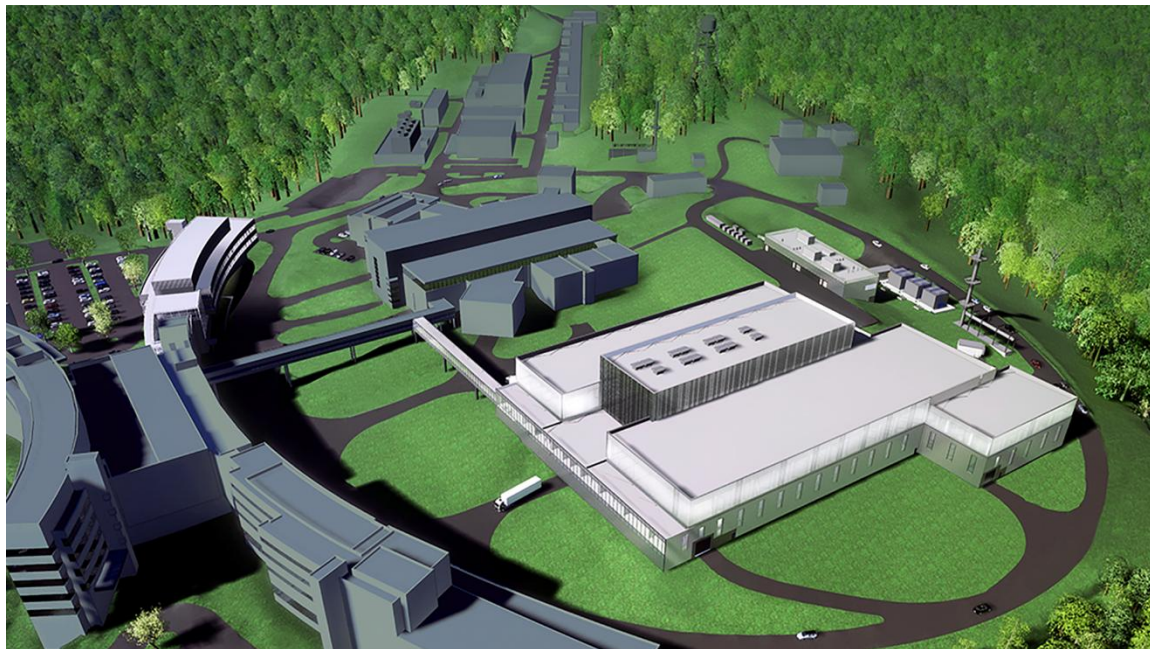


Second Target Station Project: CFD Analysis for Target Assembly



Min-Tsung Kao

April 2026

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Second Target Station Project

**STEADY STATE THERMAL & FLUID FLOW ANALYSIS FOR THE TARGET
ASSEMBLY**

Min-Tsung Kao

April 2026

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ABSTRACT

This report presents a comprehensive computational fluid dynamics (CFD) analysis of the thermal-hydraulic performance of the Second Target Station (STS) Target Assembly at Oak Ridge National Laboratory (ORNL). The study evaluates cooling effectiveness, pressure drop characteristics, flow distribution, and thermal behavior under nominal and off-normal operating conditions, including variations in beam power, beam profiles, and coolant flow rates.

The total pressure drop across the entire target assembly is determined to be approximately 13.6 psi, based on combined contributions from the target drive, target segments, and target shaft. Individually, the pressure drops are approximately 9.0 psi across a single target segment, 4.6 psi across the target drive, and 4.9 psi across the target shaft. Analysis of local geometric features, particularly in the target foot region, indicates that abrupt flow transitions can increase local pressure drops to approximately 15 psi, highlighting the importance of smooth flow-path design.

Thermal analyses under nominal conditions (700 kW beam power; 7.5 GPM per target segment) show a peak tungsten temperature of 225 °C. The maximum coolant temperature remains below the boiling limit (133.5 °C at operating pressure), ensuring single-phase flow. However, under increased beam power (900 kW) and/or reduced coolant flow (5.71 GPM), peak temperatures rise substantially, and local coolant boiling may occur under combined off-normal conditions, indicating reduced thermal margin.

System-level modeling identified a 4.8% flow maldistribution among the 20 target segments; however, further analysis reveals that peak temperatures are relatively insensitive to these variations, changing by only 2–3 °C. This insensitivity is attributed to the low thermal conductivity of the Inconel 718 shroud and the strategic placement of cooling channels to mitigate radioactive contamination, both of which effectively decouple the core temperature from minor hydraulic imbalances.

Post-shutdown and maintenance scenarios were evaluated via air-cooling analyses. For a single target segment, forced air cooling is effective in reducing peak temperatures, with performance strongly dependent on inlet flow rate and air temperature. For the full 20-segment assembly, a pressure-driven airflow system providing approximately 500 CFM with a pressure drop on the order of 1 psi is required to maintain acceptable temperature limits.

Overall, the results demonstrate that the current design meets thermal and hydraulic performance requirements under nominal conditions, while also identifying critical sensitivities to beam power, flow rate, and geometric design features. These findings support design optimization, safety evaluation, and operational planning for both normal operation and maintenance scenarios.

1. INTRODUCTION

The Second Target Station (STS) will be the third neutron source and will complement the two existing neutron sources currently in operation, the High Flux Isotope Reactor and the Spallation Neutron Source First Target Station (FTS), at Oak Ridge National Laboratory (ORNL). The STS uses a tungsten (W) target at a density of 19.3 g/cm^3 , whereas the FTS uses the mercury (Hg) target with a density of 13.6 g/cm^3 . Due to the higher density of tungsten, the STS can produce approximately $25\times$ higher peak brightness and $4\text{--}5\times$ higher time-averaged brightness than the FTS [1]. The STS target wheel is approximately 1.2 m in diameter and consists of 20 separate 0.5 mm tantalum (Ta)-clad W targets. It completes one full revolution in $4/3 \text{ s}$ (rotational speed of 45 rpm), and is synchronized with a 700 kW, 15 Hz pulsed proton beam ($15 \text{ Hz} \times 4/3 \text{ s} = 20$ pulses per revolution). Approximately 69% of the total beam power is deposited directly in the Target Assembly. The rotating solid target design enables the beam power to be distributed over the entire target disk, allowing the system to withstand a 700 kW proton beam over a 40-year design lifetime. As a result, the STS target can utilize more compact moderators and has a smaller active volume than FTS.

2. SOFTWARE AND HPC RESOURCE

Geometry modification, simplification for analysis, and fluid volume extraction were conducted in SpaceClaim 2024 R2 [2]. All results in this report are obtained from computational fluid dynamics (CFD) analyses using the commercial software STAR-CCM+ 2306 [3]. STAR-CCM+ is a finite-volume method (FVM)-based multiphase CFD code and is widely used for conjugate heat transfer, and single and multiphase flow problems. All simulations were performed on the Bernie cluster at Oak Ridge National Laboratory (ORNL), which comprises six compute nodes, each with 64 CPU cores ($2\times$ AMD EPYC™ 9355 Processor, 32 cores each, 3.55GHz, 256MB Cache, 280W) and 768 GB RAM ($24\times$ 32GB PC5-41600, 5600MHz DDR5 ECC RDIMM). Depending on the number of meshes generated and the complexity of the problems, one to three nodes were used for the CFD analyses in this report.

3. GEOMETRY DESCRIPTION

As shown in Figure 1 and Figure 2, the incoming proton beam passes through the Proton Beam Window (PBW), the bottom of the Target Viewing Periscope (TVP), and an open window in the backbone of the Moderator and Reflector Assembly (MRA), before striking the target blocks of the Target Assembly (TA). The TA is surrounded and shielded by the Core Vessel (CV) and the shielding blocks within it, followed by stainless-steel shielding blocks of the target station and monolith concrete shielding. High-density concrete is used in the vicinity of the proton beam, while standard concrete is used in regions farther away.

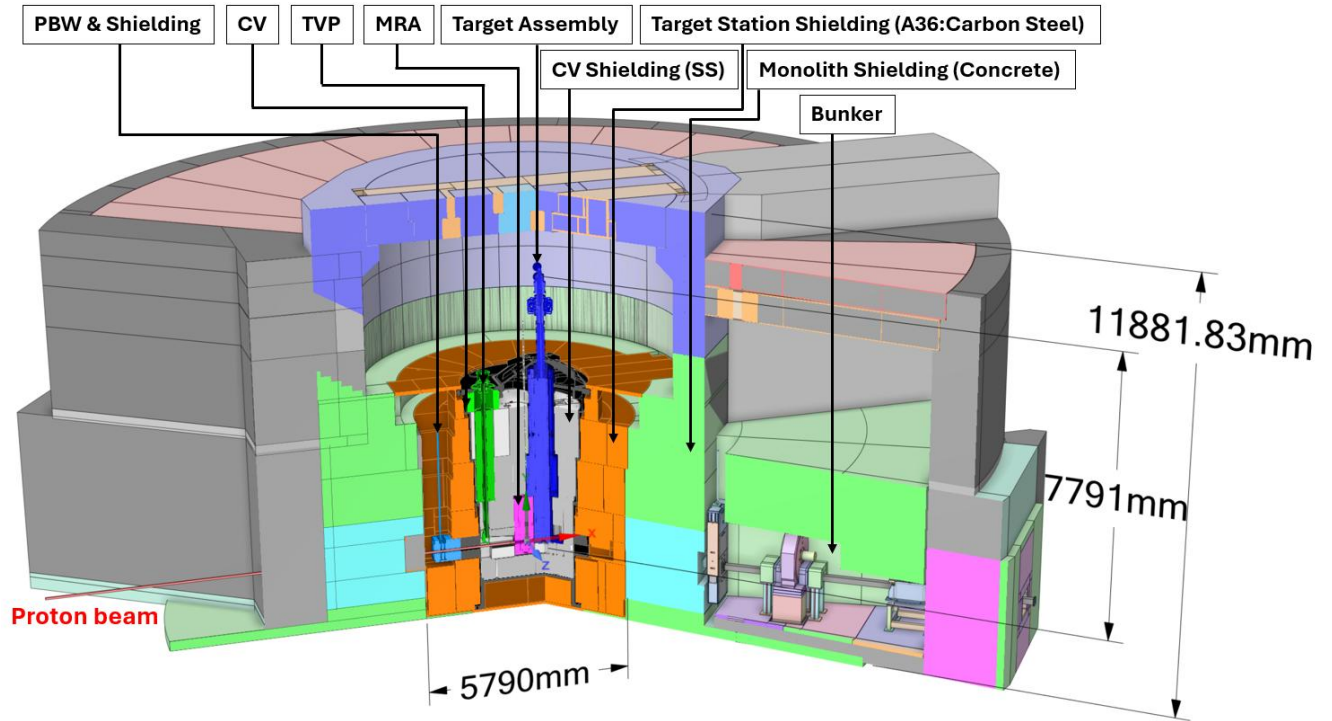


Figure 1. Relative location of the Target Assembly in STS.

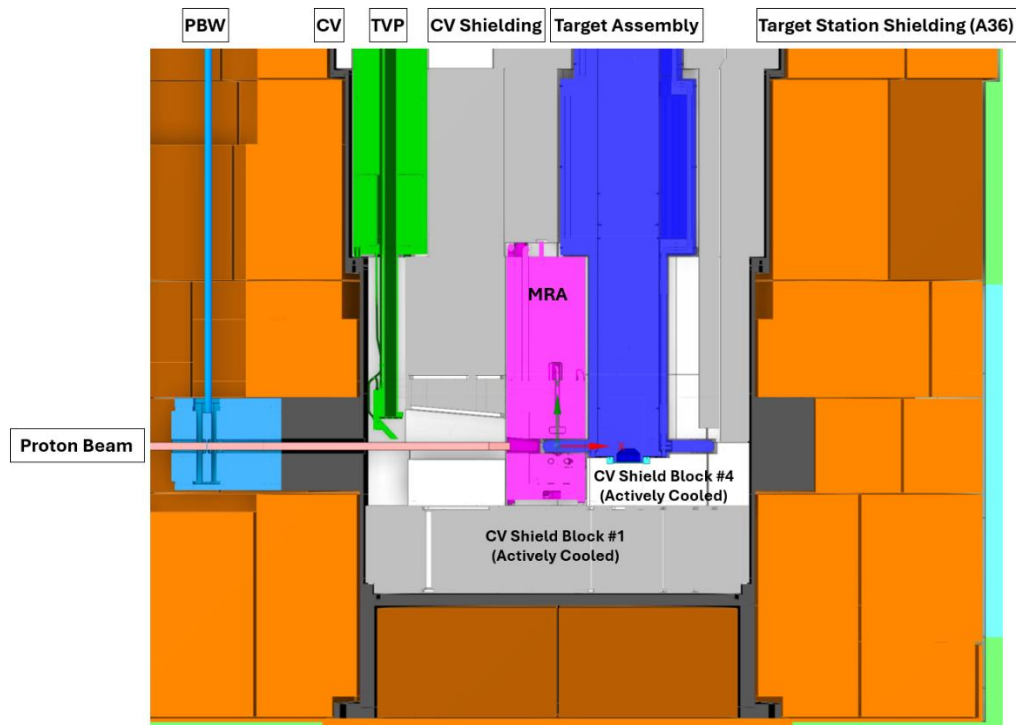


Figure 2. Proton beam and target assembly.

The Target Assembly (TA) is approximately 7.8 m tall and consists of three main components: the target drive, the target segments, and the target shaft, as shown in Figure 3. Rather than developing a single large-scale CFD model, the thermal-hydraulic analyses are performed separately for each main component to enable more detailed and accurate evaluations and to support iterative design

improvements. The TA contains 20 identical target segments; therefore, a representative segment is analyzed in this report. As shown in Figure 4, the gaps between the target segments are 5 mm.

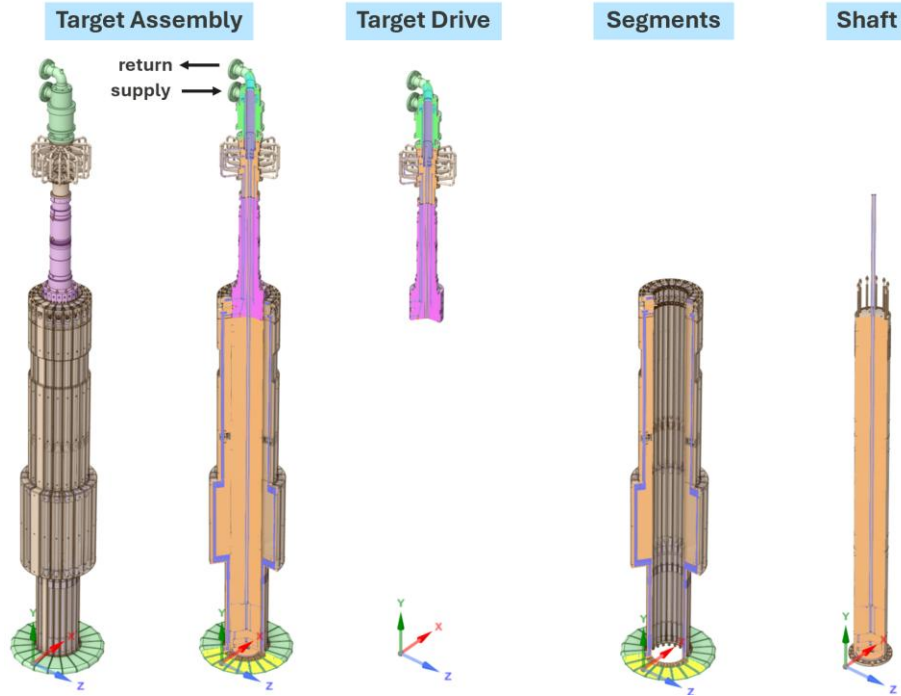


Figure 3. Second target station target assembly.

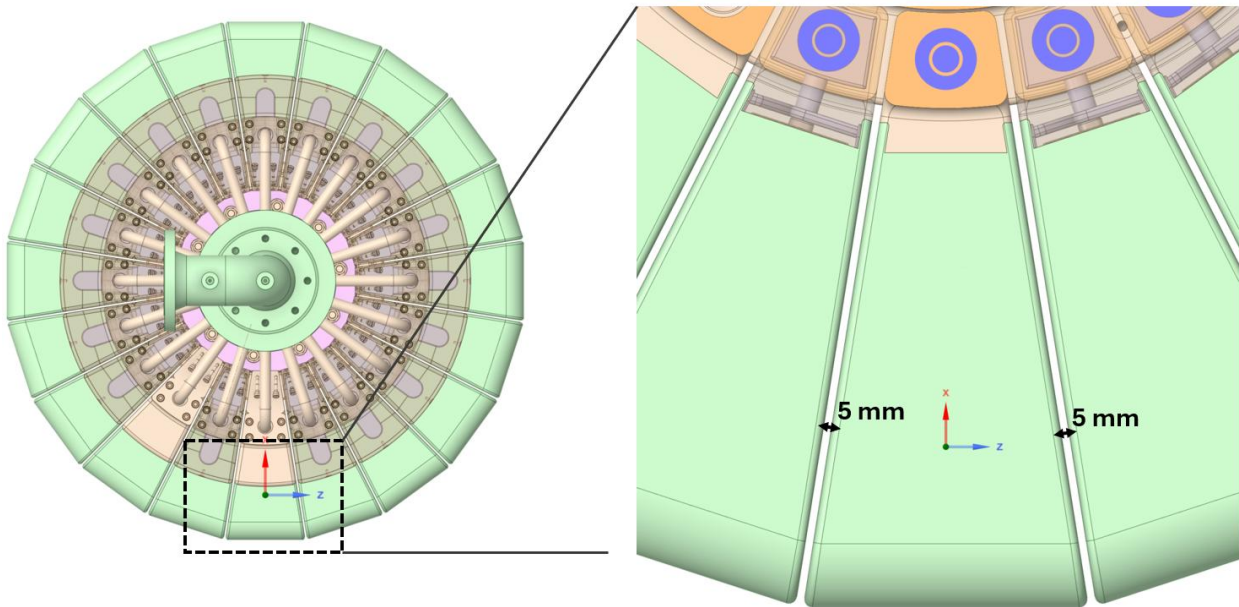


Figure 4. Gaps between target segments.

The water supply and return configuration for the TA is shown in Figure 5. Cooling water at 32.22°C (90 °F) enters the assembly through a single inlet at the top and is distributed to 20 target segment supply lines and one shaft supply line. A uniform mass flow rate of 0.47 kg/s (7.5 GPM) is assumed for each target segment and the target shaft. The resulting total mass flow rate for the TA is 9.87 kg/s ($= 0.47 \text{ kg/s} \times 21 = 9.87 \text{ kg/s}$). The CFD analyses include the Coriolis effect for both the target segments and the

target shaft at a rotation rate of 45 RPM (one revolution in $4/3$ seconds; $15 \text{ Hz} \times 4/3 \text{ s} = 20 \text{ pulses}$, $60 \text{ s} \div (4/3 \text{ s}) = 45 \text{ RPM}$).

It should be noted that no active control system exists to regulate the flow distribution among individual components. The actual flow rate entering each target segment and the target shaft is determined by the pressure drop across these components. Flow imbalance is therefore a concern and may result in insufficient cooling of certain target segments, potentially leading to non-uniform temperature distributions and reduced thermal margins.

The total pressure drop across a cooling channel is governed by both the geometric (static) hydraulic resistance and the imposed inlet flow conditions. Channel geometry—such as length, hydraulic diameter, surface roughness, bends, and internal features—defines the intrinsic frictional resistance. However, the actual pressure drop is not solely an intrinsic property of the channel. Inlet conditions also play a critical role in flow development. Specifically, the inlet velocity profile and turbulence intensity determine the magnitude of entrance effects. Higher wall shear stresses in the developing region produce localized pressure gradients that exceed those of fully developed flow, resulting in additional entrance pressure losses.

Although the target shaft and an individual target segment are analyzed separately in CFD simulations and their respective pressure drops are calculated, the predicted values are based on the assumption of uniform inlet flow conditions. This assumption does not account for realistic inlet characteristics, such as swirling flows, which are expected in the STS Target Assembly. Figure 6 shows the stationary and rotating domains in the target drive. The total flow of 157.5 GPM enters the segment and shaft inlets through an annular region near the interface between the stationary and rotating domains of the target drive. Consequently, the uniform inlet conditions assumed in the individual component simulations differ from the actual operating conditions.

Therefore, the pressure drops obtained from the individual CFD simulations should be considered reference values for cooling channel optimization; however, they are insufficient for accurately predicting the total system pressure drop. Flow balance must ultimately be assessed using a comprehensive CFD model that accounts for realistic inlet flow conditions affecting the segment and shaft supplies.

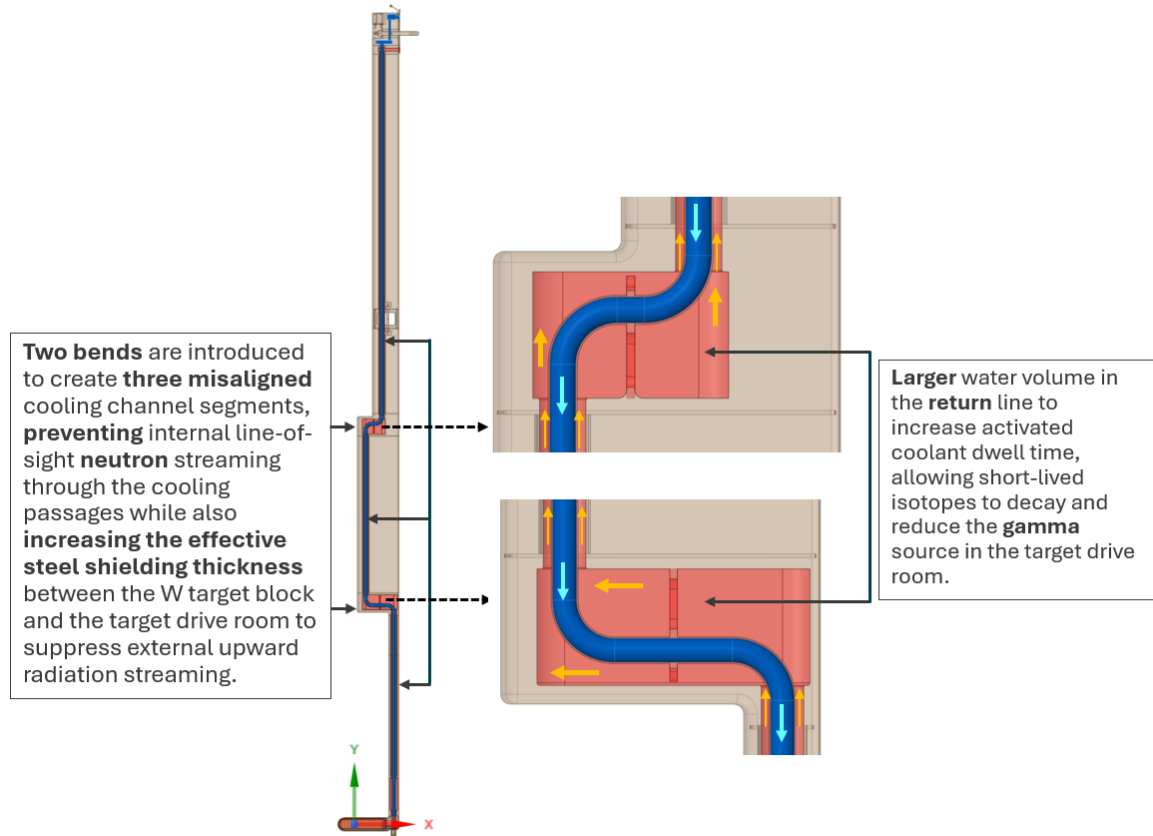


Figure 7. Cooling channels in the target segment.

As shown in Figure 7, to mitigate radiation streaming from the tungsten spallation target to the target drive room, the original continuous vertical cooling channel was redesigned to incorporate two geometric offsets (bends), forming three misaligned cooling channel segments. In high-energy spallation environments, neutron production is strongly forward peaked, and straight penetrations can act as preferential streaming pathways that bypass bulk shielding. A continuous vertical channel provides a low-attenuation path that allows high-energy neutrons to propagate with minimal interaction, potentially resulting in elevated dose rates in accessible areas such as the target drive room.

The introduction of two bends eliminates the direct line of sight between the source region (target block) and the target drive room within the cooling channels and increases the effective steel shielding thickness. Both effects increase the effective neutron transport path length and force additional scattering interactions with the surrounding structural material. These additional collisions promote energy degradation and attenuation before radiation can reach the target drive room.

In spallation neutron source facilities such as the STS at ORNL, the most significant gamma source in the cooling water during operation is nitrogen-16 (^{16}N) [4], [5]. It is primarily produced through the $^{16}\text{O}(n,p)^{16}\text{N}$ reaction, which occurs when high-energy neutrons (with an energy threshold of approximately 10 MeV) interact with the oxygen nuclei in the water. Nitrogen-16 decays with a short half-life of 7.13 seconds, emitting high-energy gamma rays at 6.17 MeV and 7.12 MeV [6]. Because it is transported within the coolant flow, activated water containing ^{16}N can travel upward to the target drive room and other accessible regions.

Nitrogen-16 dominates the prompt gamma dose in activated water systems and is therefore the primary driver for return-line shielding design in high-energy facilities such as STS. As shown in Figure 7, two enlarged water volumes are introduced in the bent regions of the return line to increase the coolant dwell time, allowing short-lived isotopes such as ^{16}N to decay before reaching the target drive room, thereby reducing gamma dose rates.

Figure 8 illustrates the cooling channels within the target drive. To reduce radiation levels associated with activated coolant in the target drive room, the cooling line routing was configured such that the activated (hot) return lines are located within the interior region, while fresh, non-activated coolant lines occupy the surrounding peripheral region. This arrangement increases the effective distance between the activated return flow and the outer boundary, thereby enhancing gamma attenuation prior to reaching occupied maintenance areas. The resulting reduction in external dose rates is achieved through increased geometric separation.

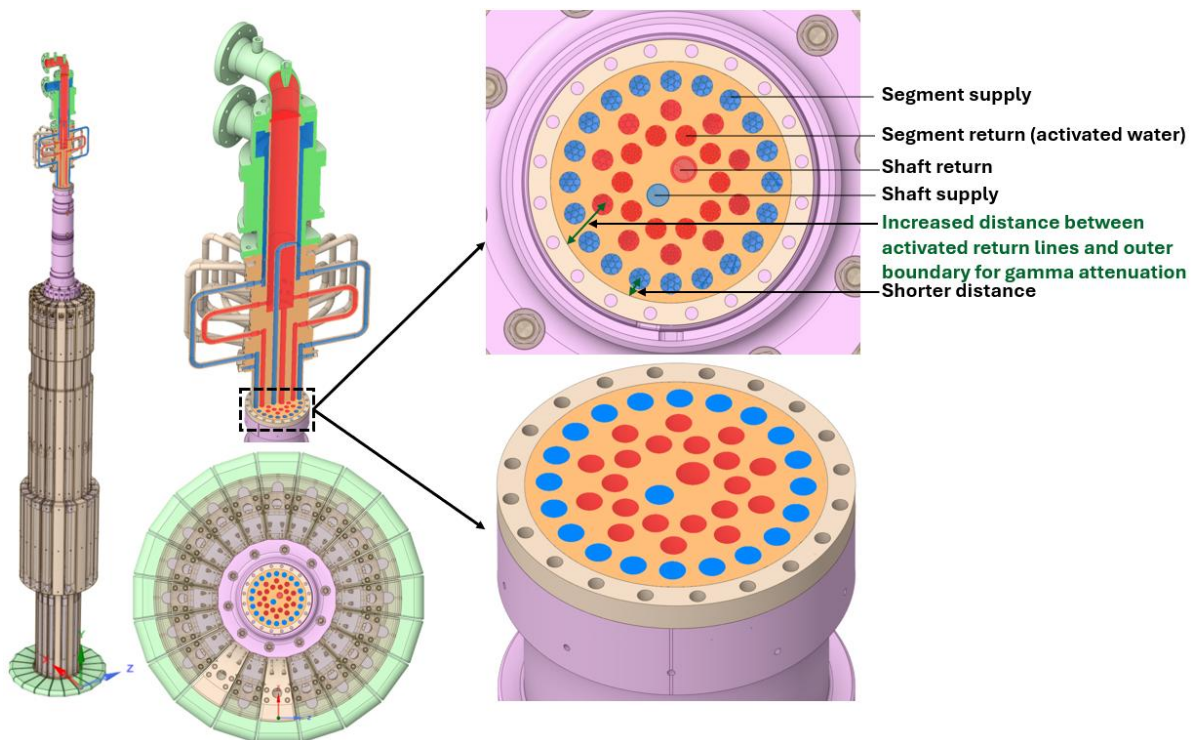


Figure 8. Cooling channels in the target drive.

The CAD model used for the target assembly (target drive, segment, and shaft) analysis in this report is [0000004343.ASM](#), version -.187.

3.1 MATERIAL INPUTS

The thermophysical properties of the materials are summarized in Table 1. During STS operation, the thermal conductivity of tungsten (W) is expected to degrade progressively due to irradiation damage. The thermal conductivity of irradiated tungsten ($k = 87 \text{ W/m-K}$) is approximately half that of unirradiated tungsten ($k = 174.9 \text{ W/m-K}$); therefore, the degraded value is used in this analysis to provide conservative results. (APPENDIX E: An analysis with dpa-dependent thermal conductivity was performed for the 2019 STS target and the resulting temperature profile was very close to that obtained using a constant value of $k = 87 \text{ W/m-K}$)

Table 1. Material thermophysical properties [[S03020000-DAC10000, Target Systems Analysis - Material Model Definitions](#)].

Material	Thermal Conductivity, k (W/m-K)	Density, rho(kg/m ³)	Specific Heat, Cp (J/kg-K)	Viscosity (Pa-s)
W (irradiated)	87	19250	128.3	N/A
Ta	57.2	16600	139	N/A
Inconel 718	11.4	8190	435	N/A
SS 316	14.58	7969	486.1	N/A
H ₂ O	0.620271	997.561	4181.72	8.89E-04
CuCrZr	323.4	8890	376	N/A

4. TARGET SEGMENT CFD ANALYSIS

4.1 GEOMETRY

The geometries¹ of a target segment and an individual target block are shown in Figure 9 and Figure 10, respectively. Figure 9 also illustrates the coolant flow direction within the target segment (supply in blue and return in red). During design iterations, it was found that the flow direction within the target segment has negligible influence on the pressure distribution and temperature profile. Therefore, the selected flow configuration was primarily chosen to position the activated return flow within the interior region of the target drive, increasing the distance to the outer boundary and thereby enhancing gamma attenuation in surrounding areas.

The ultimate goal of the ORNL STS is to create the world's brightest source of cold neutrons for neutron scattering experiments, enabling breakthroughs in materials science and related fields. This goal cannot be achieved solely by maximizing cold neutron production; it is constrained by the heat transfer performance and mechanical reliability of the target structures.

The number of blocks [7] and the dimensions of the current designs, including target height, width, and length, are important geometric parameters derived from optimization studies for earlier STS target designs [7], [8].

The STS target assembly, consisting of 20 target segments, is designed to withstand a 700 kW pulsed proton beam operating at 15 Hz and to operate 5,000 hours per year over a 10-year design lifetime. This corresponds to approximately 2.7×10^9 total pulses, and 1.35×10^8 pulses per individual target block. Each proton pulse produces rapid energy deposition in the tungsten target, resulting in an instantaneous temperature rise followed by dynamic thermal expansion and stress-wave propagation (thermal shock loading). Consequently, the target assembly operates in the high-cycle fatigue regime, and the structural design depends critically on both cooling performance and fatigue resistance. Thermal shock induced by the rapid temperature rise is the dominant driver of high-cycle fatigue in the STS target [9], [10].

Maximizing neutron production (~25 neutrons per proton from spallation in tungsten) requires maximizing the tungsten content within each target segment and minimizing the volume of non-spallation materials; however, this objective must be balanced against thermomechanical and structural constraints. A monolithic tungsten block would experience elevated thermomechanical stress, increased stress-wave amplification, and a higher risk of crack initiation and propagation. Under the high-radiation environment of STS, irradiation damage further embrittles tungsten, increasing crack growth susceptibility. In a large monolithic block, crack propagation could extend over longer distances, potentially compromising the entire structure. Segmenting the tungsten into smaller blocks reduces peak stress amplitude, mitigates stress-wave reflection amplification, and limits crack propagation length, thereby improving structural reliability.

Tantalum interlayers are inserted between adjacent tungsten blocks to further enhance structural reliability. While tungsten is inherently brittle, tantalum is significantly more ductile, offering higher fracture toughness and superior radiation resistance. The elastic modulus (Young's modulus) represents material stiffness and governs the relationship between stress and elastic strain ($\sigma = E\varepsilon$). Because thermal stress is proportional to elastic modulus ($\sigma_{th} = E\alpha\Delta T$), the lower elastic modulus of tantalum (~186 GPa)

¹ Geometry file: https://windchill-prod.ornl.gov:8443/Windchill/app/#ptcl/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792CFD_CAD/Target_Segment.zip

compared to tungsten (~400 GPa) allows the interlayer to deform more readily under thermal loading. This compliance reduces interfacial stress and accommodates differential thermal expansion between adjacent tungsten blocks during cyclic beam heating. In addition, the tantalum interlayer acts as a compliant buffer, promotes stress redistribution, and serves as a crack-arrest barrier at tungsten-tungsten interfaces.

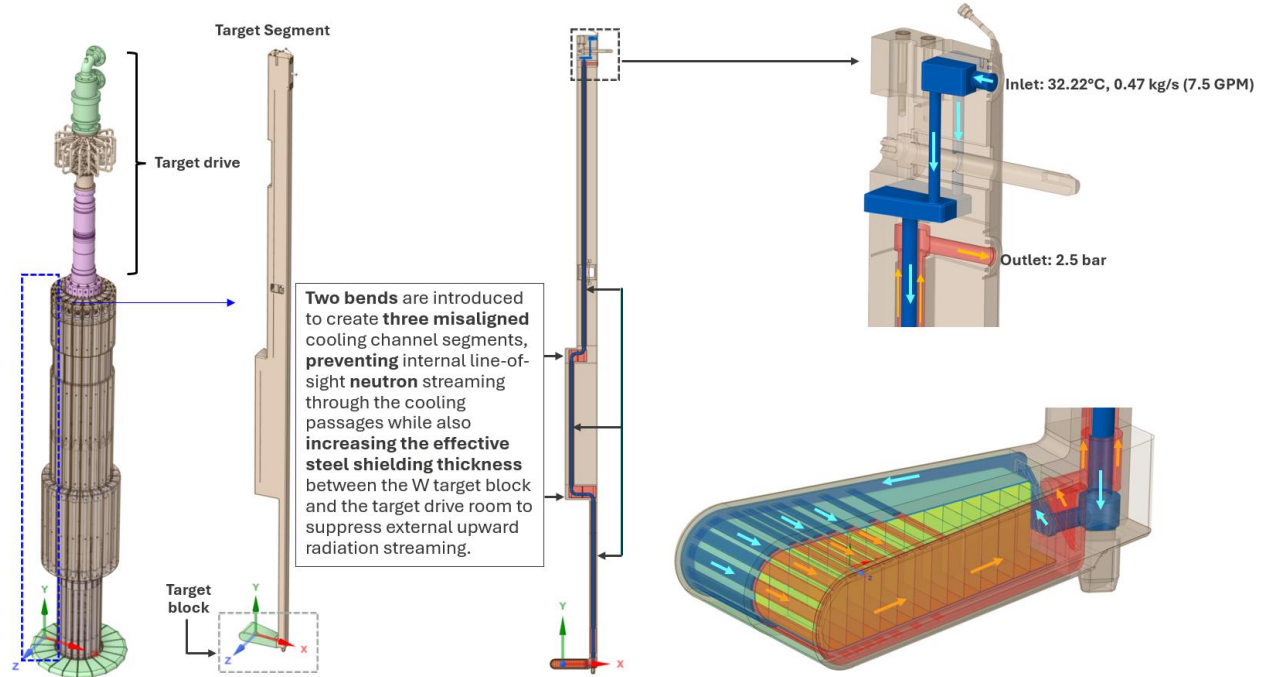


Figure 9. Target segment.

The high melting point of tungsten (~3400°C), combined with its brittleness and residual fabrication stresses, makes bonding large monolithic tungsten structures challenging. The tantalum interlayer improves metallurgical compatibility and enables more practical joining processes such as hot isostatic pressing (HIP) and diffusion bonding.

As shown Figure 10, each target block consists of fifteen 18 mm thick tungsten plates (67 mm -150 mm wide from rear to front) separated by fourteen 0.5 mm thick tantalum plates. The stack is encapsulated within a 1 mm thick tantalum cladding layer. This cladding retains the radioactive spallation products within the target block, provide efficient heat transfer to the cooling channels due to its relatively high thermal conductivity (57.2 W/m-K, Table 1), and prevents direct contact between water and tungsten, thereby reducing erosion and corrosion.

The tantalum-clad assembly is enclosed within a thick Inconel 718 shroud (10 mm at the top and bottom, 3 mm on the sides), which contains twenty 2 mm thick cooling channels and two 3.5 mm thick planar cooling channels on the sides (Figure 10 and Figure 11). Figure 11 also shows the flow covers located on the sides. The flow covers may be fabricated from either SS316 or Inconel 718. Both materials satisfy the design requirements (FOS > 1), with Inconel 718 providing a slightly higher safety margin.

However, the use of Inconel 718 in high-fluence regions of the target assembly may result in increased long-lived activation products due to its high nickel and niobium content. Neutron irradiation of nickel

produces isotopes such as Co-60 ($t_{1/2} = 5.27$ years), which dominates intermediate-term shutdown gamma dose rates, as well as Ni-59 ($t_{1/2} \approx 76,000$ years) and Ni-63 ($t_{1/2} \approx 100$ years), which contribute to long-term radiological inventory. Furthermore, the niobium content of Inconel 718 can lead to the formation of Nb-94 ($t_{1/2} \approx 20,300$ years), a long-lived gamma emitter that is significant for waste classification and disposal assessments. In contrast, SS316 contains lower nickel content and typically little to no niobium, resulting in a reduced long-lived activation inventory and more favorable decommissioning characteristics. Based on analyses performed by the STS neutronics team, waste disposal is not expected to be a limiting issue even if the flow covers are fabricated from Inconel 718. Nevertheless, unless otherwise specified, the flow covers are assumed to be SS316 in this report.

In early design iterations, the STS target employed a flood-cooled configuration in which water flowed along the outer surface of the tantalum cladding, resulting in a peak tungsten temperature of approximately 150°C. In the final design (Figure 10 and Figure 11), all cooling passages are located within the Inconel 718 shroud. Consequently, the coolant is positioned farther from the tungsten core, increasing the peak tungsten temperature to approximately 225°C. However, this configuration further reduces the likelihood of radioactive spallation products entering the coolant by introducing multiple material barriers ($W \rightarrow Ta \rightarrow \text{Inconel 718} \rightarrow \text{water}$), thereby minimizing potential contamination transport to other components of the STS.

The target segments will be inserted into the pockets on the flange of the target shaft. The triangular geometry facilitates positioning and alignment of the target segments during installation. Due to limited space, no dedicated cooling channel is designed for the target heel. Instead, CuCrZr is incorporated in the heel to enhance heat dissipation owing to its high thermal conductivity (323.4 W/m-K, Table 1). **(Note: In the latest design, the CuCrZr material has been removed, and the lower SS316 leg has been modified to address elevated stainless steel temperatures associated with manufacturing gaps. In addition, the flow covers have been updated to Inconel 718. The geometry shown here corresponds to an earlier model, for which comprehensive heat source distributions associated with different beam profiles are available from neutronics calculations; therefore, this geometry is used for the present analysis. The temperature distribution within the target block is not expected to change significantly as a result of the design updates. Results based on the latest target segment geometry are provided in Table 21.)**

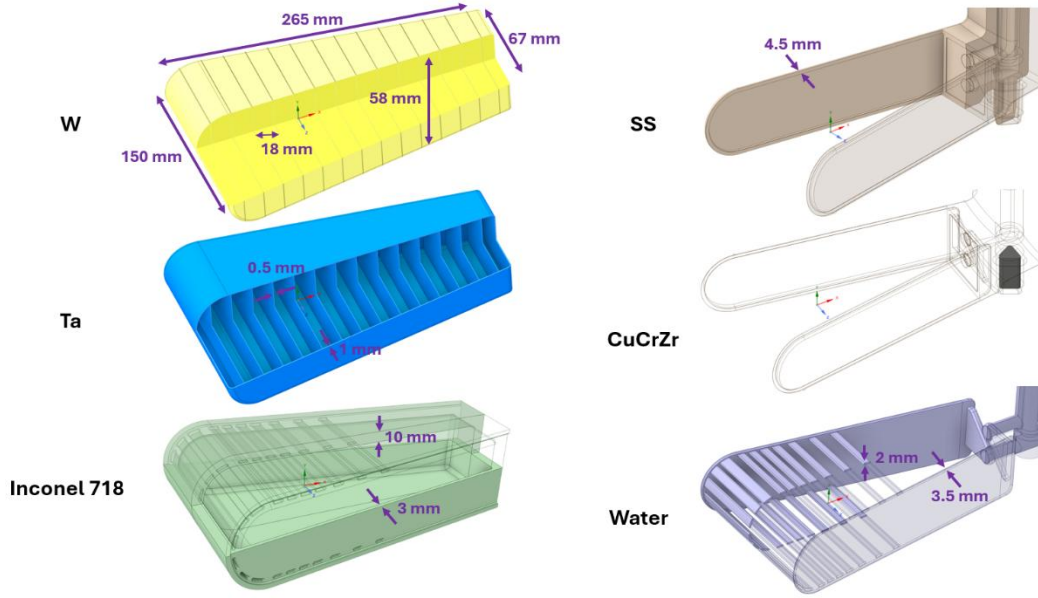


Figure 10. Target block.

