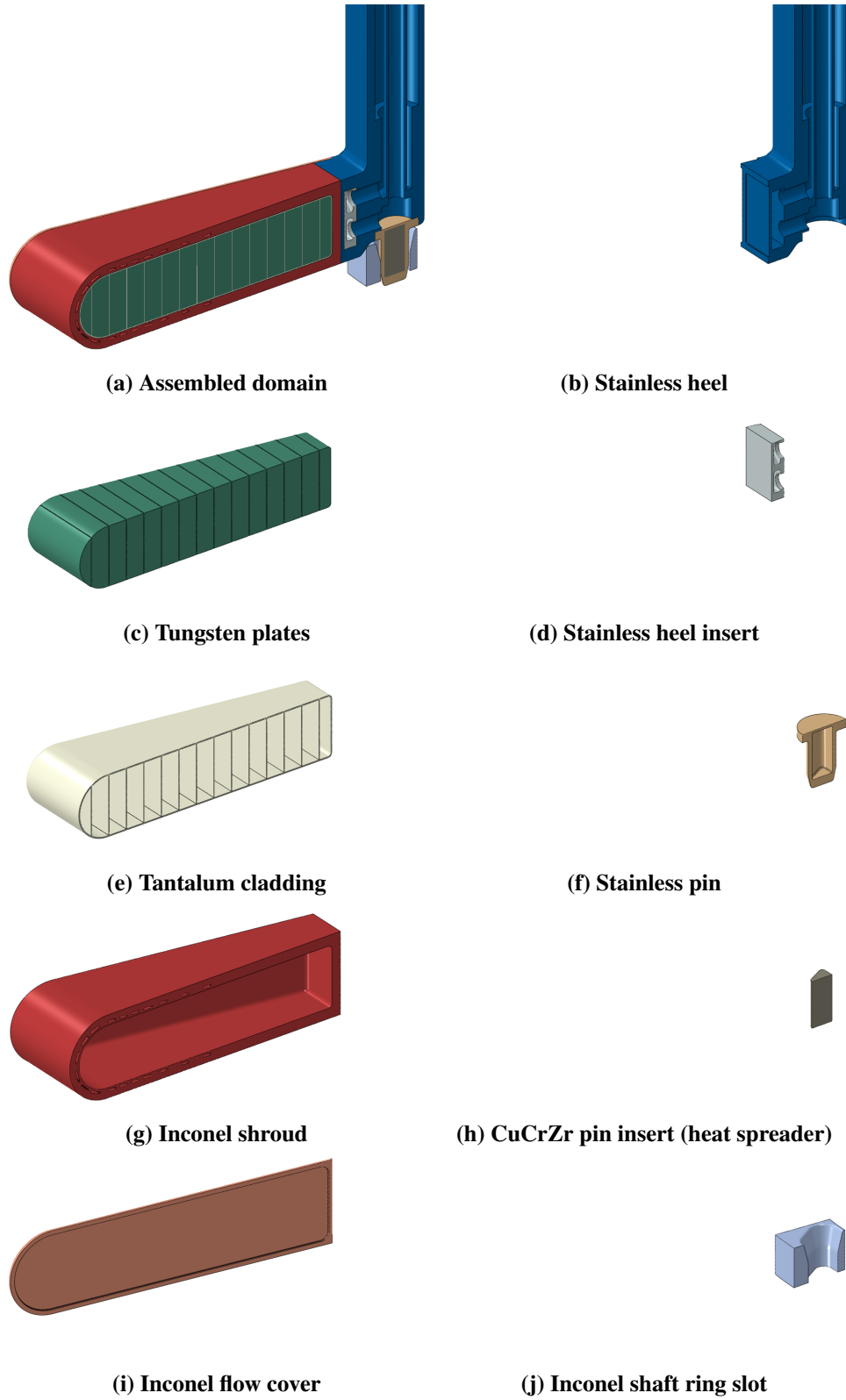


Figure 22. Call-out of every volume in the half-symmetry analysis domain. Note that the stainless heel insert is not a physically-separate part but is separated for meshing purposes only.

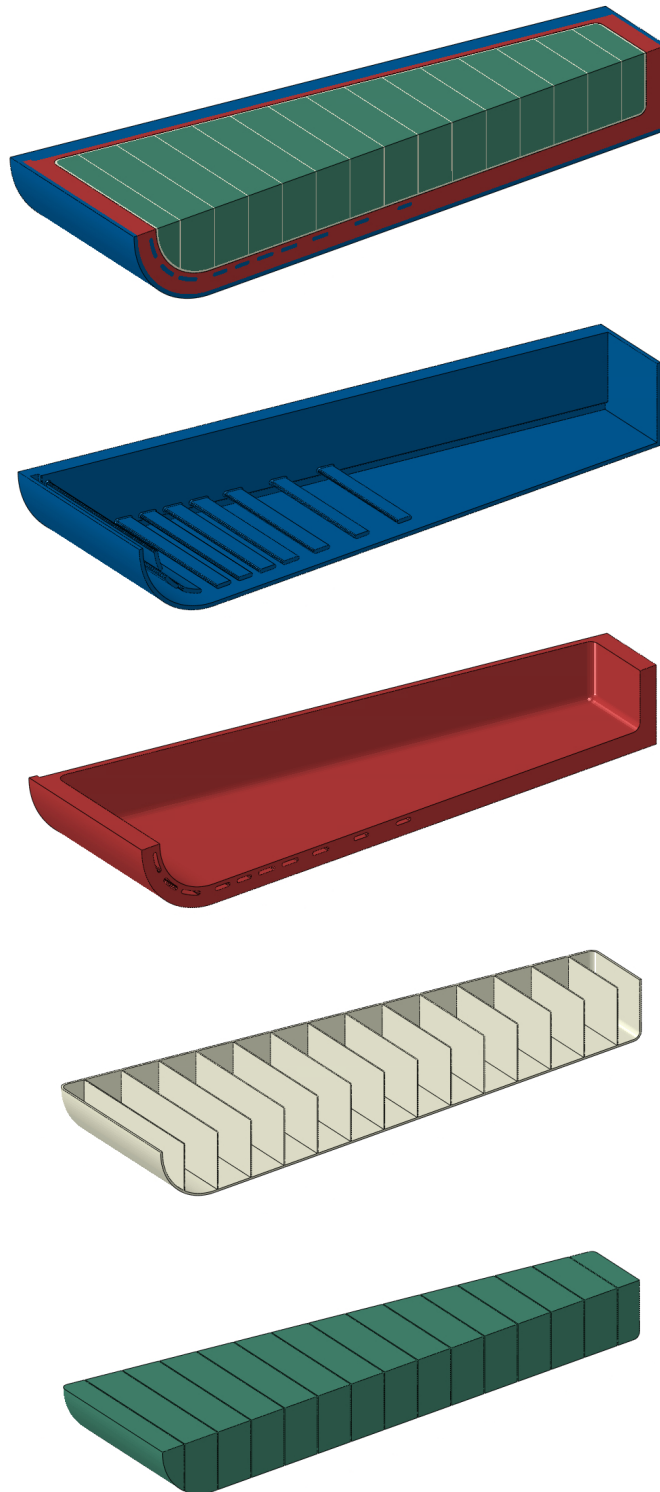


Figure 23. Call-out of every volume in the quarter-symmetry manufacturing analysis domain. From top down: assembled domain; machined-away Inconel including water passages; Inconel shroud after machining; tantalum cladding; tungsten plates.

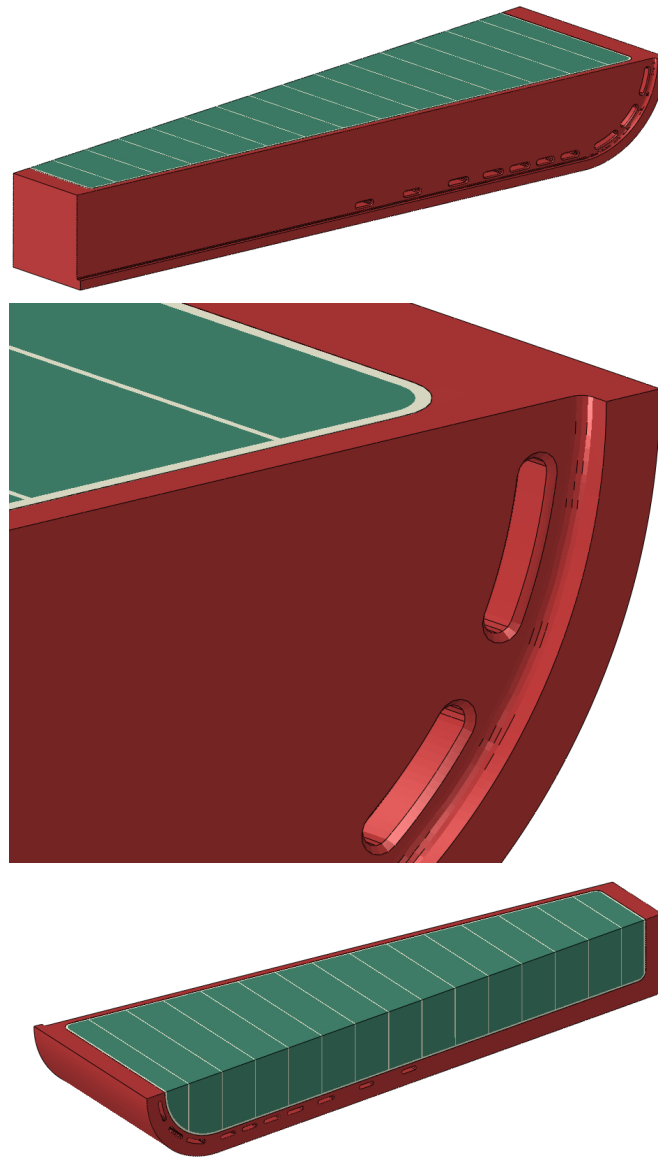


Figure 24. Detailed views of the target foot after HIP manufacturing and machining operations. Cooling passageways are shown including chamfers and radii.

3.2 MATERIAL PROPERTIES

Material properties, including fatigue properties and models, are fully-documented in the "Target Systems Materials Library" [16]. This section provides a high-level summary of the material properties used in this DAC.

The analyses in this DAC use the so-called WOL combination. This conservatively assumes the 10 years of beam pulses are applied to a target with full residual stresses from manufacturing (i.e. no irradiation induced stress relaxation) and with irradiated material properties (i.e. tungsten irradiated thermal conductivity).

3.2.1 Thermostructural Properties

Table 4. Material models used for WOL thermostructural simulations in Abaqus.

Object	Material	Model
Tungsten Plates	W	Thermoelastic
Tantalum Cladding	Tantalum	Thermoelastic-Plastic with Creep
Pin Insert	Cu_OFE	Thermoelastic-Plastic
Shroud, Cover, & Shaft Ring	IN718SA	Thermoelastic-Plastic with Creep
Heel, Pin, & Stave	SS316L	Thermoelastic-Plastic

Table 4 identifies the material name and model type used for each object in the analysis. The material names correspond to the Abaqus material model file `abq_FDR_matls.inp` documented in the "Target Systems Materials Library" Appendix [16]. This document should be referenced for detailed descriptions of each material. A summary description of each model is provided as follows.

The tungsten plates are modeled with a thermoelastic material model. It has a constant density. The modulus of elasticity, Poisson's ratio, and coefficient of thermal expansion are all functions of temperature. The effect of irradiated thermal conductivity is only manifest in the heat transfer modeling which is captured in a separate DAC [15].

The tantalum cladding is modeled with a thermoelastic-plastic material model. It has a constant density and constant Poisson's ratio. The modulus of elasticity and coefficient of thermal expansion are functions of temperature. Plastic flow curves with isotropic hardening are interpolated from a table of true stress, true plastic strain, and temperature. This table was generated from an empirical Johnson-Cook constitutive model with a fixed 0.001/s strain rate. A double power law creep model is included for the HIP manufacturing simulations.

The copper pin insert is not intended to be a structural material and is present to act as a heat spreader in the associated heat transfer modeling. In the present analysis, it is modeled by a thermoelastic-plastic material model for oxygen-free copper. This model was already available, having been previously developed when pure copper was considered as a cladding material. This is much softer than the specified CuCrZr material and is therefore conservative for the structural analyses.

The shroud, flow cover, and shaft slot structures are all solution-annealed Inconel 718 which is modeled with a thermoelastic-plastic material model. It has a constant density and constant Poisson's ratio. The modulus of elasticity and coefficient of thermal expansion are functions of temperature. Plastic flow curves with isotropic hardening are interpolated from a table of true stress, true plastic strain, and temperature. This table was generated from the addition of a yield stress and plastic hardening function. The yield stress function is based on a grain dislocation physics model. The plastic hardening function is based on a modified Voce law as part of the Mechanical Threshold Stress (MTS) model. A hyperbolic law creep model is included for the HIP manufacturing simulations.

The heel, pin, and stave structures are all 316L stainless steel which is modeled with a thermoelastic-plastic material model. It has a constant density and constant Poisson's ratio. The modulus of elasticity and coefficient of thermal expansion are functions of temperature. Plastic flow curves with isotropic hardening are interpolated from a table of true stress, true plastic strain, and temperature. All data comes directly from the ASME/BPVC.

3.2.2 Fatigue Properties

Only tungsten, Inconel, and stainless steel are considered for fatigue analyses. Inconel and stainless steel are the true structural materials of the target. Tungsten is also analyzed for historical reasons (as it is usually a structural material), and out of a desire to keep the spallation material, well-defined. (For context, the brittle nature of tungsten led to the design choice of encasing the spallation package with structural Inconel.) Per the design requirements, all fatigue curves are based on the mean life. The fatigue models and properties used in the *fe-safe* fatigue analyses are fully documented (including references) in the "Target Systems Materials Library" [16] and are summarized below for convenience.

Tungsten

Tungsten will be well below the Ductile-to-Brittle Transition Temperature (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).

Tungsten uses the Basquin HCF model shown in Equation 12,

$$\sigma_n = K_{irr} \sigma'_f (2N_f)^b \quad (12)$$

where the constants are listed in Equation 13 as:

$$\begin{aligned} K_{irr} &= 0.53 \\ \sigma'_f &= 677 \text{ MPa} \\ b &= -0.041508 \end{aligned} \quad (13)$$

Here, the effects of irradiation are accounted for as a knockdown factor (K_{irr}). The fatigue strength coefficient (σ'_f) is the fatigue strength for one half cycle and approximately represents the ultimate tensile strength (UTS) of the material. It is chosen to match the weakest direction strength for 10-20 mm tungsten plate. Table 5 lists the important fatigue parameters in the *fe-safe* material definition.

Type 316L Stainless Steel

The best source of fatigue data for SS316L comes from a U.S. Nuclear Regulatory Commission (NUREG) sponsored study in the early 2000s that was then used to update the ASME/BPVC fatigue curve. In air, at temperatures up to 400°C, the mean fatigue life for austenitic stainless steels (e.g. SS304L, SS316L, SS316NG) is best represented by Equation 14,

$$\ln(N) = 6.891 - 1.920 \ln(\epsilon_a - 0.112) \quad (14)$$

where ϵ_a is the percent applied strain amplitude.

The present study seeks to design around the mean life curves. Also, the 10 year design life dictates a HCF regime that is predominantly elastic. Accordingly, the SS316L fatigue curve uses the mean fatigue curve

Table 5. Tungsten fatigue model settings in *fe-safe* software.

Parameter Name	Value	Comment
fatigue strength coefficient (sf')	356 MPa	$K_{irr} \cdot \sigma'_f$ for 10-20mm plate
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	356 MPa	assume $\sigma'_f = \sigma_{UTS}$
ultimate compressive strength	356 MPa	Assume same as UTS
algorithm	NormalStress:-Goodman	Brittle failure mode

given in Equation 15, where σ_a/E is substituted for the applied strain amplitude. Equation 15 can then be used to solve for a fatigue life (N) for a given fully-reversing stress amplitude (σ_a).

$$\ln(N) = 6.891 - 1.920 \ln\left(\frac{\sigma_a}{E} - 0.112\right) \quad (15)$$

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." [4, 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." [3, p. 7-19] Table 6 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.

Table 6. Type 316L stainless steel fatigue model settings in *fe-safe* software.

Parameter Name	Value	Comment
stress -life table enabled	true	
sample series	<i>varies</i>	22 points logspaced from 1.0E+6 to 1.0E+11
control series	<i>varies</i>	Equation 15 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

Inconel 718 (Solution Annealed)

A literature search was conducted to create a custom fatigue curve for Inconel 718 in the solution annealed condition (as opposed to the more conventional precipitation hardened condition). The mean-life fatigue curve was fit to the Basquin HCF model shown in Equation 16.

$$\begin{aligned}\sigma_a &= K_{grain} \sigma'_f (2N_f)^b \\ \text{where } K_{grain} &= 0.72 \\ \sigma'_f &= 657.16 \text{ MPa} \\ b &= -0.019635\end{aligned}\tag{16}$$

Here, the effects of grain size are accounted for as a knockdown factor (K_{grain}). As with the stainless steel 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." [4, 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." [3, 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. Table 7 lists the important fatigue parameters in the *fe-safe* material definition.

Table 7. 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

IN718SA Welds

The Goodman diagram accounts for mean stress effects on fatigue life as a function of the fully-reversing fatigue strength and the material UTS. For Inconel welds, tensile tests of as-welded Inconel Filler Metal 718 are compared against annealed bar/round stock of Inconel 718 indicating a 10% reduction in UTS. Furthermore, fatigue testing on welded plates of IN718 indicate a fatigue strength reduction factor of 1.424 when compared to the nominal material fatigue strength at 10^8 cycles. Both of these reductions are applied to the fatigue model for Inconel welds. Any further debits (i.e. due to weld inspectability) should also be considered.

3.3 LOADS

3.3.1 Manufacturing Thermal Processing

The target foot is manufactured according to a HIP process followed by machining. The HIP pressure and temperature profiles are specified in "Specification for Hot Isostatic Pressing of Second Target Station Target Material" [13]. Figure 25 shows the "recipe" that meets this specification and reflects actual performance during MK5 target R&D manufacturing. This is input as a tabulated amplitude to drive the temperature (via *TEMPERATURE) and pressure (via *DSLOAD) during HIP simulation in Abaqus.

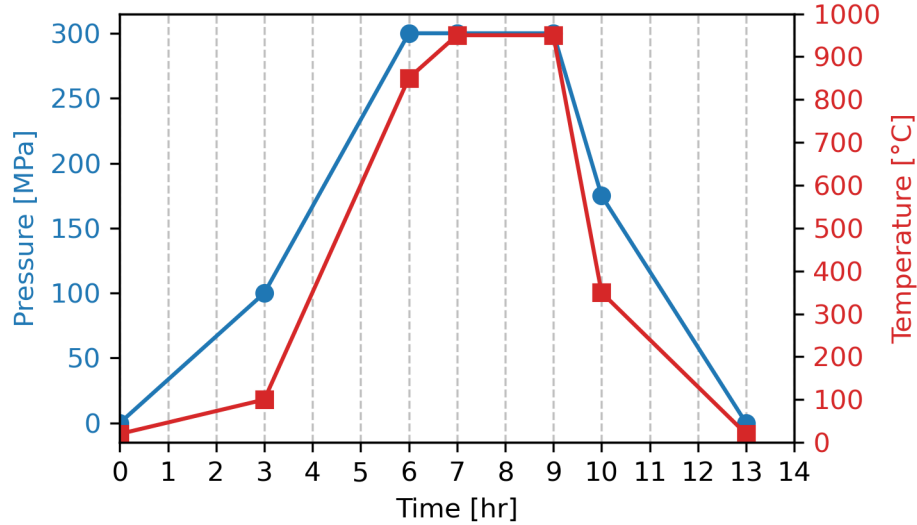


Figure 25. HIP recipe for target foot manufacturing.

3.3.2 Dead Load (*D*)

The ASME/BPVC considers this to be "Deadweight of the vessel, contents, and appurtenances at the location of interest." This is defined in the analyses (via *DLOAD with *GRAV option) as an acceleration of 9.81 m/s^2 in the negative y-direction. The water coolant mass is negligible and is not included.

3.3.3 Live Load (*L*)

The live load (*L*) is specified in the ASME/BPVC as "appurtenance live loading; effects of fluid momentum, steady state, and transient; and loads resulting from wave action." Since the target segment is a rotating component, the rotational loads are categorized as a live load. Fluid dynamic effects are judged to be negligible.

The target geometry consists of 20 segments, and the STS proton pulse rate is set at 15 Hz. To achieve one pulse per block, the target assembly must then rotate at 45 rpm or $1.5\pi \text{ rad/s}$. The corresponding angular velocity is shown in Equation 17.

$$\omega = \left(\frac{15 \text{ pulse}}{\text{sec}} \right) \left(\frac{1 \text{ rev}}{20 \text{ pulse}} \right) \left(\frac{2\pi \text{ rad}}{\text{rev}} \right) = 4.7124 \text{ rad/sec} \quad (17)$$

The dynamic pulse simulation requires an explicit transient analysis. In Abaqus/Explicit, the only way to implement a rotational load directly would be to rotate the entire target assembly in space. As an

approximation, the live load is simulated as a modification to the gravity body load (via *DLOAD with *GRAV option). The rotation arm is fixed at 483 mm. This is the location of STS_WORLD_CENTER with respect to the center of rotation of the shaft and serves as an approximation of the true center of gravity. The live load due to target rotation is then a constant acceleration as shown in Equation 18.

$$r\omega^2 = (0.483 \text{ m}) (4.7124 \text{ rad/sec})^2 = 10.7258 \text{ m/s}^2 \quad (18)$$

To incorporate this effect, the gravity acceleration is modified to have a magnitude of 14.5354 m/s² with components of -0.73791 and -0.6749 in the x- and y-directions, respectively, and according to the simulation coordinate system shown in Figure 21.

Aside from the fatigue analysis, the plastic collapse and local failure analyses are static implicit simulations. Abaqus|Standard (implicit) can incorporate the rotational load more directly via *DLOAD with the *CENTRIF option. The argument is the square of the angular velocity ($\omega^2 = 22.207 \text{ rad/s}^2$). This value can then be scaled according to the LRFD factors previously described.

3.3.4 Pressure Load (P , P_S , P_T)

The requirement for the cyclic fatigue analyses (Figure 12) directly specifies a water pressure load of 36 psia (248.211 kPa). This is the operating pressure and is applied to the surfaces of the cooling passages (via *DSLOAD) as illustrated in Figure 8.

For the plastic collapse and local failure analyses, the design pressure for the water coolant (P) is specified as 75 psia (517.107 kPa) in the interface document between the Target Assembly and Target Process Systems [6]. The design static head (P_S) from liquid on the target segment is conservatively chosen to be a uniform value equal to the hydrostatic head of a fluid column at the target foot. Figure 2 shows an elevation of 7.8 m which results in an 11.1 psi (76.5 kPa) hydrostatic head at the target foot. The pneumatic test pressure (P_T) is specified as 125 psia (862 kPa) in the interface document between the Target Assembly and Remote Handling systems [7].

3.3.5 Earthquake Loads (E)

The ASME/BPVC specifies earthquake loads (E) through ASCE SEI 7. This is captured in a separate calculation package which results in a horizontal seismic design acceleration of 0.652 g [2]. The direction of the horizontal load is not specified.

3.3.6 Neutronics Energy Deposition

Section 1.3 specifies the proton beam parameters for each load case. The corresponding neutronics analysis and output data are documented in a separate report in the Windchill PLM [9]. The data is supplied as a series of comma-separated value (CSV) files that list the XYZ coordinates of each data point along with the heat deposition in J/cc/pulse units. Each material in the analysis (e.g. Inconel, Stainless steel, CuCrZr, Tungsten, Tantalum) comes with 20 CSV files: one for each of the 20 target segment positions in a beam pulse. The mesh for each target segment is identical in element size and order. The XYZ coordinates are simply rotated about the target shaft. (In this manner, the cumulative effect of beam pulses on a single target segment as it rotates can be obtained by summing the energy deposition column of each data file, and this data can then be used to generate a time averaged rate of volumetric heat generation for computational fluid dynamics (CFD) analyses.)

Figure 26 shows the instantaneous temperature rise of a single beam pulse in a target segment for the nominal beam case. The neutronics data supplies energy deposition per beam pulse, E (J/cc/pulse). The energy

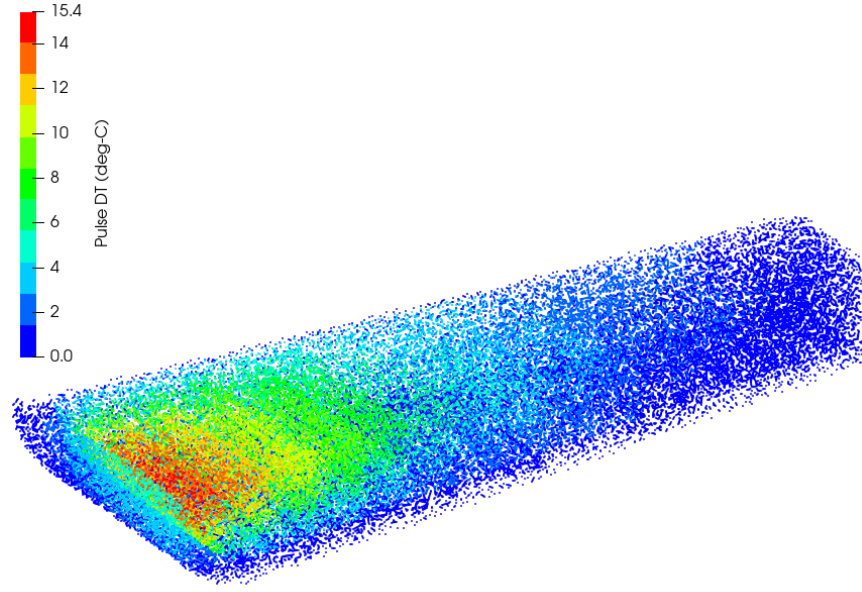


Figure 26. Energy deposition of a single proton beam pulse for nominal beam on a target segment, modeled as an instantaneous temperature rise. Units are degrees Celcius. Raw neutronics point cloud shown in quarter cut view for clarity.

deposition is divided by the thermal capacitance of the material to determine the instantaneous temperature rise (e.g. $\Delta T = E/(\rho \cdot c_p)$). The raw neutronics point cloud is shown in quarter cut view for better clarity.

The point cloud data must be interpolated onto the nodes created in the discretization (see Section 4.3). A custom Python code is used to perform this task. It uses the pyTetGen library to perform Delauney triangularization with a Barycentric interpolation for mesh nodes that have 4 surrounding data points. If a mesh node does not have 4 surrounding data points (e.g. surface nodes), then a 3 nearest-neighbor weighted algorithm from the scikit-learn library is used to interpolate. This code along with all scripts that were used for analyses in this report are archived with this DAC in the Windchill PLM.

Case A - Nominal Beam: The nominal case is given in Section 1.3 as a 60 cm^2 beam at 700 kW power and is aimed at the front center of the target. Figure 27 shows the beam after interpolation onto the Abaqus mesh and can be compared against the raw point cloud in Figure 26. In general there is very good agreement with the tungsten peak (i.e. the highest temperature region).

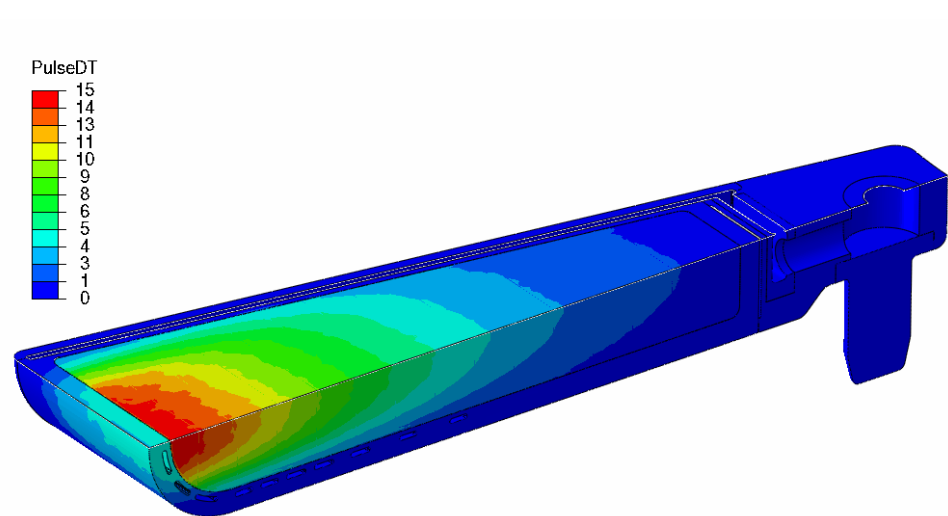


Figure 27. Nominal case instantaneous pulse temperature rise (with y-plane cut to show peak heating).

Case B - Nominal Corner Beam: The nominal corner case given in Section 1.3 takes the nominal beam and offsets it 8.5 mm vertically and 12 mm horizontally. This is shown in Figure 28 and Figure 29. It is assumed the thermostructural results for this corner case would be similar for the other 3 possible quadrants.

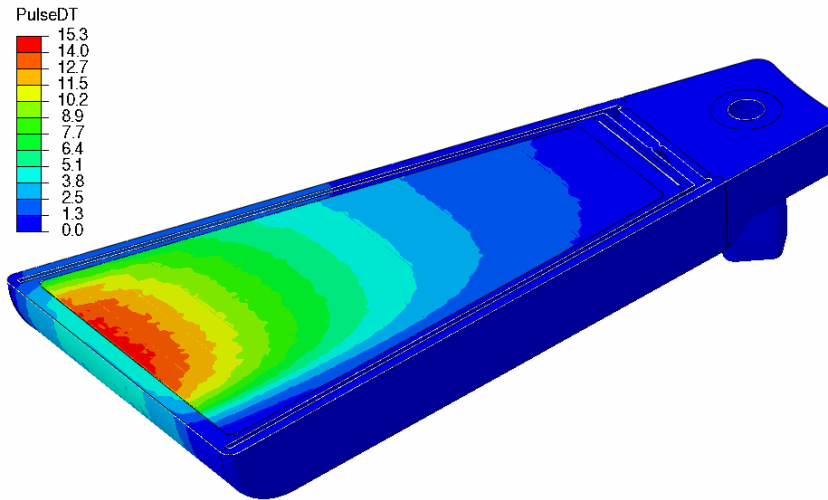


Figure 28. Nominal-Corner case instantaneous pulse temperature rise field. Showing midplane cut view to observe horizontal offset.

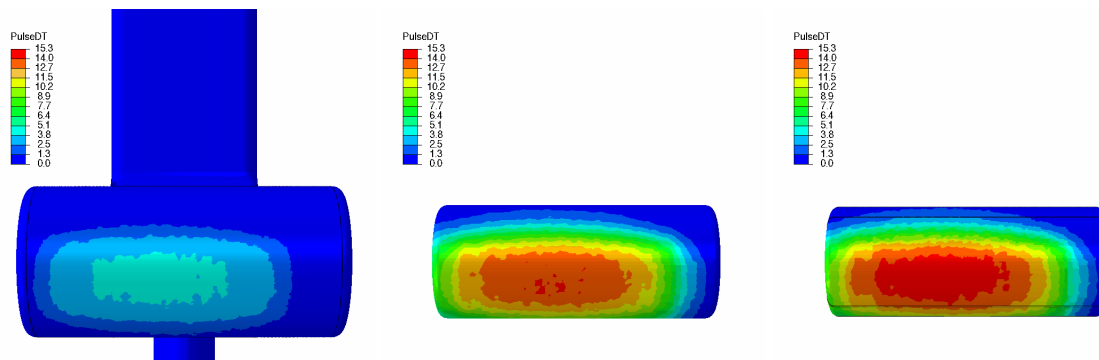


Figure 29. Nominal-Corner case instantaneous pulse temperature rise field. Showing beam path view to observe vertical and horizontal offset in (L-R) Inconel, tantalum, and tungsten.

Case C - Nominal Low Flow Beam: The nominal low-flow case given in Section 1.3 uses the nominal beam but reduces coolant flow rate to the target. The nominal beam pulse given in Figure 27 applies here.

Case D - Overfocused Beam: The overfocused case given in Section 1.3 has a 5% smaller beam area and a 2% higher beam power. As a result, the peak energy deposition for the focused beam increases by 5.8%. This is shown in Figure 30 where the peak instantaneous temperature rise increases by approximately 1°C (16°C peak) compared to the nominal case (15°C peak).

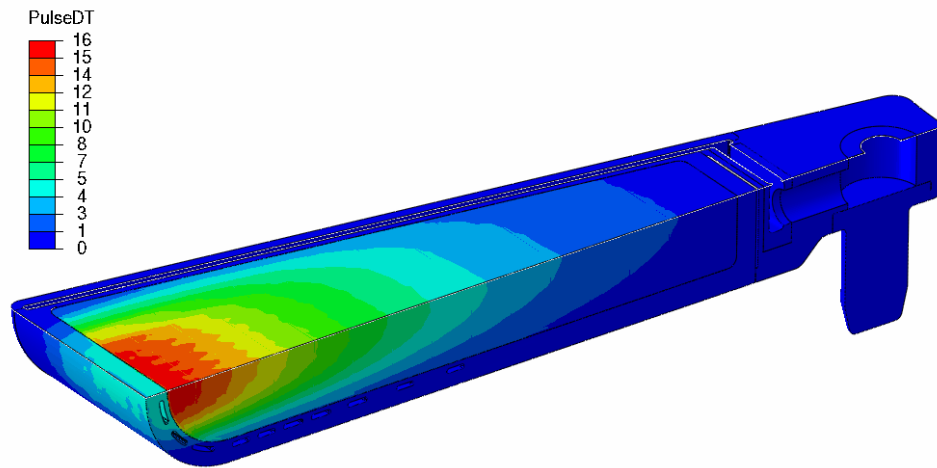


Figure 30. Overfocused case instantaneous pulse temperature rise (with y-plane cut to show peak heating).

Case E - Diffuse Beam: The diffuse case given in Section 1.3 has the same beam power as the nominal case but increases the area from 60 cm^2 to 94.5 cm^2 . This wider, less dense beam thus lowers the instantaneous temperature rise by approximately 4°C (11°C peak) compared to the nominal case (15°C peak) as shown in Figure 31.

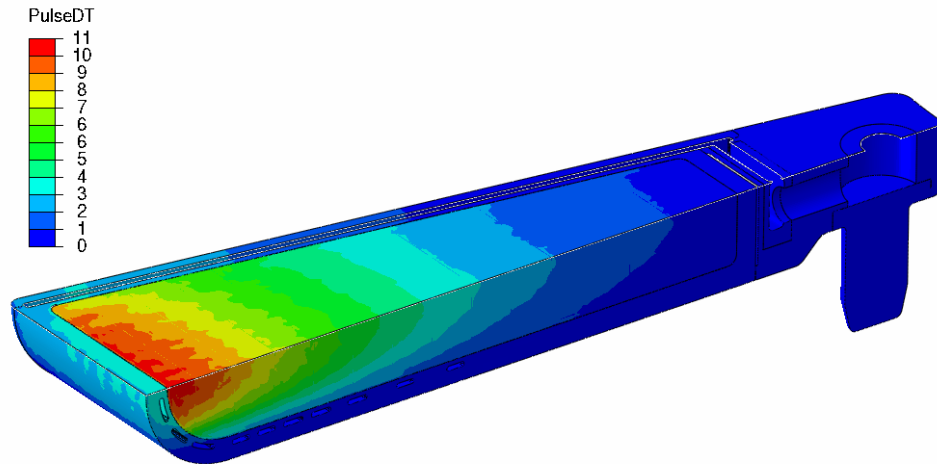


Figure 31. Diffuse case instantaneous pulse temperature rise (with y-plane cut to show peak heating).

3.3.7 Quasi-steady Thermal Field (T)

Figure 11 identifies the time scales present in the problem. Regime 3 represents the shortest timescale with significant stresses generated by the near-instantaneous temperature rise caused by a single proton beam pulse on the target. These loads are given in the previous section. The effects of regime 2 "transient" stress are deemed negligible.

Regime 1 represents the "quasi-steady-state" effects of time averaged beam loading. The proton beam energy deposition loads and water coolant flows are used to perform a steady thermo-fluid analysis of the target assembly. These analyses produce steady temperature fields for each of the analysis cases. The temperature fields are provided in CSV format, one file per material, and are documented in the "Target Assembly Thermo-Fluid Analysis" DAC [15]. The fields are interpolated onto the nodes created in the discretization using the custom Python script previously presented.

Case A - Nominal Beam: The point cloud for Case A Nominal Beam is shown in Figure 32. The interpolated field is able to capture the peak temperature as shown.

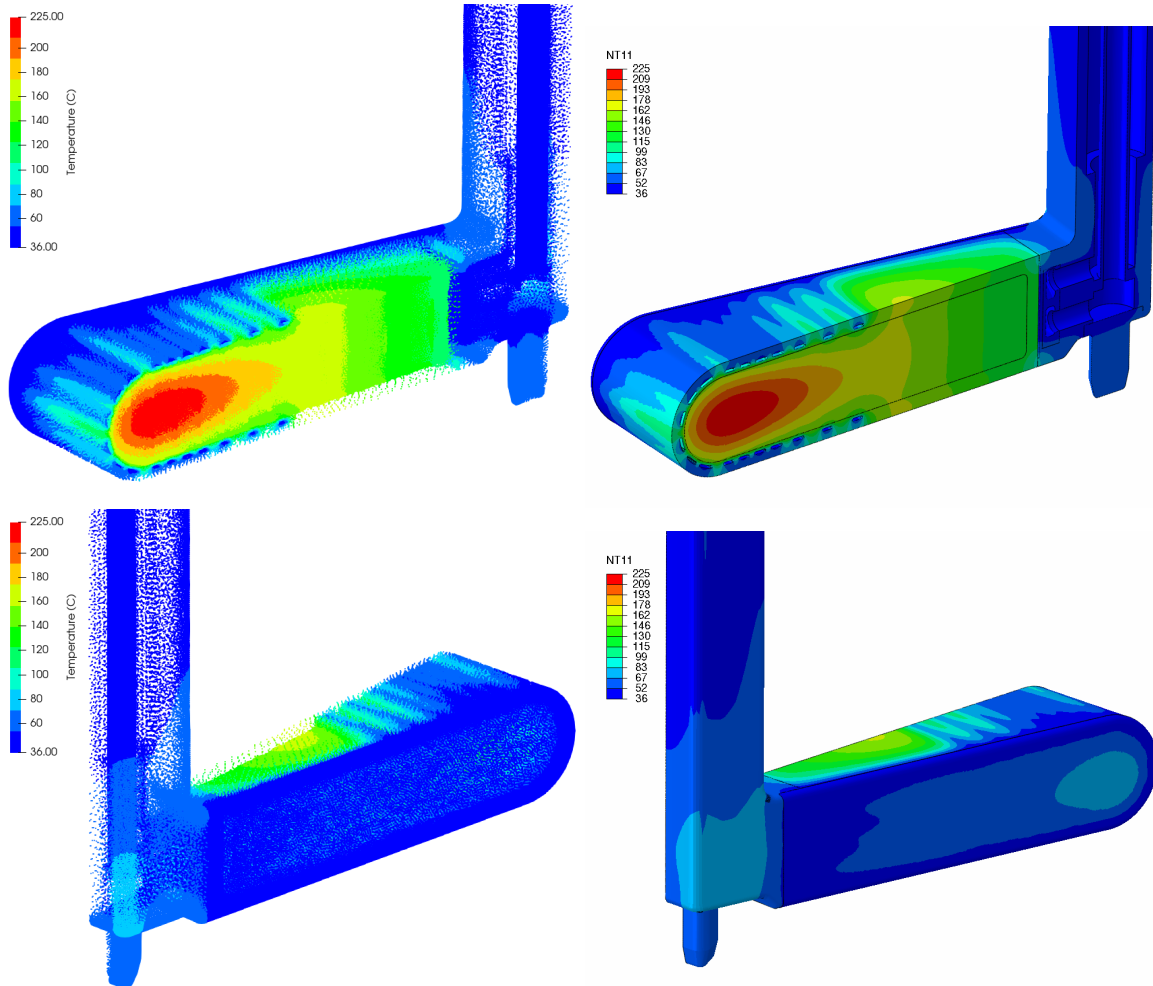


Figure 32. Comparisons between CFD point cloud (L) and interpolated field (R) for the nominal beam case.

Case B - Nominal Corner Beam: The offset beam case temperature field is shown in Figure 33 and Figure 34.

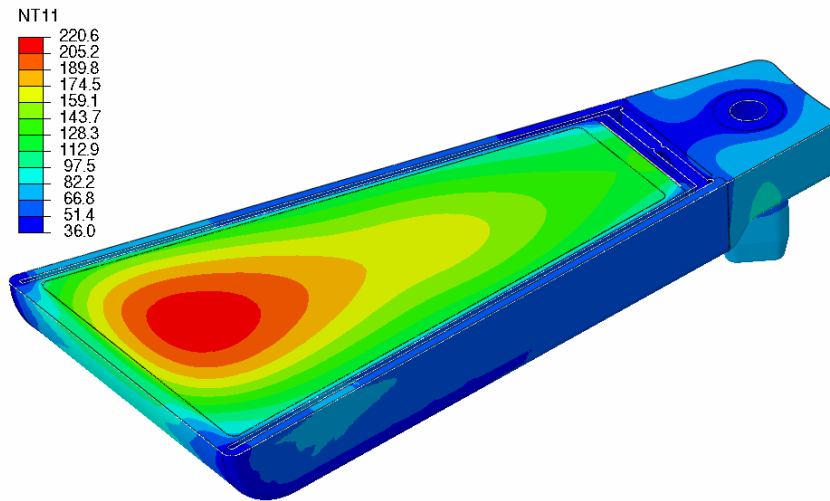


Figure 33. Nominal-Corner case steady-state temperature field. Showing midplane cut view to observe horizontal offset.

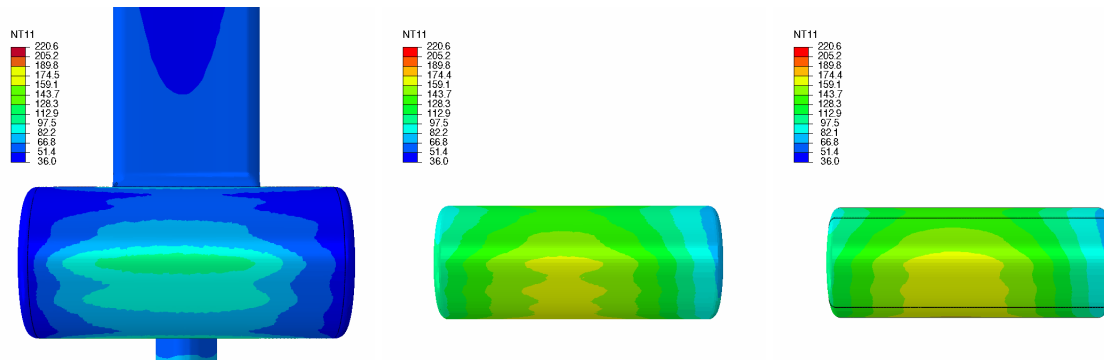


Figure 34. Nominal-Corner case steady-state temperature field. Showing beam path view to observe vertical and horizontal offset in (L-R) Inconel, tantalum, and tungsten.

Case C - Nominal Low Flow Beam: The low-flow case reduces coolant flow by almost 25% in the target. The beam pulse energy deposition remains the same while the peak steady-state temperature in the tungsten core increases from 225°C to 236°C (Figure 35).

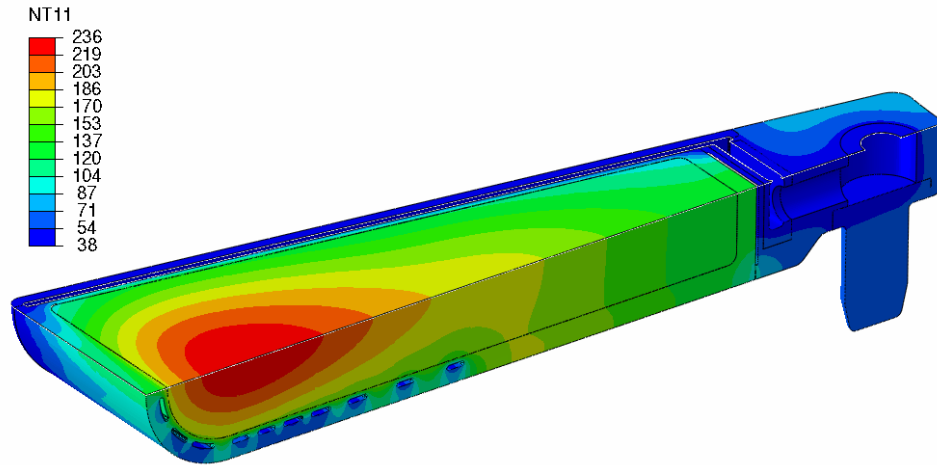


Figure 35. Nominal-Low Flow case steady-state temperature field.

Case D - Overfocused Beam: The overfocused beam case has a 5% smaller beam area and a 2% higher beam power. The peak energy deposition for the focused beam increases by 5.8%. The peak steady-state temperature in the tungsten core increases from 225°C to 234°C (Figure 36).

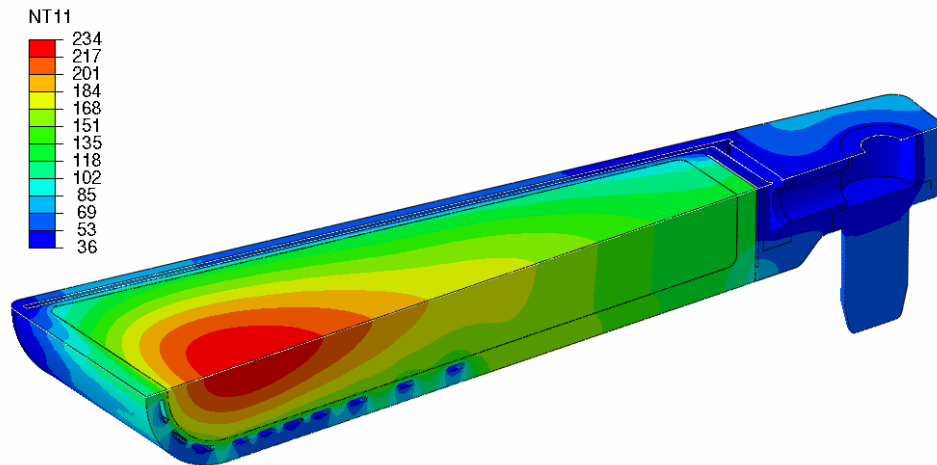


Figure 36. Overfocused case steady-state temperature field.

Case E - Diffuse Beam: The diffuse beam case uses a wider beam, less dense beam. The temperature and pulse fields are accordingly lower and more spread-out (Figure 37). The peak steady-state temperature in the tungsten core decreases from 225°C to 182°C.

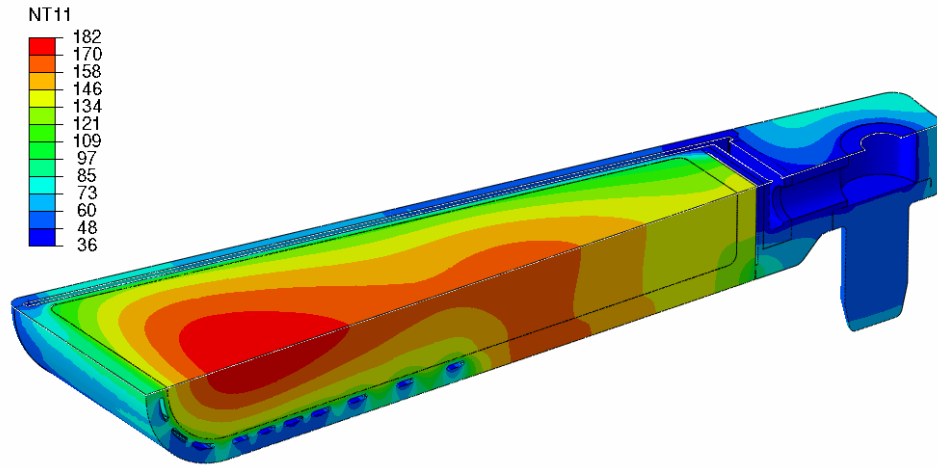


Figure 37. Diffuse case steady-state temperature field.

4. NUMERICAL SIMULATION

Abaqus FEA software is used to build the simulations necessary to analyze the target segment foot for analysis according to the load cases specified in Section 1.3. The full workflow was first developed for the fatigue analyses. Figure 38 uses a flowchart to identify the Abaqus simulation files and the manner in which information is transferred to perform each analysis. The sections that follow will further develop the components of this flowchart. At the end, the plastic collapse and local failure analysis cases will be presented as modifications of the fatigue workflow.

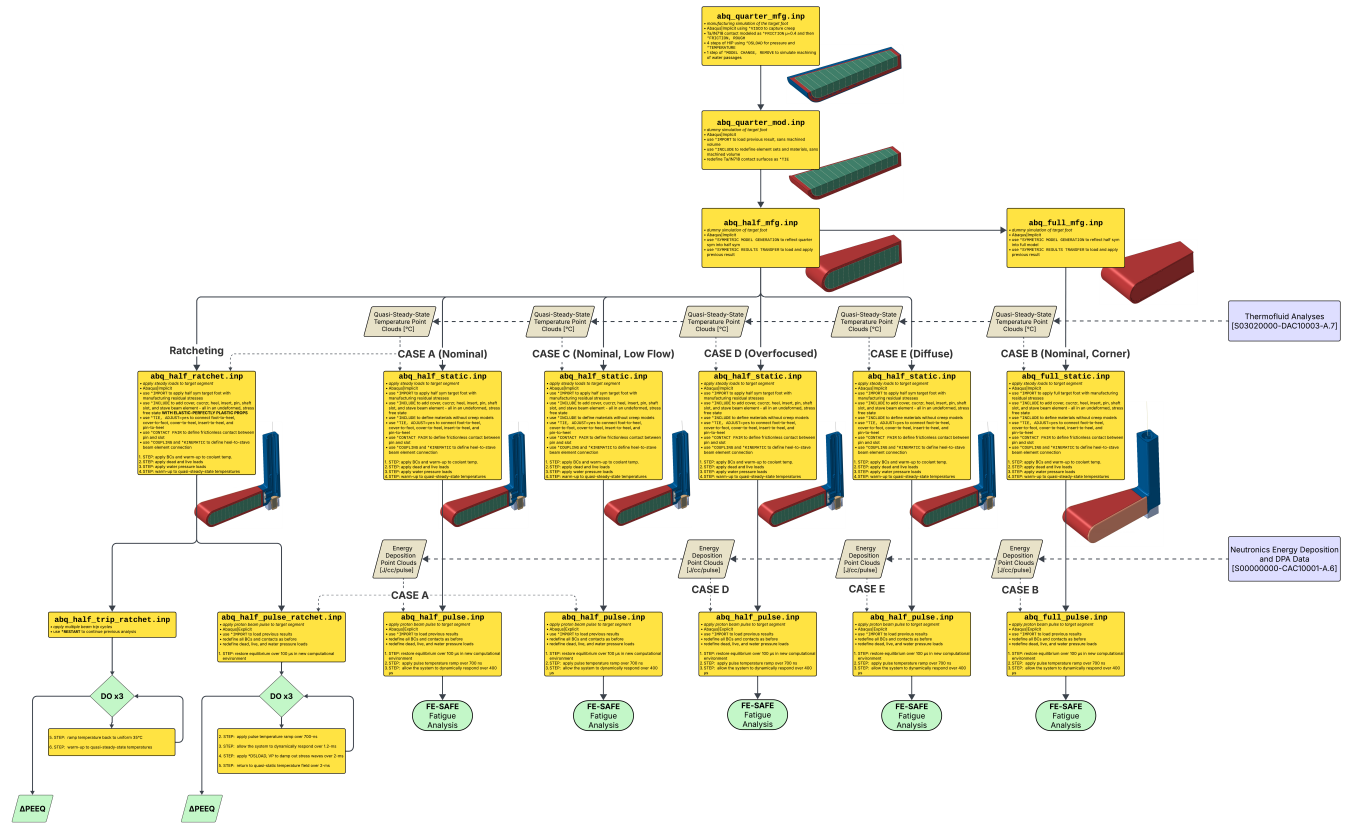


Figure 38. Flowchart of Abaqus analyses used for fatigue analysis of the target foot. (Larger version available in Appendix A.)

4.1 SOFTWARE

All analyses were performed on the BERNIE.sns.gov cluster with the Red Hat Enterprise Linux 8.10 (Ootpa) operating system. The cluster consists of 6 compute nodes. Each node has 64 processors (Intel Xeon CPU E5-2637 v2 @ 3.50GHz) and 768-GB memory.

Software used for meshing, data interpolation, and simulation includes:

- Abaqus 2025 BUILD ID: 2024_09_20-09.00.46 RELr427 198590
- fe-safe 2025[linux] Buildstamp: 2025 2439.3
- Cubit 17.02.2 Build 8d92fd222d (64 bit)

- Hypermesh 2025.1
- Python 3.9.19 with modules:
 - Numpy 2.0.2 (<https://numpy.org/>)
 - Pandas 2.2.3 (<https://pandas.pydata.org/>)
 - pyTetGen 0.2.2 (<https://pypi.org/project/pytetgen/>)
 - scikit-learn 1.5.2 (<https://scikit-learn.org/stable/>)

4.2 UNIT SYSTEM

All analyses use the standard MKS unit system. Length units are meters (m).

4.3 DISCRETIZATION

The CAD model is discretized into a mesh using hexahedron elements. Previous simulation studies with R&D prototypes revealed problems with tetrahedron (C3D10M) elements. High pressure contact regions along with high plasticity caused the quadratic elements to give erroneously high extrapolated stresses at nodes. Figure 39 shows a comparison of the Inconel contact surface for the Mark 1 R&D prototype simulation. The solution was to invest time into CAD geometry decomposition to generate a hex mesh. Hypermesh software was used for the target foot and Cubit software was used for the flow cover and heel. Linear reduced-order hex elements (C3D8R) were created with a nominal 1-mm size while also ensuring 2-3 elements spanned critical features (e.g. 2-mm thick tantalum cladding, 5-mm machined radii). It is important to note that Abaqus FEA software models the C3D8R elements with linear displacement, constant strain-stress basis functions, however, stress results are automatically extrapolated to the element nodes using a linear extrapolation function.

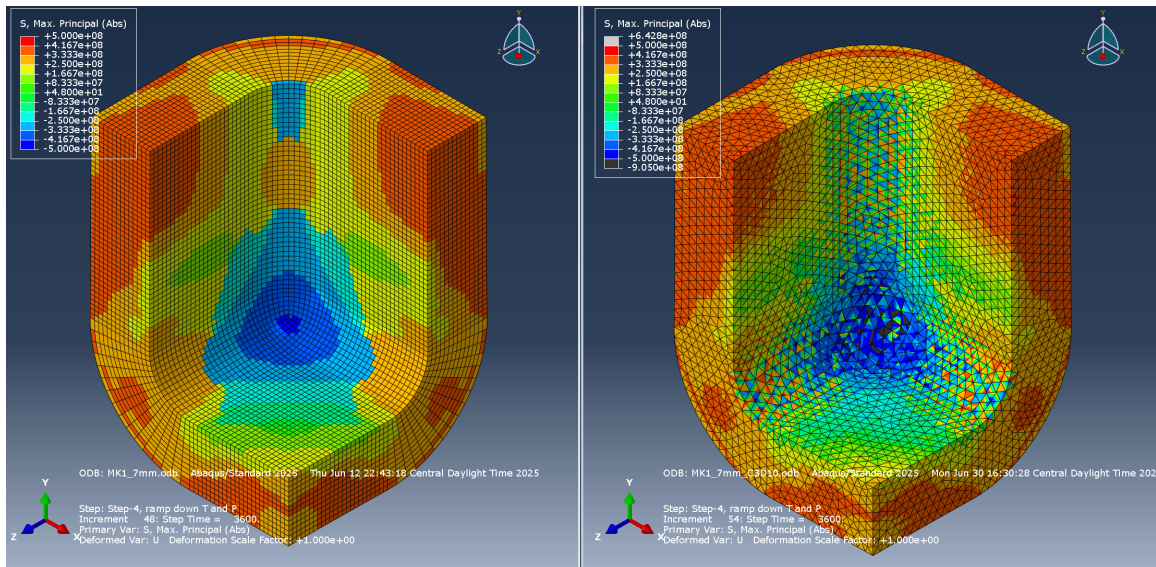


Figure 39. R&D simulation of the Inconel contact region of the Mark 1 prototype. The tetrahedral mesh (C3D10) clearly shows numerical and non-physical gradients, exacerbated by nodal extrapolations of stress using quadratic basis functions. The hexahedral mesh (C3D8R) avoids this situation completely and appears to smoothly capture stress gradients in the regions of contact.

Figure 40, Figure 43, and Figure 46 show detail views of the mesh for the target foot, flow cover, and heel regions respectively.

