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Second Target Station Project: Target Loss of Cooling Thermal Evaluation



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February, 2026



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Second Target Station Project

Target Loss of Cooling Thermal Evaluation

T McManamy

February 2026

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managed by
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1. INTRODUCTION

A bounding, mitigated loss of cooling analysis was done to evaluate if the peak tungsten temperature after an accident condition with a total loss of cooling remained below the tungsten vaporization threshold temperature of 800°C in steam. The potential for targets sagging and contacting the moderator vessels was also evaluated based on the peak temperatures reached. The proton beam was assumed to be tripped, and no credit was taken for water within any of the parts. Evaluation was done for the worst case with vacuum in the core vessel. Targets between the moderator reflector vessels were evaluated as the bounding case because the aluminum reflector vessels have a much lower emissivity than the steel shielding. Previous evaluations showed that these target segments have the highest temperatures (1). Decay heat, thermal radiation and conduction were included. Simplified models were used with conservative assumptions.

2. ABAQUS MODEL DEVELOPMENT FOR TARGETS BETWEEN THE REFLECTOR VESSELS

Figure 1 and Figure 2 show an initial model which included all 20 target segments, shaft, moderator reflector assembly (MRA) and lower cooled and uncooled core vessel shielding pieces without the core vessel. The shielding model did not include the internal cooling passages.

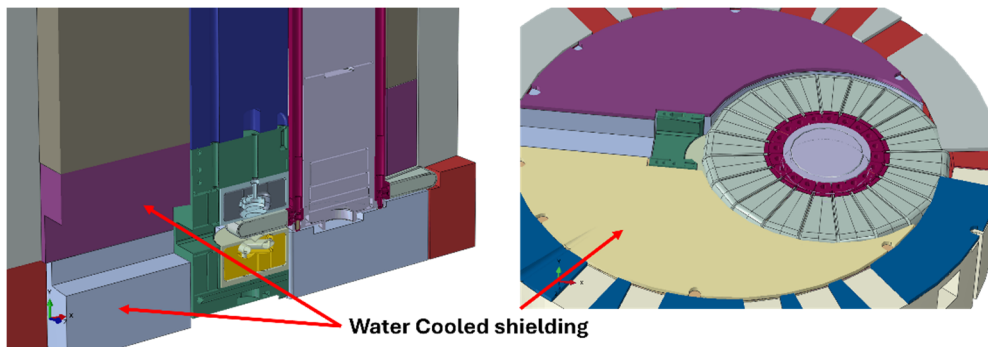


Figure 1 Initial model $z=0$ cut and y cut above targets

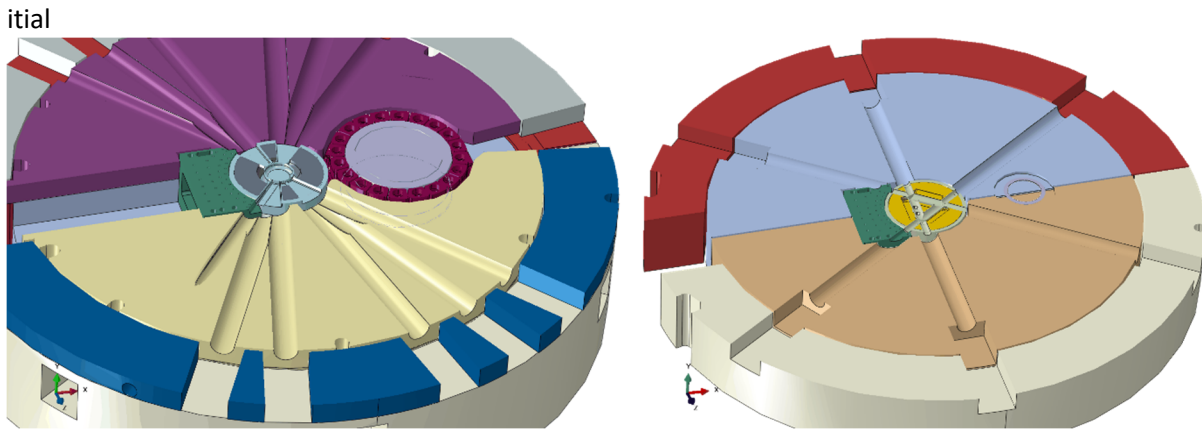


Figure 2 Initial Model view cut at the upper and lower beamline center elevations

The surfaces facing the target foot segments vary from aluminum between the MRA moderators, 316L shielding with open cutouts and between solid 316L shielding segments in the rear. If the target is rotating a given segment would view all the different facing shield configurations. To be conservative for the loss of cooling analysis, a model was made to evaluate a target centered between the moderators which was expected to have the lowest thermal radiation from the top and bottom surfaces. For the loss of cooling analysis, the uncooled shielding blocks were not included and only the four cooled shielding blocks close to the targets were retained. The blocks further away were not expected to significantly affect the thermal response over 24 hours.

2.1 TARGET SEGMENTS CENTERED ON MRA

A slice of the model was made that included three segments between the moderators as shown in Figure 3. Each of the segments subtends an 18-degree angle around the shaft axis, including half the gap between segments. The model included a 54-degree wedge centered on the shaft axis and the proton beam axis which includes the target location centered on the moderators and the nearest neighbors on each side. Only the cooled bulk shielding closest to the moderators was included. Internal cooling passages for the shielding were not included. Simplified part models for the target segments, MRA and shaft were included. The revised Abaqus model was LOC_2025_frontcae2.cae. Target segment geometry was taken from the .0004343 STEP file as described in the Appendix A.

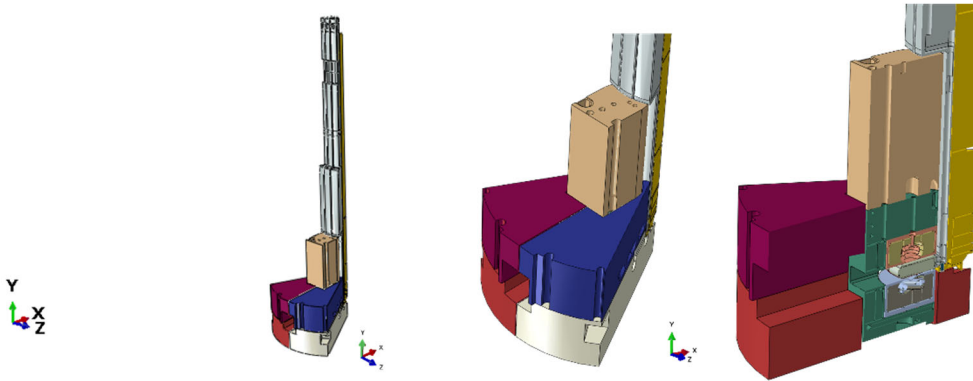


Figure 3 Monolith slice including Target segments centered on MRA

3. ASSEMBLY PARTS

3.1 TARGET SEGMENTS

A simplified model of a target segment was made in which the tungsten and tantalum and were combined into one set called a “Target Dummy” and the Inconel modeled separately. The Inconel was tied to the stalk 316L. The model is shown in Figure 4 with the lower region of the stalk.

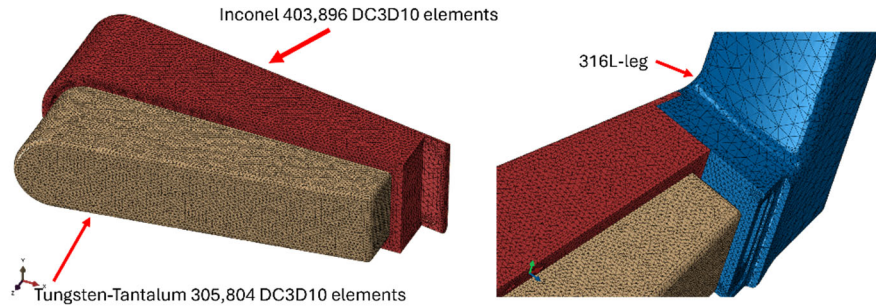


Figure 4 Target Segment model

The “Target Dummy” volume was $.00173 \text{ m}^3$ including a tungsten volume of $.00159 \text{ m}^3$ and a tantalum volume of $.00014 \text{ m}^3$. The combined mass was 33.6 kg with an assumed density of 19.4 kg/m^3 . The Inconel volume was $.00104 \text{ m}^3$ with a mass of 8.54 kg. The DC3D10 mesh for the Inconel and “Target Dummy” cells is shown with a total of approximately $7\text{e}5$ elements. The target segment instance, including the 316L stalk was radially patterned for 20 segments and segments 1, 2 and 20 included in the assembly.

3.2 TARGET STALKS

Figure 5 shows one of the 316L segment stalks. The SpaceClaim Step file was simplified by removing the internal cooling tubes and the front to rear split in some regions as shown in Figure 6. These features were not expected to contribute significantly to the heat transport up the length of the stalk from the target region.

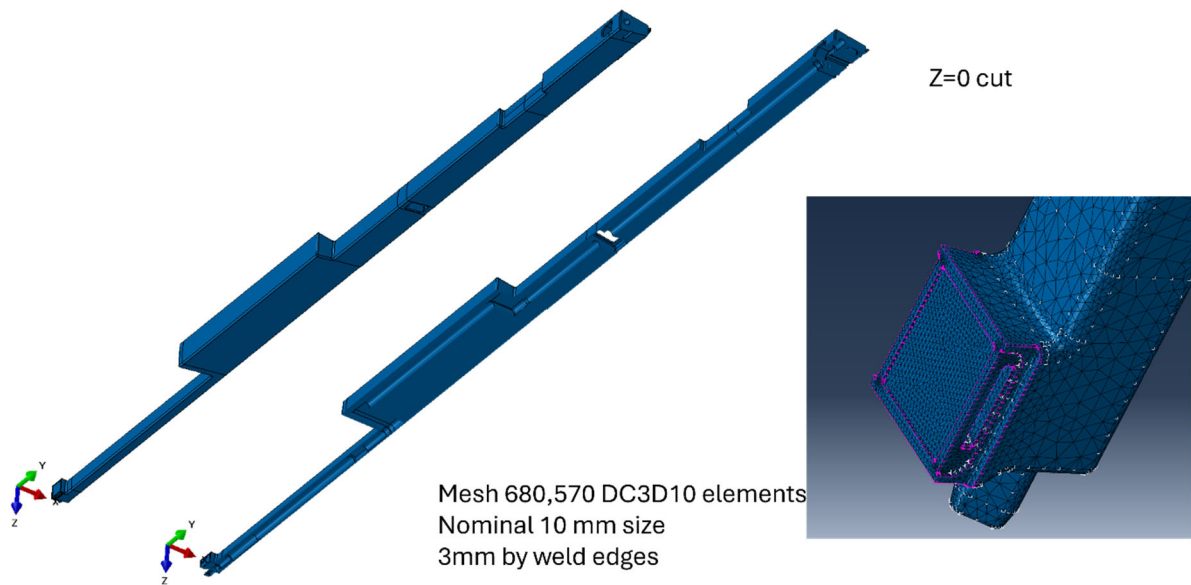


Figure 5 stalk with $z=0$ cut and DC3D10 mesh for 316L and DC3D8 elements for copper alloy

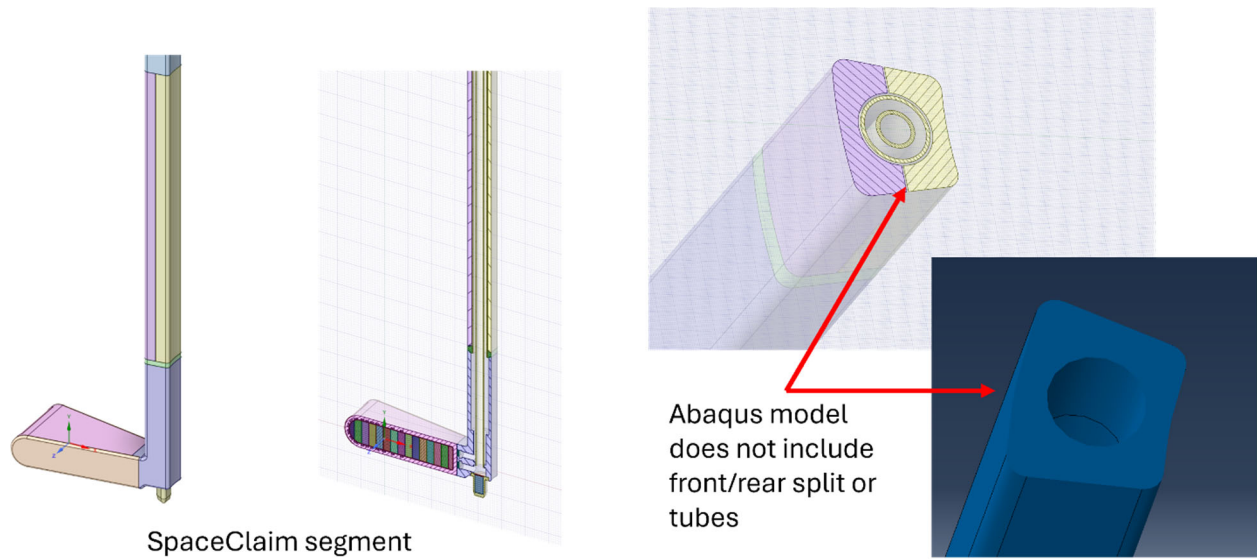


Figure 6 SpaceClaim Stalk model and comparison with Abaqus model

3.3 SHAFT BOTTOM

The Shaft design has a complex array of cooling passages in the lower region and 4 internal plates. The upper regions are nearly solid except for cooling holes. For the heat transport model, a simplified version was made of the solid sections within the 54-degree wedge without the internal cooling passages as shown in Figure 7.

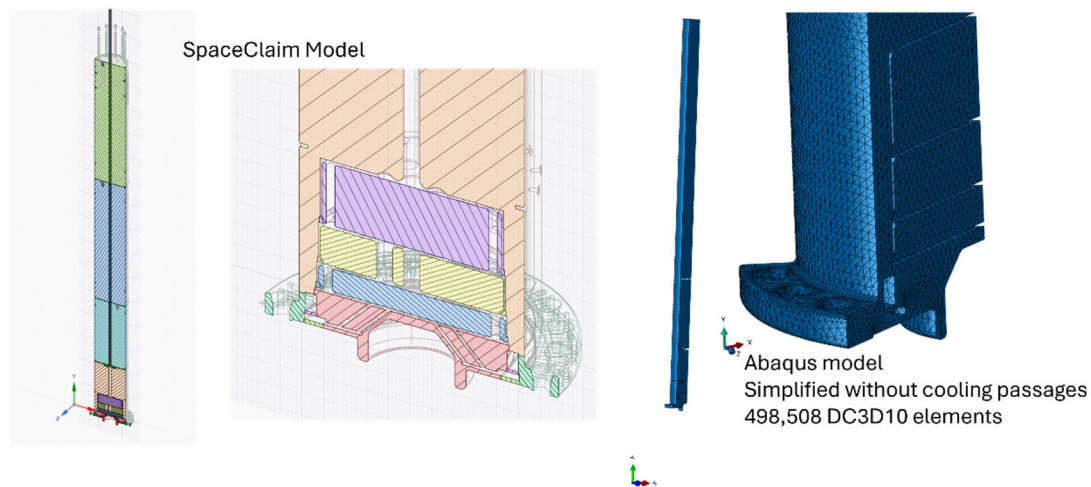


Figure 7 Shaft Bottom SpaceClaim and Abaqus model

The four sections were welded together, and the model included these welds with a gap between sections which restricted vertical heat transport as shown in Figure 8 without the 54-degree wedge cuts. The nominal mesh size for the shaft was 10 mm.

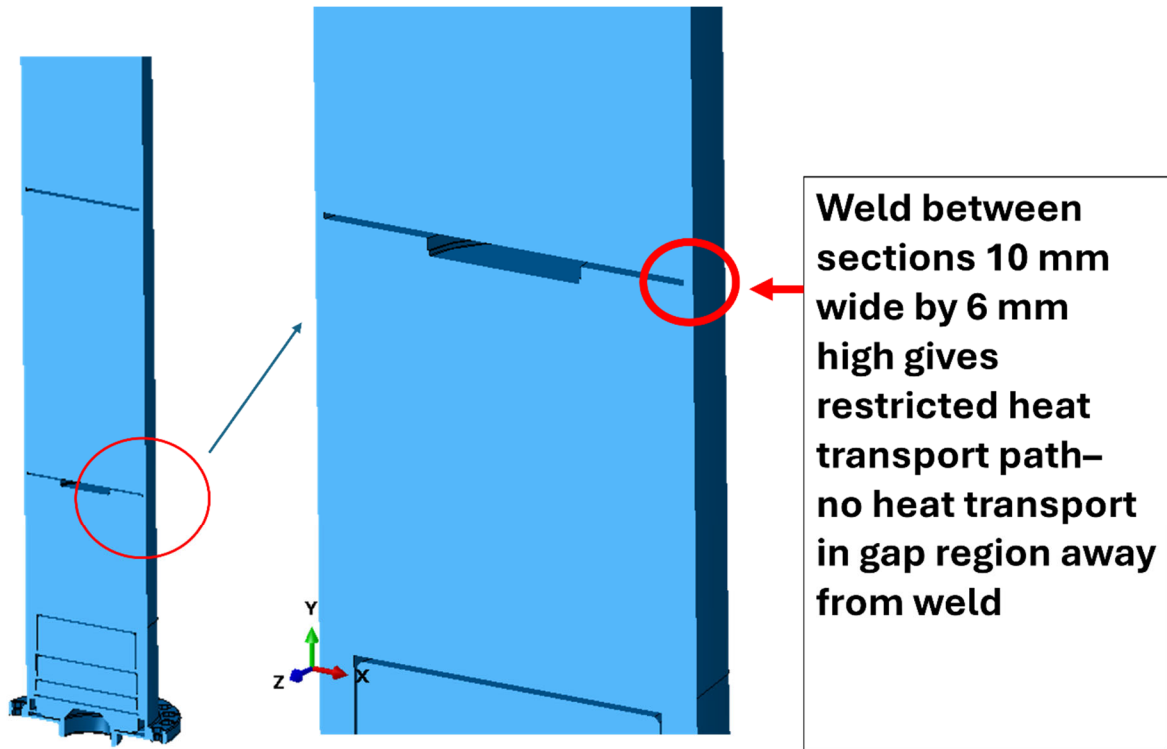


Figure 8 Shaft model near section welds

3.4 MRA REFLECTOR VESSELS, BACKBONE AND SHIELD

Figure 9 shows the MRA Reflector assembly including the upper and lower aluminum vessels, the beryllium in each and the stainless steel backbone. The model did not include the internal hydrogen vessels or water. Also, conservatively no credit was taken for conduction through the bottom supports to the bulk shielding underneath.