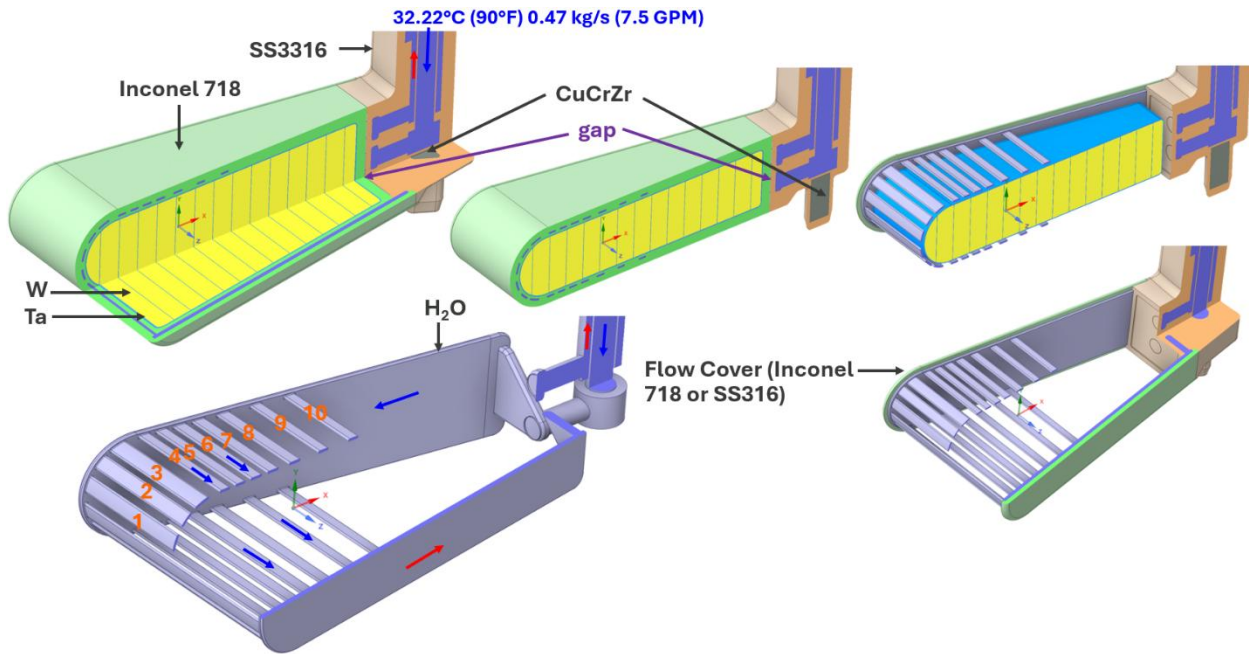


Figure 11. Water volume and flow cover.

4.2 MESH

STAR-CCM+ provides three types of volume meshers: polyhedral, tetrahedral, and trimmed-cell meshers. Compared with tetrahedral cells, polyhedral cells typically have around ten neighboring cells, enabling better gradient estimation. Furthermore, polyhedral meshes require approximately four times fewer cells, use about half the memory, and require only one-fifth to one-tenth of the computational time to achieve the same order of accuracy as tetrahedral meshes (Simcenter STAR-CCM+ 2019.2 User Guide, 2019). Therefore, polyhedral meshes are adopted for this study.

For turbulence modeling with wall treatment methods, two general approaches are available: low y^+ and high y^+ treatments. These approaches solve one or more transport equations to model near-wall turbulence quantities such as wall shear stress, turbulent production, and dissipation rates. All simulations in this report employ the realizable k - ε two-layer turbulence model with the two-layer all- y^+ wall treatment available in STAR-CCM+. This hybrid method combines the high- y^+ treatment (where the near-wall cell lies within the logarithmic region of the boundary layer, $y^+ > 30$), the low- y^+ treatment (where the viscous sublayer is well resolved, $y^+ < 1$), while also providing reasonable solutions in the buffer region ($1 < y^+ < 30$).

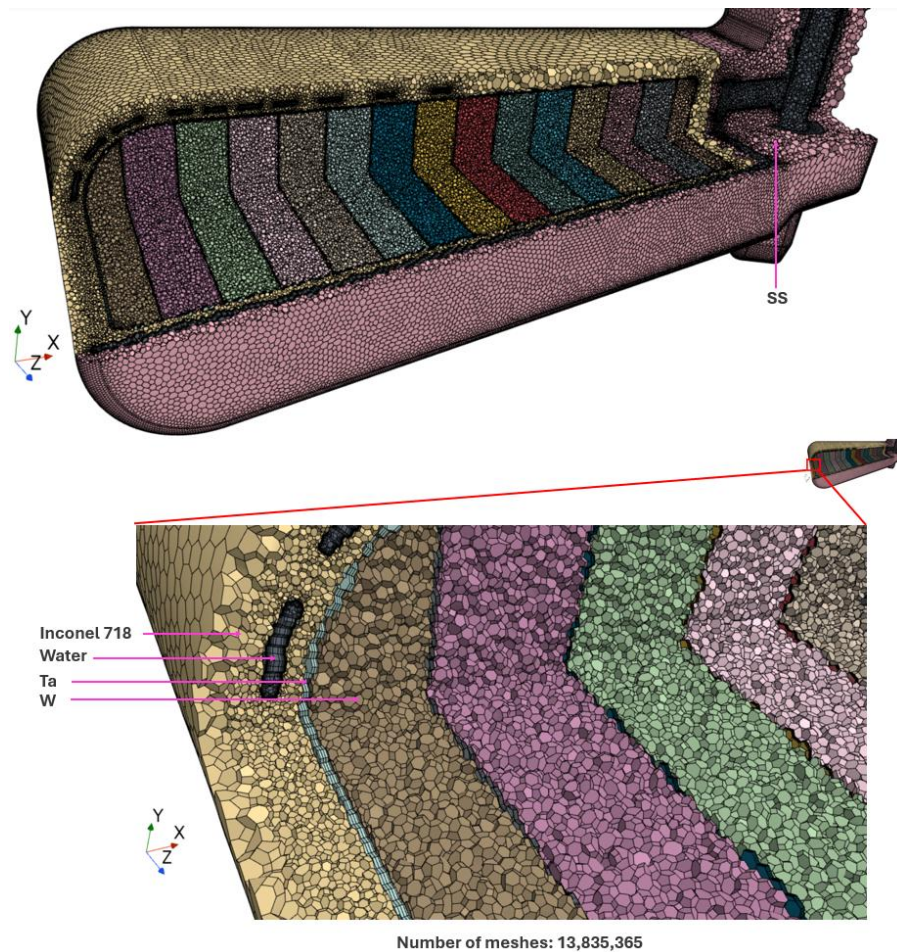


Figure 12. Mesh configuration of target segment.

The mesh configuration for the target block is shown in Figure 12. Eight prism layers are applied at the water boundaries to resolve the thermal and hydrodynamic boundary layers near the wall. Section views of the mesh configuration are shown in Figure 13 and Figure 14. As shown in Figure 14, the sizes and relative locations of the cooling channels in the target block were iteratively adjusted to achieve favorable thermal stress distributions. It should be noted that only the front half of the target block (Figure 11 and Figure 13) is actively cooled and there are no cooling channel passages on the top and bottom in the rear portion. Although additional cooling channels could be added to the rear portion to further reduce the temperature gradient (APPENDIX B) and the corresponding thermal stress, doing so would increase manufacturing complexity and cost. Moreover, additional cooling channels would increase the water inventory and thus the volume of activated coolant. Both of these factors are minimized in the target design.

The thickness of each tantalum plate is 0.5 mm, and five mesh layers are used across each plate, as shown in Figure 15. The wall y^+ values for the target segment are mostly maintained below 5 to ensure that the wall treatment method is applied appropriately, as shown in Figure 16. Overall, approximately 14 million cells are used for a single target segment. (The mesh independence study for the target segment is discussed in APPENDIX A)



Figure 13. Section view of the mesh configuration for the target segment.

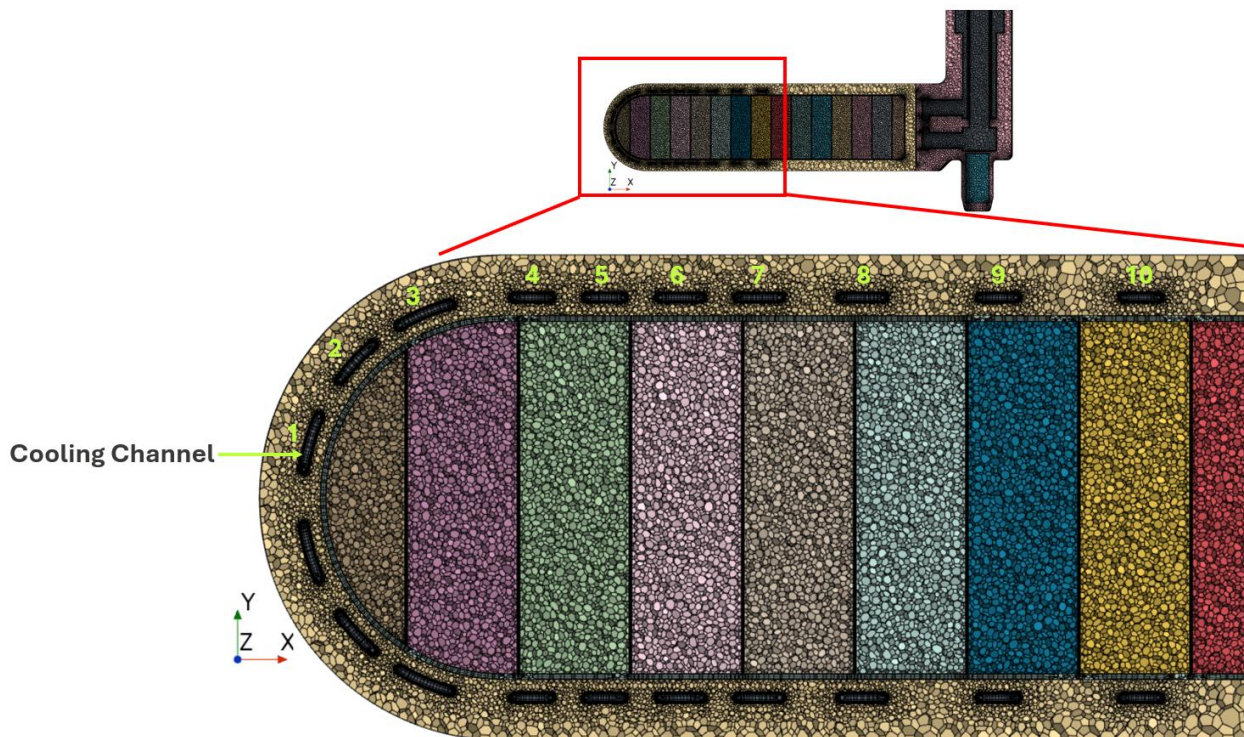


Figure 14. Section view of the mesh configuration and relative locations of the cooling channels.

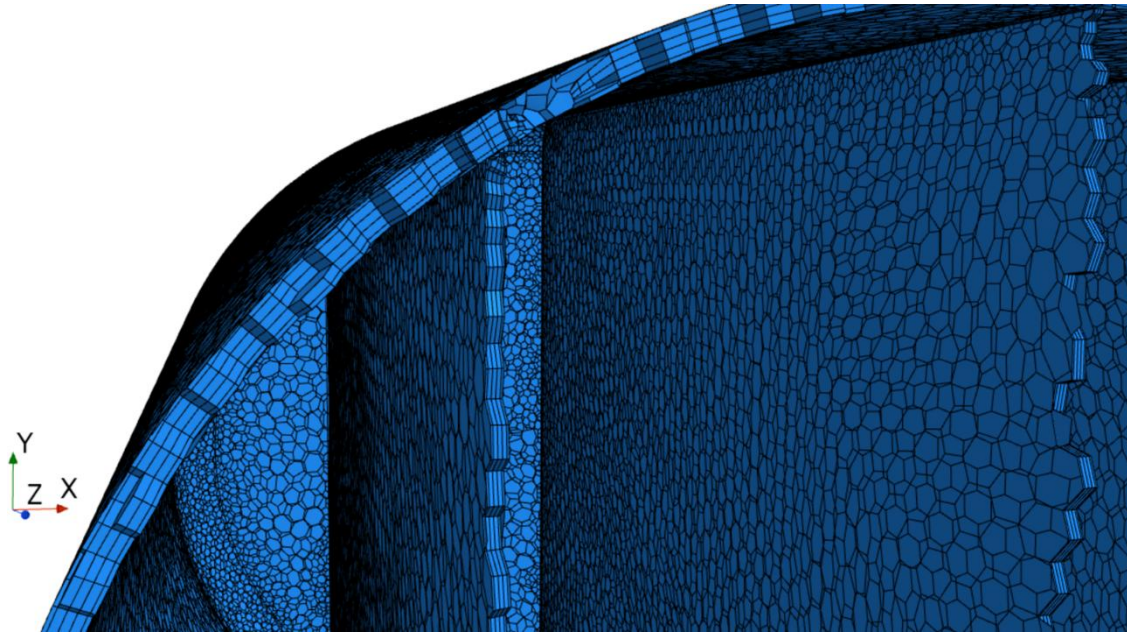


Figure 15. Mesh configuration of tantalum plates.

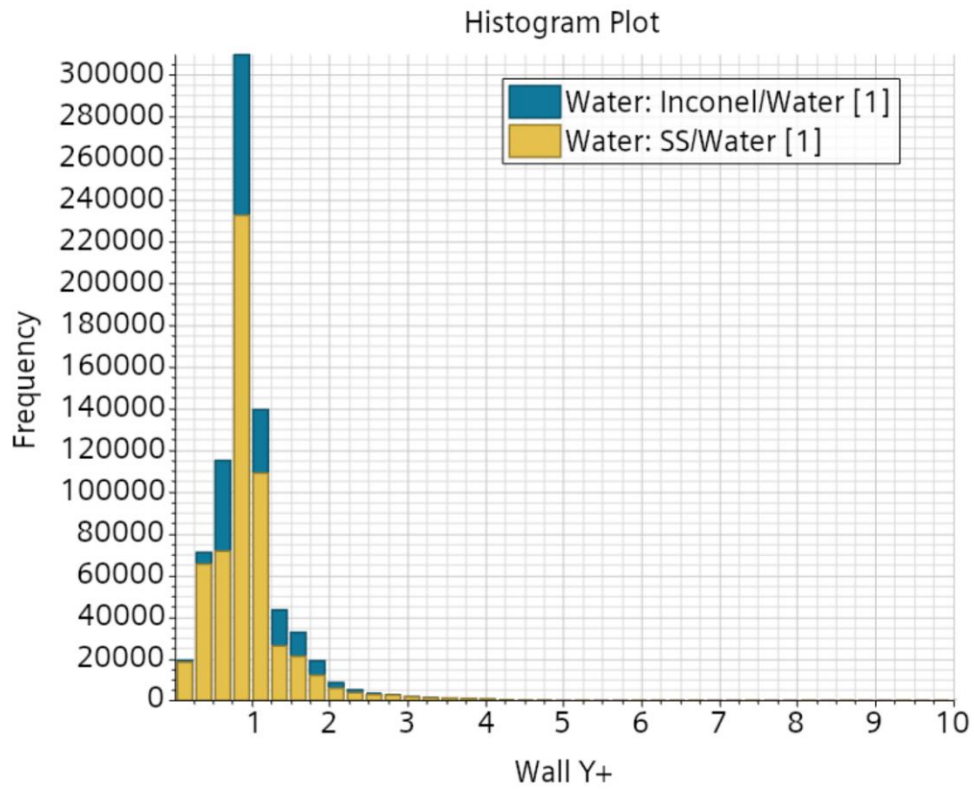


Figure 16. Wall Y^+ of target segment.

4.3 SOLVER AND BOUNDARY CONDITIONS

As shown in Figure 9, an inlet flow rate of 0.47 kg/s (7.5 GPM) of water at 32.22°C (90°F) is assumed for each individual target segment. The Reynolds number in the cooling channels of the target block ranges

from 5,000 to 8,000 (hydraulic diameter ≈ 3.3 mm), as shown in Figure 17. Therefore, a turbulent flow model is employed.

The STS target segments and shaft rotate at 45 RPM. Accordingly, the corresponding centrifugal and Coriolis forces are included in the CFD simulations by assigning a rotating reference frame at ($x = 0.483$ m, $y = 0$, $z = 0$). The impact of these forces was more pronounced in earlier flood-cooled designs, where flow diverters were required to guide the flow (APPENDIX C). In the final design (Figure 10 and Figure 11), the water is guided through the 20 cooling channels, and therefore the influence of the Coriolis force on the flow field is less significant.

The boundary conditions and numerical solvers used in STAR-CCM+ for the target segment simulations are summarized in Table 2. The Realizable k - ε two-layer turbulence model with two-layer all y^+ wall treatment, together with a segregated solver, is used for all simulations. The reference pressure at the outlet is 2.5 bar (250 kPa). Including the hydrostatic head (~ 5 m), the pressure at the target block elevation is approximately 3 bar (300 kPa), corresponding to a boiling point of 133.5 °C. This temperature represents the maximum allowable water temperature for the STS target without boiling.

The reference pressure is applied at the outlet surface in the simulations. Because no phase change is expected under normal operating conditions, a single-phase model is used. In STAR-CCM+, the reference pressure is used to evaluate the pressure drop required for the specified inlet mass flow rates. For single-phase simulations, the absolute value of the reference pressure at the outlet is therefore not critical; it serves only as a baseline for calculating pressure drop and does not affect the simulation results, even if a different reference value is specified.

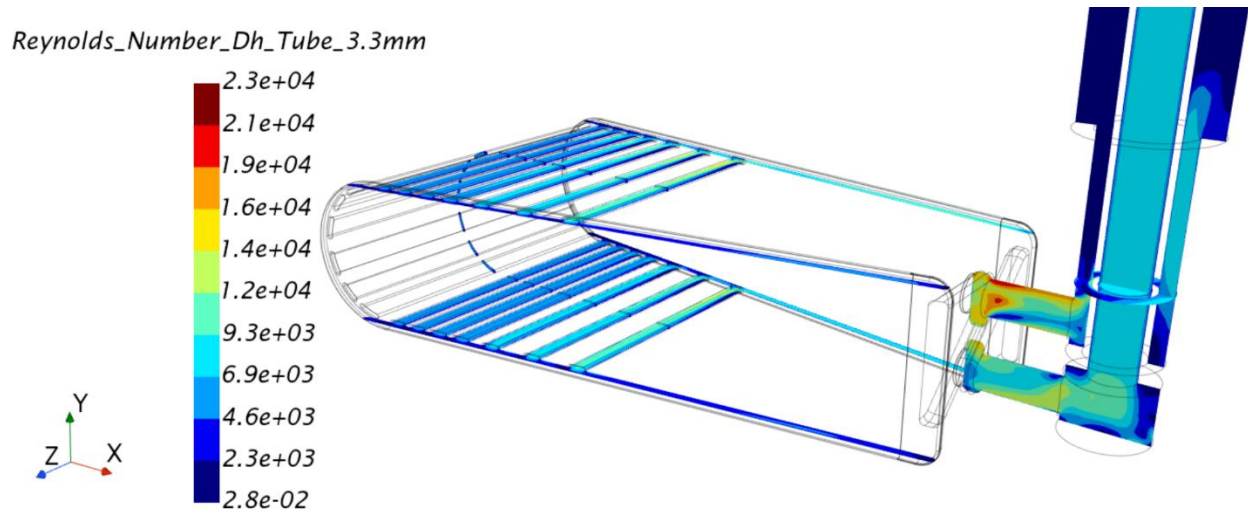


Figure 17. Reynolds number distribution in the target block with 7.5 GPM flow rate.

Table 2. Solvers and boundary conditions for the target segment.

Time model	Steady state
Flow and energy model	Segregated solver
Turbulence model	Realizable k - ε two-layer
Wall treatment	Two-layer all y^+

Inlet mass flow rate	0.47 kg/s (7.5 GPM)
Inlet temperature	32.22 °C (90 °F)
Reference pressure	2.5 bar
Boiling temperature @ 3 bar	133.5 °C

4.4 HEAT LOAD²

The energy deposition in the target segment (and also the target shaft) is obtained from MCNP neutronics calculations and is documented in report **S00000000-CAC10001**.

From the MCNP calculation, Figure 18 shows a typical example of energy deposition on STS target segments, corresponding to a single pulse of a 15 Hz proton beam on the 20 target segments. The data shown in Figure 18 can be rotated 19 additional times and then superimposed to obtain the total contribution of the 15 Hz proton beam on a single target segment during one full revolution. At a rotation rate of 45 RPM, a target segment completes one full revolution in 4/3 seconds, during which it experiences 20 proton pulses ($15 \text{ Hz} \times 4/3 \text{ seconds} = 20 \text{ pulses}$).

This method is conceptually straightforward; however, it is computationally expensive because it requires interpolation of the data points over the entire target wheel (20 target blocks) for each of the 19 additional rotations. Instead of directly superimposing 20 rotated data frames for the entire target wheel, the same results can be obtained more efficiently by rotating each target block (all 20 blocks) to a reference position (e.g., the Block 1 location, as indicated in Figure 18) and summing the corresponding energy deposition values.

In practice, this means that the fourth column of the CSV files (for the same material) (on Windchill) can be summed to obtain the total energy deposition over 20 pulses for a single target block. This approach is valid because identical mesh configurations are used for all 20 target segments, and the data in the csv files are arranged in the same order. Although the x, y, z coordinates differ among the 20 blocks, the energy deposition values correspond to the same relative spatial locations within each block in the MCNP output.

The processed steady-state heating files are imported into STAR-CCM+ and mapped onto the corresponding materials and regions (tungsten, tantalum, Inconel, water, stainless steel, and CuCrZr) as shown in Figure 19, Figure 20, and Figure 21.

The heat sources from the nominal proton beam for a single target segment are summarized in Table 3. The total heat deposited in a single target segment is 18.9 kW, corresponding to 2.7% of the 700 kW beam power. Overall, approximately 54% of the beam power ($2.7 \% \times 20$) is deposited in the 20 target segments. Within each segment, 77.5%, 9.3%, and 7.3% of the deposited heat occur in the tungsten blocks, Inconel shroud, and stainless-steel structure, respectively. Approximately 4.6%, 1.2%, and 0.08% of the heat are deposited in tantalum, water, and CuCrZr, respectively.

² Heat Source file: https://windchill-prod.ornl.gov:8443/Windchill/app/#ptcl/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792CFD_Heat_Sources/1_Nominal_Beam.zip/Target_Segment

In earlier STS target designs, a single proton pulse caused a temperature rise of approximately 14.3 °C in the target block. Comparisons between steady-state heat sources and transient heat sources representing individual pulses were performed for the earlier STS target design. These analyses show that the maximum target block temperature reached steady state after approximately 100 seconds, and that the peak temperature obtained from the transient heat source oscillated by approximately ± 5 °C around the steady-state value once steady-state conditions were reached. (Additional details are provided in APPENDIX D) Based on these findings, steady-state heat sources are used for all simulations in this report.

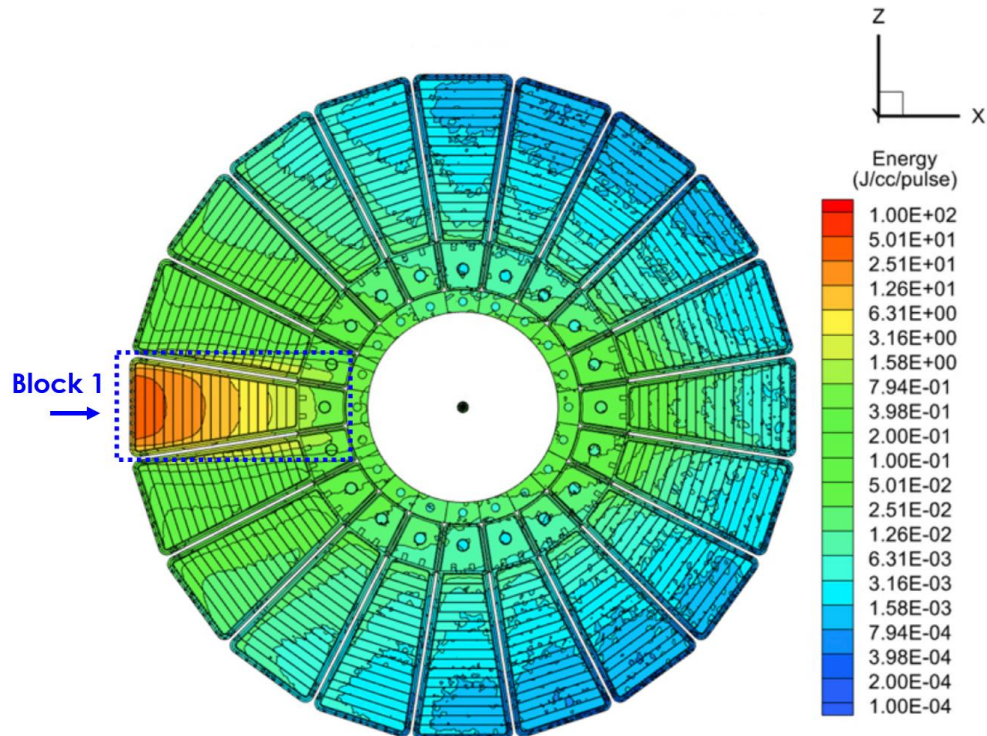


Figure 18. Example of energy deposition on a target segment from MCNP calculation (from Lukas Zavorka).

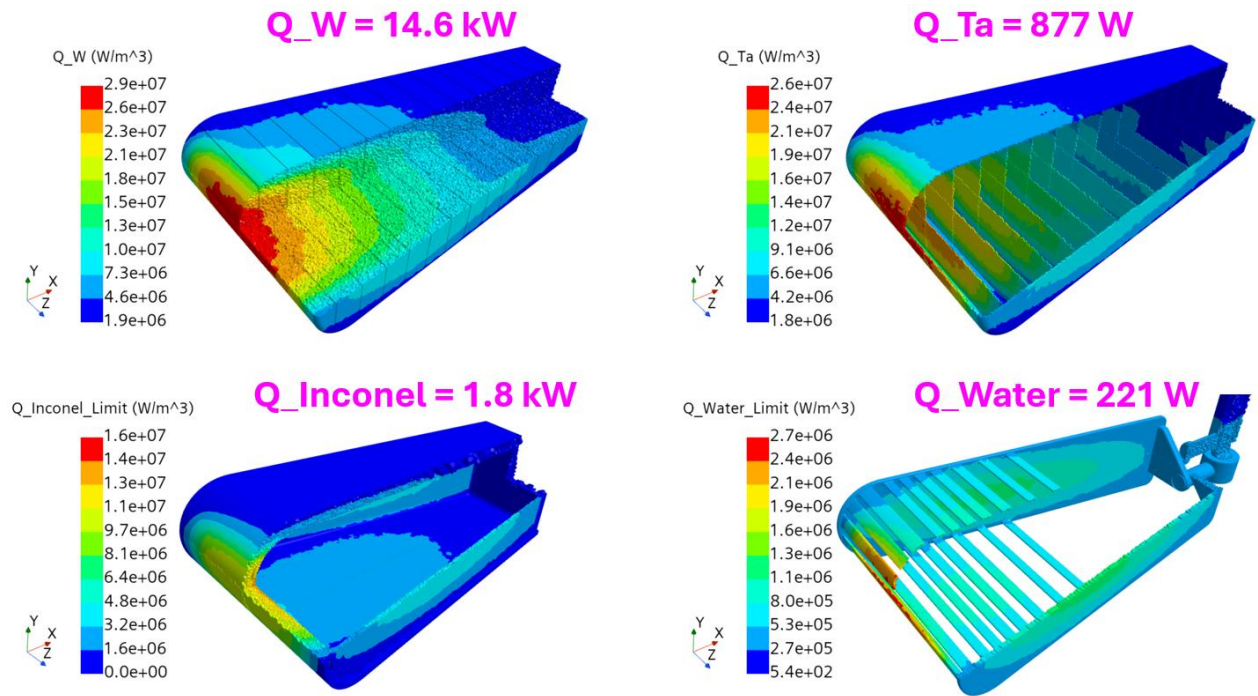


Figure 19. Heat sources in tungsten blocks, tantalum plates, Inconel shroud, and water.

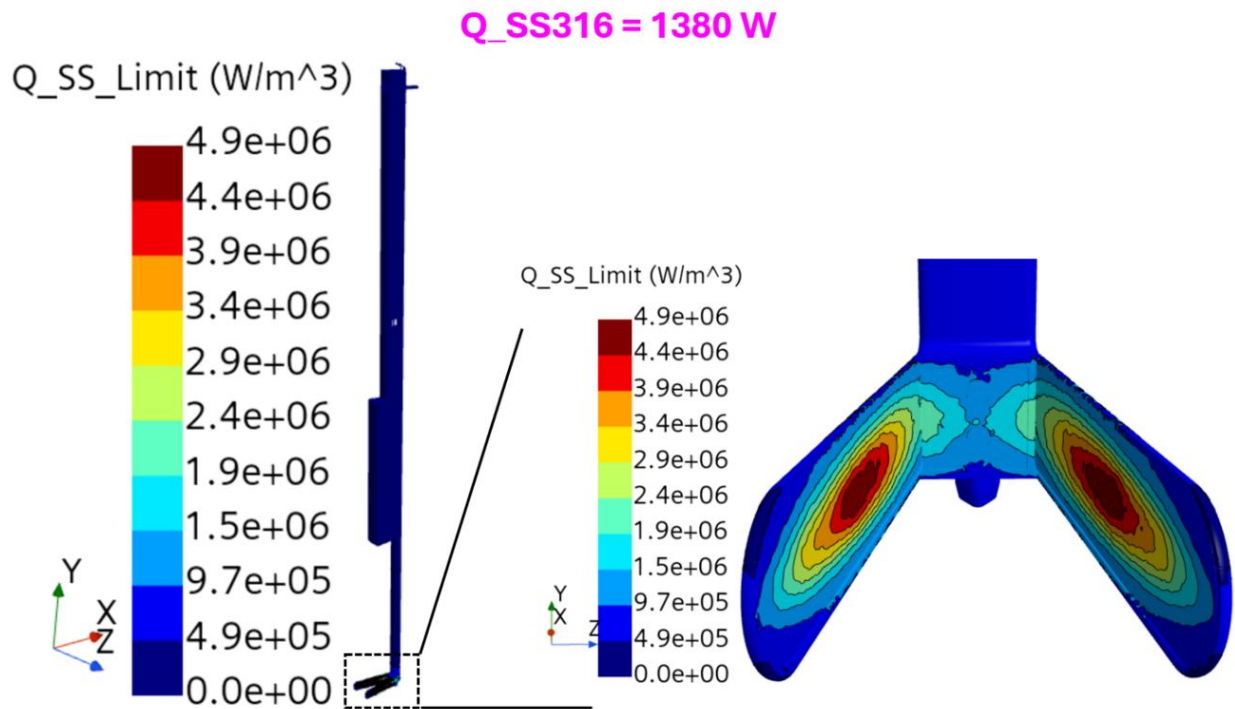


Figure 20. Heat sources in stainless-steel structure.

$$Q_{\text{CuCrZr}} = 15 \text{ W}$$

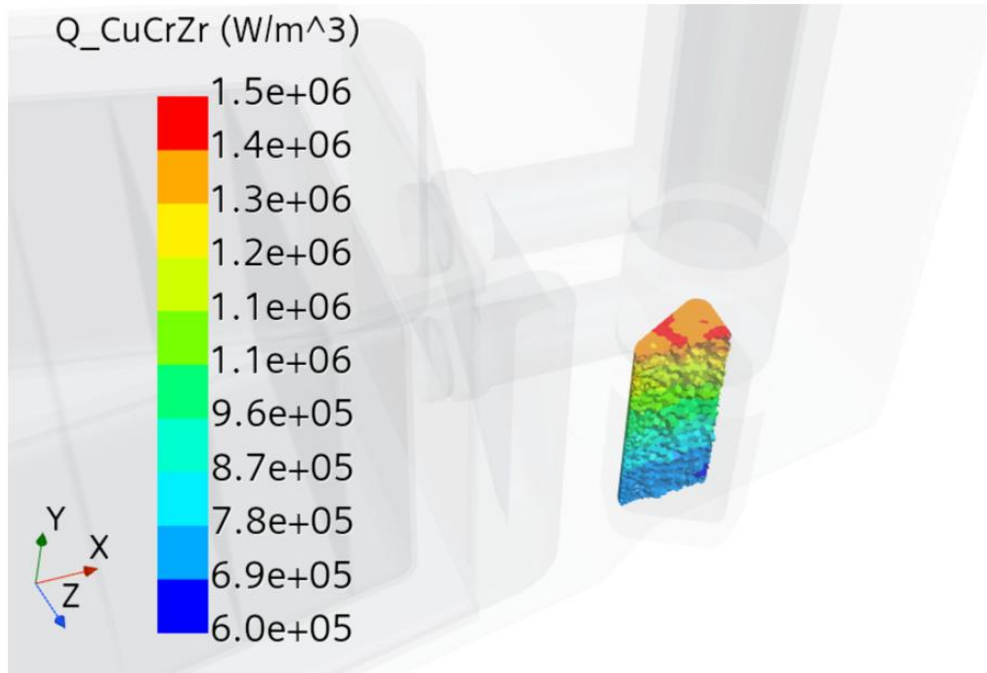


Figure 21. Heat source in CuCrZr.

Table 3. Heat sources in a single target segment.

Material	Heat (W)	%
W	14,648	77.5
Ta	877	4.6
Inconel	1,764	9.3
SS	1,380	7.3
Water	221	1.2
CuCrZr	15	0.08
Total	18,905	100.0

4.5 RESULTS WITH NOMINAL PROTON BEAM

As shown in Figure 22, the pressure drop across the target segment is 8.42 psi, and the pressure at the target elevation is 3.3 bar (48 psi). The maximum water temperature, shown in Figure 23, is 106.4 °C, which remains well below the boiling point of 133.5 °C. As expected, the highest water temperature occurs in the front nose region, where the proton beam directly impinges on the target and produces higher heat deposition.

The overall temperature distribution of the target block under the nominal proton beam is presented in Figure 24, and the results are exported for subsequent thermal stress analysis. As shown in Figure 25, Figure 26, Figure 28, and Figure 29, the maximum temperatures are 225.0 °C in the tungsten blocks,

223.9 °C in the tantalum plates, 170.1 °C in the Inconel shroud, 55.9 °C in the CuCrZr component, and 174.0 °C in the stainless-steel structure.

Because tungsten (87 W/m-K) and tantalum (57.2 W/m-K) possess relatively high thermal conductivities, heat is efficiently distributed within these components, resulting in relatively uniform temperature field. In contrast, the thermal conductivity of Inconel (11.4 W/m-K) is approximately five to eight times lower than that of these high-conductivity materials, leading to larger temperature gradients within the Inconel shroud.

As shown in Figure 26, the front inner surface of the Inconel shroud, which is in contact with the tantalum cladding, reaches 170.1 °C. Across the 10 mm thick Inconel shroud, the temperature decreases to 111.0 °C at the front outer surface, as shown in Figure 27. The front-view temperature distribution shown in Figure 27 corresponds to the surface observed by the Target Viewing Periscope (TVP) during normal operation under the nominal proton beam.

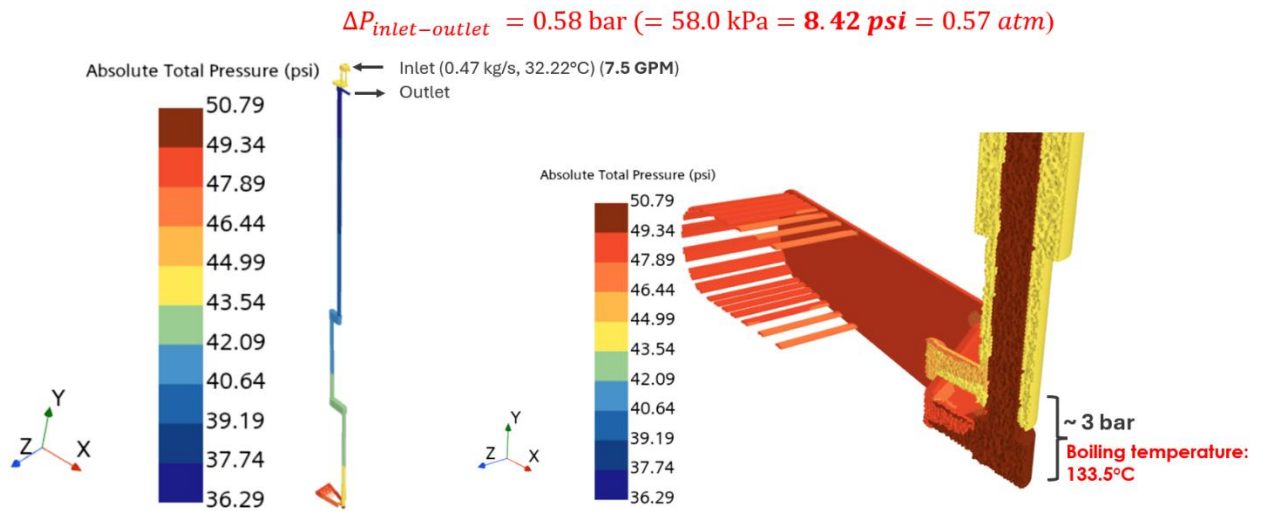


Figure 22. Pressure distribution of target segment.

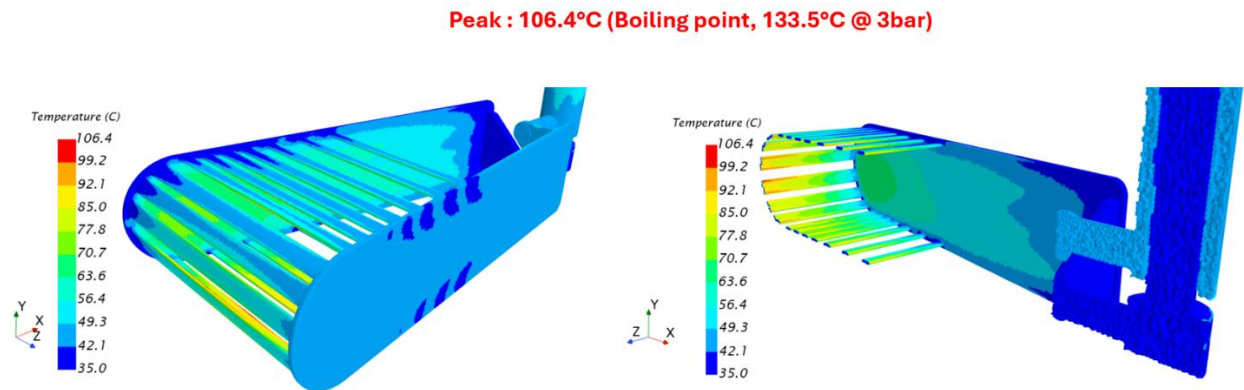


Figure 23. Water temperature distribution in the target segment.