The "Scaled Jacobian" metric is used to judge mesh quality. The Jacobian ratio is an indication of how much the hex element deviates from the ideal shape. In Cubit, the scaled Jacobian is the minimum of the Jacobian divided by the 3 edge vectors. A value of 1.0 is the ideal shape, and a range of 0.5-1.0 is considered acceptable [8]. The figures below show the overall mesh quality and also elements with poorer quality. The poorer quality elements in general are (a) few and (b) in regions of less interest of the domain. The gross element summary is:

- **quarter sym target foot:** 1,151,128 total elements with 1,138 low quality
- **half sym target heel:** 754,948 total elements with 1,150 low quality
- **flow cover:** 284,816 total elements with 554 low quality

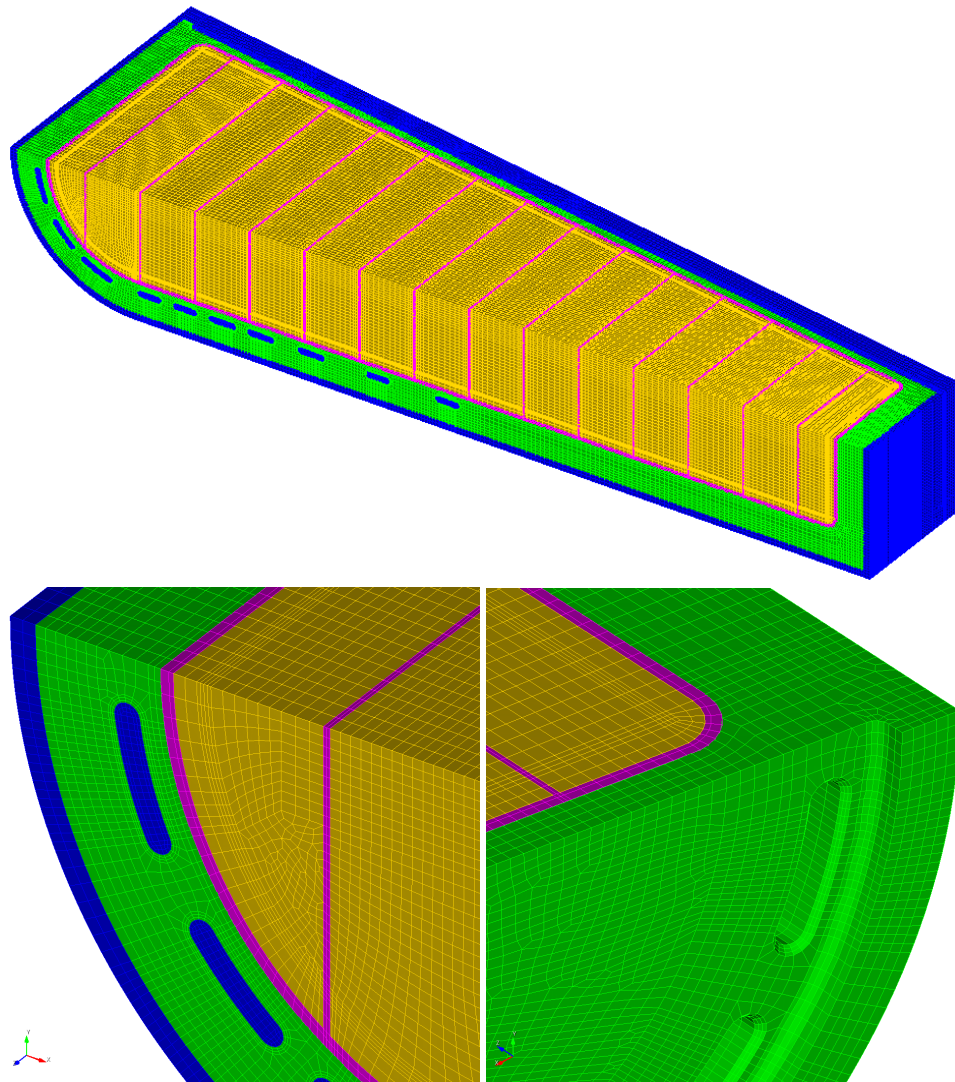


Figure 40. Detailed views of mesh for the quarter symmetry manufacturing model.

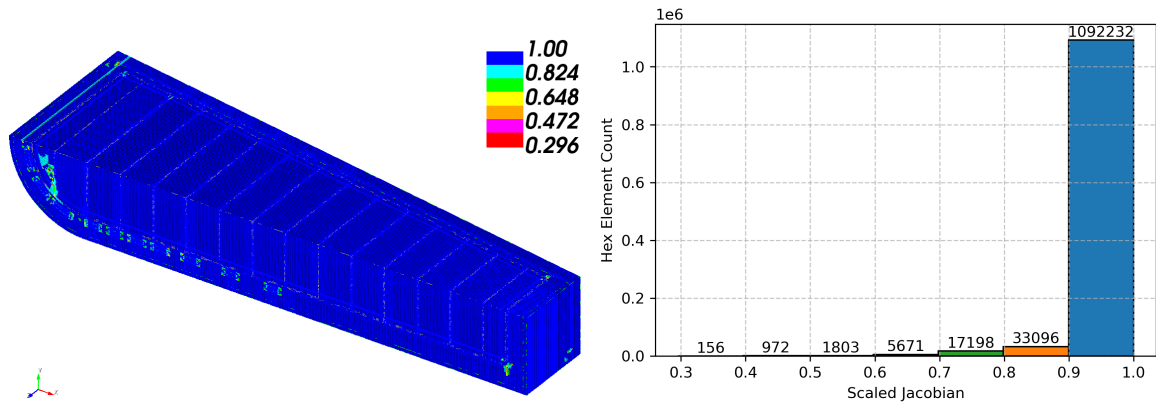


Figure 41. Scaled Jacobian mesh quality for the quarter symmetry manufacturing model.

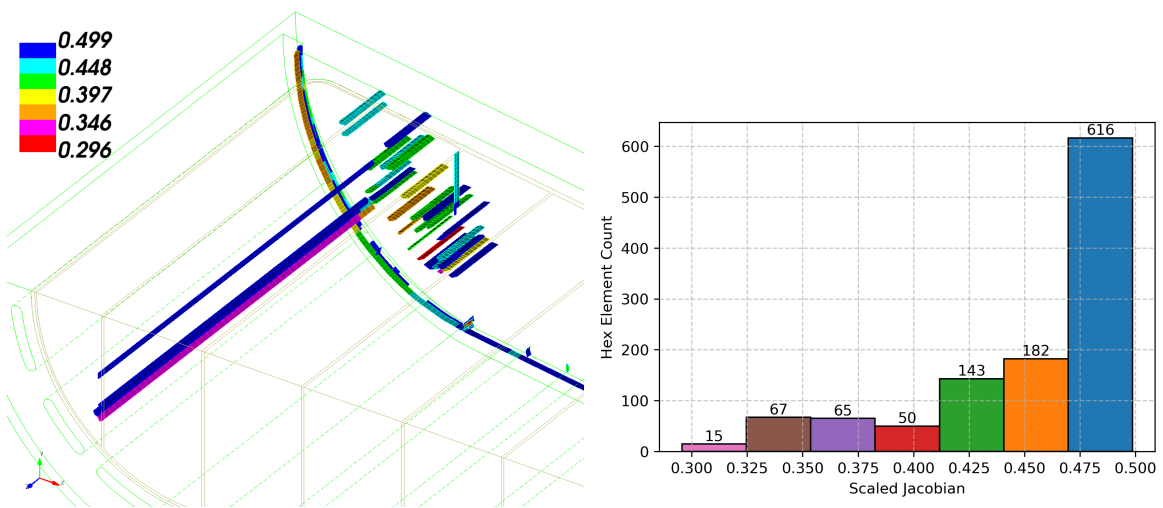


Figure 42. Regions of poorer mesh quality for the quarter symmetry manufacturing model.

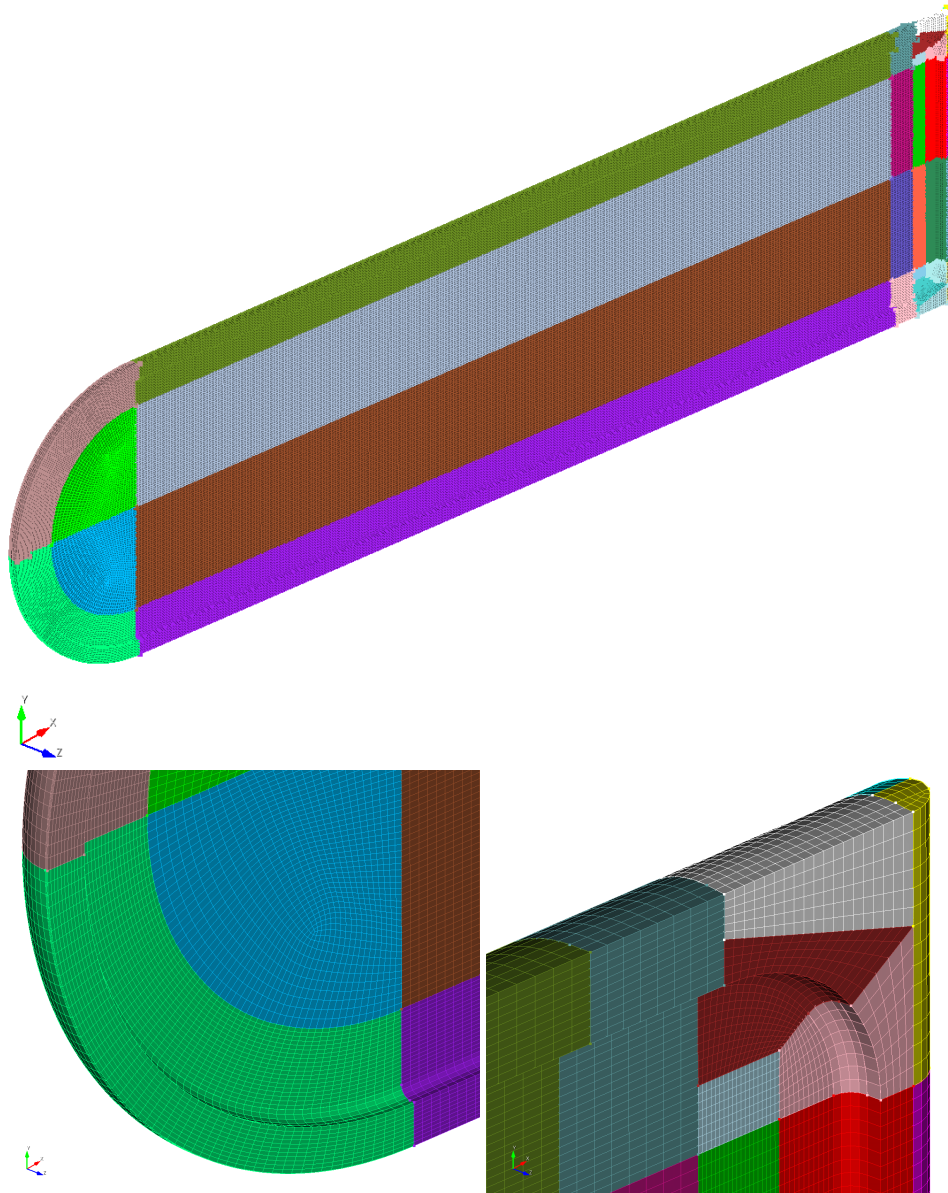


Figure 43. Detailed views of mesh for the flow cover model. (The domain has been sliced into connected regions to facilitate hex meshing.)

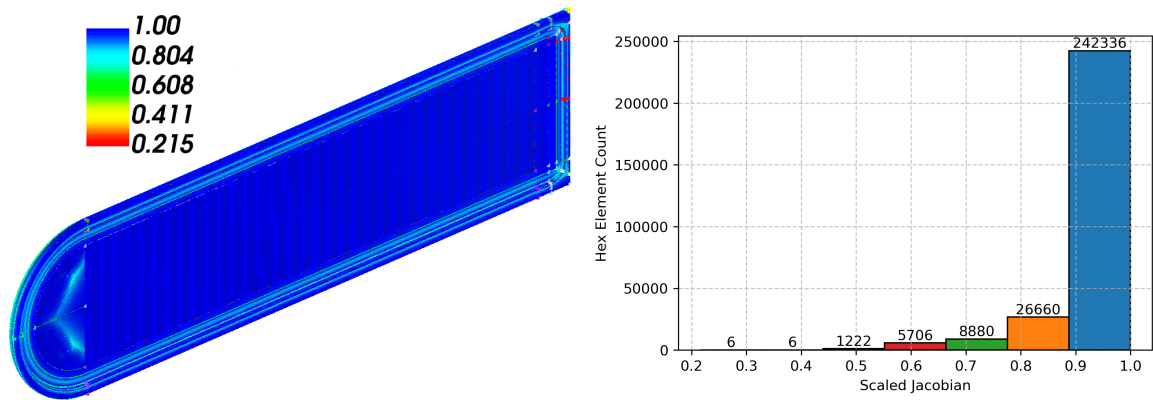


Figure 44. Scaled Jacobian mesh quality for the flow cover.

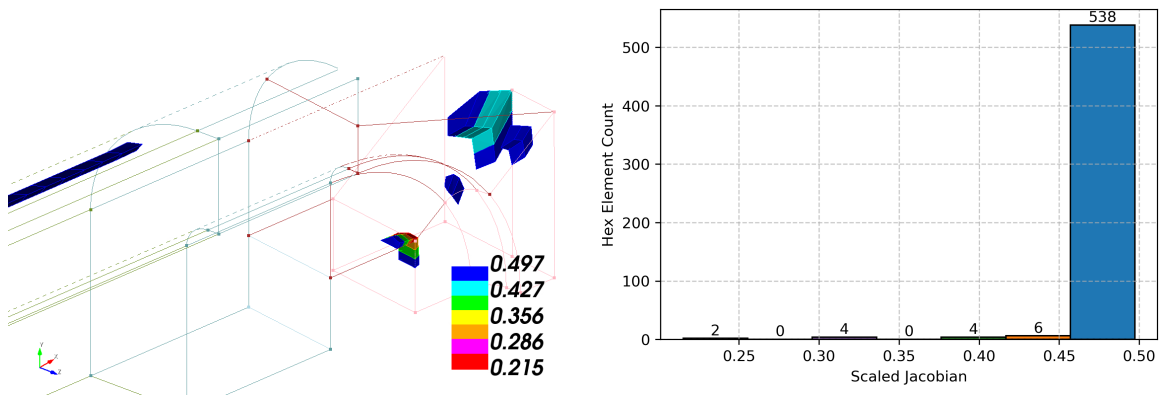


Figure 45. Regions of poorer mesh quality for the flow cover.

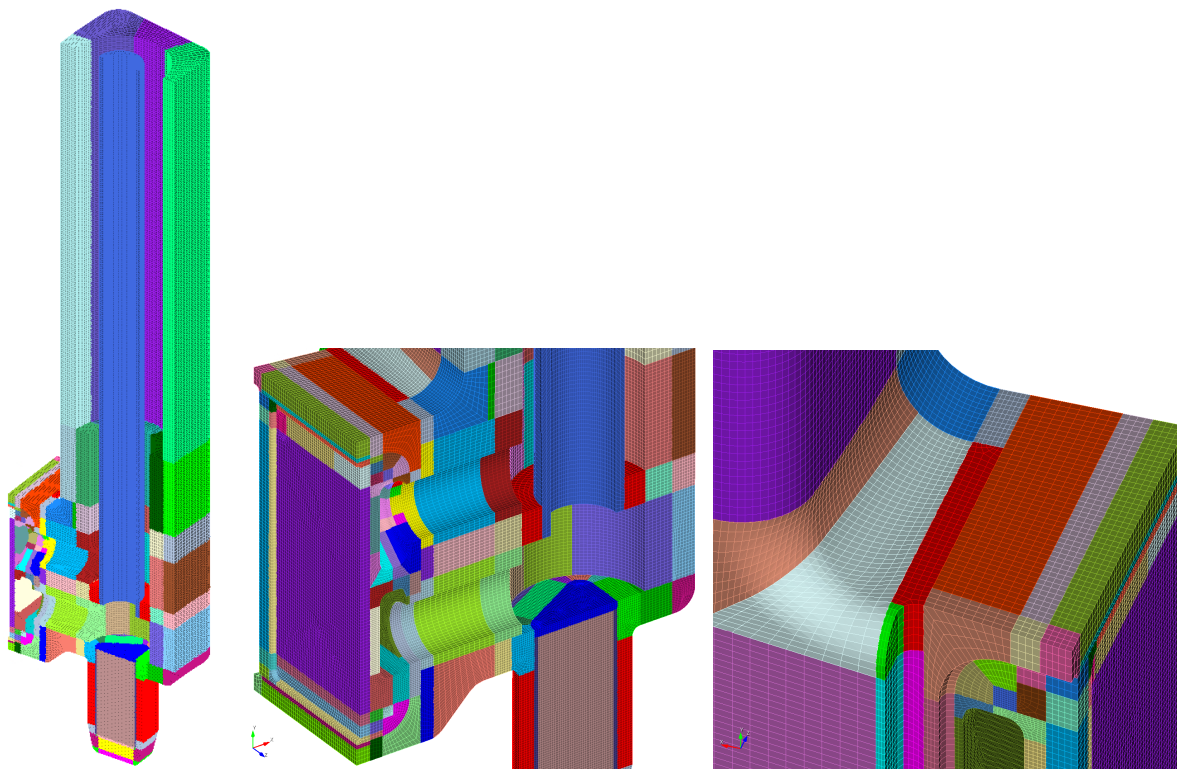


Figure 46. Detailed views of mesh for the heel. (The domain has been sliced into connected regions to facilitate hex meshing.)

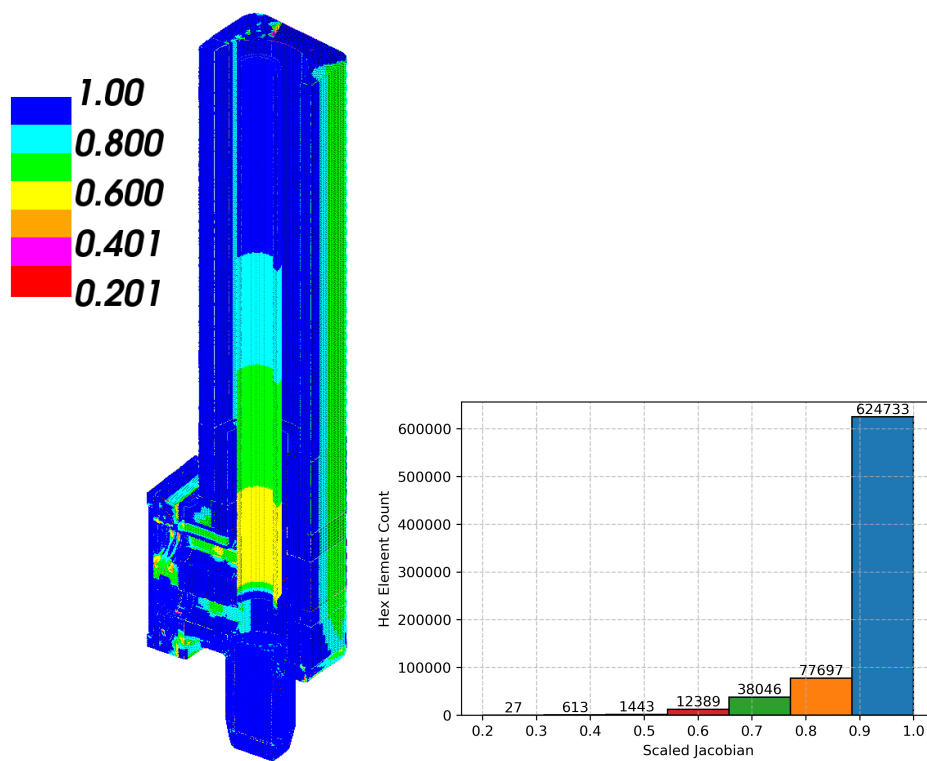


Figure 47. Scaled Jacobian mesh quality for the heel model.

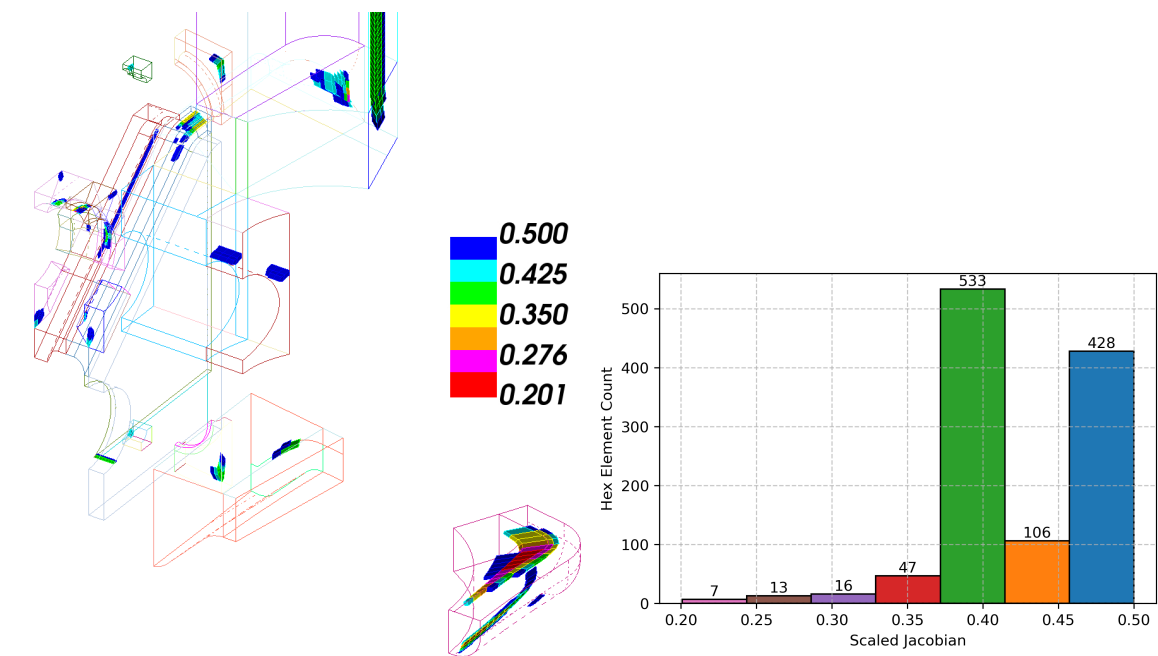


Figure 48. Regions of poorer mesh quality for the heel model.

4.4 MANUFACTURING SIMULATION

Figure 49 shows the portion of the flowchart that describes the manufacturing simulations of the target foot. The following sections explain each simulation in greater detail.

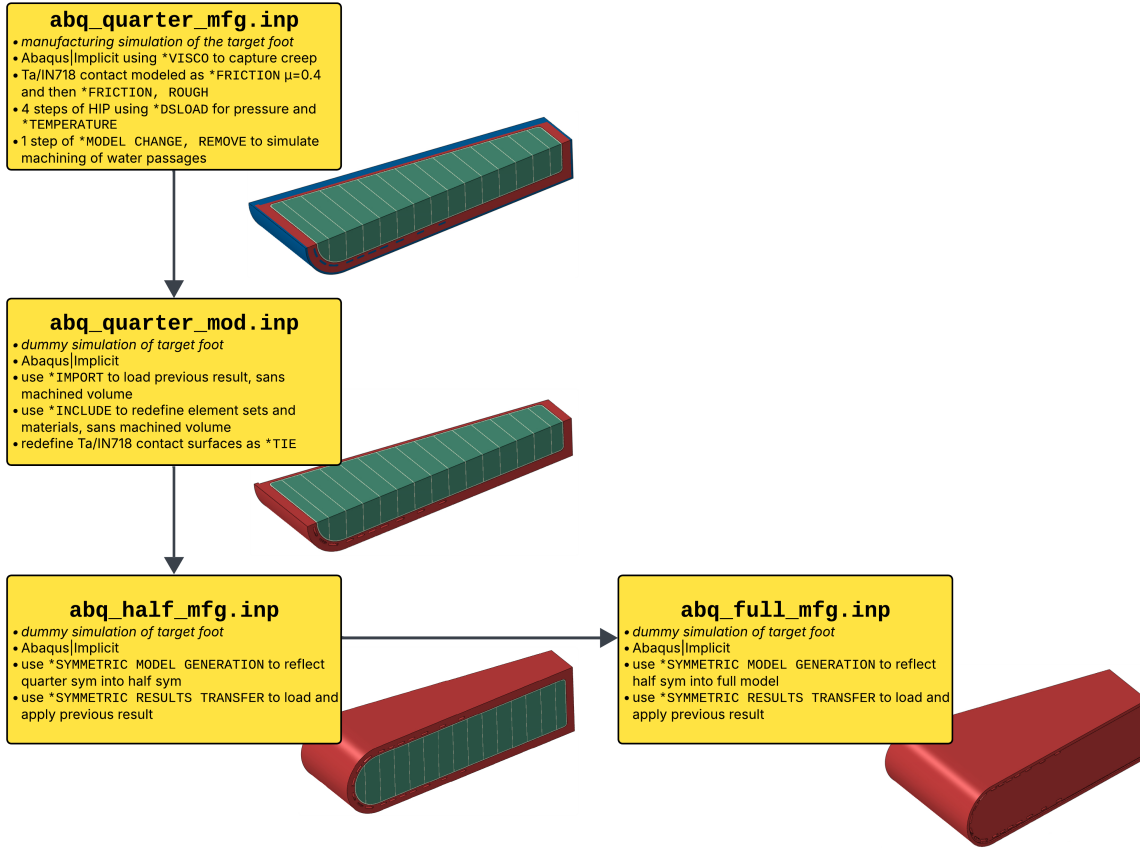


Figure 49. Flowchart showing the Abaqus simulations that comprise the manufacturing simulation of the target foot.

4.4.1 abq_quarter_mfg.inp

The manufacturing simulation uses the Abaqus|Standard (*VISCO) transient quasi-static solver to include the effects of rate-dependent creep in the tantalum and Inconel material models. It uses implicit time integration and large displacement theory. Within each time step, the system of equations with nonlinearities is solved using the Newton-Raphson method with a default force residual norm convergence of 0.5%. Time increments are controlled by a CETOL parameter of 1×10^{-4} such that the expected error is roughly 20 MPa according to Equation 19.

$$\sigma_{err} \approx E \cdot CETOL = 200 \text{ GPA} \cdot 1 \times 10^{-4} = 20 \text{ MPa} \quad (19)$$

The manufacturing simulation consists of 5 simulation steps. The simulation requires 32 hours when running on 256 cores (4 nodes) of the BERNIE cluster. The convergence table is listed in Appendix B, Table 13. The simulation requires 553 increments with the majority, 406 increments, occurring during step 2 (rapid ramp-up of temperature and pressure). This corresponds to the most significant model creep and plastic deformation.

Step 1: Slow ramp-up of temperature and pressure

- Quarter symmetry geometry of Figure 23 and Figure 24 with mesh shown in Figure 40
- Rigid body degrees of freedom (DOF) constrained via symmetry planes shown in Figure 50 and by fixing one node on shroud in the x-direction as shown in Figure 51

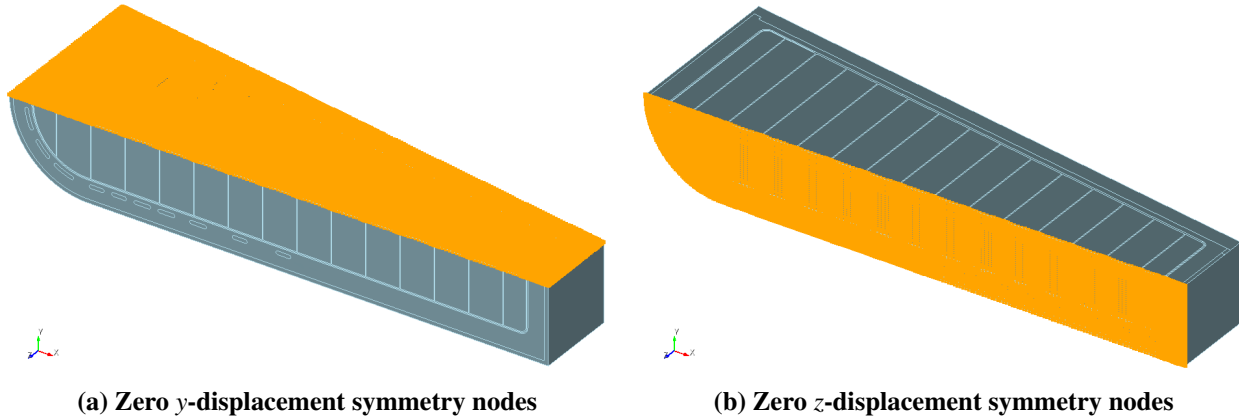


Figure 50. Mesh surface nodes used to apply symmetry boundary conditions as zero y -displacement and zero z -displacement as shown.

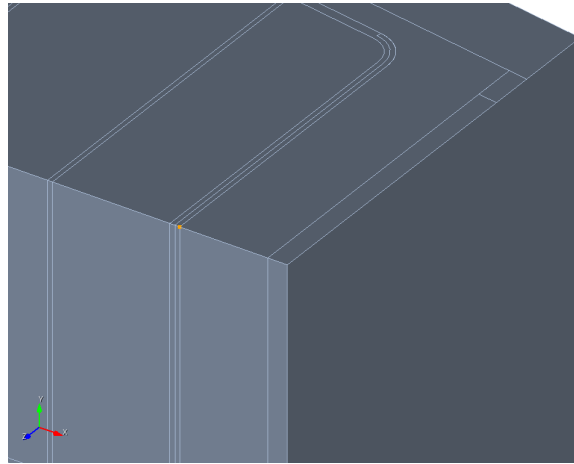


Figure 51. Inconel node used to apply zero x -displacement.

- Manufacturing loads as described in Section 3.3.1. Step 1 follows hours 0-3 of Figure 25. The temperature is applied to all nodes and the pressure is applied to the external surfaces shown in Figure 52

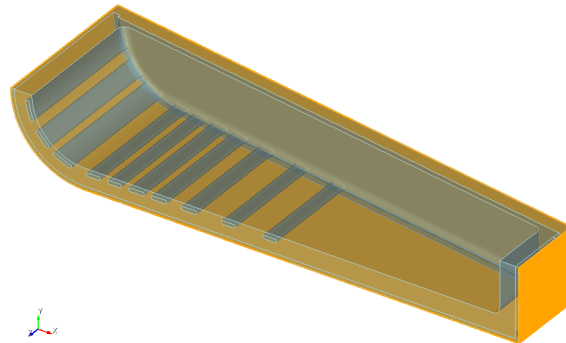


Figure 52. Mesh surfaces used to apply pressure during HIP manufacturing using *DSLOAD.

- The target block, consisting of the tungsten plates and tantalum cladding is a continuously meshed part with shared nodes at material interfaces. As listed in the assumptions, it is assumed that the target block has no residual stresses from its separate manufacturing. In other words, the target foot HIP presented here is assumed to relieve any potential residual stresses.
- Target block and Inconel shroud surfaces shown in Figure 53 are defined as a contact pair with tangential (0.4 friction - no slip) and normal (separation - no separation) interaction properties

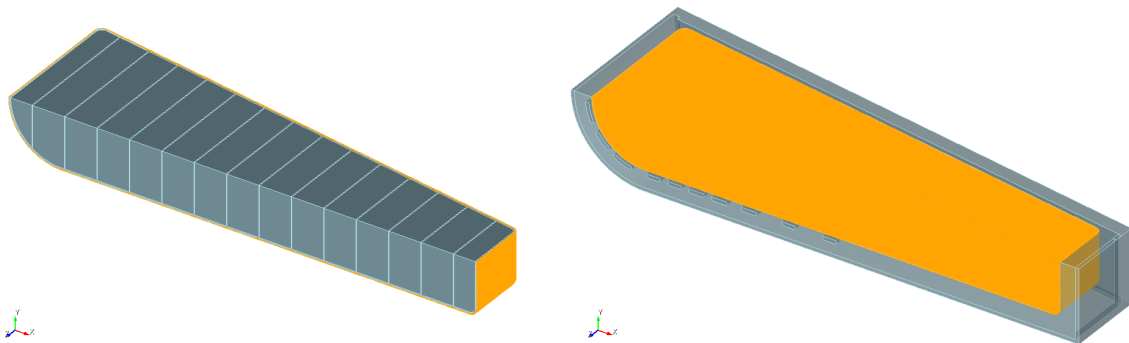


Figure 53. Target block to foot contact surfaces. Modeled as a frictional contact surface (*FRICTION) during HIP manufacturing and static loading simulation.

Step 2: Rapid ramp-up of temperature and pressure

- same boundary and contact conditions as Step 1
- 3-7 hours of Figure 25. The temperature is applied to all nodes and the pressure is applied to the external surfaces shown in Figure 52

Step 3: Hold temperature and pressure

- same boundary and contact conditions as Step 1
- 7-9 hours of Figure 25. The temperature is applied to all nodes and the pressure is applied to the external surfaces shown in Figure 52
- The tantalum and Inconel materials are allowed to creep during this step

Step 4: Ramp-down of temperature and pressure

- Same boundary and contact conditions as Step 1; however, the target block and Inconel shroud contact is changed to rough friction (*FRICTION, ROUGH) which effectively bonds the two surfaces together.
- 9-13 hours of Figure 25. The temperature is applied to all nodes and the pressure is applied to the external surfaces shown in Figure 52

Step 5: Machining

- Same boundary and contact conditions as Step 4
- Uses model change to simulate the machining operation that removes the outer surfaces of the shroud and adds the cooling channels as shown in Figure 54, Figure 23, and Figure 24

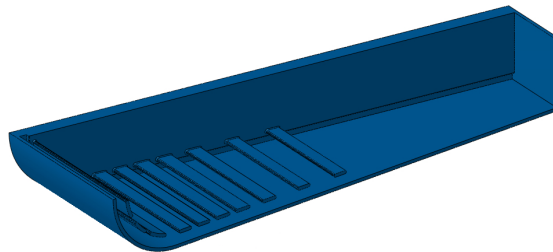


Figure 54. Volume that is machined away after HIP manufacturing step. Simulated in Abaqus with the *MODEL CHANGE, REMOVE command.

4.4.2 abq_quarter_mod.inp

This is a one step Abaqus/Implicit simulation. It is needed to keep the machined-away volume from reappearing during later simulation import operations. The Abaqus *IMPORT command is used to load the previous result at the last saved step. The element sets to be transferred are manually listed, and the machined-away volume is omitted. Finally, the Ta/IN718 contact surfaces are redefined with a *TIE constraint (instead of a contact definition) as they are now considered to be diffusion bonded. The simulation runs for 1 step with the boundary conditions previously specified (Figure 50 and Figure 51) to restore equilibrium.

4.4.3 abq_half_mfg.inp

This is needed to reflect the quarter symmetry target foot into half symmetry. An additional, 1 step static Abaqus simulation uses the `*SYMMETRIC MODEL GENERATION` and `*SYMMETRIC RESULTS TRANSFER` commands to reflect the distorted geometry and material state into half symmetry. The resulting distorted geometry and material state (temperature, stress, strain, equivalent plastic) from the manufacturing simulation can then be imported as the initial state for subsequent static and dynamic structural analyses.

4.4.4 abq_full_mfg.inp

Load Case B (Figure 12) concerns a nominal proton beam that is offset from the center of the target. Accordingly, a half-symmetry model is no longer applicable and a full target model is required. To achieve this, an additional 1 step static Abaqus simulation uses the `*SYMMETRIC MODEL GENERATION` and `*SYMMETRIC RESULTS TRANSFER` commands to reflect the (already previously reflected) half symmetry model into a full target foot. The resulting distorted geometry and material state (temperature, stress, strain, equivalent plastic) from the manufacturing simulation can then be imported as the initial state for subsequent static and dynamic structural analyses.

4.5 QUASI-STATIC STRUCTURAL SOLUTIONS

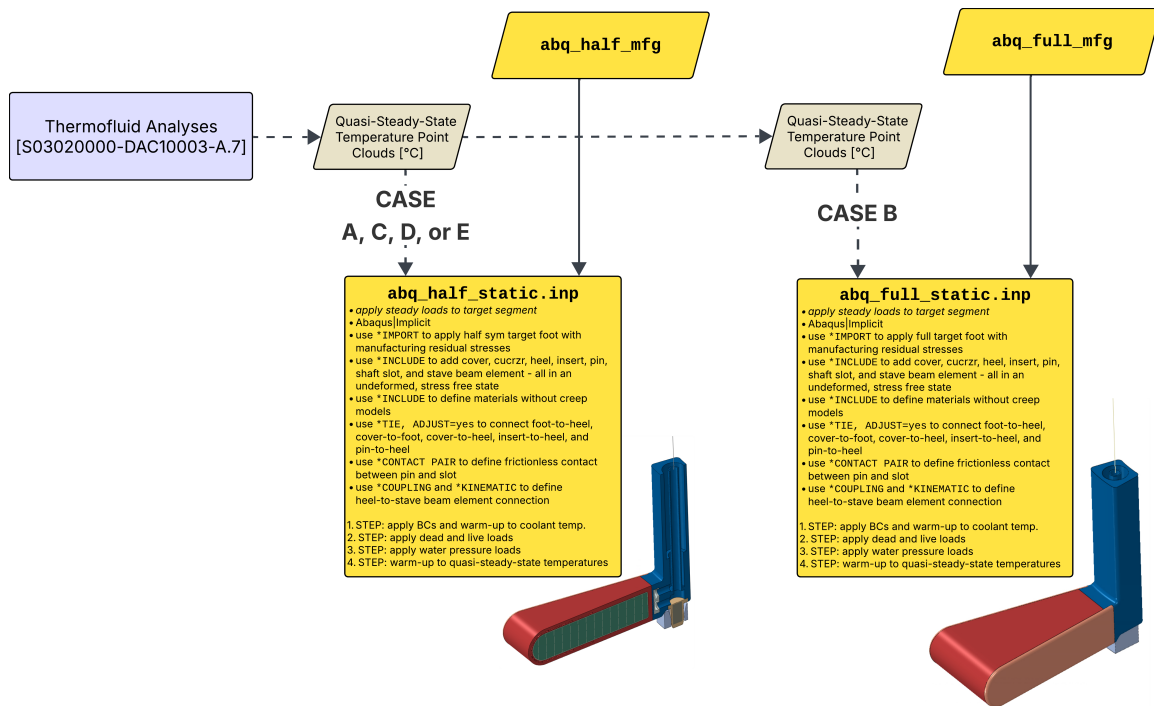


Figure 55. Flowchart showing the Abaqus simulations for the quasi-static structural loads on the target segment foot.

Figure 55 shows the portion of the flowchart that describes the quasi-static structural simulation of the target segment foot. The quasi-static structural simulation uses an Abaqus|Standard (*STATIC) static loading simulation with initial state imported from manufacturing loading simulation. This allows for variations on static loading according to the load cases without re-running the manufacturing simulation.

4.5.1 abq_half_static.inp

The geometry is shown in Figure 21 and Figure 22. Each part of the geometry is meshed according to Section 4.3. Figure 56 shows the half-symmetry model domain and contact conditions. The target stave away from the heel is approximated as a single 5-m beam element with an 8-mm C-channel cross-section that roughly matches the stave at the interface.

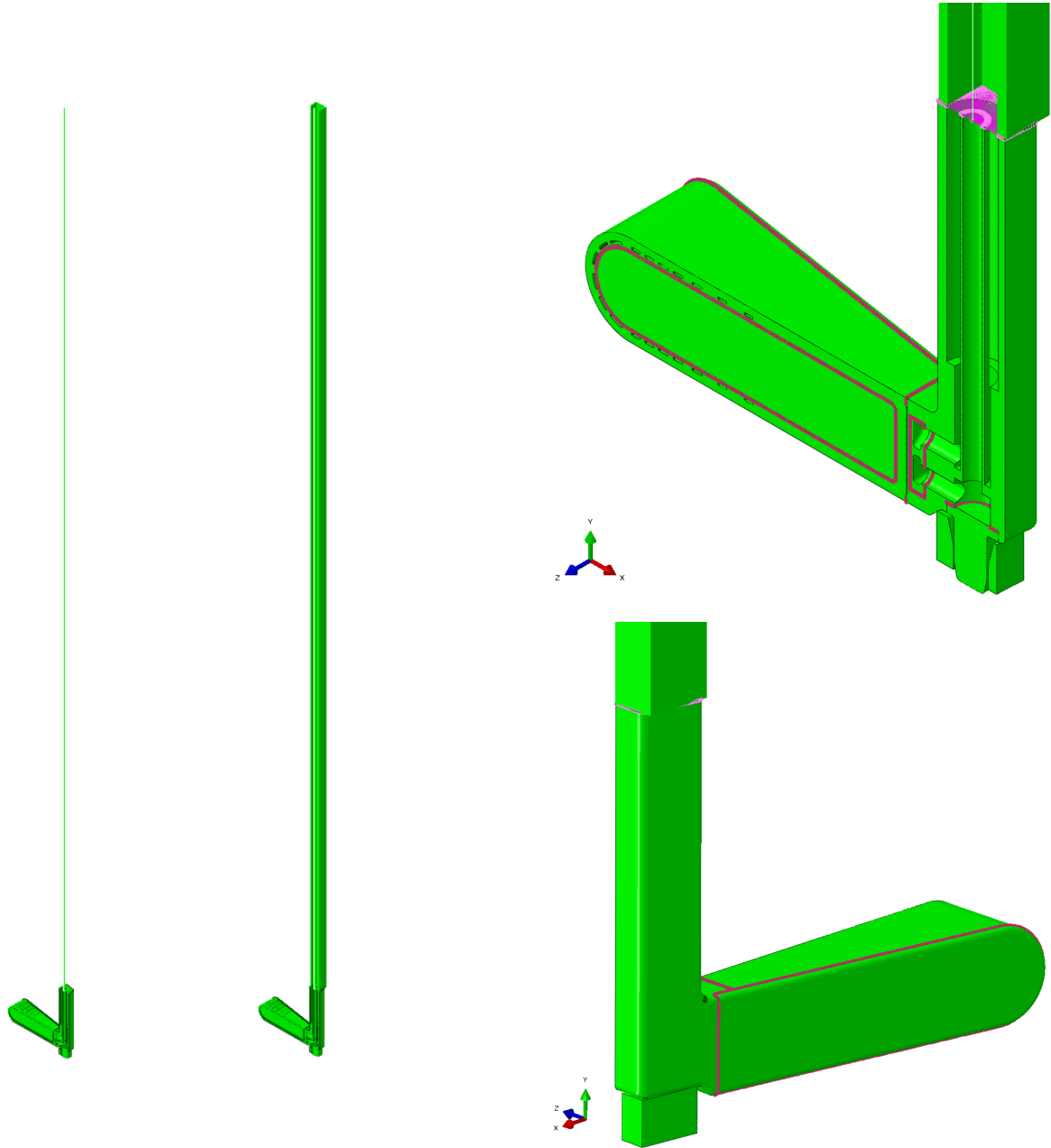


Figure 56. Static stress half symmetry model domain and contact conditions.

There are 8 separate contact definitions in the model as follows. As discussed earlier, the welds used in the target foot are all specified as full-penetration EBW [12].

1. Target block to foot (see Figure 57) - Inherited from manufacturing simulation as a surface-to-surface *TIE constraint with zero-gap adjustment
2. Flow cover to foot weld (see Figure 58) - Modeled as a surface-to-surface *TIE constraint with zero-gap adjustment.
3. Flow cover to heel weld (see Figure 59) - Modeled as a surface-to-surface *TIE constraint with zero-gap adjustment.
4. Target foot to heel weld (see Figure 60) - Modeled as a surface-to-surface *TIE constraint with zero-gap adjustment.
5. Heel to insert (see Figure 61) - The separation of the two volumes is not physical but allows the two volumes to be hex meshed independently. (A continuous hex mesh could not be achieved.) Modeled as a surface-to-surface *TIE constraint with zero-gap adjustment.
6. Pin to heel weld (see Figure 62) - Modeled as a surface-to-surface *TIE constraint with zero-gap adjustment.
7. Pin to shaft ring slot (see Figure 63) - Modeled as a surface to surface frictionless *CONTACT PAIR contact.
8. Heel to stave (see Figure 64) - Modeled as a kinematic constraint (*COUPLING with *KINEMATIC) coupling in all 6 DOF between the stave beam element and the heel surface.

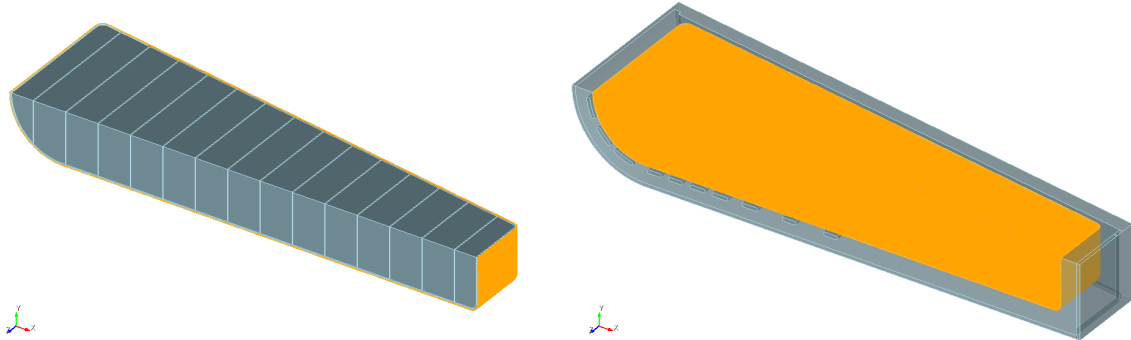


Figure 57. Target block to foot contact surfaces. Modeled as a surface-to-surface *TIE constraint with zero-gap adjustment.

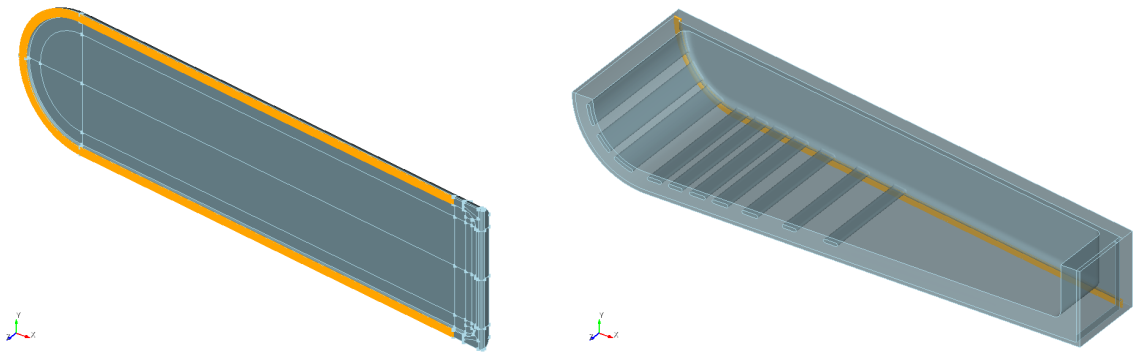


Figure 58. Cover to foot weld surfaces. Modeled as a surface-to-surface *TIE constraint with zero-gap adjustment.

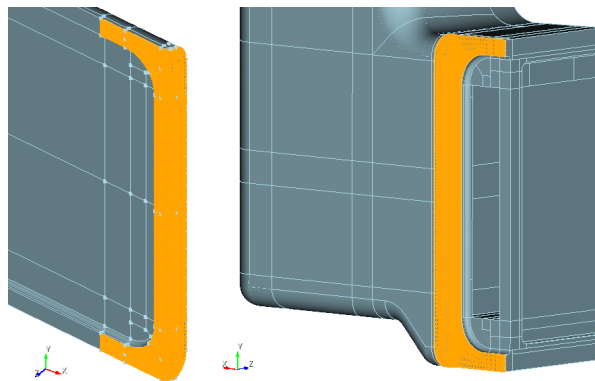


Figure 59. Cover to heel weld surfaces. Modeled as a surface-to-surface *TIE constraint with zero-gap adjustment.

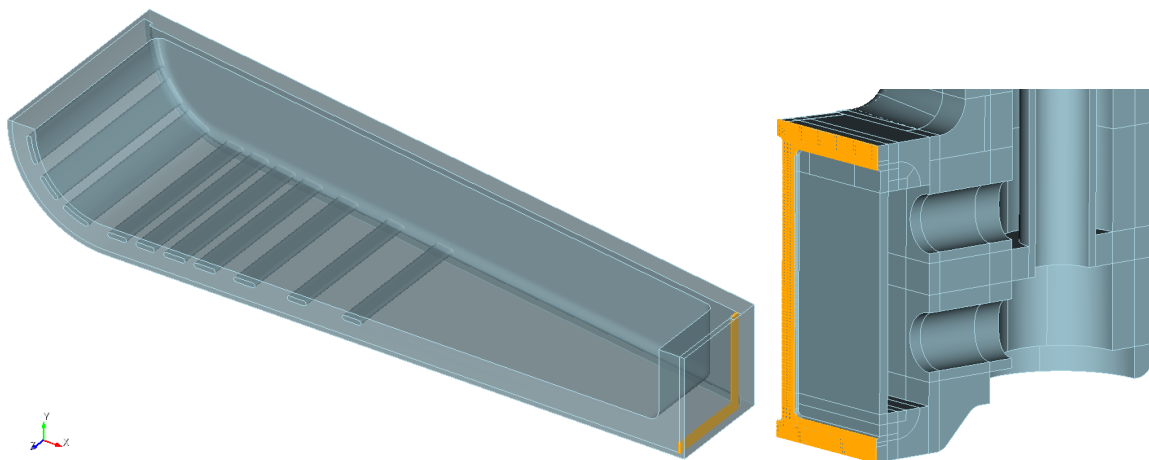


Figure 60. Target foot to heel weld surfaces. Modeled as a surface-to-surface *TIE constraint with zero-gap adjustment.

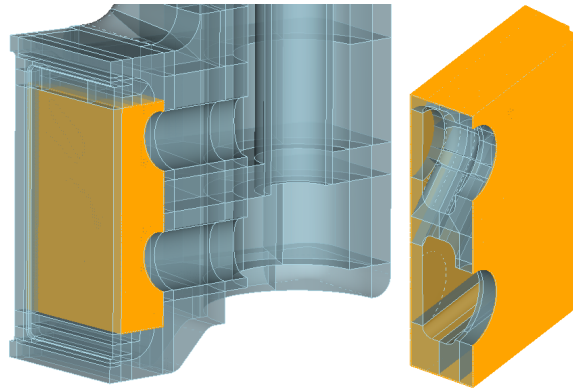


Figure 61. Heel to insert contact surfaces. The separation of the two volumes is not physical but allows the two volumes to be hex meshed independently. (A continuous hex mesh could not be achieved.) Modeled as a surface-to-surface *TIE constraint with zero-gap adjustment.

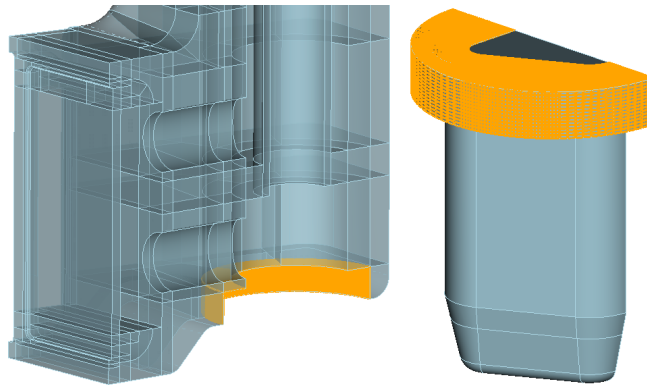


Figure 62. Pin to heel weld surfaces. Modeled as a surface-to-surface *TIE constraint with zero-gap adjustment.

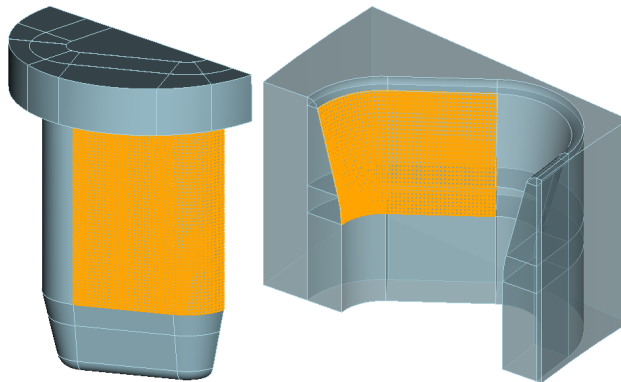


Figure 63. Pin to shaft ring slot contact surfaces. Modeled as frictionless contact interaction (via *CONTACT PAIR).

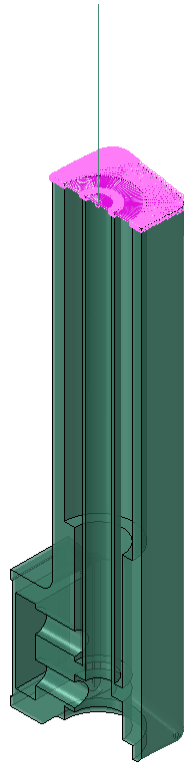


Figure 64. Heel to stave contact surfaces. Modeled as a kinematic constraint coupling (via *COUPLING and *KINEMATIC) in all 6 DOF between the stave beam element node and the heel surface.

A 5 step analysis is used as follows:

Step 1: Half-symmetry manufacturing residual stresses import

- This is not a true simulation step but rather a result of the initial setup.
- The `*IMPORT` command is used to load the manufacturing simulation results for the target foot in half-symmetry from the `abq_half_mfg` simulation.
- `*INCLUDE` statements are used to add the mesh definitions for the cover, CuCrZr, pin, heel, insert, ring, and stave components. These are all zero stress and zero deformation.
- Contacts, constraints, and couplings are defined as previously described to connect the components together.
- An `*INITIAL CONDITION` command is used to define the entire assembly at 20°C.
- This configuration is saved as Step 1 in the simulation results file.

Step 2: Warm-up to coolant temperatures

- A surface of the shaft ring structure, shown in Figure 65, is fixed in the first 3 DOF to prevent rigid body motion.
- The top node of the target stave beam element is fixed in all 6 DOF to prevent rigid body motion.
- The half-symmetry surface node sets, shown in Figure 66, (and along with the corresponding node set for the reflected target foot) are fixed in the z-direction to enforce symmetry.
- All nodes in the model are linearly ramped from 20°C (i.e. the end of the manufacturing simulation) to 35°C (i.e. the coolant temperature).

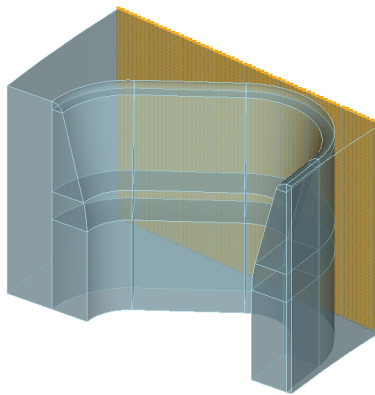


Figure 65. Mesh surface nodes used to rigidly fix the shaft ring slot feature by enforcing zero displacement in x,y,z directions.

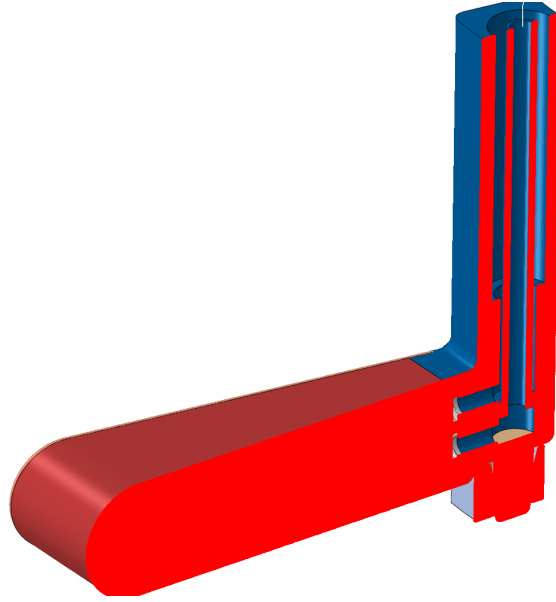


Figure 66. Mesh surface nodes used to apply half-symmetry boundary conditions (zero z-displacement).

Step 3: Dead and live loads

- Adds the dead and live loads as described in Section 3.3.2 and 3.3.3.

Step 4: Water pressure load

- Adds the water pressure as described in Section 3.3.4 as a surface load (*DSLOAD) applied to the surfaces defined in Figure 67.

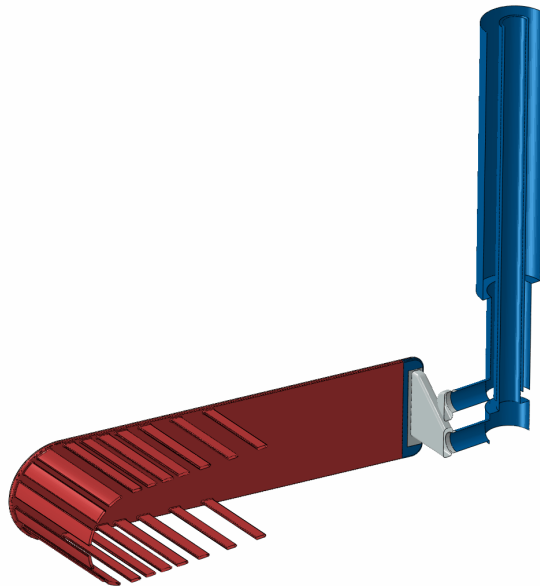


Figure 67. Mesh surfaces used to apply water pressure load via *DSLOAD.

Step 5: Warm-up to Quasi-steady operating temperatures

- Modifies the nodal temperatures in the model domain (via *TEMPERATURE, OP=mod) to linearly ramp from 35°C to the quasi-steady-state operating temperature field as defined in Section 3.3.7.
- The stave beam element stays at 35°C.
- This step requires different nodal temperature files for each of the load cases considered.

The simulation requires approximately 2 hours when running on 256 cores (4 nodes) of the BERNIE cluster. An example convergence table for the nominal beam case is given in Table 8. Step 3 has the smallest time increments which are caused by the pin/slot contact condition in response to the dead and live loads.

Table 8. Abaqus convergence table for half-symmetry quasi-static structural solution.

Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	1	1	0	3	3	2.00	1.00	1.000
3	1	1	0	2	2	2.00	0.000100	0.0001000
3	2	1	1	1	2	2.00	0.000200	0.0001000
3	3	1	0	3	3	2.00	0.000350	0.0001500
3	4	1	0	2	2	2.00	0.000575	0.0002250
3	5	1	0	1	1	2.00	0.000913	0.0003375
3	6	1	0	1	1	2.00	0.00142	0.0005062
3	7	1	0	1	1	2.00	0.00218	0.0007594
3	8	1	0	1	1	2.00	0.00332	0.001139
3	9	1	0	1	1	2.01	0.00503	0.001709
3	10	1	0	1	1	2.01	0.00759	0.002563
3	11	1	0	1	1	2.01	0.0114	0.003844
3	12	1	0	1	1	2.02	0.0172	0.005767
3	13	1	0	1	1	2.03	0.0258	0.008650
3	14	1	0	1	1	2.04	0.0388	0.01297
3	15	1	0	1	1	2.06	0.0583	0.01946
3	16	1	0	1	1	2.09	0.0875	0.02919
3	17	1	0	1	1	2.13	0.131	0.04379
3	18	1	0	1	1	2.20	0.197	0.06568
3	19	1	1	2	3	2.30	0.295	0.09853
3	20	1	1	2	3	2.44	0.443	0.1478
3	21	1	0	3	3	2.66	0.665	0.2217
3	22	1U	4	3	7	2.66	0.665	0.3325
3	22	2	1	1	2	2.75	0.748	0.08313
3	23	1	1	3	4	2.87	0.873	0.1247
3	24	1	0	2	2	3.00	1.00	0.1272
4	1	1	0	2	2	4.00	1.00	1.000
5	1	1	0	6	6	5.00	1.00	1.000

4.5.2 abq_full_static.inp

Load Case B (Figure 12) concerns a nominal proton beam that is offset from the center of the target. Accordingly, a half-symmetry model is no longer applicable and a full target model is required. The Abaqus simulation `abq_full_static.inp` repeats the analysis presented in `abq_half_static.inp` with the following modifications:

- The simulation begins with an `*IMPORT` of the full model manufacturing residual stress solution from `abq_full_mfg.inp`
- Meshing scripts in CUBIT are modified to reflect the slot, pin, cucrzt, heel, and insert meshes from half-symmetry into full geometry.
- Symmetry boundary conditions are removed.
- The stave beam element is modified to make the stave a box geometry instead of an open C-channel cross-section.