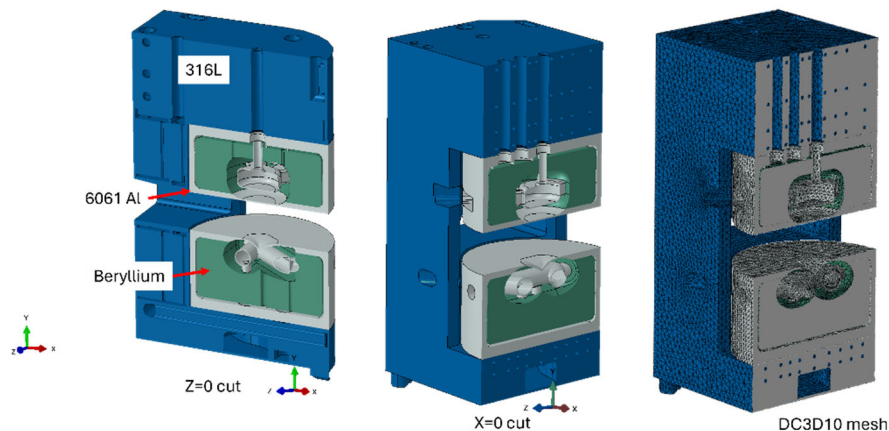


Figure 9 MRA assembly

The model was simplified by removing the bolt holes and bolts connecting the aluminum vessels to the backbone and tie rod connections to the shield block. Most piping was also removed. The backbone

internal cooling holes were retained. The MRA shield block and full MRA assembly and mesh are shown in Figure 10. There were approximately 2.4×10^6 DC3D10 elements in the assembly.

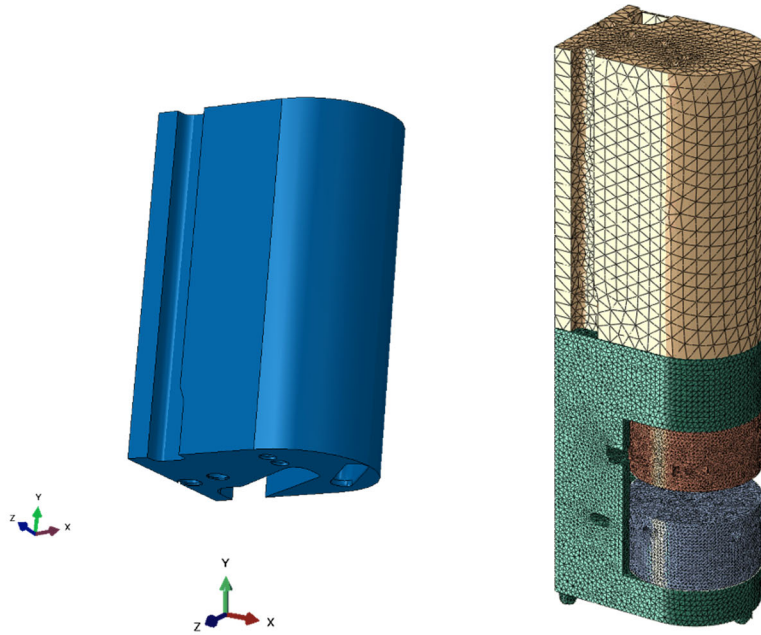


Figure 10 Full MRA assembly

3.5 CORE VESSEL SHIELDING BLOCKS

The 316L Stainless Steel shielding included in the model is shown in Figure 11. Shielding further from the targets was not expected to affect the peak target temperature within 24 hours and were not included. The blocks used 193,961 DC3D10 tet elements with a nominal size of 25 mm. Internal cooling passages were not included.

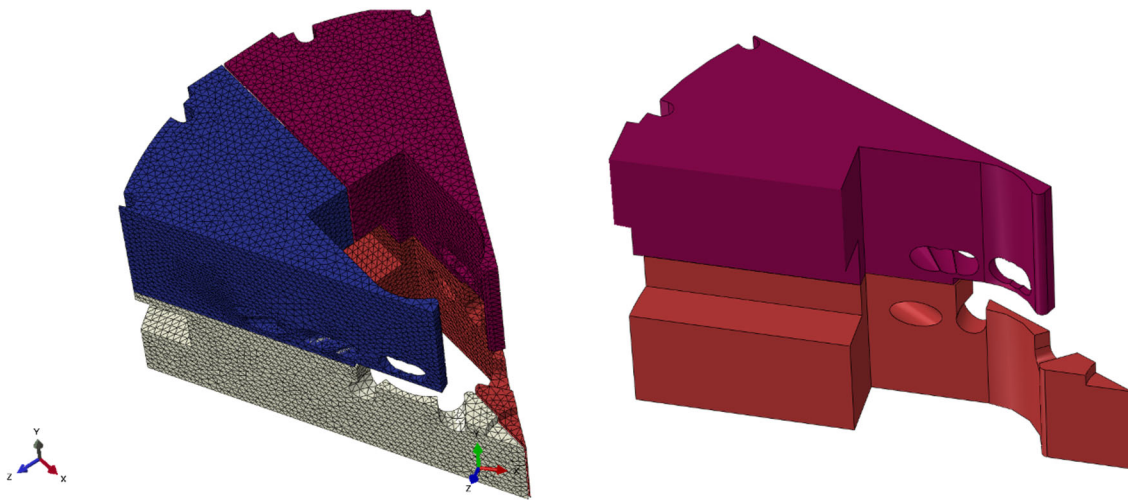


Figure 11 Core vessel shielding blocks

4. MATERIALS

The materials used are given in *Table 1*. The target dummy used an average density to give the same mass as the SpaceClaim model for tungsten and tantalum combined. Irradiated tungsten conductivity and other tungsten properties were used for this region.

Table 1 Material Properties

Material	Conductivity	Density	CTE/ reference Temperature	Specific Heat
	W/m-K	kg/m ³	/C	J/kg
6061T6 Aluminum	180	2700	2.36e-5 / 20	896
Beryllium	216	1850	1.15e-5 / 20	1925
316L SS	14.3	7969	1.61e-5 / 20	500
Inconel	9.94	8190	1.28e-5 / 20	425
Target Dummy	87	19.4	1.6e-5 / 20	128.3
Copper Zr	368	8940	1.164e-5/20	385

The Abaqus input material data is shown in Figure 12. Only the thermal properties were used in analysis

```
*Material, name=Beryllium
*Conductivity
216.,
*Density
1850.,
*Elastic
3.03e+11, 0.125
*Expansion, zero=20.
1.15e-05,
*Specific Heat
1925.,
```

```
*Material, name=Inconel
*Conductivity
9.94,
*Density
8190.,
*Elastic
2e+11, 0.3
*Expansion, zero=20.
1.28e-05,
*Specific Heat
425.,
```

```
*Material, name=al6061
*Conductivity
180.,
*Density
2700.,
*Elastic
6.89e+10, 0.33
*Expansion, zero=20.
2.36e-05,
*Specific Heat
896.,
```

```
*Material, name=Cu_Zr
*Conductivity
368.,
*Density
8940.,
*Elastic
1.164e+11, 0.33
*Specific Heat
385.,
```

```
*Material, name=SS316
*Conductivity
14.3,
*Density
7939.,
*Elastic
1.95e+11, 0.27
*Expansion, zero=20.
1.61e-05,
*Specific Heat
500.,
```

```
*Material, name=target_dummy
*Conductivity
87.,
*Density
19404.,
*Elastic
1.98e+11, 0.27
*Expansion, zero=20.
1.6e-05,
*Specific Heat
128.3,
```

Figure 12 Abaqus input material properties

5. INTERACTIONS

Previous evaluations had shown that the operating mode of vacuum in the core vessel gave higher peak temperatures than with helium or air present. Thermal radiation interactions were defined between surfaces with total hemispherical emissivity and peak temperatures calculated for vacuum operation. Conservatively, thermal radiation from the sides of targets and between targets was not included.

5.1 MATERIAL EMISSIVITY

An aluminum total hemispherical emissivity of .05 was used which should be representative of roughed material at 40°C. (2) The Inconel was assumed to be 0.24 based on a literature survey. (3) A temperature dependent emissivity was defined for the 316L Stainless Steel based on reported data for “as received” material. (4) Figure 13 shows the reference and interpolated data used for Abaqus.

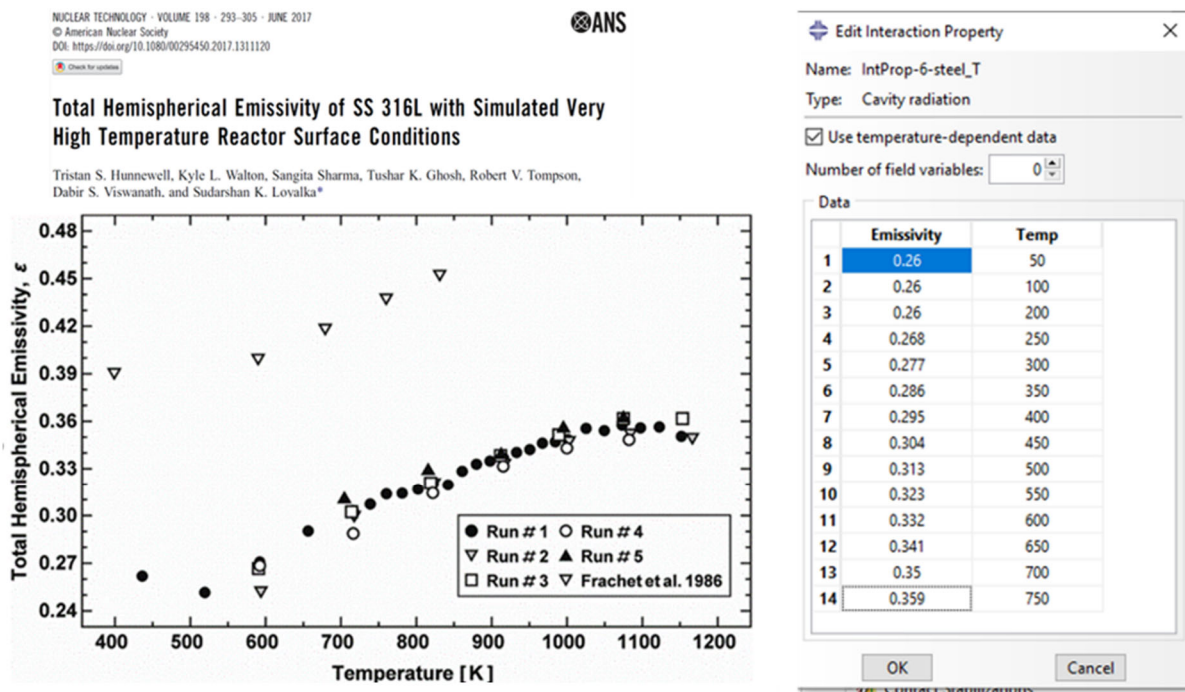


Figure 13 Emissivity for 316L Stainless Steel

5.2 TARGETS TO REFLECTOR VESSEL INTERACTIONS

Thermal radiation was defined as an open cavity between the top surfaces of the three target segments and the bottom surface of the upper MRA aluminum reflector vessel. Figure 14 shows the top targets surface and the upper MRA bottom surface. Figure 15 shows the interaction with an assumed background temperature for the open cavity of 50°C for surrounding shielding. The open cavity assumption of 50°C was made because except for the MRA surfaces, nearly surfaces surrounding the target are water cooled shielding. 50°C was assumed to be a reasonable average above the inlet temperature of 35°C and the thermal radiation should not be significant for temperatures below 100°C.

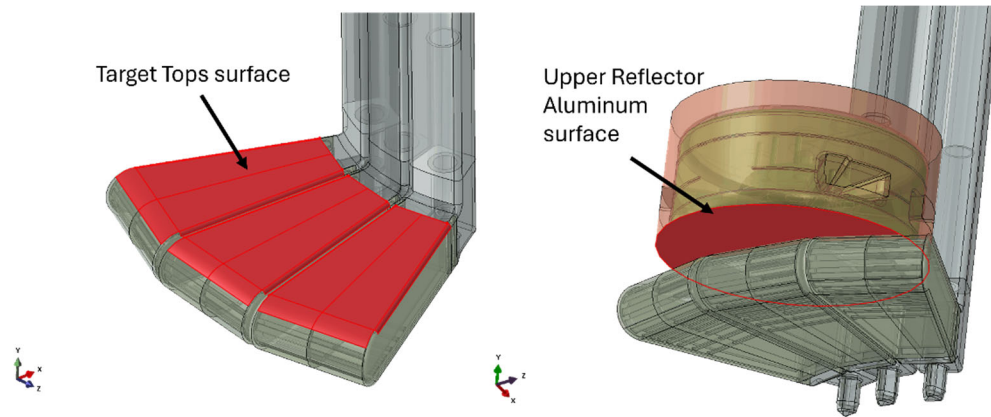


Figure 14 Targets top and upper MRA bottom surface.

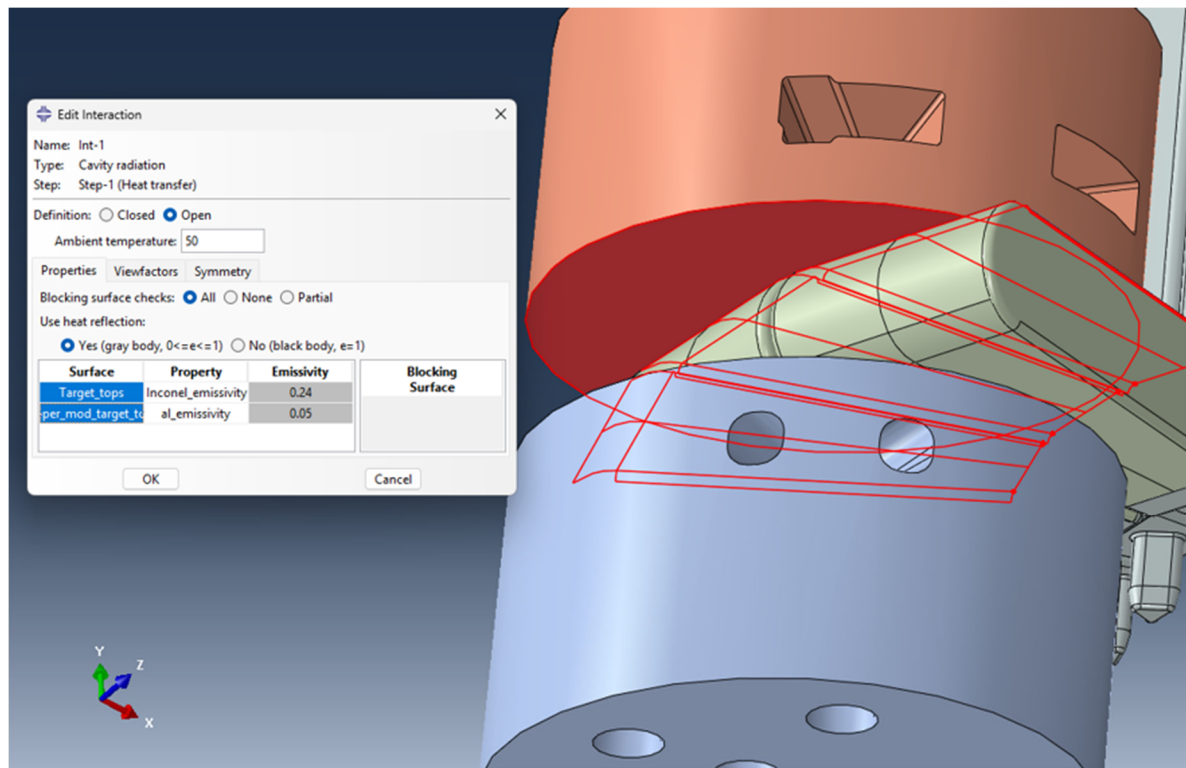


Figure 15 Target tops and upper MRA Interaction

When evaluating the target peak temperature only the results for the central target were considered. This should be conservative because it does not include the effect of rotation. When rotating, a segment will on average spend most of the time between cooled 316L shielding blocks which have an emissivity of approximately .3. If stationary, the central target top and bottom surfaces will mostly be next to the aluminum with an emissivity of approximately .05 which would result in lower net thermal radiation and higher target temperature. The two side targets only see a smaller fraction of the moderator surfaces and the open cavity assumption with a 50°C background simulates the thermal radiation to the shielding.

A similar interaction between the bottom of the targets and the lower MRA was modeled as shown in Figure 16.

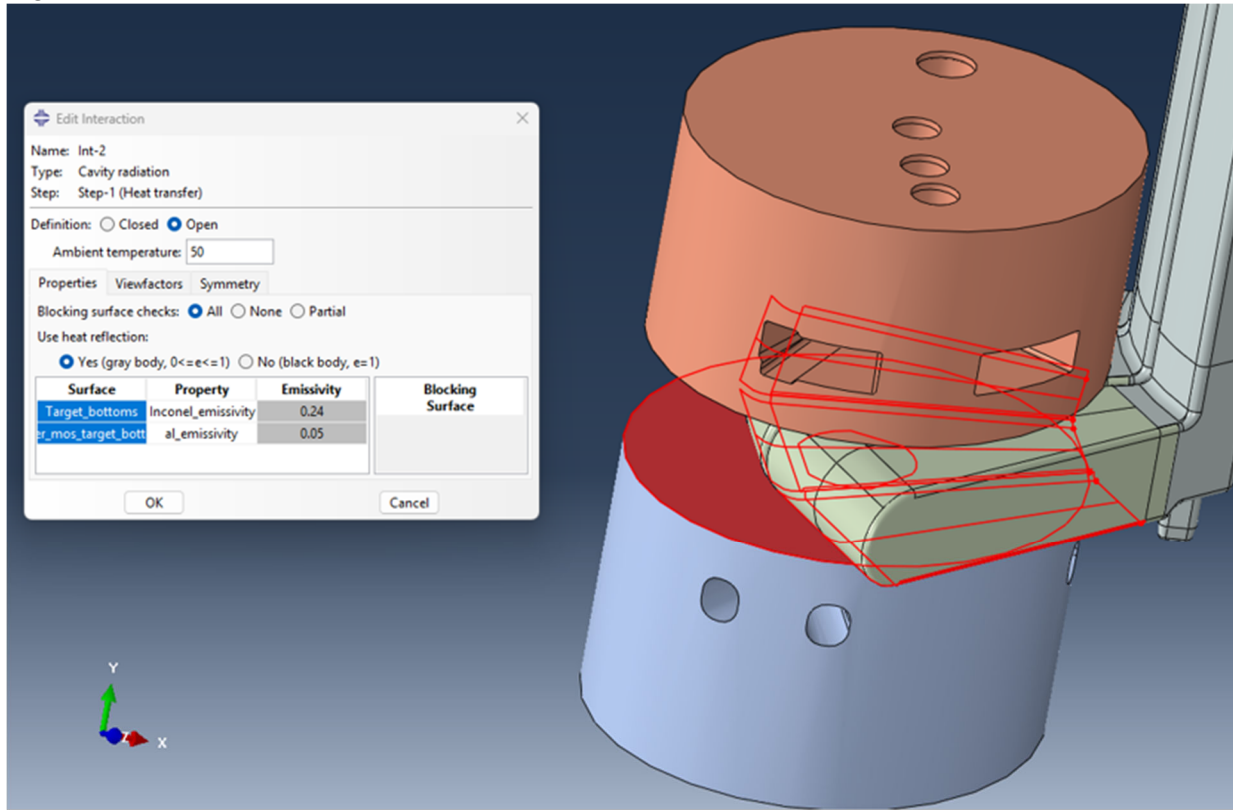


Figure 16 Targets Bottom and Lower MRA interaction

5.3 TARGET FRONT TO SHIELDING AND PROTON BEAM OPENING.

A surface on the front of the three segments was defined for thermal radiation. MRA backbone and shielding surfaces adjacent to the targets and along the opening for the proton beam line were identified as part of the cavity. The facing surfaces of the MRA reflector vessels were not included because they had been used for the top and bottom target surface cavity and analysis was restricted by Abaqus to only one cavity. The reflector vessel surface if included would provide additional cooling, but the effect would be small and not including them is conservative and simplifies the analysis. Figure 17 shows these surfaces and the open cavity interaction definition. A 50°C temperature was assumed for the surrounding area.