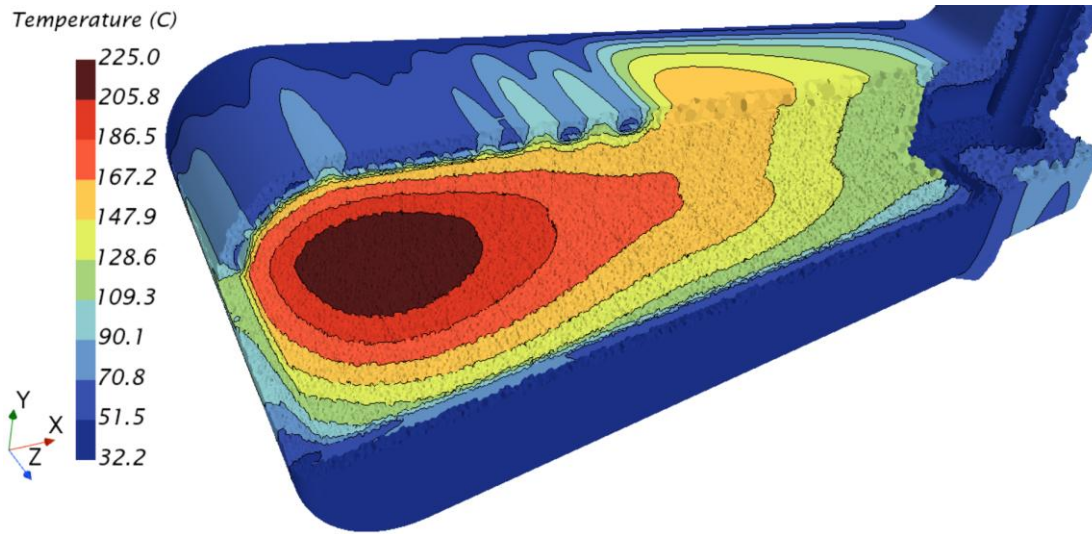


Figure 24. Target segment temperature distribution with nominal proton beam.

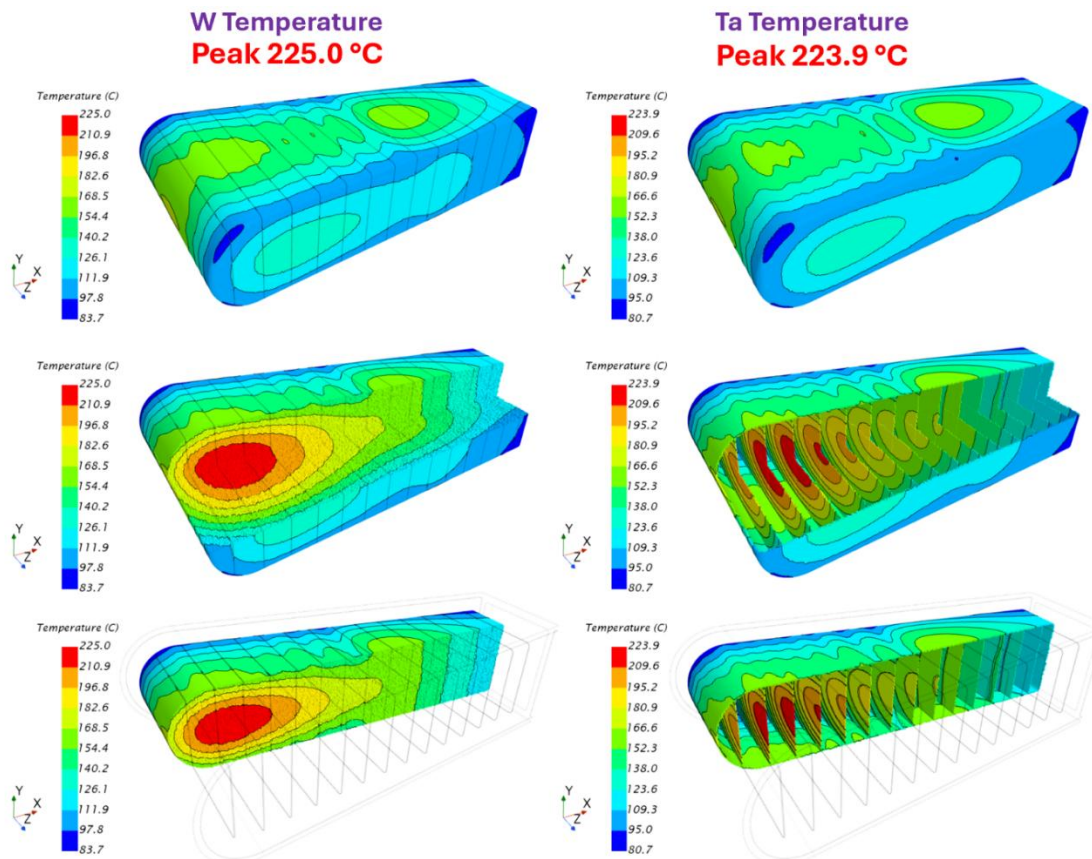


Figure 25. Temperature distribution of Tungsten blocks and Tantalum plates.

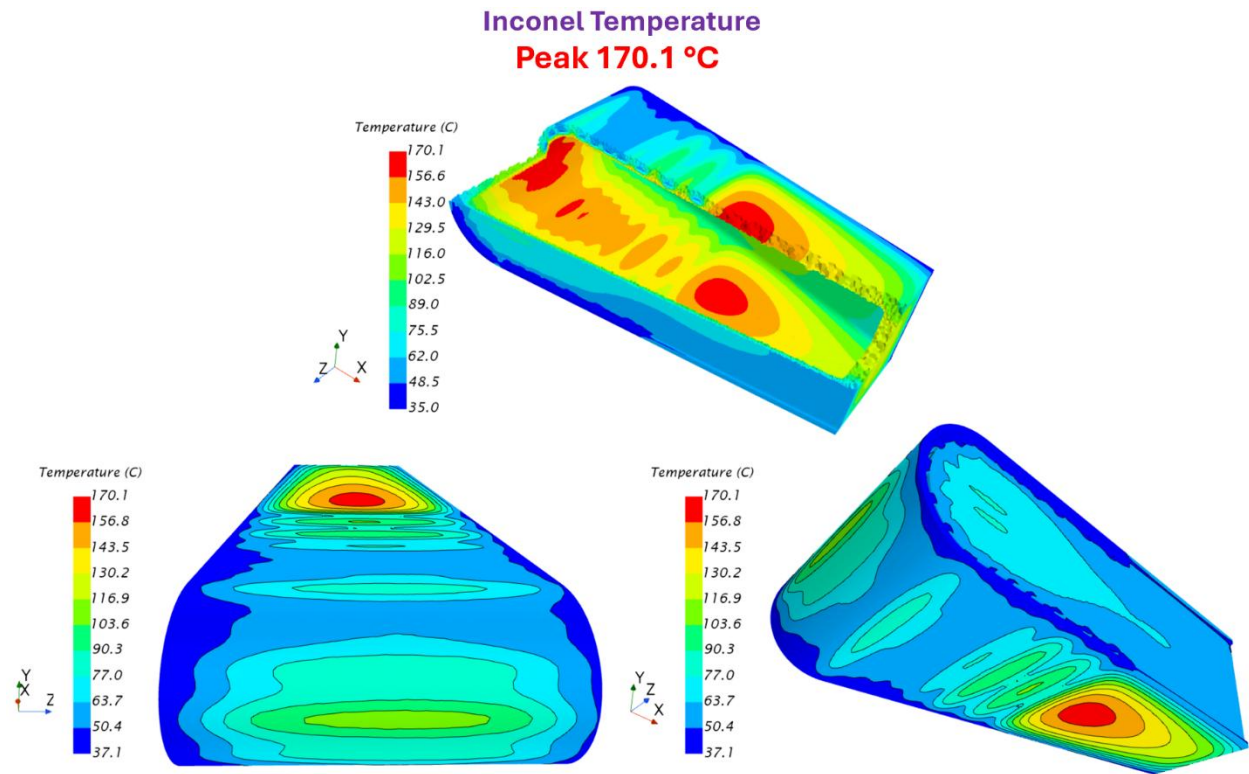


Figure 26. Inconel temperature distribution.

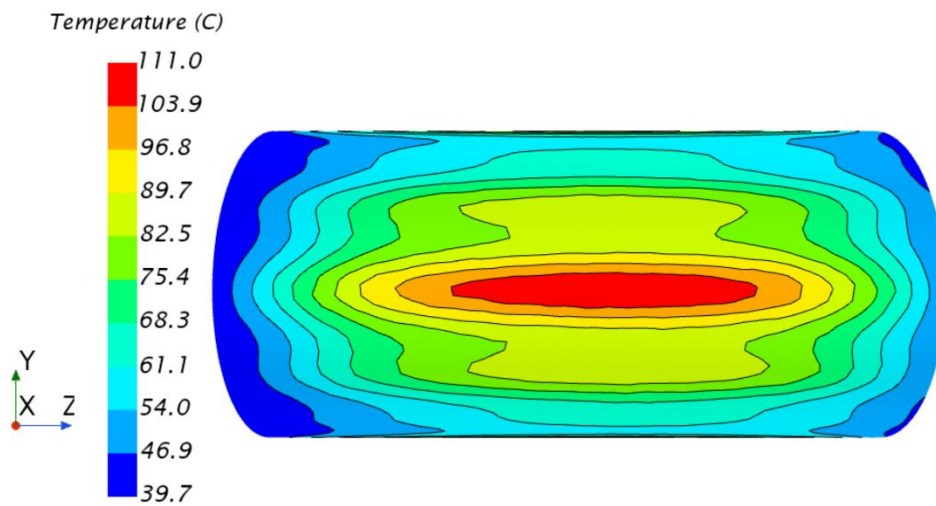


Figure 27. Front view of Inconel temperature distribution (TVP).

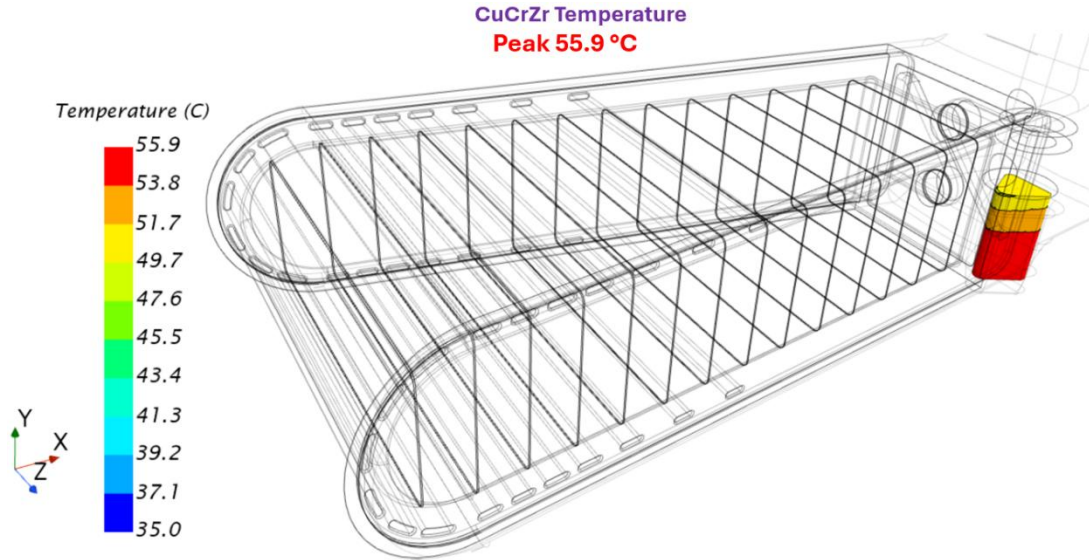


Figure 28. CuCrZr temperature distribution.

As shown in Figure 29 and Figure 30, the peak stainless-steel temperature reaches 160–174 °C between $y = 0.45$ m and $y = 0.75$ m, primarily due to the presence of manufacturing gaps. Because the STS Target Assembly operates within the Core Vessel (CV) vacuum environment, the long manufacturing gap shown in Figure 30 forms an insulating region that prevents the SS316 structure from directly contacting the cooling water. This insulation effect results in the elevated SS316 temperature of 174 °C. **(Note: In the latest design, the lower SS316 leg has been modified to address elevated stainless steel temperatures associated with manufacturing gaps. The geometry shown here corresponds to an earlier model, for which comprehensive heat source distributions associated with different beam profiles are available from neutronics calculations; therefore, this geometry is used for the present analysis. Results based on the latest target segment geometry are provided in Table 21.)**

Due to the relatively low thermal conductivity of SS316 and the limited regions of direct contact with cooling water, the peak SS316 temperature of 174 °C is predicted to require approximately 16 hours to decrease to 55 °C after the proton beam is shut down for maintenance operations. Additional discussion is provided in a later section.

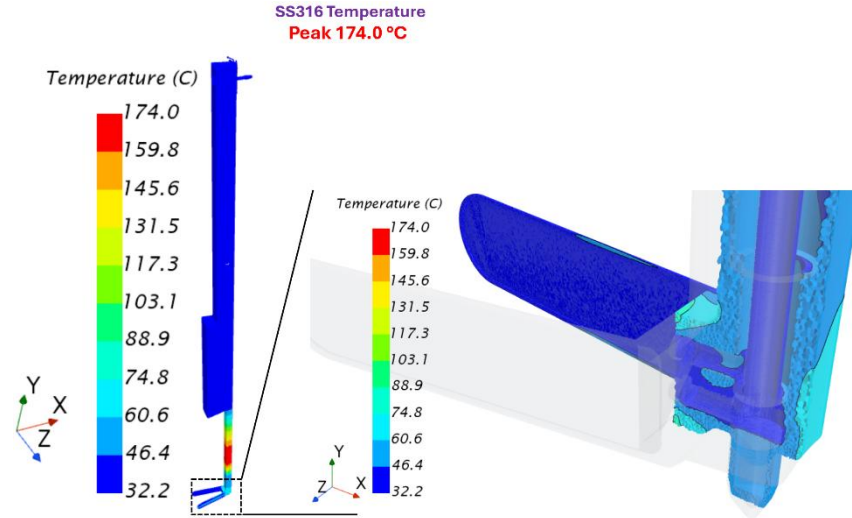


Figure 29. Stainless-steel temperature distribution.

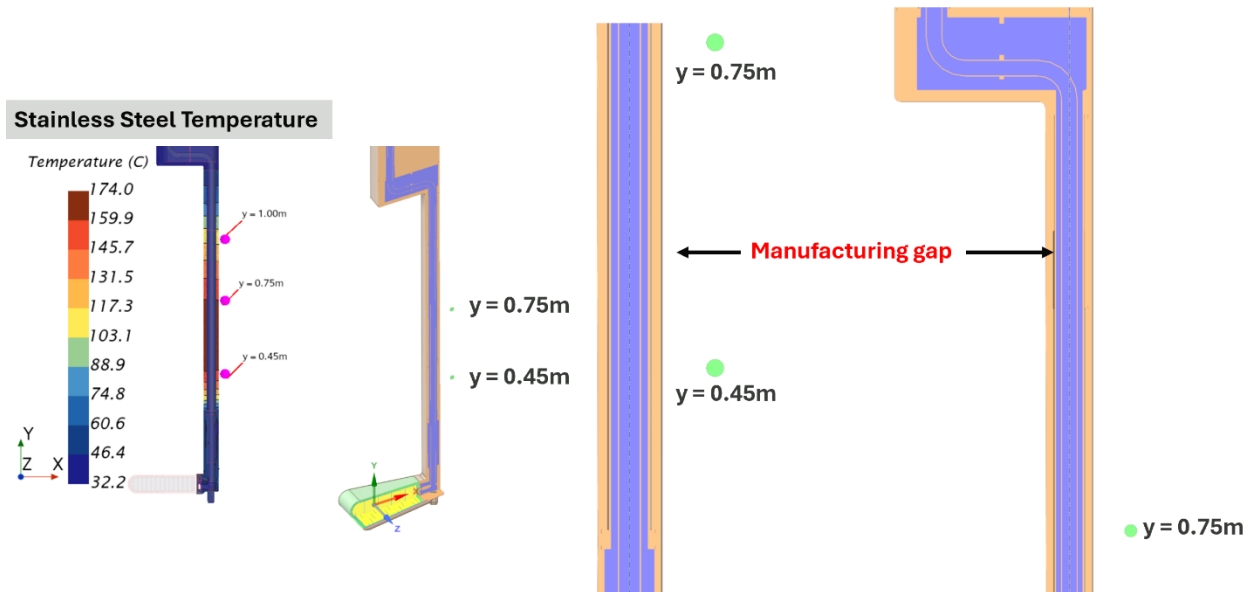


Figure 30. Stainless-steel temperature and manufacturing gaps.

The streamlines shown in Figure 31 indicate that the coolant velocity in the target block is approximately 2.5 m/s in the planar side channels and 1.1–2.0 m/s within the ten internal cooling channels, as summarized in Table 4. The flow rates within the ten cooling channels are summarized in Figure 32. Both the streamline plots (Figure 31) and the flow rate distribution (Table 4 and Figure 32) indicate that the flow distribution within the target block is relatively uniform. Consequently, the Coriolis force does not have a significant effect on the flow field in the rotating STS targets.

Figure 32 shows that the flow rates in channels 4–6 range from 7% to 9%, which is below the average value of 10% (100% / 10 channels) of the total flow rate of 7.5 GPM for a single target segment. This occurs because these channels are smaller and are located in the transition region between the nose region and the main body of the target block, where the flow field is less uniform (Figure 31).

Figure 33 presents a sectional view of the temperature distribution in the Inconel shroud together with the ten cooling channels. The front portion of the shroud is effectively cooled by the cooling passages; however, the temperature increases toward the rear portion of the shroud, and a pronounced temperature gradient appears in the central region due to the absence of cooling channels.

As shown in Figure 32, the flow rates in the rear channels (channels 8-10) range from 11% to 12.6%, which is above the average value of 10%, despite their smaller cross-sectional areas (Table 4). Channels 9 and 10 are 2 mm thick and 8 mm wide. Because the coolant both enters and exits near the rear portion of the target block (Figure 9), the cooling passages located near the rear experience lower hydraulic resistance. This configuration can promote short-circuit flow, which would otherwise reduce the flow rates in the hotter front region that is directly struck by the proton beam.

Therefore, in addition to reducing the volume of activated water, the absence of cooling channels in the rear portion of the target helps mitigate the short-circuit flow phenomenon and ensure adequate cooling performance in the front region of the target.

Although a smoother Inconel temperature profile could potentially be achieved by introducing smaller rear cooling channels (1–3 mm wide, see APPENDIX B), manufacturing such small channels would significantly increase fabrication complexity and cost.

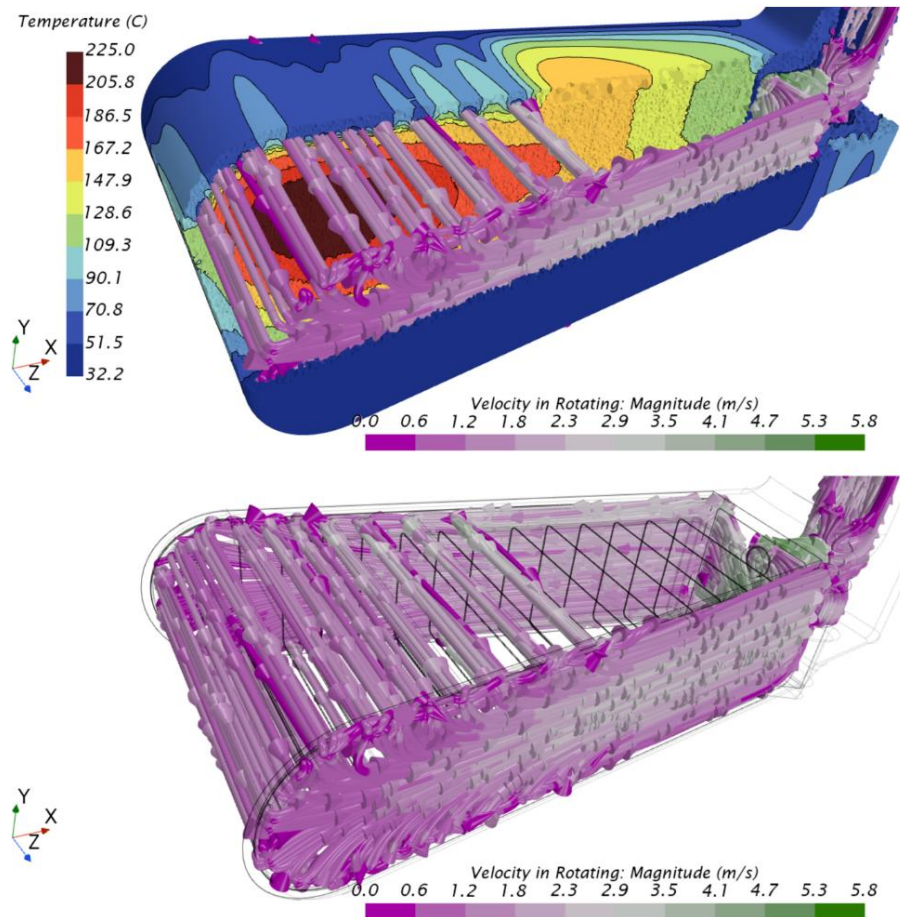


Figure 31. Streamlines in the target segment.

Table 4. Flow distribution.

Numerical (CFD simulation)						
	Volume Flow Rate (m ³ /s)	Area (m ²)	Avg. Velocity (m/s)	Flow Rate (kg/s)	%	Flow Rate (GPM)
Channel_1	2.38E-05	2.13E-05	1.12	0.02376	10.1	0.379
Channel_2	2.19E-05	1.94E-05	1.13	0.02180	9.3	0.348
Channel_3	2.47E-05	2.08E-05	1.19	0.02462	10.5	0.393
Channel_4	1.75E-05	1.49E-05	1.17	0.01747	7.4	0.279
Channel_5	1.90E-05	1.49E-05	1.27	0.01895	8.0	0.302
Channel_6	2.21E-05	1.69E-05	1.30	0.02202	9.3	0.351
Channel_7	2.42E-05	1.69E-05	1.43	0.02413	10.2	0.385
Channel_8	2.67E-05	1.69E-05	1.58	0.02663	11.3	0.425
Channel_9	2.65E-05	1.49E-05	1.78	0.02645	11.2	0.422
Channel_10	2.99E-05	1.49E-05	2.00	0.02980	12.6	0.476
Total (Top Half)				0.236	100	3.760

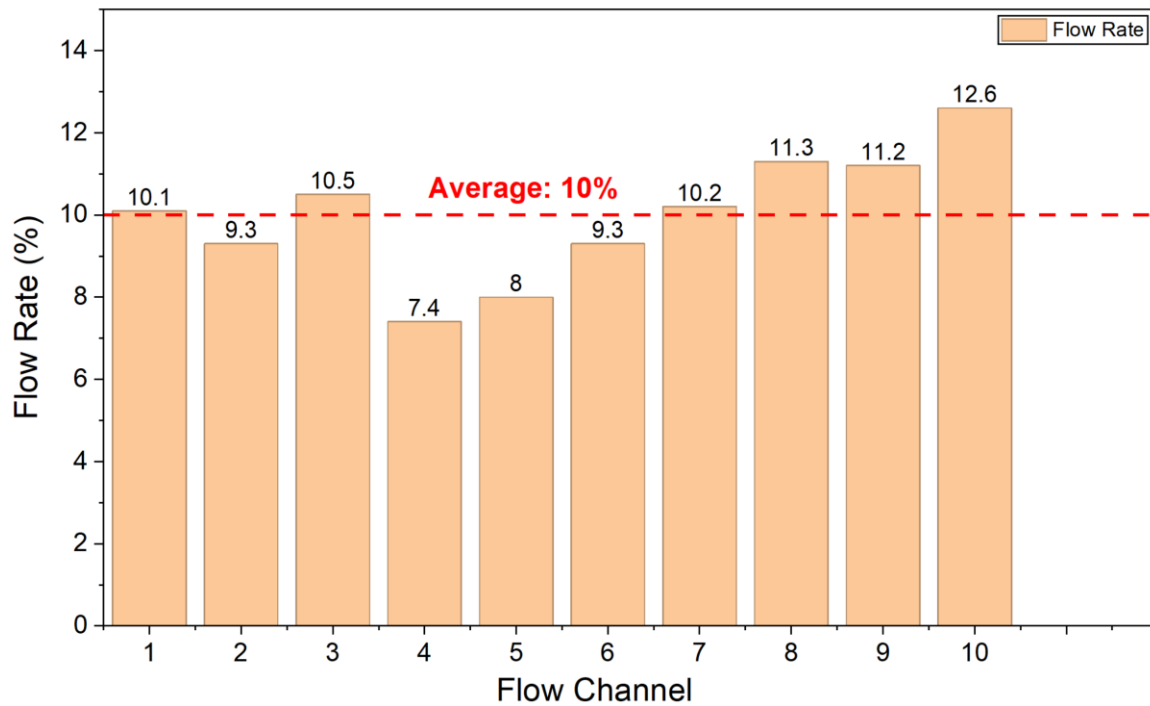


Figure 32. Flow rate distribution.

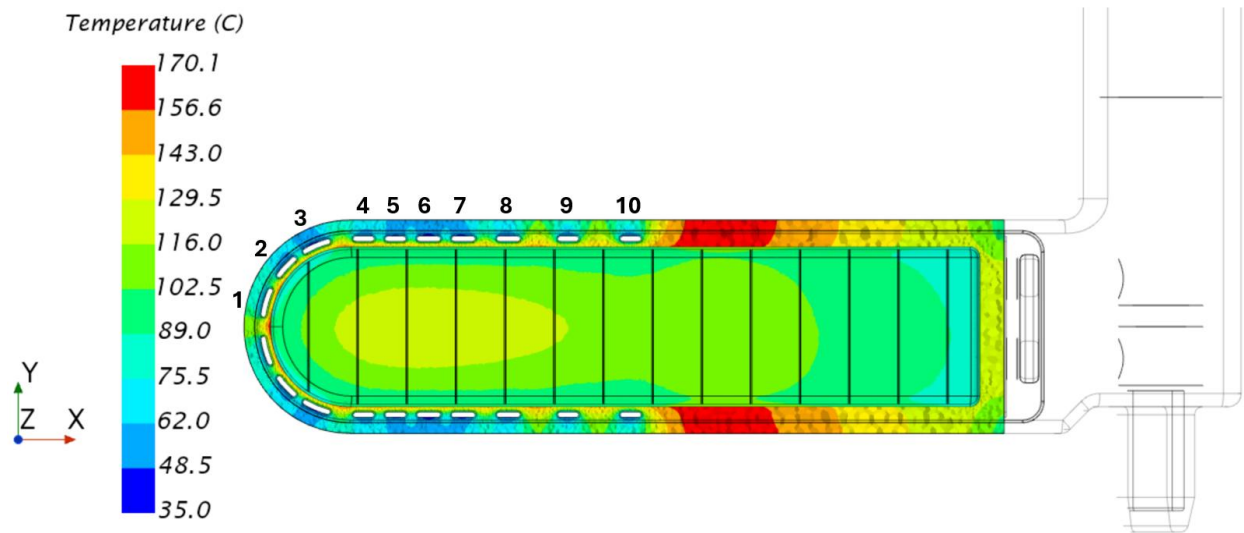


Figure 33. Sectional view of the temperature distribution in the Inconel shroud together with the ten cooling channels.

4.6 EFFECTS OF NOMINAL, OVER-FOCUSED, OFFSET, AND DIFFUSED BEAM PROFILES ON THE TARGET SEGMENT

Although proton pulses repeat at 15 Hz (15 pulses per second), each individual pulse deposits its energy in the tungsten target within approximately 1 microsecond ($\sim 10^{-6}$ s). This time scale is much shorter than the characteristic time scales for heat diffusion in metal ($\sim 10^{-2} - 10^{-1}$ s) or cooling by water (seconds).

When a beam pulse strikes the tungsten target, the proton energy is rapidly converted into heat within the material, producing a nearly instantaneous local temperature rise ($\sim 10^{-6}$ s). The heated region attempts to expand immediately; however, the surrounding material remains relatively cool and rigid. This constraint prevents free expansion and generates large mechanical stress in the heated region, which initially experiences compressive stress. This phenomenon is referred to as thermal shock.

Because the heating occurs faster than the material can mechanically respond, the rapid expansion generates stress waves that propagate through the target. The expansion of the heated region pushes against the surrounding material, producing a compressive wave that travels outward. The speed of sound in tungsten is approximately 5 km/s, meaning that a stress wave (acoustic shocks; pressure waves) can travel a 1 cm region in roughly 2 microseconds (dimensions of the STS target are shown in Figure 10).

When this compressive wave reaches a free surface—a boundary unconstrained by material on the other side—the surface moves outward. To satisfy the zero normal stress condition at the surface, a reflected tensile wave (opposite sign of the incoming compressive wave) forms within the material. Tensile stresses are particularly critical for the STS tungsten target because tungsten, like many brittle materials, is significantly stronger in compression than in tension. The tensile wave can initiate micro-cracks and propagate existing cracks, potentially leading to spallation damage.

The reflected tensile wave may subsequently reach another boundary and reflect again as a compressive wave (change its sign again). Continuous reflections between boundaries cause alternating compression-tension cycles, producing oscillating stress waves within the material. These dynamic stresses occur on microsecond time scales and can be significantly larger than the steady-state thermal stresses. Over time,

the oscillations gradually decay as energy is dissipated through mechanisms such as plastic deformation, internal damping, and heat diffusion.

In addition to these short-time-scale thermal shock effects, the STS target experiences longer-time-scale thermal cycling due to its rotational operation. The target is a rotating disk composed of 20 segments, and the rotation distributes the beam heating among these segments. When one segment is exposed to the beam, it is heated almost instantaneously by a pulse. The segment then rotates away from the beam and cools over a much longer time scale before returning to the beam again. At a rotation rate of 45 RPM, one full revolution takes $4/3$ seconds, during which each segment experiences 20 beam pulses. However, these pulses do not contribute equally to the heating of a given segment. The segment directly intersected by the beam receives the dominant energy deposition, while neighboring segments receive much smaller contributions due to the spatial spread of the beam and particle transport within the target (Figure 18).

After each pulse, the heated region begins to cool through heat diffusion and convection to the cooling water. As the temperature decreases, the heated region attempts to contract. However, the surrounding material may remain warmer and expanded relative to the cooling region. This constraint restricts the contraction of the core region and produces tensile stress. Consequently, the target core experiences compressive stress during rapid heating and tensile stress during cooling. Repeated temperature cycles therefore generate cyclic stresses that lead to thermal fatigue over time. After many cycles, microscopic damage can accumulate in the form of micro-cracks and material weakening.

Because high-energy pulsed proton beams can potentially damage the STS target through these mechanisms, it is necessary to evaluate the target response under different beam footprint conditions. These studies can support the development of the Machine Protection System (MPS), which monitors beam conditions and shuts down the proton beam within tens of microseconds if sensors detect abnormal states such as beam misalignment or excessive focusing [11].

The results for the nominal beam case (700 kW) were presented in previous sections. In this section, additional beam profiles—over-focused, offset, and diffused beams, as defined in Table 5—are evaluated to examine their effects on cooling performance and temperature distributions. The resulting temperature fields are also exported for structural stress analysis ([S03020000-DAC10001](#) and [S03020400-DAC10001](#)).

Table 5. Beam profiles³.

Case	Beam Loads			
Beam Profile	Power(kW)	Focus (Protons/mm²/s)	Beam Footprint (cm²)	Offset (v/h, mm)
Nominal	700	6.24E+11	60	0/0
Over-Focused	714	6.60E+11	57	0/0
Offset	700	6.24E+11	60	8.5/12
Diffused	700	4.61E+11	94.5	0/0

³ Heat Source file: <https://windchill-prod.ornl.gov:8443/Windchill/app/#ptcl/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792>
CFD_Heat_Sources/

1_Nominal_Beam.zip/Target_Segment

2_OverFocused_Beam.zip/Target_Segment

3_Offset_Beam.zip/Target_Segment

4_Diffused_Beam.zip/Target_Segment

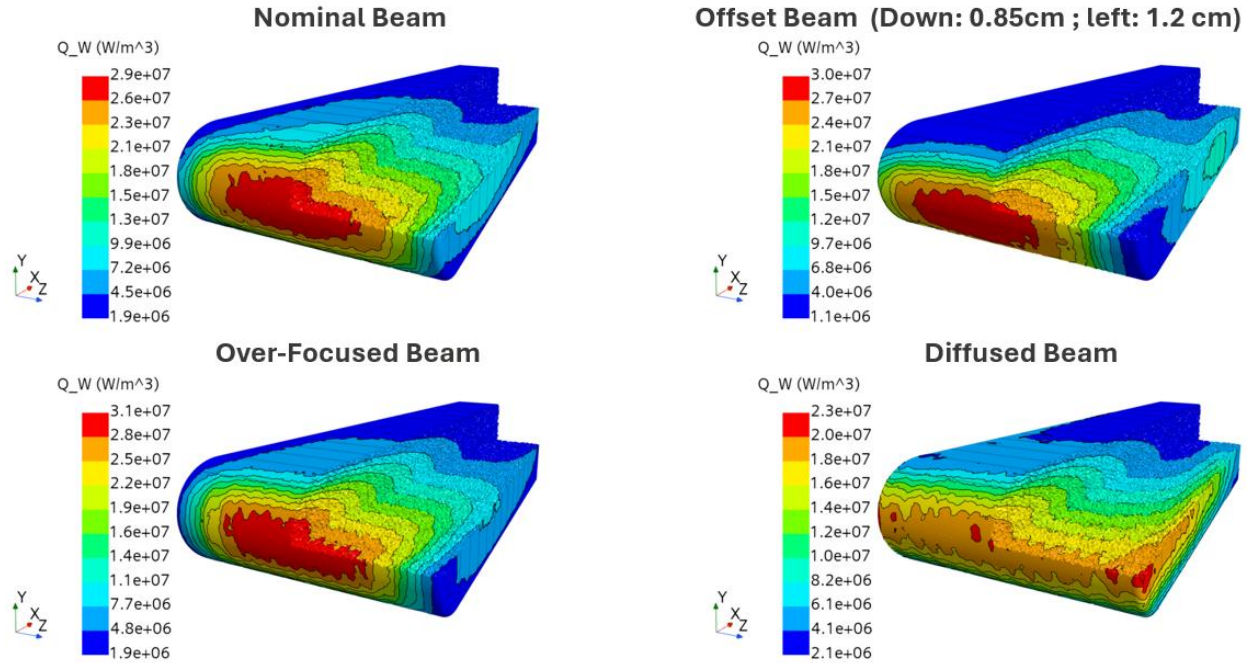


Figure 34. Heat source distributions for nominal, over-focused, offset, and diffused beam profiles.

The nominal beam at 700 kW with a beam footprint of 60 cm² serves as the baseline case and defines the standard performance and safety limits of the target. The over-focused beam concentrates the proton beam into a smaller footprint of 57 cm² at a beam power of 714 kW, resulting in higher peak temperature, larger thermal gradients, and stronger stress waves due to more intense local expansion and contraction.

The proton beam is guided and focused by powerful electromagnets, including dipole magnets for steering and quadrupole magnets for focusing. An offset beam may occur due to small errors in beam steering, magnet alignment, beam optics, or mechanical positioning. Because such deviations are unavoidable in real accelerator systems, target designs must be evaluated under offset beam conditions to ensure safe operation. An offset beam can produce asymmetric heating, localized hot spots, and uneven thermal stress. Furthermore, if the beam strikes the cooling channel instead of solid tungsten, the neutron production region moves away from the MRA (Moderator and Reflector Assembly), reducing neutron brightness. As summarized in Table 5, the offset beam case considered here is shifted 8.5 mm downward and 12 mm to the left.

In contrast to the nominal beam, which is centered on the target, the diffused beam spreads the same 700 kW beam power over a larger footprint of 94.5 cm². Because each target block receives 20 pulses during one full revolution, and some of these pulses occur when neighboring segments are exposed, the diffused beam can extend beyond a single segment. As a result, the heat deposition shifts toward the edges of the target blocks, and a larger fraction of protons passes through the gap between segments, depositing additional energy in the target shaft.

The heat source distributions for the nominal, over-focused, offset, and diffused beam cases are shown in Figure 34. Although only the tungsten heat sources are presented in the figure, heat deposition in other materials—including tantalum, Inconel 718, SS316, water, and CuCrZr—is also included in the simulations.

The peak temperatures of the target segment for all beam profiles are summarized in Table 6. The corresponding temperature distributions are shown in Figure 35 and Figure 36 (using the same color scale for direct comparison). For the nominal beam, the peak temperature is 225°C. Under the over-focused beam, the peak temperature increases to 233.7°C due to the higher power density. For the offset beam, shifted downward by 8.5mm, the peak temperature is 220.6°C, with elevated temperatures appearing in the lower portion of the target and a larger temperature gradient observed in the Inconel shroud (Figure 36). In contrast, the diffused beam produces a lower peak temperature of 182.4°C despite higher heating near the edges of the target. The edge regions are effectively cooled by the side planar cooling channels, which helps limit the peak temperature.

Table 6. Peak temperatures for the target configuration with SS316 flow covers under various beam profiles.⁴

Material	Peak Temperature (°C)			
	Nominal (700 kW)	Over-Focused (714 kW)	Offset (700 kW)	Diffused (700 kW)
Tungsten	225.0	233.7	220.6	182.4
Tantalum	223.9	232.5	219.3	181.4
Inconel 718	170.1	176.6	184.2	162.7
SS 316	174.0	176.7	163.6	176.8
H ₂ O	106.4	109.8	110.2	90.7
CuCrZr	55.9	55.9	67.8	59.4

⁴ The SS316 geometry in Table 6 includes manufacturing gaps that result in elevated SS316 temperatures. These gaps were eliminated, and the CuCrZr component was removed in the final design. Results for the final design under nominal conditions are summarized in Table 21.

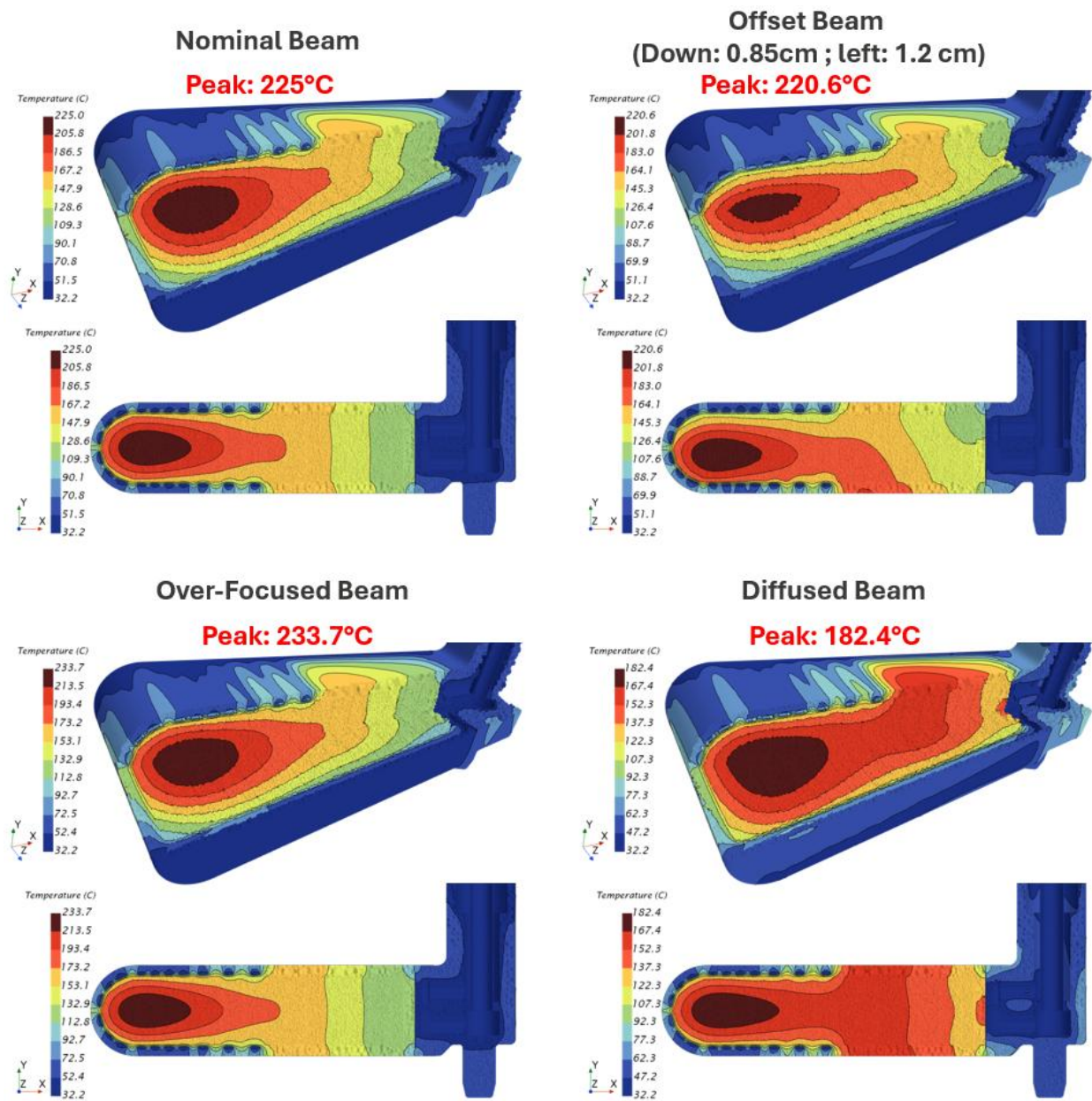


Figure 35. Temperature distributions for nominal, over-focused, offset, and diffused beam profiles.