It should be noted that the manner of reflecting the CUBIT mesh to create a full geometry introduces a discrepancy in the heel. Figure 68 shows how the heel water manifold is not truly symmetric. The reflected geometry creates a "V" shaped water passage which is then expected to have a false stress concentration at the bottom of the "V". This approximation was judged by the STS team to be acceptable when weighed against the resources needed to re-mesh the heel structure in hex elements.

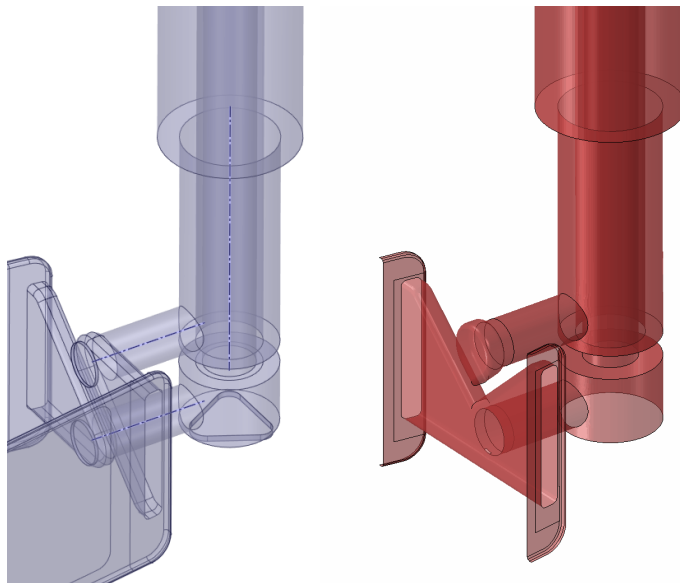


Figure 68. Comparison of the symmetry effects caused by reflecting the heel mesh from half symmetry into full. The left image shows the actual heel water manifold geometry. The right image shows the approximated geometry caused by the symmetry reflection.

4.6 EXPLICIT DYNAMIC STRUCTURAL SOLUTIONS

4.6.1 abq_half_pulse.inp and abq_full_pulse.inp

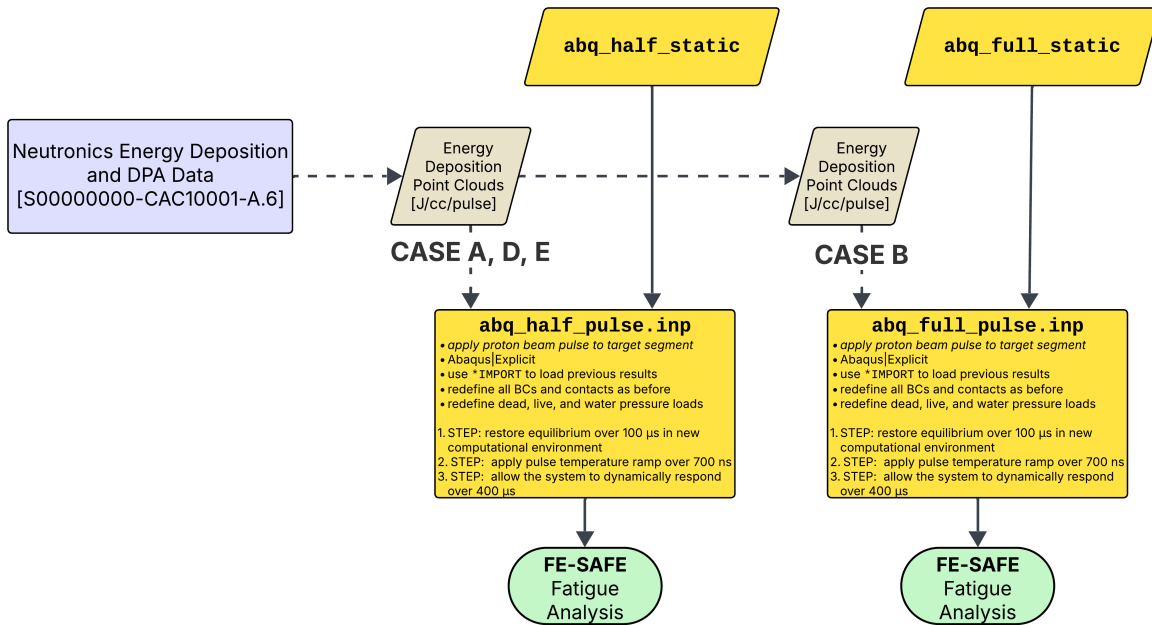


Figure 69. Flowchart showing the Abaqus simulations for the dynamic response to a proton beam pulse.

Figure 69 shows the portion of the flowchart that describes the dynamic proton pulse simulation of the target segment. The beam pulse and dynamic response is modeled as an Abaqus|Explicit (*DYNAMIC, EXPLICIT) dynamic loading simulation with initial state imported from the static loading simulation. This allows for variations on dynamic loading without re-running manufacturing and static simulations. Each of the load cases must be solved using either the full model domain (i.e. Load Case B) or the half-symmetry domain (i.e. Load Case A, C, D, E). The dynamic simulation input files (abq_half_pulse.inp and abq_full_pulse.inp) are identical, except that the full model does not include symmetry boundary conditions.

The explicit solution begins with an import of the static model and solution using *IMPORT commands. The boundary conditions, contact condition, and constraint conditions presented in the previous section all have to be redefined. The 3 simulation steps are as follows:

Step 1: Restore equilibrium

Boundary conditions, dead and live loads, and pressure loads are immediately reapplied. The temperature is already carried over from the import. The system is allowed to respond over 0.1 ms as it comes to a slightly new equilibrium point in the new simulation environment.

Step 2: Apply beam pulse

The proton pulse energy deposition is simulated as a temperature field forcing function (as there is negligible time for any appreciable thermal diffusion to occur). The full domain begins at the quasi-steady operating temperature and then linearly ramps over 700 ns to the sum of the quasi-steady temperature field (from Section 3.3.7) and pulse temperature rise field (from Section 3.3.6) using *TEMPERATURE, OP=mod. These fields are different depending on the load case considered and are shown in Figure 38.

Step 3: Pulse reaction

The third simulation step is for dynamic response. The elastic stress waves propagate through the target at the speed of sound in each material. Damping occurs relatively quickly, and only $400\ \mu\text{s}$ is needed to capture the damage-generating stress amplitudes in the target foot.

The explicit solver has guaranteed stability, however, the minimum timestep is limited by the wave propagation speed across the smallest mesh element in the model. Automatic mass scaling is used to set a minimum stable time increment of 10-ns. For the nominal mesh, the smallest element time increment is about 9-ns. Mass scaling to meet the minimum stable time increment requires a 8.629×10^{-6} percent change in system mass from the nominal 62.154 kg and is considered negligible.

The simulation contains 3 steps and requires approximately 0.5 hours when running on 256 cores (4 nodes) of the BERNIE cluster. Figure 70 shows an example of the global energy output during the solution for the nominal beam case.

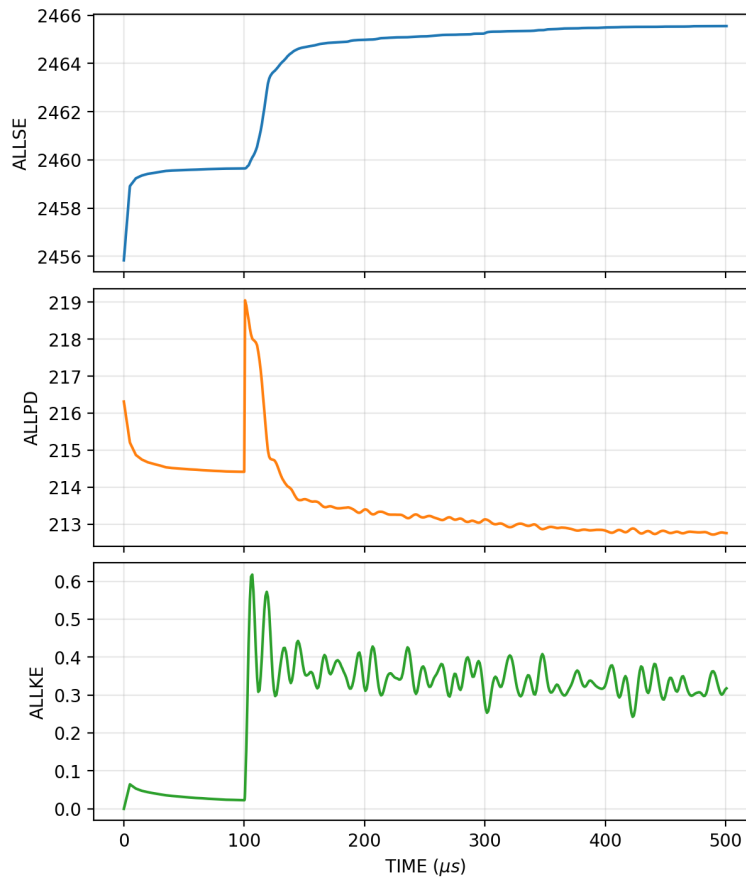


Figure 70. Global energy components for explicit dynamic structural solution under nominal beam. ALLSE is strain energy, ALLPD is plastic deformation energy, and ALLKE is kinetic energy.

4.7 FATIGUE SIMULATIONS

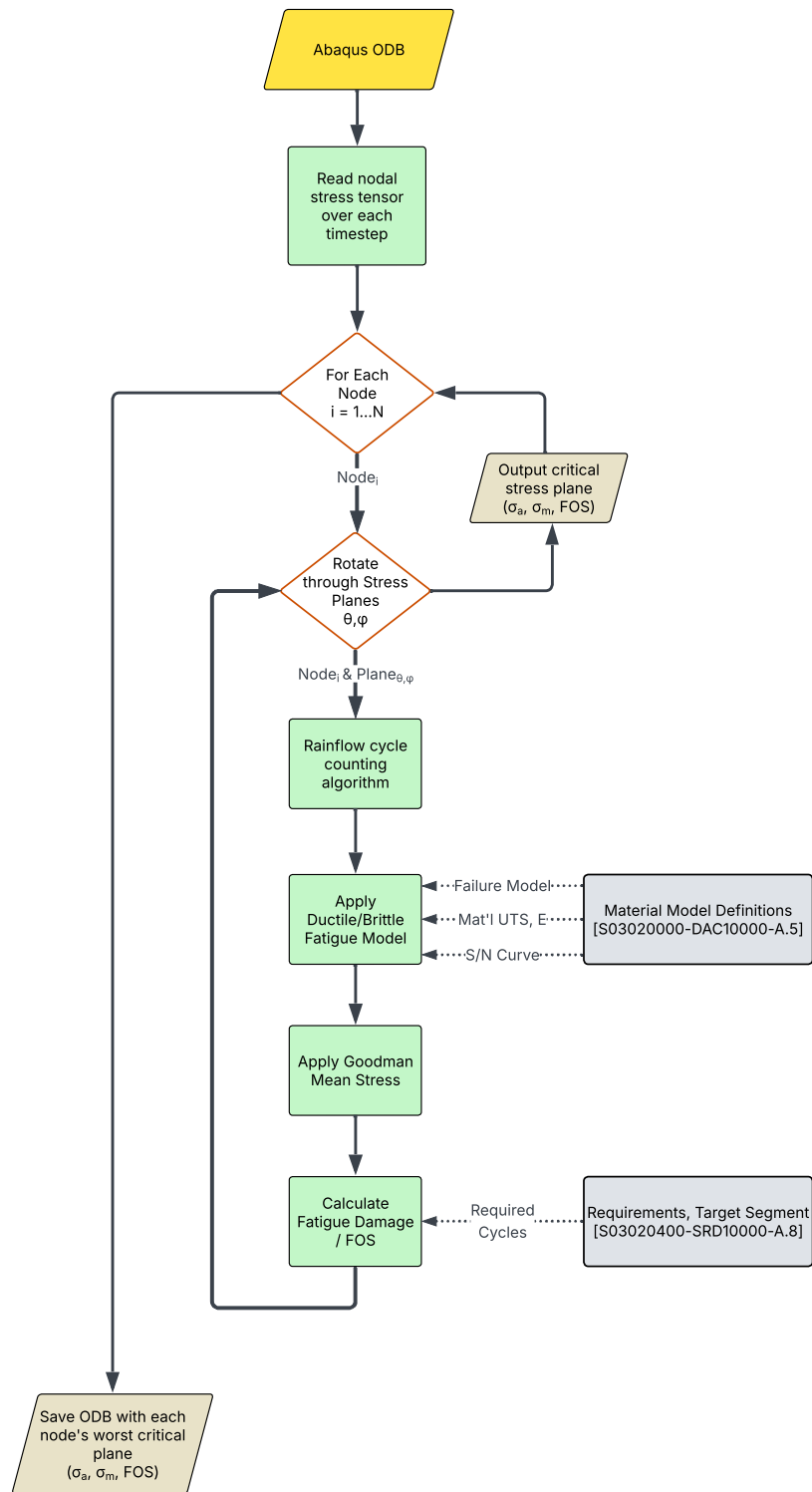


Figure 71. Conceptual flowchart of *fe-safe* fatigue analysis algorithm. (Larger version available in Appendix A.)

The cyclic fatigue life calculations are performed with *fe-safe* commercial software [4]. Figure 71 provides a conceptual flowchart of the *fe-safe* fatigue analysis algorithm. An Abaqus ODB output file is provided as input. The *fe-safe* software pre-scans the ODB to load the stress tensor for every node over each timestep. For a fatigue analysis, the software loops through each nodal stress history. For each node, it rotates through possible stress planes. For every stress plane, it analyzes the time-stress history using a "rainflow" cycle counting algorithm to count stress cycles with their mean stress and amplitudes. The actual fatigue analysis requires material properties (modulus of elasticity, ultimate strength), a S-N curve for the material, and a failure model (i.e. brittle, ductile).

The tungsten plates are modeled according to brittle normal stress theory. The Inconel shroud and flow cover are modeled according to ductile Brown-Miller stress theory. The stainless steel heel structure is also modeled according to ductile Brown-Miller stress theory. These are all documented in the "Target Systems Materials Library" [16]. The Goodman method is used to account for mean stress effects on the fatigue life. Finally, the accumulated fatigue damage for the cycles and a FOS are calculated for that node at that stress plane. This is repeated until all stress planes are considered for each node. The worst stress plane (i.e. the critical plane that yields the lowest fatigue life) is exported for each node. In addition, *fe-safe* exports an ODB with variables for the worst stress amplitude, mean stress, and FOS at each node. As the *fe-safe* User Manual describes [4]:

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.

Each load case (Figure 12) requires 6 fatigue analyses in *fe-safe*:

- beam trip fatigue
 - tungsten
 - Inconel
 - stainless steel
- beam pulse fatigue
 - tungsten
 - Inconel
 - stainless steel

The beam trip fatigue life is analyze separately from the beam pulse fatigue life. Otherwise, the *fe-safe* software would model the worst case of a beam trip occurring during the peak stress cycle of a beam pulse which is not physically realistic. (Technically, the interaction between the two loadings can be disabled in *fe-safe*. They are kept as separate analyses in this report due to the historical desire in the STS team to plot results on a Goodman diagram, and a combined analysis would not have a clear fatigue envelope to plot against. This assumption will be verified in the Results section.)

The beam trip cycle is defined as the stresses going from Step 4 to Step 5 (i.e. the warm-up to quasi-steady operating temperatures) in the Quasi-Static Structural Solution. The beam pulse fatigue event is calculated from the 400 saved timesteps during the 400 μ s response in Step 3 (i.e. the pulse reaction) of the Explicit Dynamic Structural Solution.

4.8 RATCHETING SIMULATIONS

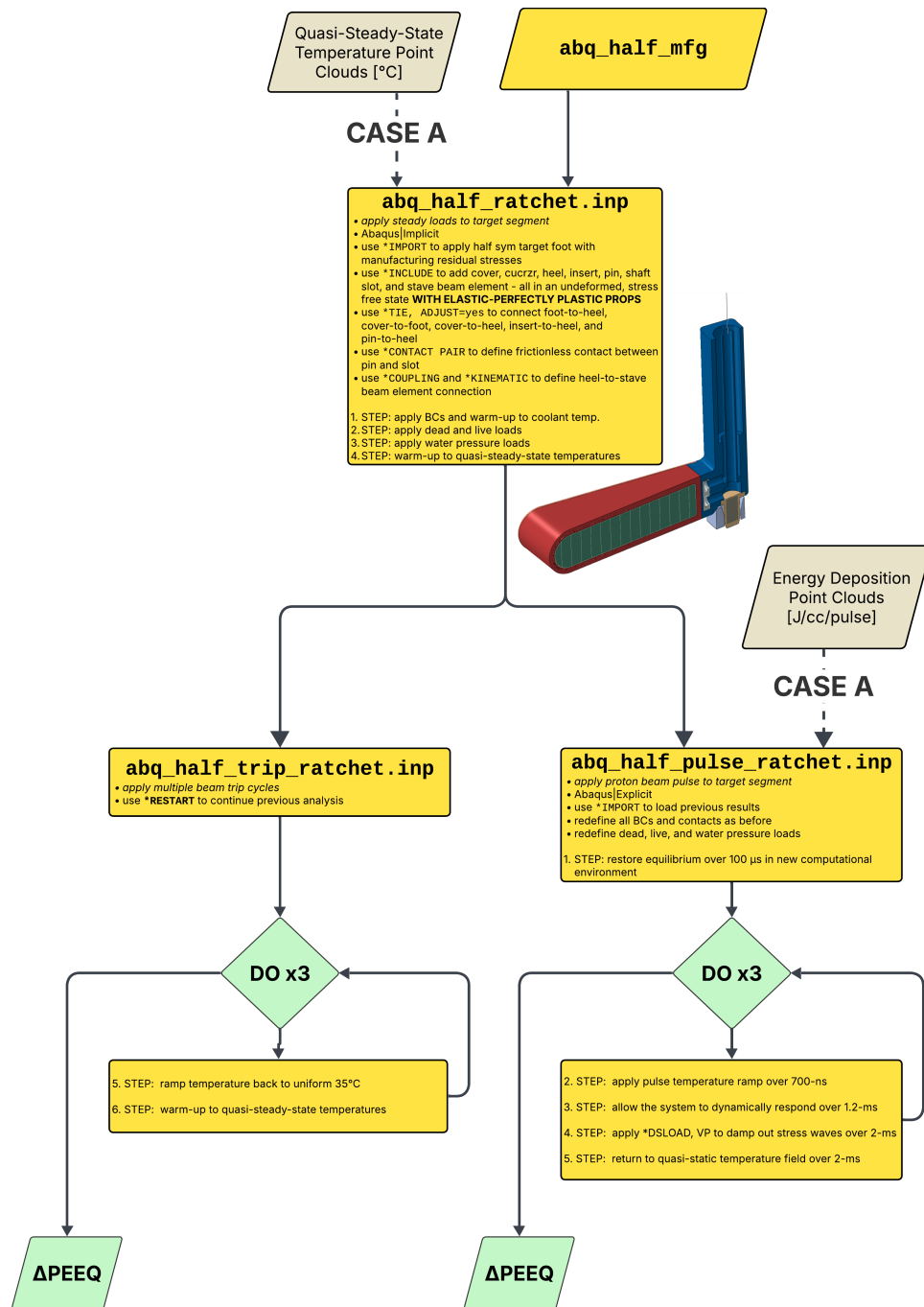


Figure 72. Flowchart showing the Abaqus simulation to perform a plastic ratcheting analysis of the target segment foot.

Figure 72 shows the portion of the flowchart that describes the plastic ratcheting analysis of the target segment foot. The plastic ratcheting load case intends to apply repeating load cycles to the target to check for plastic ratcheting and/or elastic shakedown in the target foot structure. This is performed for the half-symmetry model using the nominal beam loading scenario (Case A). (As will be seen in the results, the full fatigue analysis is insensitive to the various beam cases.)

4.8.1 abq_half_ratchet.inp

The ratcheting analyses must first begin with the quasi-static structural simulation of the target segment foot. This is a copy of `abq_half_static.inp` which was used as part of the fatigue simulations. The only modification is that the entire heel structure and the Inconel flow cover are assigned thermoelastic-perfectly plastic material properties per Section 1.4.5. (The Inconel shroud and tantalum cladding continue to use their original thermoelastic-plastic properties as the manufacturing process results in plastic hardening. The tungsten plates always remain thermoelastic due to their brittleness.) The simulation then proceeds exactly as before with application of dead loads, live loads, pressure loads, and warm-up to quasi-stead-state temperatures.

The thermoelastic-perfectly plastic material properties for this analysis are implemented by modifying the *PLASTIC field entries in the material models. For a given temperature, the first data line defines the yield stress at zero plastic strain. This line is kept, and all other non-zero plastic strain entries are deleted. Abaqus does not extrapolate plastic strain data, so the material then behaves as perfectly plastic. (For the stainless steel, the yield stress at each temperature is set to the engineering yield stress as per Annex 3-D guidelines.)

4.8.2 abq_half_trip_ratchet.inp

This simulation file is intended to check the beam trip cycle for ratcheting. It is an Abaqus|Standard static simulation that begins with a *RESTART to load the final step of the `abq_half_ratchet.inp` analysis (Step 4). At this point, the target segment foot is at quasi-stead-state temperature for the nominal beam case.

The following Steps 5-6 are then repeated 3 times over (as Steps 5-10) to explore the plastic ratcheting load case:

Step 5: Beam trip

The *TEMPERATURE, OP=mod command is used to linearly ramp the model domain back to 35°C. This simulates a beam trip event whereby the target cools back down to the coolant water temperature.

Step 6: Warm-up to Quasi-steady operating temperatures

The *TEMPERATURE, OP=mod command is again used to linearly ramp the model domain from 35°C to the quasi-steady-state operating temperature field as defined in Section 3.3.7.

4.8.3 abq_half_pulse_ratchet.inp

The simulation file is a modified copy of the fatigue pulse simulation `abq_half_pulse.inp`. The explicit solution begins with an import of the static model and solution using *IMPORT commands. Same as before, the boundary conditions, contact condition, and constraint conditions presented in the quasi-static structural solutions section all have to be redefined. The first simulation step is run only once:

Step 1: Restore equilibrium

Boundary conditions, dead and live loads, and pressure loads are immediately reapplied. The temperature is already carried over from the import. The system is allowed to respond over 0.1-ms as it comes to a slightly new equilibrium point in the new simulation environment.

The following Steps 2-5 are then repeated 3 times over (as Steps 2-13) to explore the plastic ratcheting load case:

Step 2: Apply beam pulse

The proton pulse energy deposition is simulated as a temperature field forcing function (as there is negligible time for any appreciable thermal diffusion to occur). The full domain begins at the quasi-steady operating temperature and then linearly ramps over 700-ns to the sum of the quasi-steady temperature field (from Section 3.3.7) and pulse temperature rise field (from Section 3.3.6) using *TEMPERATURE, OP=mod.

Step 3: Pulse reaction

The third simulation step is for dynamic response. The elastic stress waves propagate through the target at the speed of sound in each material. The pulse is allowed to develop for 1.2-ms.

Step 4: Damp-out dynamic stress waves

This step lasts 200-ms and applies a viscous pressure distributed surface load to the external surfaces defined in Figure 73 using *DSLOAD, VP. The viscous pressure coefficient is given as $1 \times 10^{-7} \frac{kg}{m^2s}$, and the load follows a smooth cosine ramp over the duration of the step. This serves to gradually absorb the kinetic energy in the system.

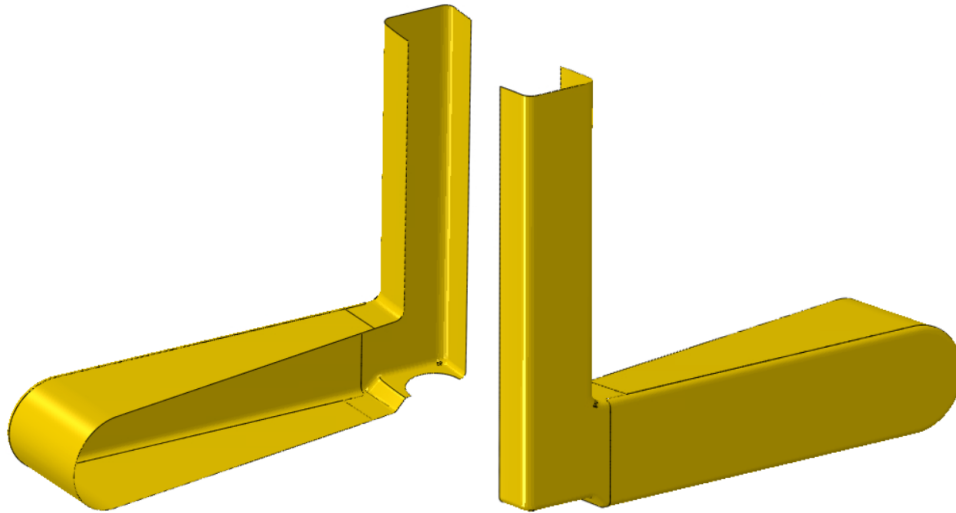


Figure 73. Mesh surfaces on external surfaces of the half-symmetry domain used to apply viscous pressure during plastic ratcheting analyses via *DSLOAD, VP.

Step 5: Return to quasi-steady heating

This step also lasts 200-ms during which the viscous pressure distributed surface load is ramped down to zero using a smooth cosine ramp. Also during the step, the nodal temperatures are linearly ramped back to the quasi-steady state temperature field (via *TEMPERATURE, OP=mod).

4.9 PLASTIC COLLAPSE SIMULATIONS

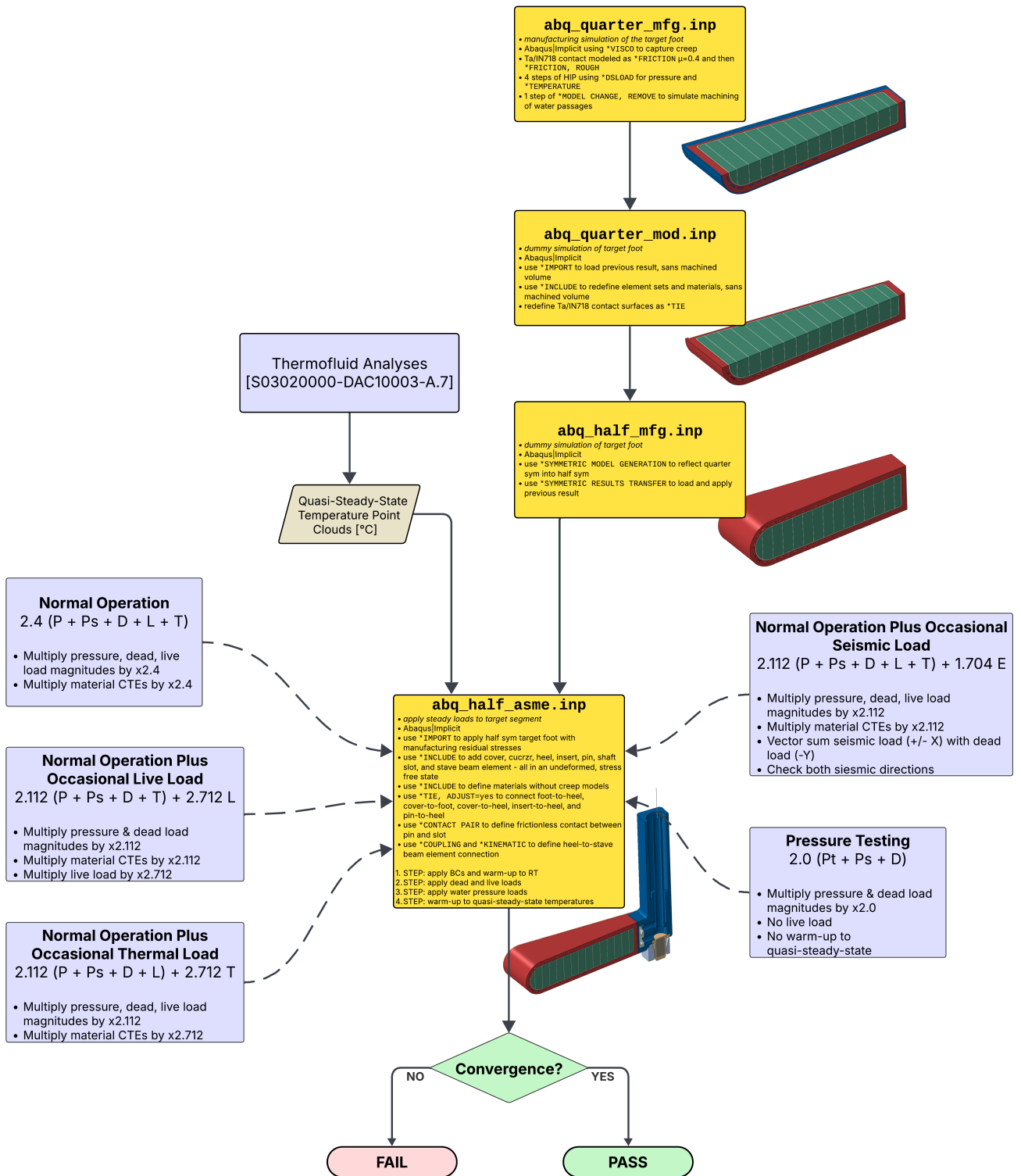


Figure 74. Conceptual flowchart of plastic collapse analysis algorithm. (Larger version available in Appendix A.)

Figure 74 shows the simulation workflow to analyze the target segment foot for protection against plastic collapse. The static analysis file `abq_half_asme.inp` is a copy of `abq_half_static.inp` which was used as part of the fatigue simulations. The analysis is run 6 times with different load variations according to the LRFD factors explained in Section 1.4.1.

Normal Operation

- Load combination:

$$2.4(P + P_S + D + L + T)$$

- Load values are specified in Section 3.3
- Multiply pressure, dead, and live load magnitudes by x2.4
- To implement the thermal load, increase the thermal expansion coefficient (α) entries under the *EXPANSION field for all material properties by x2.4 (which will increase the thermal expansion effects on the simulation without changing the temperature and hence the other temperature-dependent properties).

Normal operation plus occasional live load

- Load combination:

$$2.112(P + P_S + D + T) + 2.712L$$

- Load values are specified in Section 3.3
- Multiply pressure and dead load magnitudes by x2.112
- Multiply live load magnitude by x2.712
- To implement the thermal load, increase the thermal expansion coefficient (α) entries under the *EXPANSION field for all material properties by x2.112 (which will increase the thermal expansion effects on the simulation without changing the temperature and hence the other temperature-dependent properties).

Normal operation plus occasional thermal

- Load combination:

$$2.112(P + P_S + D + L) + 2.712T$$

- Load values are specified in Section 3.3
- Multiply pressure, dead, and live load magnitudes by x2.112
- To implement the thermal load, increase the thermal expansion coefficient (α) entries under the *EXPANSION field for all material properties by x2.712 (which will increase the thermal expansion effects on the simulation without changing the temperature and hence the other temperature-dependent properties).

Normal operation plus occasional seismic

- Load combination:

$$2.112(P + P_S + D + L + T) + 1.704E$$

- Load values are specified in Section 3.3
- Multiply pressure and live load magnitudes by x2.112

- To implement the thermal load, increase the thermal expansion coefficient (α) entries under the *EXPANSION field for all material properties by x2.112 (which will increase the thermal expansion effects on the simulation without changing the temperature and hence the other temperature-dependent properties).
- To implement the earthquake load, vector sum the 1.704 E earthquake load with the 2.112 D gravity load. Apply this vector using the *DLOAD key with the *GRAV option.
- Assume the earthquake load could occur in either the +X or –X directions. Run both cases.

Pressure testing

- Load combination:

$$2.0 (P_T + P_S + D)$$

- Load values are specified in Section 3.3
- Multiply pressure and dead load magnitudes by x2.0
- Omit the live load
- Omit the thermal load step

Per the ASME/BPVC, numerical convergence to a steady-state solution indicates protection against plastic collapse for each load case.

4.10 LOCAL FAILURE SIMULATIONS

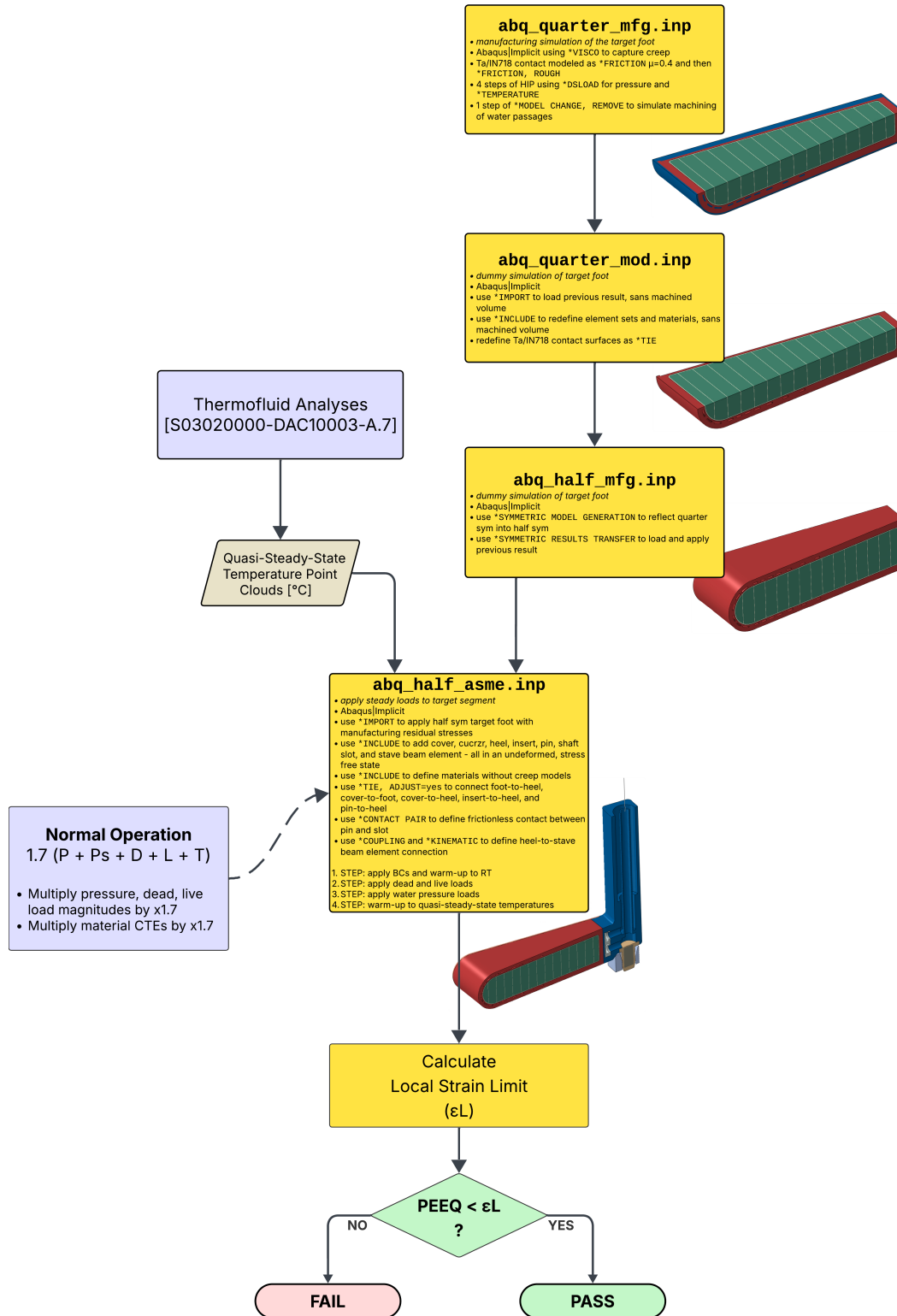


Figure 75. Conceptual flowchart of local failure analysis algorithm. (Larger version available in Appendix A.)

Figure 75 shows the simulation workflow to analyze the target segment foot for protection against local failure. The static analysis file `abq_half_asme.inp` is the same as was used to analyze for protection against plastic collapse. The analysis is run with the LRFD factor for local failure analysis as explained in Section 1.4.2.

Normal Operation

- Load combination:

$$1.7 (P + P_S + D + L + T)$$

- Load values are specified in Section 3.3
- Multiply pressure, dead, and live load magnitudes by x1.7
- To implement the thermal load, increase the thermal expansion coefficient (α) entries under the *EXPANSION field for all material properties by x1.7 (which will increase the thermal expansion effects on the simulation without changing the temperature and hence the other temperature-dependent properties).

To check for protection against local failure, the equivalent plastic strains in the solution must be compared against a calculated limiting triaxial strain (ϵ_{Lu}), given in Equation 6. The triaxial stress (TRIAX) is requested as field output variable in the simulation. An Abaqus python script (archived along with the simulation input decks) is used to perform the following steps:

- Access the element triaxial stresses (TRIAX) and equivalent plastic strains (PEEQ) extrapolated to the nodes, according to the element basis functions
- When a node is shared between multiple elements, take the largest extrapolated value for conservatism.
- For each node, calculate the corresponding limiting triaxial strain (EL) according to Equation 6.
- For each node, also calculate the margin above the limiting triaxial strain by subtracting the accumulated plastic strain (PEEQ) from the limiting triaxial strain (EL). Call this variable EMARGIN. (Note that the accumulated plastic strain result already incorporates the manufacturing residual strains.)
- Save both field variables EL and EMARGIN to the Abaqus ODB results file and create contour plots.

5. RESULTS

5.1 MANUFACTURING

The manufacturing simulation places the target foot into a complex residual stress state. Early attempts to grasp the structural physics through simpler geometry concepts (e.g. nested cylinders or spheres) were beguiled by the nature of the wedge shaped geometry with edges and corners as well as the non-uniform stress-altering machining operations. Figure 76 shows a good example with the tungsten plates. The HIP simulation is expected to place the tungsten in a compressive stress state as the coefficient of thermal expansion (CTE) mismatch drives the Inconel shroud to plastically deform around the W/Ta core. Once the water passageways are machined from the shroud, however, the tungsten plates develop tensile regions on the side, up to 280 MPa.

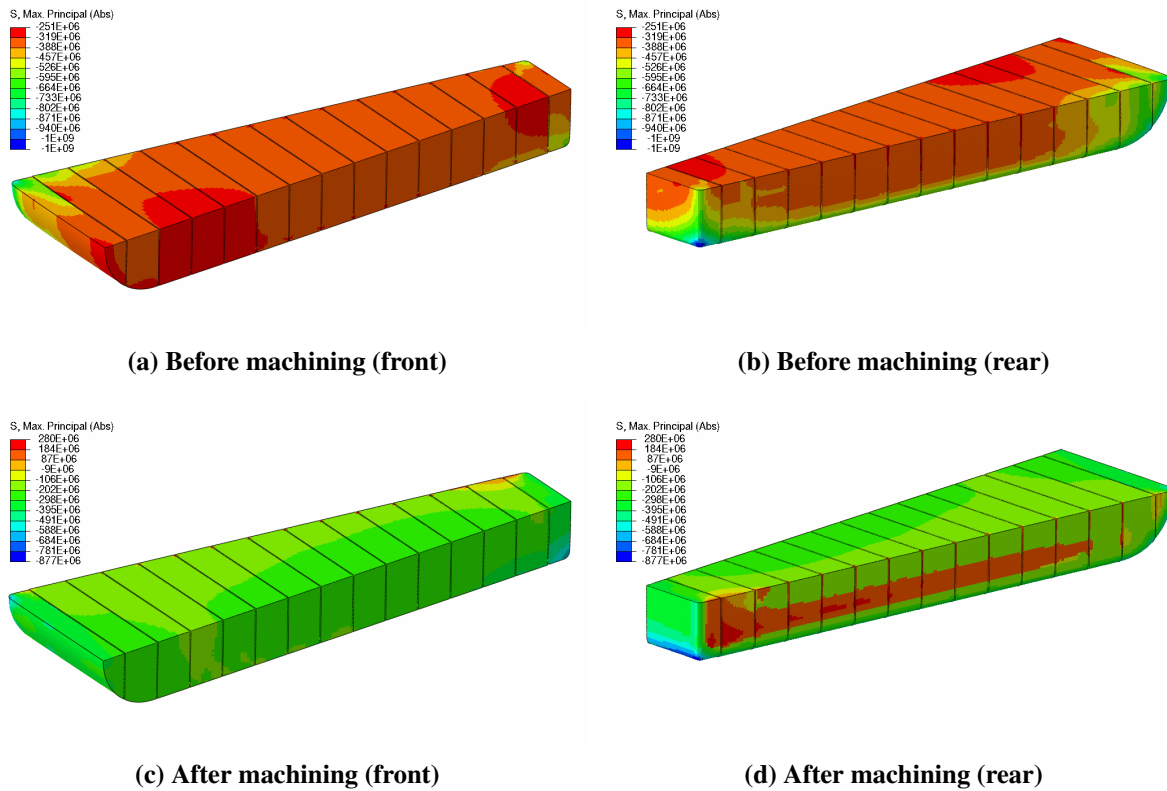


Figure 76. Stress state of the tungsten plates before and after machining.

Figure 77 shows the state of the tantalum cladding after the full manufacturing simulation. The entire structure has plastically deformed with the highest amounts of plastic strain (PEEQ) in the corners. The thin plates or foils between the tungsten plates are in compression while the thicker outer cladding is in tension away from the corners and bends. As the tantalum is fully constrained between the tungsten and Inconel, it is regarded as a compliance material, and no further structural analysis is performed.

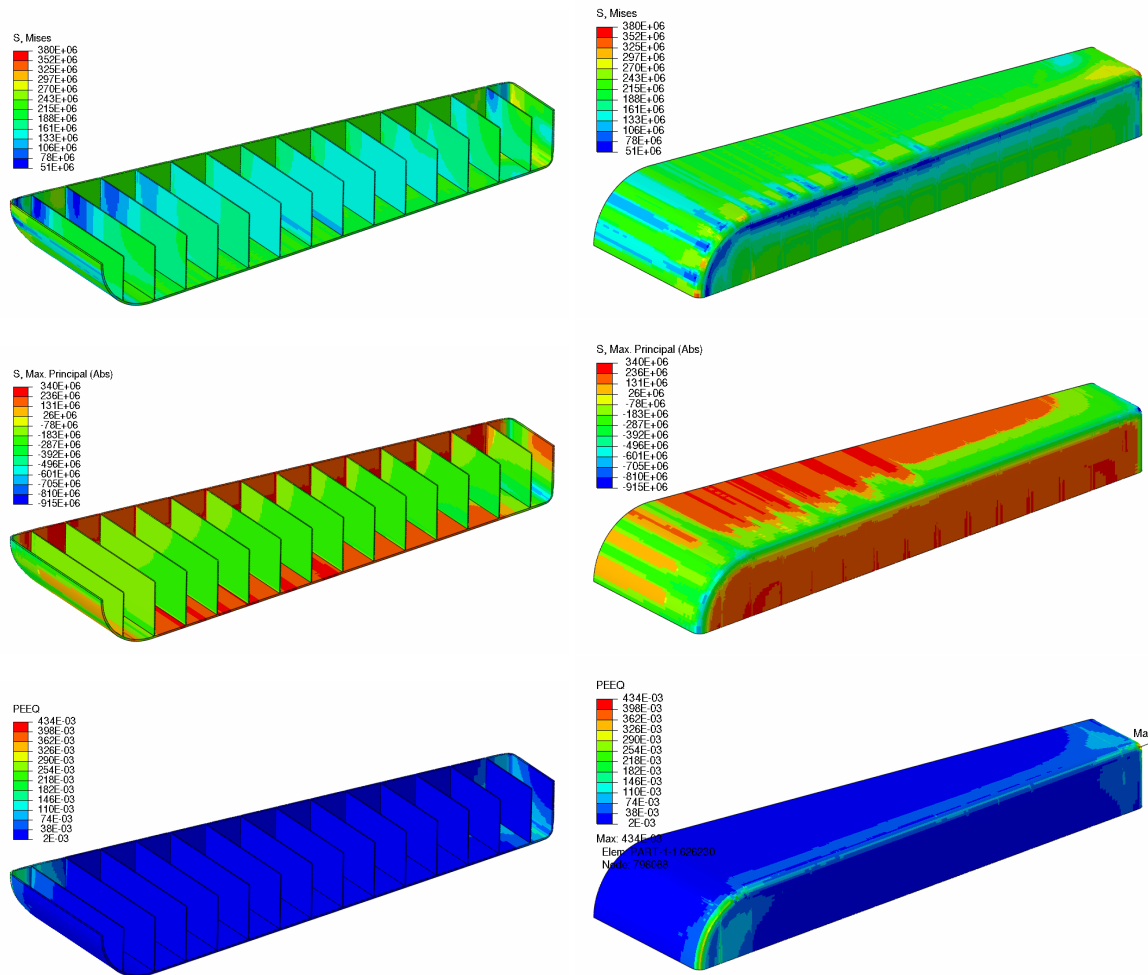


Figure 77. Stress state of the tantalum cladding after manufacturing simulation.

Figure 78 and Figure 79 show the Inconel shroud after the full manufacturing simulation. Almost the entire volume has experienced plastic deformation with the largest amount at the interface edges with the target core. Due to plastic hardening, the shroud has a residual stress higher than nominal yield. A stress discontinuity plot, seen in Figure 80 indicates an acceptable mesh apart from higher discontinuity regions in the front cooling channels and the rear contact edge with the target core.

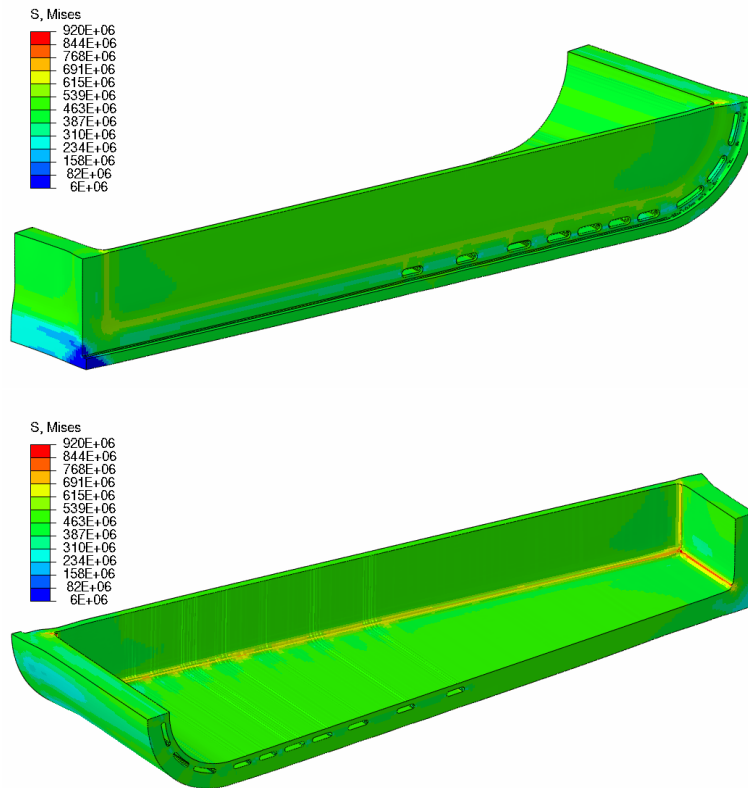


Figure 78. Inconel shroud after manufacturing with 20x displacement magnification.

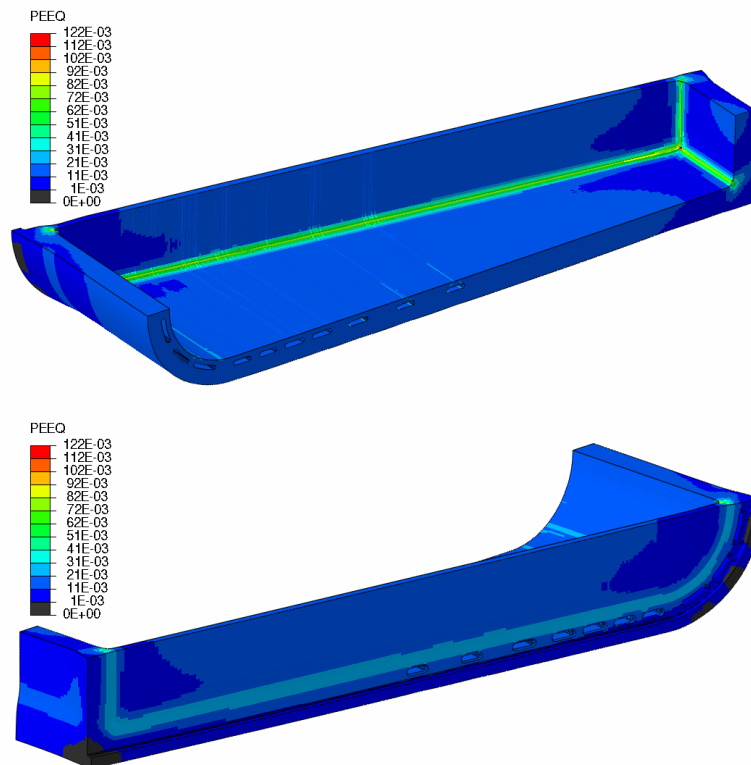


Figure 79. Inconel shroud plastic equivalent strain after manufacturing simulation.

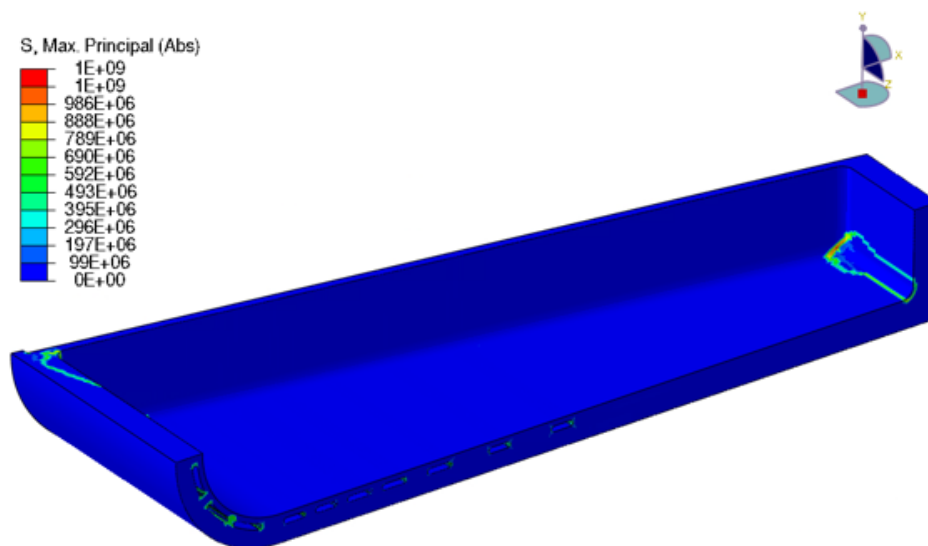


Figure 80. Stress discontinuity plot of the Inconel shroud after manufacturing simulation.

Figure 81 shows the effect of machining on the Inconel stress distribution. After the HIP operation, the shroud is in a state of tension, except for the contact edges which are in compression against the W/Ta core. After the machining operation, the stress redistributes with concentrations near the cooling channel roots. Figure 82 provides further views. Figure 83 shows the complex stress state in the rear corner of the shroud with high compressive stresses on the edges close to tensile regions on the side.

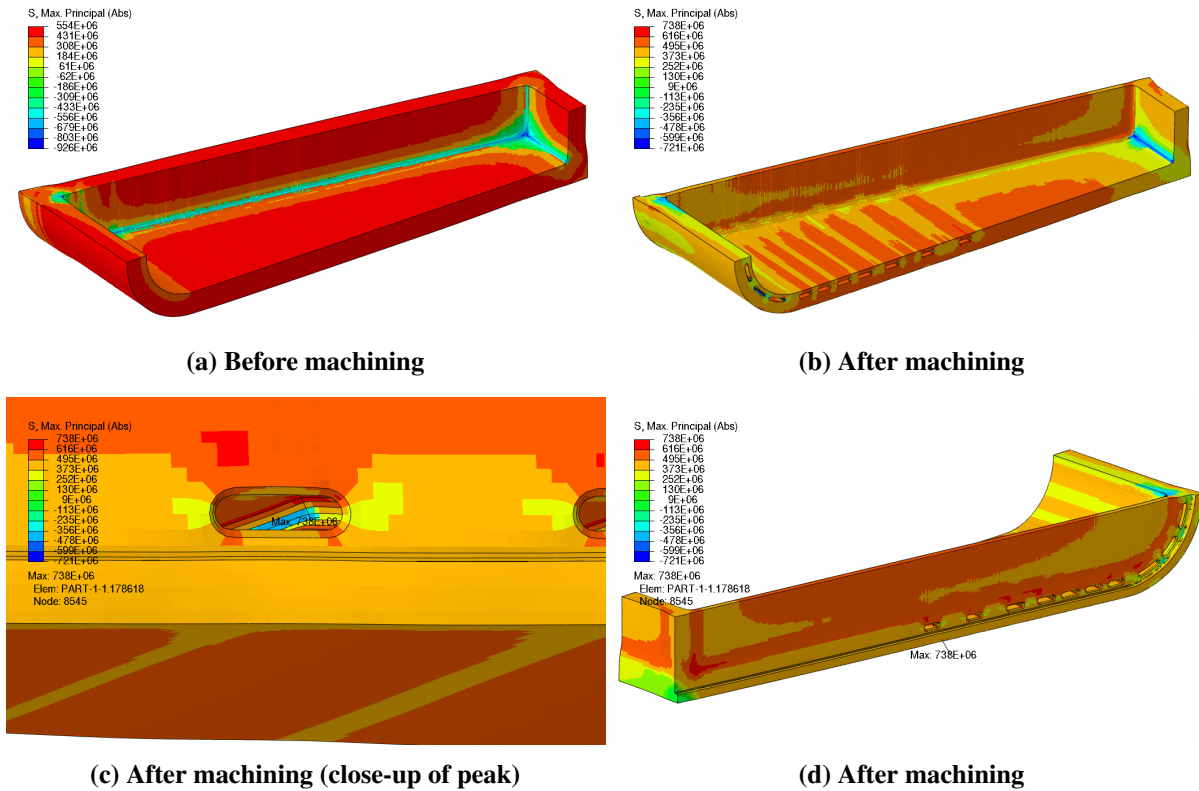


Figure 81. Effect of machining on the Inconel shroud stress state. Results show 20x displacement magnification.

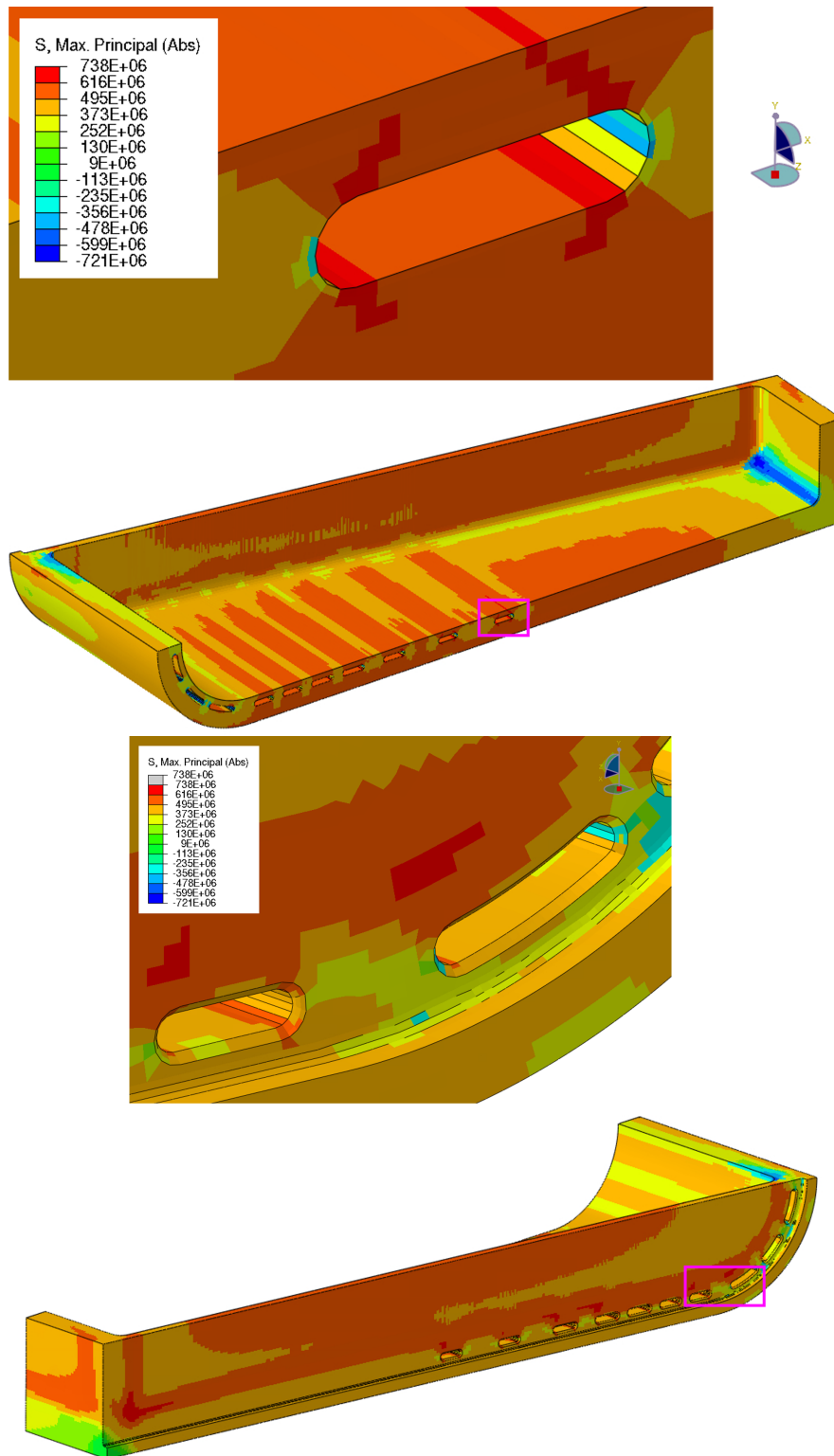


Figure 82. Detailed views of residual stress in the Inconel shroud after manufacturing simulation.