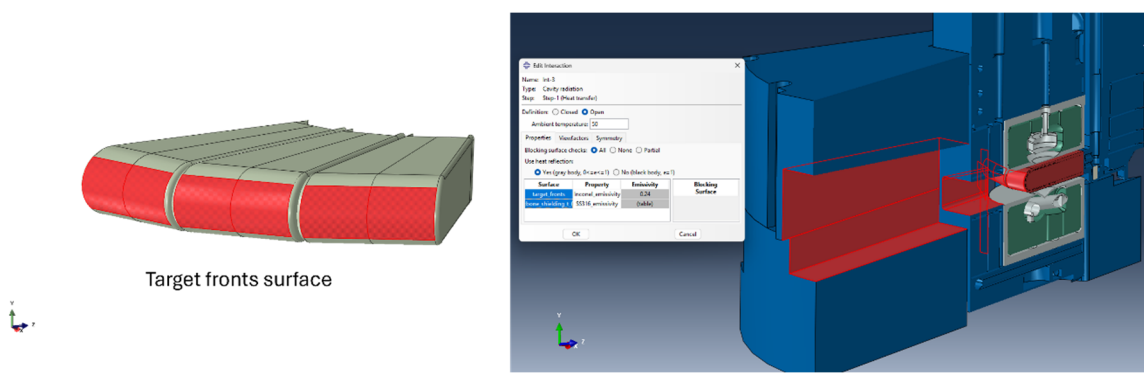


Figure 17 Target front radiation interaction showing target front surface, backbone and shielding surfaces

5.4 TARGET STALK TO SHAFT THERMAL RADIATION INTERACTION.

The lower surfaces of the target stalks facing the shaft and the outer lower shaft surface were defined as an open cavity for thermal radiation as shown in Figure 18. A background temperature of 50°C was assumed in this region. The upper regions of the stalks and shaft were not included because similar previous analysis showed they remained at low temperatures. (1) Conservatively, no thermal radiation from the front of the stalks or rear of the target segments was assumed.

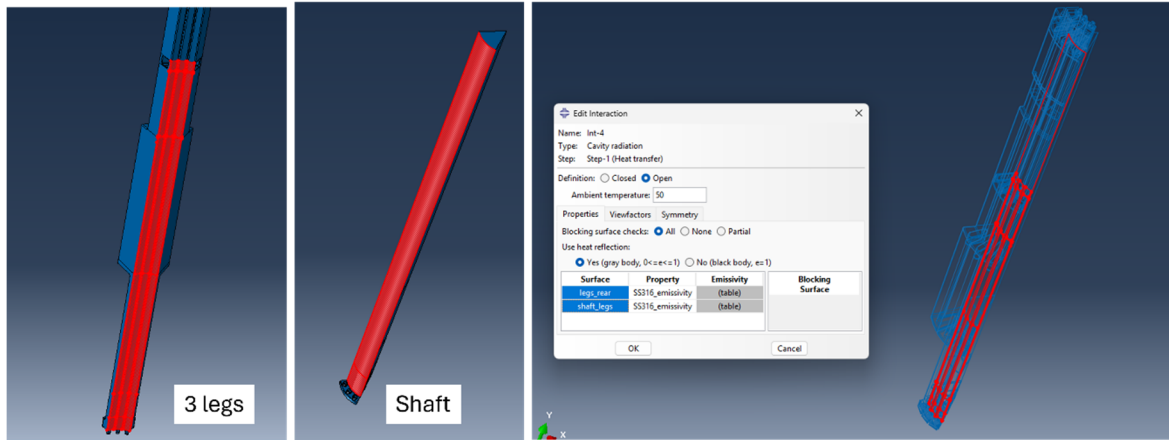


Figure 18 Target stalk to shaft thermal radiation interaction.

6. CONSTRAINTS

6.1 TARGET SEGMENTS

The target Inconel is welded to the 316L stalk. Figure 19 shows the tie connection used for the three segments.

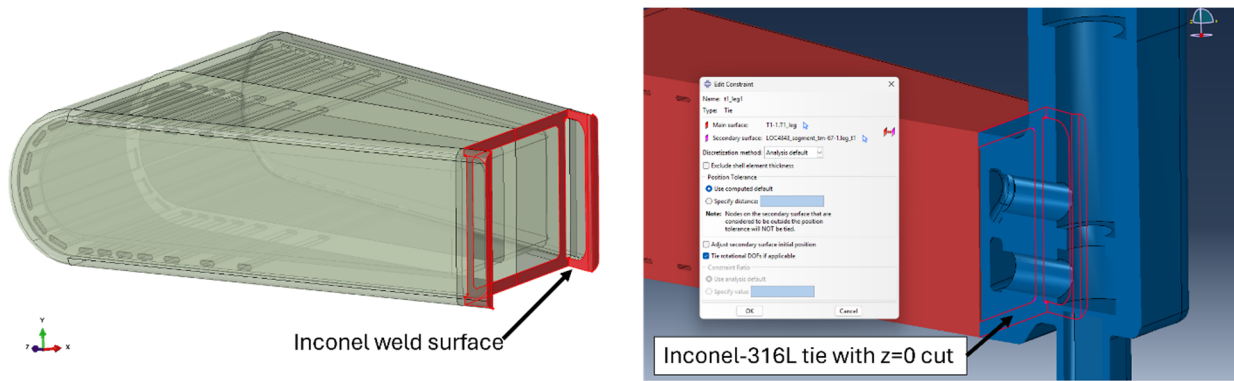


Figure 19 Target Inconel to 316L tie constraint

6.2 MRA ALUMINUM TO BERYLLIUM THERMAL TIE CONDITIONS

The upper and lower MRA reflector vessels have a beryllium block in close contact with the aluminum vessel on the side closest to the target with the other surfaces water cooled.

A tie condition was assumed for this contact, and no internal water was assumed. Figure 20 shows these two contacts.

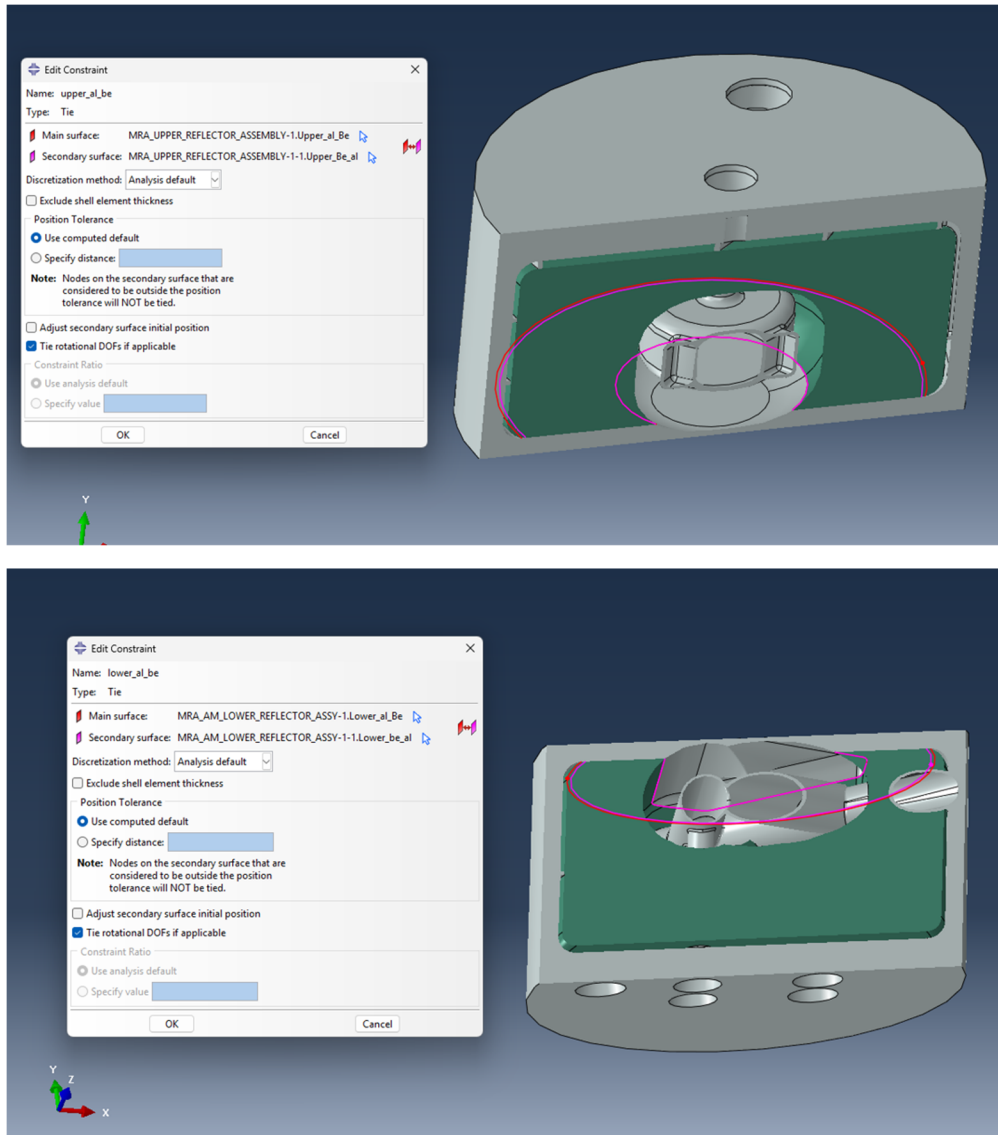


Figure 20 MRA Beryllium to Aluminum upper and lower vessel constraints.

6.3 MRA REFLECTOR VESSEL ALUMINUM AND BACKBONE CONDUCTANCE INTER-ACTIONS

The aluminum reflector vessels will be bolted to the stainless steel backbone. The bolting was not modeled and a tie condition between the contacting surfaces was assumed. *Figure 21* shows the tie constraint definitions.

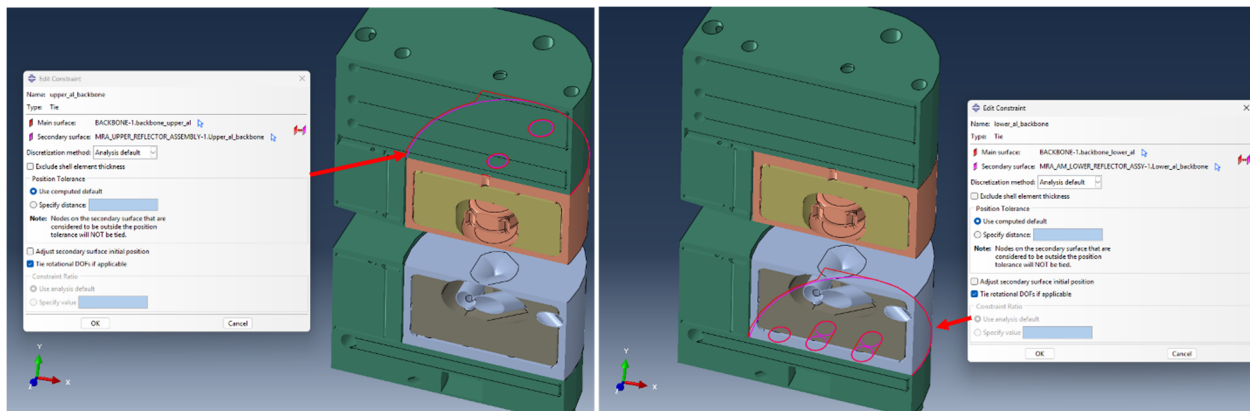


Figure 21 Upper and Lower MRA Aluminum to Stainless Steel Backbone tie conditions

6.4 MRA BACKBONE TO SHIELD

The Backbone and Shield are bolted together. The connection is simulated with a tie condition between the upper surface of the backbone and lower surface of the shield as shown in Figure 22.

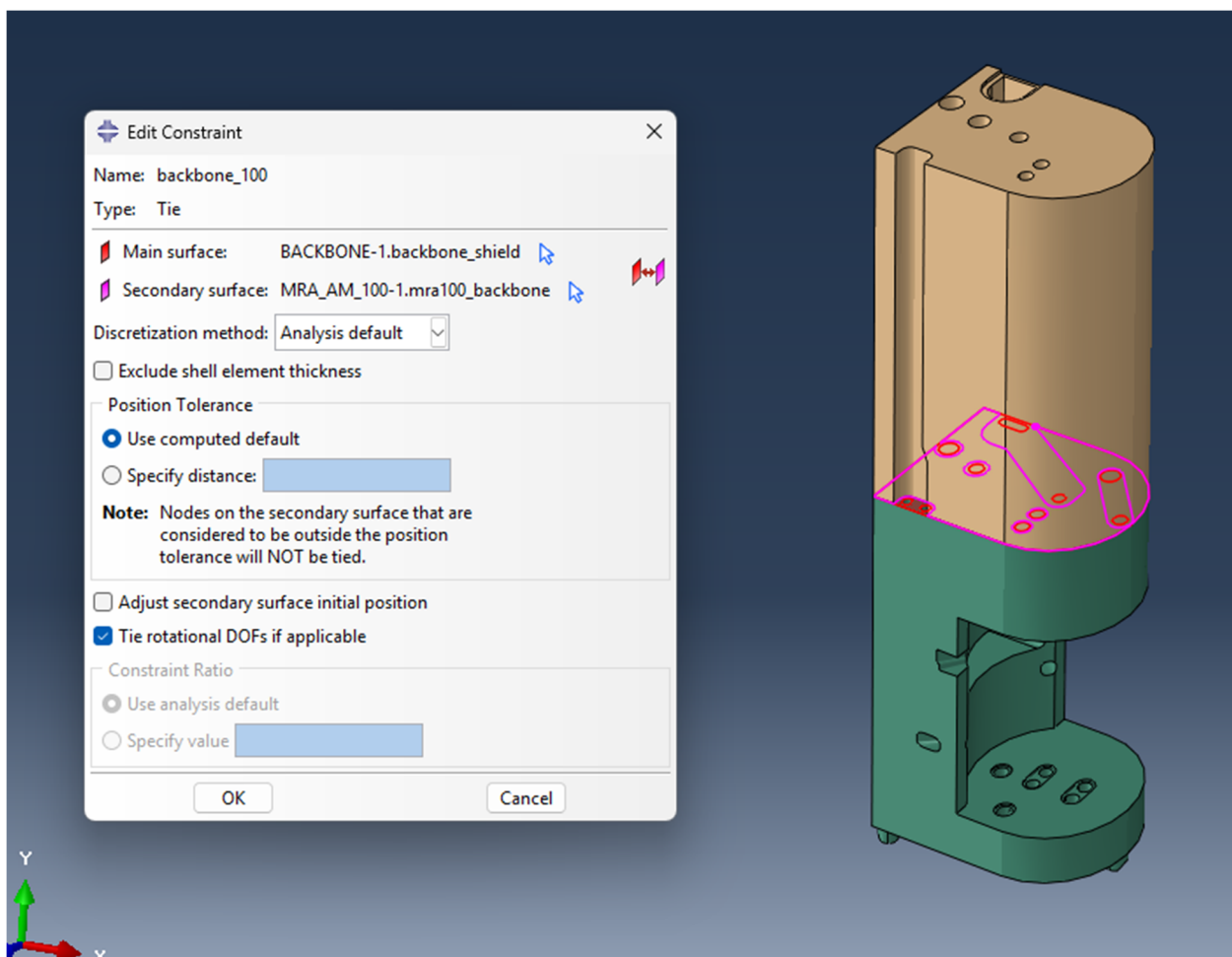


Figure 22 MRA Backbone to Shield tie

6.5 CORE VESSEL SHIELDING BLOCK AND COPPER PIN TIE CONSTRAINTS

The upper and lower cooled shield blocks on each side of the proton beam channel are tied on the contact surfaces near the midplane as shown in Figure 23.

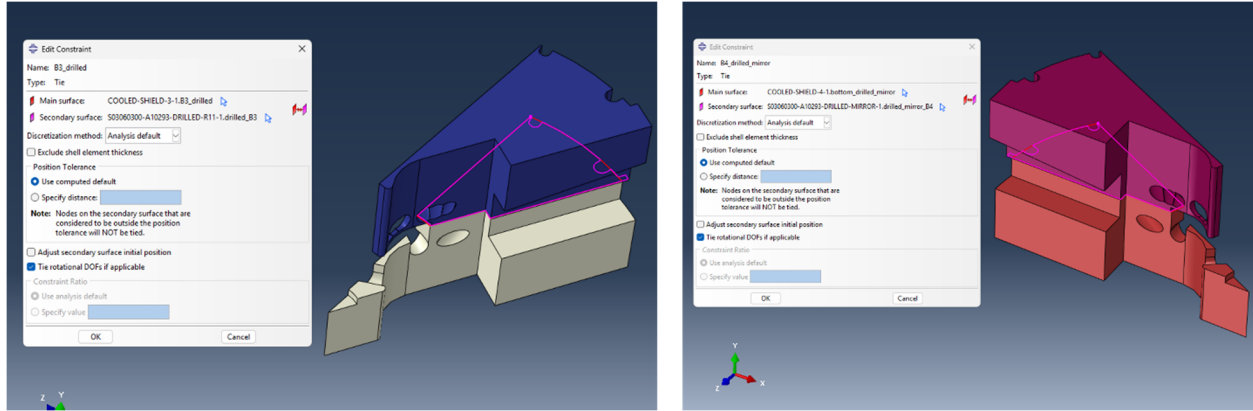


Figure 23 Core Vessel Shield Block tie constraints

Each of the three segments has a copper alloy pin insert. The CuCrZr is metallurgically bonded to the 316L so a tie constraint to the stalk 316L as shown below is appropriate.

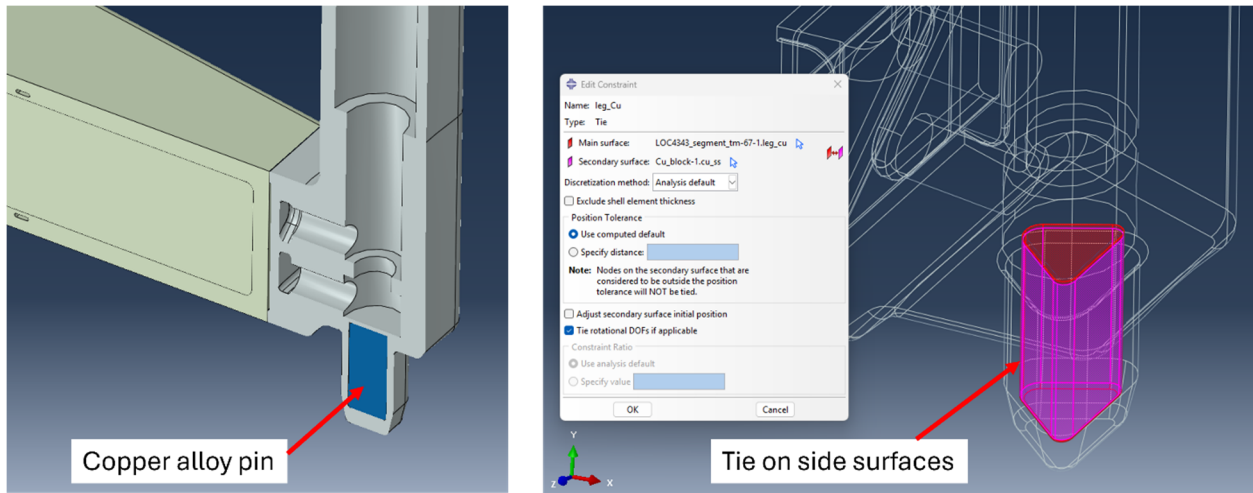


Figure 24 Copper pin tie to stalk 316L SS

7. DECAY HEAT

The decay heat by material at shutdown was given by T. McClanahan for the 2025 design. (5) For the Abaqus model the tungsten and tantalum values were combined to use in the “target dummy” shown in Figure 4. The neutronic decay heat model assumed the side manifold covers were stainless steel. The design was later changed to make them Inconel, but the neutronics had not been re-analyzed. Since the decay heat in these regions outside of the beam was relatively low (2.5 % of total at shutdown), the Stainless Steel heating was added to the Inconel heating for the Inconel volume which included the side manifolds. The same decay heating was applied to all three segments. The total power and the volumetric heating in the Abaqus model geometry for the target dummy and Inconel region are shown in

Figure 25. A linear extrapolation is used by Abaqus between the neutronic data points. This is conservative and does not account for an initial drop in heating rate within the first minute for short lived isotopes.