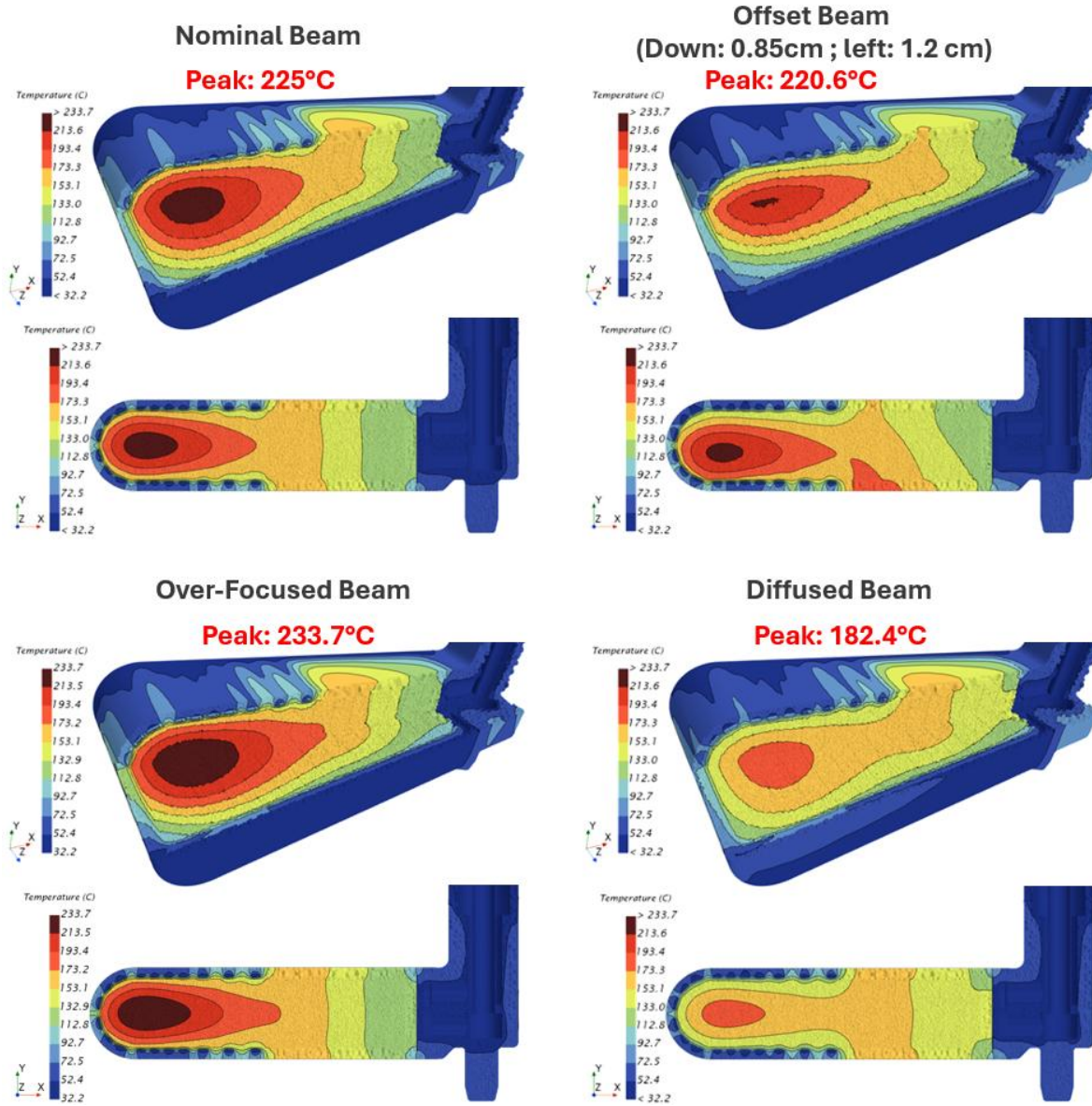


Figure 36. Temperature distributions for nominal, over-focused, offset, and diffused beam profiles (same color scale).

4.7 TARGET SEGMENT WITH INCONEL FLOW COVERS: INCREASED BEAM POWER (900 kW) OR REDUCED FLOW RATE (5.71 GPM)

The maximum proton beam power that can be delivered to the STS target by the accelerator system is 900 kW, while the minimum allowable coolant flow rate before the protection system trips is 5.71 GPM. The objective of this analysis is to evaluate whether the current cooling channel design remains adequate if the target is continuously exposed to a 900 kW beam, and to assess the impact of a reduced coolant flow rate. Four operating conditions are considered:

- Baseline: 700 kW beam power, 7.5 GPM coolant flow
- Reduced flow at nominal power: 700 kW, 5.71 GPM
- Increased power at nominal flow: 900 kW, 7.5 GPM
- Increased power with reduced flow: 900 kW, 5.71 GPM

These conditions represent a 29% increase in beam power and a 24% reduction in coolant flow rate, which could occur during a cooling-loop malfunction. In this section, the flow covers in the target block are assumed to be made of Inconel 718.

Figure 37 and Figure 38 show the heat source distributions in the various materials of the target block for the 700 kW beam case, while Figure 39 and Figure 40 present the corresponding distributions for the 900 kW beam case. The heat sources for the 700 kW beam are obtained from the MCNP neutronics calculations, which include the Inconel flow covers. The heat sources for the 900 kW case are obtained by scaling the 700 kW heat source distributions by a factor of 900/700, rather than performing a separate MCNP calculation. The resulting heat loads are summarized in Table 7.

Table 7. Summary of heat sources for the target configuration with Inconel flow covers under 700 kW and 900 kW beam power (single target segment).⁵

Material	Heat (W) with 700 kW Beam	Heat (W) with 900 kW Beam
Tungsten	1.46E+04	1.88E+04
Tantalum	8.76E+02	1.13E+03
Inconel 718	2.25E+03	2.89E+03
SS 316	9.23E+02	1.19E+03
H ₂ O	2.18E+02	2.80E+02
CuCrZr	1.54E+01	1.98E+01
Total	1.89E+04	2.43E+04

⁵ Heat Source file: https://windchill-prod.ornl.gov:8443/Windchill/app/#ptcl/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792CFD_Heat_Sources/1_Nominal_Beam.zip/Target_Segment

Table 8. Peak temperatures for the target configuration with Inconel flow covers under various beam powers and coolant flow rates.⁶

Material	Peak Temperature (°C)			
	700 kW;7.5 GPM	900 kW;7.5 GPM	700 kW;5.71 GPM	900 kW;5.71 GPM
Tungsten	225.1	280.1	235.9	294.1
Tantalum	223.9	278.6	235.0	292.9
Inconel 718	170.0	209.3	182.3	225.1
SS 316	174.0	216.5	180.4	222.7
H ₂ O	106.1	127.2	120.5	145.7
CuCrZr	56.0	62.6	58.7	66.2

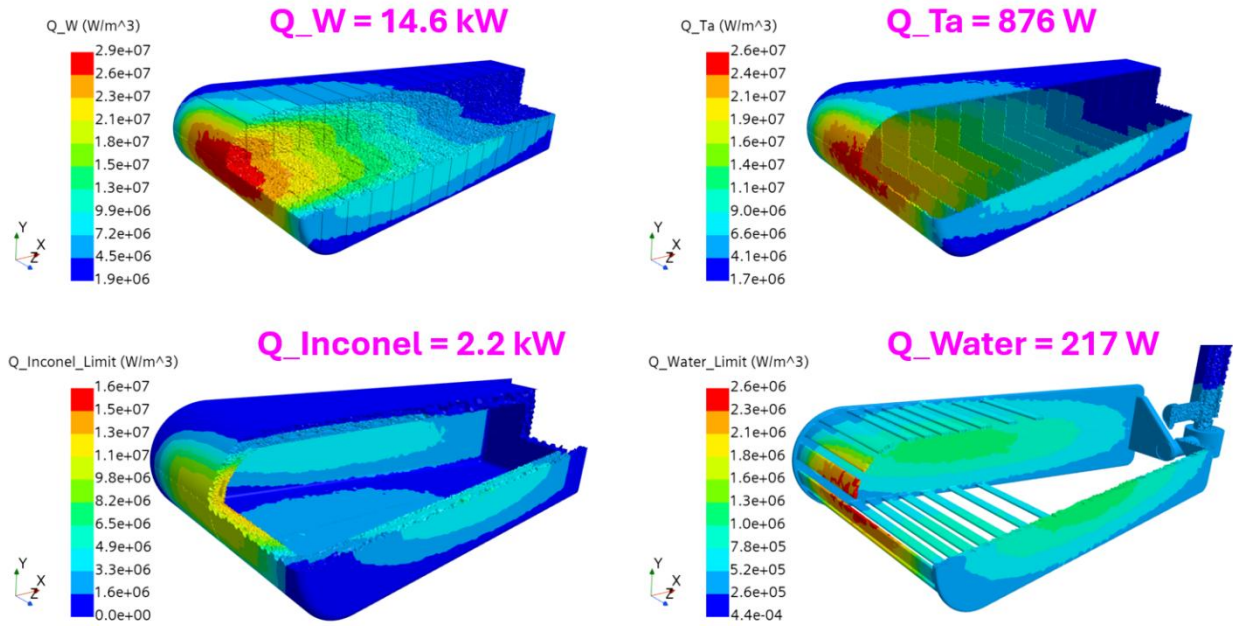


Figure 37. Heat sources in tungsten, tantalum, Inconel, and water for the target configuration with Inconel flow covers under the nominal 700 kW beam.

⁶ The SS316 geometry in Table 8 includes manufacturing gaps that result in elevated SS316 temperatures. These gaps were eliminated, and the CuCrZr component was removed in the final design. Results for the final design under nominal conditions are summarized in Table 21.

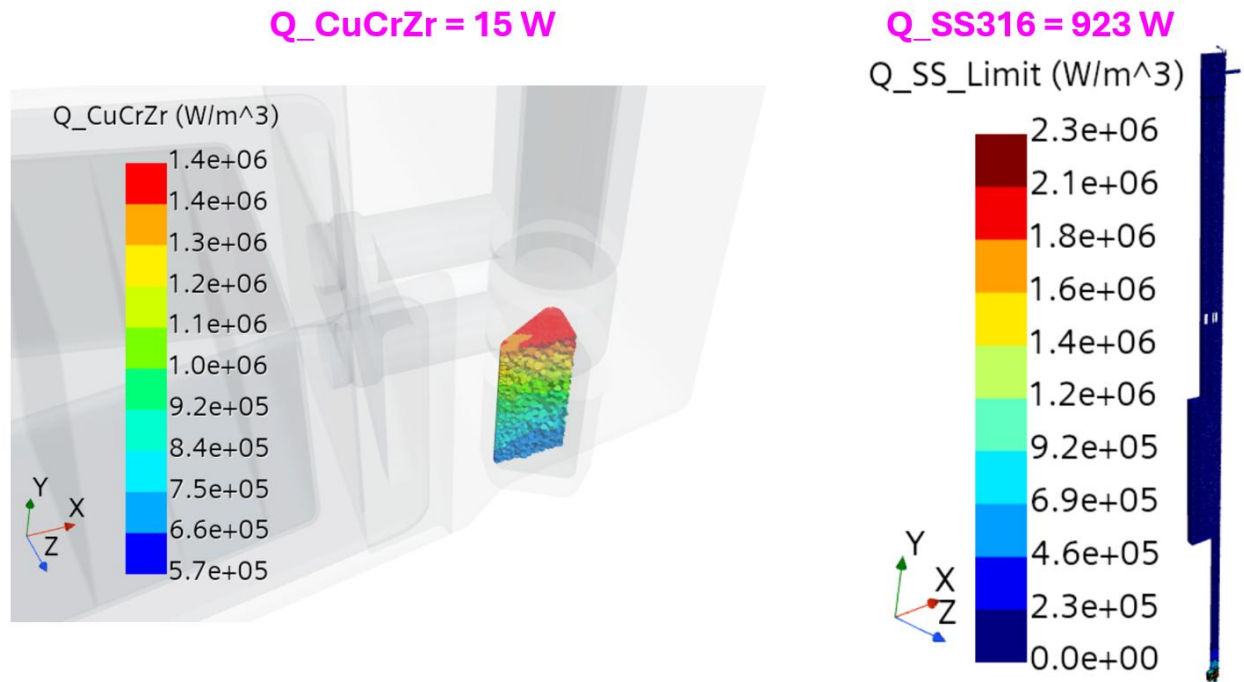


Figure 38. Heat sources in CuCrZr and SS316 for the target configuration with Inconel flow covers under the nominal 700 kW beam.

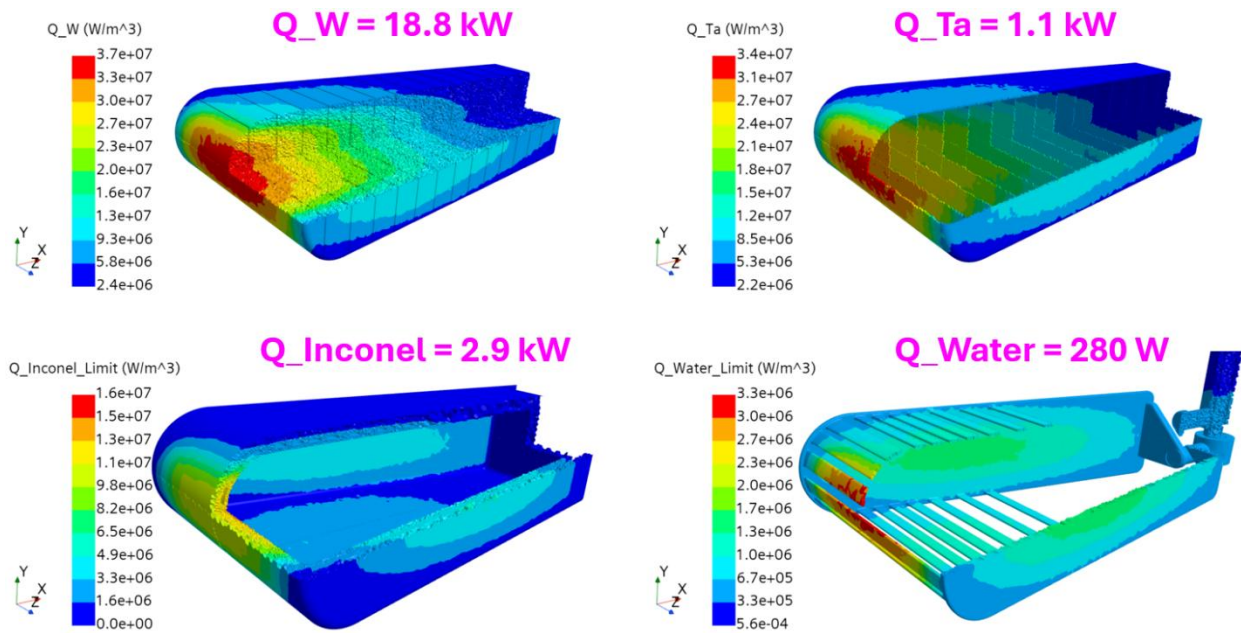


Figure 39. Heat sources in tungsten, tantalum, Inconel, and water for the target configuration with Inconel flow covers under the 900 kW beam.

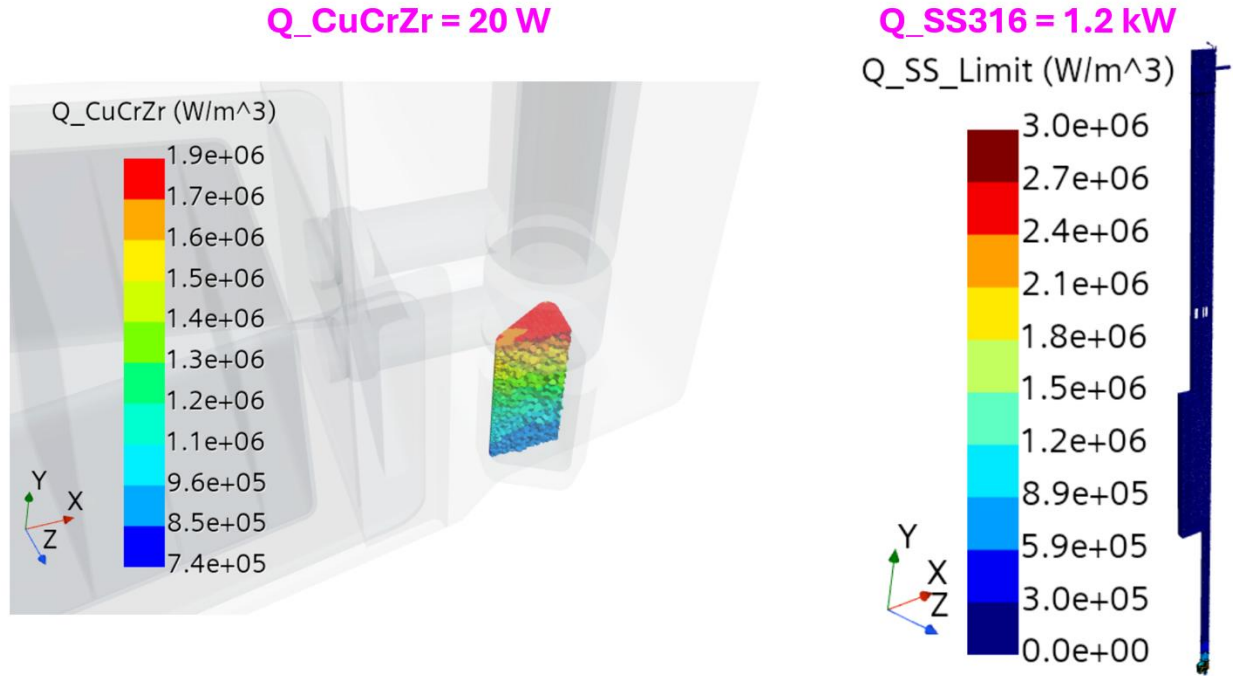


Figure 40. Heat sources in CuCrZr and SS316 for the target configuration with Inconel flow covers under the 900 kW beam.

Figure 41 compares the temperature distributions in the target segment for the four operating conditions. Under the nominal beam power of 700 kW and nominal flow rate of 7.5 GPM, the peak temperature in the tungsten target block is 225.1 °C. This value is essentially identical to the 225.0 °C obtained for the configuration with SS316 flow covers (Figure 24), indicating that the material change has a negligible effect on the peak temperature.

With the coolant flow maintained at 7.5 GPM but the beam power increased to 900 kW, the peak tungsten temperature rises to 280 °C. When the beam power remains at 700 kW but the coolant flow rate is reduced to 5.71 GPM, the peak temperature increases from 225.1 °C to 236 °C. When both the beam power is increased to 900 kW and the coolant flow rate is reduced to 5.71 GPM, the peak tungsten temperature further increases to 294 °C. Overall, the 29% increase in beam power results in a temperature rise of approximately 55-58 °C, while the 24% reduction in coolant flow rate increases the peak temperature by 11-14 °C.

Figure 42 presents the corresponding water temperature distributions under the same operating conditions. Under the nominal conditions of 700 kW beam power and 7.5 GPM flow rate, the peak water temperature is 106.1 °C. Increasing the beam power to 900 kW at the same flow rate raises the peak water temperature to 127.2 °C, which is 6.3 °C below the boiling point of 133.5 °C at approximately 3 bar, the operating pressure at the target block elevation.

Previous studies of an earlier STS target design (2019) indicated that when transient pulsed heating is considered, the peak temperature can oscillate by approximately ± 5 °C around the steady-state value once steady-state conditions are reached (see APPENDIX D). Accounting for this possible oscillation reduces the effective margin to the boiling point from 6.3 °C to approximately 1.3 °C.

When the coolant flow rate is reduced to 5.71 GPM at 700 kW beam power, the peak water temperature increases from 106.1 °C to 120.5 °C. Under the combined condition of 900 kW beam power and 5.71 GPM

flow rate, the peak water temperature reaches 145.7°C, which exceeds the 133.5 °C boiling point by 12.2°C.

Figure 43 shows the temperature distributions in the SS316 structural components under the four operating conditions. Under the nominal conditions (700 kW, 7.5 GPM), the peak SS316 temperature is 174.0 °C. Increasing the beam power to 900 kW at the same flow rate raises the peak temperature to 216.5 °C. When the coolant flow rate is reduced to 5.71 GPM at 700 kW beam power, the peak temperature increases to 180.4 °C. Under the combined condition of 900 kW beam power and 5.71 GPM flow rate, the peak SS316 temperature reaches 222.7°C.

The Target Viewing Periscope (TVP) allows operators to visually inspect the front surface of the rotating target segments during operation. This capability enables detection of abnormal conditions such as discoloration due to overheating or surface damage such as pitting. Figure 44 shows the front-view temperature distributions of the Inconel shroud for the four operating conditions, representing the surface that can be observed through the TVP.

The peak temperatures of the major materials in the target block under the four operating conditions are summarized in Table 8. In summary, the heat transfer analysis was performed for beam powers of 700 kW (nominal) and 900 kW (29% increase), with coolant flow rates of 7.5 GPM (nominal) and 5.71 GPM (24% reduction). At 700 kW, the peak tungsten temperature is approximately 225 °C. Increasing the beam power to 900 kW raises the peak temperature to approximately 280 °C under nominal flow conditions. When the flow rate is reduced to 5.71 GPM, the peak tungsten temperature further increases to 294 °C.

The results indicate that the beam power increase has a significantly larger impact on temperature than the reduction in coolant flow rate. While the 24% reduction in flow increases the peak temperature by approximately 11–14 °C, the 29% increase in beam power results in a temperature rise of approximately 55–58 °C. Under the combined condition of 900 kW beam power and reduced flow, the predicted peak water temperature exceeds the boiling point at the target operating pressure, indicating a potential risk of local boiling and reduced thermal margin under off-normal conditions.

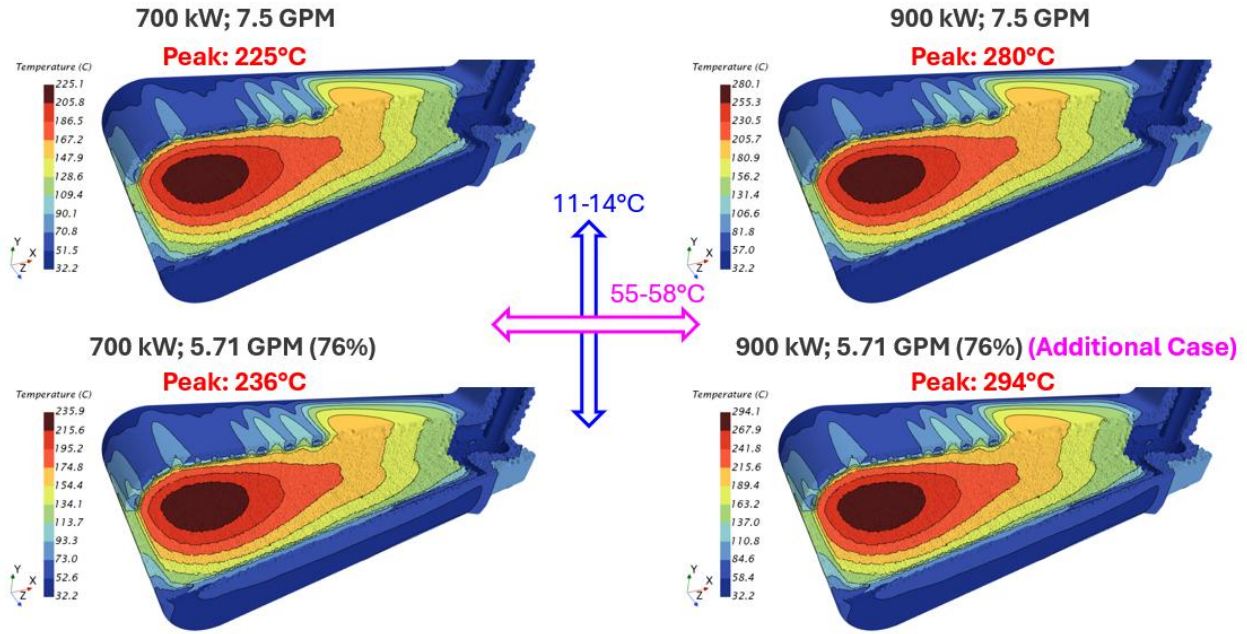


Figure 41. Temperature distributions for the target configuration with Inconel flow covers under various beam powers and coolant flow rates.

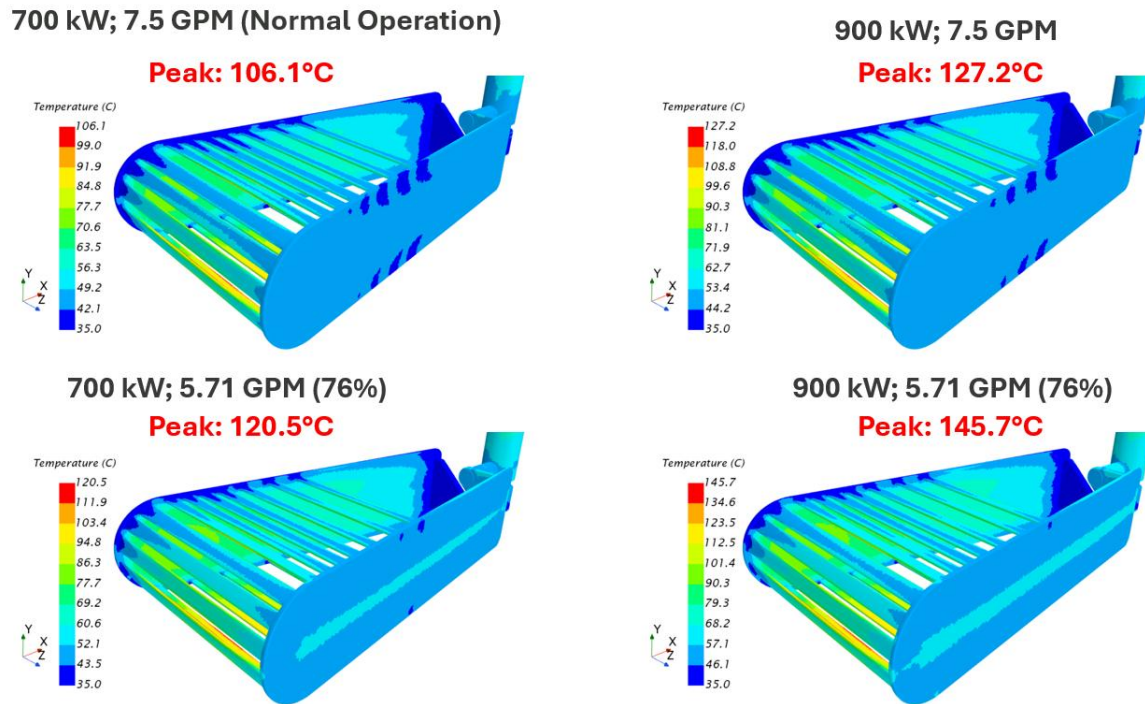
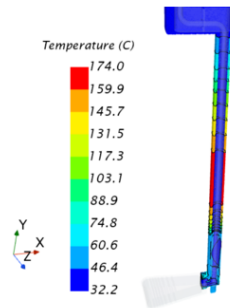


Figure 42. Water temperature distributions for the target configuration with Inconel flow covers under various beam powers and coolant flow rates.

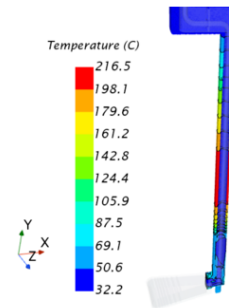
700 kW; 7.5 GPM (Normal Operation)

Peak: 174.0°C



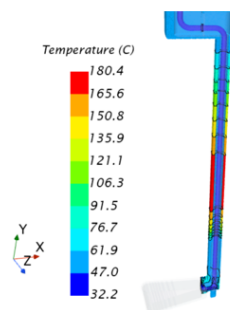
900 kW; 7.5 GPM

Peak: 216.5°C



700 kW; 5.71 GPM (76%)

Peak: 180.4°C



900 kW; 5.71 GPM (76%)

Peak: 222.7°C

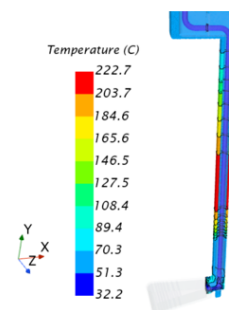
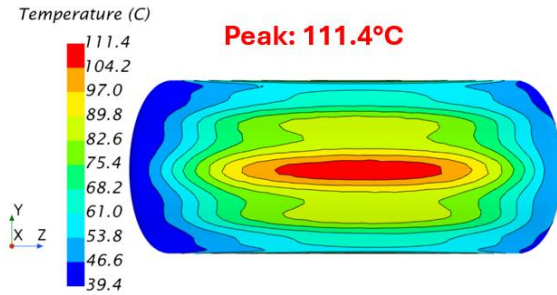


Figure 43. SS316 temperature distributions for the target configuration with Inconel flow covers under various beam powers and coolant flow rates.

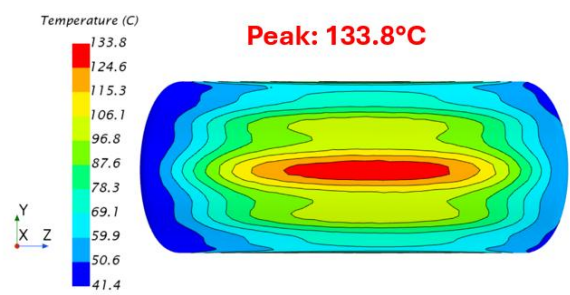
700 kW; 7.5 GPM (Normal Operation)

Peak: 111.4°C



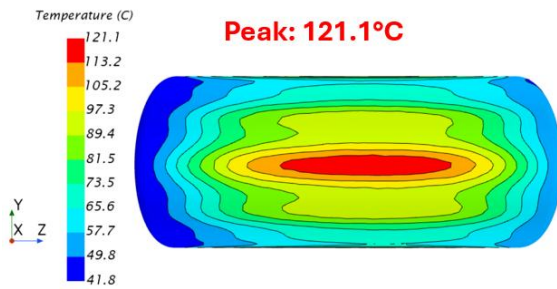
900 kW; 7.5 GPM

Peak: 133.8°C



700 kW; 5.71 GPM (76%)

Peak: 121.1°C



900 kW; 5.71 GPM (76%)

Peak: 146.5°C

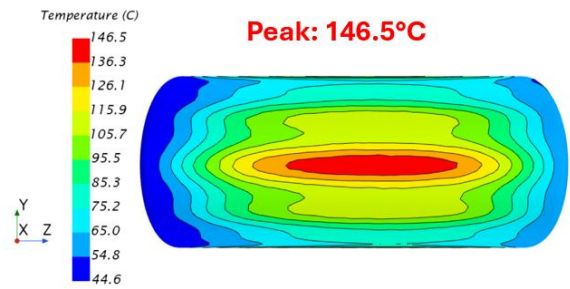


Figure 44. Front-view temperature distributions of the Inconel shroud for the target configuration with Inconel flow covers under various beam powers and coolant flow rates.

4.8 SENSITIVITY OF PRESSURE DROP TO FLOW-AREA TRANSITIONS IN THE TARGET FOOT

During earlier design iterations, the geometry of the supply and return connections to the side cooling channels (Figure 45) was identified as a primary driver of pressure drop in the target foot. A sensitivity study was conducted to evaluate the effect of flow-area transitions. As shown in Figure 46, configurations with smooth flow-area transitions result in a pressure drop of 5.47 psi, whereas abrupt flow-area changes increase the pressure drop to 15.38 psi. These results motivated the adoption of smooth transition features in the final design.

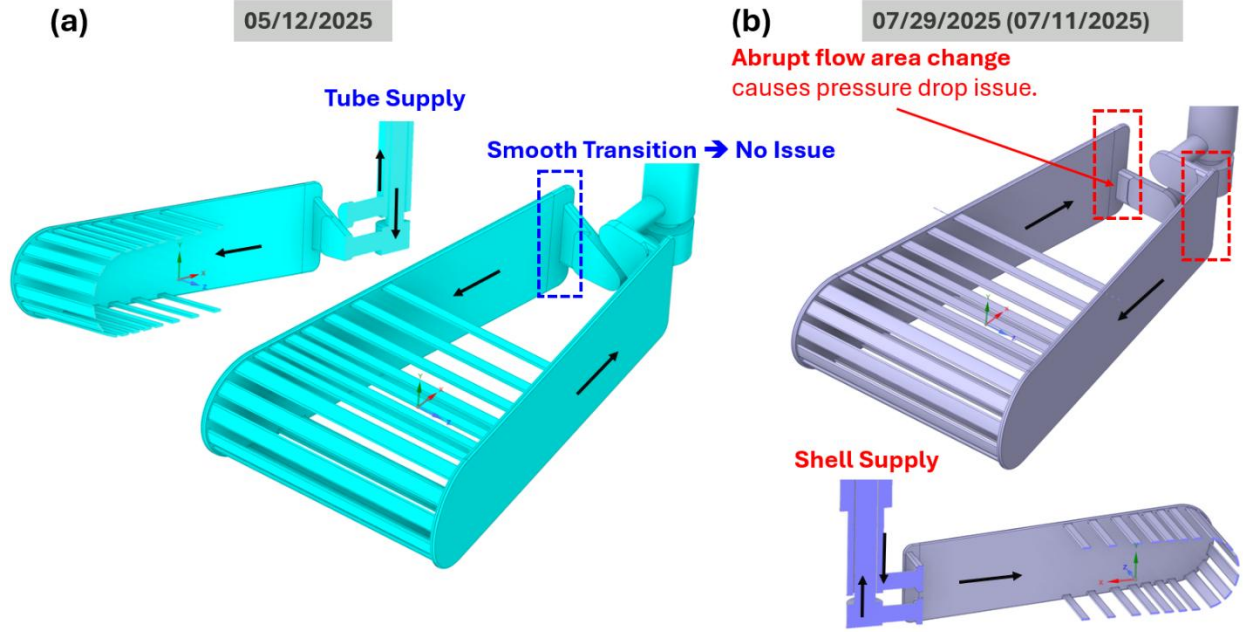


Figure 45. Cooling channel geometry in the target foot: (a) smooth transition; (b) abrupt transition.

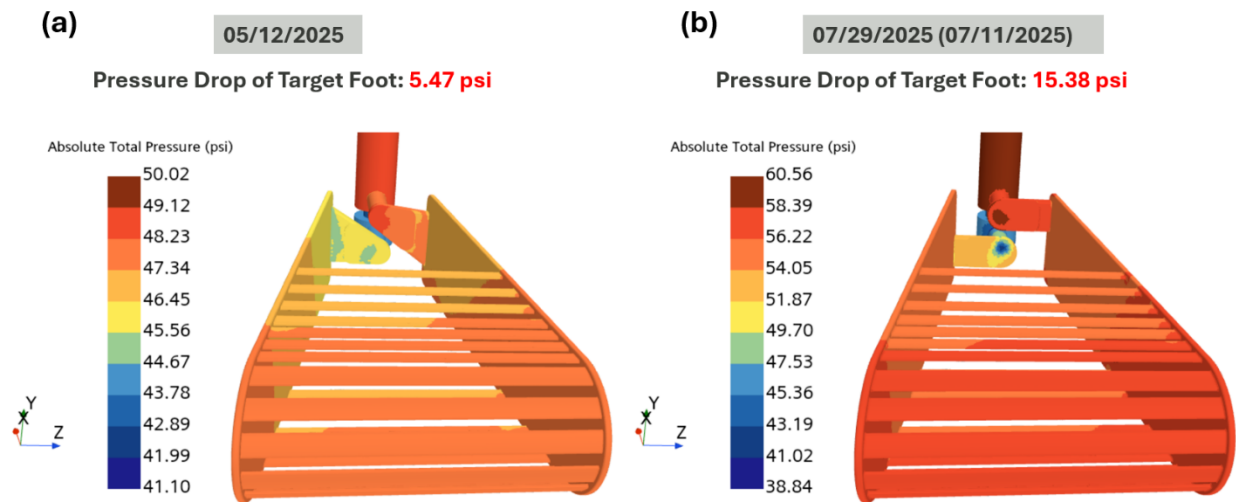


Figure 46. Comparison of pressure drop in the target foot for (a) smooth transition and (b) abrupt transition.

5. TARGET SHAFT CFD ANALYSIS

5.1 GEOMETRY⁷

As shown in Figure 47, the target shaft consists of several stainless-steel shielding blocks with a seismic restraint pin located at the bottom. For CFD simulations, components made of the same materials were merged to simplify the geometry, improve mesh quality, and reduce numerical errors. Parallel cooling channels are used to efficiently cool the target shaft while maintaining a reasonable pressure drop. As shown in Figure 47, the inner diameter (ID) of both the supply and return lines is 17.5 mm.

A coolant flow rate of 7.5 GPM enters the shaft from the top, flows into the top plenum, and distributes water to the outer wall of the shaft. The coolant then flows downward toward the bottom flange and the triangular pockets used for target segment insertion (Figure 48). After reaching the bottom region, the coolant returns through the central shaft and flows upward toward the target drive (Figure 5).

The Target Assembly is approximately 5-7 meters long and is suspended from the core vessel (CV) lid, which also provides mechanical support for the Target Viewing Periscope (TVP), as shown in Figure 1 and Figure 49. Because of its length and suspended configuration, the Target Assembly behaves like a large pendulum and can experience significant lateral deflection during a seismic event. Combined with the 45 RPM rotation rate during normal operation, excessive lateral motion could cause the Target Assembly to collide with the Moderator and Reflector Assembly (MRA) and potentially compromise the hydrogen boundary (S03020000-DES1000).

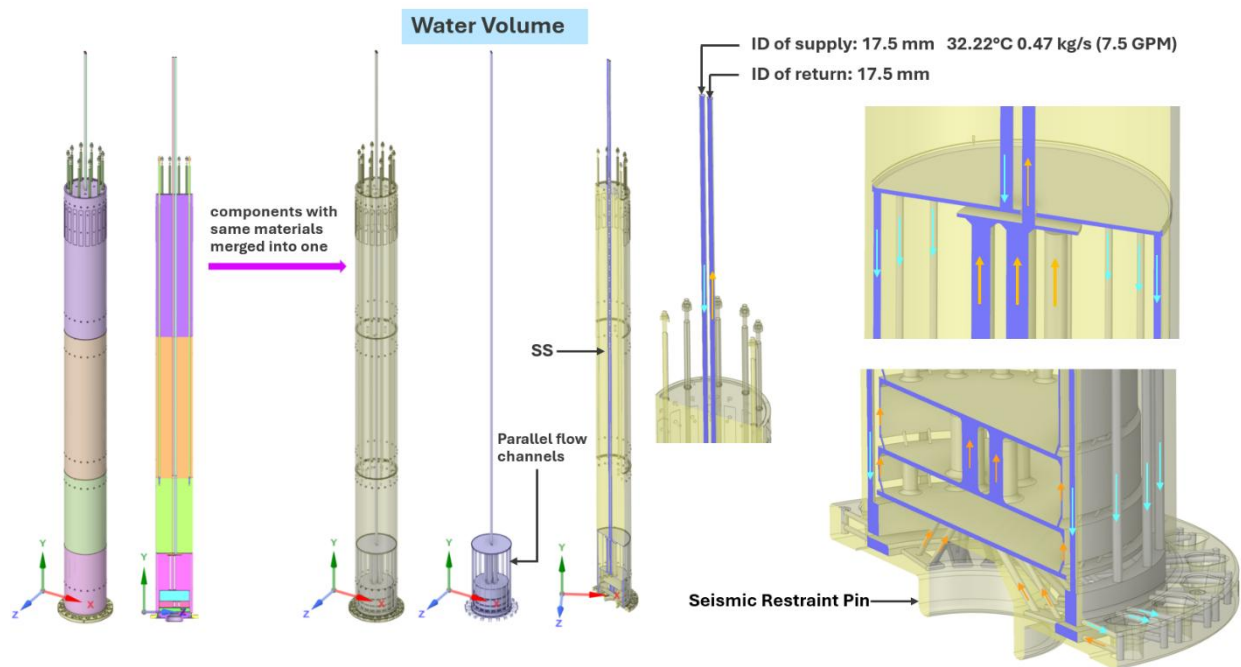


Figure 47. Target shaft.