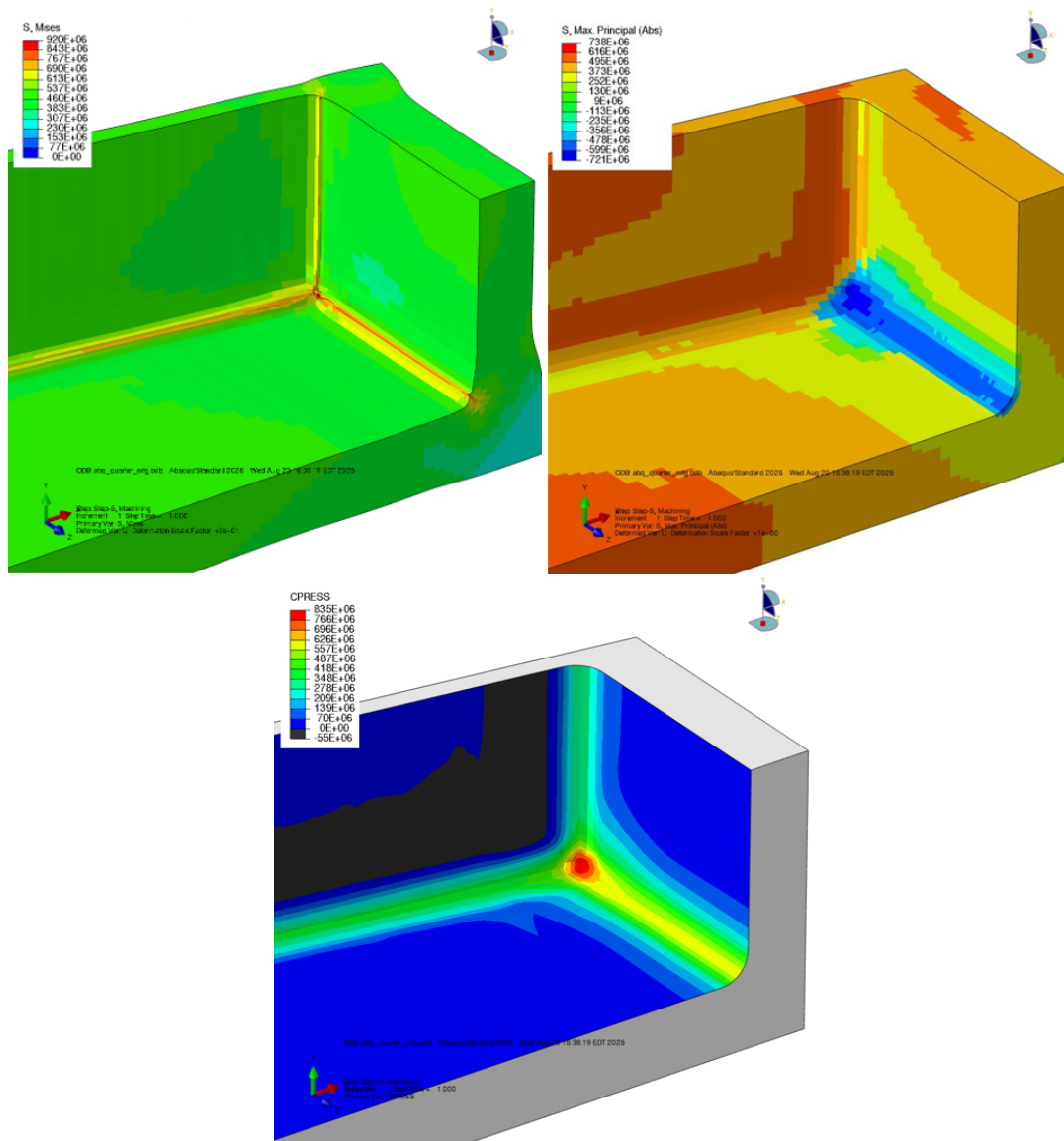


Figure 83. Stress state in the rear corner of the Inconel shroud after manufacturing simulation.

To gain a better understanding of the Inconel-to-tantalum bond strength, contact shear stresses are plotted in Figure 84 and Figure 85. The shear stress appears differently on the tantalum and Inconel surfaces due to numerical extrapolations of the contact forces onto the respective mesh element faces. Peak bond shear stresses are roughly 180 MPa. For comparison, the von Mises equivalent stress for pure shear is 312 MPa ($\sigma_{vm} = \sqrt{3} \cdot \sigma_{12}$). This is well below the expected 930 MPa UTS of Inconel. The tantalum requires further insight into the true stress-strain performance in the plastic deformation regime. Figure 86 gives a comparison of tantalum stress-strain curves from the "Target Systems Materials Library" [16]. The curve labeled *Engineering* is the engineering stress-strain curve from Oak Ridge National Laboratory (ORNL) R&D testing of tantalum sheet (specifically sample "transverse-04"). The curve labeled *True* is the true stress-strain curve calculated from the engineering test data. The curve labeled *Abaqus* is the true stress-strain curve input into Abaqus for tantalum at 25°C. The Abaqus model does not capture the Lüders bands phenomenon at the point of initial yield. Otherwise, it matches the true stress-strain data quite well. Also, both true stress-strain curves show margin above the von Mises equivalent bond strength peak value of 312 MPa. Furthermore, the peak bond shear stresses are localized at the rear corner of the target in the region of maximum PEEQ (see Figure 77), and this a region of high contact compression. Away from this, the bond shear stresses are roughly 150 MPa which gives an equivalent von Mises stress value of 260 MPa.

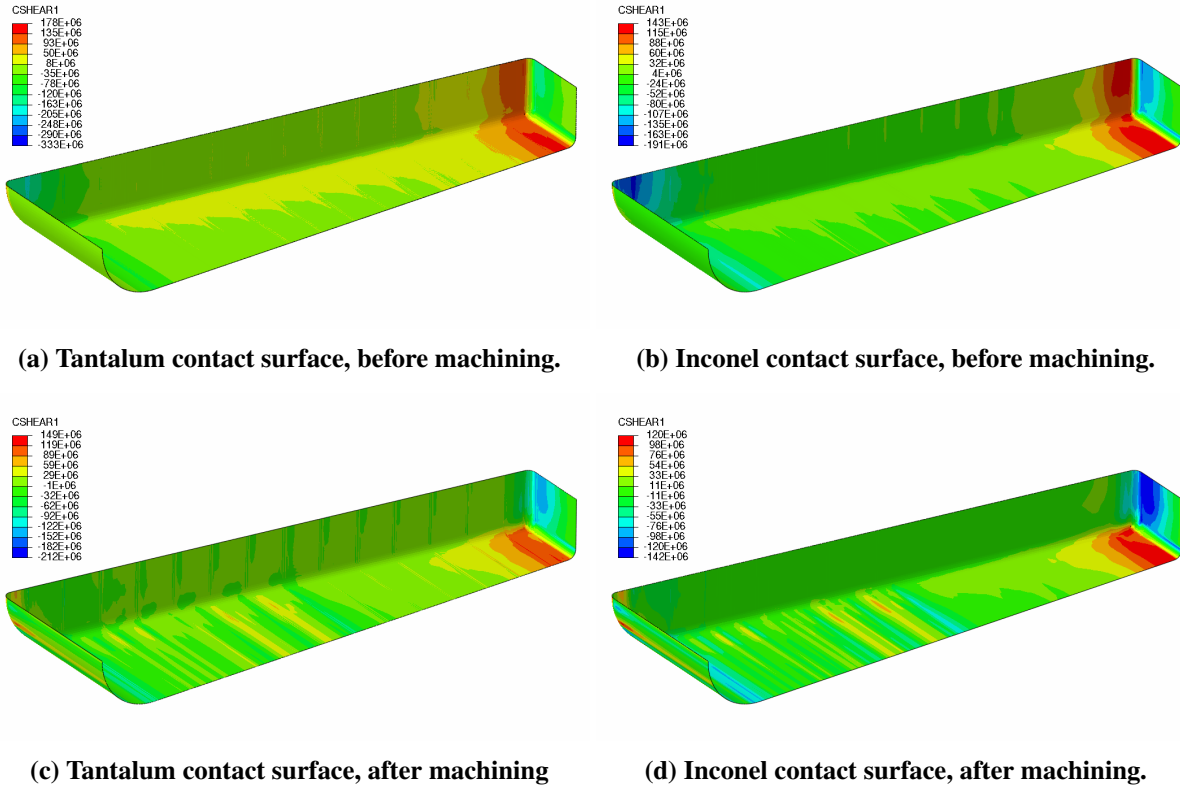
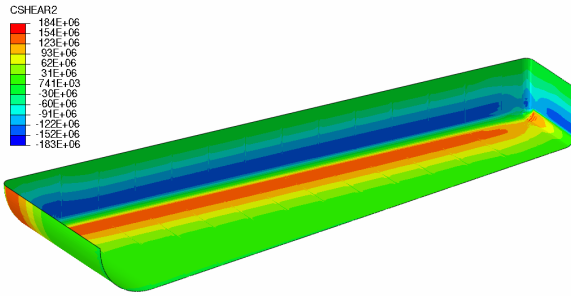
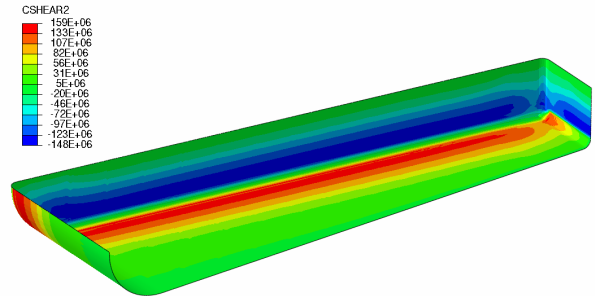


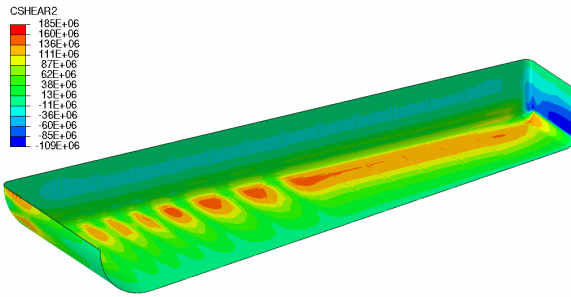
Figure 84. Shear stress (CSHEAR1 — orthogonal to the beam direction) of the contact surfaces before and after machining.



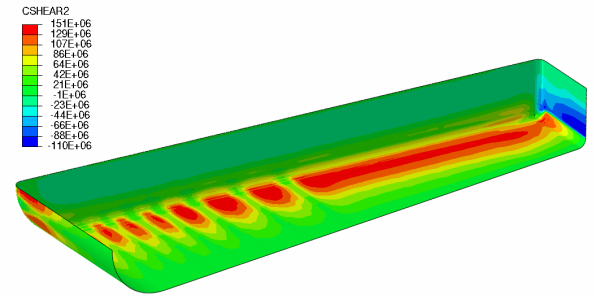
(a) Tantalum contact surface, before machining.



(b) Inconel contact surface, before machining.



(c) Tantalum contact surface, after machining.



(d) Inconel contact surface, after machining.

Figure 85. Shear stress (CSHEAR2 — parallel to the beam direction) of the contact surfaces before and after machining.

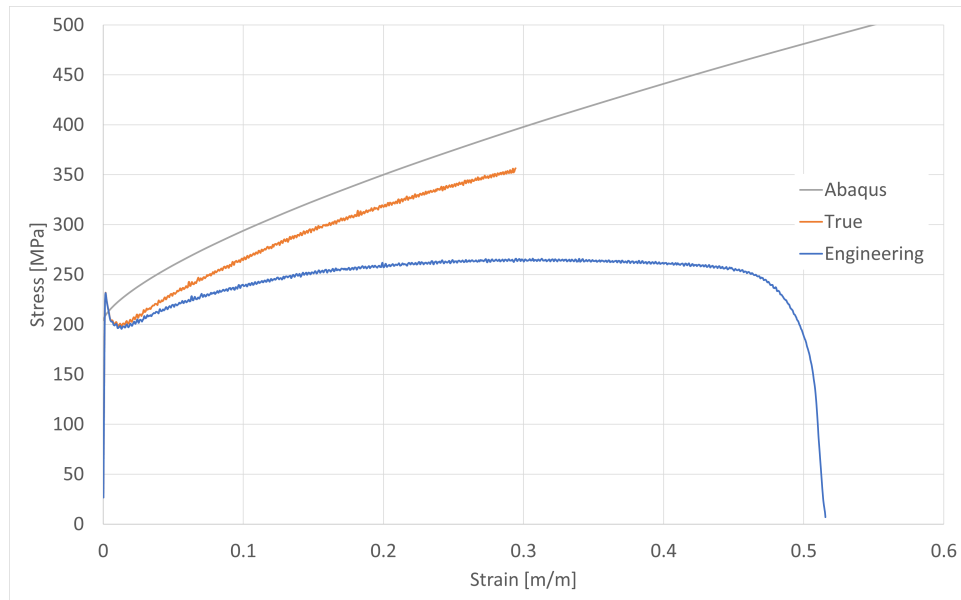


Figure 86. Tantalum tensile test data converted from engineering to true stress-strain. Comparison against Abaqus material data at room temperature.

5.2 QUASI-STATIC LOADING - NOMINAL BEAM

Figure 87 shows the deflection of the target segment after all static loads are applied. The dead load and centrifugal load tend to drop the "toe" of the foot downward while the centrifugal load brings the pin to engage with the front of the slot. Figure 88 probes the contact status of the pin/slot contact. Only a couple of elements are in contact as the pin pivots about the rounded slot feature. This engagement is at the edge of the defined contact surface. The lower surface of the slot could have also been included in the definition, however, that would only serve to reduce stresses (i.e. applying contact force over more elements). The current formulation is conservative.

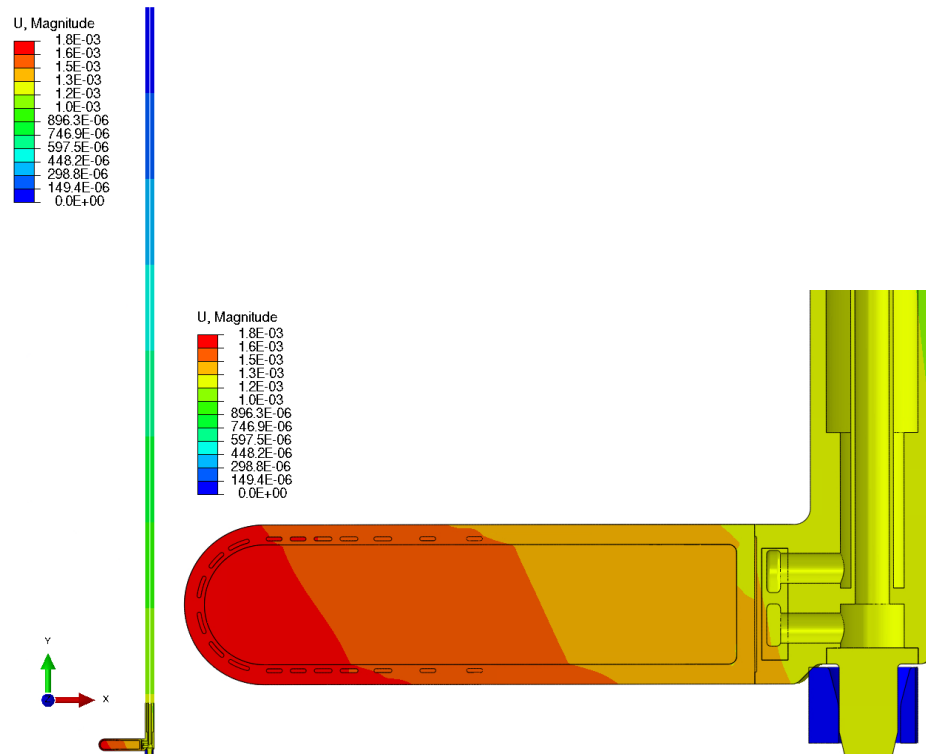
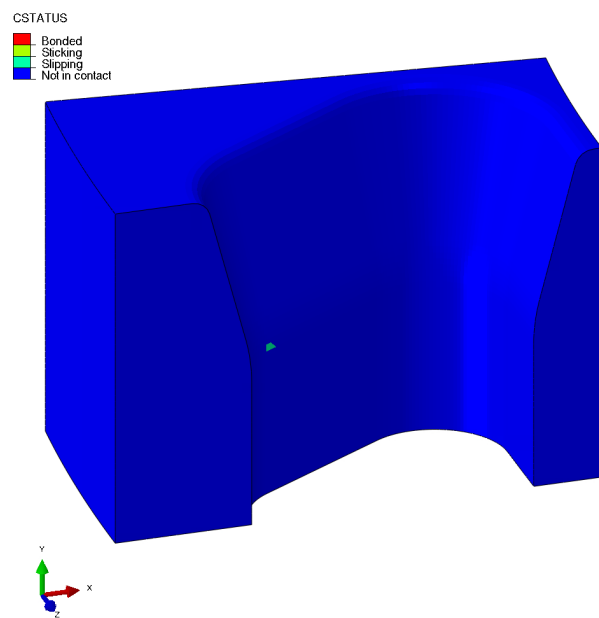
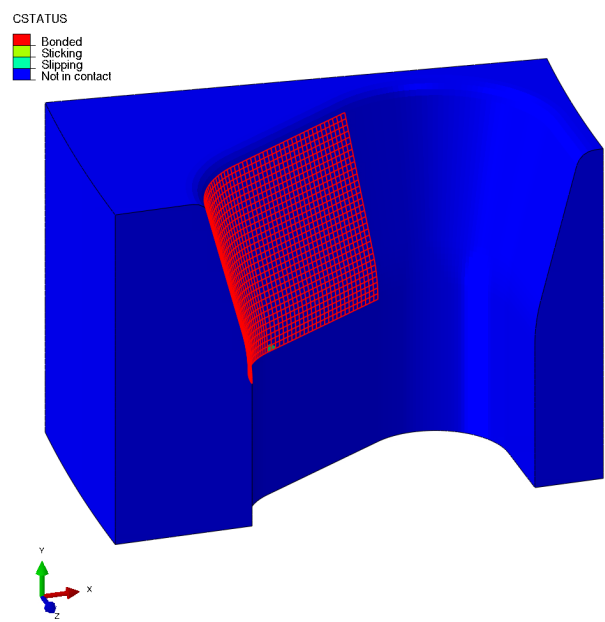


Figure 87. Deflections of the target segment under static loading conditions.



(a) Slot surface showing location of pin contact



(b) Overlay of active contact elements

Figure 88. Static stress half symmetry model pin/slot contact condition.

The flow cover and heel structures do not have any manufacturing residual stresses as they are welded to the foot after it's manufacturing. The dead, live, and pressure loads have minor impacts on these structures. The major load on these structures is the quasi-steady temperature field that was presented in Section 3.3.7. Figure 89 shows the stress state of the flow cover. The peak stress occurs at the fillet near the weld location toward the rear of the target. This is just rear of the last cooling channel and where the target core has a higher bulk temperature (but lower peak). It is the result of a design trade-off of the need to direct coolant flow at the front of the target where higher peak temperatures and larger dynamic stresses develop.

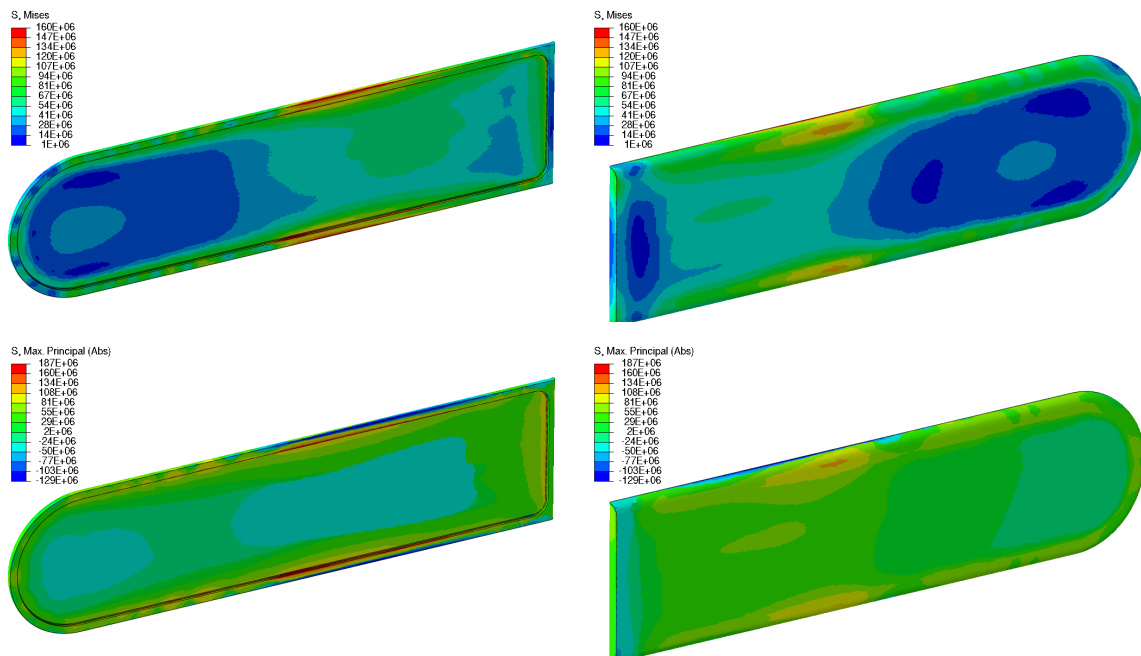


Figure 89. Stress state of the flow cover under static loading conditions. Top: von Mises equivalent stress field; Bottom: Maximum principal stress (abs) stress field

Figure 90 shows the stress state of the heel structure. The peak stress, nearly 200 MPa, occurs at the pin/slot contact point. This value is suspect as the geometry of the interface creates a near singularity as the pin rotates about the curve of the slot. Stresses around 175 MPa are generated from thermal loading at the heel weld and at the radii of the cooling manifold slot.

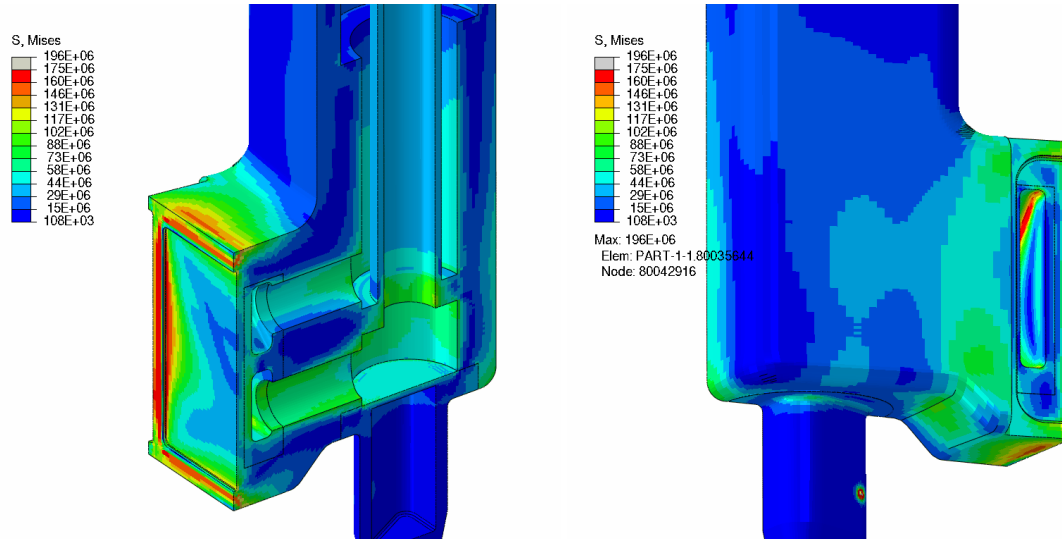


Figure 90. Stress state of the stainless heel under static loading conditions.

Figure 92 and Figure 91 show the stress state in the Inconel shroud and tungsten plates after static loading. In general, the stresses are lower than the initial state (after manufacturing) as the manufacturing residual stresses are reduced by the warm-up to quasi-steady beam heating.

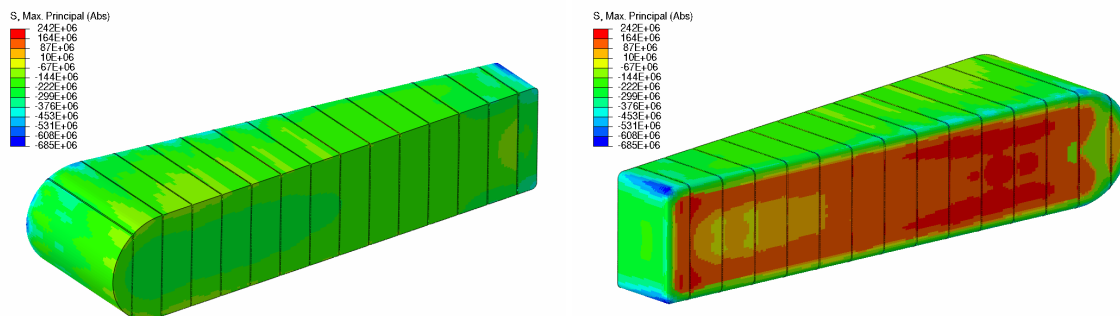


Figure 91. Stress state of the tungsten plates under static loading conditions.

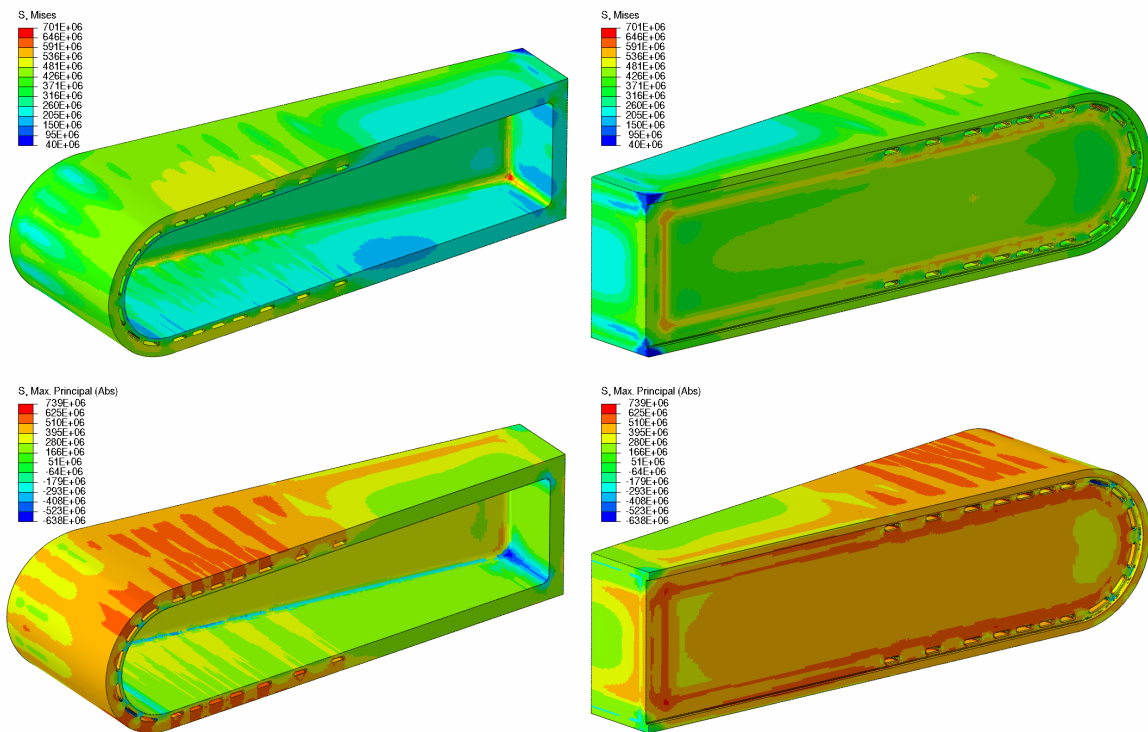


Figure 92. Stress state of the Inconel shroud under static loading conditions.

5.3 CASE A FATIGUE - NOMINAL BEAM

The fatigue analysis is driven by the quasi-steady temperature (which controls the beam trip amplitude and the mean stress of the beam pulse fatigue) and by the instantaneous pulse temperature rise (which controls the amplitude of the beam pulse). These temperature fields were discussed in Section 3.3.7 and Section 3.3.6.

5.3.1 Goodman Diagrams

Figure 93 summarizes the fatigue analyses on a Goodman diagram for each of the material models (Inconel, tungsten, stainless steel) and for each of the fatigue life types (beam trips, beam pulses). The tungsten fatigue model uses the brittle normal stress failure theory. *fe-safe* outputs worst-case mean stress and stress amplitudes for each node in the stress analysis. This data can be plotted directly on the Goodman diagram to visualize the FOS in relation to the design envelope. The design envelope is interpreted as the FOS = 1 boundary. If all nodes fall within the design envelope, then FOS > 1 and the design requirement is satisfied. If any node falls outside the design envelope, then this graphically indicates FOS < 1 and the design requirement is not satisfied.

The Inconel and stainless steel models use the stress-based Brown-Miller ductile fatigue theory. *fe-safe* outputs worst-case mean stress along with the (Kandil) Brown-Miller strain parameter ($\Delta\epsilon_{BM}$) for each node. Before this can be plotted on the Goodman diagram, it must first be converted into an equivalent stress amplitude. Equation 20 shows the full Brown-Miller strain-life equation used by *fe-safe* [3]. The combined left hand side ($(\Delta\gamma + \Delta\epsilon_n)/2$) is the (Kandil) Brown-Miller strain parameter ($\Delta\epsilon_{BM}$). The right hand side combines the low-cycle fatigue life relationship (i.e. plastic deformation) with the high-cycle fatigue life relationship (i.e. elastic deformation). If only high-cycle fatigue is assumed (which is supported by the plastic ratcheting assessment in Section 5.8), then the relationship simplifies to Equation 21. This can be re-expressed in Equation 22 to show how the (Kandil) Brown-Miller strain parameter can be converted into an equivalent fully-reversing stress amplitude ($\sigma_{a,eq}$) for plotting.

$$\frac{\Delta\gamma}{2} + \frac{\Delta\epsilon_n}{2} = 1.75\epsilon'_f (2N_f)^c + 1.665 \frac{\sigma'_f}{E} (2N_f)^b \quad (20)$$

$$\Delta\epsilon_{BM} \approx 1.665 \frac{\sigma'_f}{E} (2N_f)^b \quad (21)$$

$$\sigma_{a,eq} = \frac{\Delta\epsilon_{BM} \cdot E}{1.665} \approx \sigma'_f (2N_f)^b \quad (22)$$

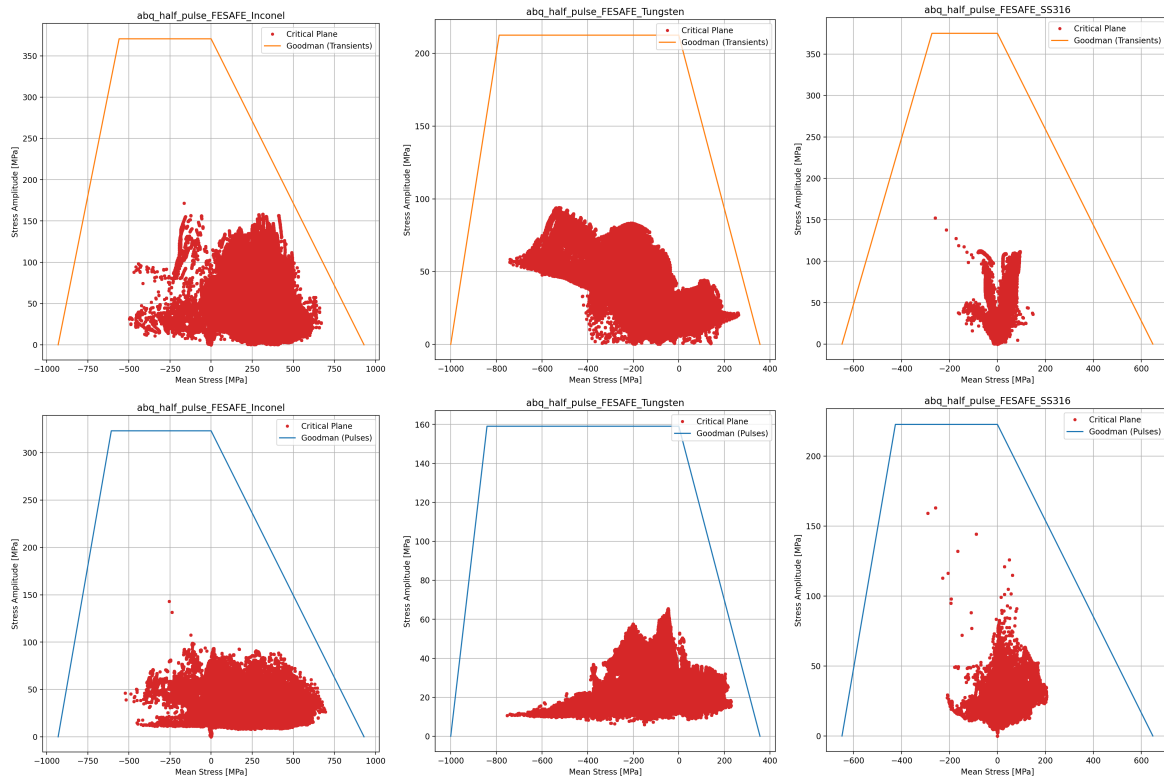


Figure 93. Nominal case Goodman diagrams: Beam trips (top) and beam pulses (bottom) for Inconel (Left), Tungsten (Mid), and Stainless (Right).

5.3.2 Fatigue Contour Plots

fe-safe also outputs contour plot solution data of the FOS, worst-case mean stress field, and worst-case amplitude field. It should be noted that *fe-safe* uses the same "Cycle-Amp" field to represent both stress amplitude (for normal stress fatigue models) and (Kandil) Brown-Miller strain parameter (for ductile Brown-Miller fatigue models).

Figure 94 and Figure 95 show these plots for the tungsten plates. For beam trips, the minimum FOS of 1.2 occurs on the side of the plates near the rear of the target and is driven mainly by high tensile residual stress. For beam pulses, the minimum FOS of 1.3 occurs on the side of the plates near the front of the target and is driven by high tensile residual stress along with higher amplitude. The highest pulse stress amplitudes occur in the beam center of the target, however, these are mitigated by a compressive mean stress.

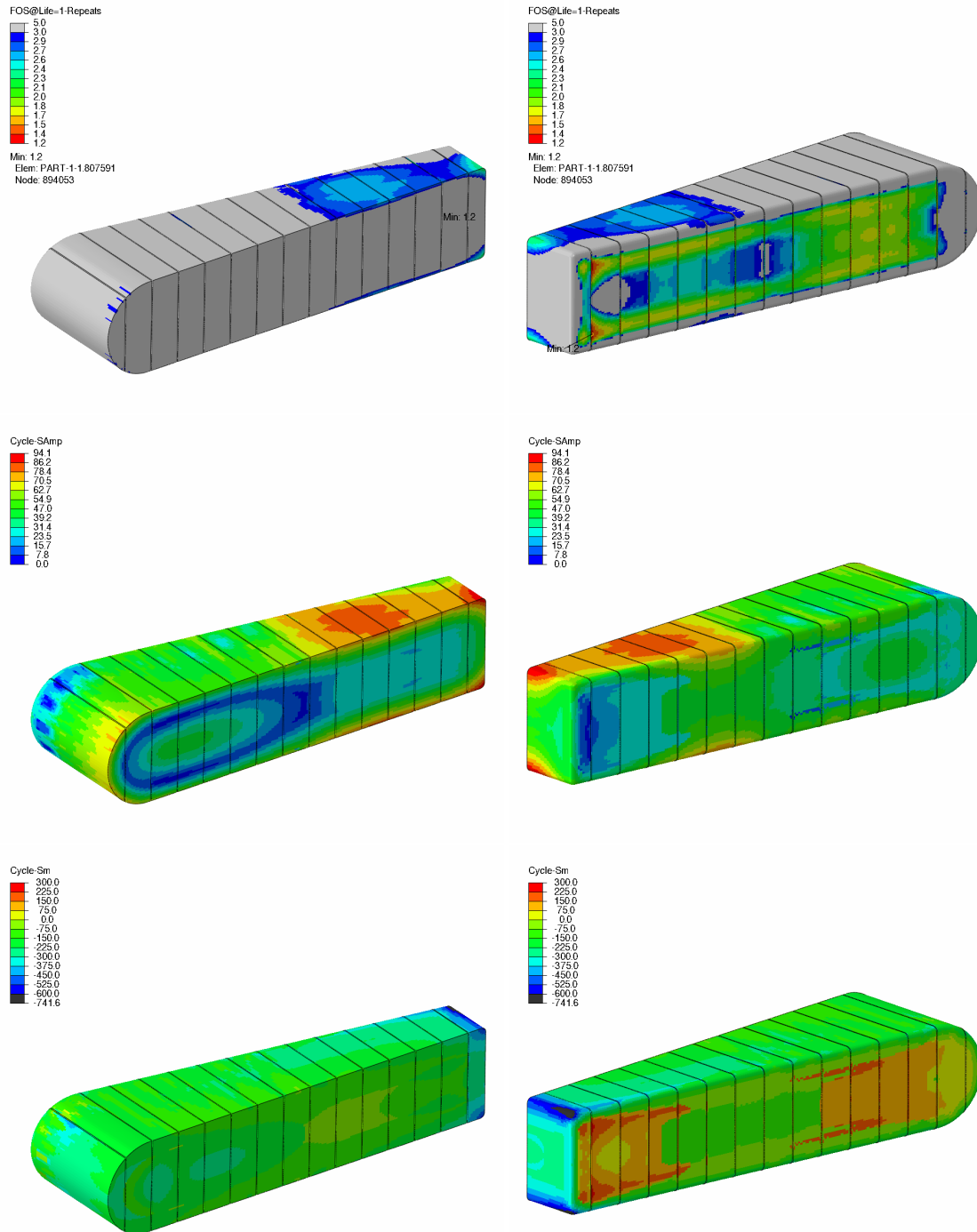


Figure 94. Nominal case fatigue contour plots for tungsten under beam trips (top to bottom): FOS, worst plane stress amplitude, worst plane mean stress.

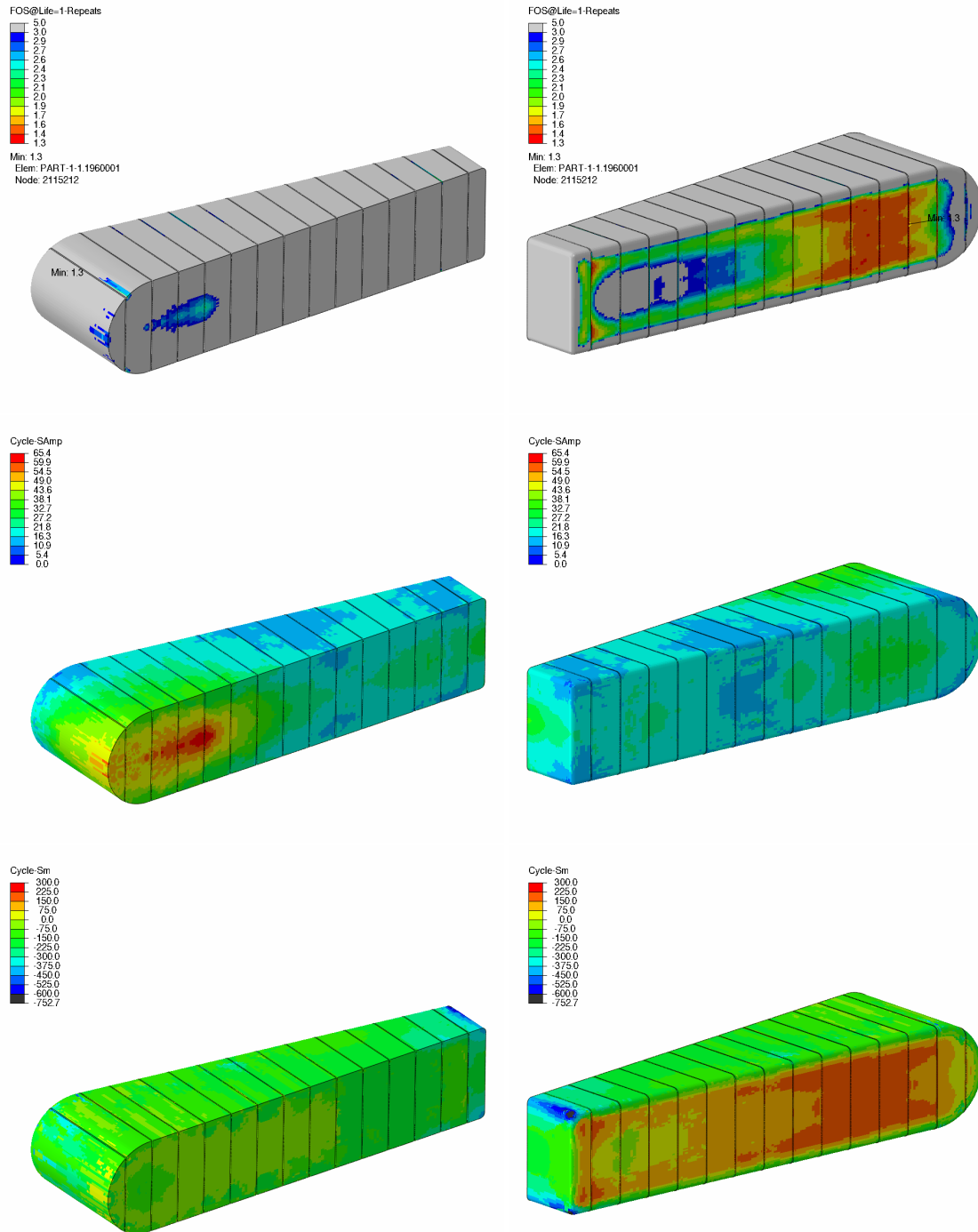


Figure 95. Nominal case fatigue contour plots for tungsten under beam pulses (top to bottom): FOS, worst plane stress amplitude, worst plane mean stress.

Figure 96 and Figure 97 show fatigue contour plots for the stainless steel heel. The region of high scatter seen in the Goodman plots corresponds to the pin/slot contact. As discussed previously, this is a region of numerical uncertainty. Even so, the structure is well-within the the failure envelope. Regions with the lowest FOS correspond to the heel weld feature and the flow manifold radii and are in the 1.8-2.0 range.

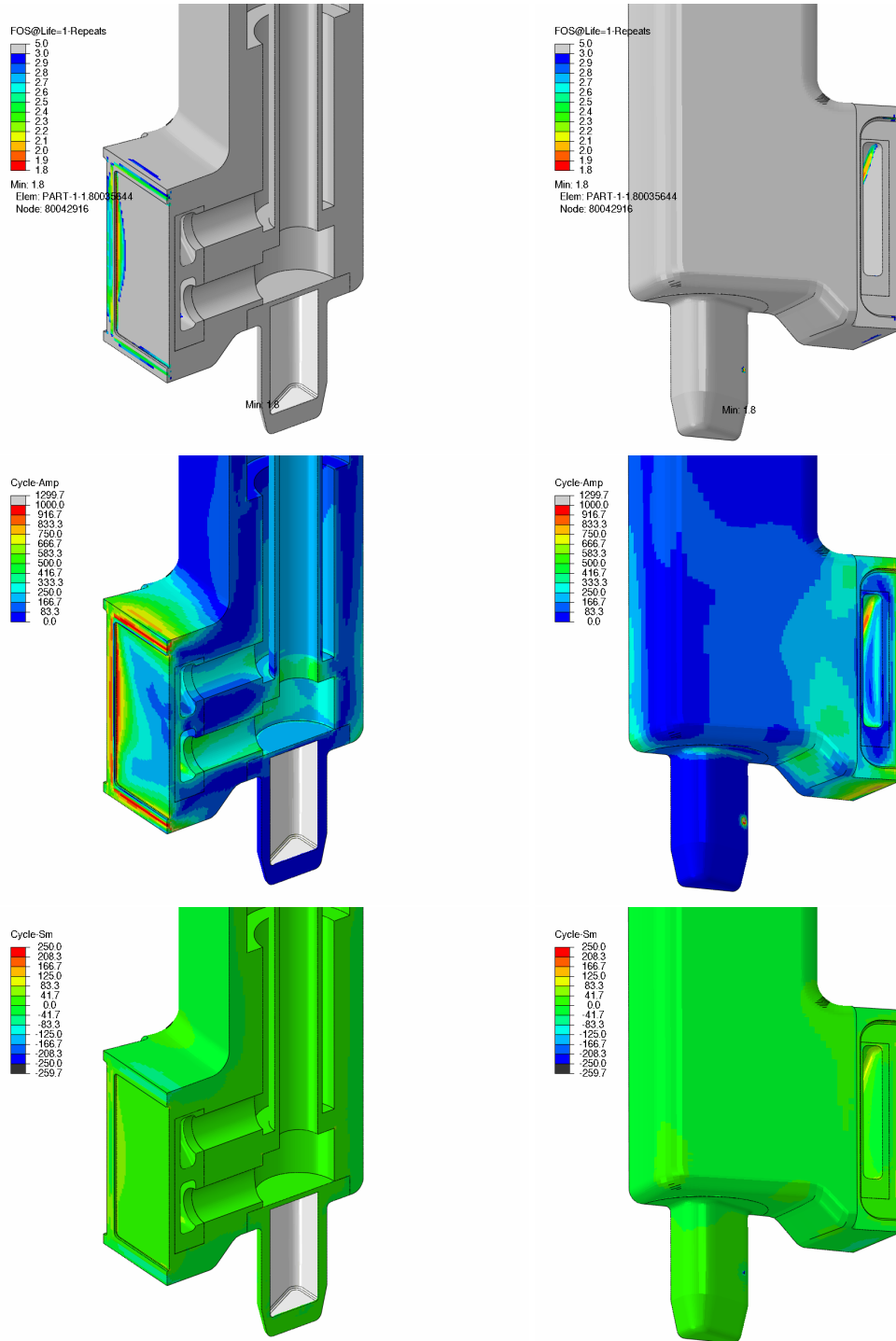


Figure 96. Nominal case fatigue contour plots for stainless heel under beam trips (top to bottom): FOS, worst plane amplitude strain parameter, worst plane mean stress.

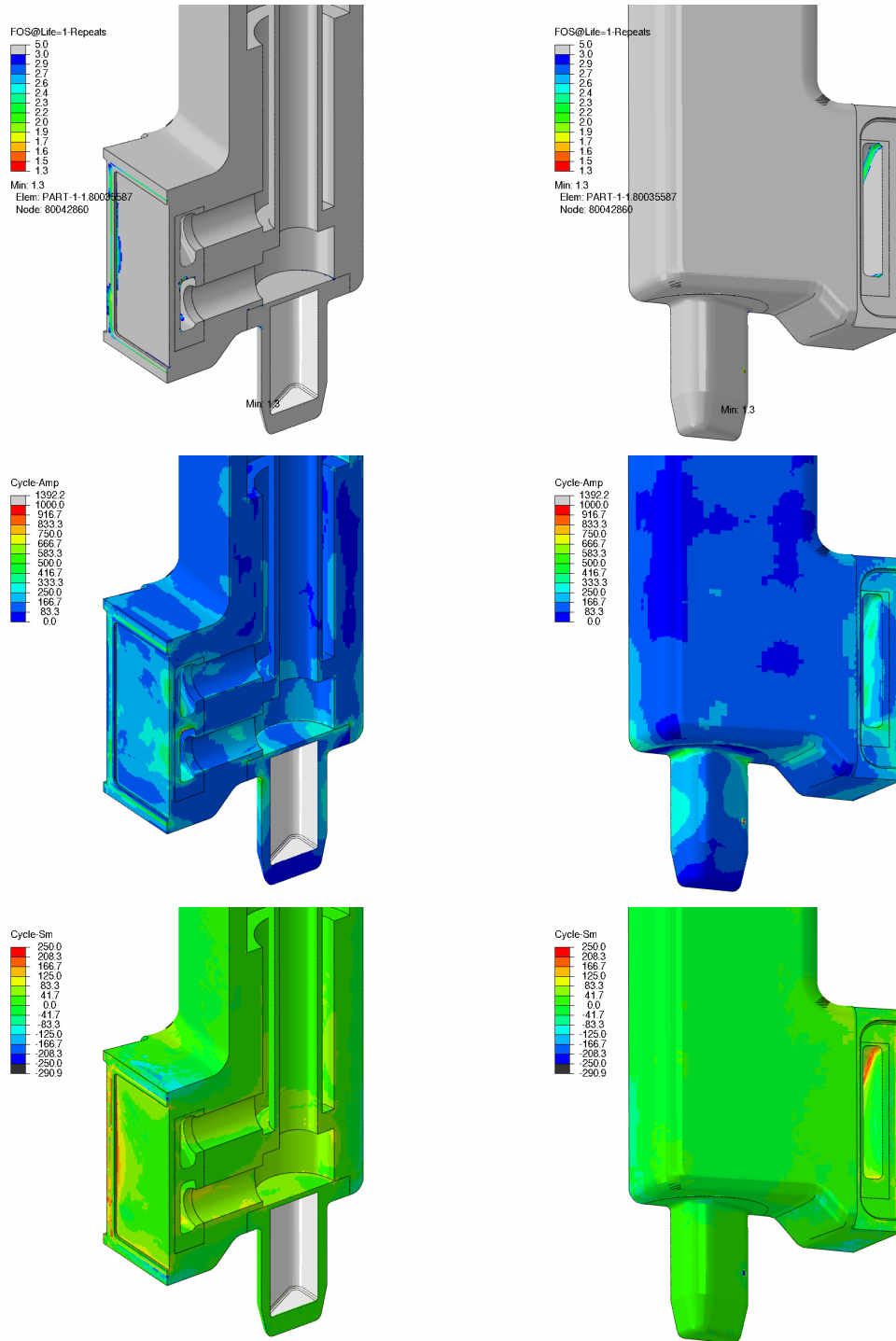


Figure 97. Nominal case fatigue contour plots for stainless heel under beam pulses (top to bottom): FOS, worst plane amplitude strain parameter, worst plane mean stress.

Figure 98. Nominal case fatigue contour plots for Inconel flow cover under beam trips (top to bottom): FOS, worst plane amplitude strain parameter, worst plane mean stress.



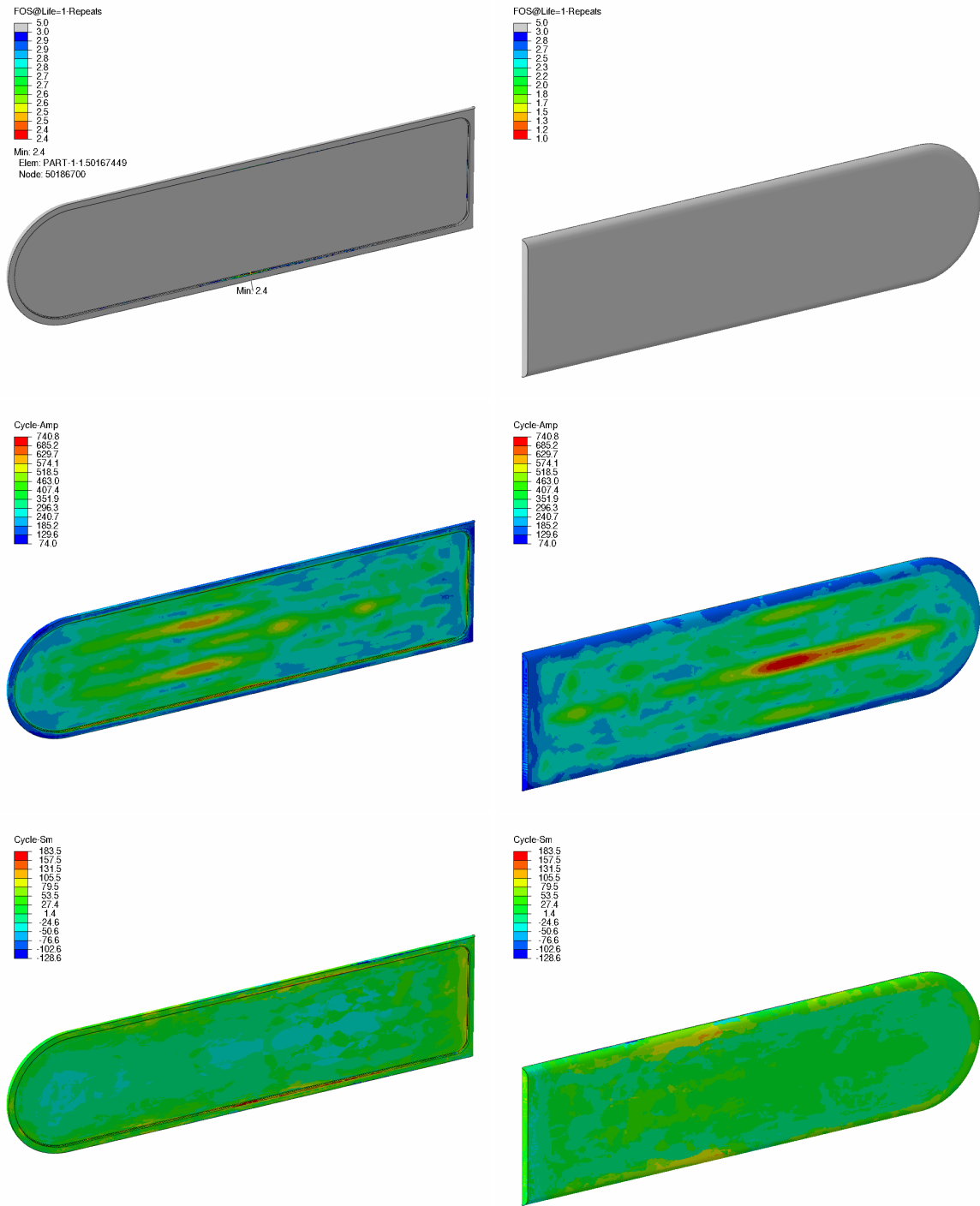


Figure 99. Nominal case fatigue contour plots for Inconel flow cover under beam pulses (top to bottom): FOS, worst plane amplitude strain parameter, worst plane mean stress.

Figure 100 and Figure 101 show fatigue contour plots for the Inconel shroud. For beam trips, the minimum FOS is 1.1 and corresponds to the center of the rear-most cooling channel. For beam pulses, the minimum FOS of 1.2 occurs in a different flow channel near the side manifold and near a weld. This will be further discussed in the next section.

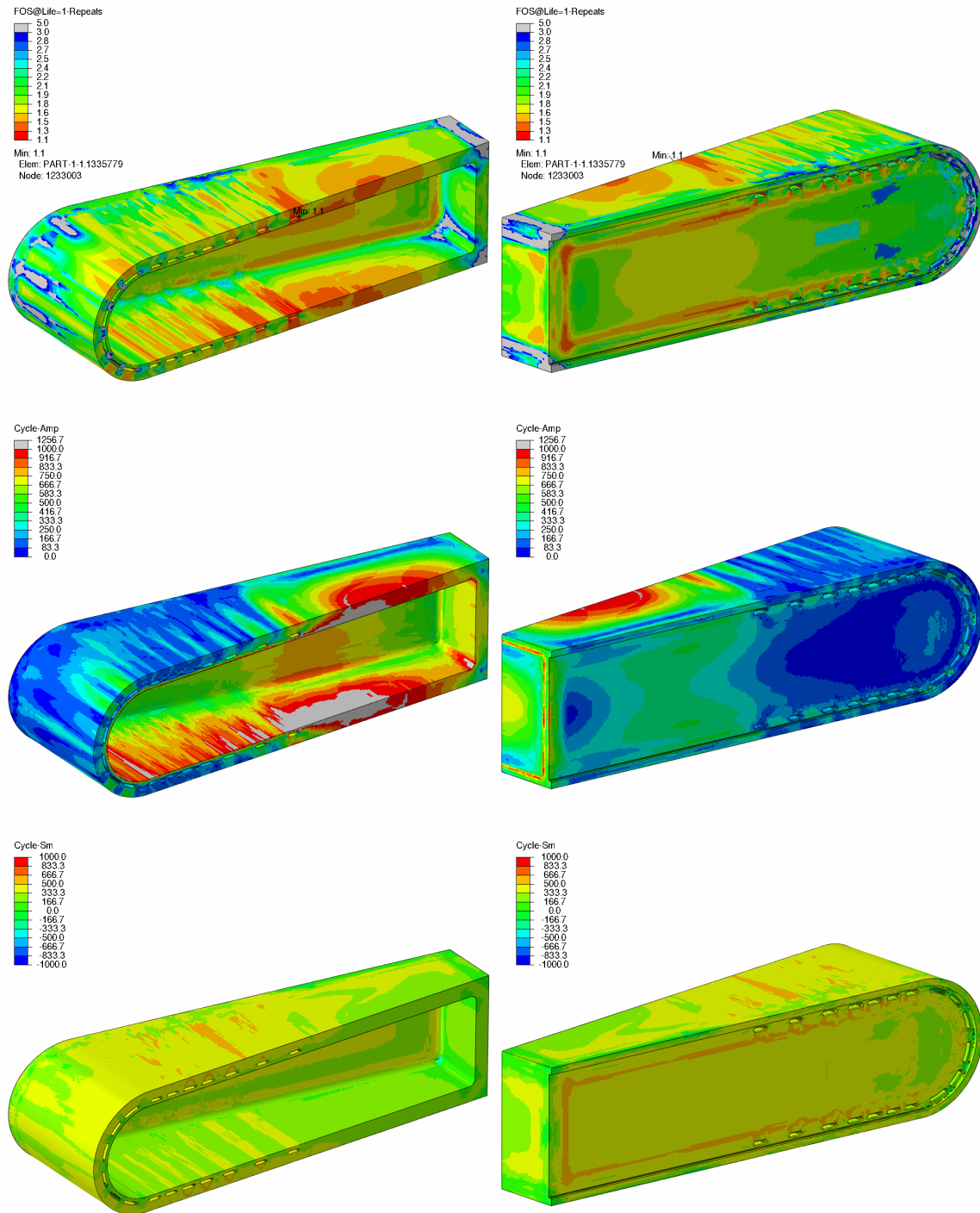


Figure 100. Nominal case fatigue contour plots for Inconel shroud under beam trips (top to bottom): FOS, worst plane amplitude strain parameter, worst plane mean stress.