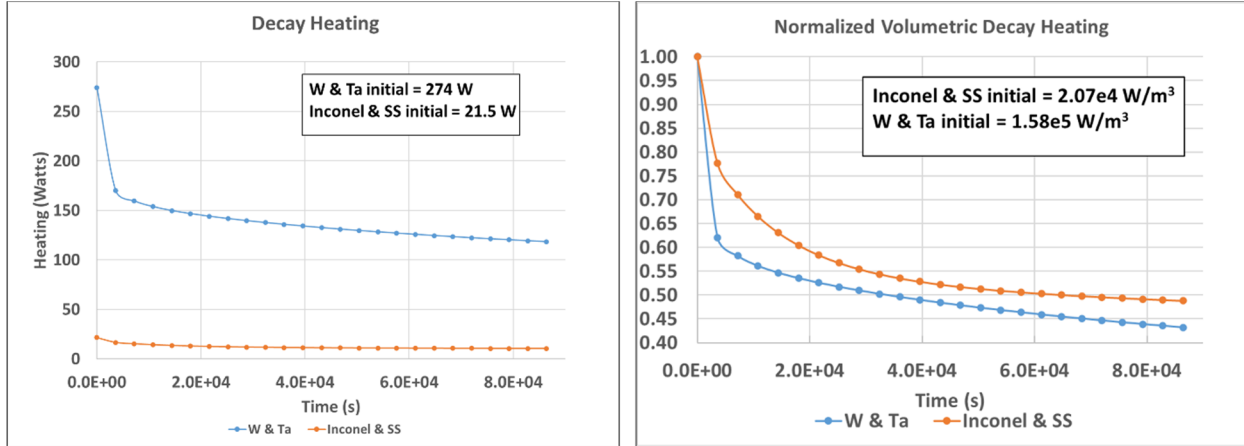


Figure 25 Decay Heat in watts and normalized volumetric heating for one target segment

The decay heat data was normalized to the starting value to develop an amplitude versus time table. The material volumes for the target dummy and the Inconel were divided by their decay heat to give initial volumetric heating. The volumetric heating was applied as loads in Abaqus for the target and Inconel volumes each segment. The normalized amplitude versus total time in seconds with the starting volumetric heating for the material as shown in Figure 26. The Abaqus decay heat loads for all segments in the target dummy and Inconel volumes as a function of time in seconds is given in Figure 26.

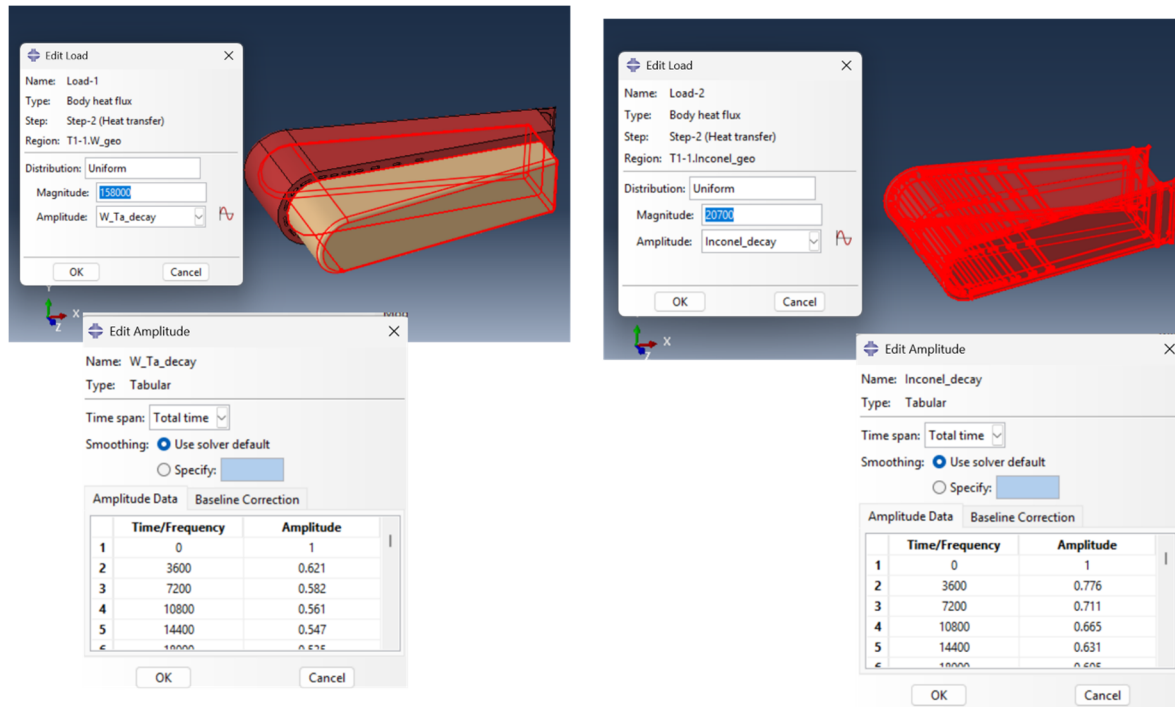
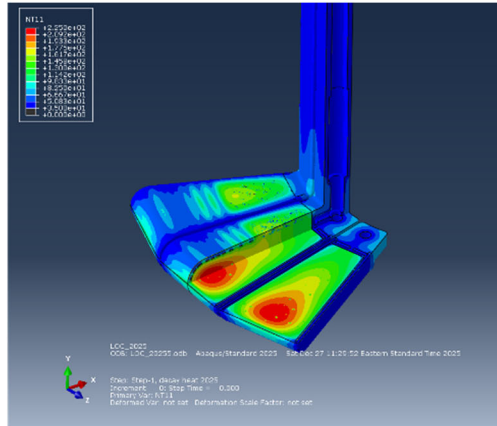


Figure 26 Abaqus target dummy and Inconel decay heat loads for all segments with time in seconds

8. INITIAL TEMPERATURE DISTRIBUTIONS

The normal operating temperature profiles for the target segments, MRA assemblies and copper pins were developed by Min-Tsung and shared by SharePoint links. The files used for this analysis are described in Appendix A which also gives links to the data files. These will later be included in SNS document references. The Tungsten and tantalum temperature files were combined and mapped by Abaqus to the “target dummy” nodes. A default value of 120°C was used for nodes which did not obtain a mapped value due to different mesh sizes. The temperature data files for the Inconel and stainless steel were combined and mapped by Abaqus to the Inconel and 316L stalk nodes. A default value of 40°C was used for nodes which did not obtain a mapped value in the Inconel or 316L regions. Temperature data for the copper pin were mapped to the pin nodes. The same temperature profiles were applied to all three segments using rotated coordinate systems for reference. The shaft and bulk shielding were assumed to be at 50°C. Figure 27 shows the operating temperatures for the three segments. Mapping of this data on the simplified Abaqus model with three segments is shown with a peak of 225°C. The initial 316L SS temperatures of the target stalk is also shown with a peak of 90°C at the bottom and most of the material below 40°C.

Targets and Stalk temperature for normal operation



Stalk Initial temperature profile as mapped in Abaqus with 90 C peak

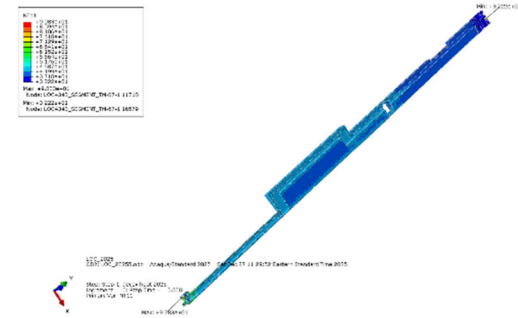


Figure 27 Target Segment initial Temperatures as mapped onto the Abaqus model.

The initial temperatures for the MRA assembly with the Backbone is shown in Figure 28 with a peak of 85°C in stainless steel.

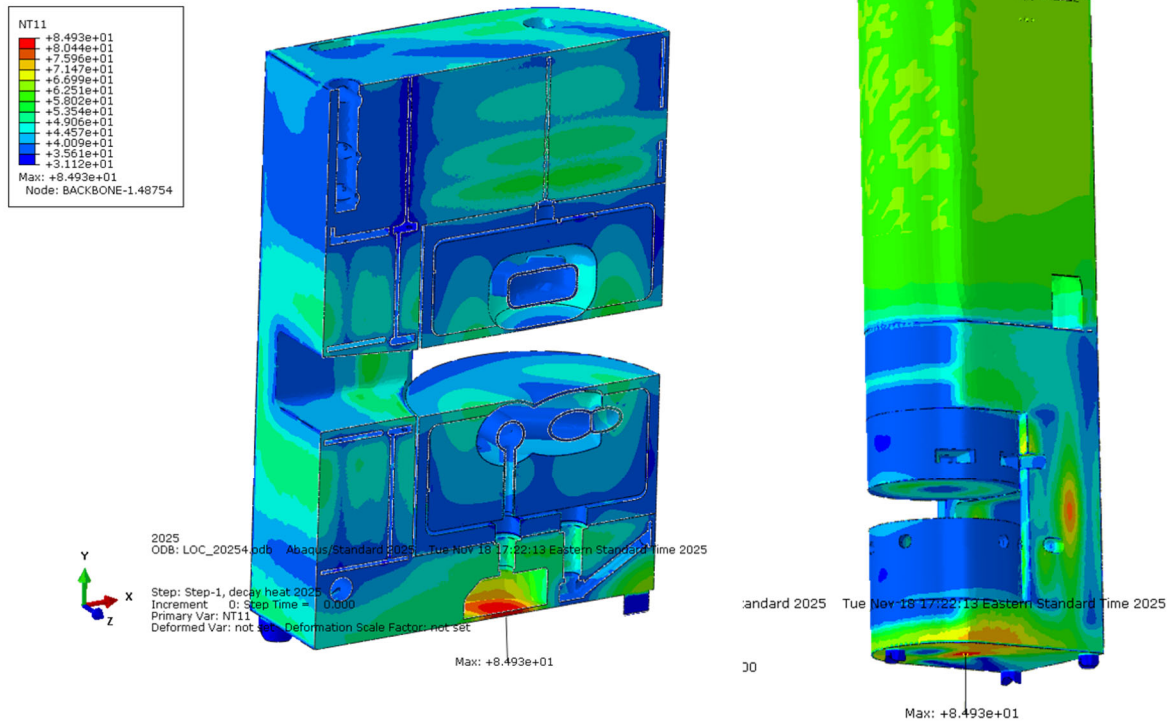


Figure 28 Initial MRA temperature profile

The overall monolith initial temperature profile is shown in Figure 29.

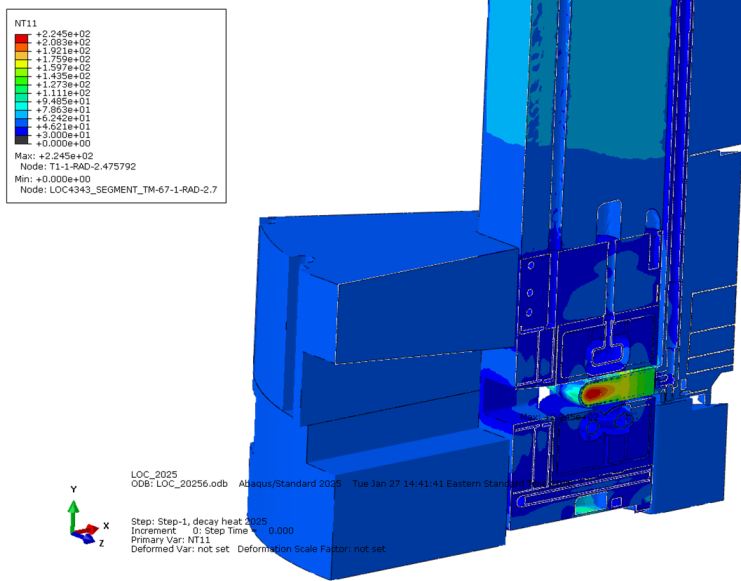


Figure 29 Monolith initial temperatures

9. RESULTS

The volumetric heating on the targets immediately after shutdown as mapped in Abaqus is shown in Figure 30 with a peak of 1.58e5 W/m^3 . The analysis (LOC_20256.inp) was done in two Steps. The first step was for 4 hours (14400 s) and the second step for 20 hours (7.2e4 s).

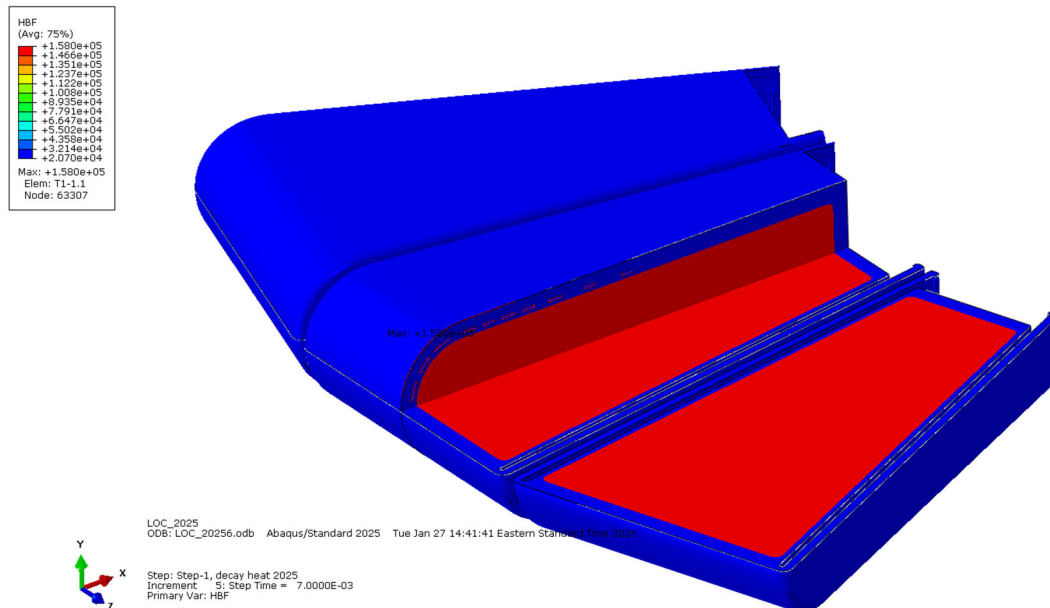


Figure 30 Target initial volumetric heating

Figure 31 shows the temperature for four selected nodes on the center target over 24 hours. One node is at the location of the peak temperature over 24 hours (288965). A second node is near the rear of the tungsten region (29983) and a third on the top of the Inconel near the front (825277). The fourth node (871100) is in the 316l stalk just above the weld zone to the Inconel.

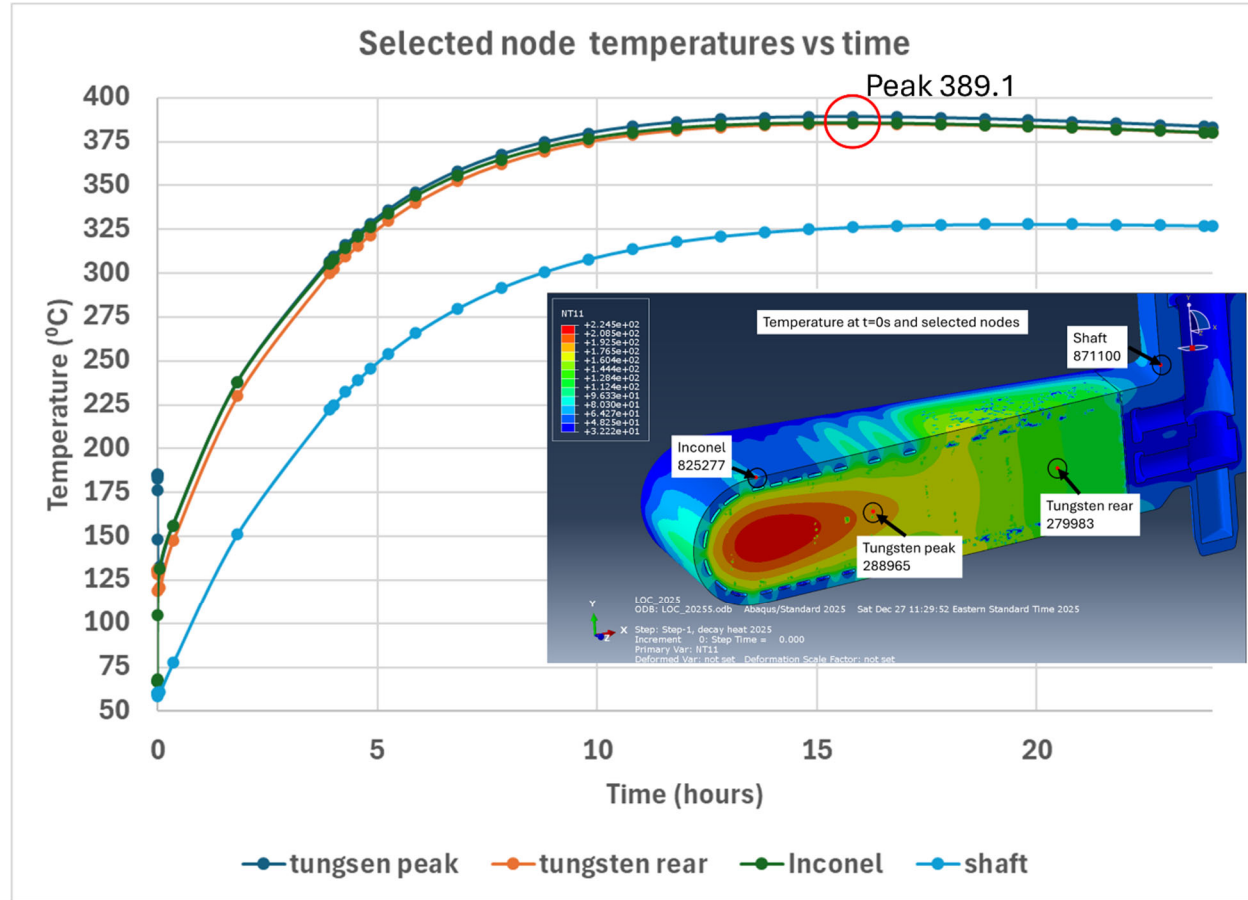


Figure 31 Temperature vs time for selected nodes over 24 hours with a peak of 389.6°C

The peak temperature is 389.1°C which occurs after approximately 15.8 hours. The initial operating peak of 225°C rapidly drops within the first minute to approximately 140°C as the temperature equilibrates within the target body. Figure 32 shows the center target and stalk temperature profile at 15.8 hours when the tungsten temperature peaks at approximately 389.1°C. The targets on either side of the center target have lower peak temperatures because of better thermal radiation to shielding away from the moderator vessels which is simulated by an open cavity assumption with a 50°C background temperature for target top and bottom surfaces as shown in Figure 15 and Figure 16. The thermal profile on the stalk is shown in Figure 33. The overall monolith profile at 15.8 hours is shown in Figure 34. Outside of the segments, the peak temperature at 15.8 hours was 87°C near the bottom of the shaft.