⁷ Geometry file: <https://windchill-prod.ornl.gov:8443/Windchill/app/#ptc1/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792>
CFD CAD/Target Shaft.zip

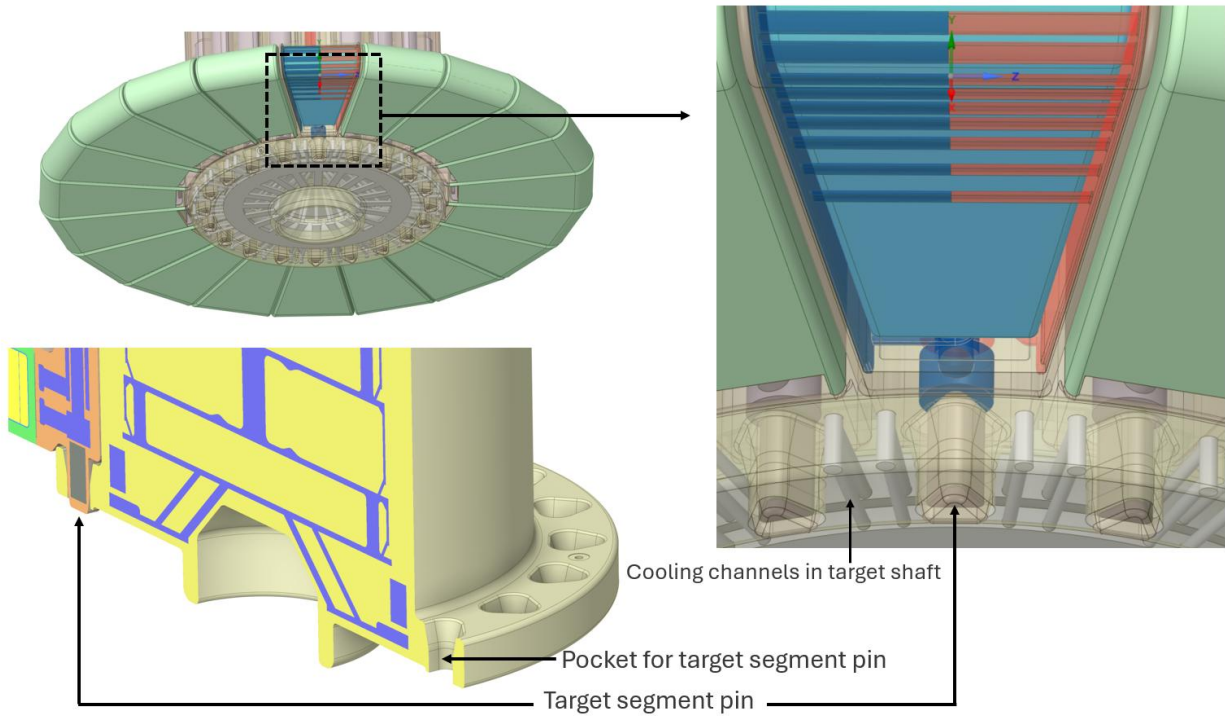


Figure 48. Pockets on the target shaft for target segment insertion.

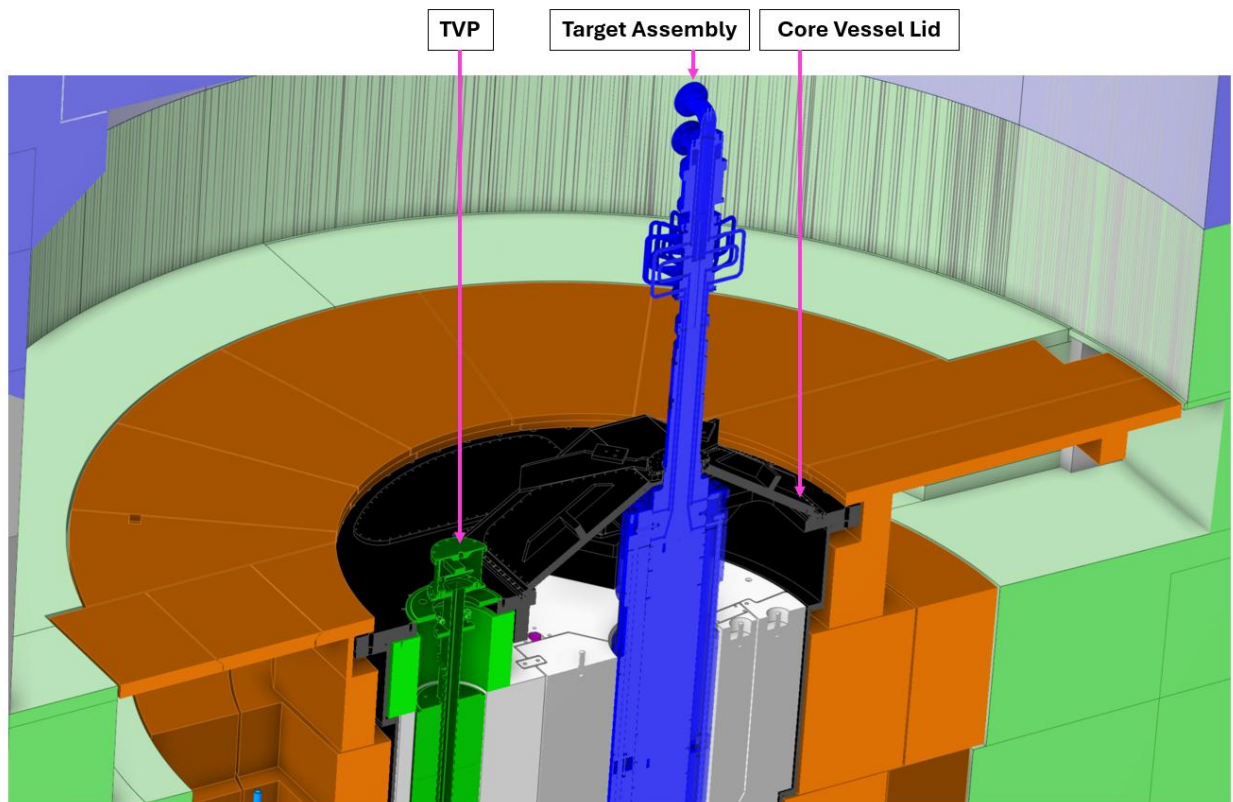


Figure 49. TVP, Target Assembly, and Core Vessel Lid.

Figure 50 shows the relative locations of the MRA, Target Assembly, and the corresponding CV shield blocks. The MRA is supported by CV shield block #1, while the suspended Target Assembly is located 8 mm above CV shield block #4 (Figure 52). Both shield blocks #1 and #4 are located close to the proton beam and receive substantial heat loads (approximately 13 kw in block #1 and ~30 kW in block #4). Therefore, both blocks contain dedicated internal cooling channels.

A collision between the Target Assembly and the MRA could potentially fracture the hydrogen loop within the MRA, leading to leakage of liquid hydrogen. The STS core vessel normally operates in an inert environment, consisting of either rough vacuum or a helium atmosphere. Liquid hydrogen (critical temperature ≈ 33 K) operations at approximately 20 K, with a density of 72.9 kg/m^3 at about 14.5 bar. If liquid hydrogen were to leak into the core vessel environment, where the pressure is significantly lower, it would rapidly boil and expand (flash boiling). Surfaces near the leak could experience extremely low temperatures due to rapid hydrogen evaporation. In addition, the large volume expansion from liquid to gaseous hydrogen could produce a pressure excursion within the core vessel, although the vent systems are present to prevent over-pressurization. Hydrogen leakage also presents a flammability risk if hydrogen mixes with air or oxygen in concentrations between 4% and 75%. Although the core vessel normally operates under vacuum or helium, this risk could arise if the core vessel vacuum boundary were compromised or if hydrogen escaped into areas where air is present, such as maintenance spaces or the high bay.

In addition to preventing collisions, the spacing among the MRA, Target Assembly, and CV shield blocks must also consider the radiation streaming gap. Analyses indicate that a streaming gap of 25–35 mm would significantly increase neutron streaming and require the high bay floor shielding to be unnecessarily thick to maintain radiation limits ([S03120100-TRT10017](#)).

Therefore, the clearance around the Target Assembly must balance two competing requirements: (1) minimizing the streaming gap to reduce radiation leakage, and (2) maintaining sufficient clearance to prevent contact between the Target Assembly and the MRA during a seismic event.

As shown in Figure 51, the radial distance (streaming gap) between the MRA and the Target Assembly is 22.5 mm, with 10 mm clearance between the target wheel and the upper and lower MRA components. A seismic restraint pin at the bottom of the target shaft engages with a seismic restraint ring to limit lateral motion and prevent collision with the MRA during a seismic event (no contact during normal operation). The seismic restraint ring is mounted on CV shield blocks #3 and #4 (blocks #3 and #4 are symmetric).

As shown in Figure 52, the radial and vertical clearances between the seismic restraint pin and the restraint ring are 5 mm. During normal operation, the vertical displacement of CV shield block #1 (which supports the MRA as shown in Figure 50) due to thermal expansion and a 5 bar pressure in the internal cooling circuit is approximately 0.2 mm, as shown in Figure 53. Similarly, the CV shield block #4, located 8 mm below the target shaft and seismic restraint pin, experiences a vertical displacement of approximately 0.1 mm under the same thermal and pressure conditions, as shown in Figure 54.

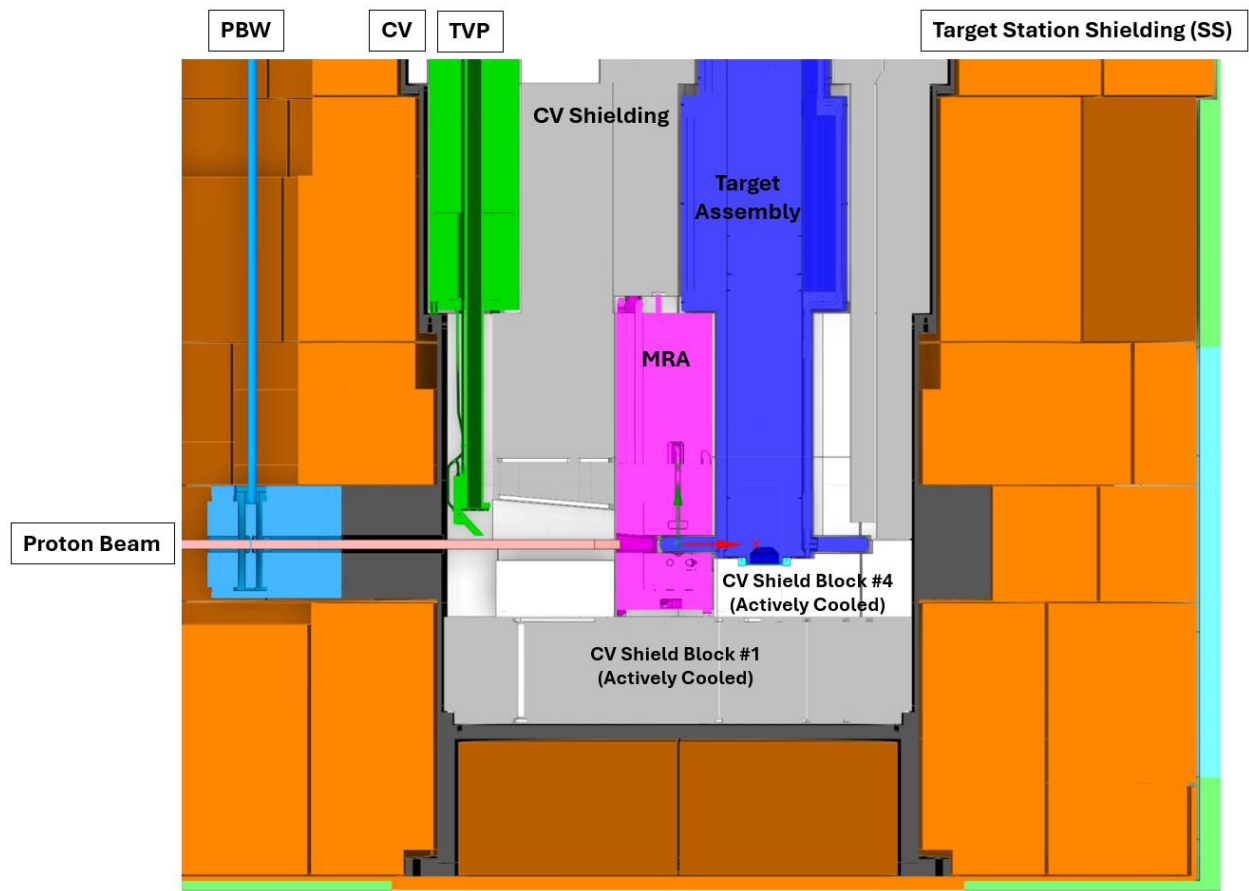


Figure 50. Proton beam, MRA, Target Assembly, and CV shield blocks.

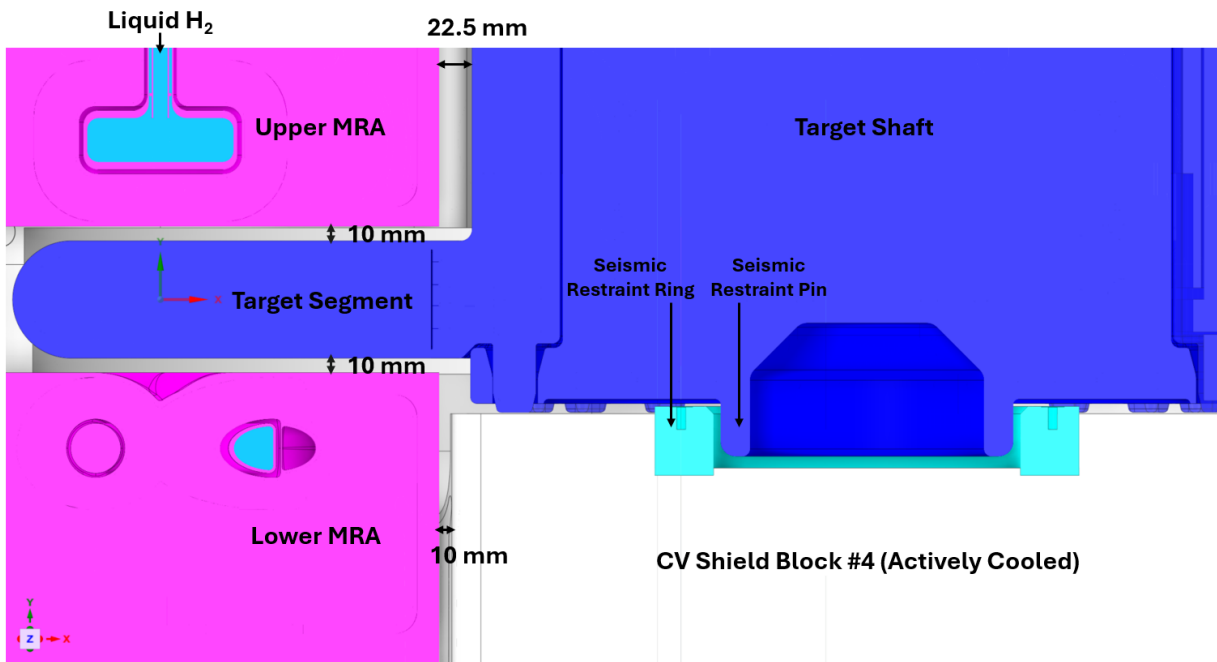


Figure 51. Clearance between Target Assembly and MRA.

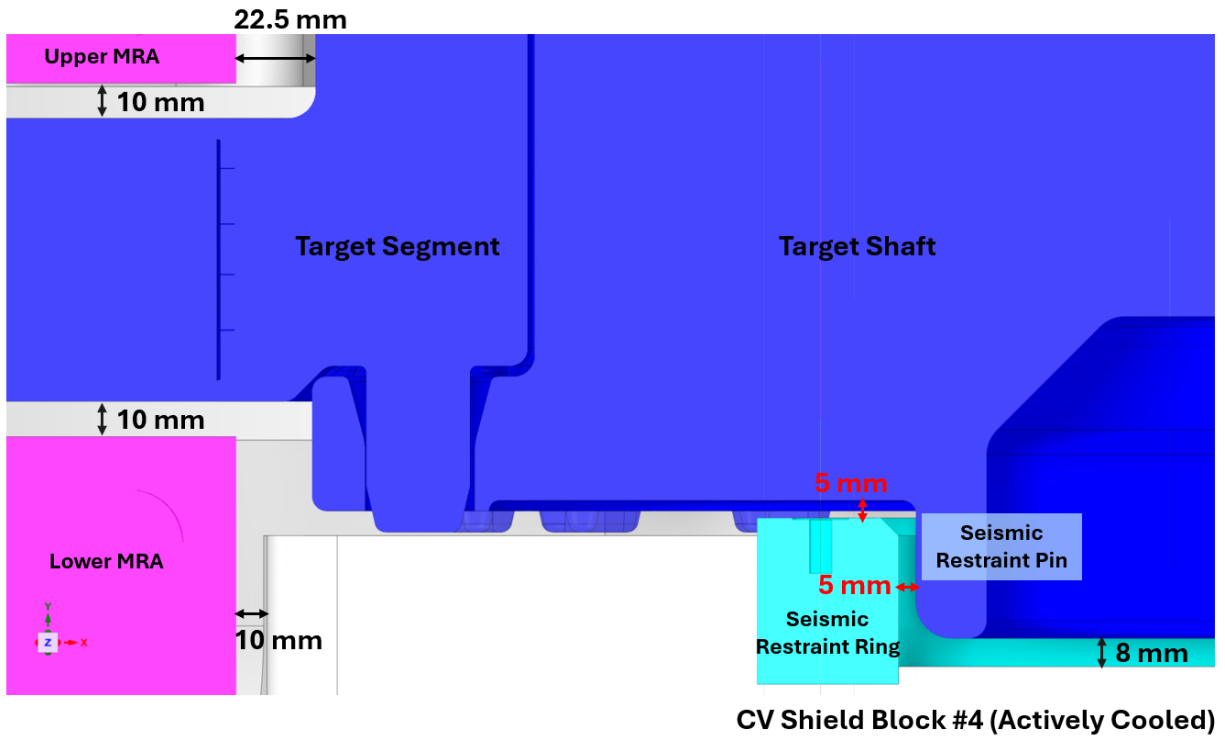


Figure 52. Clearance between Target Assembly and seismic restraint ring.

B: Static Structural

Directional Deformation_Y

Type: Directional Deformation(Y Axis)

Unit: mm

Global Coordinate System

Time: 1 s

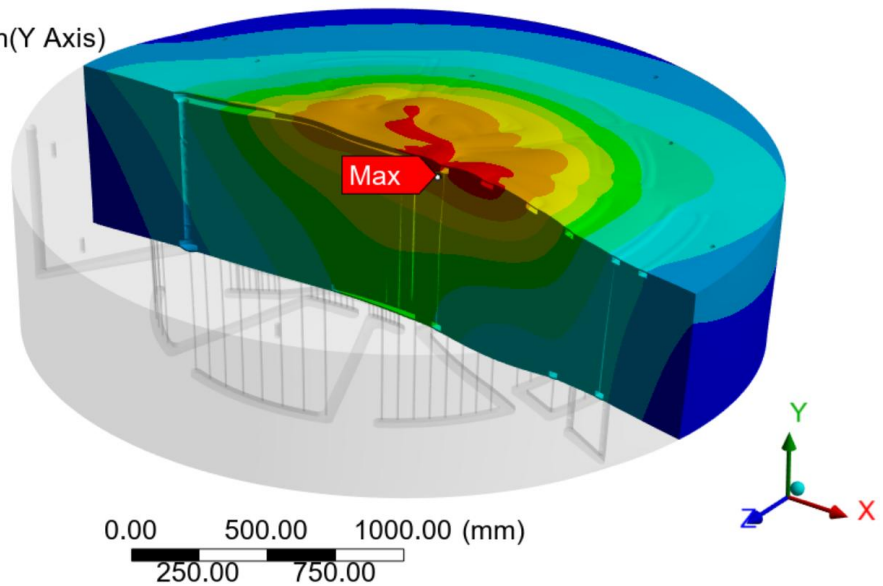
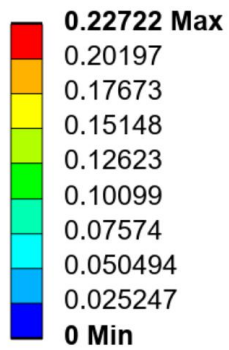


Figure 53. Vertical displacement of CV shield block #1 due to thermal expansion and 5 bar pressure in the internal cooling circuit.

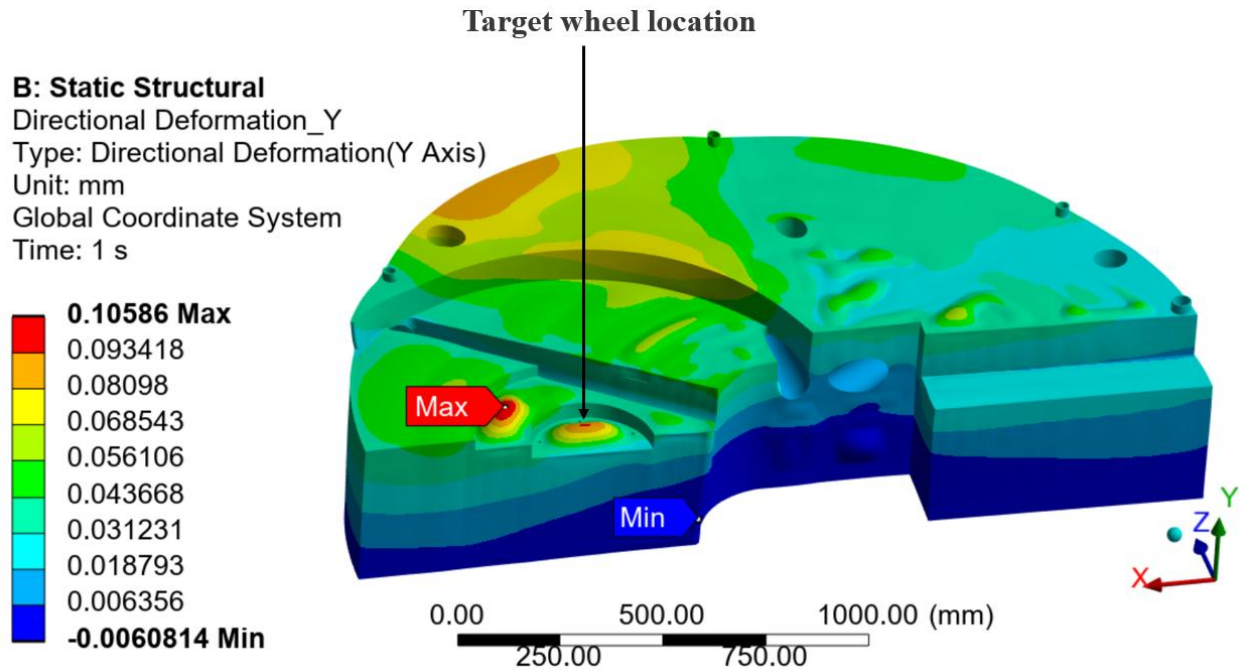


Figure 54. Vertical displacement of CV shield block #3 (symmetric to Shield Block #4) due to thermal expansion and 5 bar pressure in internal cooling circuit.

5.2 MESH

The mesh configuration for the target shaft is shown in Figure 55. Six prism layers are applied at the water boundary to resolve the thermal and hydrodynamic boundary layers near the wall. Approximately 30.9 million cells are used in the target shaft mesh. The wall y^+ values are mostly maintained below 5, as shown in Figure 56.

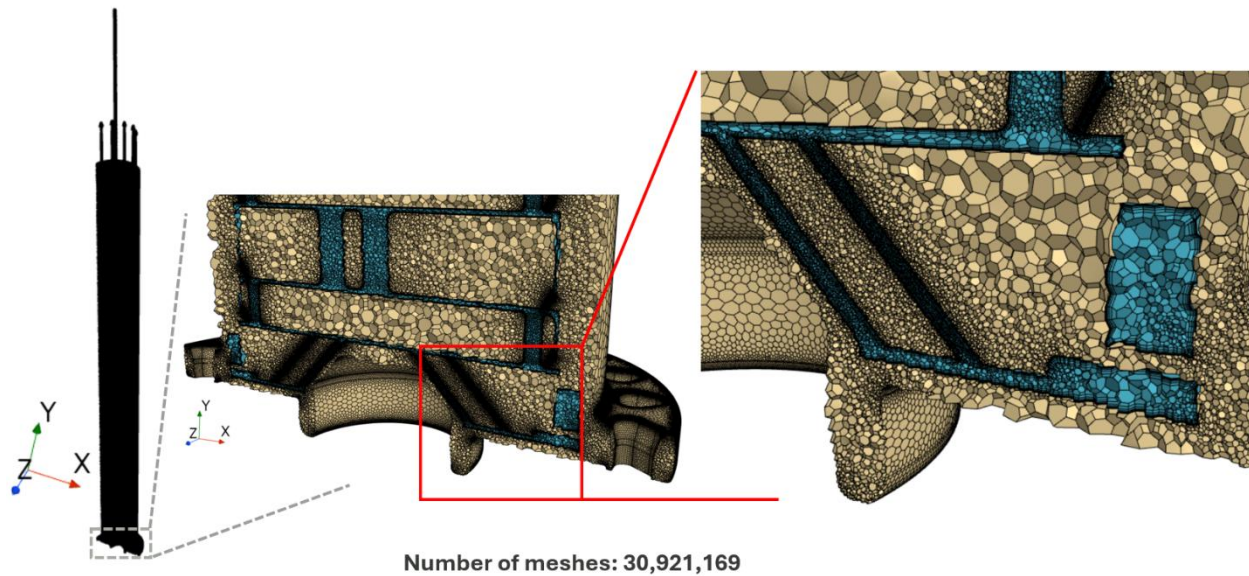


Figure 55. Mesh configuration of target shaft.

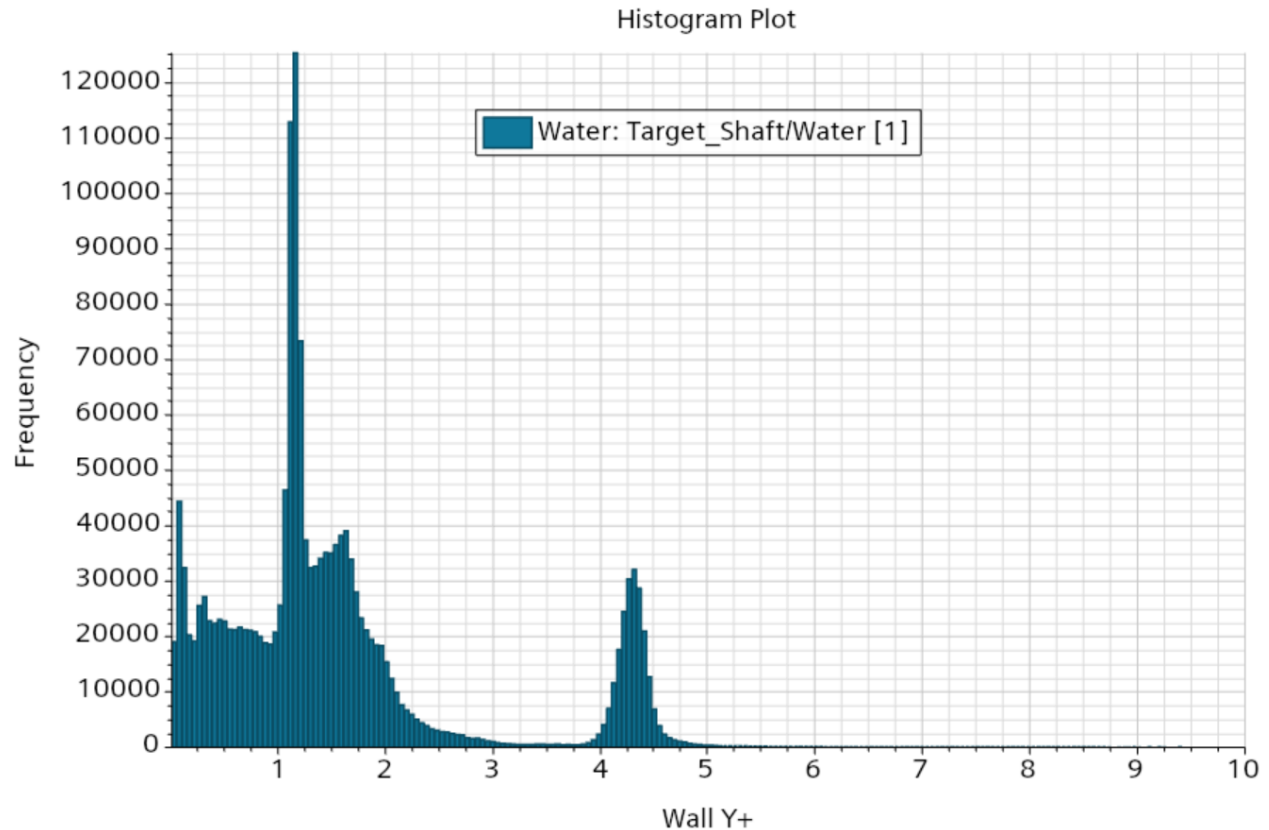


Figure 56. Wall Y^+ of target shaft.

5.3 HEAT LOAD FROM NOMINAL PROTON BEAM⁸

The energy deposition in the target shaft is obtained from MCNP neutronics calculations and is documented in report **S00000000-CAC10001**. Similar to the discussion in section 4.4, the MCNP provides the heating from a single pulse of a 15 Hz proton beam on the target shaft. Since the target shaft is not 20-segment symmetric, the approach of summing the fourth column of the CSV file is not appropriate. Instead, the heating data from a single pulse (reference frame) were rotated 19 additional times, with interpolation performed to map the data onto the coordinates of the reference frame. The data from all 20 frames were then summed (superimposed) to obtain the total heating of 20 pulses (one full revolution) on the target shaft.

Similar to the target segment analysis, the processed steady-state heating files from the nominal proton beam are imported into STAR-CCM+ and mapped onto the stainless-steel structure and the water regions, as shown in Figure 57, Figure 58, Figure 59, and Figure 60. The total heat deposited in the stainless-steel structure is 32.2 kW (4.6 % of the 700 kW beam power), while 1.3 kW is deposited in the water region.

The tops of the target segments are bolted to the target shaft near the segment inlets and outlets (as shown in Figure 9). The bottom pins of the target segments are inserted into triangular pockets on the target shaft

⁸ Heat Source file: https://windchill-prod.ornl.gov:8443/Windchill/app/#ptcl/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792CFD_Heat_Sources/1_Nominal_Beam.zip/Target_Shift

flange, as shown in Figure 57 and Figure 59. It should be noted that the primary mechanical load (i.e., the weight of the target segments) is supported by the bolts at the top. The triangular pockets on the flange are used to position the target segments during installation and to limit the radial movement of the segments during normal operation (45 RPM rotation rate). However, the flange is not intended to support the weight of the 20 target segments.

The target shaft flange is expected to have only line contact with the bottom pins of the target segments. As a result, the heat transfer between the segment pins and the shaft flange is very limited. Therefore, the heat transfer analysis of these two components can be treated separately.

Figure 59 shows the geometry of the target segment and the heat source distribution in the target shaft. As shown, the region near the target block (proton beam elevation) experiences significantly higher heat loads, including the shaft flange and the lower section of the target shaft. To remove heat from this high-power region, three planar water channels are incorporated into the lower shaft region, and one of these channels passes directly through the peak heating region (Figure 59).

For the region above the target block, three additional layers of planar water channels are distributed according to the heat source distribution. Because the shaft flange is used to constrain and position the target segments, its structural integrity and mechanical strength during normal operation are critical. The flange is also located close to the proton beam and therefore receives relatively high energy deposition.

During the design iterations, several materials—including aluminum, Inconel, CuCrZr and SS316—as well as different flange geometries and cooling channel designs were evaluated (APPENDIX F). The final flange design uses SS316 (the same material as the rest of the shaft components) and incorporates internal cooling channels, as shown in Figure 47 and Figure 48.

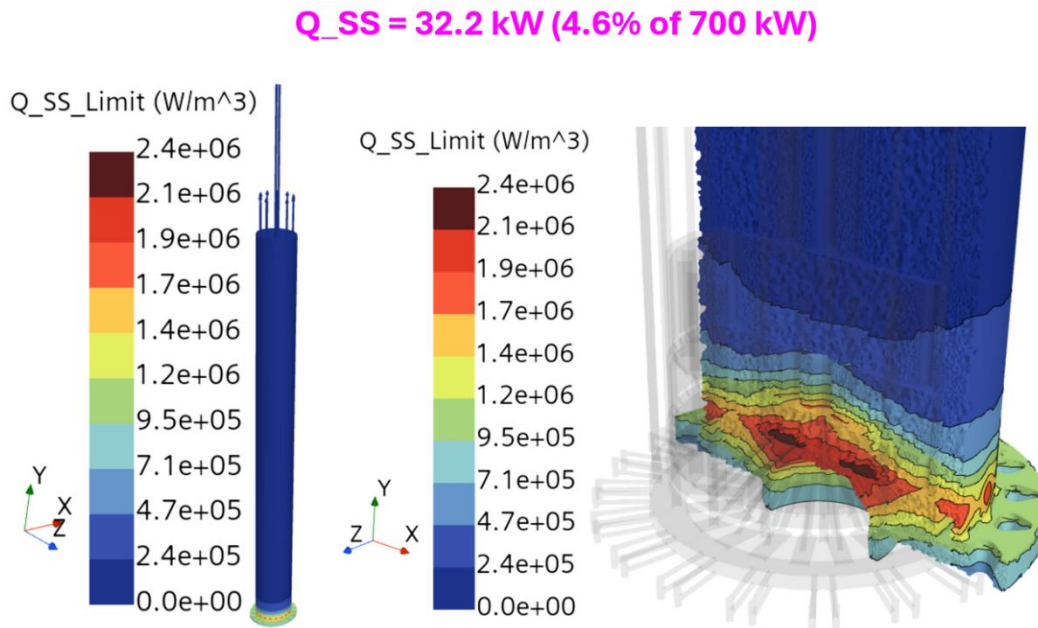


Figure 57. Heat source in the stainless steel region of the target shaft for the nominal beam case.

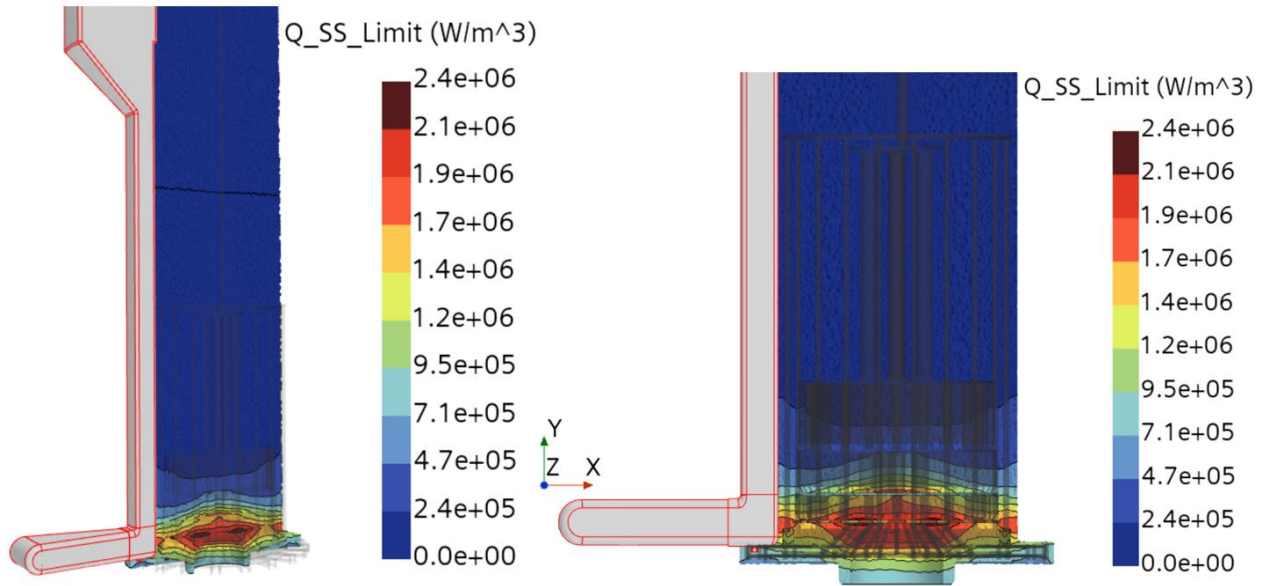


Figure 58. Geometry of the target segment and heat source in the stainless steel region of the target shaft for the nominal beam case.

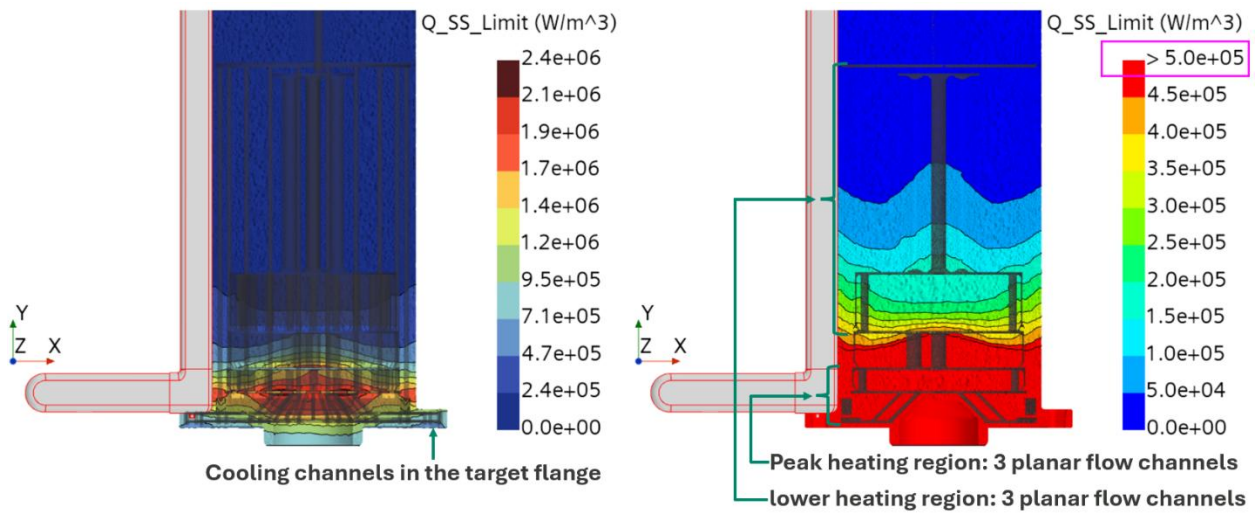


Figure 59. Geometry of the target segment, cooling channel, and heat source in the stainless steel region of the target shaft for the nominal beam case.

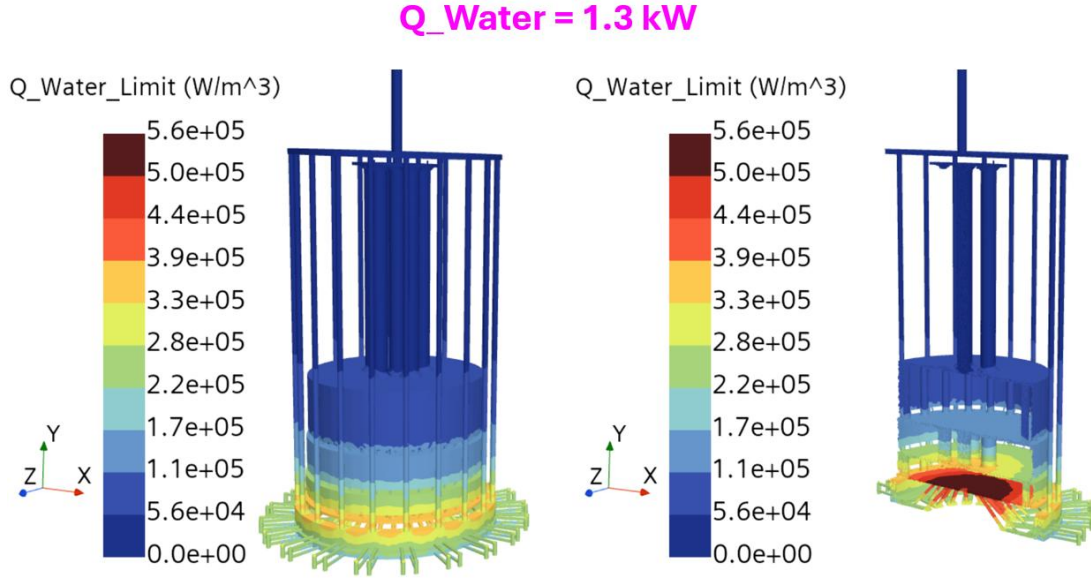


Figure 60. Heat source distribution in the water region of the target shaft for the nominal beam case.