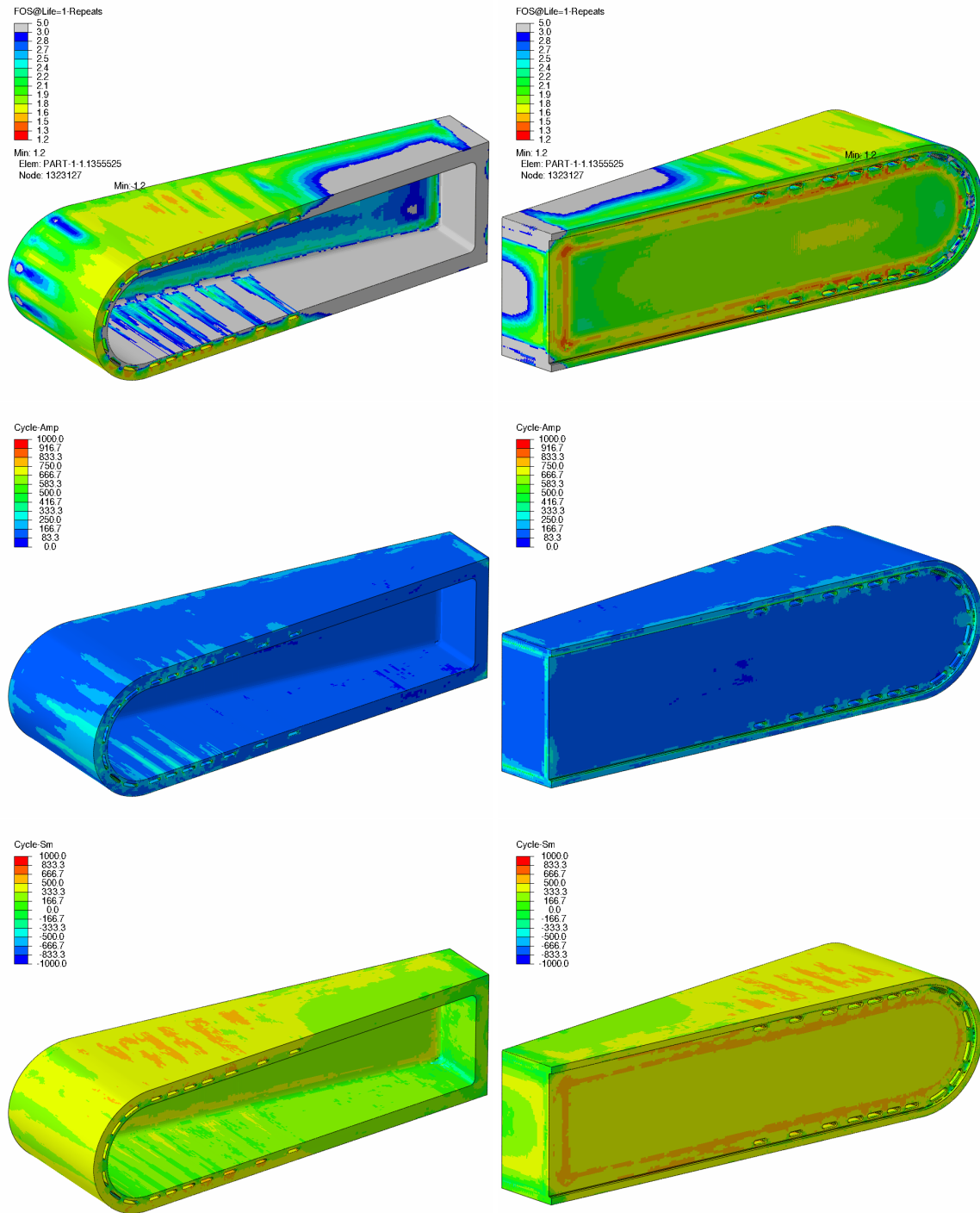


Figure 101. Nominal case fatigue contour plots for Inconel shroud under beam pulses (top to bottom): FOS, worst plane amplitude strain parameter, worst plane mean stress.

5.3.3 Inconel Side Plate Weld

The Inconel side weld is a non-symmetric feature of the otherwise symmetric target foot. The side plate and weld region are shown in Figure 5 after machining the side and flow channels. Figure 102 shows an element set that approximates the weld HAZ. Note that this is really on the opposite side of the target (see Figure 5). In Figure 103, the weld cover geometry has been reflected in the images to show the overlap between the element set and the weld location.

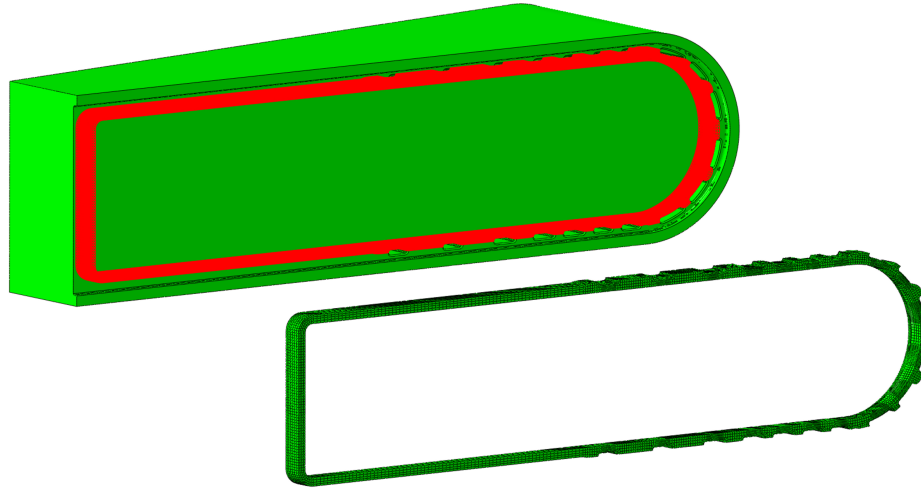


Figure 102. Inconel side weld HAZ element set.

The weld element set goes through fatigue analyses using a reduced UTS and fatigue strength as explained in the "Target Systems Materials Library" [16]. This is using Inconel weld material fatigue properties and does not incorporate any ASME/BPVC FSRF. Figure 104 shows the Goodman diagrams where the minimum FOS is 1.02 for beam transients and 0.92 for beam pulses. Figure 105 shows the worst region which lies at the outer edge of the HAZ and in the root of a flow channel.

Working backwards, a 1.0 FSRF would be required for the weld to pass the fatigue design requirement (i.e. $FOS > 1$). According to the ASME/BPVC, this then requires a full penetration weld of quality level 1.0 which is a "Machined or ground weld that receives a full volumetric examination, and a surface that receives MT/PT examination and a VT examination" (see Figure 19). The component drawings should specify this to meet requirements. Even so, a 1-element region at the edge of the HAZ has a 0.92 FOS. On the positive side, the weld takes place before HIP manufacturing so the weld goes through a post-weld heat treatment. In addition, the simulation of the cooling channel machining only removes material. It does not capture the surface effects of machining (which would be compressive) or of surface treatment (e.g. shot-peening or Kolsterizing). These treatments should be considered for the component.

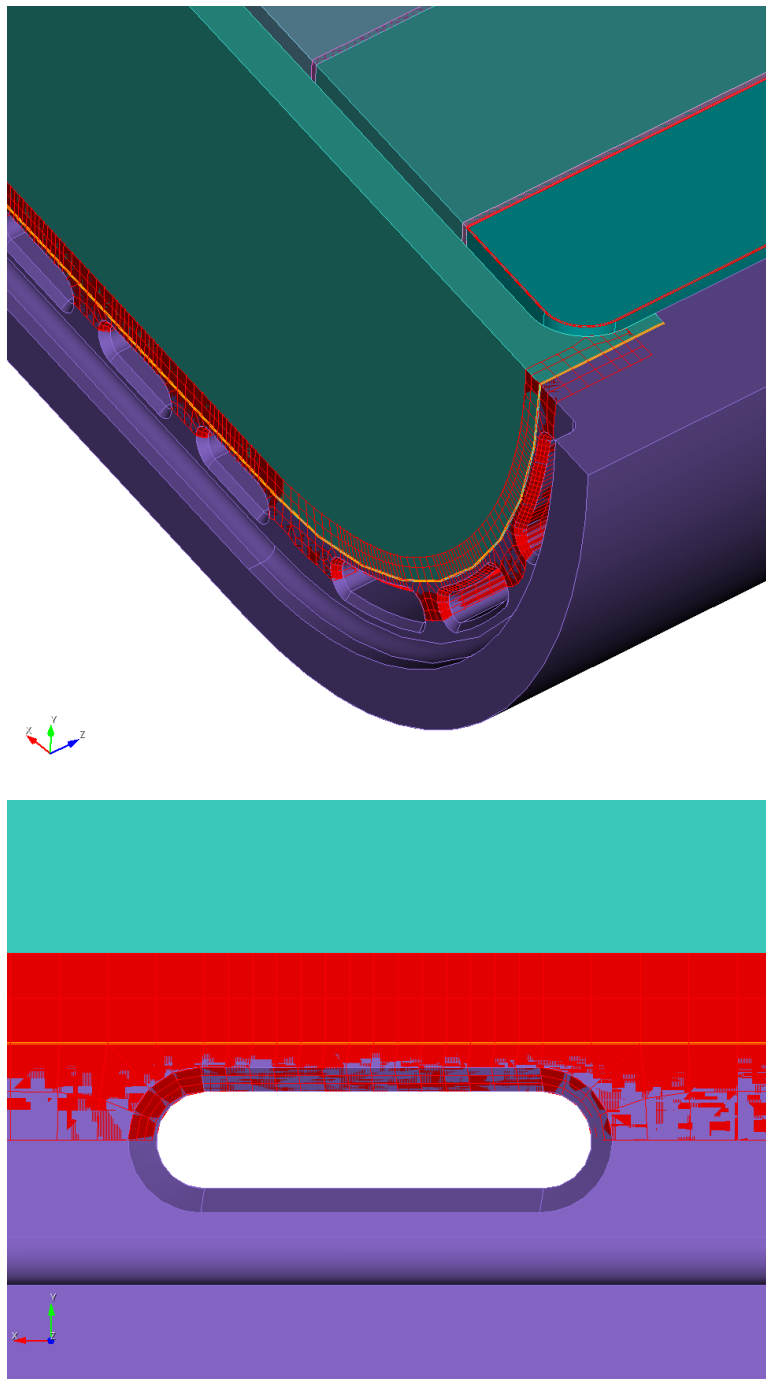


Figure 103. Inconel side weld element set in relation to (reflected) weld. The element set roughly incorporates 2-mm on either side of the weld line to the define the HAZ.

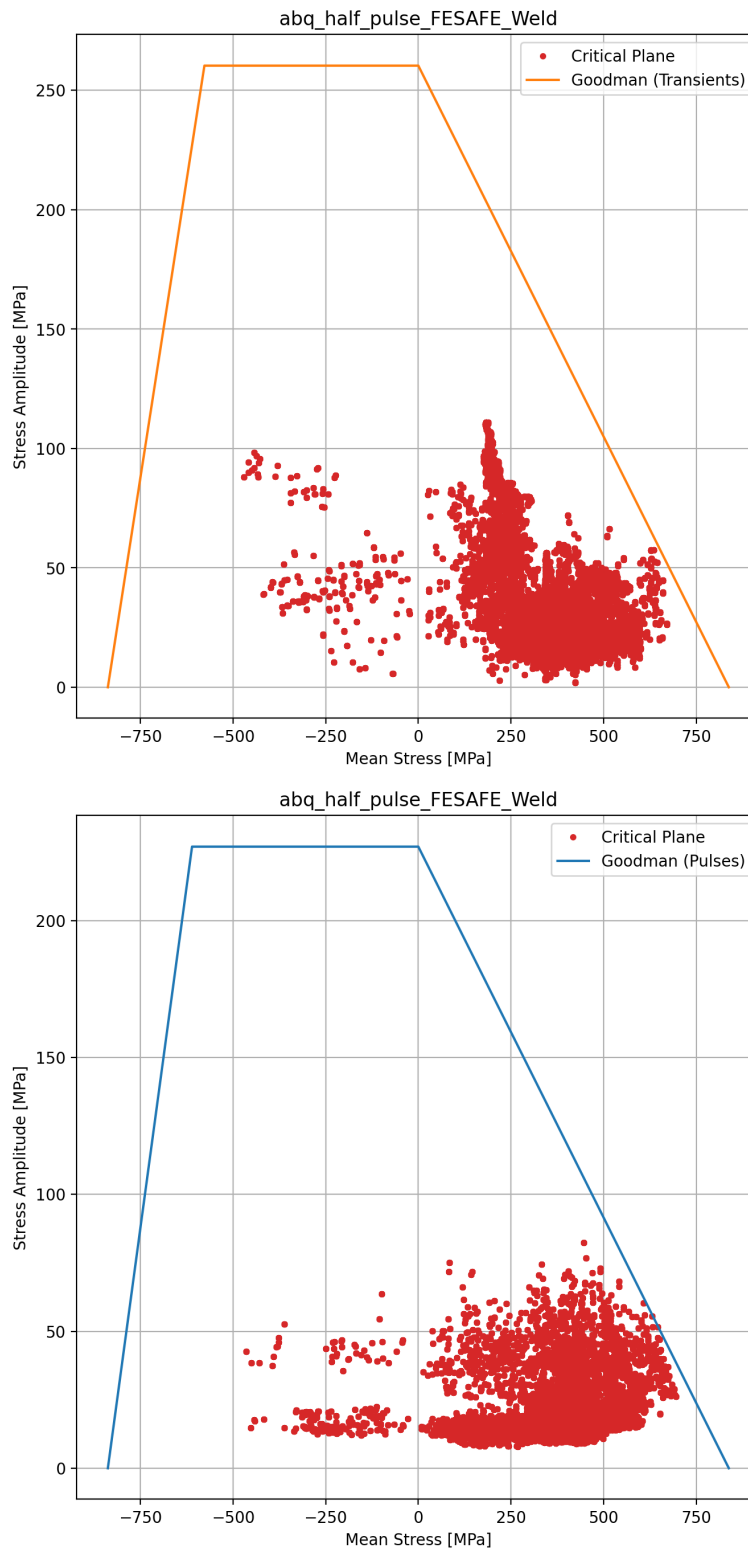


Figure 104. Weld element set Goodman diagrams for beam transients and beam pulse fatigue. The analysis uses Inconel weld filler fatigue curves but no FSRF.

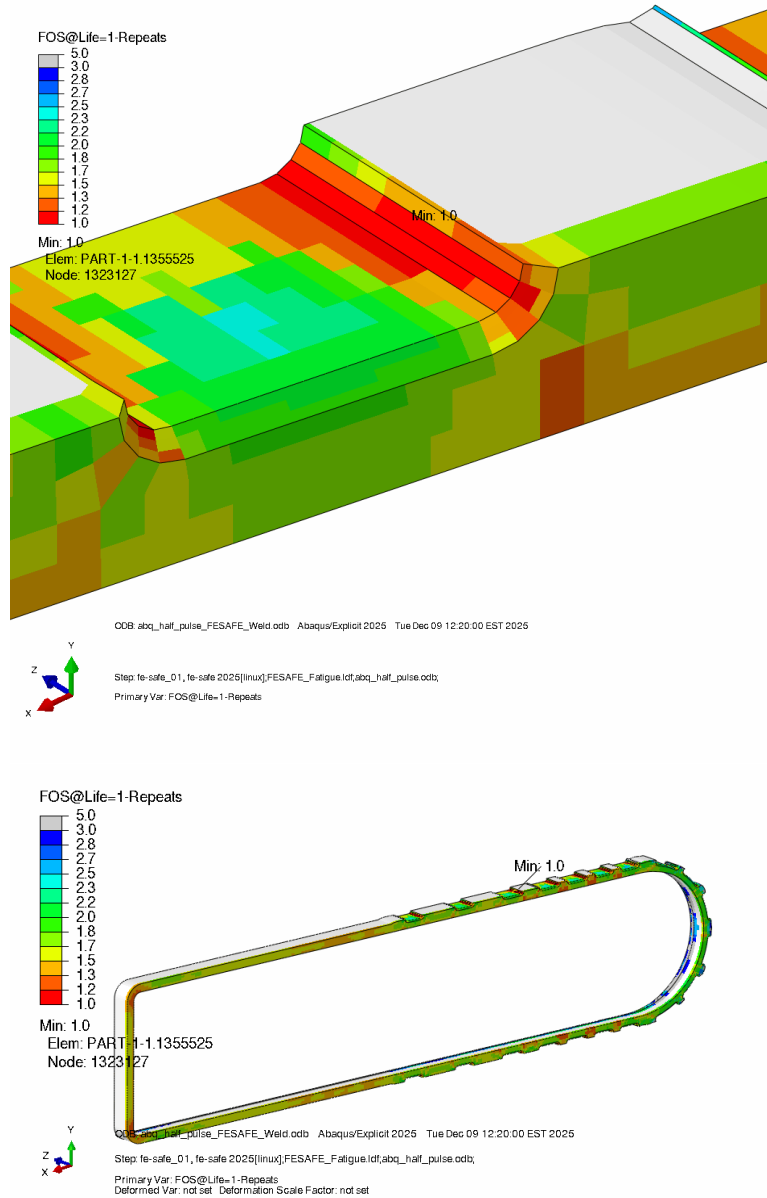


Figure 105. Weld element set FOS for beam pulse fatigue (using Inconel weld filler fatigue curves but no FSRF). The cooling channel wall at the edge of the HAZ has a continuous region at 1.0 FOS. One element within this region fails with a 0.92 FOS (shown as rounding to 1.0).

5.3.4 Inconel Flow Cover and Heel Welds

The Inconel flow cover is welded to the Inconel shroud and then, in the back, to the stainless steel heel. A weld HAZ element set is not directly available. Instead, the Inconel fatigue analysis is re-run in fe-safe using weld properties and the post-processor is used to create sliced views of the FOS. Figure 106 shows the flow cover (evaluated as a weld) along with a 2-mm slice of the shroud (to approximate a HAZ). The shroud is the limiting feature with a FOS of 1.2 and 1.1 for beam trips and beam pulses, respectively. Again, in order to pass fatigue requirements, this weld requires a 1.0 FSRF which then requires a full penetration weld of quality level 1.0 which is a "Machined or ground weld that receives a full volumetric examination, and a surface that receives MT/PT examination and a VT examination" (see Figure 19).

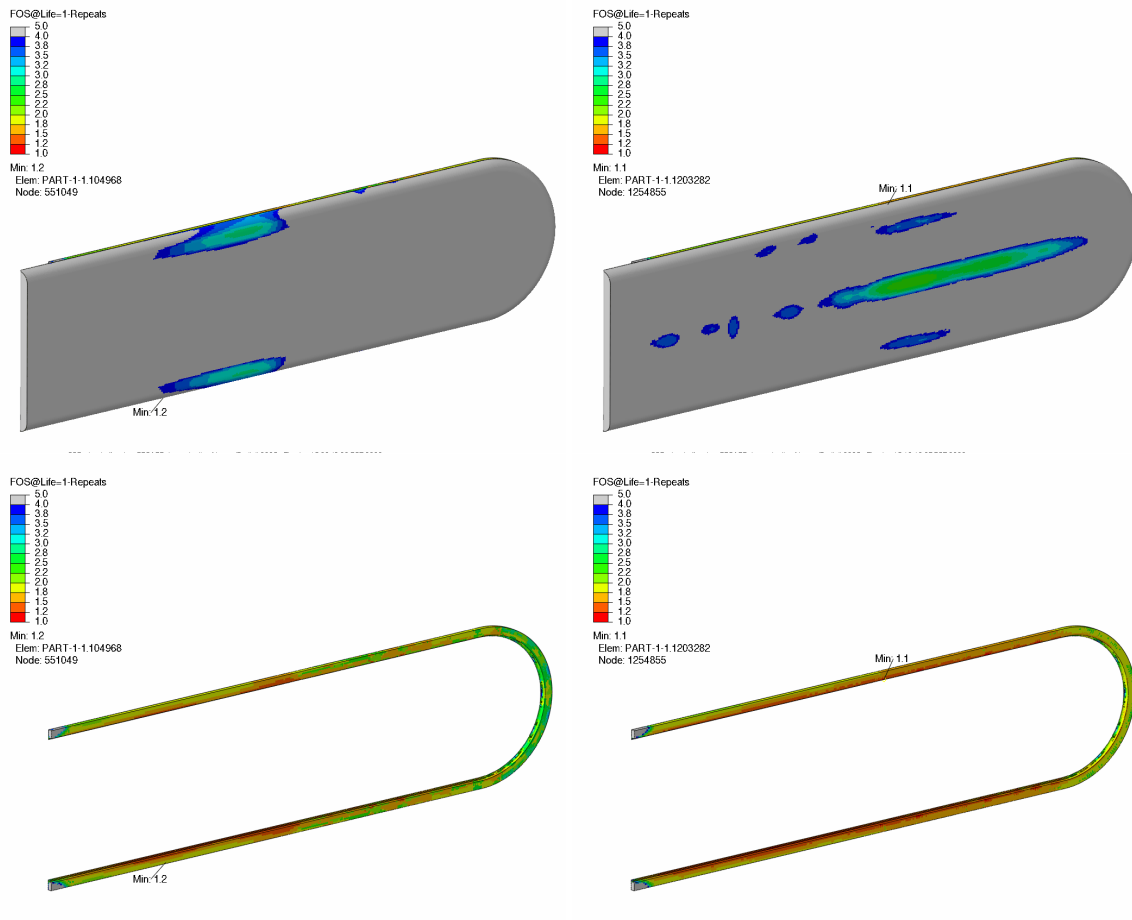


Figure 106. Weld FOS for the flow cover for beam trips (L) and beam pulses (R).

The rear of the Inconel shroud is welded to the stainless steel heel. Again, the entire Inconel shroud fatigue model is re-run using weld properties and a 3-mm slice is used to visualize FOS in the approximate HAZ. A corresponding 3-mm slice in the heel is also observed (using unmodified stainless steel fatigue results as no weld data is available). Figure 107 and Figure 108 show the results. The shroud is the limiting feature with a FOS of 1.2 and 1.4 for beam trips and beam pulses, respectively. This weld would meet the ASME/BPVC criteria with a 1.0 FSRF using the same weld specifications previously specified.

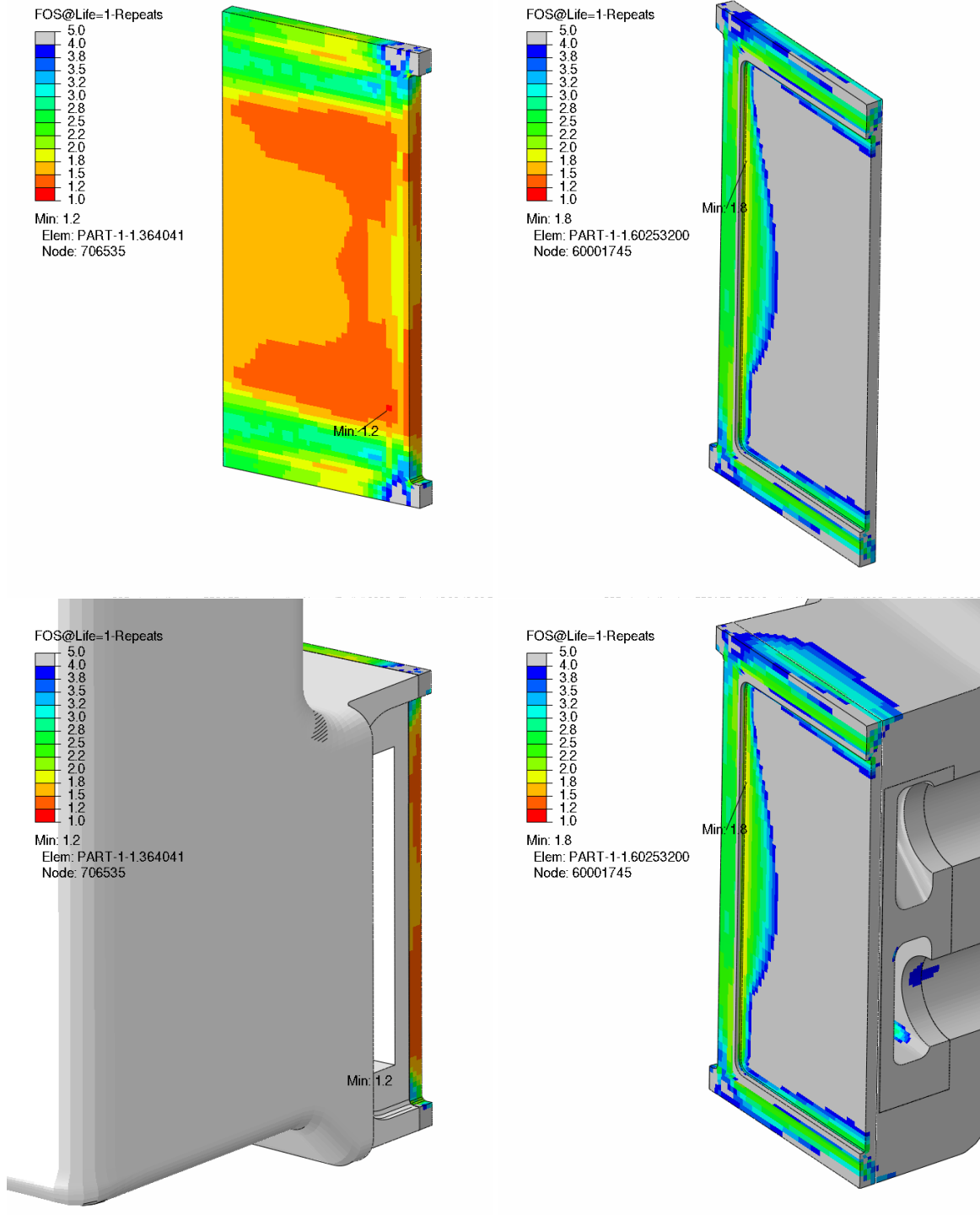


Figure 107. Weld FOS for the heel attachment for the case of beam trips. The approximate HAZ is shown for the Inconel (L) and for the stainless heel (R).

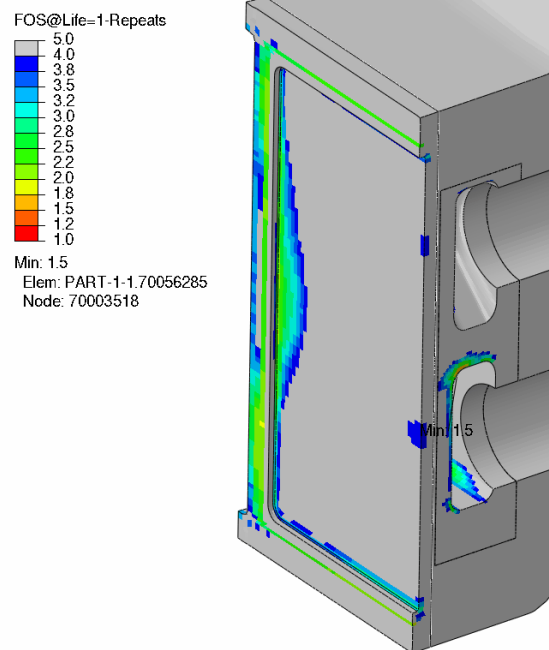
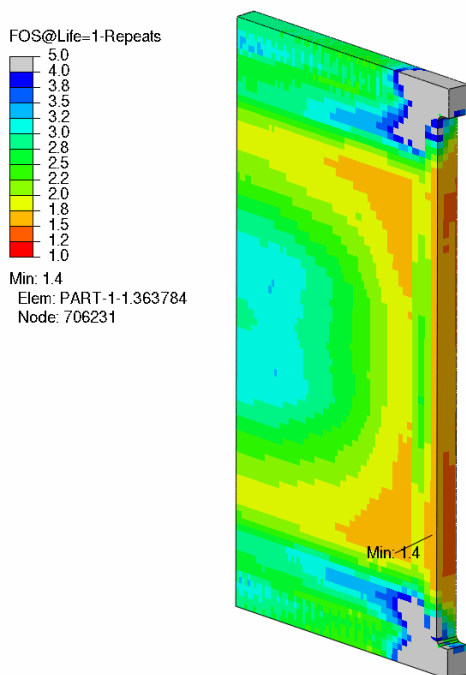
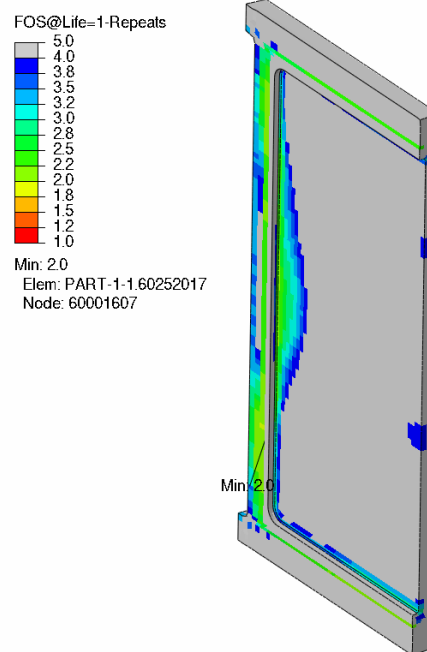
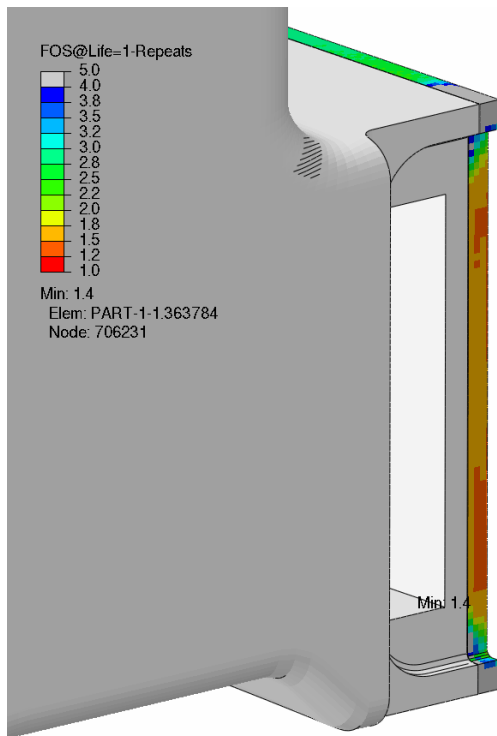


Figure 108. Weld FOS for the heel attachment for the case of beam pulses. The approximate HAZ is shown for the Inconel (L) and for the stainless heel (R).

5.4 CASE B FATIGUE - NOMINAL CORNER

The nominal-corner load case places the beam off center which makes the analysis domain no longer symmetric. To perform this analysis, the target foot undergoes a 2nd symmetry reflection analysis step, the flow cover mesh is copied, the heel mesh is reflected across the y-plane, and the stave beam element cross-section is changed to a box.

Figure 109 shows the Goodman diagram summaries. All cases pass the design requirement with $FOS > 1$. Target fatigue life does not appear to be sensitive to this load condition.

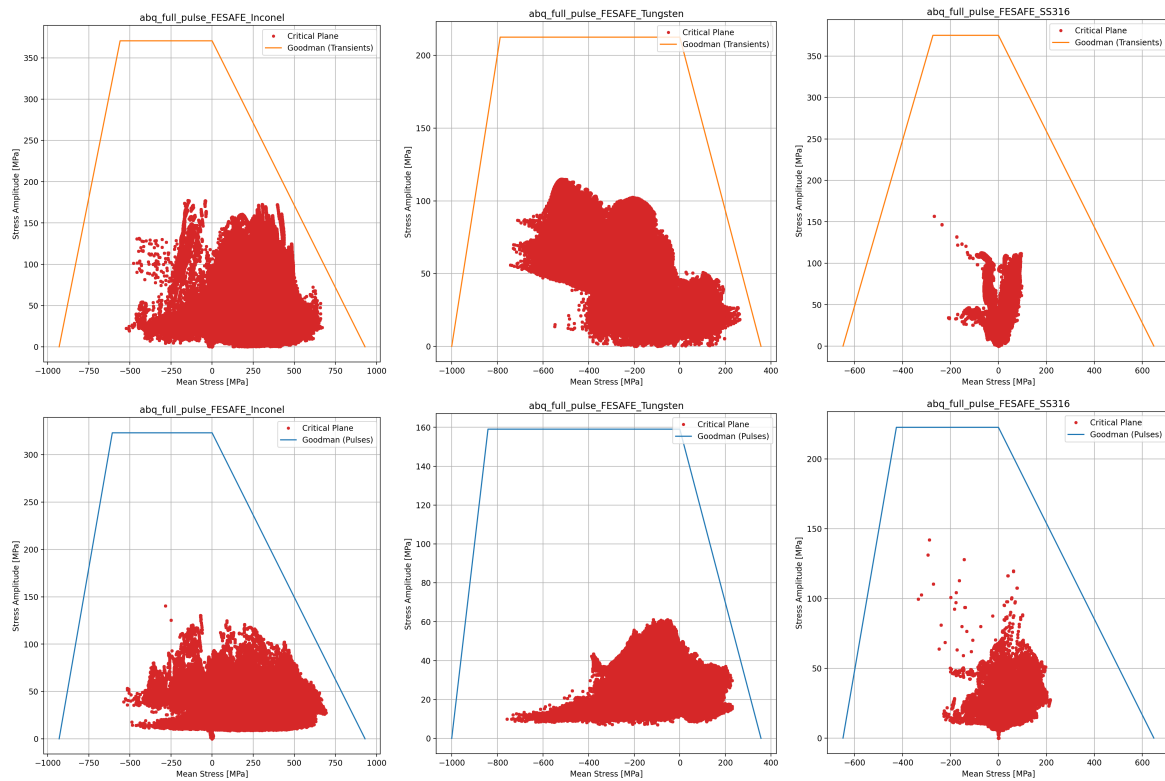


Figure 109. Nominal-Corner case Goodman diagrams: Beam trips (top) and beam pulses (bottom) for Inconel (Left), Tungsten (Mid), and Stainless (Right).

5.5 CASE C FATIGUE - NOMINAL LOW FLOW

The low-flow case reduces coolant flow by almost 25% in the target. The beam pulse energy deposition remains the same while the peak steady-state temperature in the tungsten core increases from 225°C to 236°C. The Goodman diagram shows that the fatigue analysis is insensitive to this change (Figure 110). All cases pass the design requirement with $FOS > 1$.

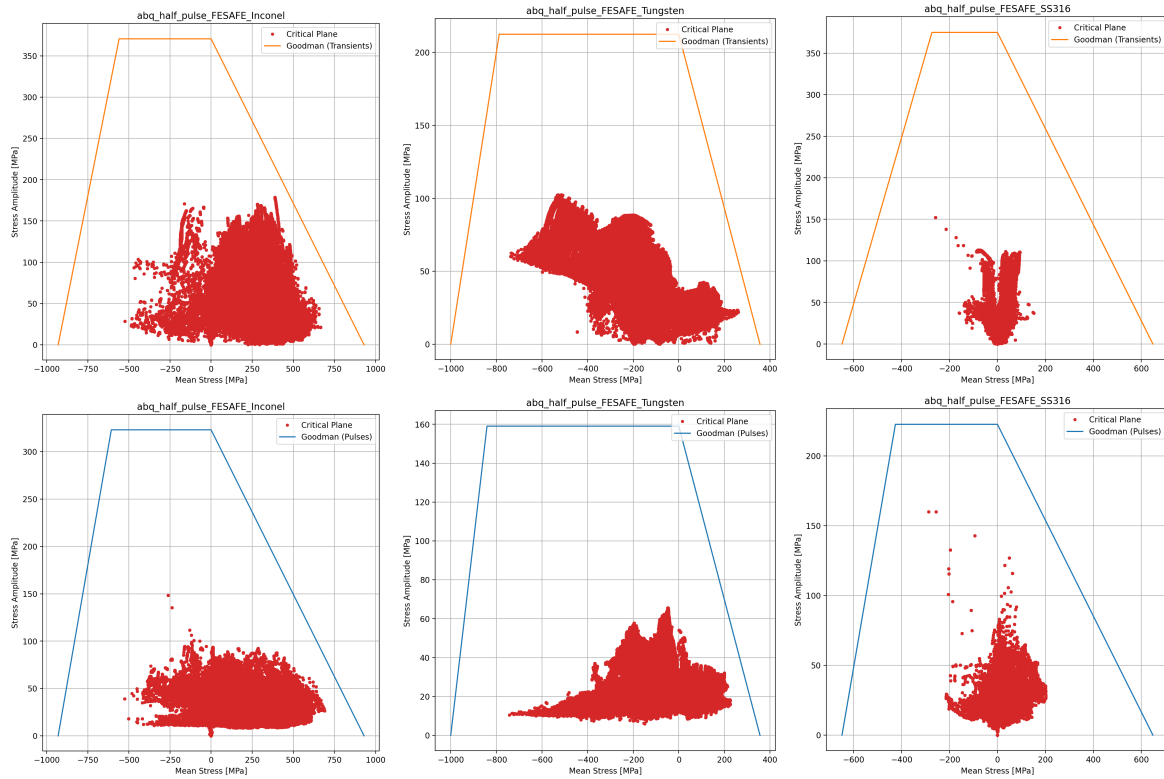


Figure 110. Nominal-Low Flow case Goodman diagrams: Beam trips (top) and beam pulses (bottom) for Inconel (Left), Tungsten (Mid), and Stainless (Right).

5.6 CASE D FATIGUE - OVERFOCUSED

The overfocused beam case has a 5% smaller beam area and a 2% higher beam power. The peak energy deposition for the focused beam increases by 5.8%. The peak pulse temperature rise goes from 15 to 16°C which is a 6.7% increase. The Goodman diagrams for fatigue analysis are shown in Figure 111 and show little change from the nominal case. All cases pass the design requirement with FOS > 1. Figure 112 directly overlays the tungsten beam pulses case for the nominal beam and overfocused beam. The peak stress amplitude appears to increase from approximately 65 to 70 MPa which scales with the peak energy deposition increase.

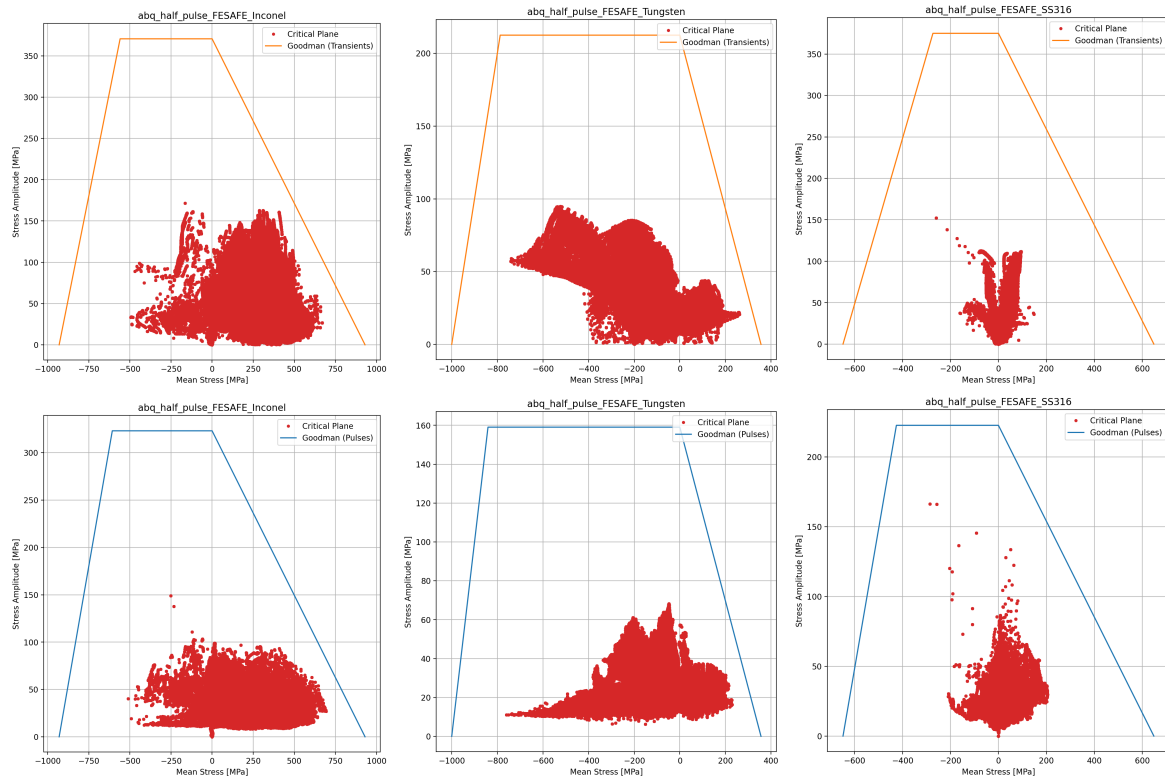


Figure 111. Overfocused case Goodman diagrams: Beam trips (top) and beam pulses (bottom) for Inconel (Left), Tungsten (Mid), and Stainless (Right).

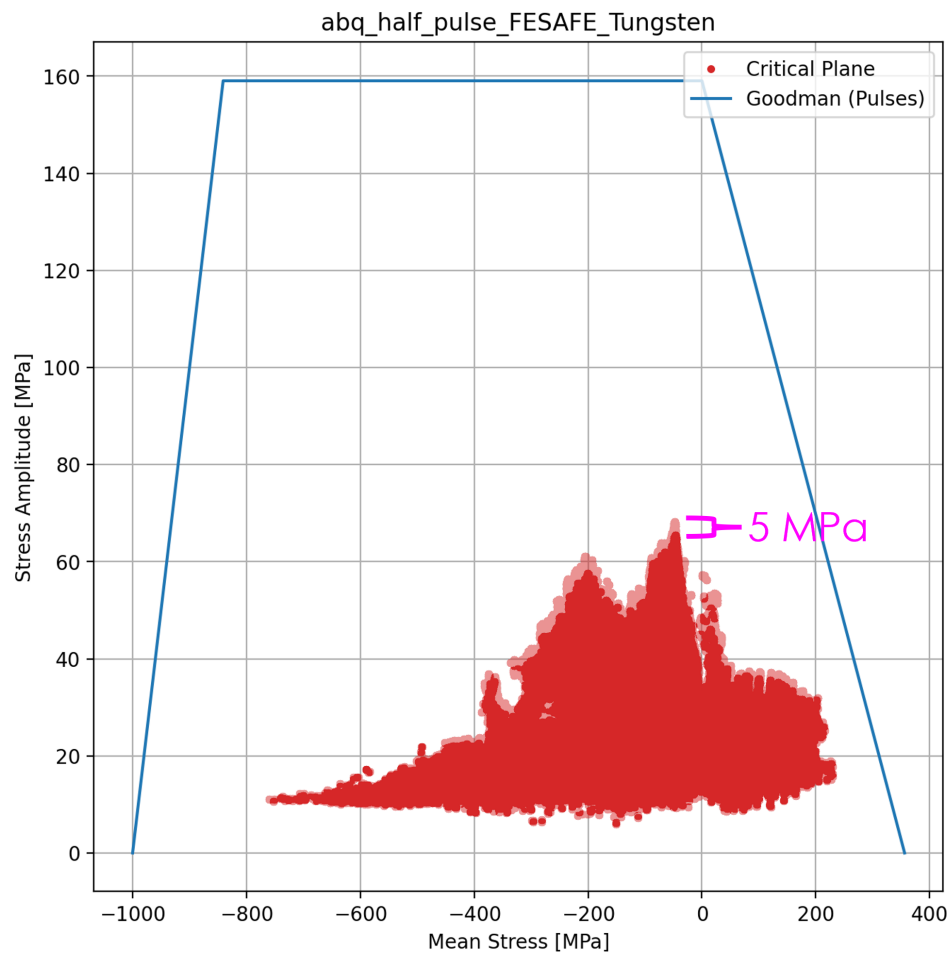


Figure 112. Overfocused case Goodman diagram for tungsten beam pulses overlaid against nominal case. Magenta bracket shows increase in peak stress amplitude from 65 MPa to 70 MPa.

5.7 CASE E FATIGUE - DIFFUSE

The diffuse beam case uses a wider beam, less dense beam. The temperature and pulse fields are accordingly lower and more spread-out. The Goodman diagram shows FOS > 1 for all cases (Figure 113). The tungsten amplitude for beam trips actually increases, however, this is in a region of mean compressive stresses. Stress amplitudes for beam pulses are lower as expected.

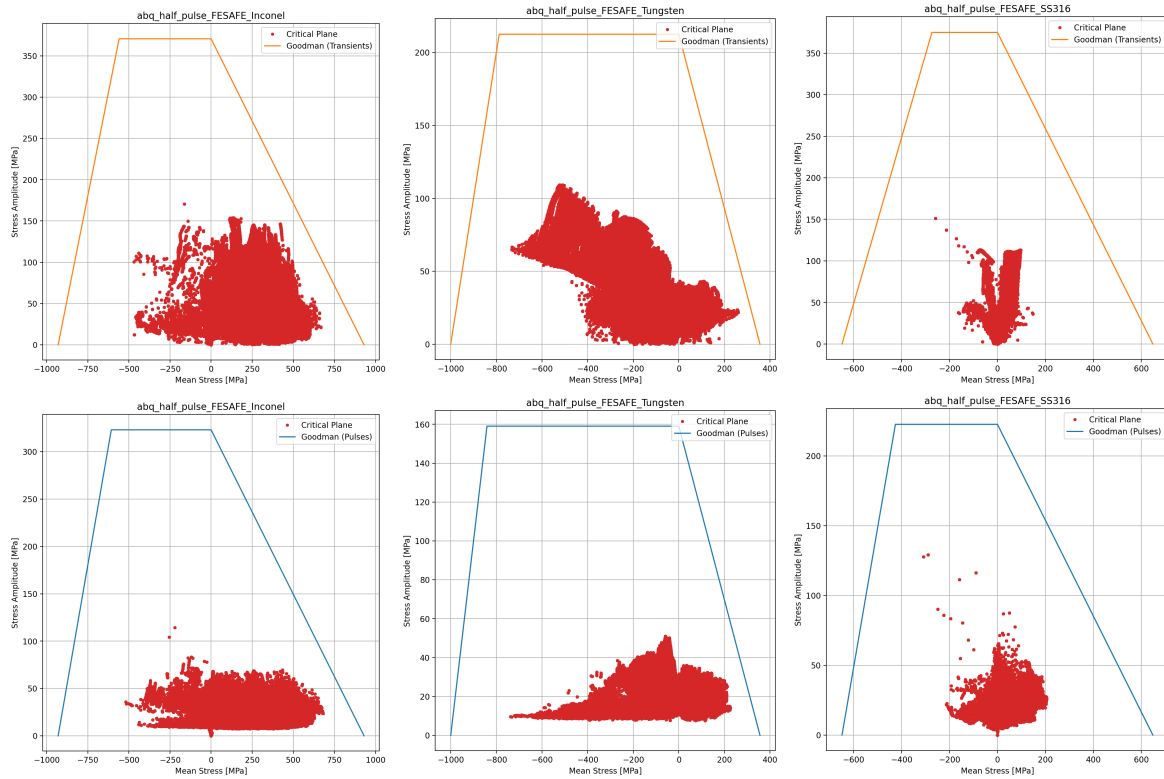


Figure 113. Diffuse case Goodman diagrams: Beam trips (top) and beam pulses (bottom) for Inconel (Left), Tungsten (Mid), and Stainless (Right).

5.8 RATCHETING - NOMINAL BEAM

As shown in the cyclic fatigue analyses, the target segment stresses are insensitive to the differences in beam cases. Thus, the ratcheting assessment was performed for the nominal beam case only.

Beam Pulse Ratcheting Analysis

Figure 114 shows the kinetic energy (ALLKE) and plastic deformation energy (ALLPD) during the ratcheting simulation. The ALLKE plot shows dynamic response during the beam pulses followed by proper damping during the quasistatic steps in between beam pulses. The ALLPD plot shows less change in plastic deformation with each pulse repetition.

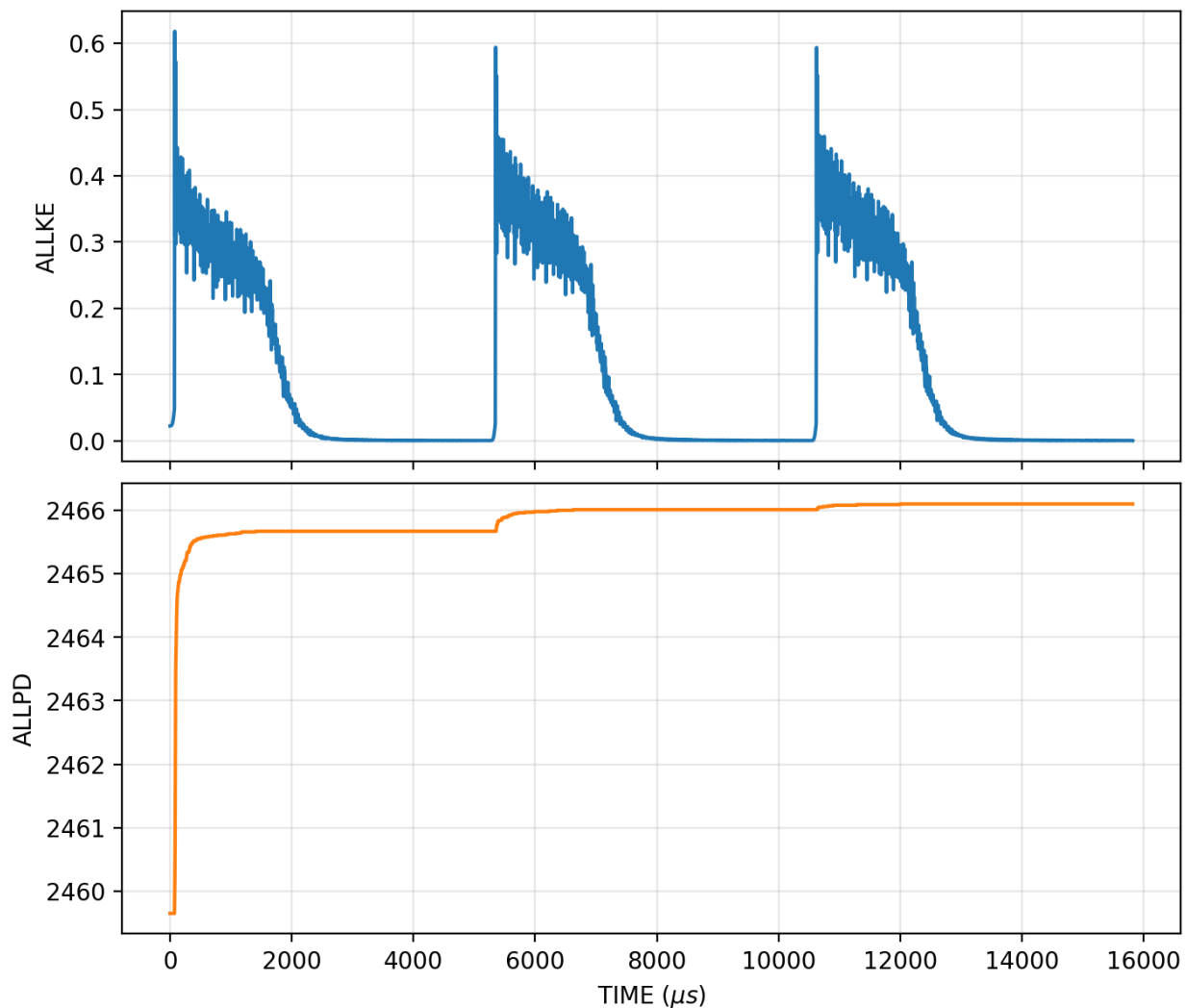


Figure 114. Plastic ratcheting analysis: Global kinetic energy and plastic deformation energy during simulation steps.

As discussed in Section 1.4.5, one method of checking against plastic ratcheting is to ensure no plastic strains occur at all. Another method is to ensure there remains an elastic core in load bearing structures. Both of these methods are not applicable since the Inconel shroud undergoes significant plastic deformation in the manufacturing simulation step.

The final method is to demonstrate no permanent change in the overall dimensions of the component. This is shown by plotting the change in PEEQ over the course of each beam pulse repetition (i.e. pulse, response, damping, return to quasi-steady heating). There is a clear, non-linear decrease in PEEQ with each pulse repetition. Figure 114 shows this at the global plastic energy level, and Figures 115 through 116 show this in local plots of PEEQ on the Inconel shroud. While this does not directly satisfy the acceptance criteria of the ASME/BPVC, this shows effective plastic shakedown of the structure to an elastic response should occur after several beam pulse events.

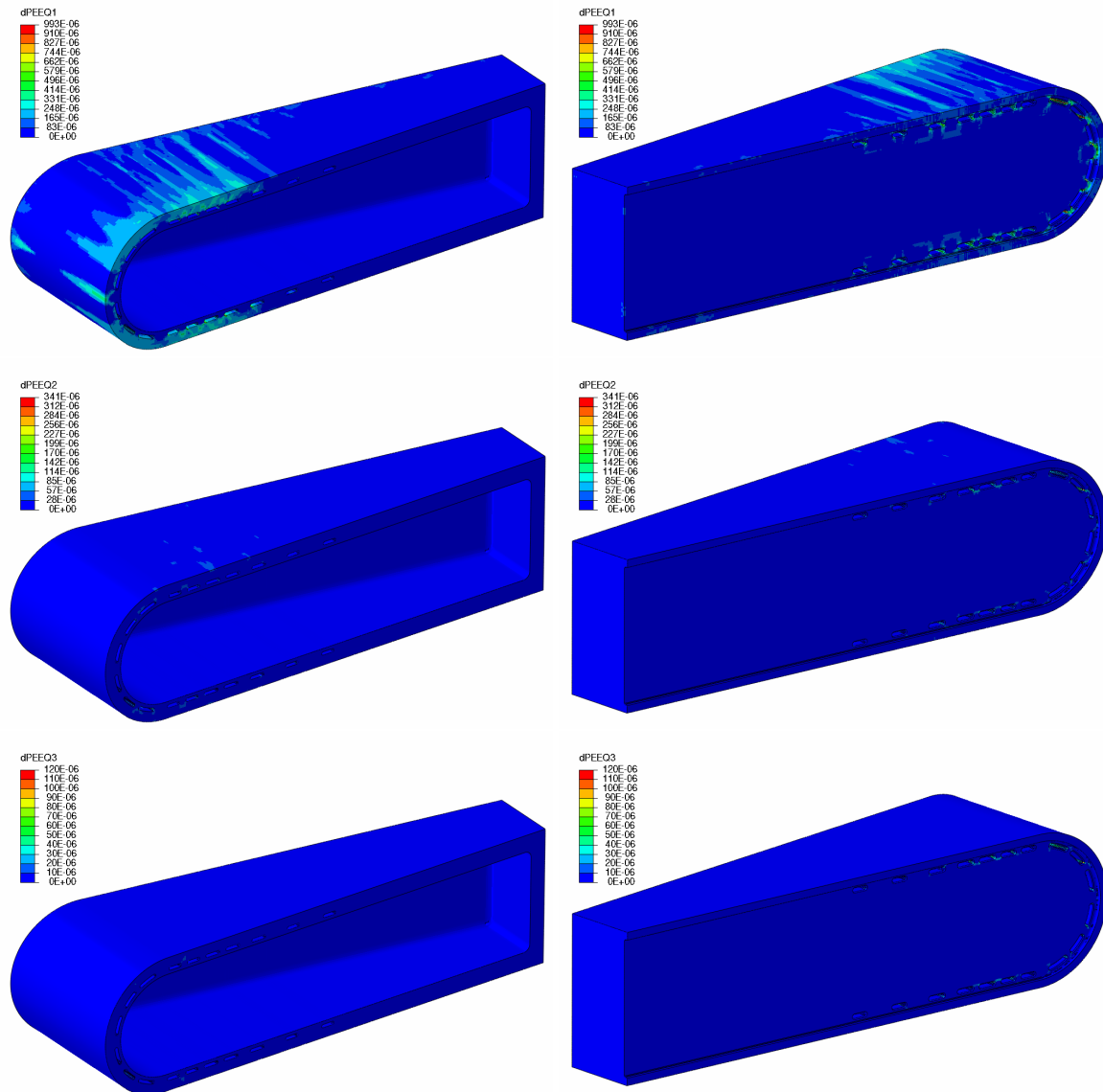


Figure 115. Plastic ratcheting analysis for beam pulse events: Change in equivalent plastic strain for the Inconel shroud over 3 pulse repetitions. Both local and peak changes in PEEQ decrease non-linearly after each repetition.

The Inconel flow cover and stainless steel heel structures are added after the manufacturing simulation and are able to utilize elastic-perfectly plastic material models. Figure 117 shows plots of the change in plastic equivalent strain after each beam pulse repetition. Plastic shakedown appears to be occurring at the weld

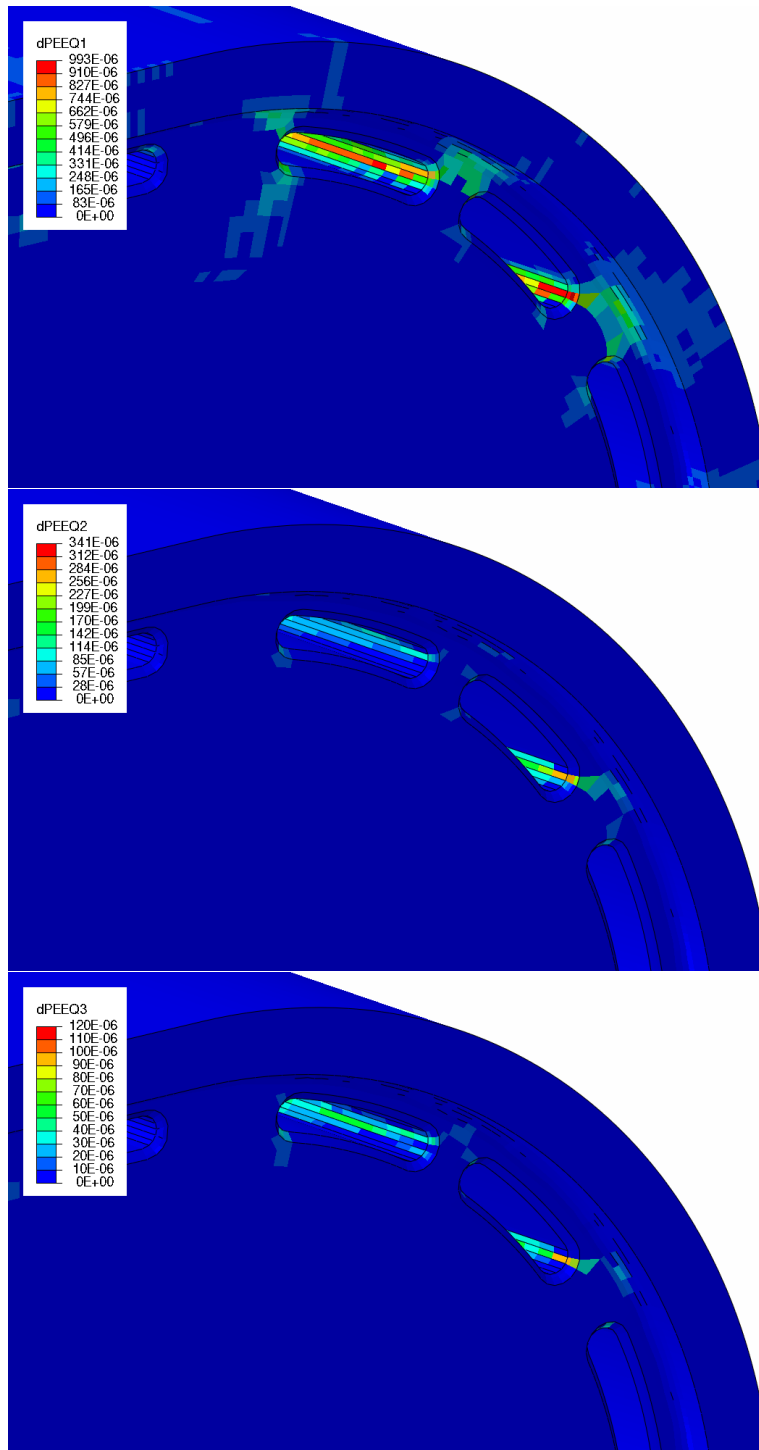


Figure 116. Plastic ratcheting analysis for beam pulse events (Zoomed view of shroud front): Change in equivalent plastic strain for the Inconel shroud over 3 pulse repetitions. Both local and peak changes in PEEQ decrease non-linearly after each repetition.

interface with the target foot. Furthermore, the inner periphery of the weld appears to maintain an elastic core.