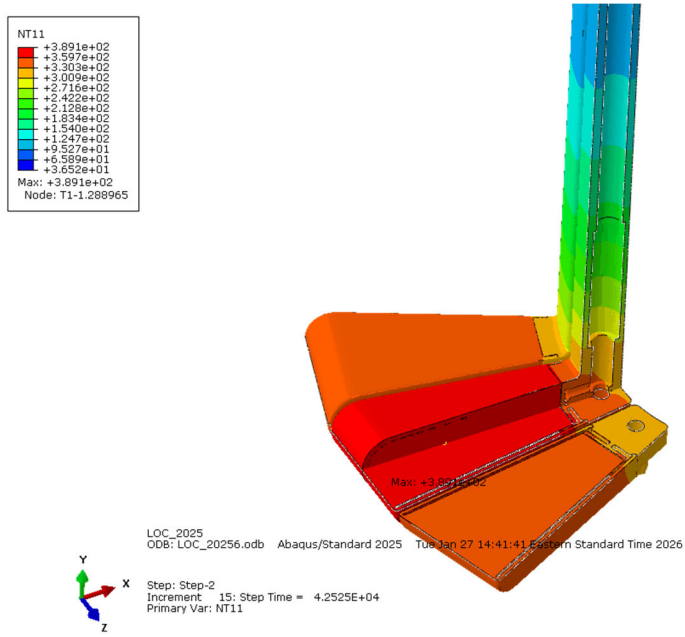


Figure 32 Temperature at 15.8 hours at peak for central target and stalk with cuts on $z=0$ and $y=0$ planes

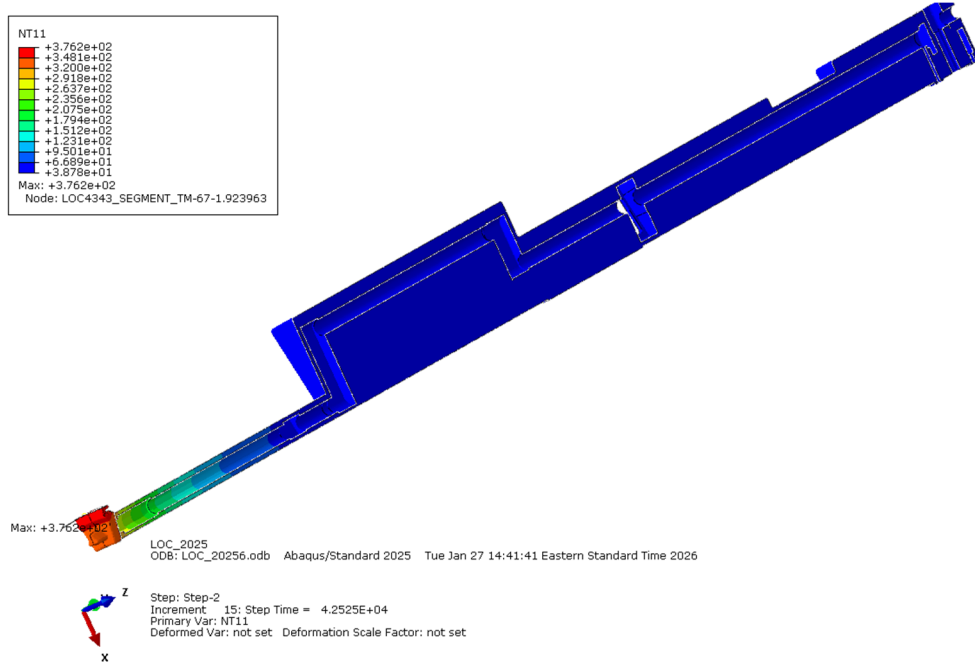


Figure 33 Stalk temperature at 15.8 hours with peak of 376°C

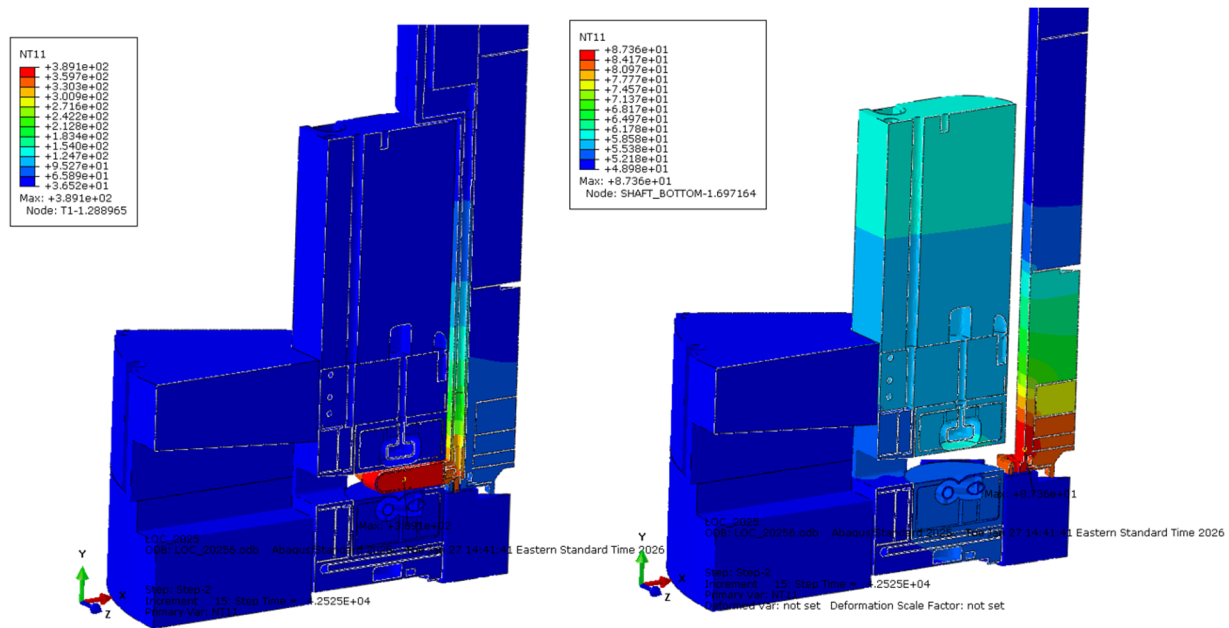


Figure 34 Monolith temperatures at 15.8 hours and with an 87°C maximum without segments

Decay heat is transported by thermal radiation and by conduction to the stalk. *Figure 35* shows the radiation flux from the target front and top surfaces and on the upper and lower MRA aluminum surfaces. Negative values are away from the surface and positive into the surface. The peak flux on the moderator surfaces was approximately 400 – 500 W/m² and the peak from the front of the center target was 2,351 W/m². These values are close to the analytical predictions of 443 W/m² for parallel plates at 390°C and 60°C and the prediction of 2.63e3 W/m² for free radiation from the Inconel front surface at 390°C (see Appendix link to excel file RADFL). The side segments which do not directly face the proton beam opening have lower front surface radiation but higher radiation from the top and bottom surfaces which view less of the moderator surfaces and more of the open cavity. They have a lower peak temperature of approximately 355°C.

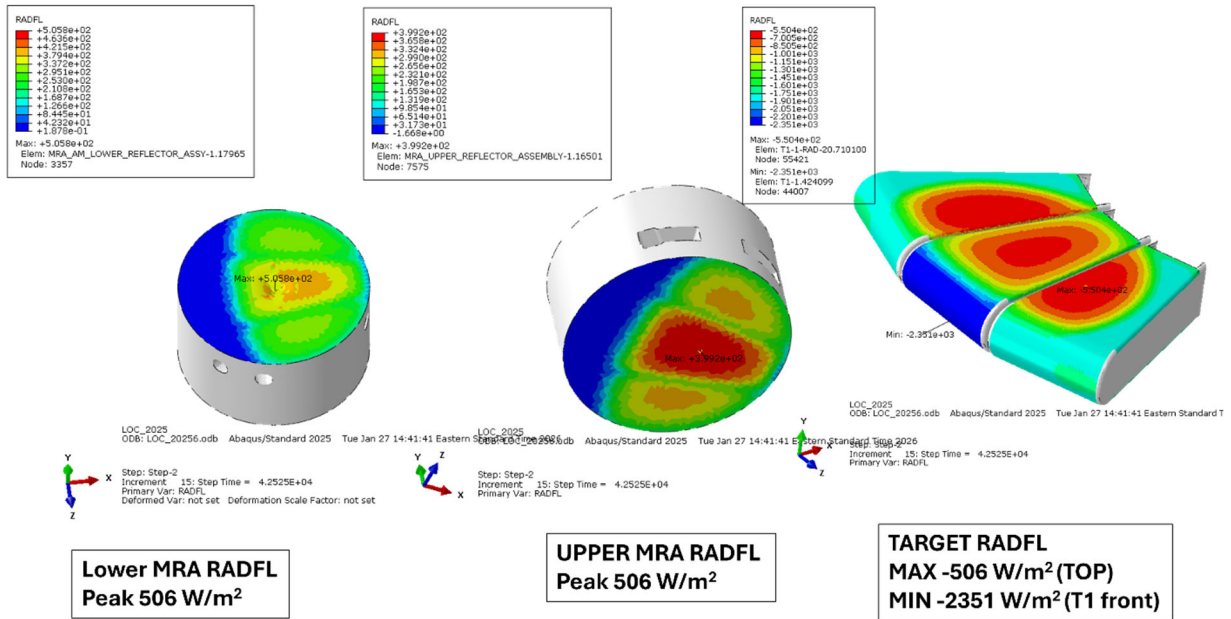


Figure 35 Thermal radiation at 15.8 hours

Radiation heat fluxes around the target cavity are shown in Figure 36. The peak flux of 1005 W/m² is from the center stalk near the target to the shaft. Fluxes on the surfaces in the opening for the proton beam are low and are shown with a scale maximum of 100 W/m².

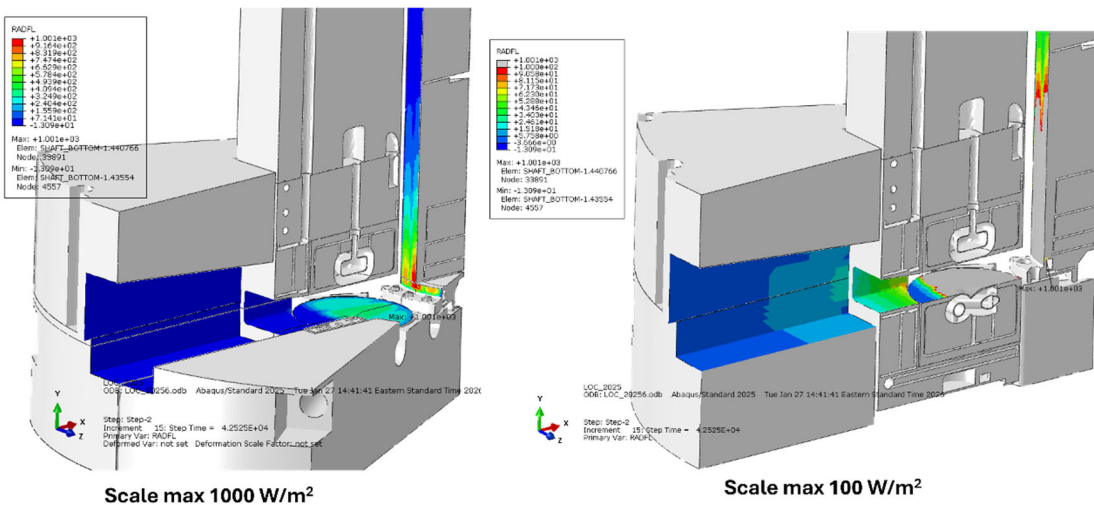


Figure 36 Thermal radiation around target cavity at 15.8 hours

The overall heat flux at 15.8 hours is shown in Figure 37 with a scale maximum of 1.5e4 W/m². A significant flux is through conduction to the stalk with the peak near the weld between the Inconel and 316L stainless steel.

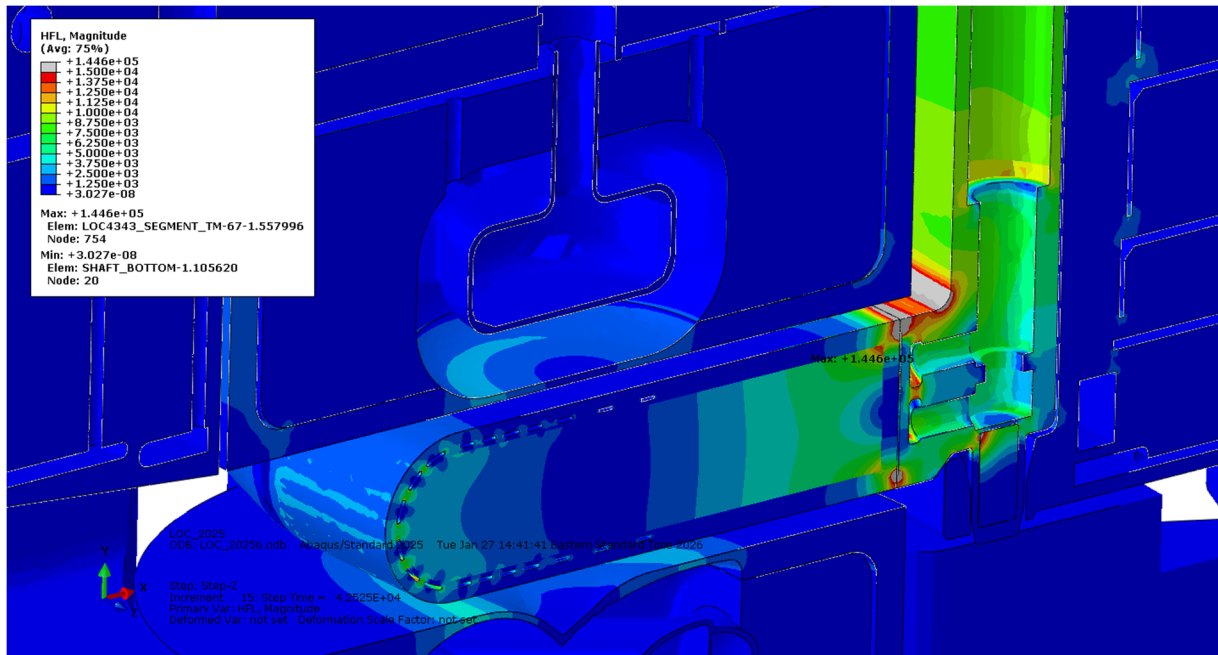


Figure 37 Heat Flux at 15.8 hours with $1.5e4 \text{ W/m}^2$ scale maximum

The vertical heat flux for the upper moderator assembly at 15.8 hours is shown in Figure 38 along with the vertical flux on the beryllium to aluminum tied surface.

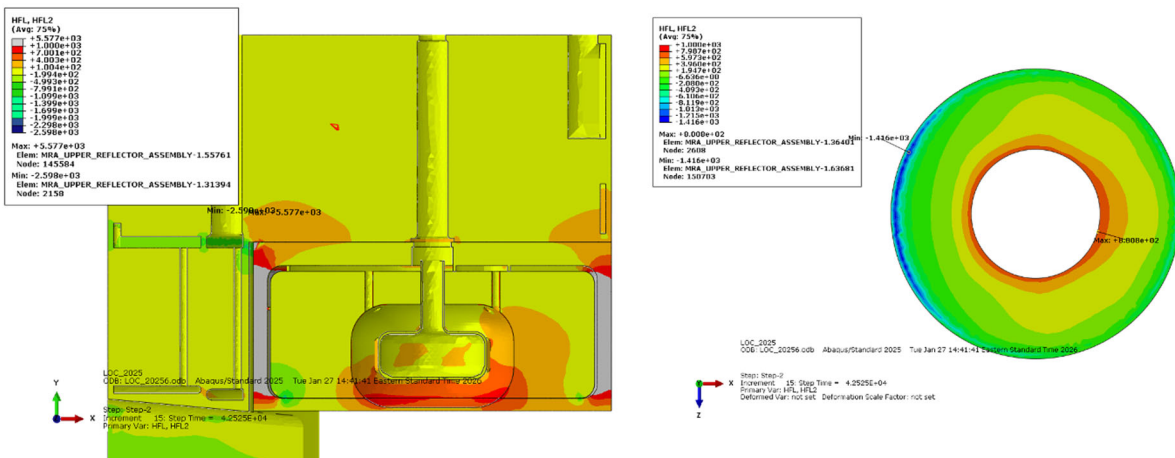


Figure 38 Upper MRA Vertical heat flux at 15.8 hours

The peak vertical heat flux on the contact surface between the aluminum and beryllium was 800 W/m^2 into the beryllium near the center and 1416 W/m^2 out of the beryllium near the outer radius when the target temperature reached a peak. This surface could have a thin water film. If this is assumed to be 0.1 mm at 50°C , the water conductivity of 0.6406 W/m-K would give a peak temperature difference of only 0.22°C across the contact. This rise would not materially change the thermal radiation with the target so the assumption of a tie condition for this surface should be acceptable. The lower MRA would see similar conditions. The average vertical heat flux on the surface between the aluminum reflector vessel and the stainless steel backbone is approximately only $100 \text{ W/m}^2\text{-K}$. The bolted connection is assumed to keep the temperature drop across this interface below 1°C and the tie assumption should be acceptable.

The temperature at 24 hours is shown in Figure 39. The target is a nearly uniform 383°C with conduction up the stalk continuing. This also showed that the upper stalk and shaft regions remained at low temperatures as assumed.