5.4 SOLVER AND BOUNDARY CONDITIONS

As shown in Figure 47, an inlet flow rate of 0.47 kg/s (7.5 GPM) water at 32.22 °C is specified at the inlet of the target shaft. The Reynolds number in the target shaft ranges from 2,500 to 5,000 (hydraulic characteristic length scale: planar channel thickness = 5 mm), as shown in Figure 61. Therefore, a turbulent flow model is used.

The Coriolis force is included in the CFD models by assigning a rotating reference frame centered at ($x = 0.483$ m, $y = 0$, $z = 0$). The boundary conditions and the numerical solvers used in STAR-CCM+ are summarized in Table 9. The realizable k - ϵ two-layer turbulence model with two-layer all- y^+ wall treatment, together with a segregated solver, is employed.

The reference pressure at the outlet is set to 2.5 bar (250 kPa). Considering the hydrostatic head, the pressure at the target block elevation is approximately 3 bar (300 kPa), corresponding to a boiling point of 133.5 °C. This temperature represents the maximum allowable water temperature for the STS target without water boiling.

As shown in Figure 52, there is an 8 mm gap filled with void or helium (core vessel environment) between the bottom of the target assembly and the closest core vessel shielding block. Therefore, the bottom surface of the shaft pin is assumed to be adiabatic.

Table 9. Solvers and boundary conditions for the target shaft.

Time model	Steady state
Flow and energy model	Segregated solver
Turbulence model	Realizable k - ϵ two-layer
Wall treatment	Two-layer all y^+
Inlet mass flow rate	0.47 kg/s (7.5 GPM)

Inlet temperature	32.22 °C (90 °F)
Reference pressure	2.5 bar
Boiling temperature @ 3 bar	133.5 °C

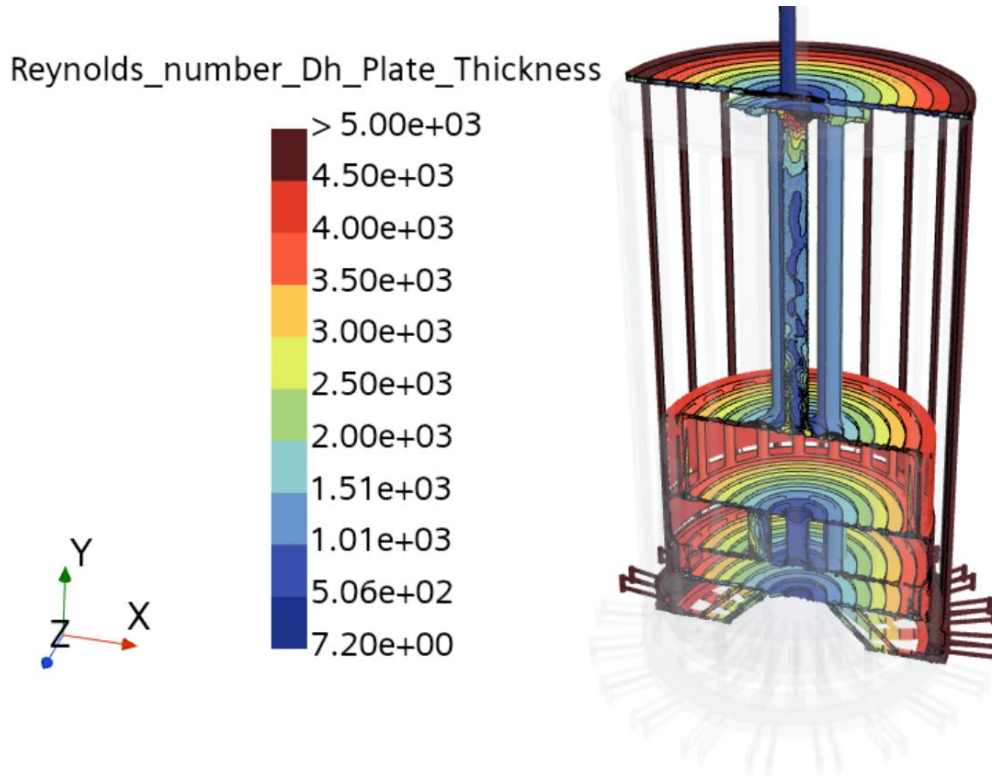


Figure 61. Renolds number in the target shaft.

5.5 RESULTS WITH NOMINAL BEAM POWER

As shown in Figure 62, the pressure drop through the target shaft is 4.93 psi, which is 3.5 psi lower than the 8.42 psi pressure drop through the target segment (Figure 22). As indicated in section 3, GEOMETRY DESCRIPTION, due to the uniform inlet velocity assumption, the pressure drops obtained from the individual CFD simulations should be considered reference values for cooling channel optimization. However, they are insufficient for accurately predicting the total system pressure drop or addressing the flow balance concern. The flow balance must ultimately be assessed using a comprehensive CFD model that accounts for realistic inlet flow conditions affecting the segment and shaft supplies.

As shown in Figure 63, the peak stainless-steel temperature is 114.0 °C. The temperature of the stainless-steel flange that constrains and positions the target segments ranges from 43 °C to 67 °C, as shown in Figure 64. As shown in Figure 65, the peak water temperature is 81 °C, which is well below the boiling point of 133.5 °C.

$$\Delta P_{inlet-outlet} = 0.34 \text{ bar} (= 34 \text{ kPa} = 4.93 \text{ psi} = 0.34 \text{ atm})$$

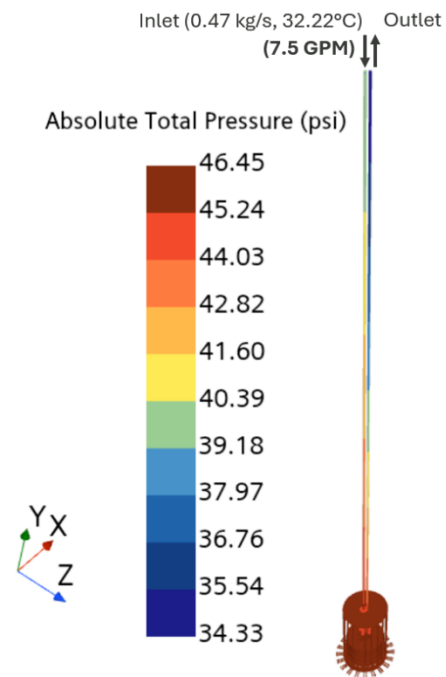


Figure 62. Pressure distribution in the target shaft.

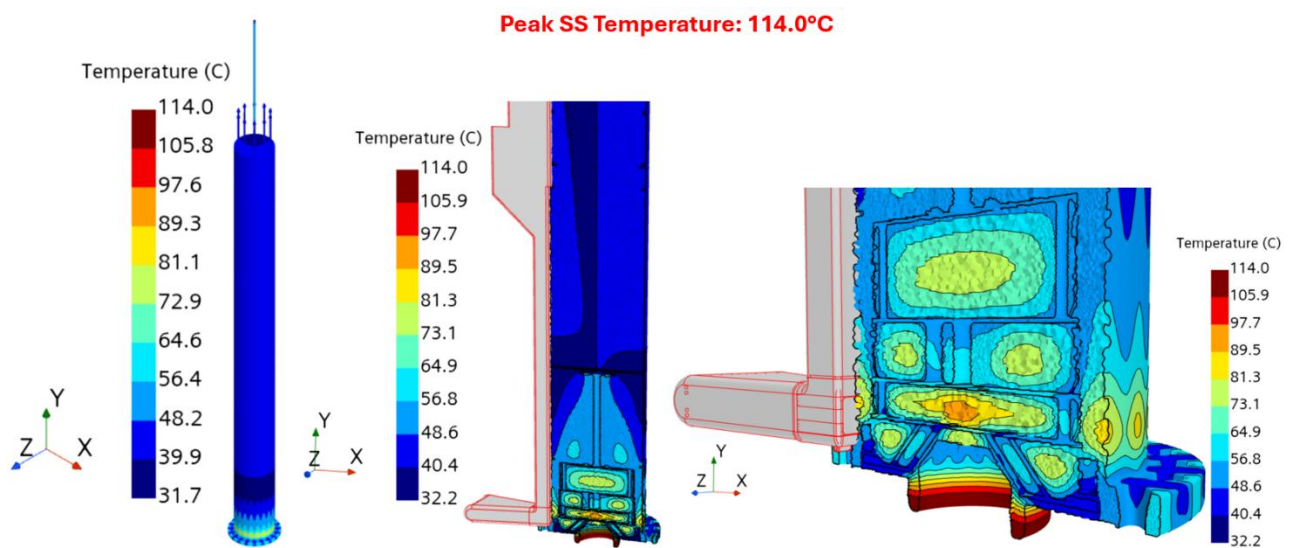


Figure 63. Target shaft temperature distribution.

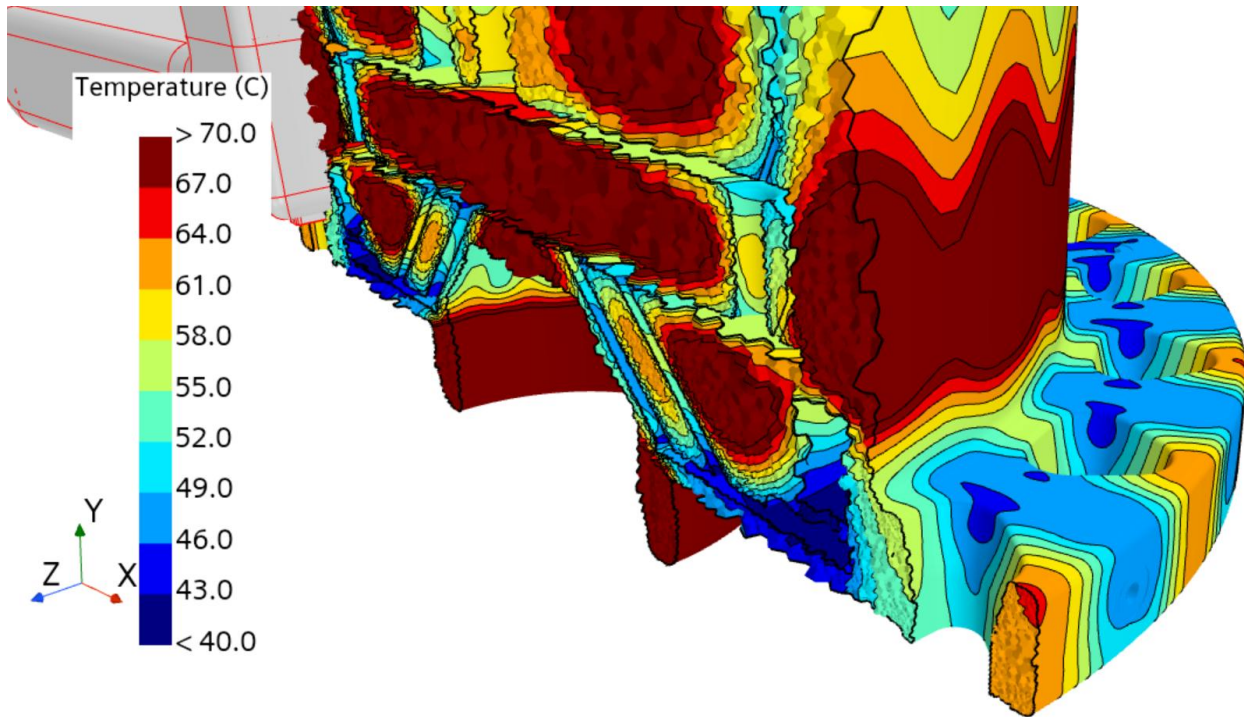


Figure 64. Temperature distribution in the target shaft flange.

Peak Water Temperature: 81.0°C

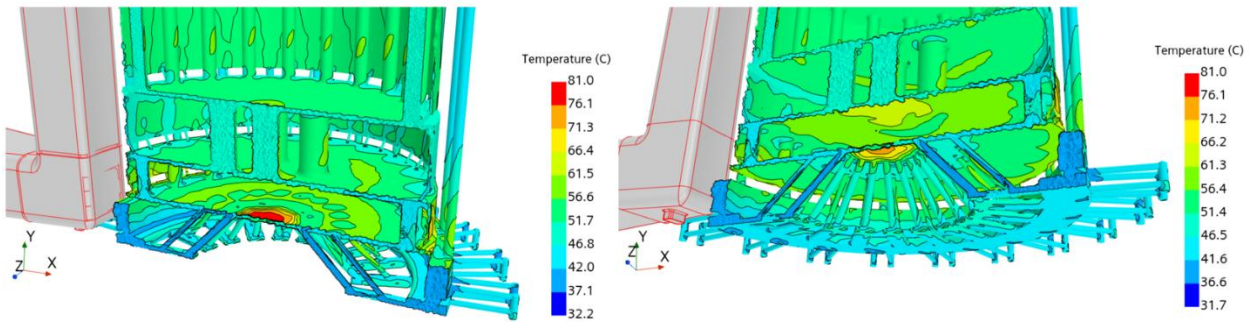


Figure 65. Water temperature distribution in the target shaft.

5.6 EFFECTS OF NOMINAL, OVER-FOCUSED, OFFSET, AND DIFFUSED BEAM PROFILES ON THE TARGET SHAFT

Section 4.6 discussed the effects of nominal, over-focused, offset, and diffused beam profiles on the target segments. These beam profiles also affect the target shaft, which is located at the center of the target assembly. The lower section of the shaft is shielded by the 20 target segments (Figure 3).

The heat deposition in the target shaft for the different beam profiles is shown in Figure 66. As illustrated, the heat load in the shaft is strongly influenced by the beam footprint on the target segments and the resulting shielding effect. The over-focused beam concentrates energy over a smaller footprint on the

target segments, thereby reducing heat deposition in the shaft. In contrast, the diffused beam spreads energy over a wider area, allowing more secondary particles to pass through the 5 mm gaps between the segments (Figure 4) and deposit energy in the shaft. When the beam is offset downward by 8.5 mm and to the left by 12 mm, it shifts closer to the seismic restraint pin, a solid SS316 component without internal cooling channels (incorporating cooling channels would replace part of the SS316 with water, thereby reducing the local energy deposition). This results in increased local energy deposition in that region.

The corresponding temperature distributions in the target shaft are shown in Figure 67 and Figure 68, with the water temperature distributions shown in Figure 69. The temperature fields follow trends consistent with the heat deposition. In particular, the offset beam results in the highest local temperature due to elevated heating in the uncooled seismic restraint pin. The over-focused beam produces the lowest temperatures due to enhanced shielding by the target segments. For the diffused beam, although the total heat load is higher, the additional heat is deposited near the target segment elevation and is effectively removed by the cooling channels, resulting in only moderate increases in temperature.

The heat deposition and corresponding peak temperatures for all beam profiles are summarized in Table 10. As shown, the over-focused beam yields the lowest heat load in the shaft (32.7 kW), while the diffused beam produces the highest total heat deposition (37.9 kW). The offset beam results in the highest peak stainless-steel temperature (154.6 °C) due to localized heating in the seismic restraint pin. Despite these variations, the peak water temperature remains below 81 °C for all cases, providing a safety margin of more than 50 °C relative to the boiling point of 133.5 °C at 3 bar.

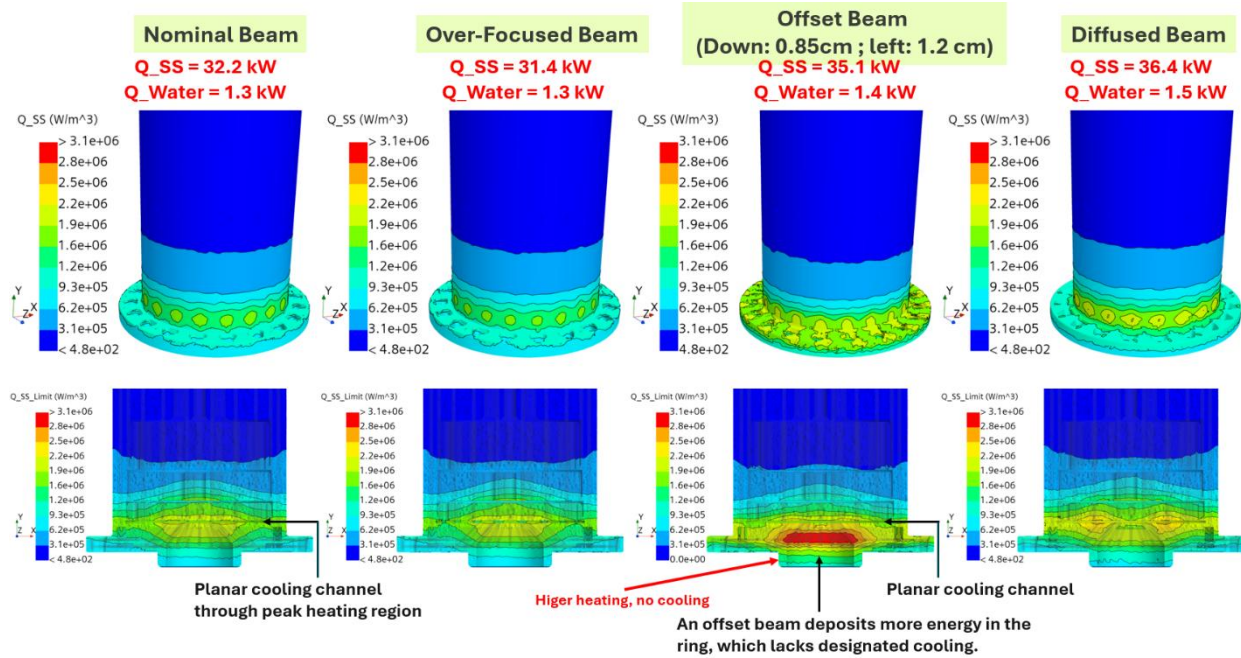


Figure 66. Heat source distributions in the target shaft under nominal, over-focused, offset, and diffused beam profiles.⁹

⁹ Heat Source file: <https://windchill-prod.ornl.gov:8443/Windchill/app/#ptcl/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792>
CFD_Heat_Sources/
1_Nominal_Beam.zip/Target_Shaft
2_OverFocused_Beam.zip/Target_Shaft
3_Offset_Beam.zip/Target_Shaft
4_Diffused_Beam.zip/Target_Shaft

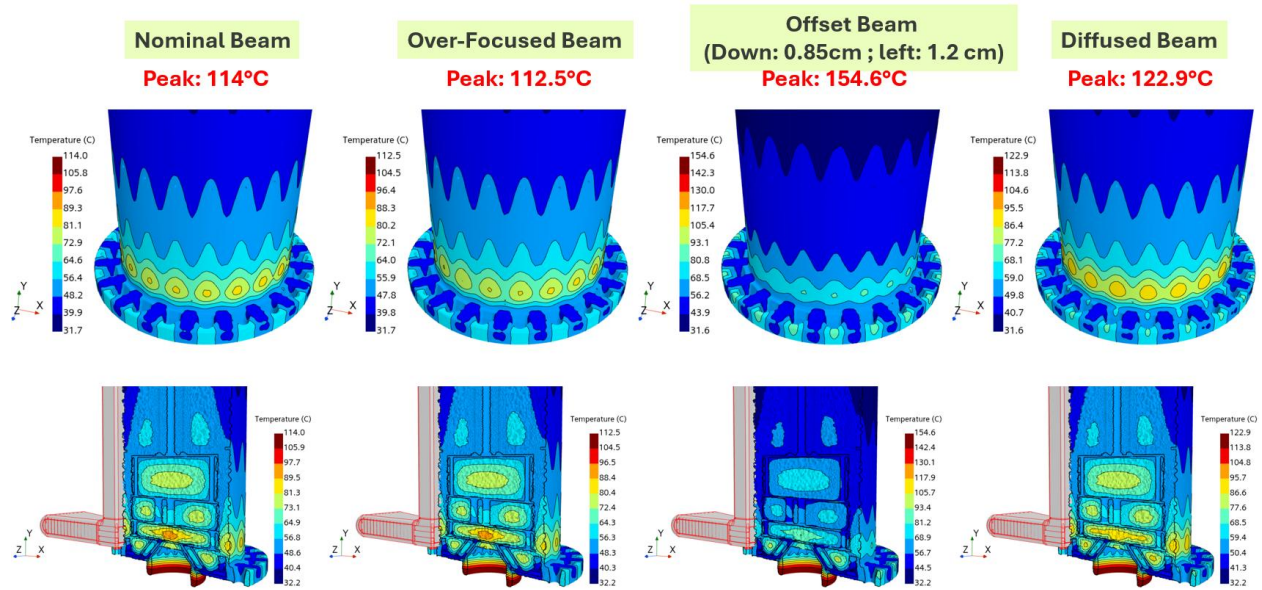


Figure 67. Temperature distributions in the target shaft under nominal, over-focused, offset, and diffused beam profiles.

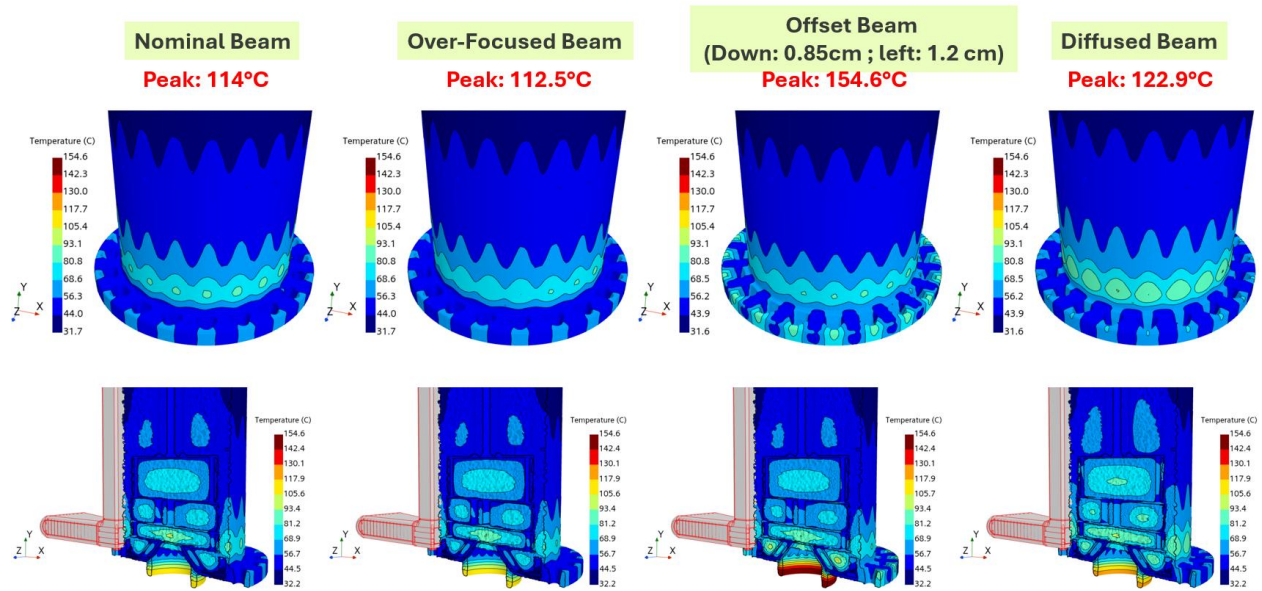


Figure 68. Temperature distributions in the target shaft under nominal, over-focused, offset, and diffused beam profiles (same color scale).

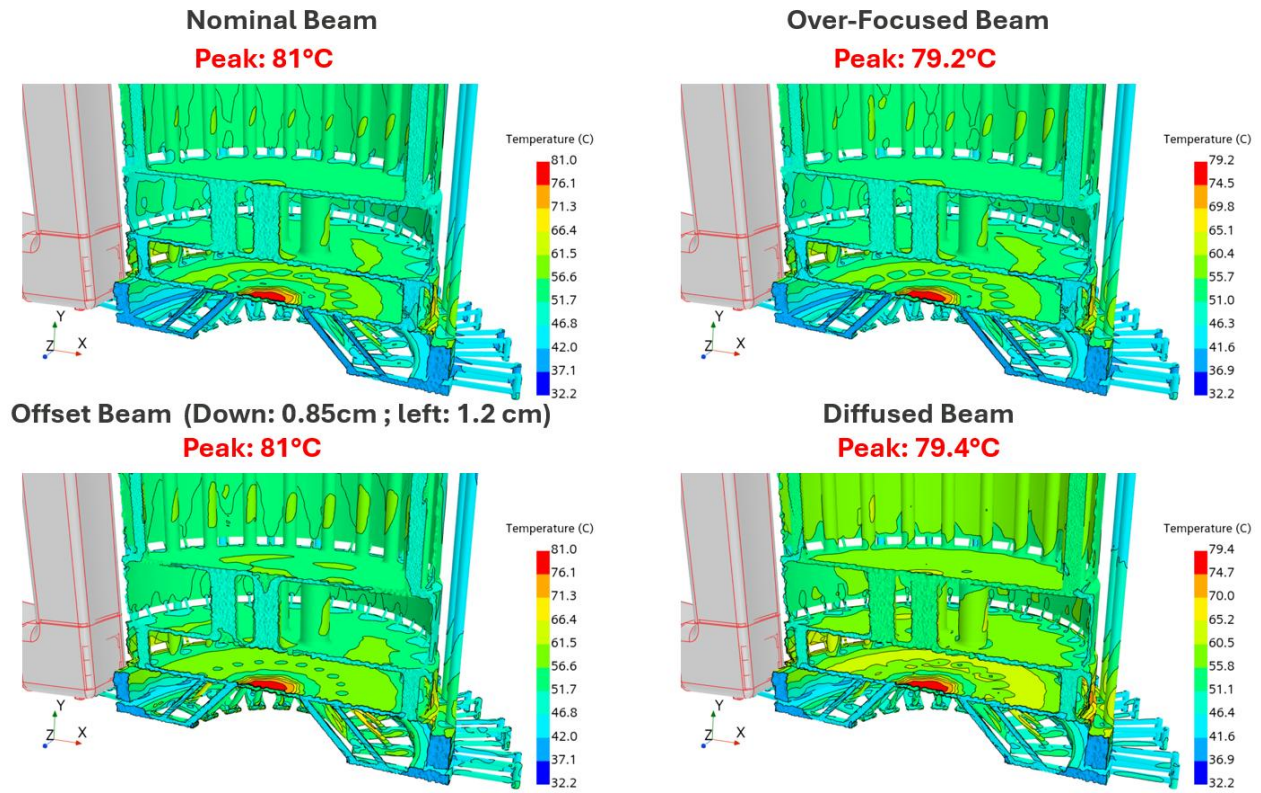


Figure 69. Water temperature distributions in the target shaft under nominal, over-focused, offset, and diffused beam profiles.

Table 10. Heat deposition and peak temperatures in the target shaft under different beam profiles.

Heat Deposition and Peak Temperature in Target Shaft (Boiling Temperature = 133.5°C at 3 bar)						
Beam Profile	Heat Deposition			Temperature Response		
	Total Heat (kW)	SS316 (kW)	Water (kW)	Peak SS316 Temp (°C)	Peak Water Temp (°C)	Margin to Boiling (°C)
Nominal	33.5	32.2	1.3	114	81	52.5
Over-Focused	32.7	31.4	1.3	112.5	79.2	54.3
Offset	36.5	35.1	1.4	154.6	81	52.5
Diffused	37.9	36.4	1.5	122.9	79.4	54.1

6. MAINTENANCE TEMPERATURE

6.1 DECAY HEAT

In the Second Target Station (STS) at ORNL, high-energy proton beam (1.3 GeV, 700 kW) interacts with the tungsten target segments to produce neutrons through spallation reactions. In addition to prompt energy deposition during beam operation, radioactive isotopes are generated within the target materials. Following beam shutdown, these activated materials continue to release energy in the form of decay heat, which decreases over time but can remain significant for extended periods.

The magnitude and temporal behavior of decay heat depend on the material composition (e.g., tungsten, tantalum, Inconel, and stainless steel) and the irradiation history (beam power, beam profile, irradiation duration, and time since shutdown). Immediately after shutdown, decay heat can represent a non-negligible fraction of the operating power and contributes to elevated temperatures in the target segments even in the absence of beam heating. Over time, the decay heat decreases as short-lived isotopes decay, while longer-lived isotopes (e.g., tantalum-182 with a half-life of 114.74 days) sustain residual heating over hours to days.

Accurate prediction of decay heat is critical for the design and operation of the STS target assembly, particularly for cooling system performance, thermal stress evaluation, and safety analysis. It is especially important for maintenance and handling operations, which are typically performed after beam shutdown. During these periods, the target segments may still be at elevated temperatures due to decay heat, posing potential risks such as overheating, thermal damage to components, or safety hazards for remote handling systems.

Understanding the decay heat as a function of time enables engineers to:

- determine appropriate **cool-down times** before maintenance,
- ensure **safe handling and storage conditions**,
- evaluate the need for **continued cooling during shutdown**, and
- assess **thermal margins** under off-normal or loss-of-cooling scenarios.

Therefore, decay heat analysis is an essential component of the thermal and safety evaluation of the STS target system, ensuring reliable operation and safe maintenance of the highly activated components.

Several tools are available for decay heat evaluation. One approach uses MCNP coupled with CINDER ([12], [13], [14]), in which MCNP calculates the particle fluxes and reaction rates within the geometry, and CINDER uses these reaction rates to determine isotope inventories and the corresponding decay heat. In this approach, decay heat is assumed to be deposited locally at the site of activation.

FLUKA ([15], [16]) is also a Monte Carlo code but integrates both particle transport and decay physics. In FLUKA, beta particles, gamma rays, and other secondary radiation are explicitly transported, allowing energy released from radioactive decay to be deposited non-locally within the geometry. As a result, FLUKA can capture spatial variations in energy deposition caused by decay particle transport, which could be used to compute temperature distributions.

Although both approaches can be used for decay heat calculations, the majority of decay heat in the STS target segment is generated by beta decay and associated gamma emission from activation products in tungsten and tantalum. Beta particles (electrons) carry electric charge and interact strongly with matter, resulting in very short ranges in high-density materials such as tungsten, tantalum, and Inconel 718, typically on the order of microns to millimeters. In the STS target design, some beta particles may traverse the thin 0.5 mm tantalum interlayers (Figure 10 and Figure 11), but most of the beta energy is still deposited locally within the target block.

Gamma rays can travel longer distances and contribute to non-local energy deposition; however, their transport is significantly attenuated within the high-Z materials of the target assembly. Therefore, the overall spatial redistribution of decay heat due to particle transport is limited.

The STS target segment consists of multiple layers of high thermal conductivity materials, including tungsten and tantalum, which promote efficient heat conduction within the target block. In addition, the target is encapsulated by tantalum cladding and enclosed within an Inconel 718 shroud, forming a compact, thermally well-coupled structure. Due to the relatively high thermal conductivity of tungsten and tantalum, the temperature within the target block is relatively uniform after beam shutdown when heating is driven solely by decay heat. As a result, the thermal response of the target block is primarily governed by the total heat load rather than its exact spatial distribution.

Based on these considerations, the use of MCNP/CINDER for decay heat calculations is appropriate for the STS target analysis and provides a conservative evaluation of post-shutdown temperature. This approach assumes local deposition of all decay energy, including gamma rays, without explicitly tracking their transport through the geometry. Despite this approximation, it accurately predicts the total decay heat, which is the primary parameter of interest for thermal analysis and cooling system design.

Therefore, MCNP/CINDER provides a computationally efficient and sufficiently accurate approach for evaluating decay heat in the STS target block. Detailed results are documented in report [S03120100-TRT10024](#).

Table 11. Decay heat in tungsten (W) blocks of a single target segment over 0 – 48 hours[S03120100-TRT10024].

Decay Time (h)	W_01 (W)	W_02 (W)	W_03 (W)	W_04 (W)	W_05 (W)	W_06 (W)	W_07 (W)	W_08 (W)	W_09 (W)	W_10 (W)	W_11 (W)	W_12 (W)	W_13 (W)	W_14 (W)	W_15 (W)	W_Total (W)
0.00	15.08	26.73	24.54	21.90	19.18	16.51	14.04	11.80	9.83	8.18	6.82	5.69	4.79	4.11	2.44	191.64
1.00	5.91	11.11	10.74	10.03	9.16	8.18	7.19	6.23	5.32	4.52	3.84	3.25	2.77	2.42	1.50	92.17
2.00	5.09	9.66	9.41	8.86	8.15	7.32	6.47	5.63	4.82	4.12	3.50	2.97	2.54	2.22	1.39	82.16
3.00	4.68	8.92	8.72	8.24	7.60	6.85	6.07	5.30	4.54	3.88	3.31	2.81	2.40	2.11	1.32	76.77
4.00	4.40	8.41	8.25	7.81	7.22	6.53	5.79	5.06	4.34	3.72	3.17	2.69	2.30	2.02	1.27	73.00
5.00	4.19	8.03	7.89	7.48	6.93	6.27	5.57	4.86	4.18	3.58	3.05	2.60	2.22	1.95	1.23	70.03
6.00	4.02	7.72	7.59	7.21	6.68	6.04	5.37	4.70	4.04	3.46	2.95	2.51	2.15	1.89	1.19	67.52
7.00	3.88	7.45	7.33	6.96	6.46	5.85	5.20	4.55	3.91	3.35	2.86	2.43	2.08	1.83	1.16	65.31
8.00	3.75	7.21	7.10	6.75	6.26	5.67	5.04	4.41	3.80	3.25	2.78	2.36	2.02	1.78	1.12	63.32
9.00	3.64	7.00	6.89	6.55	6.08	5.50	4.90	4.29	3.69	3.16	2.70	2.30	1.97	1.73	1.09	61.47
10.00	3.53	6.80	6.70	6.37	5.91	5.36	4.76	4.17	3.59	3.08	2.62	2.23	1.91	1.68	1.06	59.77
11.00	3.44	6.61	6.51	6.20	5.75	5.21	4.64	4.06	3.49	2.99	2.55	2.18	1.86	1.64	1.03	58.17
12.00	3.35	6.44	6.35	6.04	5.61	5.08	4.52	3.96	3.40	2.92	2.49	2.12	1.81	1.59	1.01	56.67
13.00	3.26	6.28	6.19	5.89	5.46	4.95	4.40	3.86	3.32	2.84	2.43	2.07	1.77	1.55	0.98	55.24
14.00	3.18	6.12	6.04	5.74	5.33	4.83	4.30	3.76	3.23	2.77	2.37	2.01	1.72	1.52	0.95	53.88
15.00	3.11	5.98	5.90	5.61	5.20	4.71	4.19	3.67	3.16	2.70	2.31	1.96	1.68	1.48	0.93	52.59
16.00	3.04	5.85	5.76	5.48	5.08	4.60	4.09	3.58	3.08	2.64	2.25	1.92	1.64	1.44	0.91	51.36
17.00	2.97	5.72	5.63	5.35	4.97	4.50	4.00	3.50	3.01	2.58	2.20	1.87	1.60	1.41	0.89	50.18
18.00	2.90	5.59	5.51	5.23	4.85	4.39	3.91	3.42	2.94	2.52	2.15	1.83	1.56	1.37	0.86	49.05
19.00	2.84	5.48	5.39	5.12	4.75	4.30	3.82	3.34	2.87	2.46	2.10	1.79	1.53	1.34	0.84	47.97
20.00	2.78	5.36	5.28	5.01	4.65	4.20	3.74	3.27	2.81	2.41	2.05	1.75	1.49	1.31	0.82	46.93
21.00	2.73	5.25	5.17	4.91	4.55	4.11	3.66	3.20	2.75	2.35	2.01	1.71	1.46	1.28	0.80	45.94
22.00	2.67	5.15	5.07	4.81	4.46	4.03	3.58	3.13	2.69	2.30	1.96	1.67	1.43	1.25	0.78	44.97
23.00	2.62	5.05	4.97	4.72	4.37	3.95	3.50	3.06	2.63	2.25	1.92	1.63	1.40	1.22	0.77	44.05
24.00	2.57	4.95	4.87	4.62	4.28	3.87	3.43	3.00	2.57	2.20	1.88	1.60	1.37	1.20	0.75	43.16
25.00	2.52	4.86	4.78	4.54	4.19	3.79	3.36	2.94	2.52	2.16	1.84	1.56	1.34	1.17	0.73	42.30
26.00	2.48	4.77	4.69	4.45	4.11	3.71	3.29	2.88	2.47	2.11	1.80	1.53	1.31	1.15	0.72	41.48
27.00	2.43	4.69	4.61	4.37	4.04	3.64	3.23	2.82	2.42	2.07	1.76	1.50	1.28	1.12	0.70	40.68
28.00	2.39	4.60	4.53	4.29	3.96	3.57	3.17	2.76	2.37	2.03	1.73	1.47	1.25	1.10	0.68	39.91
29.00	2.35	4.52	4.45	4.21	3.89	3.51	3.11	2.71	2.32	1.99	1.69	1.44	1.23	1.08	0.67	39.16
30.00	2.31	4.45	4.37	4.14	3.82	3.44	3.05	2.66	2.28	1.95	1.66	1.41	1.20	1.05	0.66	38.44
31.00	2.27	4.37	4.30	4.07	3.75	3.38	2.99	2.61	2.24	1.91	1.63	1.38	1.18	1.03	0.64	37.74
32.00	2.23	4.30	4.23	4.00	3.68	3.32	2.94	2.56	2.19	1.87	1.60	1.36	1.16	1.01	0.63	37.07
33.00	2.19	4.23	4.16	3.93	3.62	3.26	2.88	2.51	2.15	1.84	1.56	1.33	1.13	0.99	0.61	36.42
34.00	2.16	4.17	4.09	3.86	3.56	3.20	2.83	2.47	2.11	1.80	1.54	1.30	1.11	0.97	0.60	35.78
35.00	2.13	4.10	4.03	3.80	3.50	3.15	2.78	2.42	2.07	1.77	1.51	1.28	1.09	0.95	0.59	35.17
36.00	2.09	4.04	3.96	3.74	3.44	3.09	2.73	2.38	2.04	1.74	1.48	1.26	1.07	0.94	0.58	34.58
37.00	2.06	3.98	3.90	3.68	3.39	3.04	2.69	2.34	2.00	1.71	1.45	1.23	1.05	0.92	0.57	34.00
38.00	2.03	3.92	3.84	3.63	3.33	2.99	2.64	2.30	1.97	1.68	1.43	1.21	1.03	0.90	0.55	33.45
39.00	2.00	3.86	3.79	3.57	3.28	2.94	2.60	2.26	1.93	1.65	1.40	1.19	1.01	0.88	0.54	32.91
40.00	1.97	3.81	3.73	3.52	3.23	2.90	2.56	2.22	1.90	1.62	1.38	1.17	0.99	0.87	0.53	32.38
41.00	1.94	3.75	3.68	3.46	3.18	2.85	2.51	2.18	1.87	1.59	1.35	1.15	0.98	0.85	0.52	31.87
42.00	1.92	3.70	3.63	3.41	3.13	2.81	2.47	2.15	1.84	1.56	1.33	1.13	0.96	0.84	0.51	31.38
43.00	1.89	3.65	3.58	3.36	3.09	2.76	2.44	2.11	1.81	1.54	1.31	1.11	0.94	0.82	0.50	30.90
44.00	1.86	3.60	3.53	3.32	3.04	2.72	2.40	2.08	1.78	1.51	1.28	1.09	0.93	0.81	0.49	30.44
45.00	1.84	3.55	3.48	3.27	3.00	2.68	2.36	2.05	1.75	1.49	1.26	1.07	0.91	0.79	0.48	29.98
46.00	1.81	3.50	3.43	3.23	2.95	2.64	2.33	2.01	1.72	1.46	1.24	1.05	0.90	0.78	0.47	29.55
47.00	1.79	3.46	3.39	3.18	2.91	2.60	2.29	1.98	1.69	1.44	1.22	1.04	0.88	0.77	0.47	29.12
48.00	1.77	3.42	3.35	3.14	2.87	2.57	2.26	1.95	1.67	1.42	1.20	1.02	0.87	0.75	0.46	28.70

Table 12. Decay heat in tantalum (Ta) plates of a single target segment over 0 – 48 hours[S03120100-TRT10024].