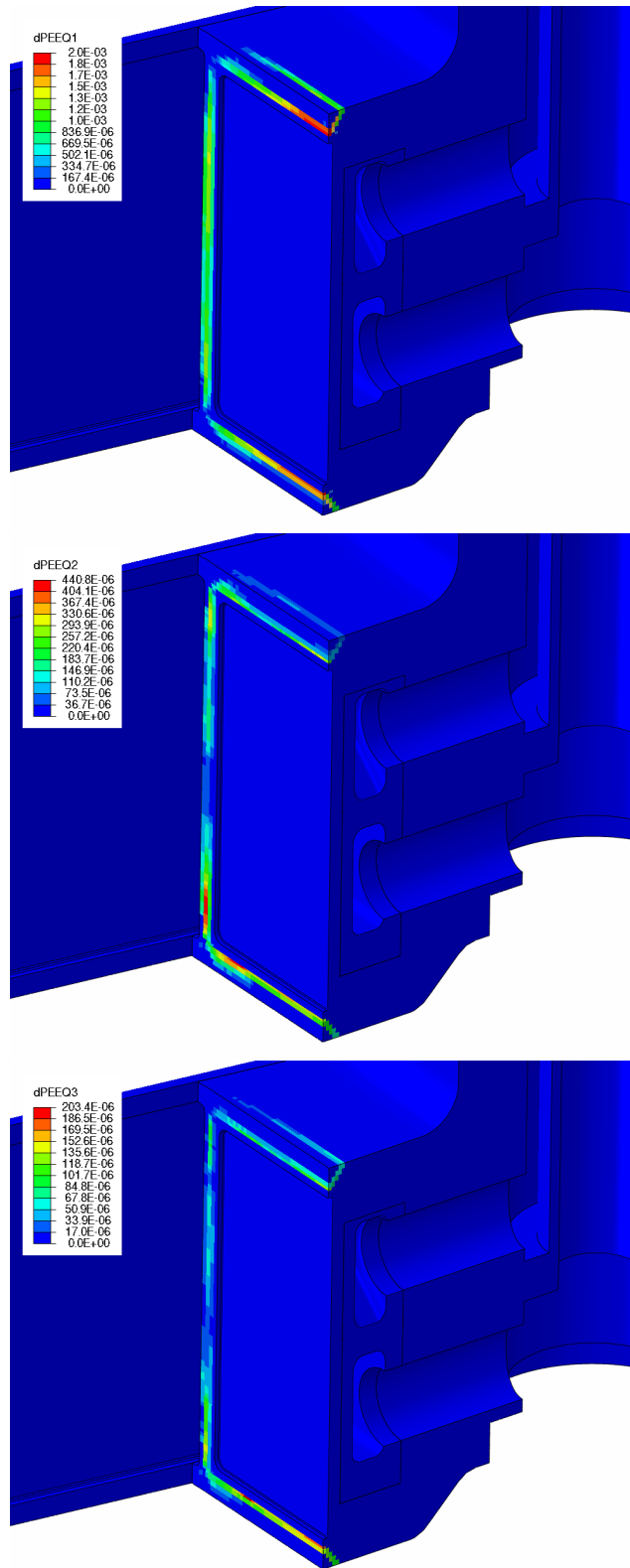


Figure 117. Plastic ratcheting analysis for beam pulse events: Change in equivalent plastic strain for the stainless steel heel and Inconel flow cover over 3 pulse repetitions. Both local and peak changes in PEEQ decrease non-linearly after each repetition, and an elastic core remains along the interior periphery of the weld surface.

Beam Trip Ratcheting Analysis

Compared to beam pulse events, beam trip ratcheting is a more demanding environment due to the large differential between the quasi-steady-state operating temperature field and the uniform 35°C beam-off environment. Figure 118 shows the change in plastic equivalent strain after beam trips. The computational cost for this static simulation step is lower than the explicit beam pulse events, so a total of 5 beam trip events were modeled. There is a region near the flow cover weld and behind the last flow channel that appears to experience an approximately $0.5 \mu\epsilon$ plastic strain ratchet with each cycle and that does not diminish. Technically this passes the ratcheting test as an elastic core surrounding this location remains, however, it also identifies a potential area of concern with the fatigue analysis that tacitly assumes only elastic stress cycles.

Figure 119 helps to identify what is happening. The quasi-steady-state temperature field for the nominal beam case is plotted on the shroud and also on the flow cover. The flow cover (with no manufacturing residual stress to make visualization difficult) has 300x displacement magnification to show how it deforms. The region of ratcheting corresponds with the shroud bulging outward due to thermal expansion. This places the weld in a state of tensile shear and is concerning. The lack of shakedown in this location seems to be due to the larger temperature swing. The change of yield stress with temperature is larger than the change of yield stress due to plastic hardening. If this is accurate, this location would then see $0.5 \mu\epsilon$ of plastic ratcheting over 125,000 cycles for a total of 6.25% strain increase ($0.5 \mu\epsilon \times 125,000 = 0.0625 \epsilon$).

The Inconel flow cover and stainless steel heel structures are added after the manufacturing simulation and are able to utilize elastic-perfectly plastic material models. Figure 120 shows plots of the change in plastic equivalent strain after each beam trip repetition. This region appears to pass the ratcheting test on the grounds of an elastic core being maintained at the weld periphery.

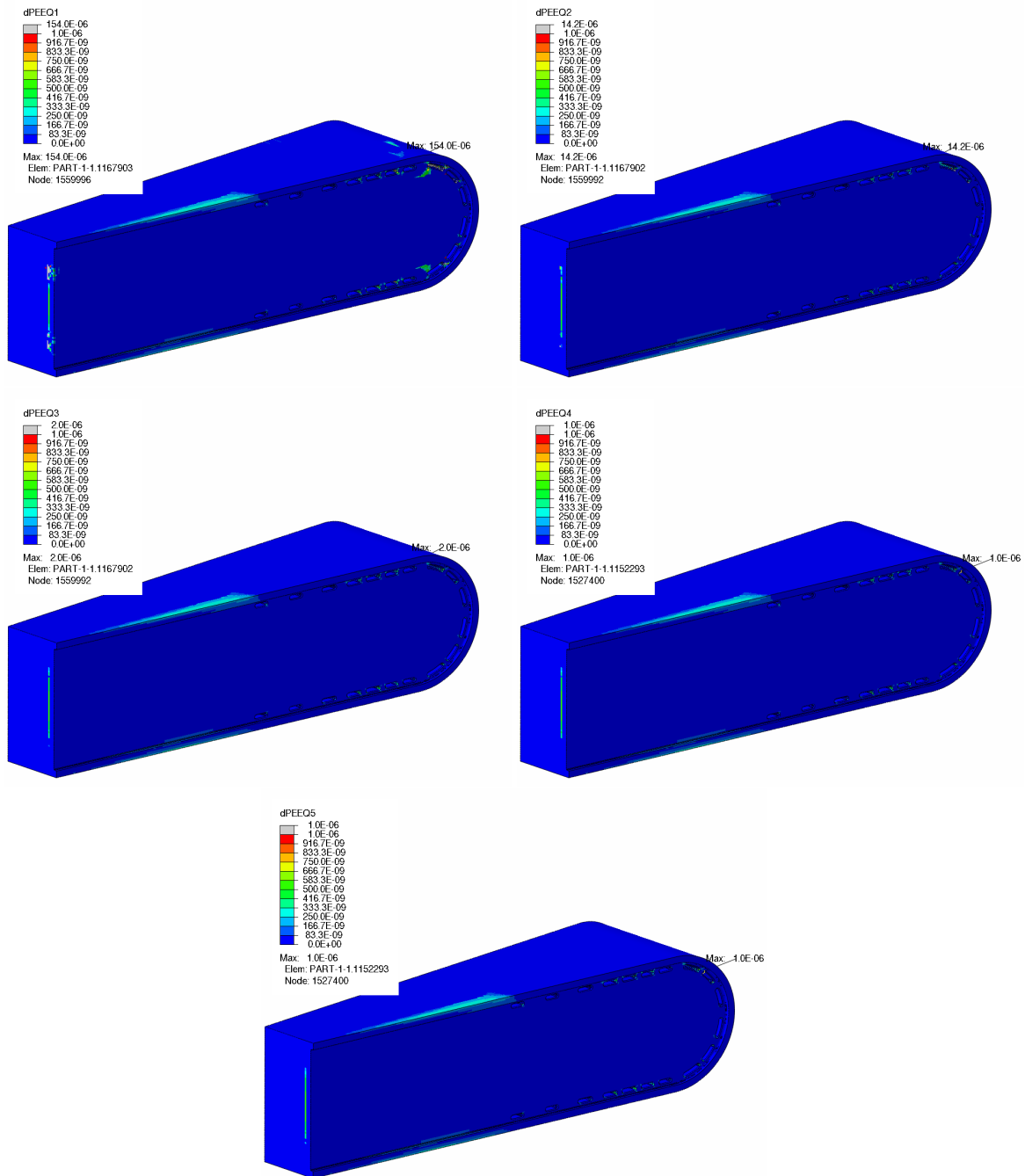


Figure 118. Plastic ratcheting analysis for beam trip events: Change in equivalent plastic strain for the Inconel shroud over 5 beam trip repetitions.

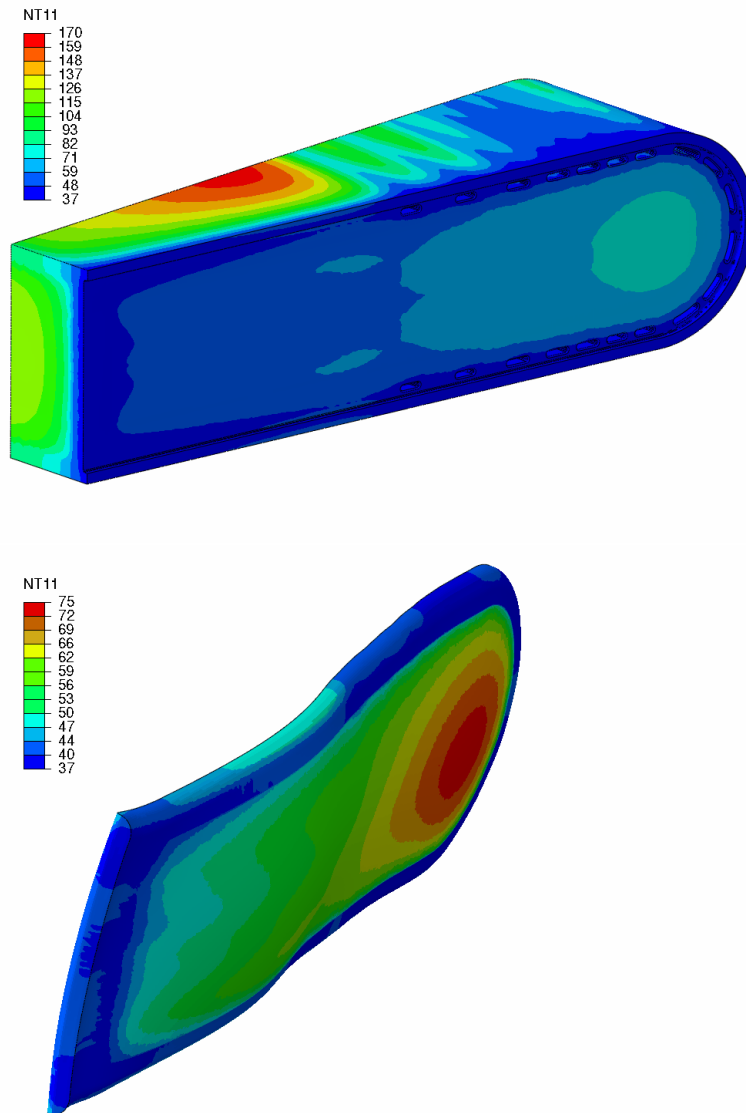


Figure 119. Contour plot of the quasi-steady-state temperature field in the Inconel shroud and flow cover for nominal beam conditions. The flow cover has 300x displacement magnification to show the bulge due to thermal expansion in the shroud.

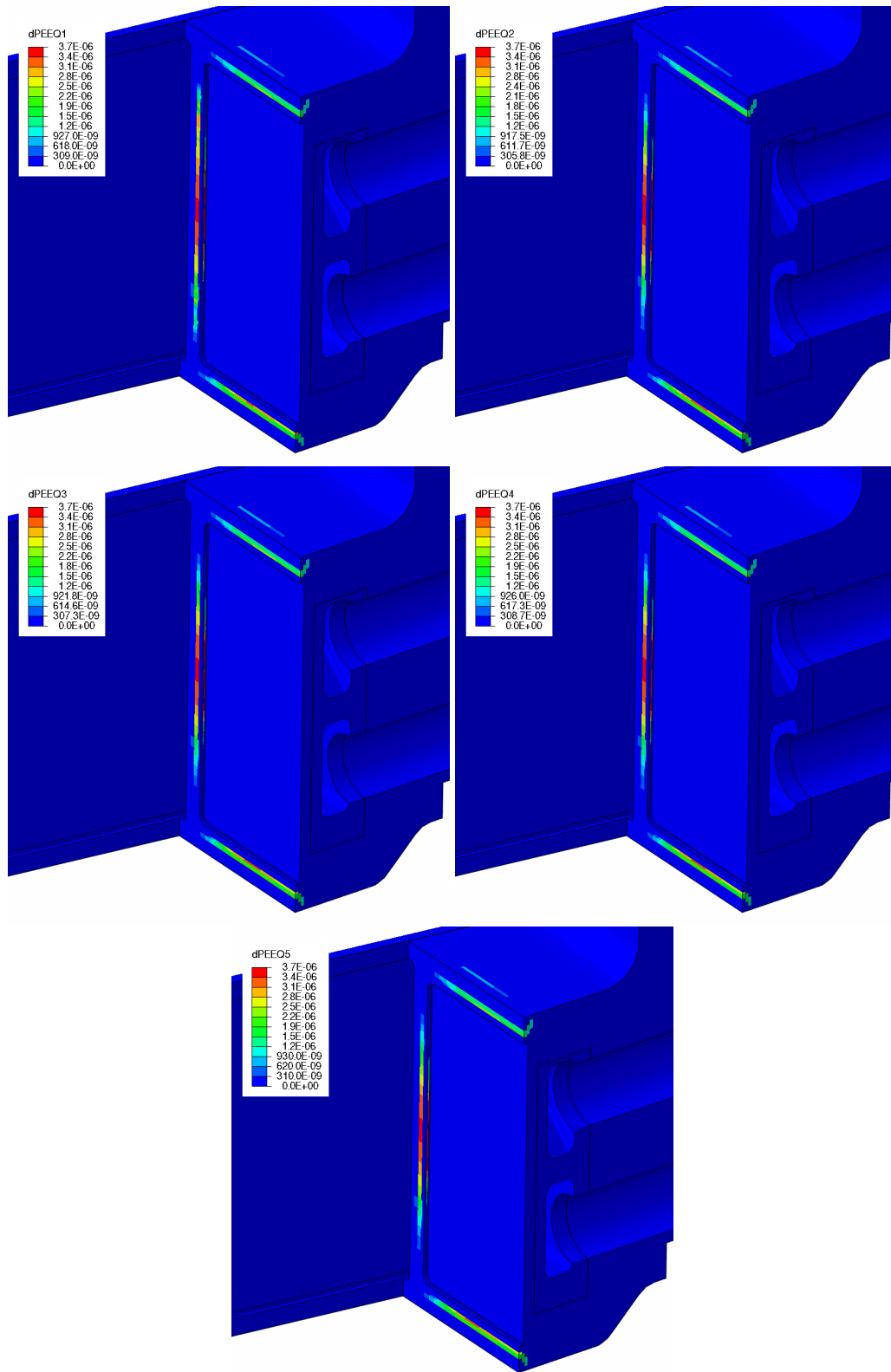


Figure 120. Plastic ratcheting analysis for beam trip events: Change in equivalent plastic strain for the stainless steel heel and Inconel flow cover over 5 beam trip repetitions.

5.9 PLASTIC COLLAPSE - NOMINAL BEAM

As shown in the cyclic fatigue analyses, the target segment stresses are insensitive to the differences in beam cases. Thus, the plastic collapse assessment was performed using the nominal beam case only. To pass the design requirement under elastic-plastic analysis conditions, the static simulation should converge to a solution.

All load cases for protection against plastic collapse numerically converge to static solutions. One nuance, however, is that the Inconel stress-strain curves do not turn perfectly plastic at the UTS. There is uncertainty as to how UTS varies with temperature for Inconel. Also - at the time the models were created - the required UTS for Inconel specifications was not known. The material models were thus defined to 100% strain. And now, the project has specified a room-temperature minimum UTS of 930 MPa.

The solution is to manually interrogate the solution to confirm the converged Inconel stresses are below UTS limits. Figure 121 shows the von Mises equivalent stress of the converged solution for the normal operation LRFD load case. The results for the other 3 normal operation plus occasional live load, seismic, and thermal LRFD load cases are comparable and are not duplicated here. The peak stress in the Inconel is approximately 620 MPa which has very large margin against the specified 930 MPa UTS.

Figure 122 shows the von Mises equivalent stress of the converged solution for the pressure test LRFD load case. Here, the stresses are higher because the target segment remains at 35°C with the high residual stresses from manufacturing. (Warm-up to quasi-steady-state operating temperatures serves to reduce the manufacturing residual stresses.) The peak stress in the Inconel is a true stress of 952 MPa at an equivalent plastic strain of 12.2%. When converted to an engineering stress as shown in Equation 23, the value of 843 MPa shows margin above the specified 930 MPa UTS.

$$\sigma_e = \frac{\sigma_t}{\exp(\epsilon_t)} = \frac{952 \text{ MPa}}{\exp(0.122)} = 843 \text{ MPa} \quad (23)$$

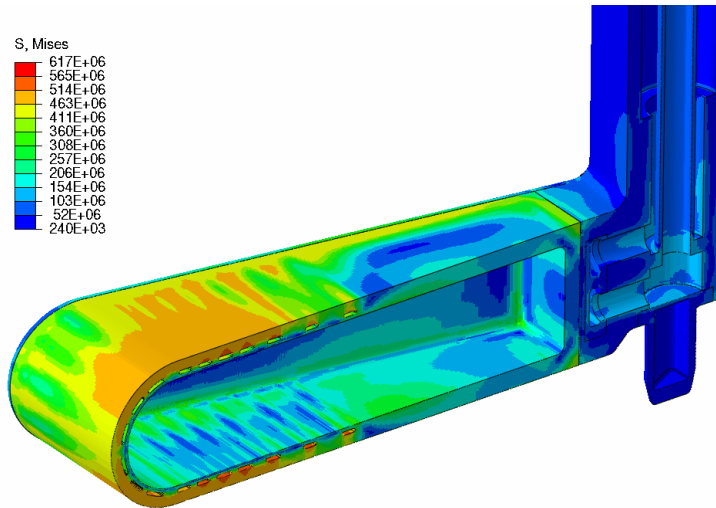


Figure 121. Contour plot of von Mises equivalent stress field under plastic collapse "normal operation" LRFD loading conditions.

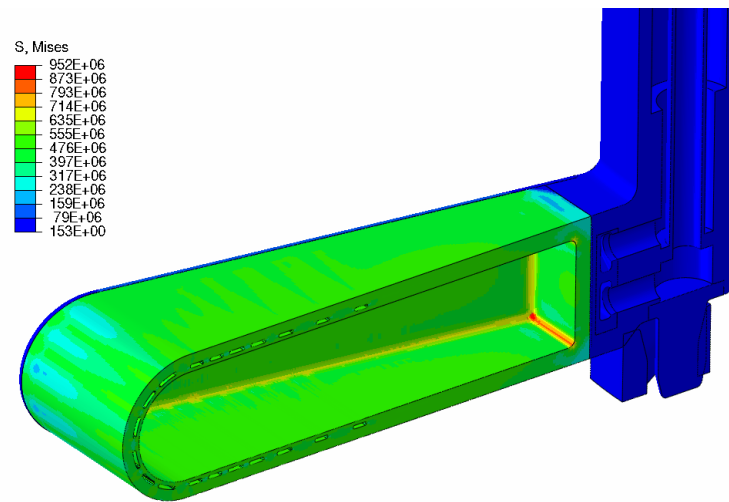


Figure 122. Contour plot of von Mises equivalent stress field under plastic collapse "pressure test" LRFD loading conditions.

5.10 LOCAL FAILURE - NOMINAL BEAM

As shown in the cyclic fatigue analyses, the target segment stresses are insensitive to the differences in beam cases. Thus, the local failure assessment was performed using the nominal beam case only. To pass the design requirement under elastic-plastic analysis conditions, the plastic equivalent strain should be less than the limiting triaxial strain.

For the protection against local failure analysis, Figures 123, 124, and 125 give the triaxial stress fields in the heel, shroud, and flow cover. In the heel, the regions of high stress triaxiality are away from regions of high stress. In the shroud, the last two cooling channels show regions of high triaxiality. In the flow cover, the highest triaxiality occurs in the edge radii and in the back weld region.

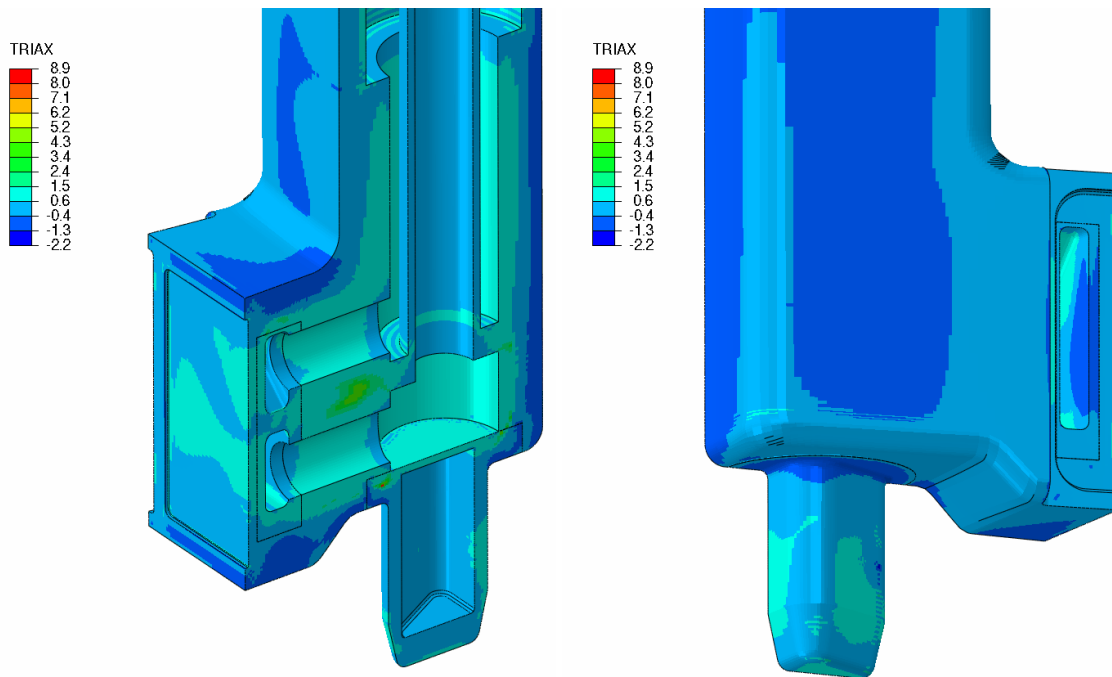


Figure 123. Contour plot of stress triaxiality for the heel under local failure loading conditions.

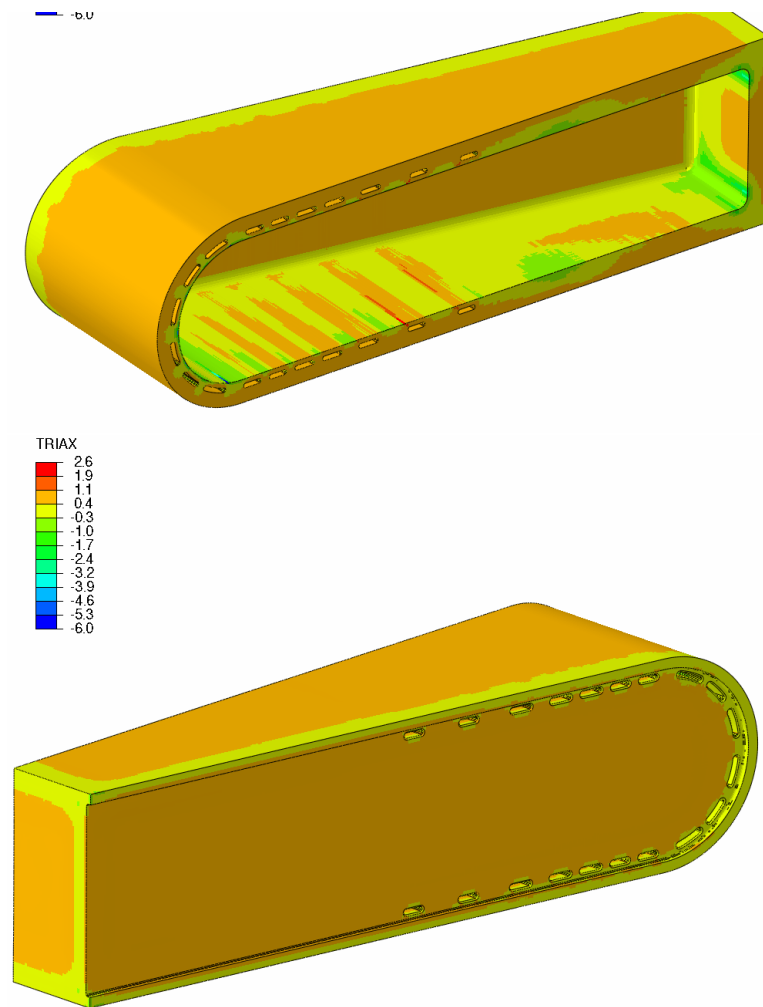


Figure 124. Contour plot of stress triaxiality for the shroud under local failure loading conditions.

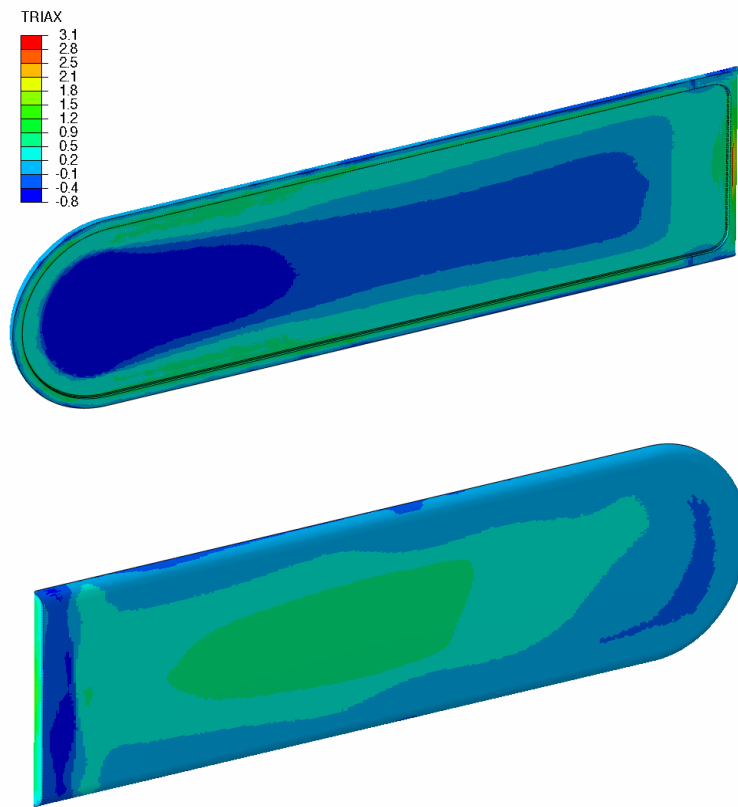


Figure 125. Contour plot of stress triaxiality for the flow cover under local failure loading conditions.

Figures 126, 127, and 128 show contour plots of the user variable "EL" which is the limiting triaxial strain calculated from Equation 6. These strain limits are fairly high with minimum values ranging from 1.4 to 3% strain corresponding to locations of high stress triaxiality. Discontinuities in the plots are a result of conservatism in the user script which takes the maximum nodal value from adjacent elements.

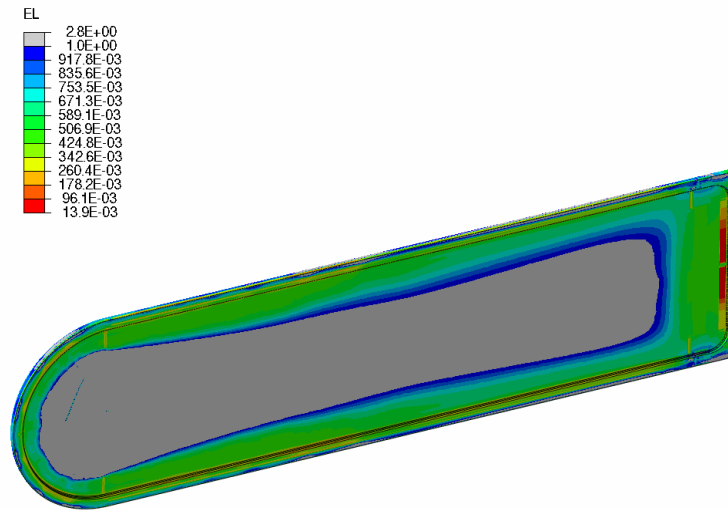


Figure 126. Contour plot of limiting triaxial strain for the flow cover under local failure loading conditions.

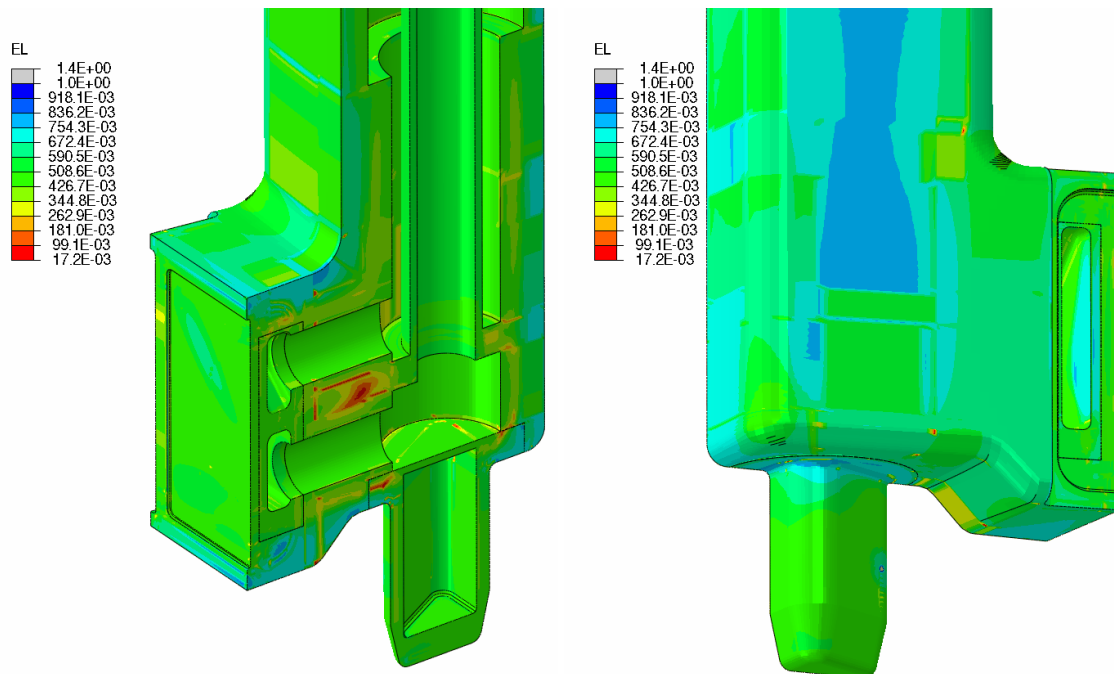


Figure 127. Contour plot of limiting triaxial strain for the heel under local failure loading conditions.

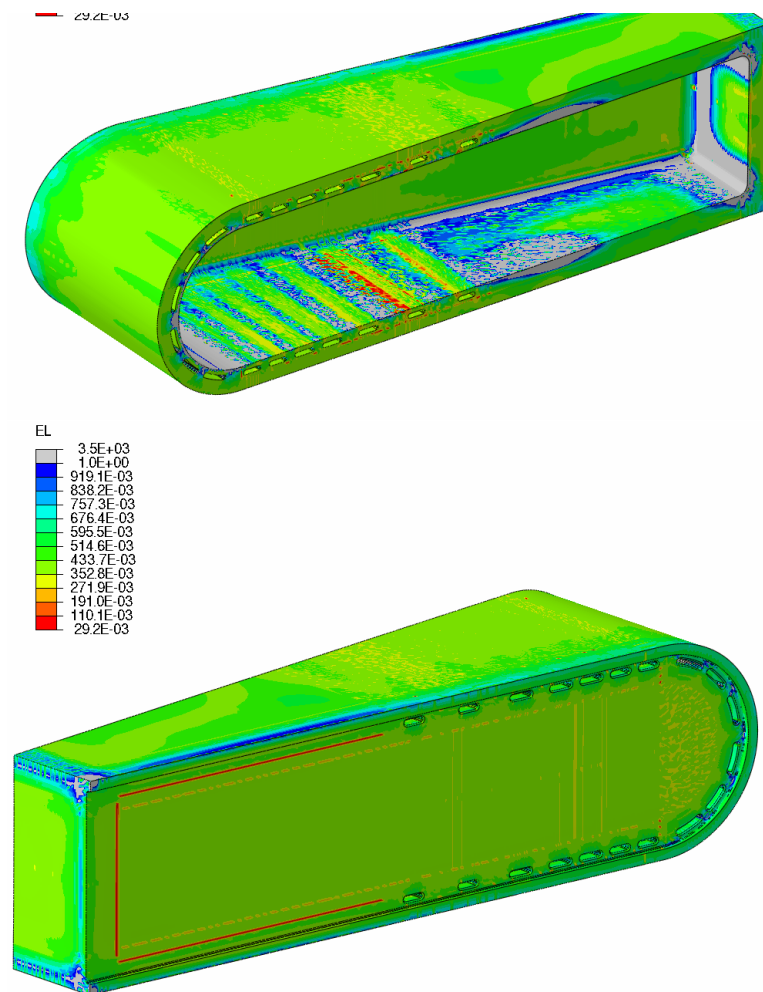


Figure 128. Contour plot of limiting triaxial strain for the shroud under local failure loading conditions.

Figures 129, 130, and 131 show contour plots of the user variable "Emargin" which is the difference between the limiting triaxial strain and the plastic equivalent strain. Values are everywhere positive which indicates successful protection against local failure.

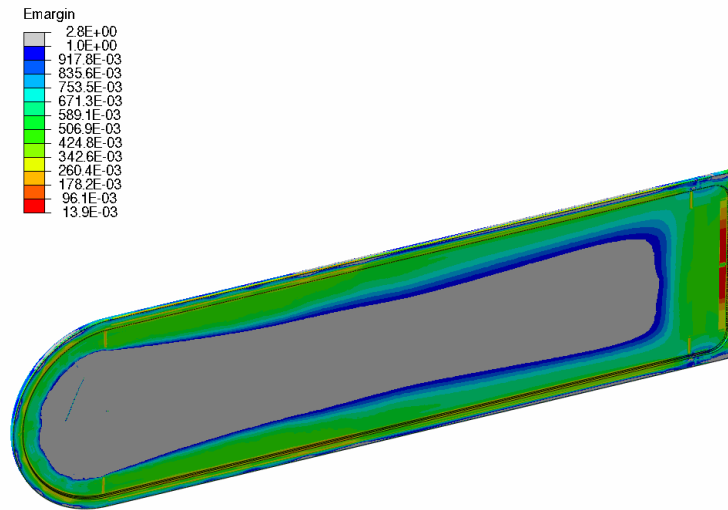


Figure 129. Contour plot of strain margin above the limiting triaxial strain for the cover under local failure loading conditions. Positive values indicate successful protection against local failure.

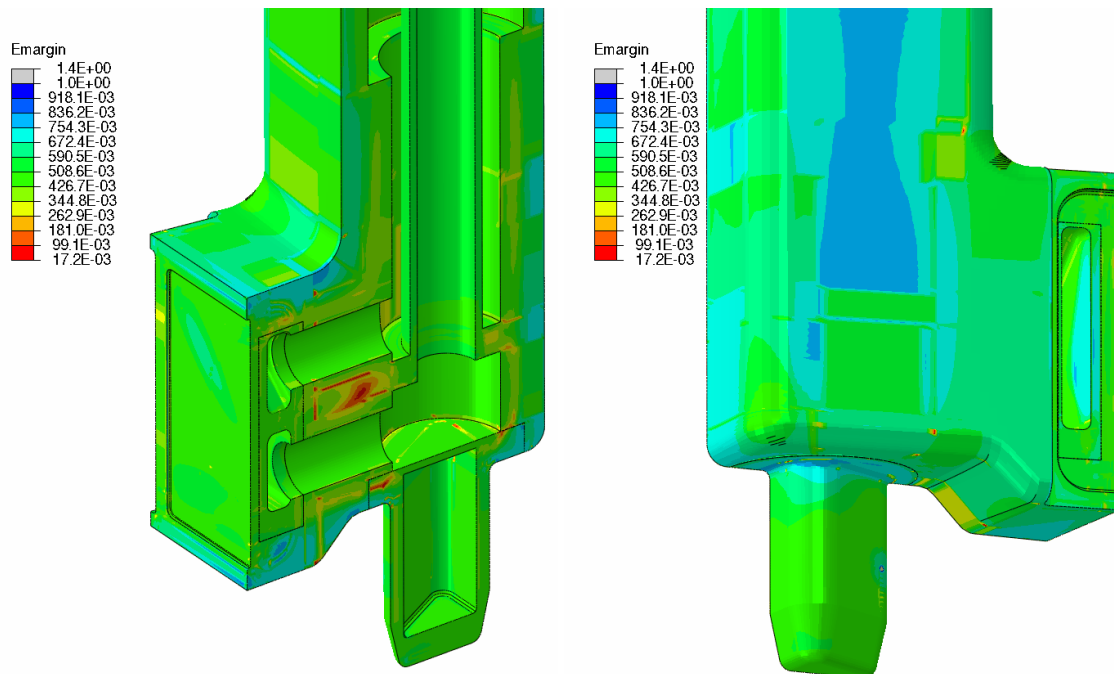


Figure 130. Contour plot of strain margin above the limiting triaxial strain for the heel under local failure loading conditions. Positive values indicate successful protection against local failure.

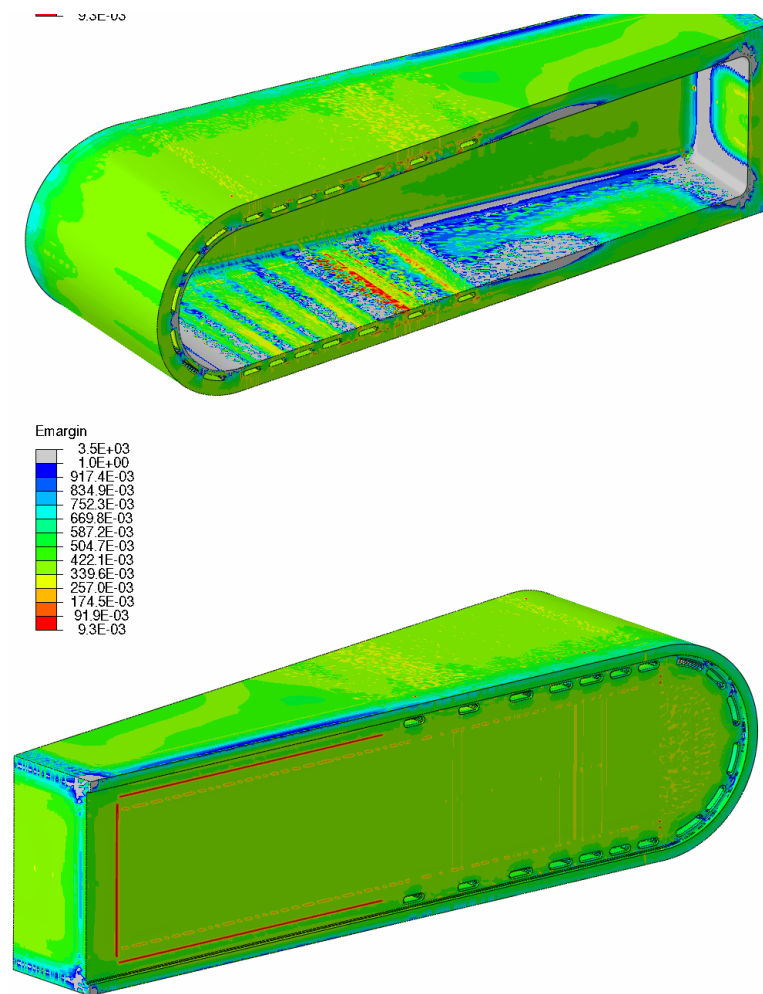


Figure 131. Contour plot of strain margin above the limiting triaxial strain for the shroud under local failure loading conditions. Positive values indicate successful protection against local failure.

5.11 VERIFICATION & SENSITIVITY ANALYSES

5.11.1 Mesh Refinement

In an attempt to verify mesh independence, the manufacturing simulation presented in Section 4.4 was performed with a partially refined mesh. The Inconel shroud mesh was refined via bisection as shown in Figure 132 and Figure 133. The rest of the domain mesh (i.e. the tantalum and tungsten core package) was unaltered. The element count for the manufacturing simulation increased from 1.25M to 5.64M elements, and the solution time increased from 8 to 540 hours. Figures 134 to 139 compare the results against the nominal mesh. Stress discontinuities were higher in the refined mesh. Deformation "ripples" developed at the contact interface that are likely due to the larger difference between mesh sizes at the two contacting surfaces. Peak contact pressure decreases while peak stress increases – both in areas of higher discontinuity. The peak stress increase is concerning. On the positive side, it is away from the welds. On the negative side, it is in the rear cooling channel near the minimum FOS for the beam trip fatigue case. It is also highly peaked at near UTS which are both suspect.

In summary, mesh convergence was not demonstrated. The mesh is both robust (consisting of C3D8R hex elements) and of high quality in the regions of interest. With the lack of demonstrated mesh independence, however, peak stress results should be expected to vary. A 10-20% systematic error would be a reasonable expectation.

The current mesh is at the limit of computational and software license resources. A future attempt at mesh refinement would need to uniformly refine all volumes while keeping the total mesh count reasonable. This would require considerable effort to re-mesh the domain with a hex mesh of smaller size. Another option would be to consider a much smaller R&D simulation domain, demonstrate mesh convergence, and draw qualitative comparisons.

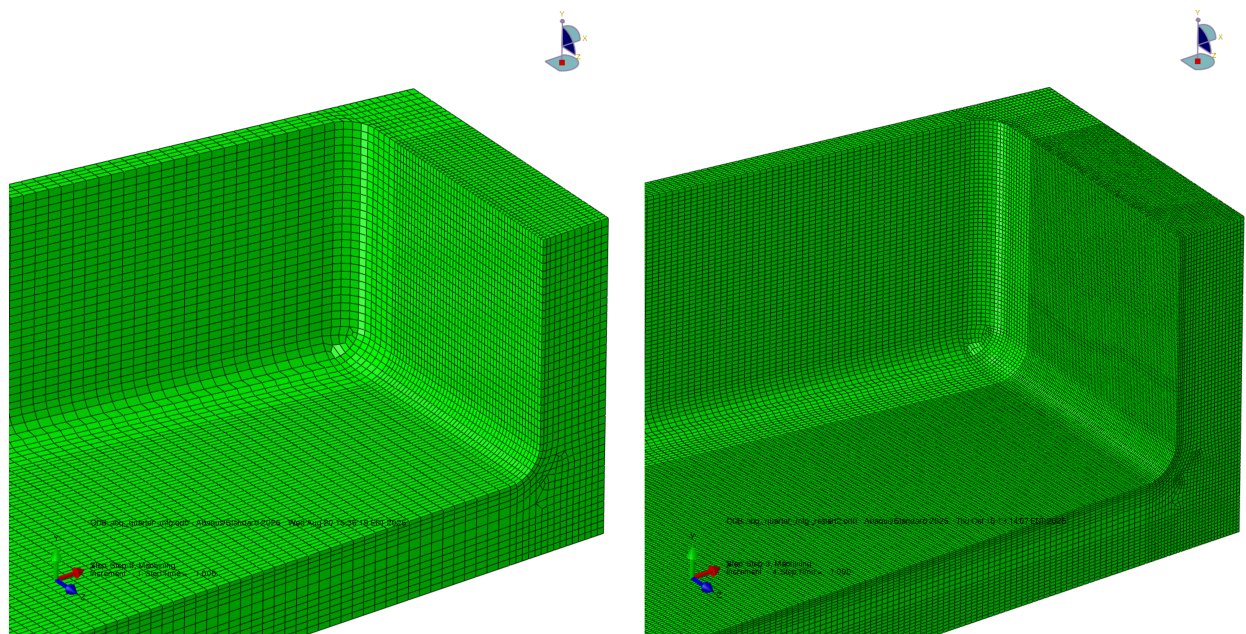


Figure 132. Mesh refinement study showing Inconel shroud with original mesh (L) and refined mesh (R).

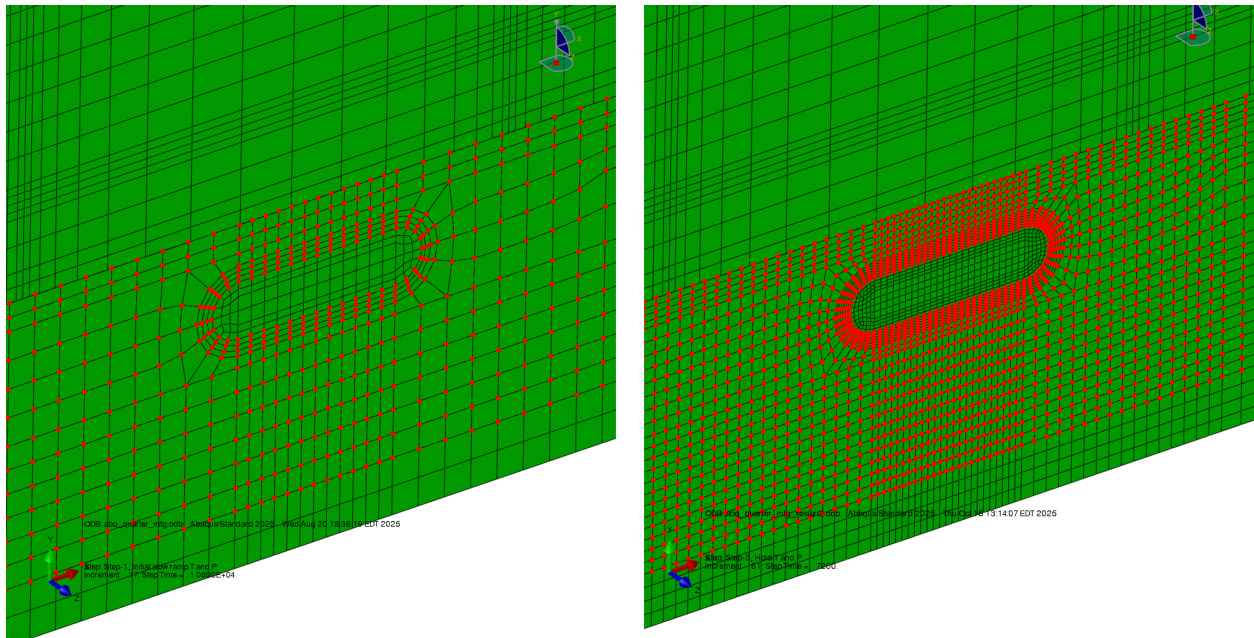


Figure 133. Mesh refinement study showing Inconel shroud with original mesh (L) and refined mesh (R). The highlighted region shows the shroud after machining operations.

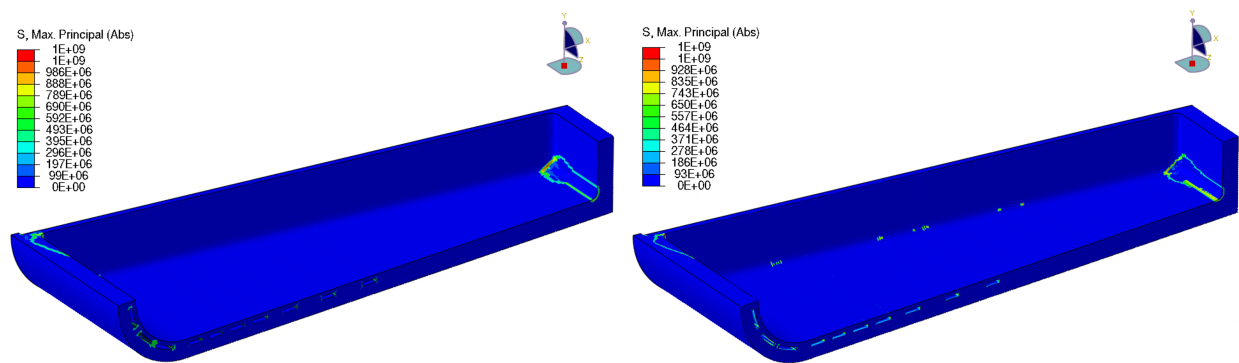


Figure 134. Mesh discontinuity plots of the Inconel shroud after manufacturing simulation for original mesh (L) and refined mesh (R).

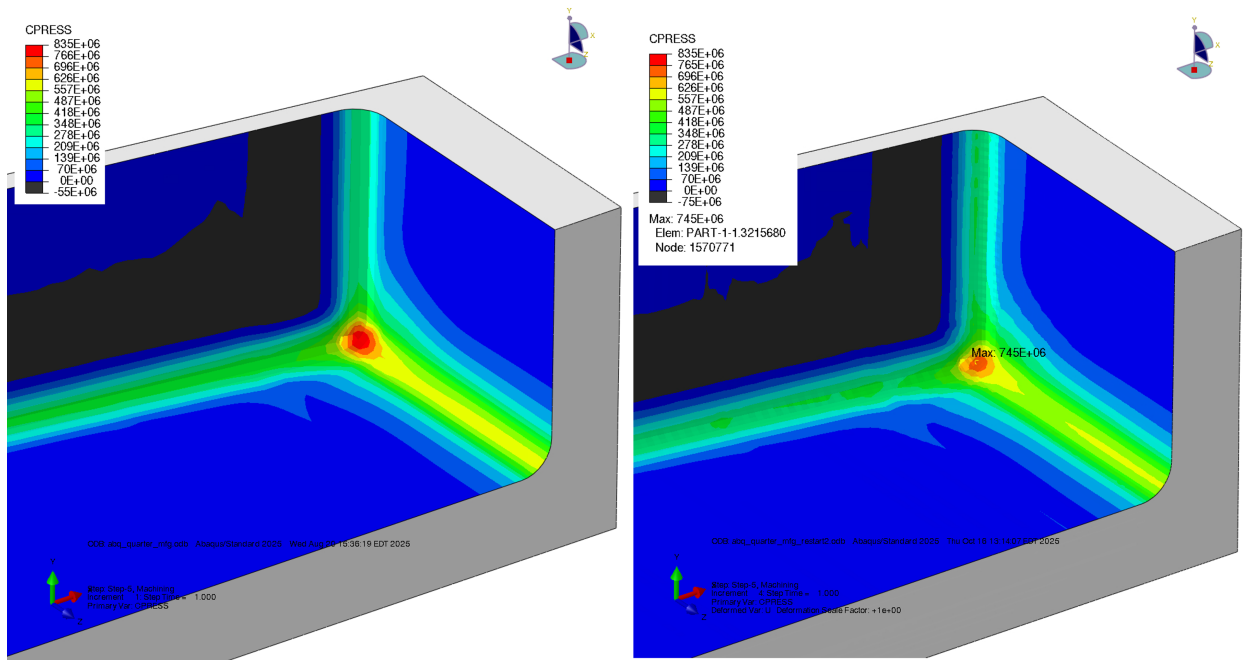


Figure 135. Inconel contact surface pressure after manufacturing simulation for original mesh (L) and refined mesh (R).

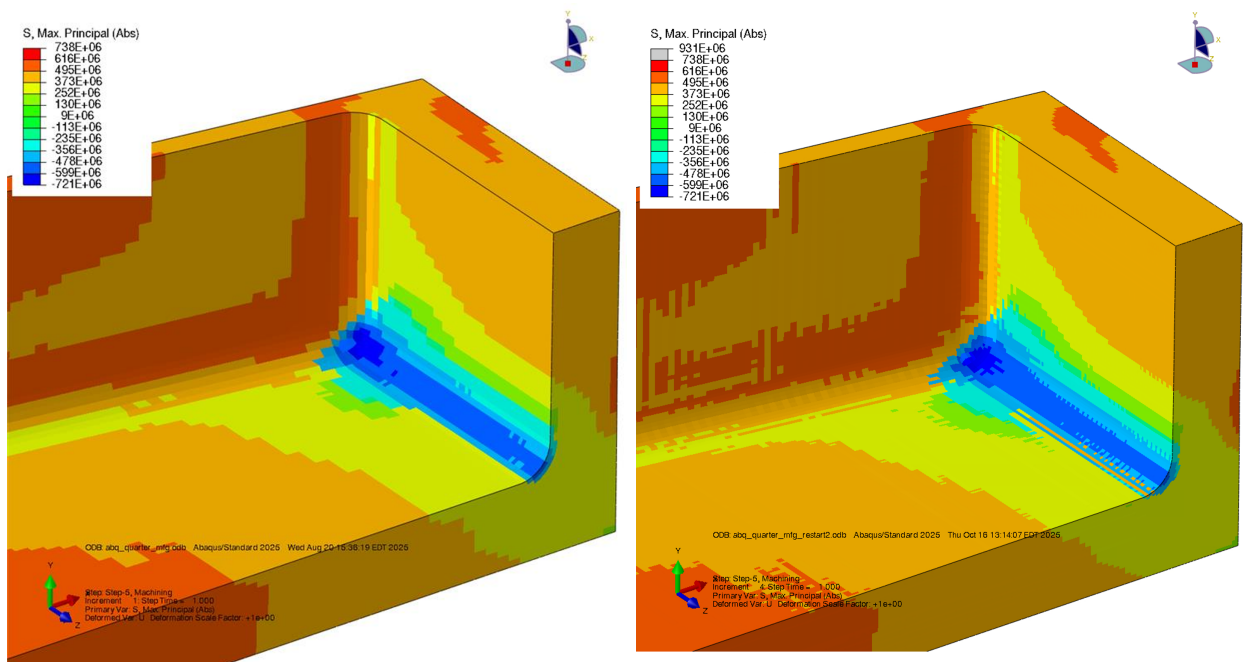


Figure 136. Inconel shroud largest principal stresses after manufacturing simulation for original mesh (L) and refined mesh (R).

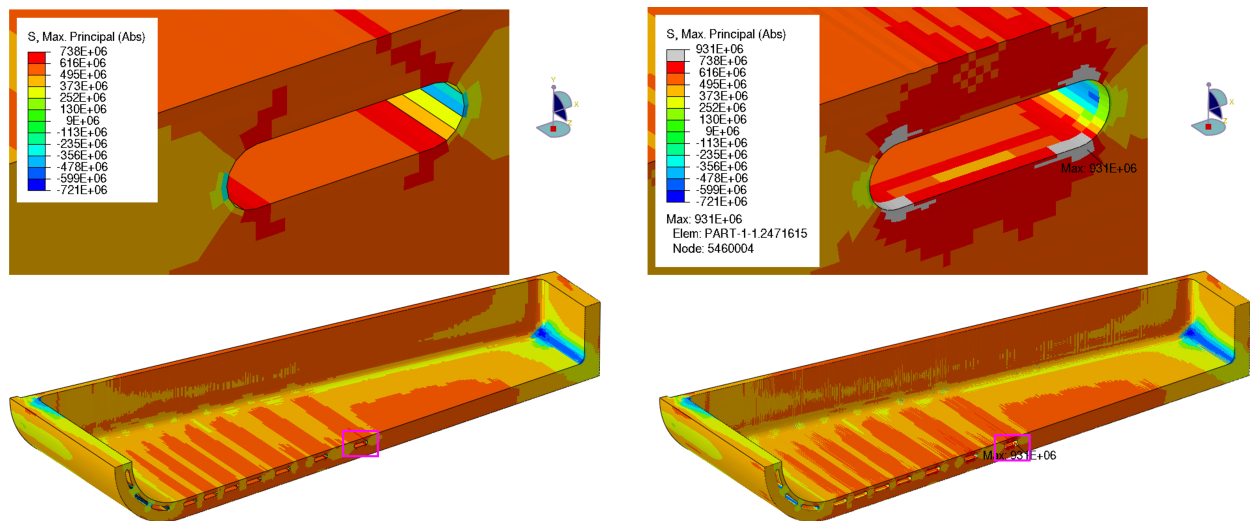


Figure 137. Inconel shroud largest principal stresses after manufacturing simulation for original mesh (L) and refined mesh (R). View of cooling channels at center of target.