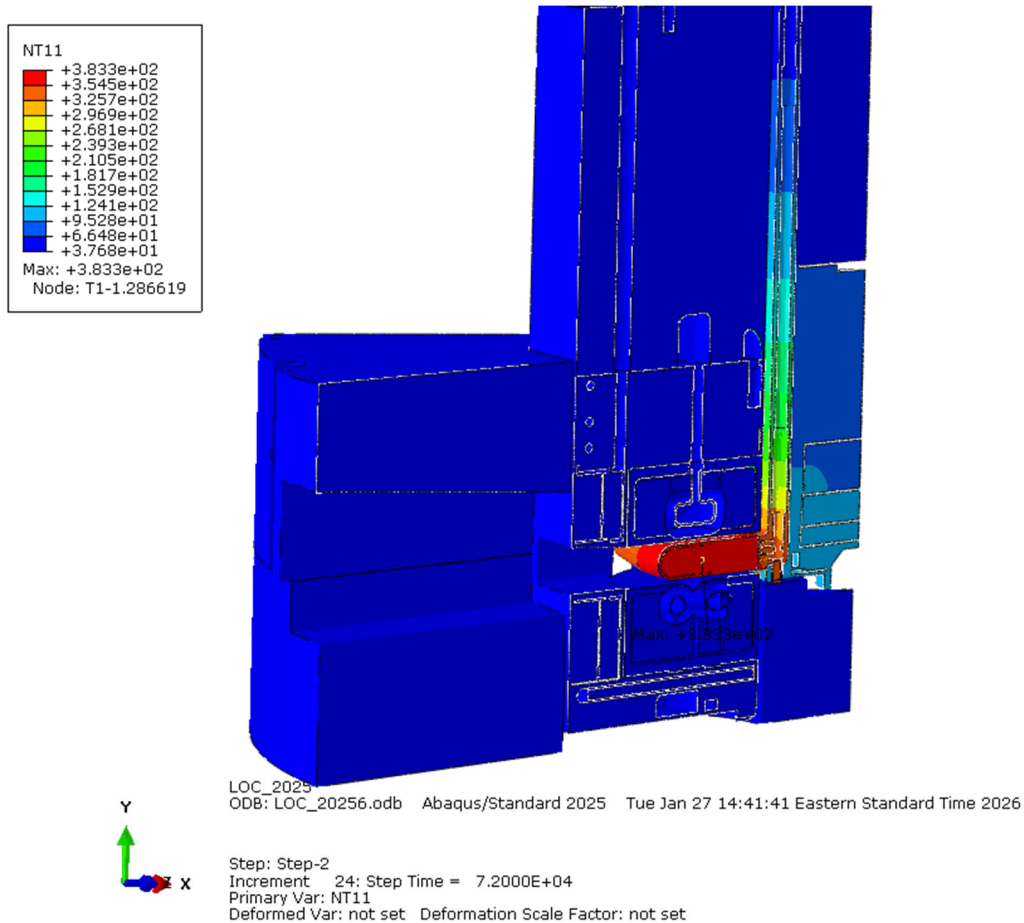


Figure 39 Temperatures at 24 hours

The MRA temperatures remain below 62°C for 24 hours as shown in Figure 40 because of good conduction to the backbone stainless steel which has a high heat capacity. No credit was taken for thermal radiation between the backbone and other surfaces. Also, no credit was taken for conduction through the supports to the bulk shielding under the MRA.

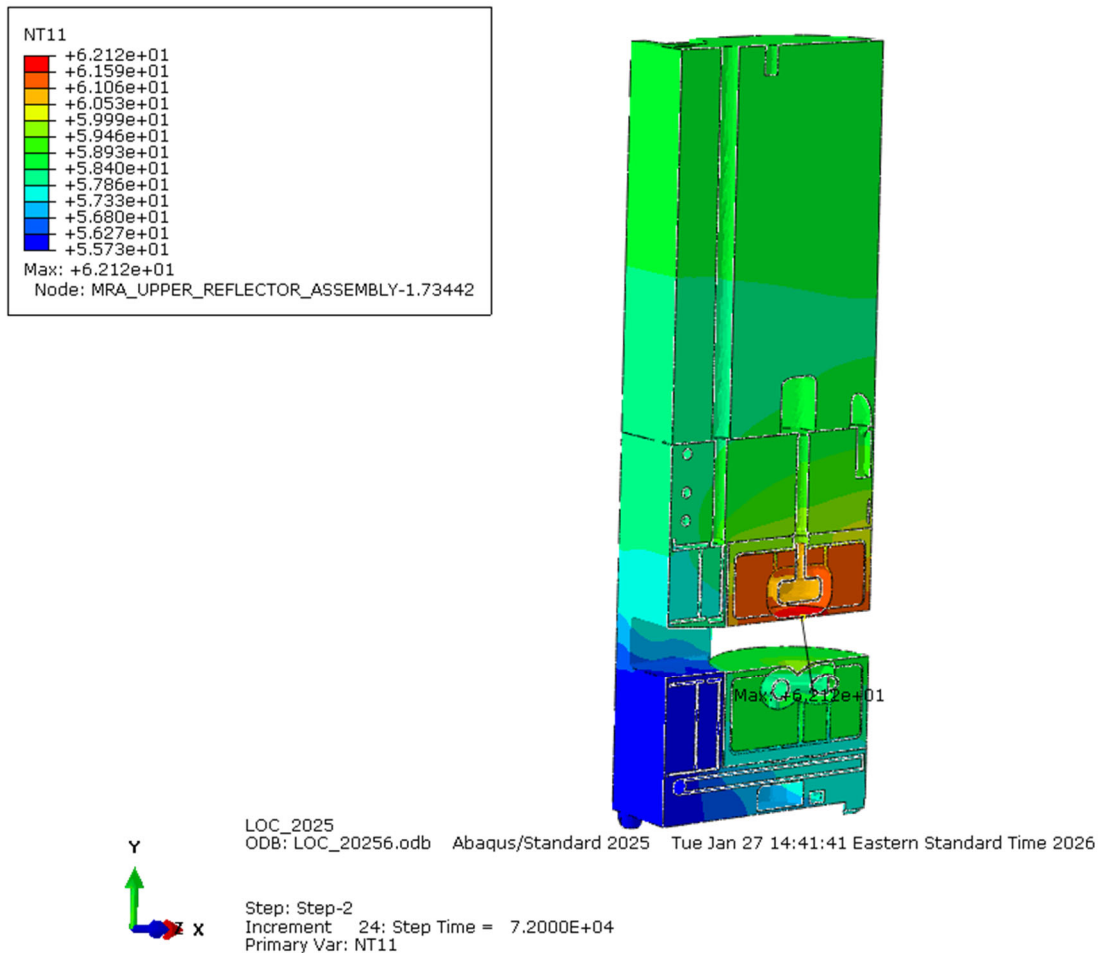


Figure 40 MRA temperature at 24 hours

10. THERMAL ANALYSIS SUMMARY AND CONCLUSION

The loss of cooling cases with a beam trip had a peak target temperature of approximately 389.1 °C for segments rotated between the moderators. The peak temperature occurred after approximately 15.8 hours and decreased after that within the 24-hour period analyzed. The analysis model was a conservative bounding calculation that did not credit all thermal radiation or water within components. The target temperatures were very uniform within the target/tungsten region because of the high tungsten thermal conductivity internally and a high external thermal resistance due to radiation. Also, the lower thermal conductivity through Inconel and 316L Stainless Steel for conduction to the welded stalk contributed to a more uniform temperature in the tungsten region. Targets segments only partially between the moderators had lower peak temperatures because of the higher open cavity thermal radiation to shielding compared to the reflector vessel aluminum.

The decay heat data did not include a spatial distribution within the target, but this probably does not affect the peak significantly because of the high internal thermal conductivity versus high external thermal impedance. These temperatures are well below the approximate threshold of 800°C for tungsten vaporization in steam.

11. STRUCTURAL ANALYSIS

11.1 INTRODUCTION

The objective of the structural analysis was to evaluate if the temperature increase from a Loss of Cooling event was enough to cause the target to contact the lower moderator aluminum pre-moderator vessel.

This could potentially be caused by a loss of strength in the target Inconel or 316L stalk including the welded connection and downward displacement due to gravity. The increase in temperature between the target and the fixed connection at the top of the stalk also causes downward displacement of the target between the moderators due to overall thermal expansion. The nominal clearance between the moderator vessels and the target is 10 mm.

11.2 ABAQUS STRUCTURAL MODEL

The Abaqus structural analysis model is based on the thermal analysis model. This model only evaluated the expansion of one segment including the target and stalk. The simplified shaft model from the thermal analysis was included to provide a constraint on the target pin against radial displacement. The Abaqus model (LOC_2025_front2cae_droop2) assembly is shown in Figure 41.

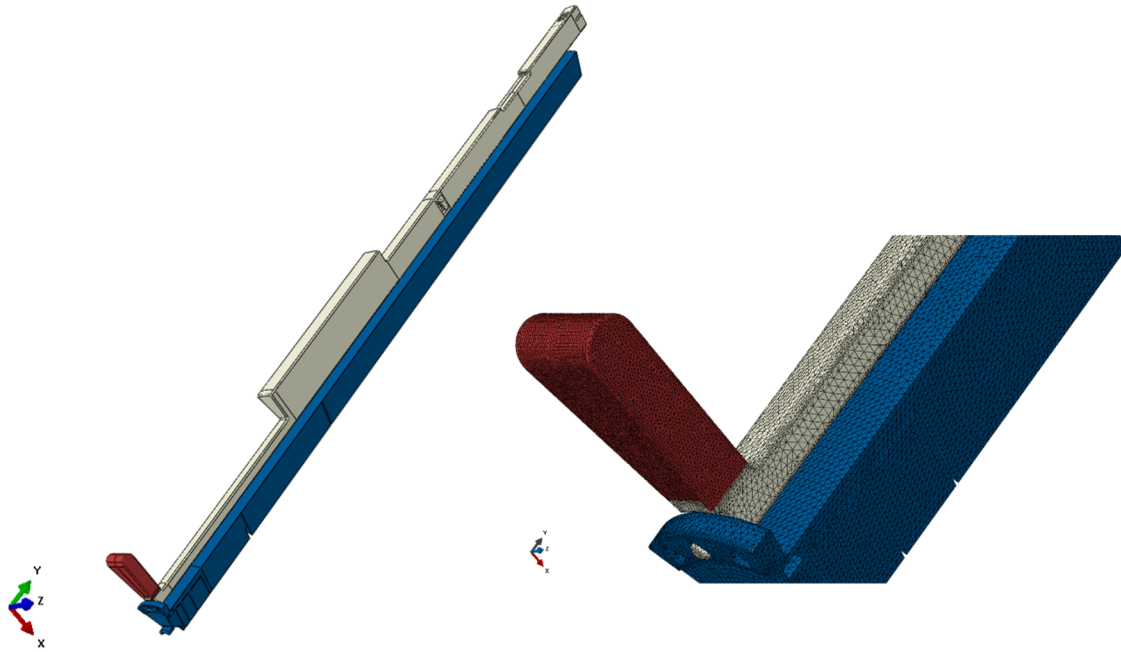


Figure 41 Abaqus assembly for structural analysis

The same target, stalk and shaft mesh models from the thermal analysis were used. The DC3D10 and DC3D8 element types from the thermal model were all changed to C3D10 and C3D8 respectively. Material models were changed to include temperature dependent elastic plastic properties for 316L SS and Inconel 718. Figure 42 shows views of the target and stalk mesh near where they are welded.

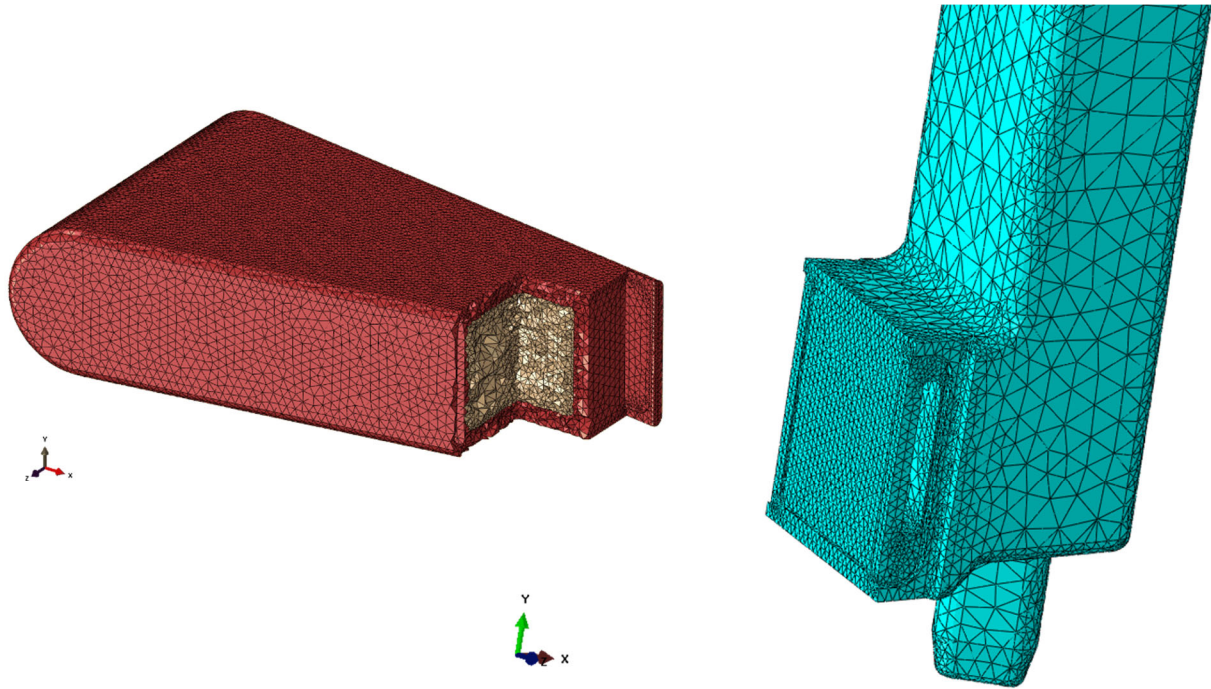


Figure 42 Target mesh with "target dummy" and Inconel materials shown and stalk mesh

Tungsten Modulus and CTE properties were used for the target dummy region with the same reduced density to account for the tantalum volume fraction as used in the thermal analysis. Including the thin tantalum regions as tungsten likely increases the local thermal stress with the Inconel in contact but should not significantly change the overall vertical displacement.

11.3 MECHANICAL PROPERTIES FOR INCONEL, 316L SS AND TUNGSTEN REGION

The temperature dependent mechanical properties for 316L Stainless Steel and Inconel 718 used for the target fatigue analysis were applied. (6) A plot of the 316L properties for several temperatures over the range of interest is shown in Figure 43. The 316L yield strength starts at 172 MPa at 40 °C and drops to 101 MPa at 400°C. The Youngs Modulus and Coefficient of Thermal Expansion are also shown as a function of temperature. Figure 44 shows the Inconel mechanical properties. The yield strength starts at 400 MPa at 20 °C and reduces to 283 MPa at 400°C. The modulus and coefficient of thermal expansion over this temperature range are also shown. The target tungsten and tantalum region used tungsten properties with a reduced density to account for the tantalum content with the Abaqus input given in Figure 45.

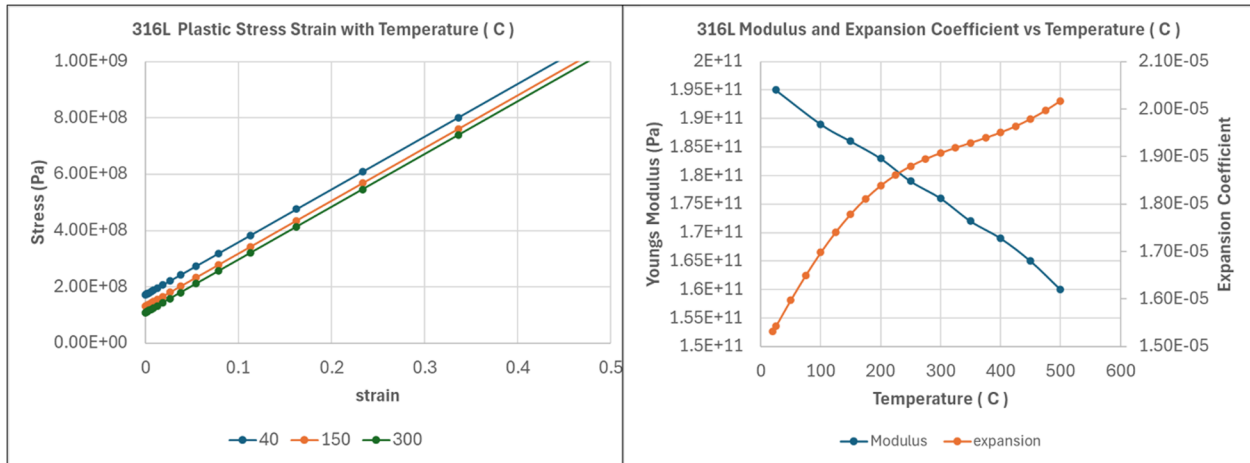


Figure 43 SS 316L Mechanical Properties

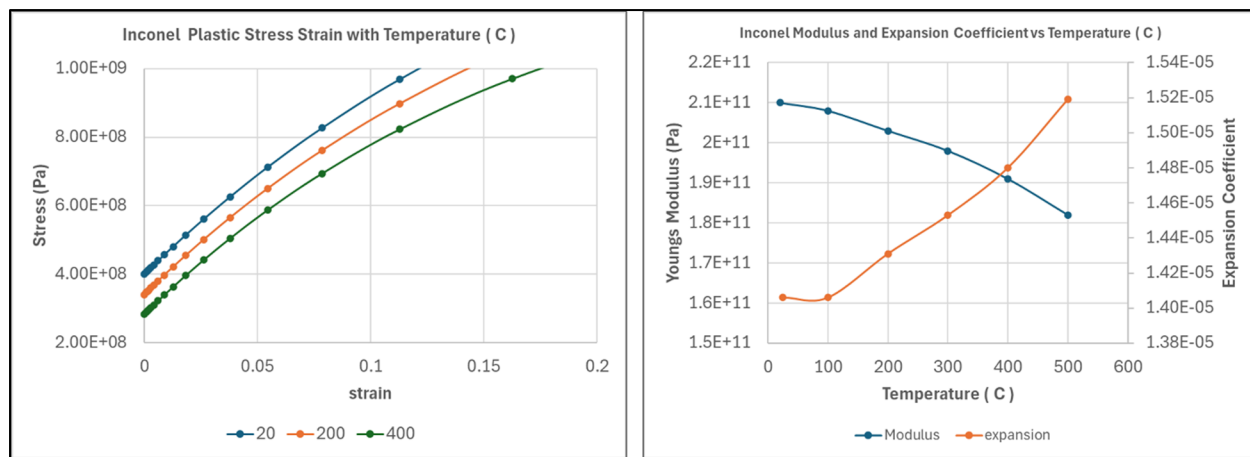


Figure 44 Inconel Mechanical Properties

```

*Material, name=target_dummy_m
*Conductivity
87.,
*Density
19043.,
*Elastic
3.95e+11, 0.282
*Expansion, zero=20.
4.58e-06,
*Specific Heat
128.3,

```

Figure 45 Target tungsten and tantalum region properties

11.4 ABAQUS STRUCTURAL MODEL BOUNDARY CONDITIONS, INTERACTIONS AND CONSTRAINTS

The target segments are connected to the crown by bolts at the top of the stalk as shown in Figure 46.