Decay Time (h)	Ta_01 (W)	Ta_02 (W)	Ta_03 (W)	Ta_04 (W)	Ta_05 (W)	Ta_06 (W)	Ta_07 (W)	Ta_08 (W)	Ta_09 (W)	Ta_10 (W)	Ta_11 (W)	Ta_12 (W)	Ta_13 (W)	Ta_14 (W)	Ta_15 (W)	Ta_Total (W)
0	1.80	1.98	1.93	1.87	1.76	1.63	1.48	1.33	1.18	1.04	0.91	0.80	0.70	0.66	63.41	82.47
1	1.45	1.66	1.65	1.63	1.56	1.46	1.35	1.23	1.09	0.97	0.86	0.75	0.67	0.63	60.96	77.91
2	1.41	1.62	1.62	1.60	1.54	1.45	1.34	1.21	1.08	0.96	0.85	0.75	0.66	0.62	60.67	77.38
3	1.40	1.61	1.60	1.59	1.52	1.44	1.33	1.21	1.08	0.96	0.85	0.75	0.66	0.62	60.47	77.06
4	1.38	1.59	1.59	1.58	1.52	1.43	1.32	1.20	1.07	0.96	0.84	0.74	0.66	0.62	60.37	76.88
5	1.37	1.58	1.58	1.57	1.51	1.42	1.32	1.20	1.07	0.95	0.84	0.74	0.66	0.62	60.28	76.72
6	1.37	1.58	1.58	1.56	1.50	1.42	1.31	1.20	1.07	0.95	0.84	0.74	0.66	0.62	60.18	76.57
7	1.36	1.57	1.57	1.56	1.50	1.42	1.31	1.19	1.06	0.95	0.84	0.74	0.66	0.62	60.13	76.47
8	1.36	1.57	1.57	1.55	1.50	1.41	1.31	1.19	1.06	0.95	0.84	0.74	0.66	0.62	60.03	76.34
9	1.35	1.56	1.56	1.55	1.49	1.41	1.31	1.19	1.06	0.95	0.84	0.74	0.65	0.62	59.98	76.25
10	1.35	1.56	1.56	1.55	1.49	1.41	1.30	1.19	1.06	0.95	0.84	0.74	0.65	0.61	59.93	76.17
11	1.34	1.55	1.55	1.54	1.49	1.40	1.30	1.19	1.06	0.94	0.83	0.74	0.65	0.61	59.88	76.10
12	1.34	1.55	1.55	1.54	1.48	1.40	1.30	1.18	1.06	0.94	0.83	0.74	0.65	0.61	59.79	75.97
13	1.34	1.55	1.55	1.54	1.48	1.40	1.30	1.18	1.06	0.94	0.83	0.73	0.65	0.61	59.74	75.90
14	1.34	1.54	1.55	1.53	1.48	1.40	1.30	1.18	1.05	0.94	0.83	0.73	0.65	0.61	59.69	75.83
15	1.33	1.54	1.54	1.53	1.48	1.40	1.29	1.18	1.05	0.94	0.83	0.73	0.65	0.61	59.69	75.81
16	1.33	1.54	1.54	1.53	1.48	1.39	1.29	1.18	1.05	0.94	0.83	0.73	0.65	0.61	59.64	75.74
17	1.33	1.54	1.54	1.53	1.47	1.39	1.29	1.18	1.05	0.94	0.83	0.73	0.65	0.61	59.59	75.67
18	1.33	1.53	1.54	1.53	1.47	1.39	1.29	1.18	1.05	0.94	0.83	0.73	0.65	0.61	59.54	75.60
19	1.32	1.53	1.53	1.52	1.47	1.39	1.29	1.18	1.05	0.94	0.83	0.73	0.65	0.61	59.49	75.53
20	1.32	1.53	1.53	1.52	1.47	1.39	1.29	1.17	1.05	0.94	0.83	0.73	0.65	0.61	59.44	75.47
21	1.32	1.53	1.53	1.52	1.47	1.39	1.29	1.17	1.05	0.94	0.83	0.73	0.65	0.61	59.40	75.40
22	1.32	1.52	1.53	1.52	1.47	1.39	1.29	1.17	1.05	0.94	0.83	0.73	0.65	0.61	59.40	75.39
23	1.32	1.52	1.53	1.52	1.46	1.38	1.28	1.17	1.05	0.93	0.83	0.73	0.65	0.61	59.35	75.32
24	1.31	1.52	1.53	1.52	1.46	1.38	1.28	1.17	1.05	0.93	0.83	0.73	0.65	0.61	59.30	75.26
25	1.31	1.52	1.52	1.51	1.46	1.38	1.28	1.17	1.04	0.93	0.82	0.73	0.65	0.61	59.25	75.20
26	1.31	1.52	1.52	1.51	1.46	1.38	1.28	1.17	1.04	0.93	0.82	0.73	0.65	0.61	59.25	75.18
27	1.31	1.52	1.52	1.51	1.46	1.38	1.28	1.17	1.04	0.93	0.82	0.73	0.65	0.61	59.20	75.12
28	1.31	1.51	1.52	1.51	1.46	1.38	1.28	1.17	1.04	0.93	0.82	0.73	0.65	0.61	59.15	75.06
29	1.31	1.51	1.52	1.51	1.46	1.38	1.28	1.17	1.04	0.93	0.82	0.73	0.65	0.61	59.15	75.05
30	1.31	1.51	1.52	1.51	1.46	1.38	1.28	1.17	1.04	0.93	0.82	0.73	0.64	0.61	59.10	74.99
31	1.31	1.51	1.51	1.51	1.45	1.38	1.28	1.16	1.04	0.93	0.82	0.73	0.64	0.61	59.05	74.93
32	1.30	1.51	1.51	1.50	1.45	1.37	1.28	1.16	1.04	0.93	0.82	0.73	0.64	0.61	59.05	74.92
33	1.30	1.51	1.51	1.50	1.45	1.37	1.28	1.16	1.04	0.93	0.82	0.72	0.64	0.61	59.00	74.86
34	1.30	1.51	1.51	1.50	1.45	1.37	1.27	1.16	1.04	0.93	0.82	0.72	0.64	0.61	58.95	74.80
35	1.30	1.51	1.51	1.50	1.45	1.37	1.27	1.16	1.04	0.93	0.82	0.72	0.64	0.60	58.95	74.79
36	1.30	1.50	1.51	1.50	1.45	1.37	1.27	1.16	1.04	0.93	0.82	0.72	0.64	0.60	58.91	74.73
37	1.30	1.50	1.51	1.50	1.45	1.37	1.27	1.16	1.04	0.93	0.82	0.72	0.64	0.60	58.91	74.72
38	1.30	1.50	1.51	1.50	1.45	1.37	1.27	1.16	1.04	0.93	0.82	0.72	0.64	0.60	58.86	74.66
39	1.30	1.50	1.51	1.50	1.45	1.37	1.27	1.16	1.04	0.93	0.82	0.72	0.64	0.60	58.81	74.60
40	1.30	1.50	1.50	1.50	1.45	1.37	1.27	1.16	1.04	0.93	0.82	0.72	0.64	0.60	58.81	74.59
41	1.29	1.50	1.50	1.50	1.44	1.37	1.27	1.16	1.03	0.93	0.82	0.72	0.64	0.60	58.76	74.53
42	1.29	1.50	1.50	1.49	1.44	1.37	1.27	1.16	1.03	0.92	0.82	0.72	0.64	0.60	58.76	74.53
43	1.29	1.50	1.50	1.49	1.44	1.37	1.27	1.16	1.03	0.92	0.82	0.72	0.64	0.60	58.71	74.47
44	1.29	1.50	1.50	1.49	1.44	1.36	1.27	1.16	1.03	0.92	0.82	0.72	0.64	0.60	58.66	74.41
45	1.29	1.49	1.50	1.49	1.44	1.36	1.27	1.16	1.03	0.92	0.82	0.72	0.64	0.60	58.66	74.40
46	1.29	1.49	1.50	1.49	1.44	1.36	1.27	1.16	1.03	0.92	0.82	0.72	0.64	0.60	58.61	74.34
47	1.29	1.49	1.50	1.49	1.44	1.36	1.27	1.15	1.03	0.92	0.82	0.72	0.64	0.60	58.61	74.34
48	1.29	1.49	1.50	1.49	1.44	1.36	1.26	1.15	1.03	0.92	0.82	0.72	0.64	0.60	58.56	74.28

This section summarizes the main results from report [S03120100-TRT10024](#) for thermal analysis. The decay heat in tungsten blocks and tantalum plates of a single target block over 0 – 48 hours is summarized in Table 11 and Table 12, respectively. The temporal behavior is shown in Figure 70 and Figure 71.

The primary contribution to decay heat from tungsten originates from block W_02 and W_03, which have the largest volume (Figure 72 and Figure 73). Similarly, the dominant contribution from tantalum arises from the cladding (Ta_15), which also has the largest volume (Figure 74 and Figure 75). The total decay heat contributions from tungsten, tantalum, Inconel 718, and SS316 are summarized in Table 13 and shown in Figure 76 and Figure 77.

Immediately after beam shutdown, the total decay heat in one target block is 294.15 W. After 8 hours, the decay heat decreases to 151 W, with 41.8% (63.32 W) from tungsten and 50.4 % (76.34 W) from tantalum. Approximately 39.7% of heat (60 W) of the total decay heat originates from the tantalum cladding. The total heat load in the target assembly (20 segments) is approximately 3 kW.

After 48 hours, the total decay heat in one target block decreases to 112.45 W. The contribution from tungsten decreases to 25.4% (28.7 W), while tantalum contributes 65.8% (74.28 W). Approximately 52% (60 W) of the total decay heat originates from the tantalum cladding. The total heat load in the target assembly is approximately 2.2 kW.

The decay heat is curve-fitted using Eq. (1), shown below:

$$Q(t) = d + \frac{a - d}{1 + \left(\frac{t}{c}\right)^b} \quad (1)$$

where Q is the decay heat (W) and t is the decay time (hours). The coefficients for tungsten, tantalum, Inconel 718, and SS316 are summarized in Table 14, Table 15, and Table 16. The fitted heat sources are used in the CFD simulations.

The total decay heat in a single target block is also curve-fitted using:

$$Q(t) = -4259.667 + \frac{4555.329}{1 + \left(\frac{t}{5.74797 \times 10^{11}}\right)^{0.1368283}} \quad (2).$$

A comparison between the original data and the fitted results is presented in Table 17, Figure 78, and Figure 79. After 8 hours, the decay heat in one target block decreases to approximately half of its initial value (zero minutes). Equation (2) is used in APPENDIX H for loss-of-coolant simulations.

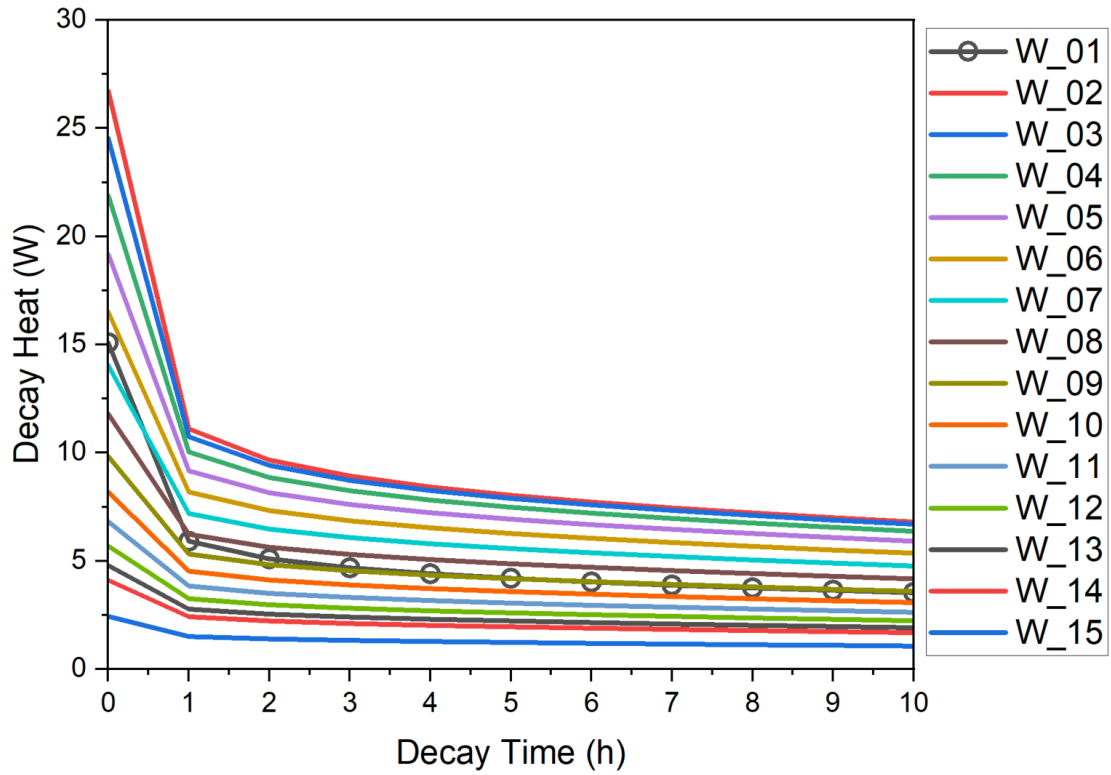


Figure 70. Decay heat in individual tungsten (W) blocks.

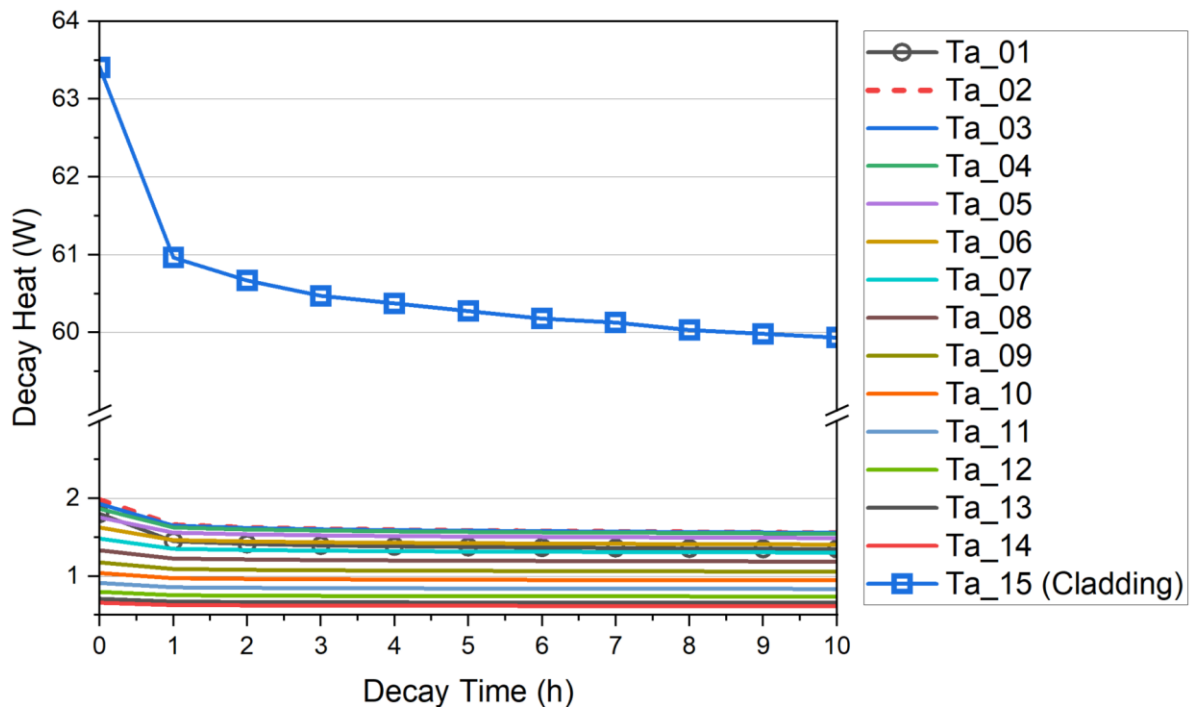


Figure 71. Decay heat in individual tantalum (Ta) plates.

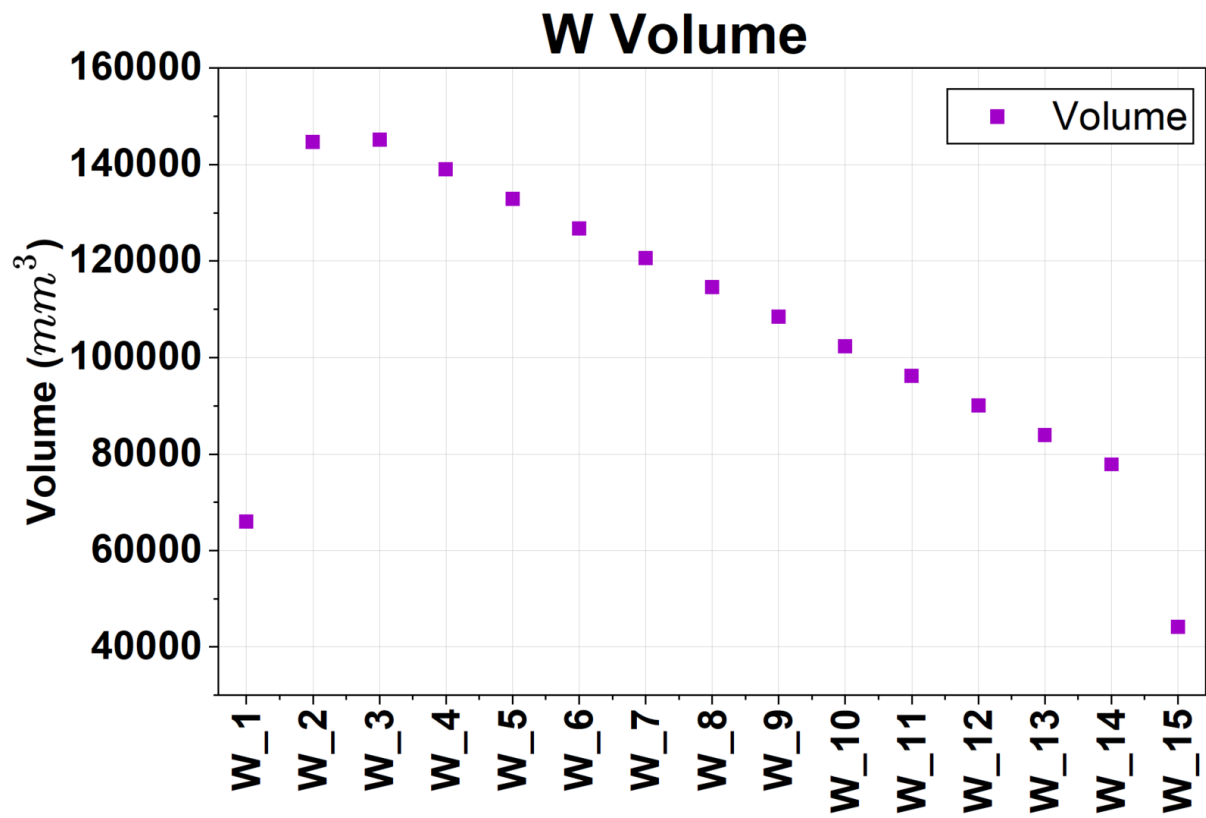


Figure 72. Volume of W blocks.

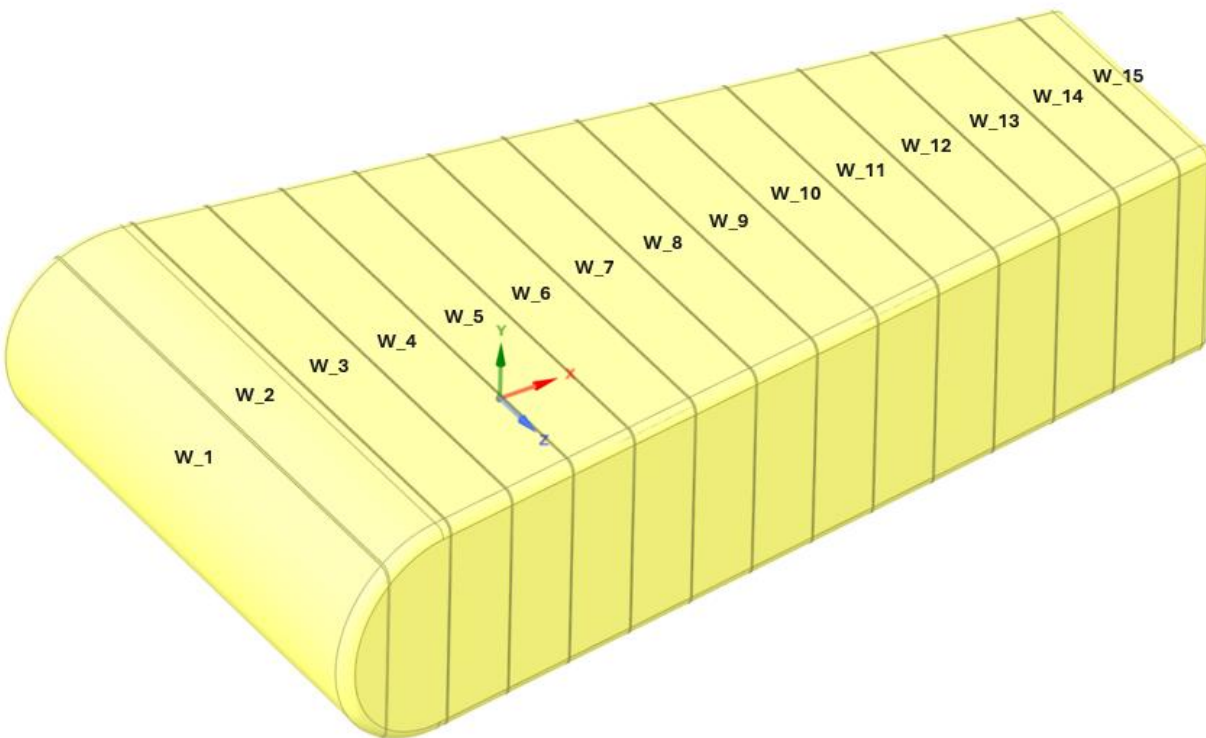


Figure 73. W blocks.

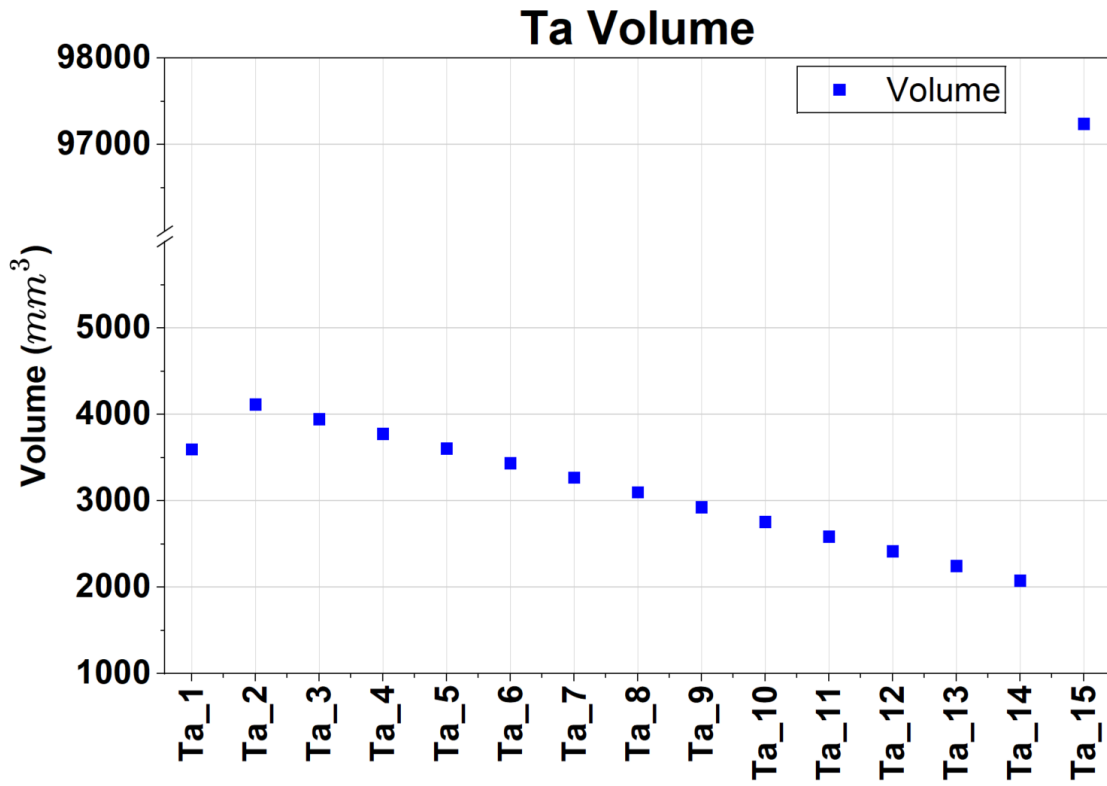


Figure 74. Volume of Ta plates.

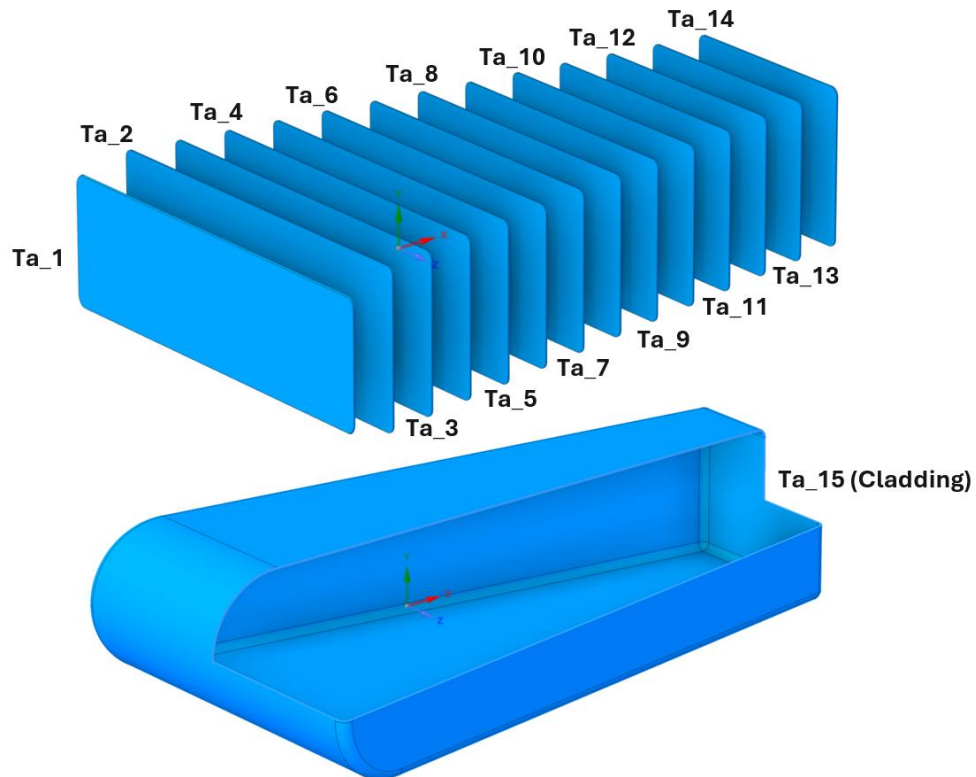


Figure 75. Tantalum plates.

Table 13. Decay heat in one target segment over 0 – 48 hours.

Decay Time (h)	W(W)	Ta (W)	Inconel 718 (W)	SS (W)	Total Decay Heat (W)	W (%)	Ta (%)	Inconel 718 (%)	SS (%)	Sum (%)
0	191.64	82.47	14.14	7.41	294.15	64.8	27.9	4.8	2.5	100
1	92.17	77.91	11.28	5.46	186.17	49.3	41.7	6.0	2.9	100
2	82.16	77.38	10.70	4.62	174.26	47.0	44.3	6.1	2.6	100
3	76.77	77.06	10.32	4.02	167.59	45.6	45.8	6.1	2.4	100
4	73.00	76.88	10.03	3.56	162.90	44.7	47.0	6.1	2.2	100
5	70.03	76.72	9.81	3.22	159.22	43.8	48.0	6.1	2.0	100
6	67.52	76.57	9.63	2.95	156.12	43.1	48.9	6.1	1.9	100
7	65.31	76.47	9.49	2.74	153.46	42.4	49.7	6.2	1.8	100
8	63.32	76.34	9.37	2.58	151.06	41.8	50.4	6.2	1.7	100
9	61.47	76.25	9.26	2.46	148.91	41.1	51.0	6.2	1.6	100
10	59.77	76.17	9.17	2.36	146.95	40.5	51.7	6.2	1.6	100
11	58.17	76.10	9.10	2.28	145.12	39.9	52.2	6.2	1.6	100
12	56.67	75.97	9.03	2.22	143.37	39.4	52.8	6.3	1.5	100
13	55.24	75.90	8.97	2.17	141.76	38.8	53.3	6.3	1.5	100
14	53.88	75.83	8.92	2.13	140.25	38.3	53.9	6.3	1.5	100
15	52.59	75.81	8.87	2.10	138.86	37.7	54.4	6.4	1.5	100
16	51.36	75.74	8.82	2.08	137.50	37.2	54.9	6.4	1.5	100
17	50.18	75.67	8.78	2.06	136.19	36.7	55.4	6.4	1.5	100
18	49.05	75.60	8.74	2.04	134.94	36.2	55.8	6.5	1.5	100
19	47.97	75.53	8.71	2.02	133.75	35.7	56.3	6.5	1.5	100
20	46.93	75.47	8.67	2.01	132.60	35.3	56.7	6.5	1.5	100
21	45.94	75.40	8.64	2.00	131.49	34.8	57.1	6.5	1.5	100
22	44.97	75.39	8.61	1.99	130.48	34.3	57.6	6.6	1.5	100
23	44.05	75.32	8.58	1.98	129.46	33.9	58.0	6.6	1.5	100
24	43.16	75.26	8.55	1.97	128.47	33.5	58.4	6.6	1.5	100
25	42.30	75.20	8.52	1.96	127.51	33.1	58.8	6.7	1.5	100
26	41.48	75.18	8.49	1.96	126.64	32.6	59.2	6.7	1.5	100
27	40.68	75.12	8.47	1.95	125.75	32.2	59.5	6.7	1.5	100
28	39.91	75.06	8.44	1.94	124.89	31.8	59.9	6.7	1.6	100
29	39.16	75.05	8.41	1.94	124.10	31.4	60.3	6.8	1.6	100
30	38.44	74.99	8.39	1.93	123.30	31.1	60.6	6.8	1.6	100
31	37.74	74.93	8.36	1.93	122.51	30.7	60.9	6.8	1.6	100
32	37.07	74.92	8.34	1.92	121.80	30.3	61.3	6.8	1.6	100
33	36.42	74.86	8.32	1.92	121.06	30.0	61.6	6.8	1.6	100
34	35.78	74.80	8.30	1.91	120.34	29.6	61.9	6.9	1.6	100
35	35.17	74.79	8.27	1.91	119.70	29.3	62.3	6.9	1.6	100
36	34.58	74.73	8.25	1.90	119.03	28.9	62.6	6.9	1.6	100
37	34.00	74.72	8.23	1.90	118.42	28.6	62.9	6.9	1.6	100
38	33.45	74.66	8.21	1.89	117.78	28.3	63.2	6.9	1.6	100
39	32.91	74.60	8.19	1.89	117.16	28.0	63.4	7.0	1.6	100
40	32.38	74.59	8.17	1.88	116.60	27.7	63.7	7.0	1.6	100
41	31.87	74.53	8.15	1.88	116.01	27.4	64.0	7.0	1.6	100
42	31.38	74.53	8.14	1.87	115.49	27.1	64.3	7.0	1.6	100
43	30.90	74.47	8.12	1.87	114.93	26.8	64.6	7.0	1.6	100
44	30.44	74.41	8.10	1.87	114.39	26.5	64.8	7.1	1.6	100
45	29.98	74.40	8.08	1.86	113.91	26.2	65.1	7.1	1.6	100
46	29.55	74.34	8.07	1.86	113.40	26.0	65.3	7.1	1.6	100
47	29.12	74.34	8.05	1.86	112.94	25.7	65.6	7.1	1.6	100
48	28.70	74.28	8.03	1.85	112.45	25.4	65.8	7.1	1.6	100

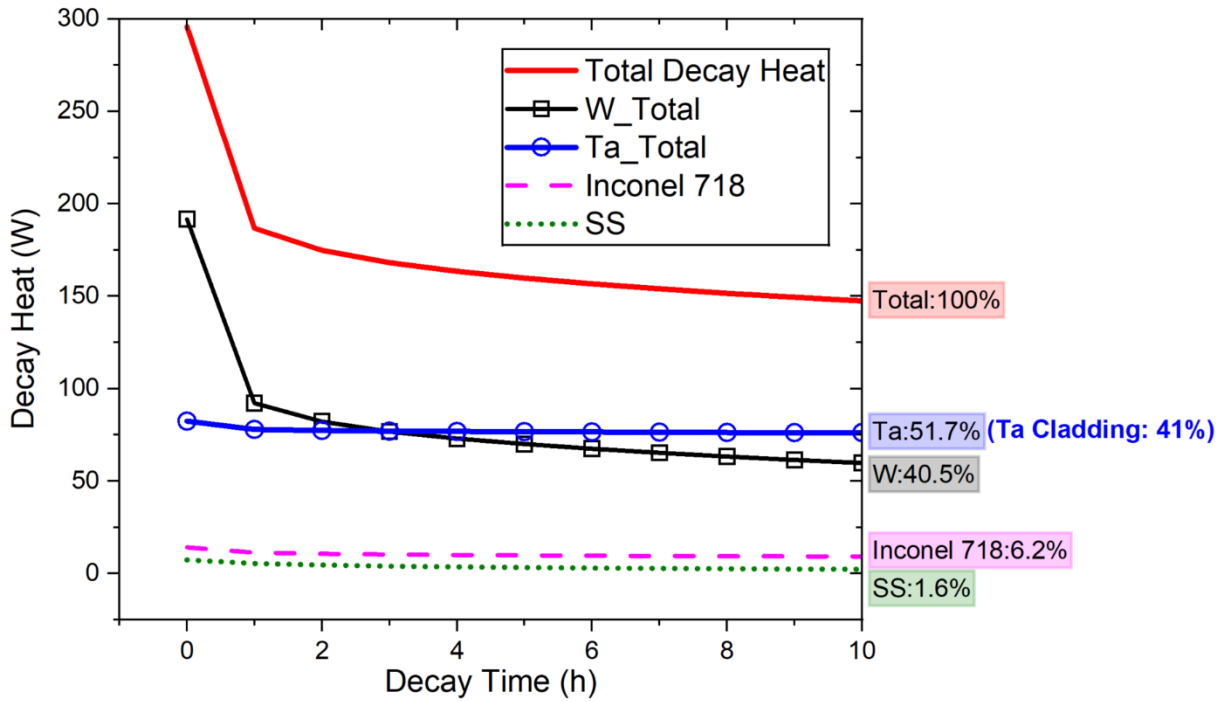


Figure 76. Decay heat in one target segment over 0 – 10 hours for W, Ta, Inconel 718, and SS316.

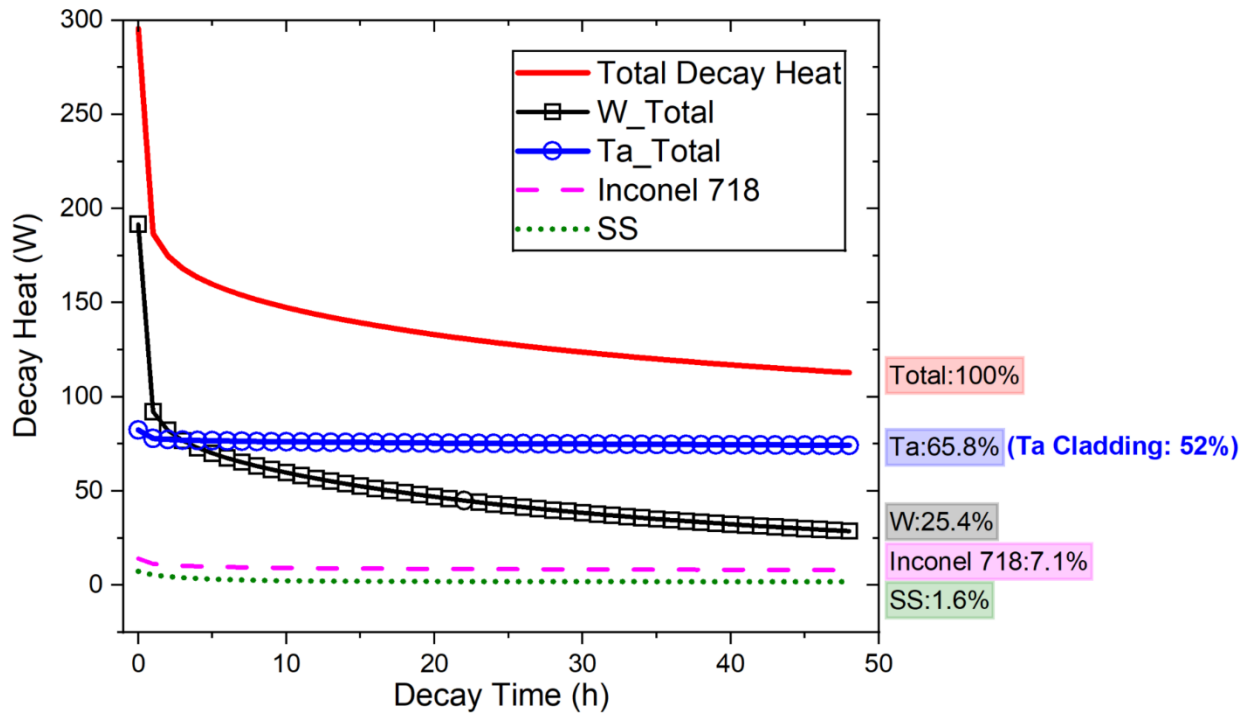


Figure 77. Decay heat in one target segment over 0 – 48 hours for W, Ta, Inconel 718, and SS316.

Table 14. Curve-fitting coefficients for decay heat as a function of time in 15 tungsten (W) blocks.

Decay Heat Curve Fitting for W Blocks (0 - 48 h)				
	a	b	c	d
W_01	15.080130	0.1598773	72.35063	-12.41904
W_02	26.730220	0.1416047	5406.121	-42.03172
W_03	24.540200	0.1256165	24236510	-106.8483
W_04	21.899190	0.1229489	1.791484E+11	-278.2665
W_05	19.177680	0.1304229	1.632649E+11	-281.6891
W_06	16.506270	0.1375327	1.407020E+11	-275.5078
W_07	14.035490	0.1446627	1.198556E+11	-265.6722
W_08	11.794660	0.1519768	1.025245E+11	-253.9937
W_09	9.824581	0.1579417	8.436496E+10	-231.8440
W_10	8.174282	0.1638925	7.149259E+10	-212.0294
W_11	6.814846	0.1691633	5.788092E+10	-190.1606
W_12	5.685178	0.1732931	4.812788E+10	-166.7797
W_13	4.785462	0.1773506	4.147881E+10	-148.2734
W_14	4.105295	0.1838072	3.496418E+10	-140.5474
W_15	2.435836	0.2009417	2.044680E+10	-105.3074

Table 15. Curve-fitting coefficients for decay heat as a function of time in 15 tantalum (Ta) plates.

Decay Heat Curve Fitting for Ta Plates (0 - 48 h)				
	a	b	c	d
Ta_01	1.800017	0.2866434	0.5475617	1.1497870
Ta_02	1.980019	0.2272657	3.923793	1.2141670
Ta_03	1.930006	0.2377814	3.531218	1.2692550
Ta_04	1.870013	0.2004179	32.51226	1.1396620
Ta_05	1.759999	0.2149219	24.05547	1.1641150
Ta_06	1.629897	0.1316430	3959346000	-1.5986750
Ta_07	1.479992	0.1804059	6332.87	0.7283023
Ta_08	1.329979	0.1493265	2974912000	-1.4572650
Ta_09	1.179953	0.1389281	2502151000	-0.7307162
Ta_10	1.039850	0.1434454	1976228000	-0.5323205
Ta_11	0.909990	0.1499774	1566836000	-0.3779287
Ta_12	0.799844	0.1416275	1415899000	-0.1688567
Ta_13	0.700044	0.5750483	1.241188	0.6332149
Ta_14	0.660044	0.5750491	1.241186	0.5932150
Ta_15 (Cladding)	63.401960	0.1827662	48666410000	-153.01190

Table 16. Curve-fitting coefficients for decay heat as a function of time in Inconel 718 and SS316 components.