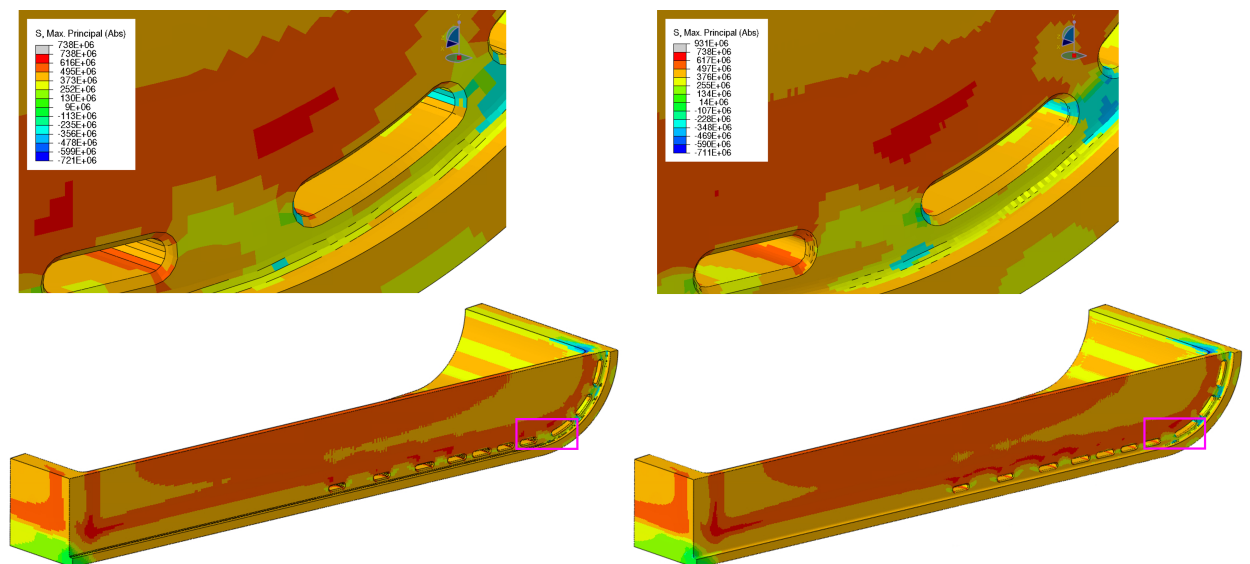


Figure 138. Inconel shroud largest principal stresses after manufacturing simulation for original mesh (L) and refined mesh (R). View of cooling channels at side manifold region.

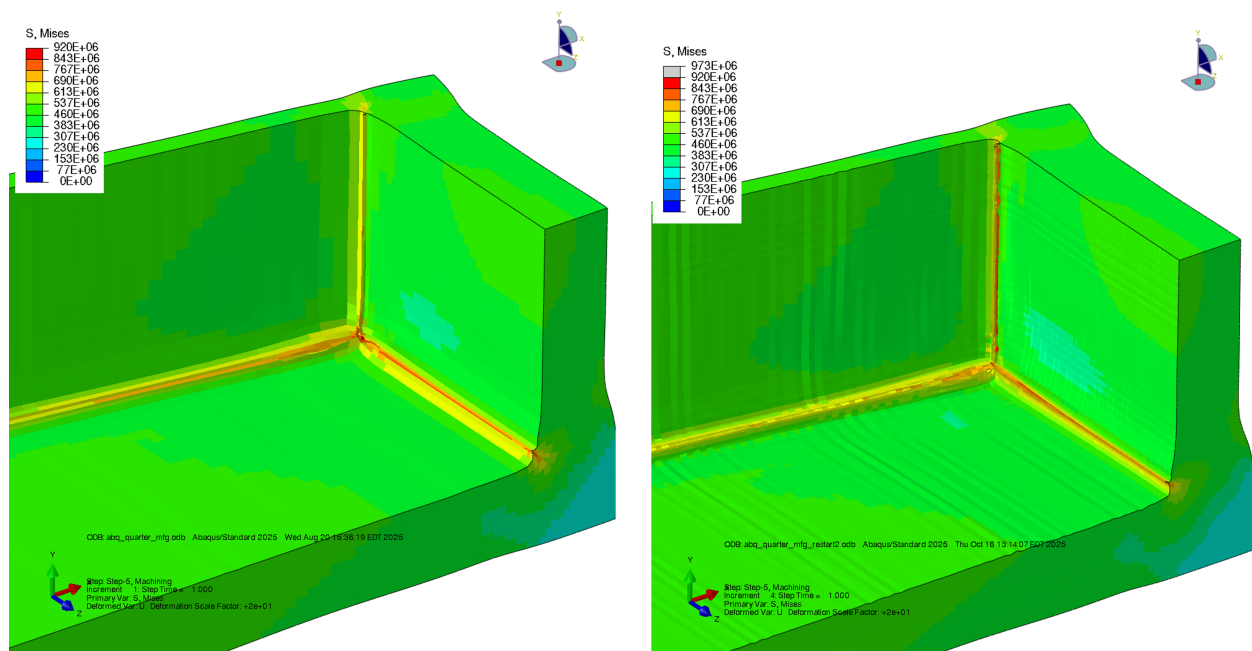


Figure 139. Inconel shroud von Mises stress with 20x displacement after manufacturing simulation for original mesh (L) and refined mesh (R).

5.11.2 Effect of Water Pulses

One of the modeling assumptions in Section 2 is that the water volume does not participate in the structural solution except for static pressure on the wetted surfaces. This was explored earlier in the FDR project phase with the "v12" target geometry. At that time, the target was modeled with second-order tetrahedral elements. The manufacturing simulation followed the same procedure as described in Section 4. The static simulation included the water domain as shown in Figure 140 and modeled it as an isotropically elastic weak solid with high Poisson's ratio (0.495) and modulus of elasticity calculated from the bulk modulus of water. Dead loads, live loads, and static temperature loads were applied as previously described. (The static pressure load was not applied as it would not correctly propagate through the elastic solid model for water.)

For the dynamic simulation, the water volume was modeled with an Abaqus equation of state (EOS) as shown in Figure 141 that included the speed of sound and a tensile cut-off. The pulse in the water domain was not directly modeled as energy deposition in the (lower density) water is much lower than the surrounding metals. Instead, the water volume could transmit pressure from the beam pulse into the solid and possibly increase stresses on the flow cover. Otherwise, the dynamic simulation followed the same procedure as described in Section 4.

Figure 142 shows the pressure along the centerline of the front water channel over the first 8 μs after the beam pulse. The peak water pressure event occurs roughly 2 μs elapsed time and then decreases. There is no significant pressure rise away from the beam centerline and near the flow cover. Furthermore, Figure 143 shows the stress state of the flow cover across from the exit of the front flow channel during the pulse response. The stress in this region is actually lower than it is between the flow channels (where the shroud has more stiffness). It would appear the dominant effect of the flow channels is to actually reduce flow cover stress by reducing stiffness. The effect of pressure transmission through the water is negligible by comparison.

This simulation is also archived with the project files in the Windchill PLM.