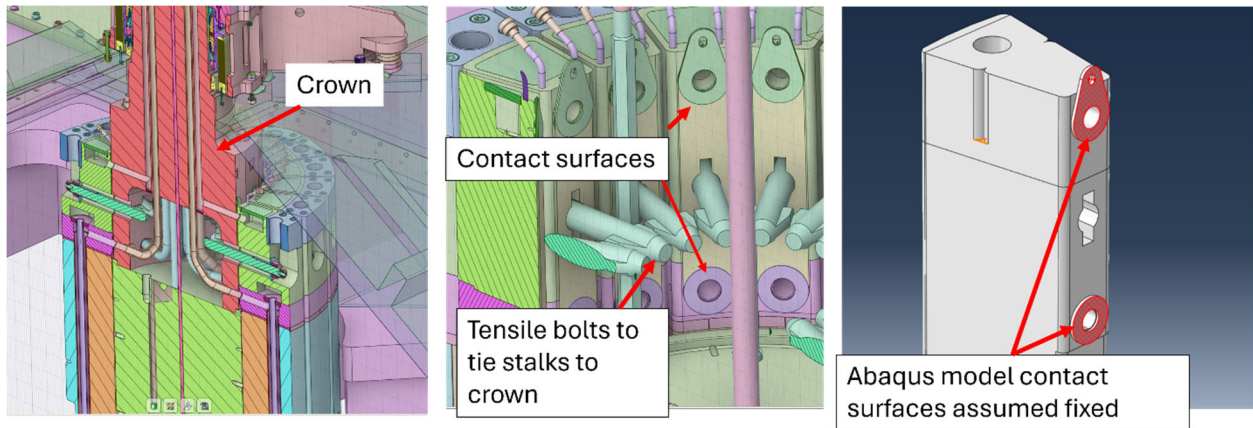


Figure 46 Step file showing crown and segment connection and Abaqus model for contact

11.5 BOUNDARY CONDITIONS

The primary boundary condition assumed the nodes on the stalk parts which would be compressed into the crown to be fixed. This was a simplified assumption for the segment overall displacement analysis and not intended to evaluate local stresses around the connection. Displacements were calculated relative to this location. The shaft was included in the model to have a contact interface with the target pin. The boundary conditions for the shaft were restrained vertical motion on the top of the shaft and constraints on displacement normal to the side cut faces. These boundary conditions are shown Figure 47.

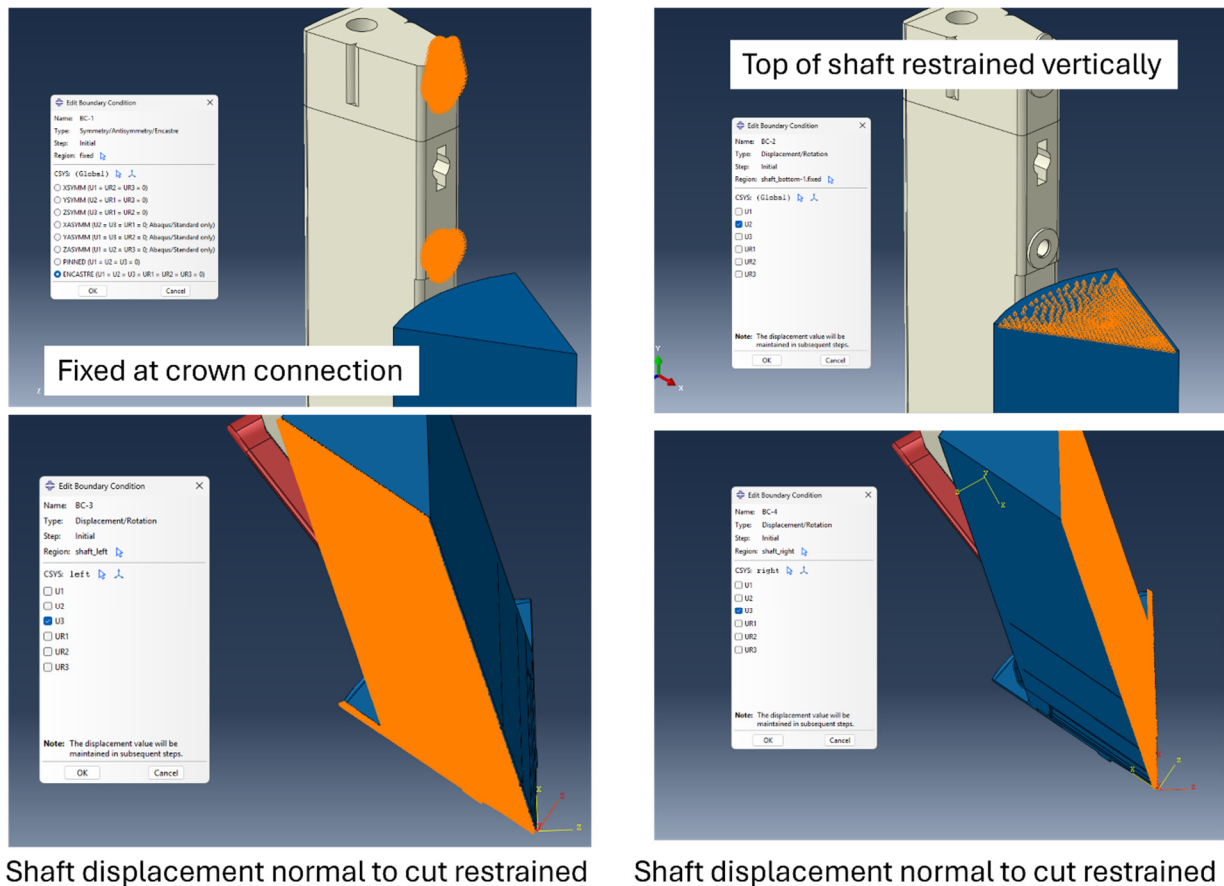


Figure 47 Droop model boundary condition

The pin at the bottom of the target was restrained against outward radial motion. The vertical surfaces on the outer half of the pin and shaft hole were used for a surface to surface contact. The property was hard contact allowing separation without friction. The interaction is shown in Figure 48 with a $z=0$ cut.

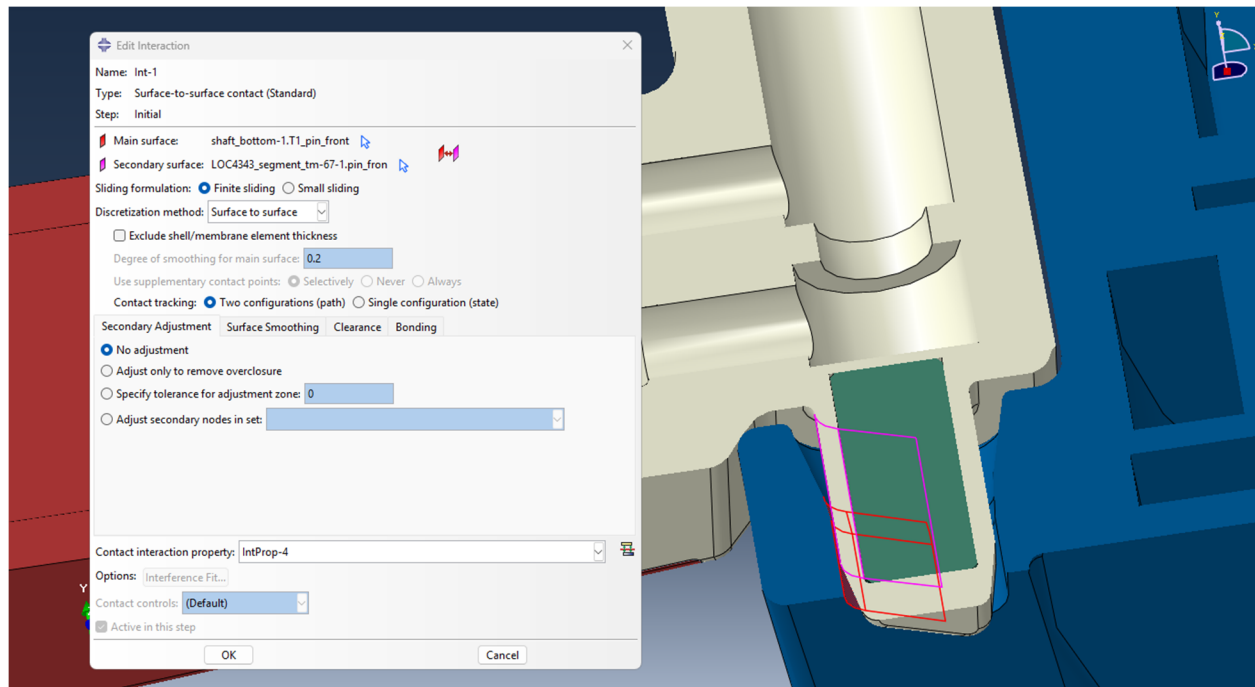


Figure 48 pin to shaft interaction

The same Inconel to 316L tie constraint as shown in Figure 19 and below in Figure 49 was applied.

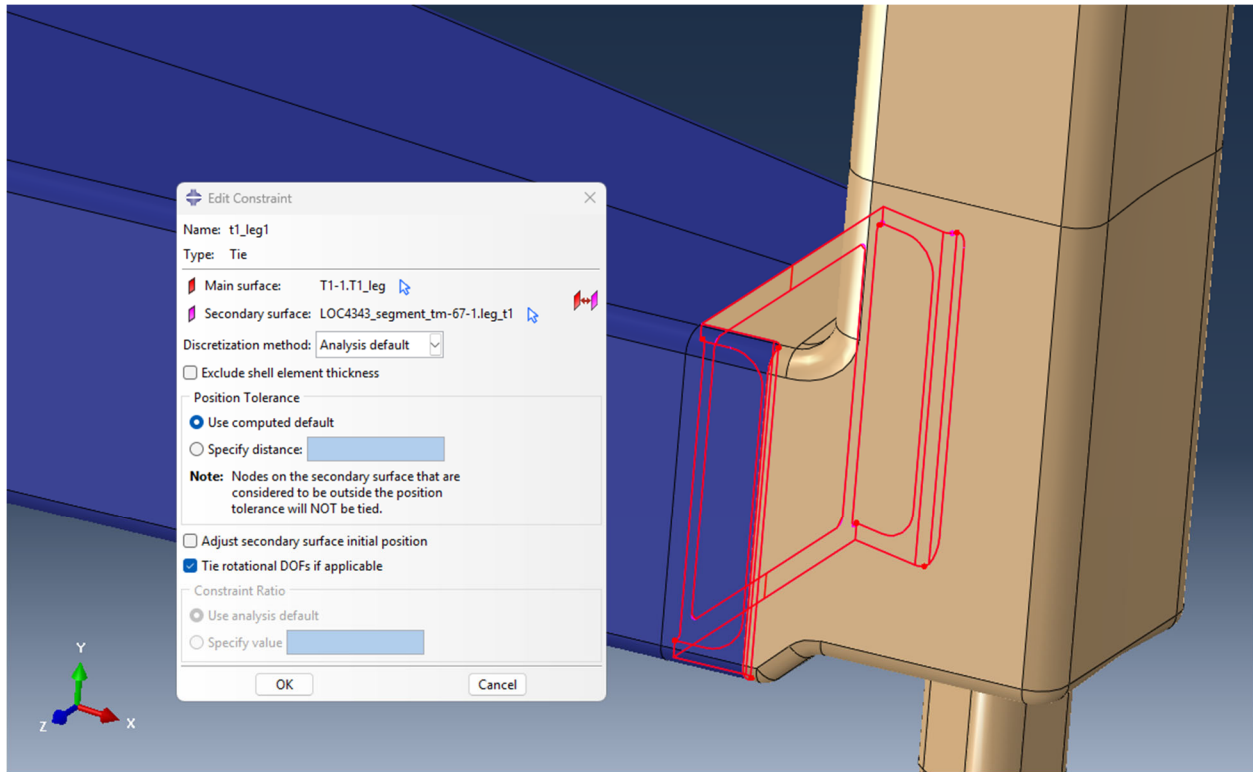


Figure 49 Tie constraint target Inconel to 316L stalk

Also, the same copper to 316l constraint as shown in Figure 24 was applied.

11.6 INITIAL CONDITIONS AND ANALYSIS STEP FORMAT

The steady state model had three steps including initial, step1 and step 2. The initial step applied 20 °C to all nodes in the model. This assumed installation at 20 °C and that 20 °C was the stress-free state. Step 1 imported the peak temperature profile at 15.8 hours (LOC_20256 step 2 increment 15) as shown in Figure 32 and Figure 33 and as imported for the structural model in Figure 51. A 1 G gravity load was applied in step 1 and a rotational body force load from 45 rpm was added in step 2 to all segment elements. These loads are shown in Figure 50 and Table 2.

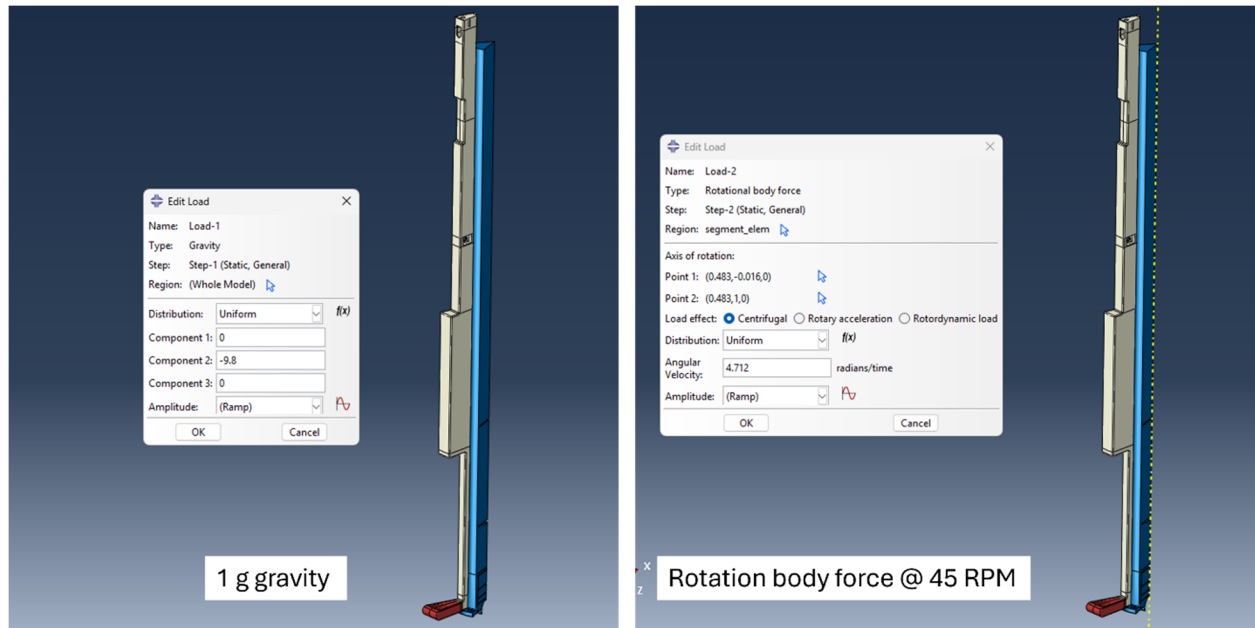


Figure 50 Step 1 gravity and Step 2 rotation loads

Table 2 Structural model temperature profiles and loads

Step	Temperature Profile	Gravity load	Centripetal load
Initial	20 C all nodes		
Step 1 segment	Peak temperatures profile @ 15.8 hr	9.8 m/s ²	0
Step 1 shaft	Peak temperatures profile @ 15.8 hr	9.8 m/s ²	0
Step 2 segment	Peak temperatures profile @ 15.8 hr	9.8 m/s ²	4.702 rad/s
Step 2 shaft	Peak temperatures profile @ 15.8 hr	9.8 m/s ²	0

11.7 STRUCTURAL RESULTS

The Abaqus result file was LOC_drop_rot5m.odb. The initial stress-free temperature was 20 °C and the displacements relative to the crown connection were evaluated using the temperature profile at 15.8 hours when the temperature peak of 389.1°C was reached. This is shown in Figure 51.

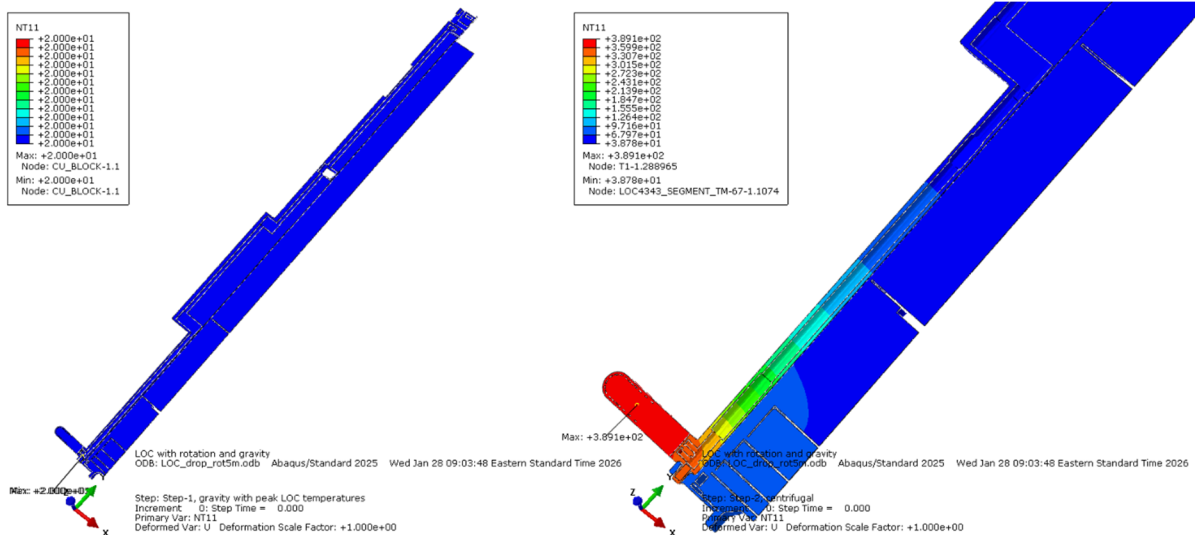


Figure 51 Structural analysis initial and peak temperature profiles

Step 1 displacements with only gravity and temperature are shown in Figure 52. The peak horizontal displacement in the direction of the beam at the bottom of the target was 1.9 mm. No constraint within the shaft hole for motion in this direction was included and the displacement was past the nominal clearance of approximately 1 mm. The downward deflection maximum was 4.5 mm at the nose of the target.

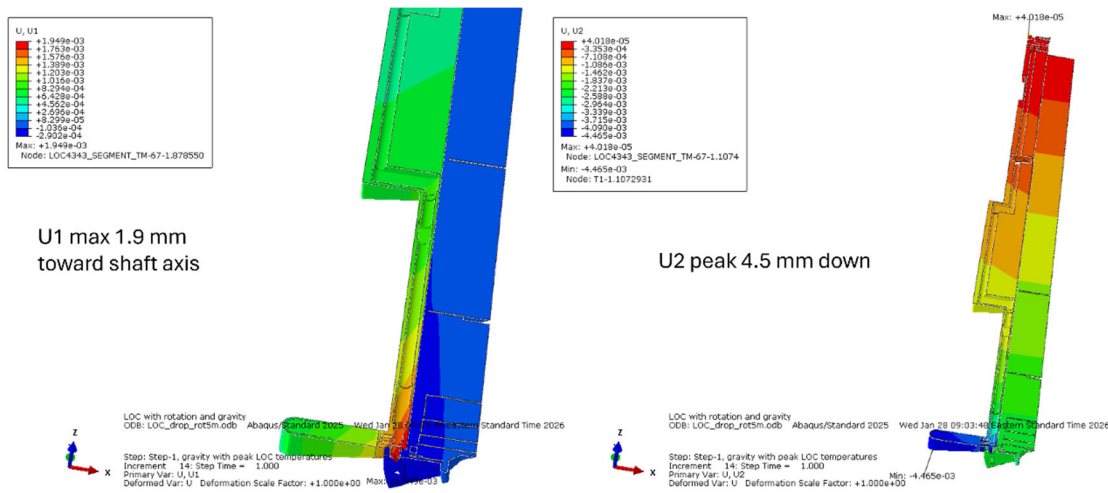


Figure 52 Displacements with only gravity at peak temperature

Rotational body force was added in Step 2. The displacements for this case are shown in Figure 53 with a peak downward deflection of 5.1 mm.