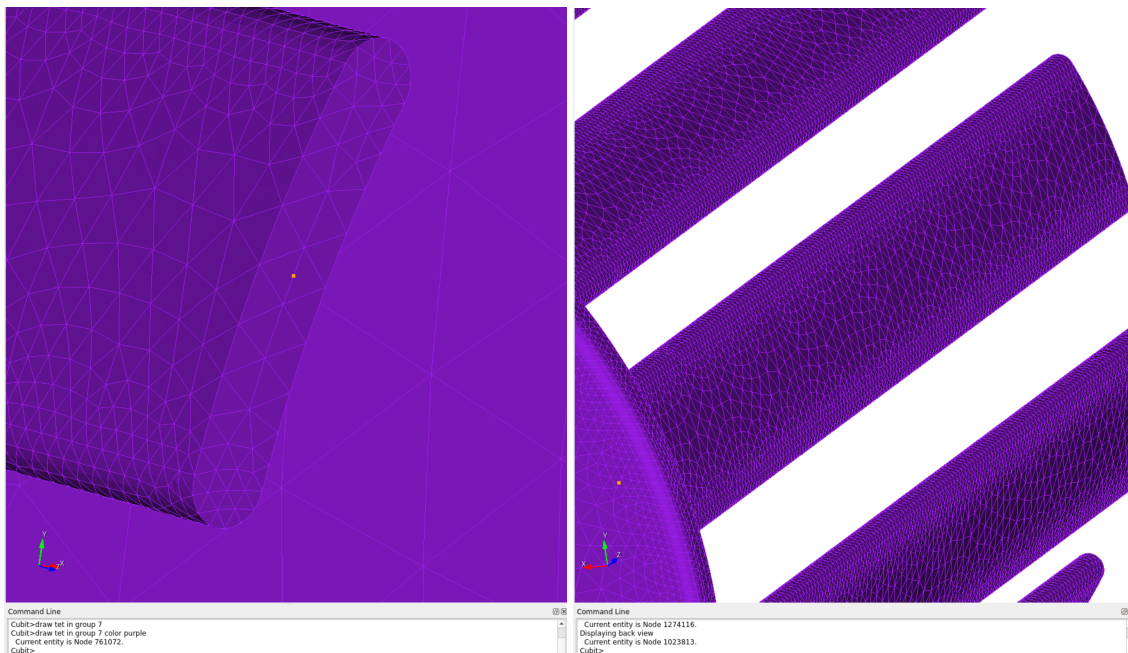


Figure 140. Water domain tetrahedral mesh showing (L) beginning and (R) end nodes to define a path through the center of the first water channel.

```

**
*MATERIAL, NAME=water_elastic
*DENSITY
1000.0, 0.0
*Eos, type=usup
1515., 0., 0.
*Tensile failure, element deletion=no, pressure=ductile, shear=ductile
1.5e+5,
*Viscosity
0.001,
*PHYSICAL CONSTANTS, ABSOLUTE ZERO = -273.15
*INCLUDE, INPUT =dynamic
*****

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Figure 141. Water EOS for Abaqus showing a speed of sound of 1515 m/s and a tensile cut-off pressure.

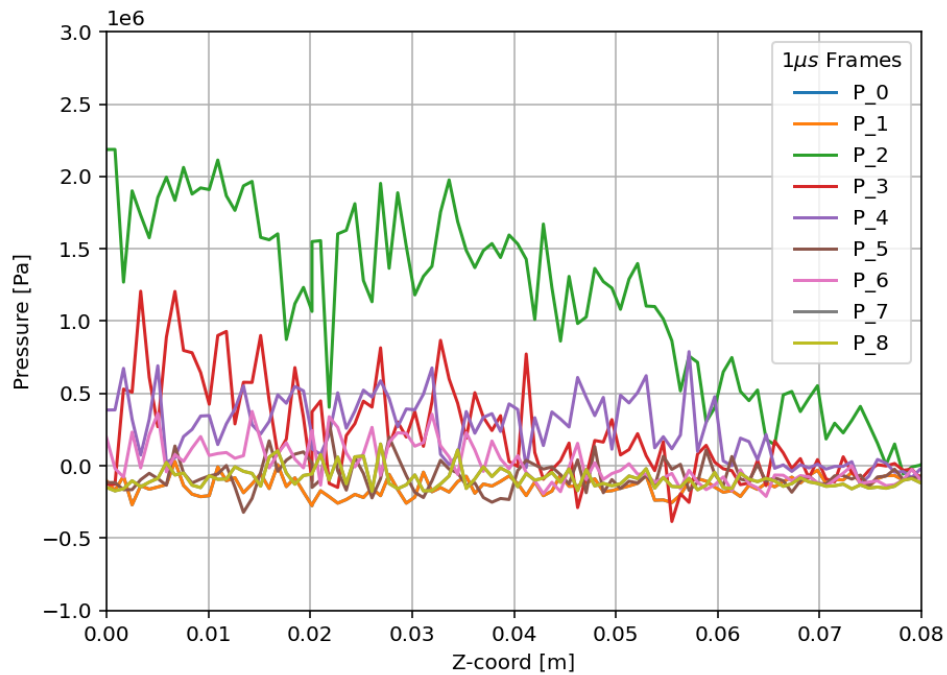


Figure 142. Water pressure along centerline of first water channel during pulse response, measured from the target centerline. Each frame represents $1 \mu s$ time intervals.

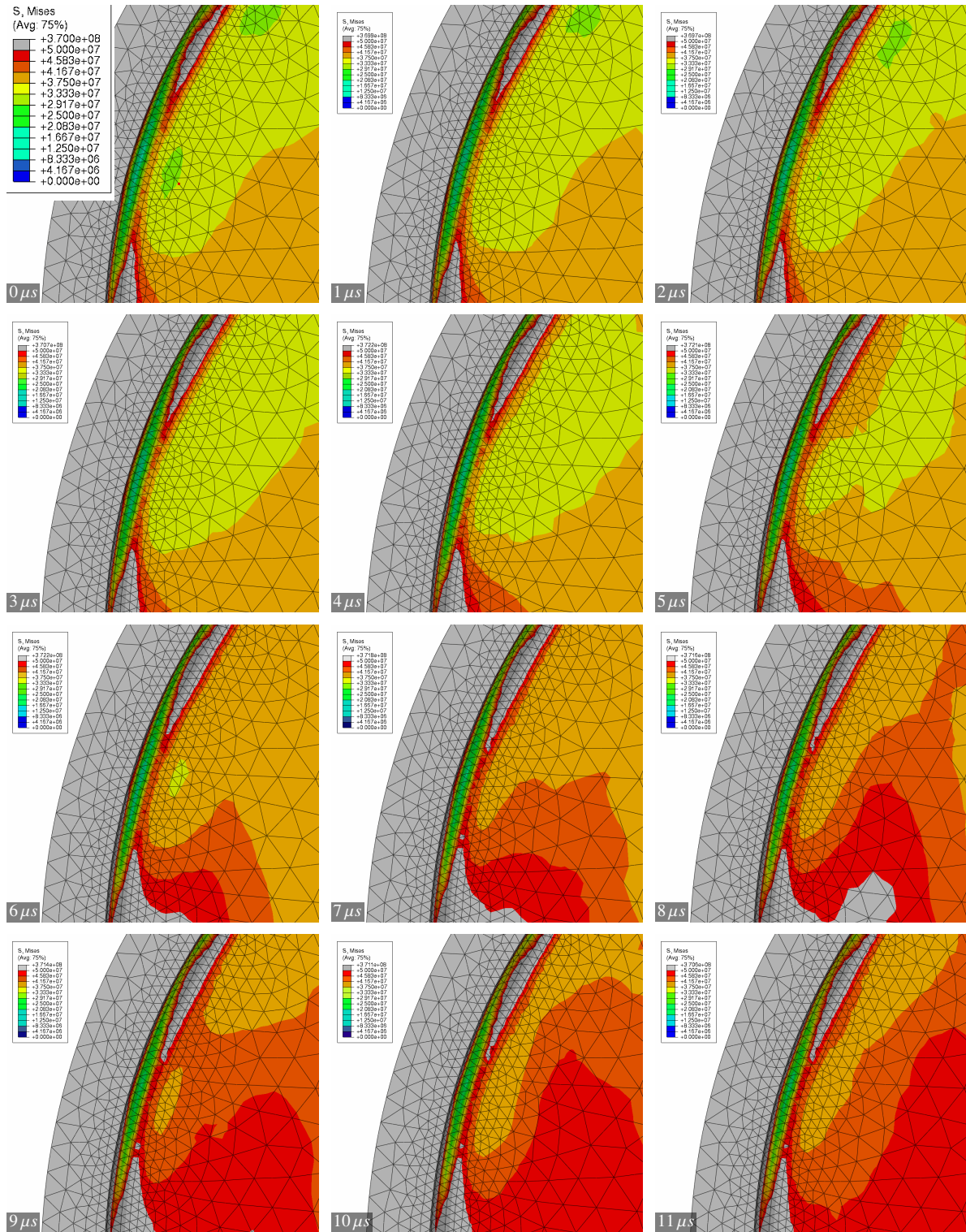


Figure 143. Time frames during pulse response of von Mises equivalent stress on the inner surface of the flow cover. Each frame represents a $1 \mu s$ time interval. The first frame identifies the location corresponding to the centerline of the first flow channel.

5.11.3 Sensitivity to Tungsten Modulus

As discussed in the "Target Systems Materials Library" [16], there is some debate about the effect of irradiation on the modulus of elasticity for tungsten. Accordingly, the nominal case is re-run with a 20% higher elastic modulus for the quasi-static structural simulation, the explicit dynamic structural solution, and the fatigue solution. The manufacturing simulation was left unaltered since the tungsten will always be unirradiated during manufacture. Table 9 and Figure 144 compare the results against the baseline. The stainless steel remains essentially unchanged as it is not thermally or structurally connected to the tungsten. The stresses increase for both tungsten and Inconel in the WOL configuration as the tungsten responds with increased stiffness.

Table 9. FOS comparisons for sensitivity to a 20% increase in tungsten elastic modulus.

Material	Nominal FOS		Sensitivity FOS	
	Trips	Pulses	Trips	Pulses
Inconel	1.149	1.169	1.11	1.139
Tungsten	1.202	1.298	1.037	1.144
Stainless	1.76	1.332	1.76	1.484

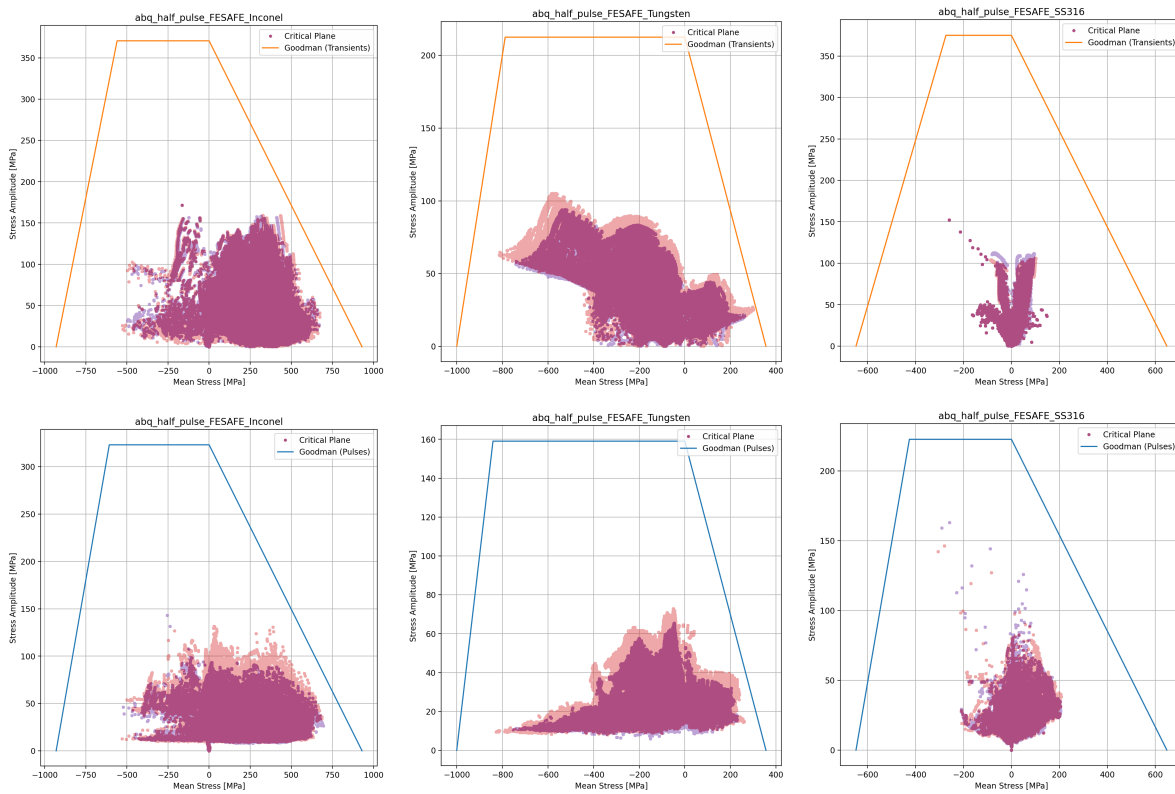


Figure 144. Goodman diagrams comparing the sensitivity of fatigue analysis to tungsten elastic modulus. Baseline nominal results are shown in transparent purple against results with a 20% higher tungsten elastic modulus (red).

5.11.4 Sensitivity to Duration of Simulation

In the nominal case, the response of the system to the beam pulse is recorded over a span of $400\ \mu\text{s}$. To test this parameter, the simulation for the nominal case was re-run with the pulse response recorded for $600\ \mu\text{s}$. Figure 145 compares the fatigue results. There is no change for the beam trips as those utilize static solution data. The beam pulse diagrams show negligible change for all materials. It is expected that the worse fatigue stress event occurs early in the pulse response before significant damping has occurred.

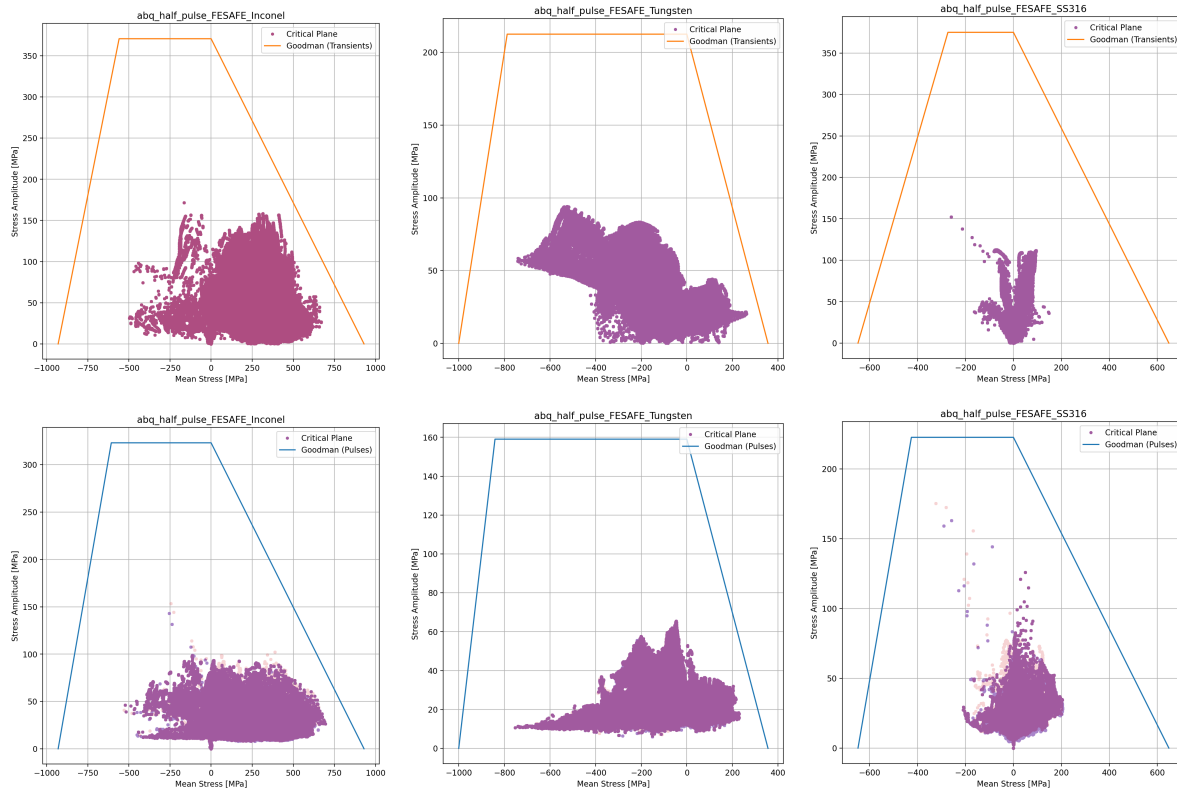


Figure 145. Goodman diagrams comparing the sensitivity of fatigue analysis to the length of time over which the system responds. Baseline nominal results are shown in transparent purple against results with a 50% longer simulation response.

5.11.5 Sensitivity to Pulse Duration

The nominal proton beam pulse is applied as a forced temperature rise, ramped over a duration of 700-ns. To test this effect, the simulation for the nominal case was re-run with the pulse temperature field ramped over 350-ns. Figure 146 compares the fatigue results. There is no change for the beam trips as those utilize static solution data. The beam pulse diagrams show minimal change for all materials. The inertia of the system is too large to respond at the time scale of the pulse.

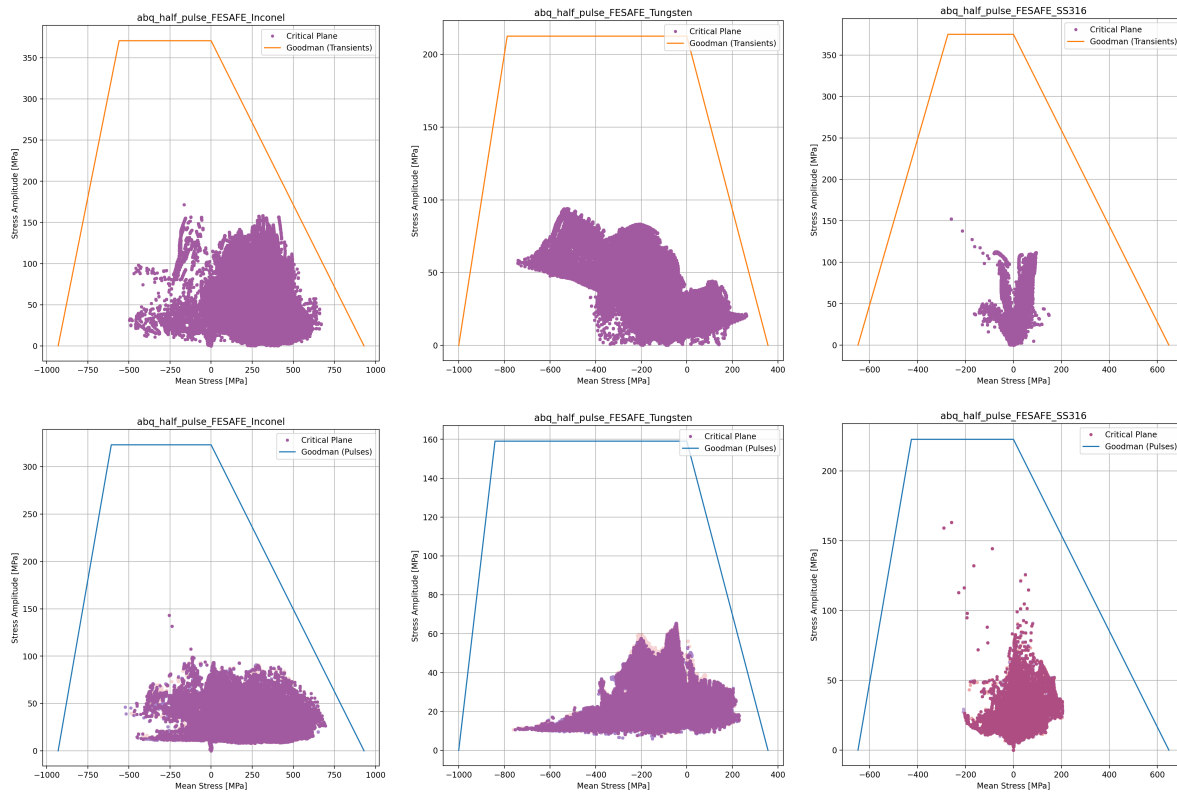


Figure 146. Goodman diagrams comparing the sensitivity of fatigue analysis to the duration of the beam pulse. Baseline nominal results are shown in transparent purple against results using a 50% shorter pulse duration.

5.11.6 Sensitivity to Data Output Frequency

The fatigue analyses in this report use pulse response data written at a $1.0\ \mu s$ intervals. The simulation for the nominal case was re-run with the stress fields output at $0.5\ \mu s$ intervals. Figure 147 compares the fatigue results. There is no change for the beam trips as those utilize static solution data. The beam pulse diagrams show minimal change for all materials.

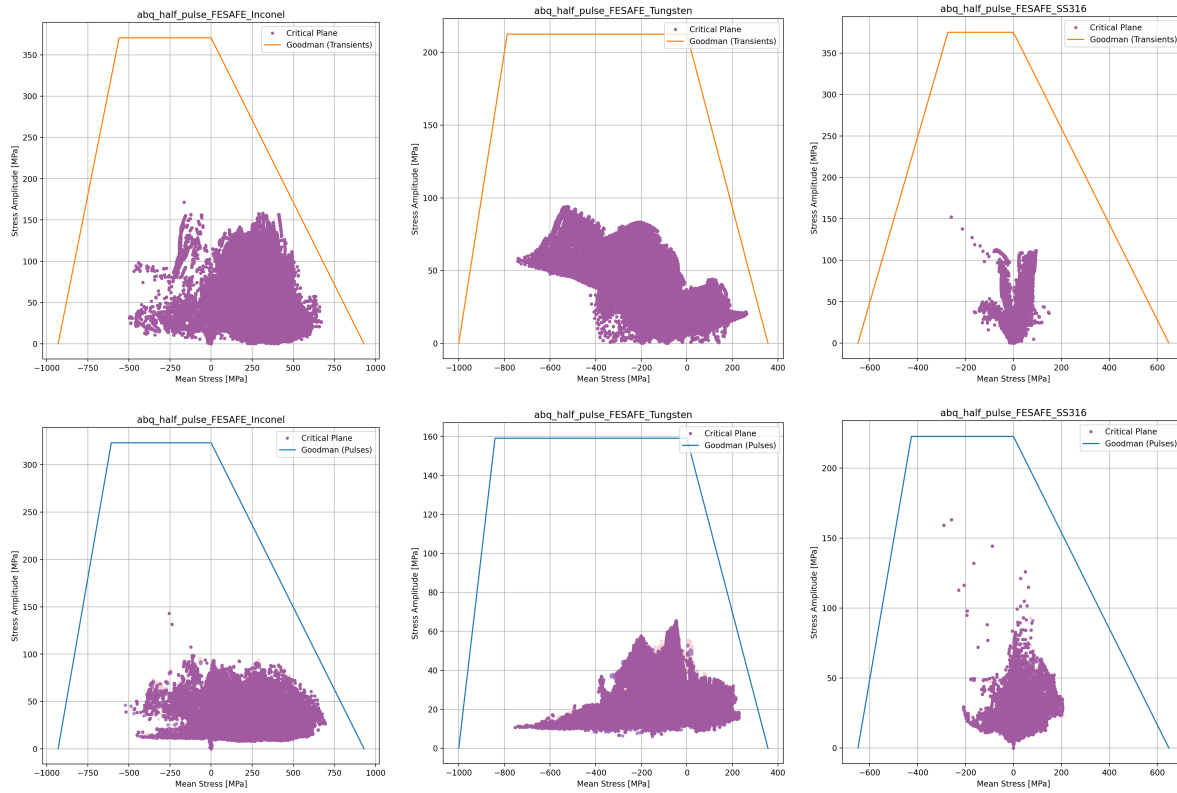


Figure 147. Goodman diagrams comparing the sensitivity of fatigue analysis to the simulation output frequency. Baseline nominal results are shown in transparent purple against results using data written at twice the rate (red).

5.11.7 Sensitivity to Fatigue Model

As discussed in the "Target Systems Materials Library" [16], there is some debate about the fatigue failure mode in the very high cycle fatigue regime. Accordingly, the *fe-safe* fatigue analysis is re-run using the brittle normal stress model for Inconel and stainless steel instead of the Brown-Miller ductile model. Figure 148 attempts to compare the changes by overlaying the Goodman diagrams over the baseline normal case. The tungsten data remains unchanged as the model is well-understood to be that of a brittle failure mode. When comparing the Inconel and stainless steel, there is little overall change in model performance. The heel does show 2 nodes with FOS < 1, however, these are at the pin/slot contact and are numerically suspect. It would appear the simulations are comparable in terms of normal stress amplitudes and the combined effects of shear stress with normal stress amplitudes.

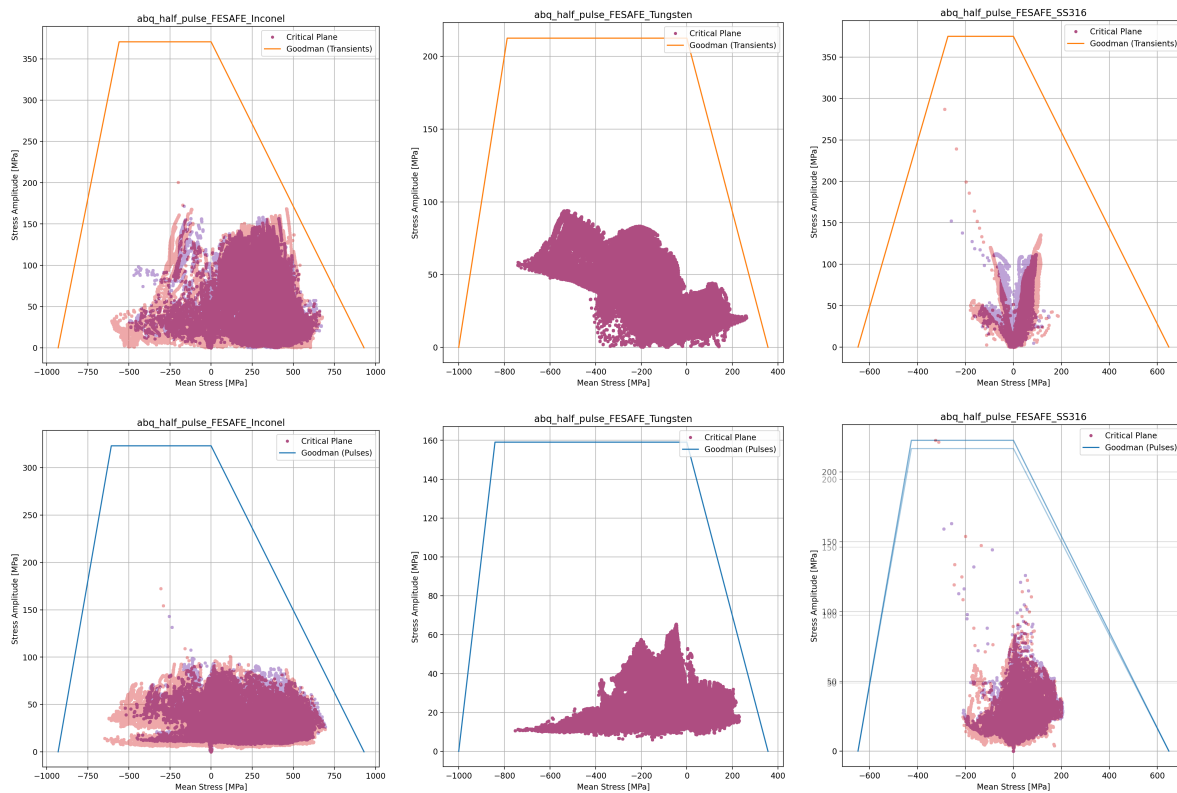


Figure 148. Goodman diagrams comparing the effects of fatigue model on FOS. Baseline nominal results are shown in transparent purple against results using only the normal stress failure theory (red).

5.11.8 Sensitivity to Fatigue UTS

The sensitivity of FOS to UTS was examined in *fe-safe*. (Note that the UTS is the failure point on the x-axis of the Goodman diagram at zero stress amplitude.) The UTS of each material was reduced by 15%, and the *fe-safe* analysis was re-run. Table 10 and Figure 149 summarize the results. In the Goodman diagrams, the mean stress limit at zero stress amplitude (i.e. the UTS) has been accordingly reduced by 15%. The point cloud of critical plane results for each finite element in the model remain unchanged. Put another way, only the design envelope has been moved, causing a 10-12% reduction in FOS. With the high mean stress nature of the target foot manufacturing, the design is most sensitive to the effects of UTS.

Table 10. FOS comparisons for sensitivity to a 15% reduction in UTS.

Material	Nominal FOS		Sensitivity FOS	
	Trips	Pulses	Trips	Pulses
Inconel	1.149	1.169	1.04	1.023
Tungsten	1.202	1.298	1.04	1.141
Stainless	1.76	1.332	1.705	1.332

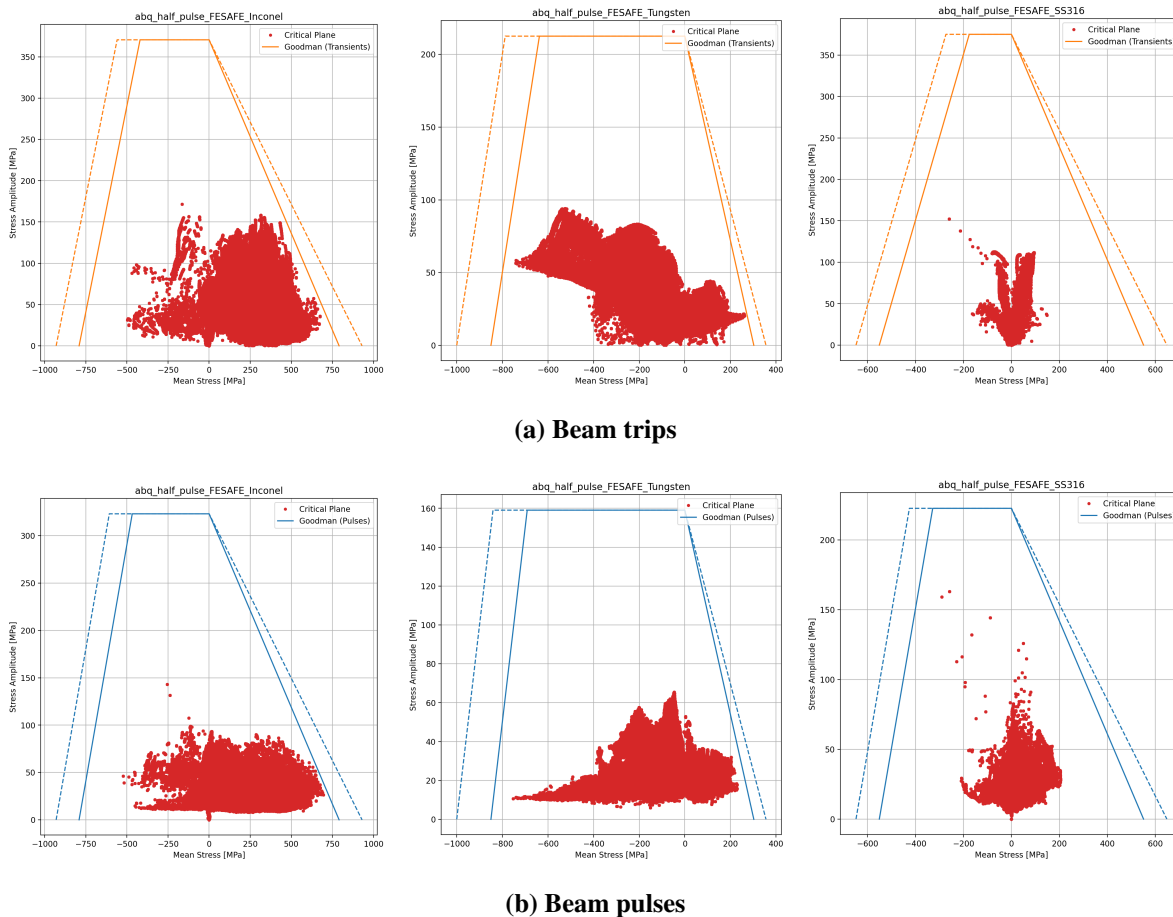


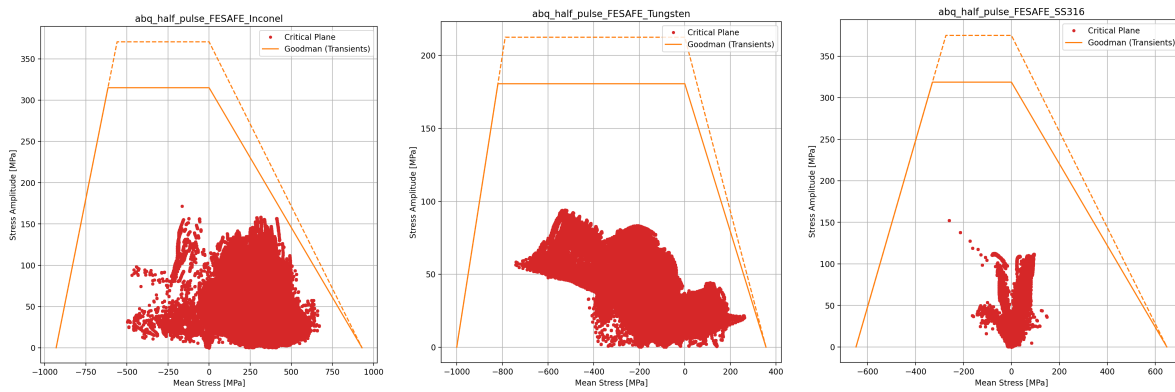
Figure 149. Goodman diagrams for fatigue analysis with a 15% reduction in UTS. The original fatigue failure envelope is indicated with a dashed line.

5.11.9 Sensitivity to Fatigue Strength

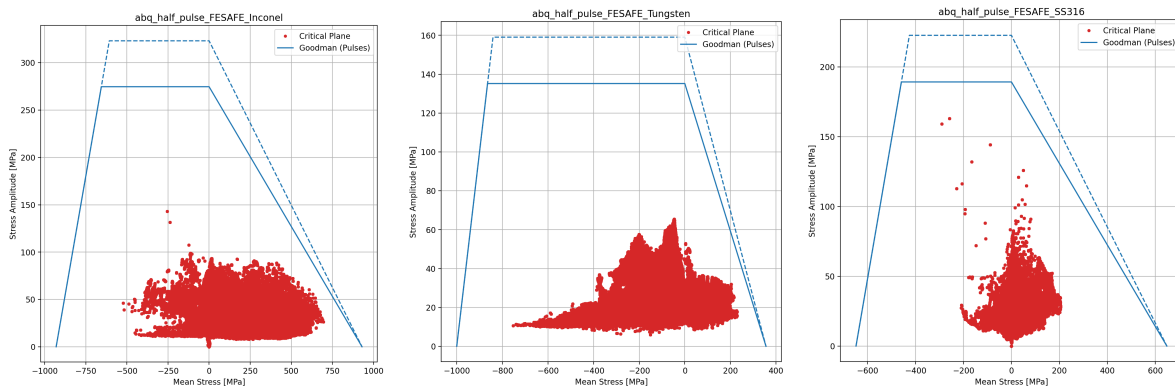
The sensitivity of FOS to fatigue strength was examined in *fe-safe*. The fatigue strength of each material was reduced by 15%, and the *fe-safe* analysis was re-run. Table 11 and Figure 150 summarize the results. In the Goodman diagrams, the stress amplitude limit at zero mean stress (i.e. the fatigue strength) has been accordingly reduced by 15%. The point cloud of critical plane results for each finite element in the model remain unchanged. Put another way, only the design envelope has been moved.

Table 11. FOS comparisons for sensitivity to a 15% reduction in fatigue strength.

Material	Nominal FOS		Sensitivity FOS	
	Trips	Pulses	Trips	Pulses
Inconel	1.149	1.169	1.06	1.132
Tungsten	1.202	1.298	1.177	1.133
Stainless	1.76	1.332	1.496	1.24



(a) Beam trips



(b) Beam pulses

Figure 150. Goodman diagrams for fatigue analysis with a 15% reduction in fatigue strength. The original fatigue failure envelope is indicated with a dashed line.

5.11.10 Sensitivity to Combined Fatigue Damage

A key assumption to the fatigue simulations is that beam trips do not interact with beam pulses in fatigue life. Otherwise, the *fe-safe* software would model the worst case of a beam trip occurring during the peak stress cycle of a beam pulse which is not physically realistic. Another aspect is the possibility of damage accumulation from beam trip cycle fatigue that affects beam pulse cycle fatigue and vice versa. This is plausible. To test this, a single fatigue analysis was performed for the nominal beam case with combined loading. Interactions were disabled via the `Transitions=No` command in the loading definition. Table 12 compares the results against the individual fatigue analyses. The combined loading analysis reports the minimum of the two independent fatigue analyses. This indicates the lack of cumulative damage effects between the two fatigue loadings.

Table 12. FOS comparisons for sensitivity to combined loading in *fe-safe*.

Material	Trips	Pulses	Combined Loading (No Interaction)
Inconel	1.149	1.169	1.149
Inconel Side Weld	1.02	0.92	0.92
Tungsten	1.202	1.298	1.202
Stainless	1.76	1.332	1.332

6. SUMMARY & CONCLUSIONS

Figure 151 visually summarizes the outcome of each analysis performed to satisfy the design requirements. The following paragraphs summarize this document and further explain the assessments.

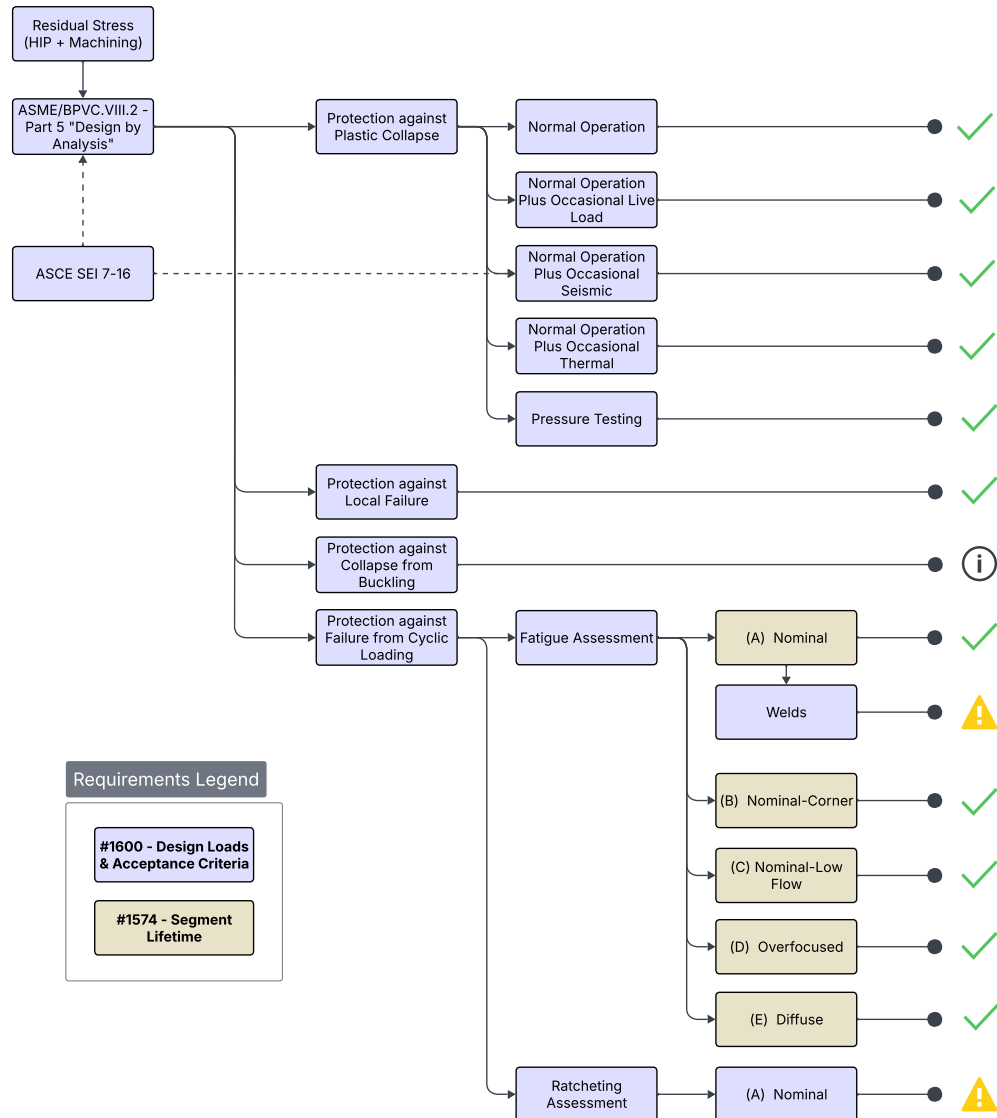


Figure 151. Target segment foot design requirement cases with assessments.

Thermostructural analyses have been completed for the lower portion of a target segment in support of a final design review. The worst-of-life (WOL) methodology assumes the entire service life occurs with full manufacturing residual stresses and with irradiated tungsten thermal conductivity. Accordingly, all analyses incorporate a manufacturing simulation that captures residual stresses in the target foot (tungsten plates, tantalum cladding, and Inconel shroud) as it goes through HIP with creep followed by machining of cooling passages in the shroud.

The design requirements specify ASME/BPVC Sec. VIII.2, Part 5 "Design by Analysis" methodology. This Code has been used with some modifications as necessary to analyze the lower target segment against the following failure modes:

Protection Against Plastic Collapse - PASS The elastic-plastic method with LRFD load factors was used to demonstrate protection from failure under 6 loading conditions:

- Normal operation,
- Normal operation plus occasional live load,
- Normal operation plus occasional seismic load (both directions),
- Normal operation plus occasional thermal load, and
- Pressure testing.

The seismic load is defined through ASCE SEI 7-16. All cases pass by demonstrating converged solutions.

Protection Against Local Failure - PASS The elastic-plastic method with LRFD load factors was used to demonstrate protection from failure. Limiting triaxial strains were calculated for each element nodal result and compared against total accumulated plastic strain. The entire domain passes with positive strain margin.

Protection Against Collapse from Buckling - OMIT This is not a credible failure mode under operational conditions. Transportation and installation activities could generate compressive stress fields on the structure, however, this is outside the scope of this DAC.

Protection Against Failure from Cyclic Loading (Ratcheting) - CONDITIONAL PASS At least 3 loading repetitions were simulated for both the case of beam trips and beam pulses. The flow cover and heel structures are able to use the required thermoelastic-perfectly plastic material models. In both loading scenarios, they demonstrate an elastic core. The shroud structure must continue to use a thermoelastic-plastic material model as it incorporates the significant manufacturing residual stresses with plastic hardening. The beam pulse repetition scenario shows a trend of finite ratcheting, indicating plastic shakedown to elastic stress cycles. The beam trip repetition scenario continues to show plastic strain increments in a region of the shroud-to-cover weld and in some forward cooling channels. These regions are surrounded by a shakedown elastic core, however, which could be viewed as passing the requirement.

Protection Against Failure from Cyclic Loading (Fatigue) - CONDITIONAL PASS FEA simulations incorporated manufacturing, static, and dynamic pulse loading on the lower target segment. Commercial *fe-safe* software was used to perform critical plane fatigue analysis on tungsten, Inconel, and stainless steel components for the following beam scenarios:

- Nominal beam,
- Nominal offset (corner),
- Nominal low-flow,
- Overfocused, and
- Diffuse.

All cases pass for a 10 year life of beam trips and beam pulses, using custom mean-life fatigue curves.

All welds require full penetration, machined welds that receive a full volumetric examination (radio-graphic or ultrasonic) and a surface that receives magnetic particle or liquid penetrant examination and a visual examination. Even with this, the Inconel side weld is marginal with one element failing at the edge of a hypothetical HAZ that coincides with a flow channel surface. This highlights the need for the flow channels to be as smooth as possible and to have as much surface compression as possible through machining and/or surface treatments.

The other welds pass, however, the beam trip ratcheting simulation reveals the potential presence of cyclic plastic deformation while the fatigue analyses assume elastic stress cycles. Whether this is truly cyclic plastic deformation depends upon the complex interaction between yield stress as a function of temperature and also plastic hardening.

Several sensitivity analyses were explored, and the fatigue analyses were found to be insensitive to these changes. An attempt at mesh refinement for the manufacturing simulation was not able to demonstrate convergence. This is due to the need of a high quality hex mesh to resolve manufacturing contact surfaces combined with computational limitations (i.e. lack of additional hardware or software licenses). In lieu of a demonstrated mesh independent solution, results should be expected to vary on the order of 10-20%. If the target segment were to fail, analyses indicate the critical points would be flow channel side walls near the entrance to the channels and the flow cover weld. The former could see a crack propagate between flow channels which does not seem to be an operational issue. The later would result in cooling water flowing into the core vessel. The spallation materials, however, would remain encapsulated.

In conclusion, the lower target segment design is found to be thermostructurally viable. It is found to conditionally pass the ASME/BPVC "Design by Analysis" requirements with a design that appears to be robust in areas of low failure margin.

7. REFERENCES

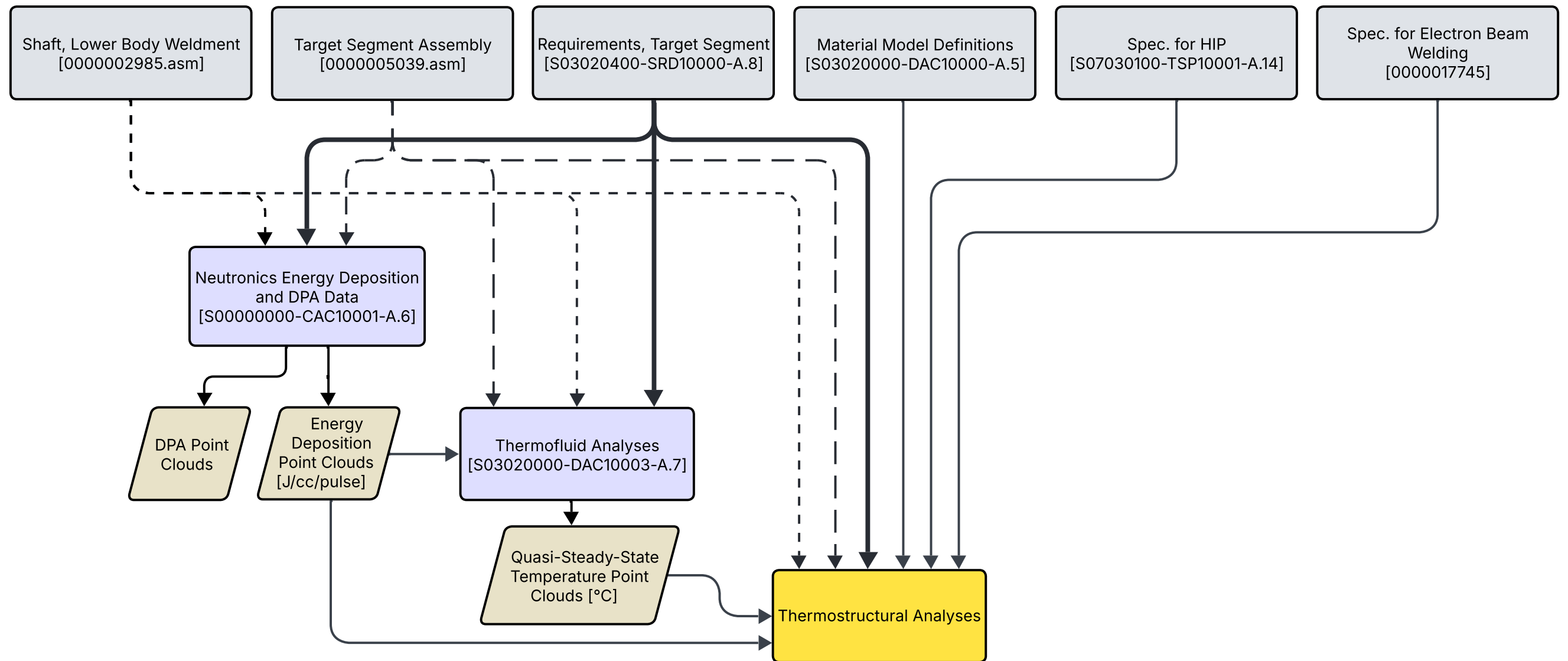
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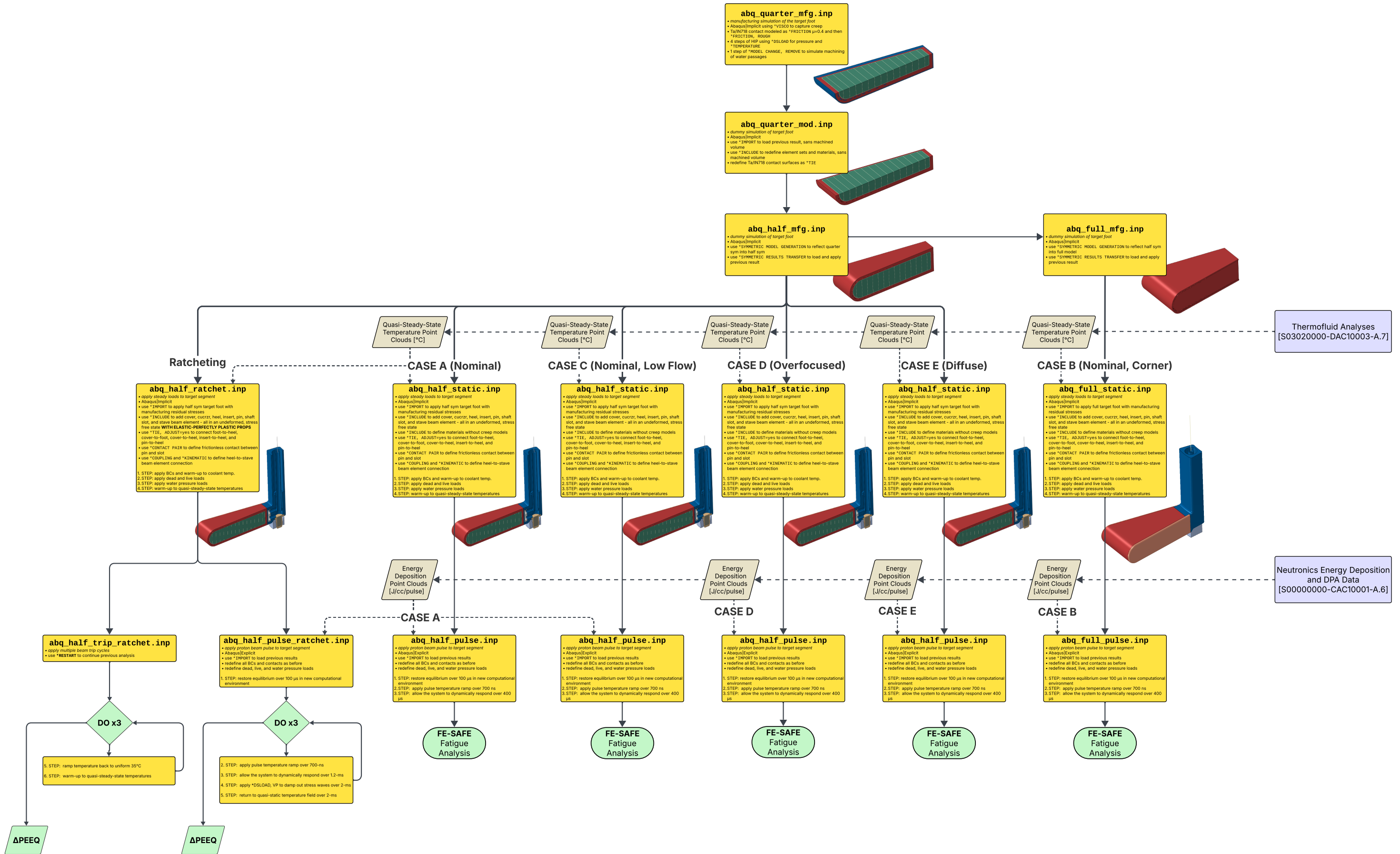
APPENDIX A. ANALYSIS FLOWCHARTS

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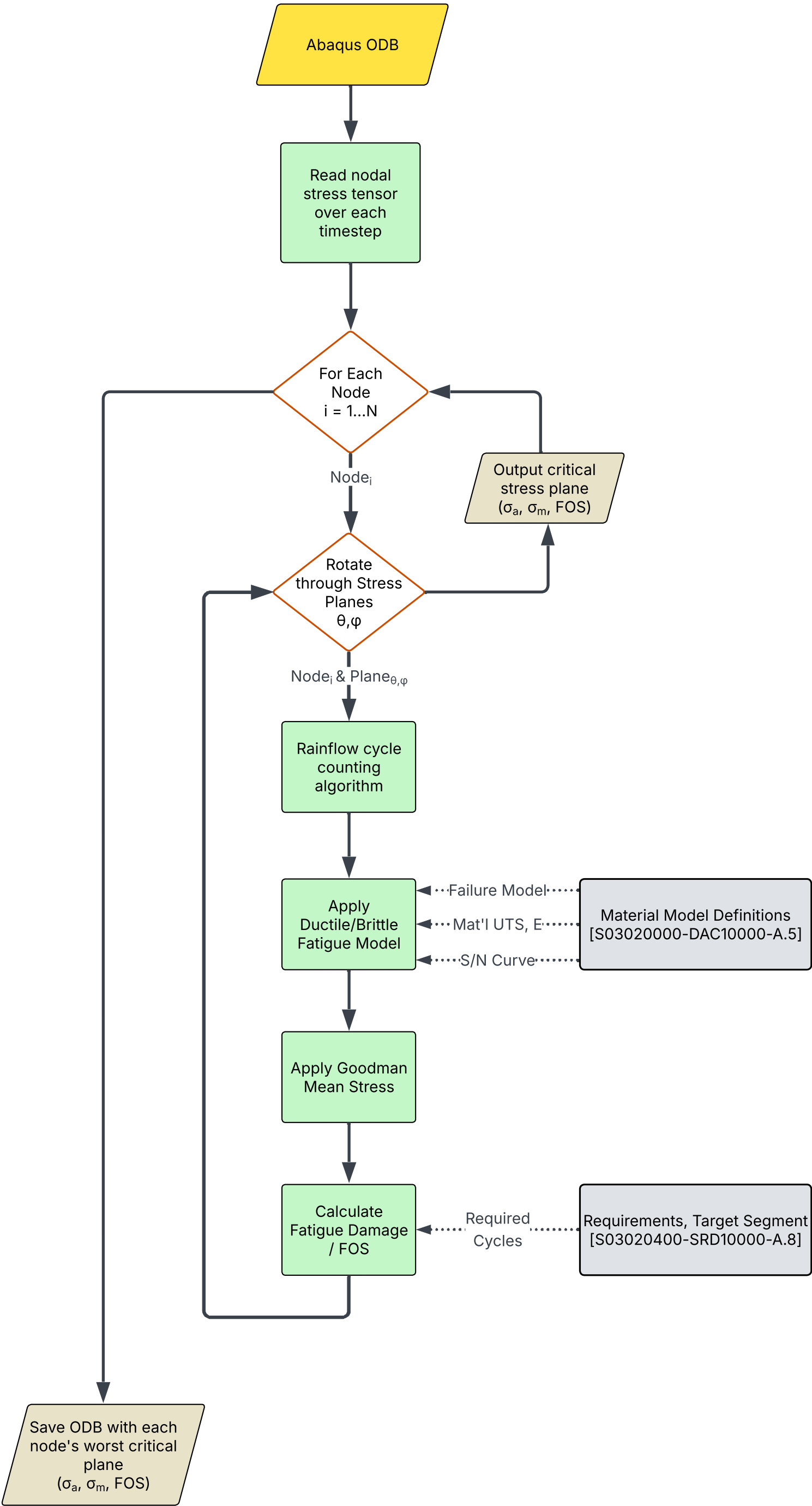
A.0.1 FDR Analysis Flowchart



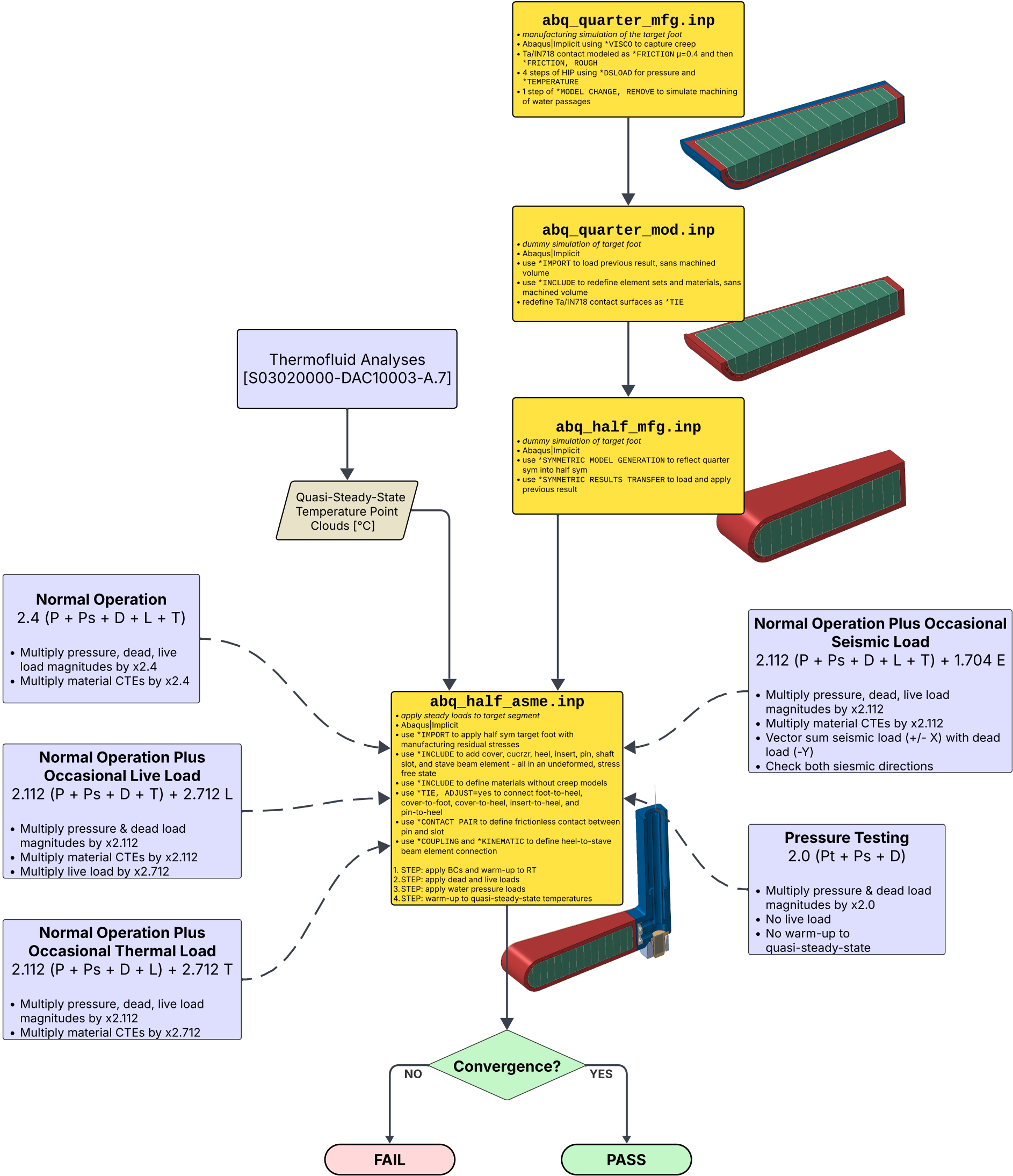
A.0.2 Abaqus Fatigue Flowchart



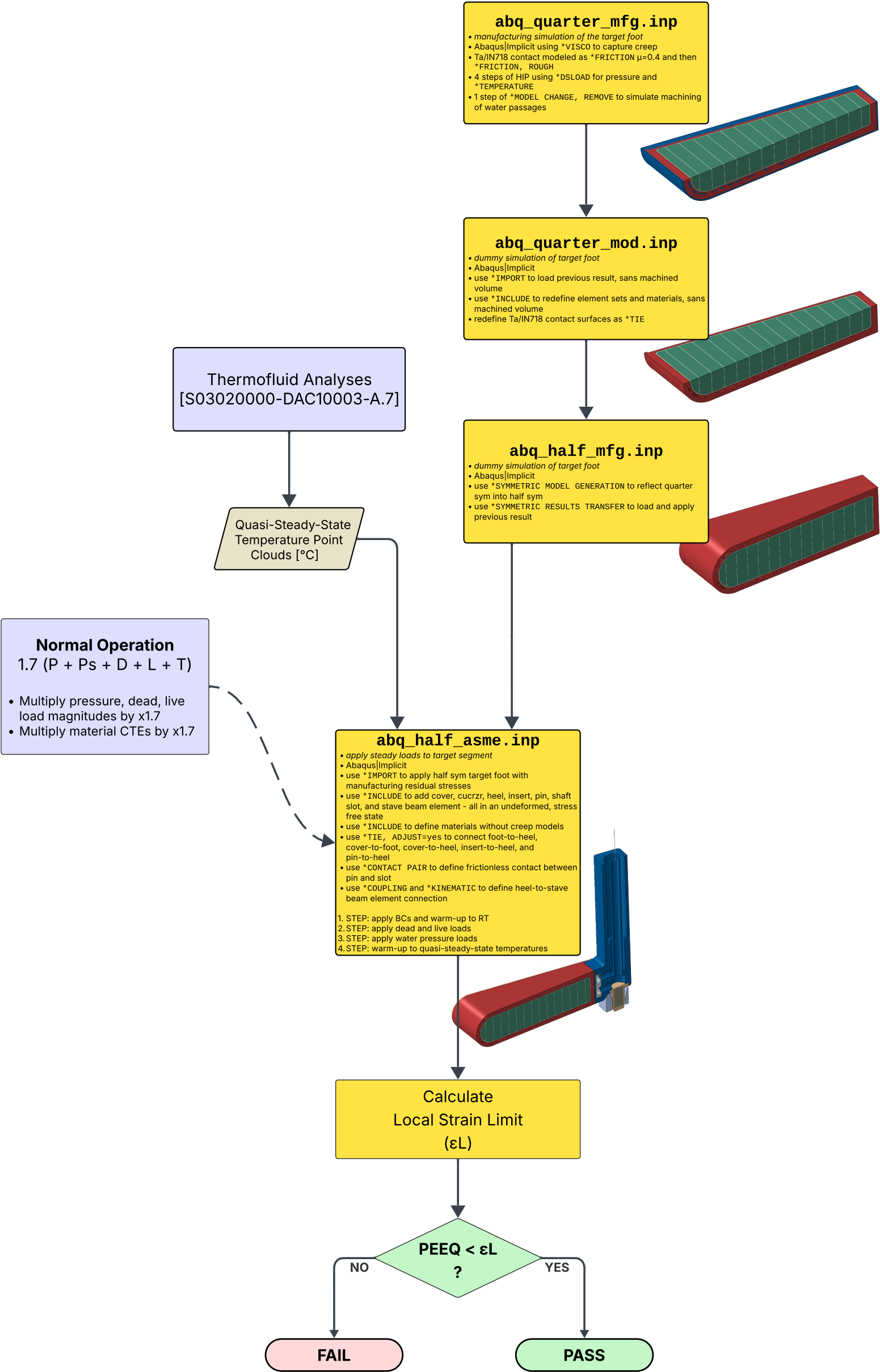
A.0.3 *fe-safe* Fatigue Flowchart



A.0.4 Abaqus Plastic Collapse Flowchart



A.0.5 Abaqus Local Failure Flowchart



APPENDIX B. CONVERGENCE TABLES

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B.0.1 Manufacturing Simulation

Table 13. Abaqus convergence table for quarter-symmetry target foot manufacturing simulation.

Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
1	1	1	4	1	5	1.00	1.00	1.000
1	2	1	3	1	4	2.00	2.00	1.000
1	3	1	2	1	3	3.00	3.00	1.000
1	4	1	2	1	3	5.00	5.00	2.000
1	5	1	3	0	3	9.00	9.00	4.000
1	6	1	2	1	3	15.0	15.0	6.000
1	7	1	3	1	4	27.0	27.0	12.00
1	8	1	3	1	4	51.0	51.0	24.00
1	9	1	3	1	4	99.0	99.0	48.00
1	10	1	2	1	3	195.	195.	96.00
1	11	1	3	1	4	387.	387.	192.0
1	12	1	2	2	4	771.	771.	384.0
1	13	1	3	1	4	1.35e+03	1.35e+03	576.0
1	14	1	4	1	5	2.50e+03	2.50e+03	1152.
1	15	1	5	1	6	4.80e+03	4.80e+03	2304.
1	16	1	5	1	6	9.41e+03	9.41e+03	4608.
1	17	1	3	1	4	1.08e+04	1.08e+04	1389.
2	1	1	1	1	2	1.08e+04	1.00	1.000
2	2	1	0	1	1	1.08e+04	2.00	1.000
2	3	1	0	1	1	1.08e+04	3.00	1.000
2	4	1	0	1	1	1.08e+04	5.00	2.000
2	5	1	0	2	2	1.08e+04	9.00	4.000
2	6	1	0	1	1	1.08e+04	15.0	6.000
2	7	1	1	1	2	1.08e+04	27.0	12.00
2	8	1	1	1	2	1.09e+04	51.0	24.00
2	9	1	2	1	3	1.09e+04	99.0	48.00
2	10	1	2	1	3	1.10e+04	195.	96.00
2	11	1	2	1	3	1.12e+04	387.	192.0
2	12	1U	5	0	5	1.12e+04	387.	384.0
2	12	2	2	1	3	1.13e+04	483.	96.00
2	13	1	2	2	4	1.15e+04	675.	192.0
2	14	1	3	1	4	1.18e+04	963.	288.0
2	15	1U	5	0	5	1.18e+04	963.	576.0
2	15	2	2	2	4	1.19e+04	1.11e+03	144.0
2	16	1	3	1	4	1.21e+04	1.32e+03	216.0
2	17	1	3	1	4	1.26e+04	1.76e+03	432.0
2	18	1U	5	1	6	1.26e+04	1.76e+03	864.0
2	18	2	3	0	3	1.28e+04	1.97e+03	216.0
2	19	1U	6	0	6	1.28e+04	1.97e+03	324.0

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	19	2	3	0	3	1.29e+04	2.05e+03	81.00
2	20	1	3	1	4	1.30e+04	2.17e+03	121.5
2	21	1	4	0	4	1.32e+04	2.42e+03	243.0
2	22	1	4	0	4	1.36e+04	2.78e+03	364.5
2	23	1U	6	1	7	1.36e+04	2.78e+03	546.8
2	23	2	3	0	3	1.37e+04	2.92e+03	136.7
2	24	1	3	0	3	1.39e+04	3.12e+03	205.0
2	25	1	3	1	4	1.42e+04	3.43e+03	307.5
2	26	1	4	1	5	1.48e+04	4.05e+03	615.1
2	27	1U	4	0	4	1.48e+04	4.05e+03	1230.
2	27	2	4	1	5	1.52e+04	4.35e+03	307.5
2	28	1	5	1	6	1.58e+04	4.97e+03	615.1
2	29	1U	5	0	5	1.58e+04	4.97e+03	1230.
2	29	2	3	2	5	1.61e+04	5.28e+03	307.5
2	30	1U	5	1	6	1.61e+04	5.28e+03	461.3
2	30	2	3	1	4	1.62e+04	5.39e+03	115.3
2	31	1	3	2	5	1.64e+04	5.62e+03	230.7
2	32	1	3	3	6	1.68e+04	5.97e+03	346.0
2	33	1U	10	4	14	1.68e+04	5.97e+03	519.0
2	33	2	3	1	4	1.69e+04	6.10e+03	129.7
2	34	1	4	1	5	1.72e+04	6.36e+03	259.5
2	35	1U	6	3	9	1.72e+04	6.36e+03	519.0
2	35	2	2	1	3	1.73e+04	6.49e+03	129.7
2	36	1	3	2	5	1.75e+04	6.75e+03	259.5
2	37	1U	4	1	5	1.75e+04	6.75e+03	259.5
2	37	2	3	1	4	1.76e+04	6.76e+03	12.19
2	38	1	1	2	3	1.76e+04	6.77e+03	12.19
2	39	1	1	2	3	1.76e+04	6.78e+03	12.19
2	40	1	1	1	2	1.76e+04	6.80e+03	18.28
2	41	1	3	0	3	1.76e+04	6.84e+03	36.56
2	42	1	2	2	4	1.77e+04	6.89e+03	54.83
2	43	1U	3	1	4	1.77e+04	6.89e+03	82.25
2	43	2	2	1	3	1.77e+04	6.92e+03	32.60
2	44	1	2	1	3	1.78e+04	6.96e+03	32.60
2	45	1	2	1	3	1.78e+04	6.99e+03	32.60
2	46	1U	3	0	3	1.78e+04	6.99e+03	65.20
2	46	2	2	1	3	1.78e+04	7.02e+03	31.62
2	47	1	2	1	3	1.79e+04	7.05e+03	31.62
2	48	1	2	1	3	1.79e+04	7.08e+03	31.62
2	49	1U	2	1	3	1.79e+04	7.08e+03	63.25
2	49	2	2	1	3	1.79e+04	7.11e+03	27.53
2	50	1	2	1	3	1.79e+04	7.14e+03	27.53
2	51	1	2	1	3	1.80e+04	7.17e+03	27.53
2	52	1U	2	1	3	1.80e+04	7.17e+03	55.07
2	52	2	2	1	3	1.80e+04	7.20e+03	28.63

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	53	1	2	1	3	1.80e+04	7.22e+03	28.63
2	54	1	2	1	3	1.81e+04	7.25e+03	28.63
2	55	1U	3	1	4	1.81e+04	7.25e+03	52.90
2	55	2	2	1	3	1.81e+04	7.28e+03	26.68
2	56	1	2	1	3	1.81e+04	7.31e+03	26.68
2	57	1	2	1	3	1.81e+04	7.33e+03	26.68
2	58	1U	3	1	4	1.81e+04	7.33e+03	51.42
2	58	2	2	1	3	1.82e+04	7.36e+03	25.30
2	59	1	3	1	4	1.82e+04	7.38e+03	25.30
2	60	1	3	1	4	1.82e+04	7.41e+03	25.30
2	61	1U	2	2	4	1.82e+04	7.41e+03	50.04
2	61	2	2	1	3	1.82e+04	7.43e+03	24.17
2	62	1	2	1	3	1.83e+04	7.46e+03	24.17
2	63	1	1	2	3	1.83e+04	7.48e+03	24.17
2	64	1	2	1	3	1.83e+04	7.52e+03	36.26
2	65	1	3	1	4	1.84e+04	7.55e+03	36.26
2	66	1U	2	1	3	1.84e+04	7.55e+03	36.26
2	66	2	2	1	3	1.84e+04	7.58e+03	30.29
2	67	1	2	1	3	1.84e+04	7.61e+03	30.29
2	68	1	3	0	3	1.84e+04	7.65e+03	30.29
2	69	1	2	1	3	1.85e+04	7.68e+03	33.95
2	70	1	2	1	3	1.85e+04	7.71e+03	33.95
2	71	1	2	1	3	1.85e+04	7.75e+03	33.95
2	72	1	2	1	3	1.86e+04	7.78e+03	33.95
2	73	1	3	1	4	1.86e+04	7.81e+03	33.95
2	74	1	2	1	3	1.86e+04	7.85e+03	33.95
2	75	1	3	1	4	1.87e+04	7.88e+03	33.95
2	76	1	2	2	4	1.87e+04	7.92e+03	33.95
2	77	1	3	1	4	1.88e+04	7.95e+03	33.95
2	78	1	2	1	3	1.88e+04	7.98e+03	33.95
2	79	1	2	2	4	1.88e+04	8.02e+03	33.95
2	80	1	2	2	4	1.89e+04	8.05e+03	33.95
2	81	1	1	3	4	1.89e+04	8.09e+03	33.95
2	82	1	2	1	3	1.89e+04	8.12e+03	33.95
2	83	1	2	2	4	1.90e+04	8.15e+03	33.95
2	84	1	2	2	4	1.90e+04	8.19e+03	33.95
2	85	1	3	2	5	1.90e+04	8.22e+03	33.95
2	86	1U	2	2	4	1.90e+04	8.22e+03	33.95
2	86	2	3	1	4	1.90e+04	8.25e+03	26.82
2	87	1	2	2	4	1.91e+04	8.28e+03	26.82
2	88	1	1	3	4	1.91e+04	8.30e+03	26.82
2	89	1	2	2	4	1.91e+04	8.34e+03	36.57
2	90	1	2	2	4	1.92e+04	8.38e+03	36.57
2	91	1	3	1	4	1.92e+04	8.41e+03	36.57
2	92	1	2	2	4	1.92e+04	8.45e+03	36.57

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	93	1U	3	1	4	1.92e+04	8.45e+03	36.57
2	93	2	1	2	3	1.93e+04	8.46e+03	12.84
2	94	1	1	2	3	1.93e+04	8.47e+03	12.84
2	95	1	2	1	3	1.93e+04	8.49e+03	12.84
2	96	1	2	1	3	1.93e+04	8.51e+03	25.67
2	97	1	2	2	4	1.93e+04	8.54e+03	25.67
2	98	1	3	1	4	1.94e+04	8.56e+03	25.67
2	99	1	2	2	4	1.94e+04	8.59e+03	25.67
2	100	1	2	2	4	1.94e+04	8.63e+03	38.51
2	101	1	3	1	4	1.95e+04	8.67e+03	38.51
2	102	1U	2	2	4	1.95e+04	8.67e+03	38.51
2	102	2	3	1	4	1.95e+04	8.70e+03	29.00
2	103	1	2	2	4	1.95e+04	8.73e+03	29.00
2	104	1	2	1	3	1.96e+04	8.75e+03	29.00
2	105	1U	2	2	4	1.96e+04	8.75e+03	37.81
2	105	2	2	2	4	1.96e+04	8.78e+03	27.81
2	106	1	3	1	4	1.96e+04	8.81e+03	27.81
2	107	1	2	2	4	1.96e+04	8.84e+03	27.81
2	108	1	3	0	3	1.97e+04	8.87e+03	27.81
2	109	1	1	3	4	1.97e+04	8.89e+03	27.81
2	110	1	2	2	4	1.97e+04	8.92e+03	27.81
2	111	1	1	2	3	1.97e+04	8.95e+03	27.81
2	112	1	2	1	3	1.98e+04	8.98e+03	27.81
2	113	1	2	1	3	1.98e+04	9.00e+03	27.81
2	114	1	2	1	3	1.98e+04	9.03e+03	27.81
2	115	1U	1	2	3	1.98e+04	9.03e+03	27.81
2	115	2	1	2	3	1.99e+04	9.05e+03	20.44
2	116	1	2	1	3	1.99e+04	9.07e+03	20.44
2	117	1	2	1	3	1.99e+04	9.09e+03	20.44
2	118	1U	2	2	4	1.99e+04	9.09e+03	29.72
2	118	2	1	2	3	1.99e+04	9.12e+03	22.72
2	119	1	1	3	4	1.99e+04	9.14e+03	22.72
2	120	1	1	2	3	2.00e+04	9.16e+03	22.72
2	121	1	1	2	3	2.00e+04	9.18e+03	22.72
2	122	1	1	2	3	2.00e+04	9.21e+03	22.72
2	123	1	1	3	4	2.00e+04	9.23e+03	22.72
2	124	1	1	2	3	2.01e+04	9.25e+03	22.72
2	125	1	1	2	3	2.01e+04	9.28e+03	22.72
2	126	1	1	2	3	2.01e+04	9.30e+03	22.72
2	127	1	1	2	3	2.01e+04	9.32e+03	22.72
2	128	1	1	2	3	2.01e+04	9.34e+03	22.72
2	129	1	1	3	4	2.02e+04	9.37e+03	22.72
2	130	1	1	2	3	2.02e+04	9.39e+03	22.72
2	131	1	2	2	4	2.02e+04	9.41e+03	22.72
2	132	1U	2	2	4	2.02e+04	9.41e+03	22.72

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	132	2	2	2	4	2.02e+04	9.43e+03	15.83
2	133	1	1	2	3	2.02e+04	9.44e+03	15.83
2	134	1	1	3	4	2.03e+04	9.46e+03	15.83
2	135	1U	1	3	4	2.03e+04	9.46e+03	23.69
2	135	2	1	2	3	2.03e+04	9.47e+03	14.14
2	136	1	2	2	4	2.03e+04	9.49e+03	14.14
2	137	1	2	2	4	2.03e+04	9.50e+03	14.14
2	138	1U	2	2	4	2.03e+04	9.50e+03	18.33
2	138	2	2	2	4	2.03e+04	9.52e+03	15.43
2	139	1	2	2	4	2.03e+04	9.53e+03	15.43
2	140	1	1	2	3	2.03e+04	9.55e+03	15.43
2	141	1U	1	2	3	2.03e+04	9.55e+03	15.43
2	141	2	1	2	3	2.04e+04	9.56e+03	12.39
2	142	1	1	2	3	2.04e+04	9.57e+03	12.39
2	143	1	1	2	3	2.04e+04	9.59e+03	12.39
2	144	1	3	1	4	2.04e+04	9.60e+03	12.39
2	145	1	1	3	4	2.04e+04	9.61e+03	12.39
2	146	1	2	1	3	2.04e+04	9.62e+03	12.39
2	147	1U	2	2	4	2.04e+04	9.62e+03	17.16
2	147	2	2	1	3	2.04e+04	9.63e+03	9.291
2	148	1	2	1	3	2.04e+04	9.64e+03	9.291
2	149	1	1	3	4	2.05e+04	9.65e+03	9.291
2	150	1U	2	2	4	2.05e+04	9.65e+03	13.94
2	150	2	2	1	3	2.05e+04	9.66e+03	9.308
2	151	1	1	2	3	2.05e+04	9.67e+03	9.308
2	152	1	2	2	4	2.05e+04	9.68e+03	9.308
2	153	1	2	2	4	2.05e+04	9.69e+03	13.96
2	154	1	2	1	3	2.05e+04	9.71e+03	13.96
2	155	1U	2	2	4	2.05e+04	9.71e+03	13.96
2	155	2	2	1	3	2.05e+04	9.71e+03	8.572
2	156	1	3	1	4	2.05e+04	9.72e+03	8.572
2	157	1	1	3	4	2.05e+04	9.73e+03	8.572
2	158	1	2	1	3	2.05e+04	9.74e+03	10.05
2	159	1	3	1	4	2.06e+04	9.75e+03	10.05
2	160	1	3	1	4	2.06e+04	9.76e+03	10.05
2	161	1	2	2	4	2.06e+04	9.77e+03	10.05
2	162	1	2	2	4	2.06e+04	9.78e+03	10.05
2	163	1	2	2	4	2.06e+04	9.79e+03	10.05
2	164	1	1	2	3	2.06e+04	9.80e+03	10.05
2	165	1	2	2	4	2.06e+04	9.81e+03	10.05
2	166	1	2	1	3	2.06e+04	9.82e+03	10.05
2	167	1	1	2	3	2.06e+04	9.83e+03	10.05
2	168	1	1	2	3	2.06e+04	9.84e+03	10.05
2	169	1U	3	1	4	2.06e+04	9.84e+03	13.82
2	169	2	1	2	3	2.07e+04	9.85e+03	10.15

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	170	1	2	2	4	2.07e+04	9.86e+03	10.15
2	171	1	2	2	4	2.07e+04	9.87e+03	10.15
2	172	1	2	2	4	2.07e+04	9.88e+03	10.15
2	173	1	1	2	3	2.07e+04	9.89e+03	10.15
2	174	1	1	2	3	2.07e+04	9.90e+03	10.15
2	175	1	1	2	3	2.07e+04	9.91e+03	10.15
2	176	1	1	2	3	2.07e+04	9.92e+03	10.15
2	177	1	1	2	3	2.07e+04	9.93e+03	10.15
2	178	1	1	2	3	2.07e+04	9.94e+03	10.15
2	179	1	1	2	3	2.08e+04	9.95e+03	10.15
2	180	1	1	2	3	2.08e+04	9.96e+03	10.15
2	181	1	1	2	3	2.08e+04	9.97e+03	10.15
2	182	1	1	2	3	2.08e+04	9.98e+03	10.15
2	183	1	1	2	3	2.08e+04	9.99e+03	10.15
2	184	1	2	1	3	2.08e+04	1.00e+04	10.15
2	185	1	1	2	3	2.08e+04	1.00e+04	10.15
2	186	1U	1	3	4	2.08e+04	1.00e+04	15.23
2	186	2	2	1	3	2.08e+04	1.00e+04	9.446
2	187	1	1	2	3	2.08e+04	1.00e+04	9.446
2	188	1	1	2	3	2.08e+04	1.00e+04	9.446
2	189	1U	1	3	4	2.08e+04	1.00e+04	14.17
2	189	2	2	1	3	2.09e+04	1.01e+04	7.735
2	190	1	1	2	3	2.09e+04	1.01e+04	7.735
2	191	1	2	1	3	2.09e+04	1.01e+04	7.735
2	192	1	2	1	3	2.09e+04	1.01e+04	15.47
2	193	1U	2	2	4	2.09e+04	1.01e+04	22.43
2	193	2	1	2	3	2.09e+04	1.01e+04	11.44
2	194	1U	1	3	4	2.09e+04	1.01e+04	11.44
2	194	2	1	3	4	2.09e+04	1.01e+04	9.718
2	195	1	1	2	3	2.09e+04	1.01e+04	9.718
2	196	1	2	1	3	2.09e+04	1.01e+04	9.718
2	197	1U	2	2	4	2.09e+04	1.01e+04	12.30
2	197	2	2	1	3	2.09e+04	1.01e+04	5.539
2	198	1	1	2	3	2.09e+04	1.01e+04	5.539
2	199	1	1	2	3	2.09e+04	1.01e+04	5.539
2	200	1	2	1	3	2.09e+04	1.01e+04	8.309
2	201	1	2	2	4	2.10e+04	1.02e+04	8.309
2	202	1	1	2	3	2.10e+04	1.02e+04	8.309
2	203	1	2	1	3	2.10e+04	1.02e+04	8.309
2	204	1	2	2	4	2.10e+04	1.02e+04	8.309
2	205	1	2	1	3	2.10e+04	1.02e+04	8.309
2	206	1	1	2	3	2.10e+04	1.02e+04	8.309
2	207	1	1	2	3	2.10e+04	1.02e+04	8.309
2	208	1	1	2	3	2.10e+04	1.02e+04	8.309
2	209	1	1	2	3	2.10e+04	1.02e+04	8.309

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	210	1	2	1	3	2.10e+04	1.02e+04	10.37
2	211	1U	1	2	3	2.10e+04	1.02e+04	10.37
2	211	2	1	2	3	2.10e+04	1.02e+04	7.254
2	212	1	1	1	2	2.10e+04	1.02e+04	7.254
2	213	1	1	2	3	2.11e+04	1.03e+04	7.254
2	214	1U	1	2	3	2.11e+04	1.03e+04	10.88
2	214	2	1	2	3	2.11e+04	1.03e+04	8.159
2	215	1	1	2	3	2.11e+04	1.03e+04	8.159
2	216	1	1	2	3	2.11e+04	1.03e+04	8.159
2	217	1	2	1	3	2.11e+04	1.03e+04	8.159
2	218	1	1	2	3	2.11e+04	1.03e+04	8.159
2	219	1	3	1	4	2.11e+04	1.03e+04	8.159
2	220	1	1	3	4	2.11e+04	1.03e+04	8.159
2	221	1	1	2	3	2.11e+04	1.03e+04	8.159
2	222	1	1	2	3	2.11e+04	1.03e+04	8.159
2	223	1	2	1	3	2.11e+04	1.03e+04	11.07
2	224	1U	2	2	4	2.11e+04	1.03e+04	11.07
2	224	2	2	1	3	2.11e+04	1.03e+04	6.415
2	225	1	1	2	3	2.12e+04	1.04e+04	6.415
2	226	1	1	2	3	2.12e+04	1.04e+04	6.415
2	227	1	2	1	3	2.12e+04	1.04e+04	9.623
2	228	1	1	2	3	2.12e+04	1.04e+04	9.623
2	229	1	1	2	3	2.12e+04	1.04e+04	9.623
2	230	1	1	2	3	2.12e+04	1.04e+04	9.623
2	231	1	1	2	3	2.12e+04	1.04e+04	9.623
2	232	1	1	2	3	2.12e+04	1.04e+04	9.623
2	233	1U	1	2	3	2.12e+04	1.04e+04	14.43
2	233	2	1	2	3	2.12e+04	1.04e+04	10.30
2	234	1U	2	1	3	2.12e+04	1.04e+04	10.30
2	234	2	1	2	3	2.12e+04	1.04e+04	7.608
2	235	1	2	1	3	2.12e+04	1.04e+04	7.608
2	236	1	1	2	3	2.12e+04	1.04e+04	7.608
2	237	1U	2	1	3	2.12e+04	1.04e+04	10.05
2	237	2	1	2	3	2.13e+04	1.05e+04	7.237
2	238	1	1	2	3	2.13e+04	1.05e+04	7.237
2	239	1	2	1	3	2.13e+04	1.05e+04	7.237
2	240	1	2	1	3	2.13e+04	1.05e+04	8.270
2	241	1U	1	2	3	2.13e+04	1.05e+04	8.270
2	241	2	2	1	3	2.13e+04	1.05e+04	6.904
2	242	1	1	2	3	2.13e+04	1.05e+04	6.904
2	243	1	1	2	3	2.13e+04	1.05e+04	6.904
2	244	1	1	2	3	2.13e+04	1.05e+04	6.904
2	245	1	1	2	3	2.13e+04	1.05e+04	8.517
2	246	1	2	1	3	2.13e+04	1.05e+04	8.517
2	247	1	1	2	3	2.13e+04	1.05e+04	8.517

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	248	1	1	2	3	2.13e+04	1.05e+04	8.517
2	249	1	1	2	3	2.13e+04	1.05e+04	8.517
2	250	1	1	2	3	2.14e+04	1.06e+04	8.517
2	251	1	1	2	3	2.14e+04	1.06e+04	9.540
2	252	1U	1	2	3	2.14e+04	1.06e+04	9.540
2	252	2	1	2	3	2.14e+04	1.06e+04	7.220
2	253	1	1	2	3	2.14e+04	1.06e+04	7.220
2	254	1	1	2	3	2.14e+04	1.06e+04	7.220
2	255	1U	3	1	4	2.14e+04	1.06e+04	10.83
2	255	2	1	3	4	2.14e+04	1.06e+04	3.949
2	256	1	1	2	3	2.14e+04	1.06e+04	3.949
2	257	1	1	2	3	2.14e+04	1.06e+04	3.949
2	258	1	1	3	4	2.14e+04	1.06e+04	5.924
2	259	1	1	2	3	2.14e+04	1.06e+04	5.924
2	260	1	1	2	3	2.14e+04	1.06e+04	5.924
2	261	1	1	2	3	2.14e+04	1.06e+04	5.924
2	262	1	1	2	3	2.14e+04	1.06e+04	5.924
2	263	1	1	2	3	2.14e+04	1.06e+04	5.924
2	264	1	1	2	3	2.14e+04	1.06e+04	5.924
2	265	1	1	2	3	2.14e+04	1.06e+04	5.924
2	266	1	1	2	3	2.15e+04	1.07e+04	5.924
2	267	1	1	2	3	2.15e+04	1.07e+04	5.924
2	268	1U	1	2	3	2.15e+04	1.07e+04	7.555
2	268	2	2	1	3	2.15e+04	1.07e+04	5.951
2	269	1	1	2	3	2.15e+04	1.07e+04	5.951
2	270	1	1	2	3	2.15e+04	1.07e+04	5.951
2	271	1	1	2	3	2.15e+04	1.07e+04	5.951
2	272	1	1	3	4	2.15e+04	1.07e+04	5.951
2	273	1	1	2	3	2.15e+04	1.07e+04	7.068
2	274	1	1	2	3	2.15e+04	1.07e+04	7.068
2	275	1	1	2	3	2.15e+04	1.07e+04	7.068
2	276	1	1	1	2	2.15e+04	1.07e+04	7.068
2	277	1	1	2	3	2.15e+04	1.07e+04	11.06
2	278	1	1	1	2	2.15e+04	1.07e+04	11.06
2	279	1U	1	2	3	2.15e+04	1.07e+04	11.06
2	279	2	1	2	3	2.15e+04	1.07e+04	8.369
2	280	1	1	2	3	2.16e+04	1.08e+04	8.369
2	281	1	1	2	3	2.16e+04	1.08e+04	8.369
2	282	1U	1	3	4	2.16e+04	1.08e+04	12.55
2	282	2	1	2	3	2.16e+04	1.08e+04	9.916
2	283	1	1	1	2	2.16e+04	1.08e+04	9.916
2	284	1	1	1	2	2.16e+04	1.08e+04	9.916
2	285	1U	1	2	3	2.16e+04	1.08e+04	13.92
2	285	2	1	2	3	2.16e+04	1.08e+04	9.324
2	286	1	2	1	3	2.16e+04	1.08e+04	9.324

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	287	1	1	1	2	2.16e+04	1.08e+04	9.324
2	288	1	1	2	3	2.16e+04	1.08e+04	9.324
2	289	1	1	2	3	2.16e+04	1.08e+04	9.324
2	290	1	1	2	3	2.17e+04	1.09e+04	13.04
2	291	1	1	2	3	2.17e+04	1.09e+04	13.04
2	292	1	0	2	2	2.17e+04	1.09e+04	13.04
2	293	1	1	1	2	2.17e+04	1.09e+04	13.04
2	294	1	1	2	3	2.17e+04	1.09e+04	13.04
2	295	1	0	1	1	2.17e+04	1.09e+04	13.04
2	296	1	1	2	3	2.17e+04	1.09e+04	26.08
2	297	1U	1	2	3	2.17e+04	1.09e+04	39.13
2	297	2	0	2	2	2.18e+04	1.10e+04	23.27
2	298	1U	1	3	4	2.18e+04	1.10e+04	23.27
2	298	2	1	3	4	2.18e+04	1.10e+04	11.44
2	299	1	1	2	3	2.18e+04	1.10e+04	11.44
2	300	1	1	1	2	2.18e+04	1.10e+04	11.44
2	301	1	1	1	2	2.18e+04	1.10e+04	22.89
2	302	1U	1	2	3	2.18e+04	1.10e+04	32.75
2	302	2	0	2	2	2.18e+04	1.10e+04	10.51
2	303	1	1	2	3	2.18e+04	1.10e+04	10.51
2	304	1	0	2	2	2.19e+04	1.11e+04	10.51
2	305	1	1	2	3	2.19e+04	1.11e+04	15.77
2	306	1U	2	1	3	2.19e+04	1.11e+04	23.65
2	306	2	2	1	3	2.19e+04	1.11e+04	18.91
2	307	1U	1	2	3	2.19e+04	1.11e+04	18.91
2	307	2	1	2	3	2.19e+04	1.11e+04	14.80
2	308	1U	1	2	3	2.19e+04	1.11e+04	14.80
2	308	2	1	1	2	2.19e+04	1.11e+04	12.04
2	309	1	0	1	1	2.19e+04	1.11e+04	12.04
2	310	1	1	2	3	2.19e+04	1.11e+04	12.04
2	311	1	1	1	2	2.20e+04	1.12e+04	12.04
2	312	1	1	1	2	2.20e+04	1.12e+04	23.34
2	313	1	1	2	3	2.20e+04	1.12e+04	23.34
2	314	1U	0	2	2	2.20e+04	1.12e+04	23.34
2	314	2	0	2	2	2.20e+04	1.12e+04	17.56
2	315	1	0	1	1	2.20e+04	1.12e+04	17.56
2	316	1	2	1	3	2.21e+04	1.13e+04	17.56
2	317	1U	1	2	3	2.21e+04	1.13e+04	29.23
2	317	2	1	2	3	2.21e+04	1.13e+04	23.46
2	318	1U	1	1	2	2.21e+04	1.13e+04	23.46
2	318	2	1	1	2	2.21e+04	1.13e+04	19.08
2	319	1	0	1	1	2.21e+04	1.13e+04	19.08
2	320	1	0	1	1	2.21e+04	1.13e+04	19.08
2	321	1	0	1	1	2.22e+04	1.14e+04	19.08
2	322	1	1	2	3	2.22e+04	1.14e+04	38.16

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	323	1U	1	1	2	2.22e+04	1.14e+04	57.24
2	323	2	1	1	2	2.22e+04	1.14e+04	32.04
2	324	1U	1	2	3	2.22e+04	1.14e+04	32.04
2	324	2	1	1	2	2.22e+04	1.14e+04	18.73
2	325	1U	0	2	2	2.22e+04	1.14e+04	18.73
2	325	2	0	3	3	2.23e+04	1.15e+04	13.35
2	326	1	0	1	1	2.23e+04	1.15e+04	13.35
2	327	1	0	1	1	2.23e+04	1.15e+04	13.35
2	328	1	1	2	3	2.23e+04	1.15e+04	23.75
2	329	1	0	2	2	2.23e+04	1.15e+04	34.91
2	330	1	1	1	2	2.24e+04	1.16e+04	41.47
2	331	1U	1	2	3	2.24e+04	1.16e+04	41.47
2	331	2	1	2	3	2.24e+04	1.16e+04	31.20
2	332	1U	1	2	3	2.24e+04	1.16e+04	31.20
2	332	2	1	2	3	2.24e+04	1.16e+04	19.14
2	333	1U	1	2	3	2.24e+04	1.16e+04	19.14
2	333	2	1	2	3	2.24e+04	1.16e+04	15.02
2	334	1	0	1	1	2.25e+04	1.17e+04	15.02
2	335	1	1	1	2	2.25e+04	1.17e+04	15.02
2	336	1	0	2	2	2.25e+04	1.17e+04	15.02
2	337	1	2	1	3	2.25e+04	1.17e+04	22.53
2	338	1U	2	2	4	2.25e+04	1.17e+04	44.79
2	338	2	1	2	3	2.25e+04	1.17e+04	28.66
2	339	1U	1	2	3	2.25e+04	1.17e+04	28.66
2	339	2	1	2	3	2.26e+04	1.18e+04	15.24
2	340	1	0	2	2	2.26e+04	1.18e+04	15.24
2	341	1	1	2	3	2.26e+04	1.18e+04	15.24
2	342	1	0	2	2	2.26e+04	1.18e+04	22.86
2	343	1	1	1	2	2.26e+04	1.18e+04	22.86
2	344	1	1	1	2	2.27e+04	1.19e+04	22.86
2	345	1	0	3	3	2.27e+04	1.19e+04	22.86
2	346	1	1	1	2	2.27e+04	1.19e+04	22.86
2	347	1	1	2	3	2.27e+04	1.19e+04	22.86
2	348	1	1	1	2	2.28e+04	1.20e+04	22.86
2	349	1	1	2	3	2.28e+04	1.20e+04	45.72
2	350	1U	2	2	4	2.28e+04	1.20e+04	45.72
2	350	2	1	2	3	2.28e+04	1.20e+04	17.72
2	351	1	0	3	3	2.28e+04	1.20e+04	17.72
2	352	1	1	2	3	2.29e+04	1.21e+04	17.72
2	353	1U	0	2	2	2.29e+04	1.21e+04	25.94
2	353	2	0	2	2	2.29e+04	1.21e+04	18.82
2	354	1	1	2	3	2.29e+04	1.21e+04	18.82
2	355	1	1	2	3	2.29e+04	1.21e+04	18.82
2	356	1	1	1	2	2.29e+04	1.21e+04	24.21
2	357	1U	2	1	3	2.29e+04	1.21e+04	24.21

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	357	2	1	2	3	2.29e+04	1.21e+04	12.34
2	358	1	1	1	2	2.30e+04	1.22e+04	12.34
2	359	1	1	2	3	2.30e+04	1.22e+04	12.34
2	360	1	0	2	2	2.30e+04	1.22e+04	18.51
2	361	1	1	2	3	2.30e+04	1.22e+04	22.16
2	362	1	1	2	3	2.30e+04	1.22e+04	22.16
2	363	1	1	1	2	2.31e+04	1.23e+04	22.16
2	364	1U	2	1	3	2.31e+04	1.23e+04	29.89
2	364	2	2	1	3	2.31e+04	1.23e+04	21.28
2	365	1	1	2	3	2.31e+04	1.23e+04	21.28
2	366	1	2	1	3	2.31e+04	1.23e+04	21.28
2	367	1	1	3	4	2.31e+04	1.23e+04	26.13
2	368	1	1	1	2	2.32e+04	1.24e+04	26.13
2	369	1	1	2	3	2.32e+04	1.24e+04	26.13
2	370	1	0	1	1	2.32e+04	1.24e+04	26.13
2	371	1	1	1	2	2.33e+04	1.25e+04	52.25
2	372	1U	1	2	3	2.33e+04	1.25e+04	74.61
2	372	2	1	1	2	2.33e+04	1.25e+04	38.12
2	373	1	1	2	3	2.33e+04	1.25e+04	38.12
2	374	1	1	1	2	2.34e+04	1.26e+04	38.12
2	375	1U	1	2	3	2.34e+04	1.26e+04	67.78
2	375	2	1	1	2	2.34e+04	1.26e+04	45.97
2	376	1U	0	3	3	2.34e+04	1.26e+04	45.97
2	376	2	0	3	3	2.35e+04	1.27e+04	32.43
2	377	1	0	1	1	2.35e+04	1.27e+04	32.43
2	378	1	0	1	1	2.35e+04	1.27e+04	32.43
2	379	1	1	1	2	2.36e+04	1.28e+04	60.51
2	380	1U	1	2	3	2.36e+04	1.28e+04	60.51
2	380	2	0	1	1	2.36e+04	1.28e+04	23.24
2	381	1	1	2	3	2.36e+04	1.28e+04	23.24
2	382	1	1	1	2	2.37e+04	1.29e+04	23.24
2	383	1	0	2	2	2.37e+04	1.29e+04	38.42
2	384	1	1	2	3	2.37e+04	1.29e+04	38.42
2	385	1	1	2	3	2.38e+04	1.30e+04	38.42
2	386	1	1	1	2	2.38e+04	1.30e+04	38.42
2	387	1	1	1	2	2.39e+04	1.31e+04	76.83
2	388	1	1	2	3	2.40e+04	1.32e+04	76.83
2	389	1	1	2	3	2.40e+04	1.32e+04	76.83
2	390	1	1	1	2	2.41e+04	1.33e+04	76.83
2	391	1U	1	1	2	2.41e+04	1.33e+04	112.7
2	391	2	0	1	1	2.42e+04	1.34e+04	88.15
2	392	1	1	2	3	2.43e+04	1.35e+04	88.15
2	393	1	1	0	1	2.44e+04	1.36e+04	88.15
2	394	1U	1	2	3	2.44e+04	1.36e+04	107.8
2	394	2	1	1	2	2.44e+04	1.36e+04	41.13

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
2	395	1	1	2	3	2.45e+04	1.37e+04	41.13
2	396	1	0	1	1	2.45e+04	1.37e+04	41.13
2	397	1	1	1	2	2.46e+04	1.38e+04	71.97
2	398	1	1	1	2	2.47e+04	1.39e+04	71.97
2	399	1U	1	1	2	2.47e+04	1.39e+04	71.97
2	399	2	0	3	3	2.47e+04	1.39e+04	23.32
2	400	1	1	1	2	2.47e+04	1.39e+04	23.32
2	401	1	0	1	1	2.47e+04	1.39e+04	23.32
2	402	1	0	1	1	2.48e+04	1.40e+04	46.65
2	403	1	1	1	2	2.49e+04	1.41e+04	93.30
2	404	1	0	2	2	2.50e+04	1.42e+04	123.4
2	405	1	0	1	1	2.51e+04	1.43e+04	123.4
2	406	1	1	0	1	2.52e+04	1.44e+04	89.20
3	1	1	1	3	4	2.52e+04	1.00	1.000
3	2	1	0	2	2	2.52e+04	2.00	1.000
3	3	1	0	1	1	2.52e+04	3.00	1.000
3	4	1	0	1	1	2.52e+04	5.00	2.000
3	5	1	0	1	1	2.52e+04	9.00	4.000
3	6	1	0	1	1	2.52e+04	17.0	8.000
3	7	1	0	1	1	2.52e+04	33.0	16.00
3	8	1	0	2	2	2.53e+04	65.0	32.00
3	9	1	0	2	2	2.53e+04	113.	48.00
3	10	1	0	2	2	2.54e+04	185.	72.00
3	11	1	0	2	2	2.55e+04	287.	102.3
3	12	1	0	2	2	2.56e+04	390.	102.3
3	13	1	2	1	3	2.57e+04	532.	142.8
3	14	1	1	1	2	2.59e+04	675.	142.8
3	15	1	0	2	2	2.61e+04	934.	259.0
3	16	1	1	2	3	2.64e+04	1.19e+03	259.0
3	17	1	0	2	2	2.68e+04	1.56e+03	366.5
3	18	1	0	1	1	2.71e+04	1.93e+03	366.5
3	19	1	0	1	1	2.76e+04	2.41e+03	484.7
3	20	1	0	1	1	2.81e+04	2.90e+03	484.7
3	21	1U	1	2	3	2.81e+04	2.90e+03	709.0
3	21	2	0	1	1	2.84e+04	3.16e+03	264.0
3	22	1	1	2	3	2.86e+04	3.42e+03	264.0
3	23	1U	1	2	3	2.86e+04	3.42e+03	264.0
3	23	2	0	2	2	2.88e+04	3.59e+03	170.8
3	24	1	1	2	3	2.90e+04	3.77e+03	170.8
3	25	1	0	1	1	2.91e+04	3.94e+03	170.8
3	26	1	1	1	2	2.95e+04	4.28e+03	341.6
3	27	1U	0	2	2	2.95e+04	4.28e+03	549.2
3	27	2	0	2	2	2.99e+04	4.69e+03	413.0
3	28	1	0	1	1	3.03e+04	5.10e+03	413.0
3	29	1	0	1	1	3.07e+04	5.52e+03	413.0

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
3	30	1	1	1	2	3.14e+04	6.24e+03	720.3
3	31	1	0	2	2	3.24e+04	7.20e+03	962.8
4	1	1	0	1	1	3.24e+04	1.00	1.000
4	2	1	0	1	1	3.24e+04	2.00	1.000
4	3	1	0	1	1	3.24e+04	3.00	1.000
4	4	1	0	1	1	3.24e+04	5.00	2.000
4	5	1	0	1	1	3.24e+04	9.00	4.000
4	6	1	0	1	1	3.24e+04	17.0	8.000
4	7	1	0	1	1	3.24e+04	33.0	16.00
4	8	1U	0	1	1	3.24e+04	33.0	32.00
4	8	2	0	1	1	3.25e+04	51.2	18.24
4	9	1	0	1	1	3.25e+04	69.5	18.24
4	10	1	0	1	1	3.25e+04	87.7	18.24
4	11	1	0	1	1	3.25e+04	113.	25.03
4	12	1	0	2	2	3.25e+04	138.	25.03
4	13	1	0	2	2	3.26e+04	163.	25.03
4	14	1	0	2	2	3.26e+04	188.	25.03
4	15	1	0	2	2	3.26e+04	221.	32.94
4	16	1	0	2	2	3.27e+04	254.	32.94
4	17	1	0	2	2	3.27e+04	293.	39.37
4	18	1	0	2	2	3.27e+04	332.	39.37
4	19	1	0	2	2	3.28e+04	372.	39.37
4	20	1	1	2	3	3.28e+04	411.	39.37
4	21	1	0	2	2	3.29e+04	451.	39.37
4	22	1	0	2	2	3.29e+04	490.	39.37
4	23	1	0	1	1	3.29e+04	529.	39.37
4	24	1	1	0	1	3.30e+04	569.	39.37
4	25	1	1	2	3	3.30e+04	608.	39.37
4	26	1U	0	2	2	3.30e+04	608.	39.37
4	26	2	0	2	2	3.30e+04	638.	29.95
4	27	1	0	2	2	3.31e+04	668.	29.95
4	28	1	0	1	1	3.31e+04	698.	29.95
4	29	1	0	1	1	3.31e+04	734.	36.39
4	30	1	0	2	2	3.32e+04	771.	36.39
4	31	1	0	2	2	3.32e+04	807.	36.39
4	32	1	0	2	2	3.32e+04	843.	36.39
4	33	1	0	2	2	3.33e+04	880.	36.39
4	34	1	0	2	2	3.33e+04	916.	36.39
4	35	1	0	2	2	3.34e+04	953.	36.39
4	36	1	0	2	2	3.34e+04	989.	36.39
4	37	1U	1	2	3	3.34e+04	989.	36.39
4	37	2	1	2	3	3.34e+04	1.02e+03	28.09
4	38	1	0	2	2	3.34e+04	1.05e+03	28.09
4	39	1	0	2	2	3.35e+04	1.07e+03	28.09
4	40	1	0	2	2	3.35e+04	1.11e+03	32.29

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
4	41	1	0	2	2	3.35e+04	1.14e+03	32.29
4	42	1	0	2	2	3.36e+04	1.17e+03	32.29
4	43	1	0	2	2	3.36e+04	1.20e+03	32.29
4	44	1	0	2	2	3.36e+04	1.23e+03	32.29
4	45	1	0	2	2	3.37e+04	1.27e+03	32.29
4	46	1	0	2	2	3.37e+04	1.30e+03	32.29
4	47	1	0	2	2	3.37e+04	1.33e+03	32.29
4	48	1	0	2	2	3.38e+04	1.36e+03	32.29
4	49	1	0	2	2	3.38e+04	1.40e+03	32.29
4	50	1	0	2	2	3.38e+04	1.43e+03	32.29
4	51	1U	0	2	2	3.38e+04	1.43e+03	32.29
4	51	2	0	2	2	3.39e+04	1.46e+03	27.10
4	52	1	0	2	2	3.39e+04	1.48e+03	27.10
4	53	1	0	2	2	3.39e+04	1.51e+03	27.10
4	54	1	1	2	3	3.39e+04	1.54e+03	27.10
4	55	1	0	2	2	3.40e+04	1.56e+03	27.10
4	56	1	0	2	2	3.40e+04	1.59e+03	27.10
4	57	1	0	2	2	3.40e+04	1.62e+03	27.10
4	58	1	0	2	2	3.40e+04	1.65e+03	27.10
4	59	1	1	2	3	3.41e+04	1.67e+03	27.10
4	60	1	0	2	2	3.41e+04	1.70e+03	27.10
4	61	1	0	2	2	3.41e+04	1.73e+03	27.10
4	62	1	0	2	2	3.42e+04	1.75e+03	27.10
4	63	1	0	2	2	3.42e+04	1.78e+03	27.10
4	64	1	0	2	2	3.42e+04	1.81e+03	27.10
4	65	1	0	2	2	3.42e+04	1.83e+03	27.10
4	66	1	0	2	2	3.43e+04	1.86e+03	27.10
4	67	1	0	2	2	3.43e+04	1.89e+03	27.10
4	68	1	0	2	2	3.43e+04	1.92e+03	27.10
4	69	1	0	2	2	3.43e+04	1.94e+03	27.10
4	70	1	0	2	2	3.44e+04	1.97e+03	27.10
4	71	1	0	2	2	3.44e+04	2.00e+03	27.10
4	72	1	0	2	2	3.44e+04	2.02e+03	27.10
4	73	1	0	3	3	3.45e+04	2.05e+03	27.10
4	74	1	0	2	2	3.45e+04	2.08e+03	27.10
4	75	1	0	2	2	3.45e+04	2.11e+03	27.10
4	76	1	0	2	2	3.45e+04	2.13e+03	27.10
4	77	1	0	3	3	3.46e+04	2.16e+03	30.12
4	78	1	0	2	2	3.46e+04	2.19e+03	30.12
4	79	1	0	2	2	3.46e+04	2.22e+03	30.12
4	80	1	0	2	2	3.47e+04	2.25e+03	30.12
4	81	1	0	2	2	3.47e+04	2.28e+03	30.12
4	82	1	0	2	2	3.47e+04	2.31e+03	30.12
4	83	1	0	2	2	3.48e+04	2.36e+03	45.18
4	84	1	0	3	3	3.48e+04	2.43e+03	67.77

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Step	Inc	Att	Discon Iters	Equil Iters	Total Iters	Total Time	Step Time	Inc Time
4	85	1	0	2	2	3.49e+04	2.49e+03	67.77
4	86	1	0	2	2	3.50e+04	2.60e+03	101.7
4	87	1	0	2	2	3.51e+04	2.75e+03	152.5
4	88	1	0	2	2	3.54e+04	2.98e+03	228.7
4	89	1	0	3	3	3.57e+04	3.32e+03	343.1
4	90	1	0	3	3	3.62e+04	3.83e+03	514.6
4	91	1	0	4	4	3.70e+04	4.61e+03	771.9
4	92	1	0	2	2	3.82e+04	5.76e+03	1158.
4	93	1	0	2	2	3.99e+04	7.50e+03	1737.
4	94	1	0	4	4	4.25e+04	1.01e+04	2605.
4	95	1U	0	4	4	4.25e+04	1.01e+04	3908.
4	95	2	0	3	3	4.35e+04	1.11e+04	977.0
4	96	1	0	7	7	4.49e+04	1.25e+04	1465.
4	97	1	0	5	5	4.64e+04	1.40e+04	1465.
4	98	1	0	3	3	4.68e+04	1.44e+04	385.2
5	1	1	0	6	6	4.68e+04	1.00	1.000