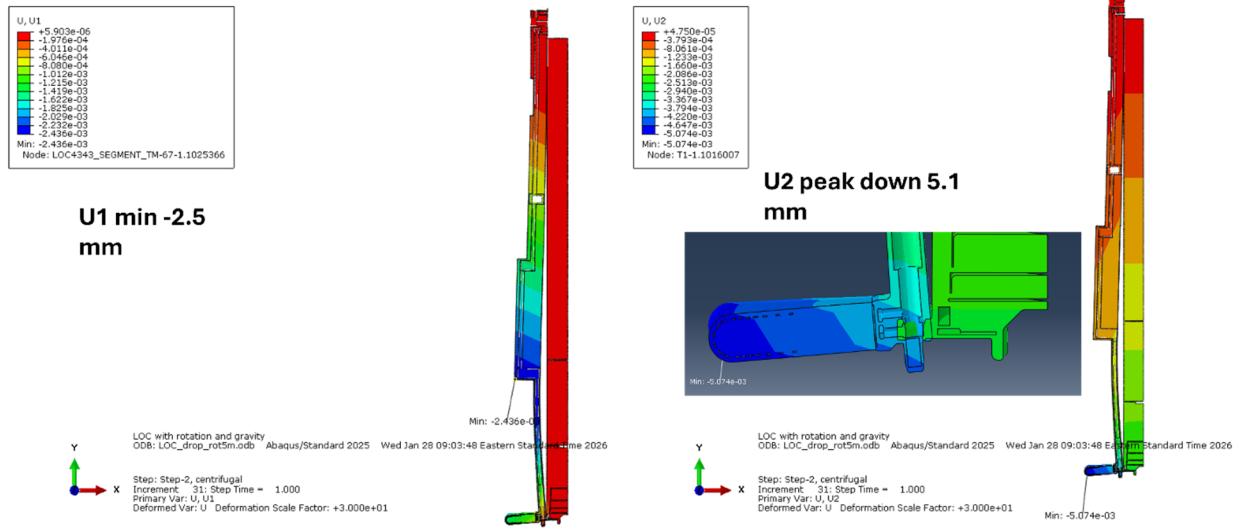


Figure 53 Displacements with gravity and rotation at peak temperature

Radial displacement in the U1 direction was restrained at the bottom of the segment by the surface-to-surface contact between the target pin and shaft hole. The peak horizontal displacement away from the shaft axis was 2.5 mm. The contact pressure for the pin and shaft is shown in Figure 54. Further mesh refinement would be needed to resolve the local stresses.

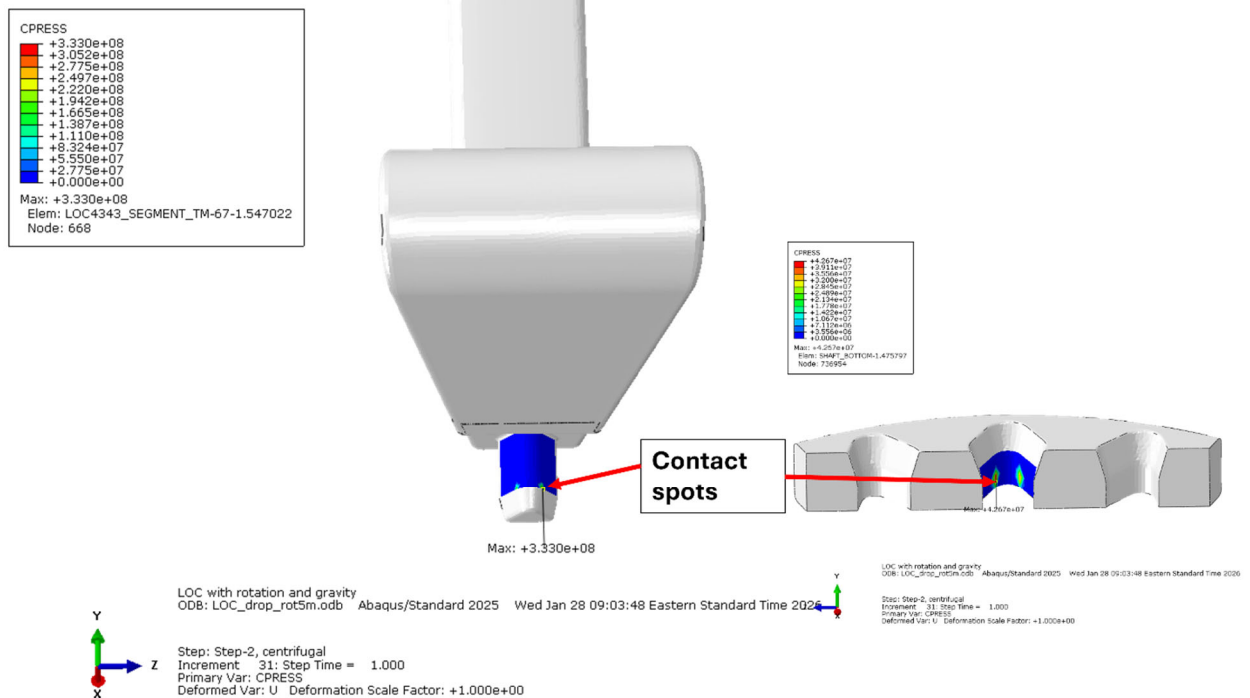


Figure 54 Contact Pressure for Pin contact with shaft hole with rotation at peak temperature

The Von Mises stress distribution for the target and stalk with a scale maximum of 400 MPa with a z=0 cut is shown in Figure 55 with a displacement scale factor of 50.

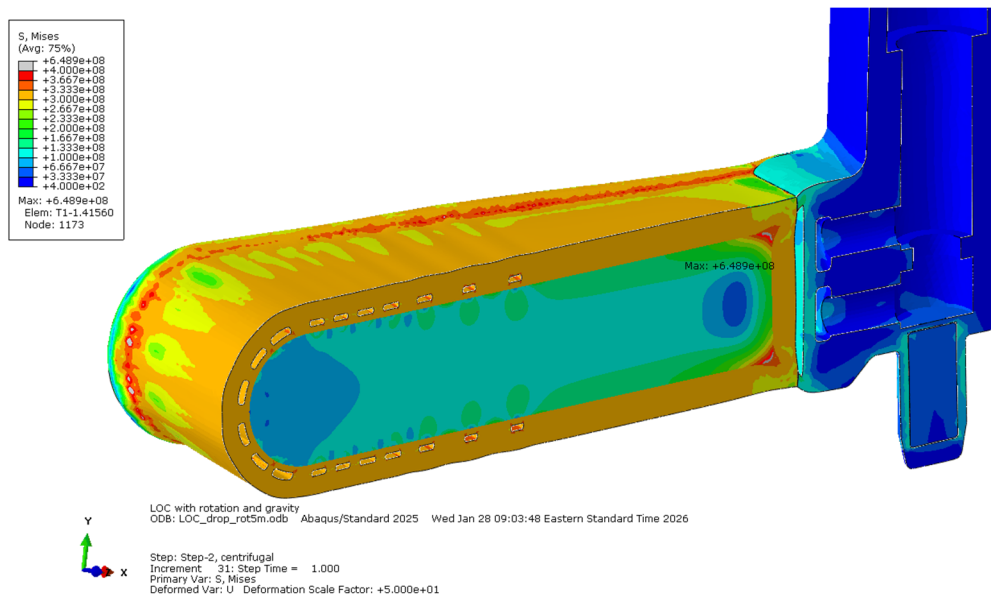


Figure 55 target and stalk stress with gravity, rotation and peak temperature and a scale maximum of 400 MPa

The equivalent plastic strain PEEQ for the Inconel and Stainless Steel is shown in Figure 56 with a scale maximum of .02. This scale was used to show the equivalent plastic strain over most of the assembly except for very localized spots and by singularities. Thermal expansion of the Stainless Steel is restrained by the weld connection to the Inconel. The Inconel tie to the tungsten without a tantalum layer likely also give artificially high localized strains at the interface since the softer tantalum layer is not included. The PEEQ strains for the Stainless Steel at the weld interface are shown in Figure 57 including the C3D10 mesh. Most of the strain is due to the mismatch in thermal expansion. There is no gross deformation due to gravity and rotational loads.

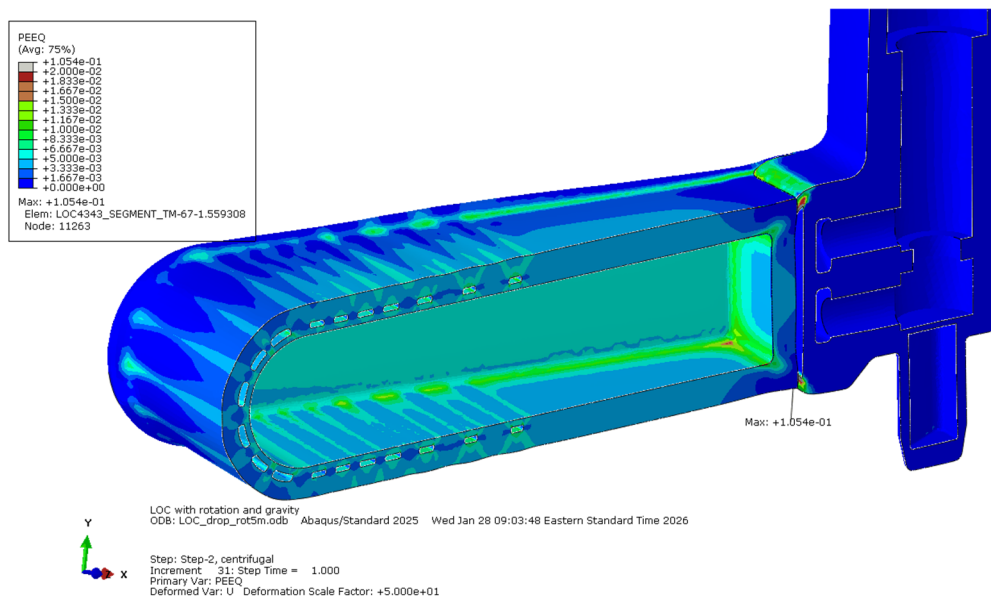


Figure 56 Inconel and 316L PEEQ with rotation, gravity and peak temperature

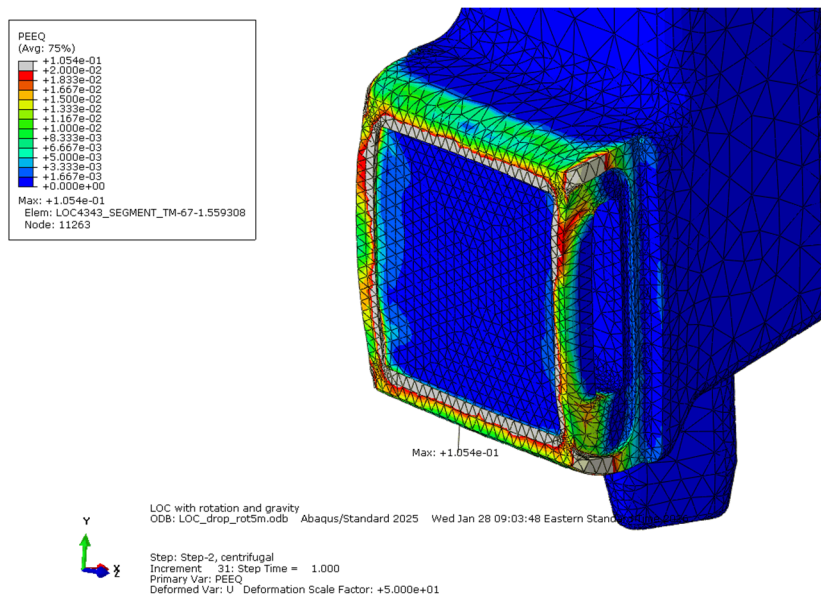


Figure 57 PEEQ in 316L by weld connection

The majority of the displacement is due to the thermal expansion of the stalk with approximately 1 mm added by target rotation around the pin restraint. There is no significant sagging due to a loss of strength in the 316L SS or Inconel at the peak temperature.

11.8 NORMAL OPERATION DISPLACEMENT

An estimate of the displacements for normal operation was done using the same model, but with the normal operation temperature profiles instead of the 15.8 hr. peak profile. For this case the input file was LOC_drop_rot_NO5m.inp. The temperature and vertical displacement with gravity and rotation are shown in Figure 58 with a peak displacement of 2.85mm down at the target nose relative to the crown connection. The loss of cooling case with rotation and gravity had a peak U2 displacement down of 5.1 mm or an additional 2.2 mm down relative to normal operation.

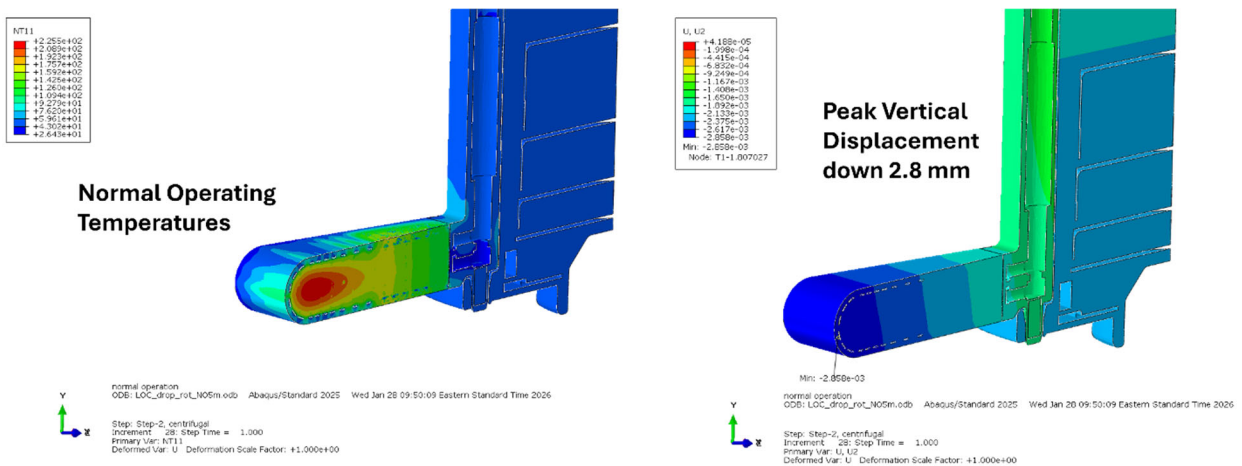


Figure 58 Temperature and vertical displacement for normal operation

12. SUMMARY

The thermal analysis used conservative and bounding assumptions to estimate the temperatures reached over 24 hours from a total loss of water cooling with an immediate beam trip. A peak of 389.1 °C was reached after 15.8 hours with a slow decrease up to 24 hours to 383 °C. This was far below the approximate 800 °C threshold for a tungsten steam reaction which could produce an aerosol. The effect of the temperature increase gave a 5.1 mm target displacement down relative to the connection at the crown. This was approximately 2.2 mm more than for normal operation. The nominal clearance to the MRA aluminum reflector vessel is 10 mm so the 5.1 mm displacement will not cause a contact. Vertical displacements of the core vessel mount are expected to be small on the order of 1mm and target drive support structure displacements between the mounts and crown segment connection are also expected to be small.

12. REFERENCES

1. McManamy, T. *S03020000-DAC10001-R0*. 2024.
2. SPFE HANDBOOK . 2016. Vol. page 111, 5th edition.
3. Finfrock, G.A. Greene and C. C. *DEPENDENCE OF TOTAL HEMISPHERICAL EMISSIVITY OF INCONEL-718 ON SURFACE OXIDATION AND TEMPERATURE* . Stony Brook, N.Y. : Brookhaven National Laboratory, 1999. BNL-52579.
4. *Total Hemispherical Emissivity of SS316 with Simulated Very High Temperature Reactor Surface Conditions*. June pp293 305, s.l. : American Nuclear Society, 2017, Vol. 198.
5. McClanahan, T. *Neutronics - Decay heat & radionuclide Inventory*. 2015 (data as of April, 2025). S03120100-TRT10012.
6. Tipton, J. *Target Segment Thermostructural*. 2026. S03020400-DAC10000 .

APPENDIX A. Data Files

Copies of the data files used are attached to the Windhcell document, with the following folders.
“

There are 7 folders attached:

- Abaqus model - Abaqus cae and inp files for thermal and structural analysis
- Decay Heat –

Decay heat original data comparison were received by email from Min-Tsung on 9/15/25. This data was copied to a new workbook “target_decay_power_2025_tm” and used to combine the tantalum and tungsten data as a volumetric heating as function of time using the volume from the Abaqus model. This was also done to combine the Inconel and Stainless Steel heating. This was done in the worksheet “working”. The neutron data was later documented in reference (5)

- Excel Analysis

The file RADFL estimates thermal radiation for infinite parallel plates between target and moderator surface at the peak temperature and target open cavity simulating radiation to the proton beam opening from the target from. Also included are files for potting the peak temperature versus time, material mechanical properties as a function of temperature and a data file for the 316L emissivity as a function of temperature

- MRA Temperatures

The data was developed by Min-Tsung and included under the folder:

<https://ornl.sharepoint.com/sites/sts/targetsystems/Shared%20Documents/Forms/AllItems.aspx?id=%2Fsites%2Fsts%2Ftargetsystems%2FShared%20Documents%2FS%2E03%2E02%20Target%20Assembly%2F99%5FSAND-BOX%2FKA0%2F2025%2FMRA%2FMRA%5F04%5F07%5F2025%2FTemperature%5Ffor%5FFEM&viewid=9be9bc88%2D5a13%2D48c7%2D9fff%2Dd22f94ffdeb5&click-params=eyJWC1BcHBOYW1lIiA6ICJNaWNyb3NvZnQgT3V0bG9vayIsICJYLUFwcFZlcnp24iIDogIjE2LjAuMTkyMzEuMjAyNDYiLCAiTlMiIDogIldpbmRvd3MiIH0%3D>

Finer mesh data was used for the backbone parts and the whole model data for the rest of the assembly

- Segment Temperatures

The segment temperatures for the revised Stalk design were provided by Min-Tsung at the link:

☐ [Temperature For Stress Analysis](#)

The material data files are in the folder Data from CFD. The data files for tungsten and tantalum were combined into the file “Tungsten_Ta_Temperature_deg_C” and the Inconel and Stainless Steel files were combined into the file “Inconel_SS_deg_C”.

The steady state CFD temperature results for the target segments and MRA will be documented in S03020000-DAC10003

- Space claim models

The segment geometry was developed from the step file 0000004343_asm.stp. The MRA simplified model was developed from the file mra_am_001_tm2.stp. This was sent by email from Jim Janney on 4/10/25. The shielding geometry was given in Core_Vessel_Shielding-Loss_of_Cooling_Nov25.stp. This was sent by email from Chris Anton on 10/27/25.