Decay Heat Curve Fitting for Inconel 718 and SS (0 - 48 h)				
	a	b	c	d
Inconel 718	13.40937	0.4894982	2.92127	6.143613
SS	7.783984	1.113557	1.97162	1.727172

Table 17. Comparison of decay heat in one target segment between original data and curve-fitting results as a function of time.

Decay Time (h)	Original: Total Decay Heat (W)	Curve Fit: Total Decay Heat (W)	Difference (W)	%
0	295.66	295.66	0.00	0.001
1	186.82	186.28	-0.53	0.286
2	174.86	175.69	0.83	0.474
3	168.17	169.04	0.87	0.517
4	163.47	164.10	0.62	0.381
5	159.78	160.14	0.36	0.226
6	156.67	156.82	0.15	0.096
7	154.01	153.95	-0.06	0.039
8	151.60	151.42	-0.18	0.119
9	149.44	149.16	-0.29	0.193
10	147.48	147.10	-0.38	0.259
11	145.64	145.21	-0.43	0.296
12	143.89	143.47	-0.42	0.294
13	142.28	141.85	-0.43	0.301
14	140.76	140.34	-0.43	0.302
15	139.37	138.91	-0.45	0.326
16	138.00	137.57	-0.43	0.309
17	136.69	136.30	-0.39	0.282
18	135.43	135.09	-0.34	0.251
19	134.24	133.94	-0.29	0.218
20	133.08	132.85	-0.24	0.177
21	131.98	131.79	-0.18	0.138
22	130.96	130.79	-0.17	0.130
23	129.93	129.82	-0.11	0.088
24	128.94	128.88	-0.06	0.043
25	127.98	127.98	0.00	0.002
26	127.11	127.12	0.01	0.008
27	126.21	126.28	0.06	0.048
28	125.35	125.46	0.11	0.091
29	124.56	124.67	0.11	0.091
30	123.75	123.91	0.16	0.128
31	122.96	123.17	0.20	0.166
32	122.25	122.44	0.19	0.157
33	121.51	121.74	0.23	0.190
34	120.79	121.06	0.27	0.222
35	120.14	120.39	0.25	0.205
36	119.46	119.74	0.27	0.228
37	118.85	119.10	0.25	0.208
38	118.21	118.48	0.27	0.227
39	117.59	117.88	0.28	0.242
40	117.03	117.28	0.25	0.213

41	116.44	116.70	0.26	0.224
42	115.92	116.14	0.22	0.187
43	115.36	115.58	0.22	0.193
44	114.82	115.03	0.22	0.190
45	114.33	114.50	0.17	0.146
46	113.82	113.98	0.16	0.139
47	113.36	113.46	0.10	0.091
48	112.87	112.96	0.09	0.081

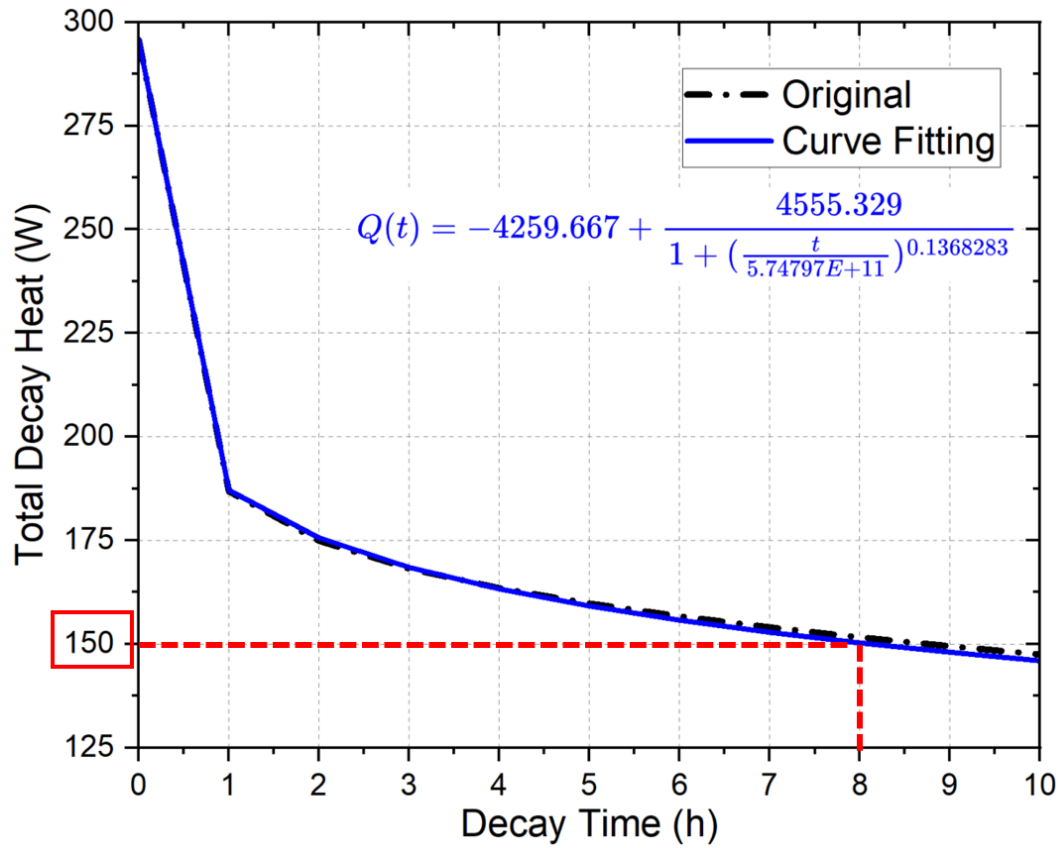


Figure 78. Total decay heat in one target segment over 0 – 10 hours.

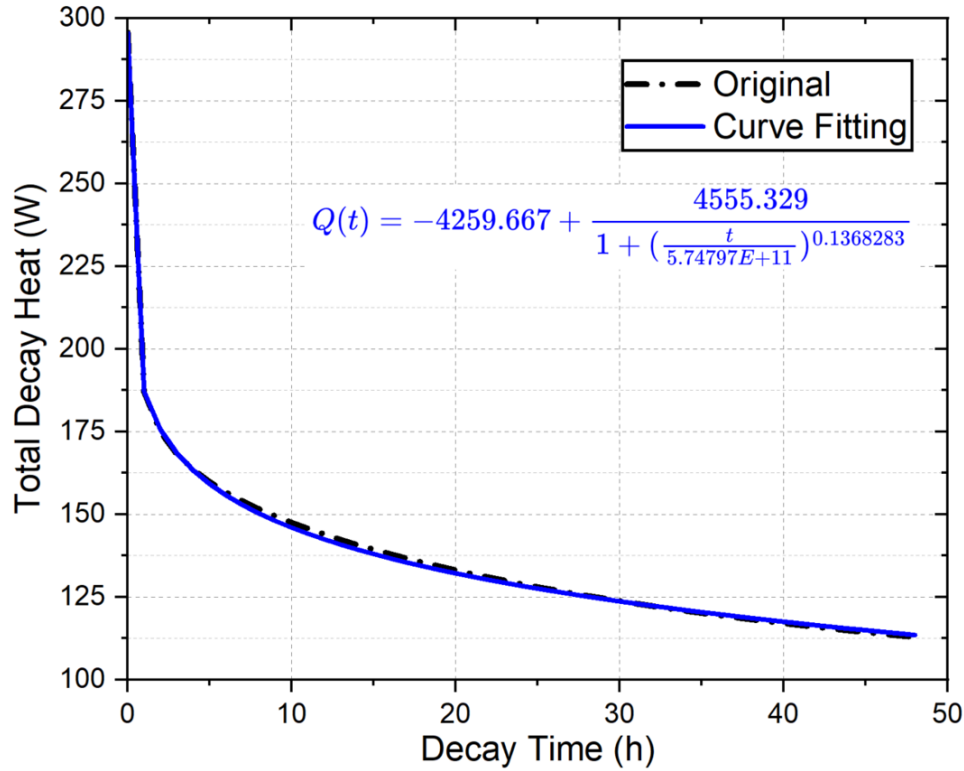


Figure 79. Total decay heat in one target segment over 0 – 48 hours.

6.2 MAINTENANCE TEMPERATURE UNDER REDUCED FLOW CONDITIONS

The target block was analyzed at decay times of 0 and 8 hours and at water flow rates of 0.1 and 0.2 GPM. In the CFD model, the decay heat summarized in Table 11 and Table 12 is applied to the 15 tungsten blocks and 15 tantalum plates (including the cladding), respectively, while the decay heat summarized in Table 13 is applied to Inconel 718 shroud and SS316 structures. As indicated in Table 13 and Figure 76, at 0 hours, the tungsten blocks contribute 64.8% and the tantalum plates contribute 27.9% of the total decay heat of 294.15 W. At 8 hours, the total decay heat decreases to 151.06 W, with the contribution from the tungsten blocks decreasing to 41.8% and that from the tantalum plates increasing to 50.4%. After 8 hours of decay, approximately 40% of the total decay heat originates from the tantalum cladding alone.

The Reynolds number in the channels of the target segment ranges from approximately 150 to 300 (corresponding to 0.1 - 0.2 GPM), as shown in Figure 80; therefore, a laminar flow model is used. Since the primary objective of this analysis is to estimate a reasonable flow rate for cooling the target segment under beam-off conditions, steady-state simulations are performed using fixed decay heat levels at 0 and 8 hours, rather than a time-varying decay heat profile with transient analysis.

The results are summarized in Figure 81 and Table 18. As shown in Figure 81, under beam-off conditions, the temperature distribution in the Ta-clad core is relatively uniform. Immediately after beam shutdown (0 hours), the decay heat within the target block is 294.15 W, which can be effectively cooled with a water flow rate of 0.1 GPM, maintaining the target block temperature below 99.0 °C. Increasing the flow rate to 0.2 GPM reduces the peak temperature to 54.5 °C. After 8 hours of decay, the peak temperature further decreases to 67 °C at a flow rate of 0.1 GPM.

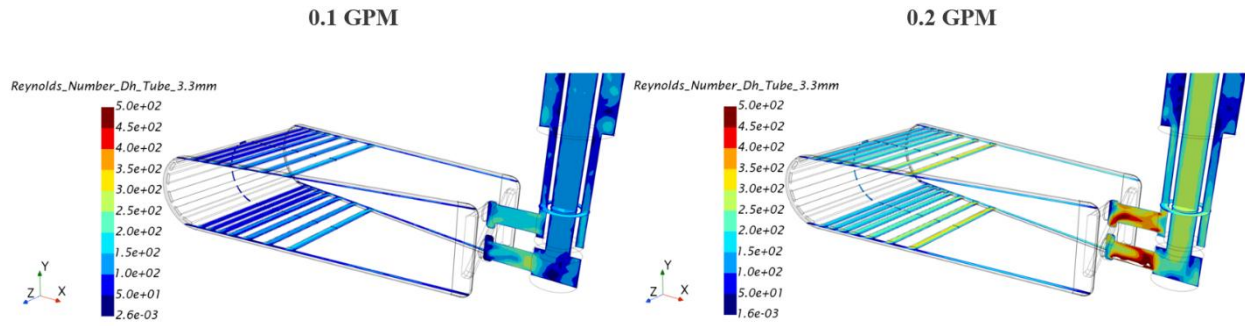


Figure 80. Reynolds number distribution in the target block with 0.1 and 0.2 GPM flow rates.

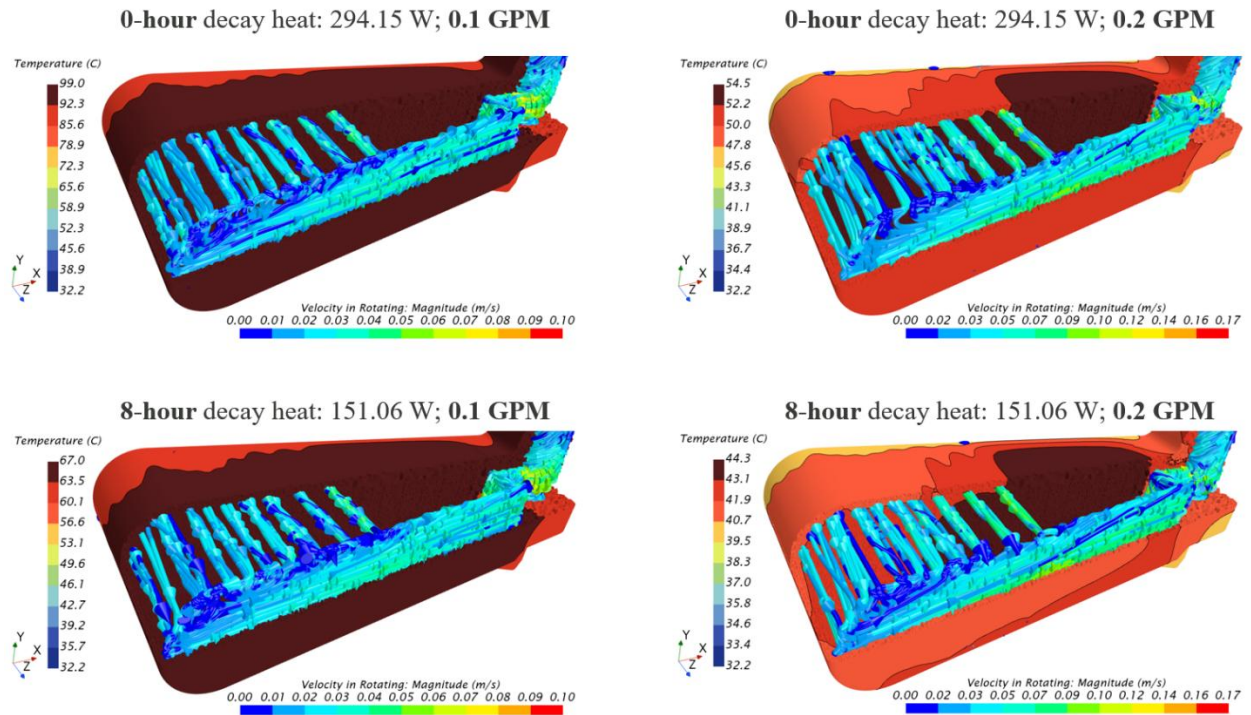


Figure 81. Temperature distribution under beam-off conditions at flow rates of 0.1 and 0.2 GPM and decay times of 0 and 8 hours.

Table 18. Peak temperatures in the target segment under the beam-off conditions at flow rates of 0.1 and 0.2 GPM and decay times of 0 and 8 hours.

	0-hour decay heat: 294.15 W		8-hour decay heat: 151.06 W	
Material	Peak Temperature (°C)			
	0.1 GPM	0.2 GPM	0.1 GPM	0.2 GPM
Tungsten	99.0	54.5	67.0	44.3
Tantalum	99.0	54.5	67.0	44.3
Inconel 718	99.0	54.5	67.0	44.3
SS 316	97.9	53.0	66.4	43.4
H ₂ O	98.8	53.9	66.8	43.9
CuCrZr	87.8	46.6	60.8	39.8

6.3 TEMPERATURE IMMEDIATELY AFTER SHUTDOWN WITH ACTIVE INTERNAL WATER COOLING

During maintenance, an auxiliary cooling system can be mounted on the target assembly to provide the required cooling flow rate, as discussed in the previous section. Following proton beam shutdown and prior to activation of the auxiliary cooling system, it is important to evaluate the cool-down period for decay heat removal under a nominal flow rate of 7.5 GPM for a single target segment.

Figure 82 shows the steady-state temperature distribution of the target segment and the stainless-steel structures. As indicated in Figure 30, the elevated stainless-steel temperature of 174 °C is caused by the manufacturing gap in the vacuum (Core Vessel) environment.

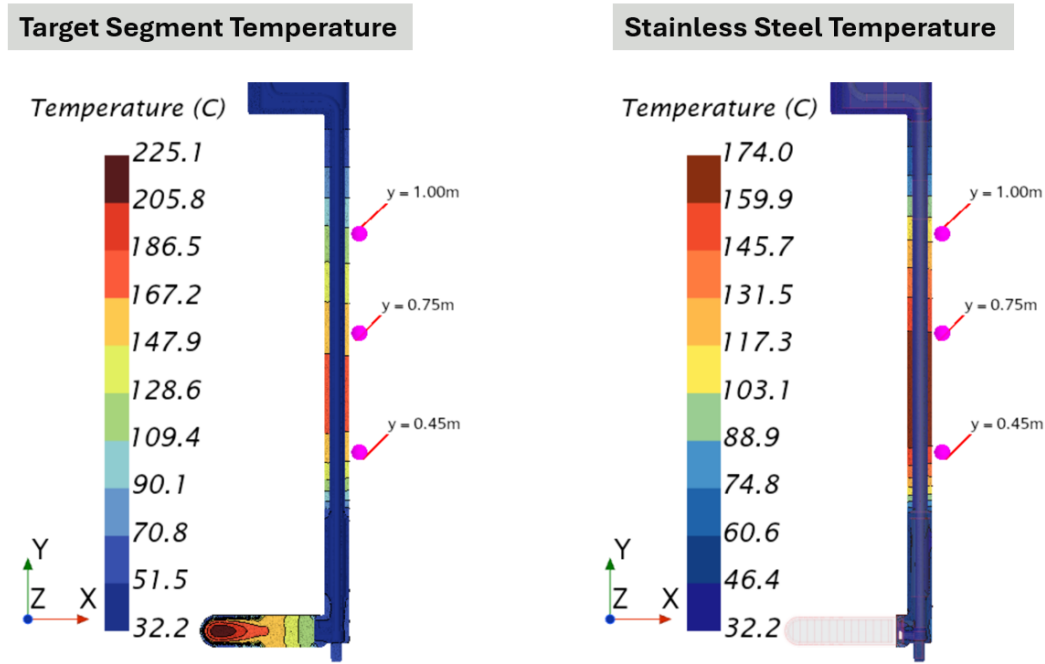


Figure 82. Steady-state temperature distribution of the target segment and the associated stainless-steel structure.

The curve-fitted decay heat correlation (Eq. (1)), along with the coefficients summarized in Table 14, Table 15, and Table 16 for the 15 tungsten blocks, 15 tantalum plates (including cladding), Inconel 718 shroud, and SS316 structures, is used in this analysis. At a nominal flow rate of 7.5 GPM, Figure 83, Figure 84, and Figure 85 show the temporal evolution of the target segment temperature. With active cooling at 7.5 GPM for 5 minutes, the temperature of the target block decreases to 37 °C. After approximately 10 minutes of active cooling, the block temperature approaches 34.4 °C (close to the inlet water temperature (32.22 °C [90 °F])).

However, due to the relatively low thermal conductivity of stainless steel and the presence of the vacuum gap, which further impedes heat diffusion, the stainless-steel temperature in the vicinity of the gap decreases much more slowly. As shown in Figure 85 and Figure 86, it takes approximately 16 hours for the stainless-steel temperature to decrease to 55 °C under active cooling at 7.5 GPM.

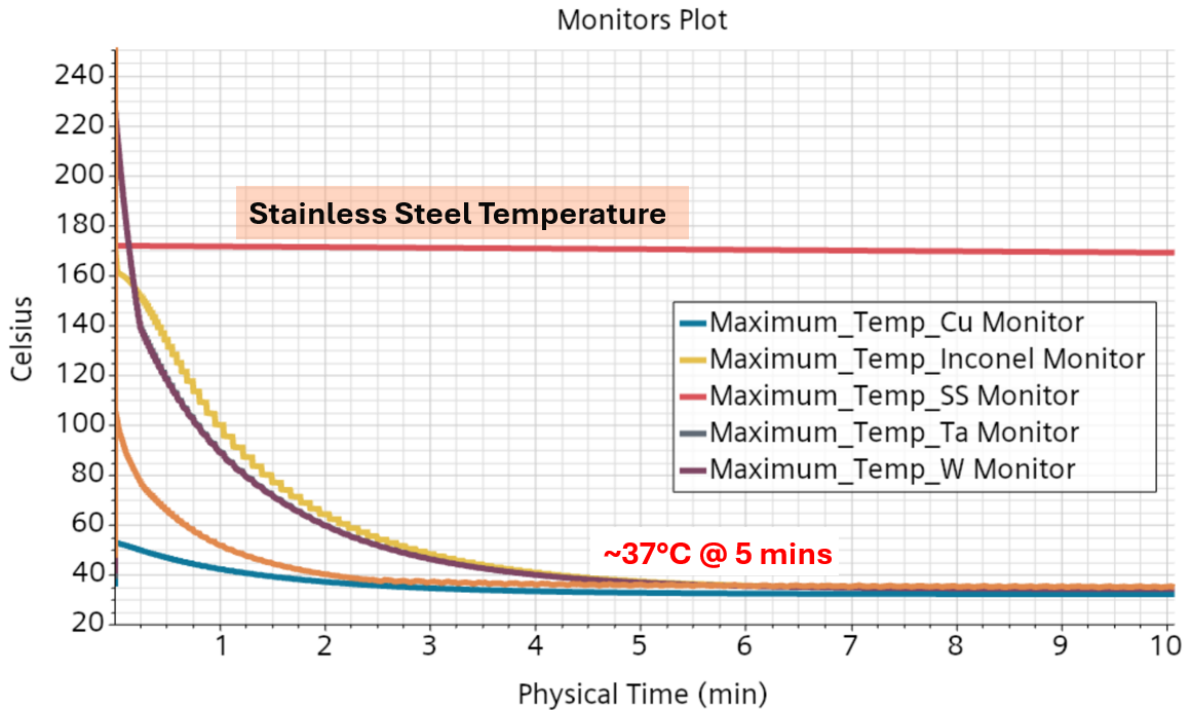


Figure 83. Target segment temperature variation over 0 – 10 minutes under decay heat with a nominal flow rate of 7.5 GPM.

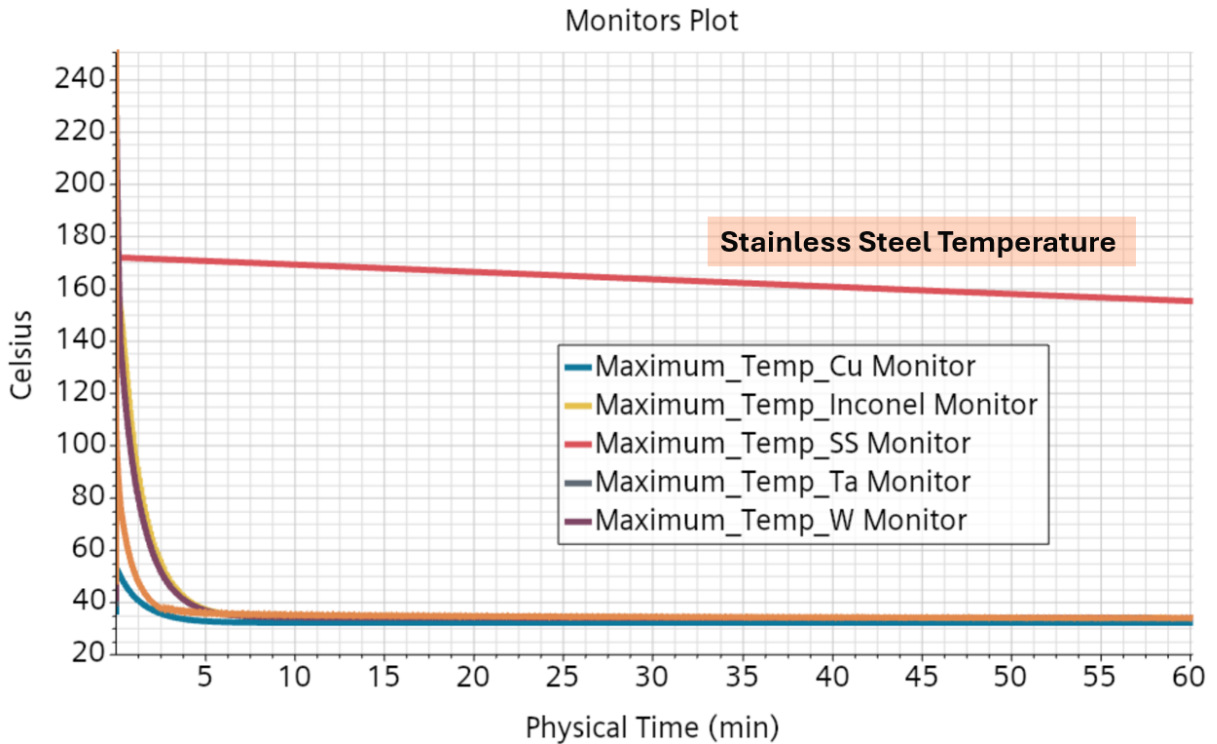


Figure 84. Target segment temperature variation over 0 – 60 minutes under decay heat with a nominal flow rate of 7.5 GPM.

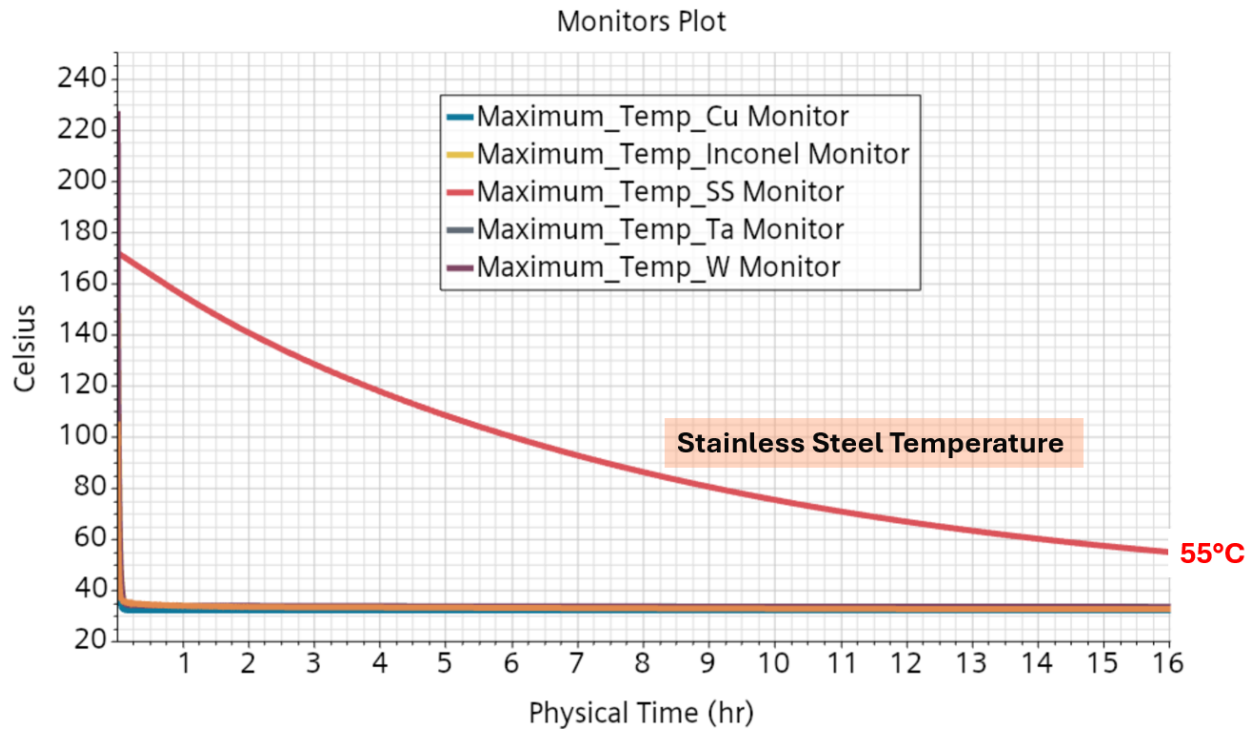


Figure 85. Target segment temperature variation over 0 – 16 hours under decay heat with a nominal flow rate of 7.5 GPM.

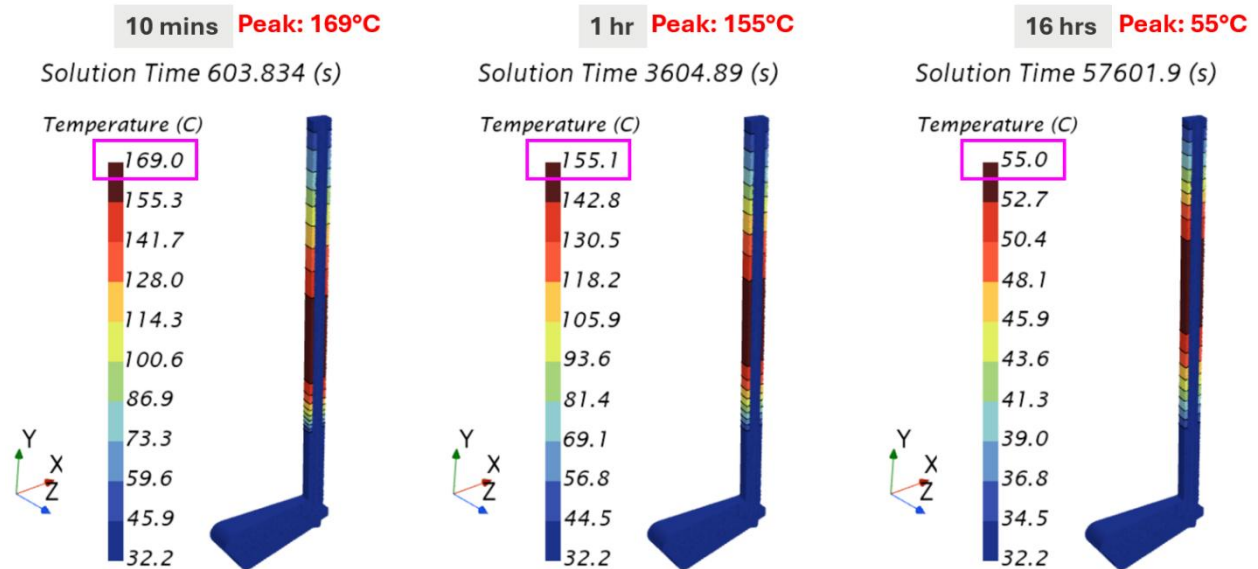


Figure 86. Comparison of SS316 temperatures at $t=10$ minutes, 1 hour, and 16 hours.

6.4 MAINTENANCE TEMPERATURE WITHOUT ACTIVE COOLING

While the auxiliary cooling system can provide sufficient cooling during normal maintenance, a loss-of-cooling (LOC) event could cause the target segment temperature to rise rapidly. The temperature at which

debonding initiates has not yet been conclusively established, as ongoing R&D efforts are focused on characterizing the bond strength between tantalum and Inconel 718. Preliminary numerical analyses suggested that debonding could occur at elevated temperatures (approximately 120–150°C), even though the temperature distribution during the LOC event is relatively uniform and lower than normal operating conditions; these results are not formally documented. A transient analysis further shows that the peak temperature of the target reaches 664 °C after 870 seconds when debonding occurs between the Inconel shroud and the tantalum cladding ([S03020400-DAC10001](#)). Estimating the time required to reach 100°C–120 °C is therefore critical, since debonding could permanently reduce cooling performance even after active cooling is restored. Moreover, secondary cooling approaches, such as air cooling, should be considered to complement the auxiliary cooling system during LOC events.

For the LOC analysis, the simulation domain is shown in Figure 87. The temperature of the target block immediately below the MRA (on the right in Figure 87) is the primary focus. Neighboring components, including two adjacent target segments, the target shaft, the MRA, shielding blocks, and water within these components, are included to account for heat conduction and radiative heat transfer. The core vessel environment is modeled as air-filled (instead of vacuum under normal operation) for heat conduction purposes only; no natural circulation is considered. Boundaries far from the region of interest are fixed at 30 °C (Figure 87). Decay heat sources summarized in Table 14, Table 15, and Table 16 are applied to the target segment of interest and its two neighboring segments. The maximum time step in the simulation is 5 s, determined from a calculation of a target segment heated solely by decay heat without cooling, in which the temperature rises rapidly (see APPENDIX H for details).

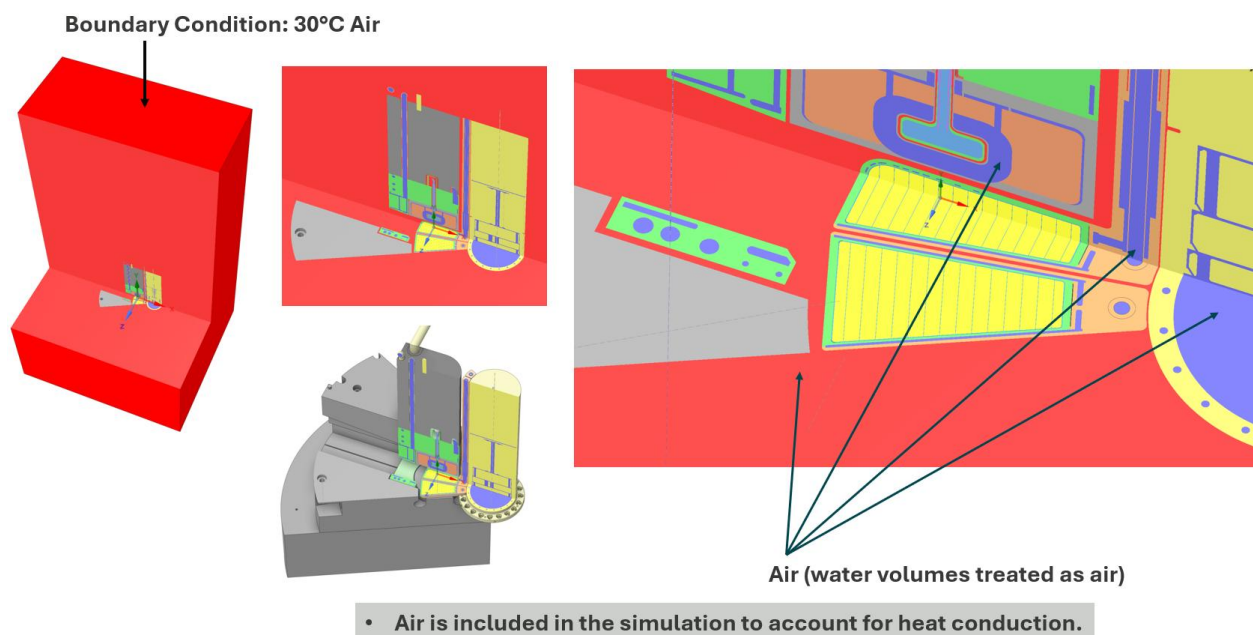


Figure 87. Simulation domain.¹⁰

¹⁰ Geometry file: <https://windchill-prod.ornl.gov:8443/Windchill/app/#ptcl/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792>
CFD_CAD/Thermal_Radiation.zip

Table 19. Emissivity of stainless steel.[17]

Temperature (K)	SS Emissivity
323.15	0.26
373.15	0.26
473.15	0.26
523.15	0.268
573.15	0.277
623.15	0.286
673.15	0.295
723.15	0.304
773.15	0.313
823.15	0.323
873.15	0.332
923.15	0.341
973.15	0.35
1023.15	0.359

Thermal radiation can contribute significantly to heat transfer in high-temperature systems, particularly across vacuum gaps where convective heat transfer is negligible. STAR-CCM+ provides several radiation modeling approaches, including the Surface-to-Surface (S2S) radiation model and participating media models such as the Discrete Ordinates (DO) method. Participating media models account for absorption, emission, and scattering within a fluid medium and are typically used for combustion or optically thick gases. In contrast, the S2S model assumes a non-participating medium and computes radiative heat exchange directly between surfaces, making it suitable for vacuum or transparent environments.

In this study, the S2S model is employed to simulate radiative heat transfer across gaps and fluid domains (water and air) within the simulation domain. The model uses the view-factor method, which determines the fraction of radiation leaving one surface that is intercepted by another. Radiative exchange is calculated using the Stefan–Boltzmann law, accounting for surface temperatures, emissivities, and geometric relationships, including shadowing and multiple reflections within an enclosure. A gray thermal radiation assumption is adopted, treating emissivity as independent of wavelength. This simplification is appropriate for Inconel 718 shroud and SS316 over the temperature range considered.

In STAR-CCM+, the S2S model allows control of radiation exchange at the **region level** via Radiation Transfer setting. Four options are available: *Internal*, *External*, *Internal and External*, and *None*. The *Internal* option restricts radiative exchange to surfaces within the same region, preventing interaction with neighboring regions. The *External* option allows radiation exchange only between surfaces belonging to different regions, while excluding radiation within the region itself. The *Internal and External* option enables both intra-region and inter-region radiation, providing the most comprehensive representation of radiative heat transfer. Finally, the *None* option disables radiation entirely for the selected region.

For this simulation, the radiation options are assigned based on the physical characteristics of the target assembly. The primary region of interest is a single target segment, surrounded by neighboring segments, the MRA, CV shielding blocks, the target shaft, and an external environment at 30 °C. Within the target segment, the Inconel 718 and SS316 structures are assigned the **External** option because the enclosed Ta-

clad core (tungsten blocks and tantalum layers) has high thermal conductivity, making conduction the dominant heat transfer mechanism. Consequently, internal radiation within the target segment is negligible, while radiation to surrounding components is retained. For surrounding components, including adjacent target segments, the MRA, shielding blocks, and the target shaft, the **Internal and External** option is applied to allow intra-and inter-component radiation. The external environment serves as a thermal boundary at 30 °C, acting as a radiative heat sink.

With the External option, radiative heat exchange between regions is enabled and surface emissivities are specified for all participating boundaries. Radiative exchange is governed by computed view factors, which depend on geometric visibility between surfaces. Exchange is limited to surfaces with direct line-of-sight; for example, the target segment radiates to the outer surfaces of the target shaft, shielding blocks, and the MRA, while internal structures such as the hydrogen loop do not participate due to geometry shielding.

Radiative heat transfer in the simulation can also be modeled in Abaqus, though the approach differs. Abaqus does not offer region-level radiation options. Instead, radiation is defined by explicitly selecting surfaces grouped into **radiation cavities**, with exchange occurring only among surfaces within the same cavity that have line-of-sight. Surface emissivities are assigned, and view factors are used to compute radiative exchange. Physically, this produces equivalent results to STAR-CCM+ if the radiation network is correctly defined.

For this analysis, the shielding blocks are initially at 32.22 °C. The MRA and target shaft are initialized at their steady-state temperatures, mapped from prior simulations. The target segment of interest and its two neighbors start with the temperature field obtained after 10 minutes of active cooling at 7.5 GPM. Emissivities are set as follows: Al6061 (MRA vessel) = 0.04, Inconel 718 = 0.24 [18], and temperature-dependent emissivities for SS316 and A36 (MRA shielding block) are provided in Table 19 [17].

As shown in Figure 83, after 10 minutes of active cooling, the target temperature is close to 32°C, while decay heat remains near 294 W (Table 13 and Figure 78). Figure 88 compares temperature evolution with and without air included in fluid regions. For the case with air, all fluid regions (including water in the MRA, shaft, and target segments) are assumed to be filled with air. In both cases, the target reaches 100 °C in less than one hour. Without air, the temperature approaches 225 °C (steady-state under normal operation) at 3.6 h; with air, it reaches 225°C at 4 h. Figure 89 and Figure 90 show the temperature distribution at $t = 3.4$ h after beam shutdown, which remains relatively uniform throughout the target block.

Figure 91 compares two scenarios: air-filled fluid domains, and a more realistic case with stagnant water in the target segments, MRA, target shaft, and air in the surrounding environment. With air, the target reaches 100 °C in 53 minutes; with stagnant water, 100 °C is reached in 60 minutes (temperature distribution shown in Figure 92). Even with water, only 7 minutes of additional margin is achieved before the risk of debonding increases.

Although the target segment can be actively cooled to room temperature (32 °C) at 7.5 GPM, decay heat remains near 294 W at $t = 0$ h. As shown in Figure 78, extending the decay time to 8 hours reduces decay heat to ~150 W, roughly half of the initial value. Figure 93 compares cases with initial temperature field after 10 minutes versus 8 hours of active cooling. Even with reduced decay heat, the target block reaches 100 °C within 85 minutes.

From all analyzed scenarios, during a LOC event, the target block reaches 100 °C in approximately 60–85 minutes, which is insufficient for typical maintenance operations. Without additional decay heat removal approaches (such as air cooling), debonding between the Inconel shroud and the tantalum

cladding could occur, posing a significant safety risk and potential financial loss, as each target segment is costly (~\$500,000 or more).

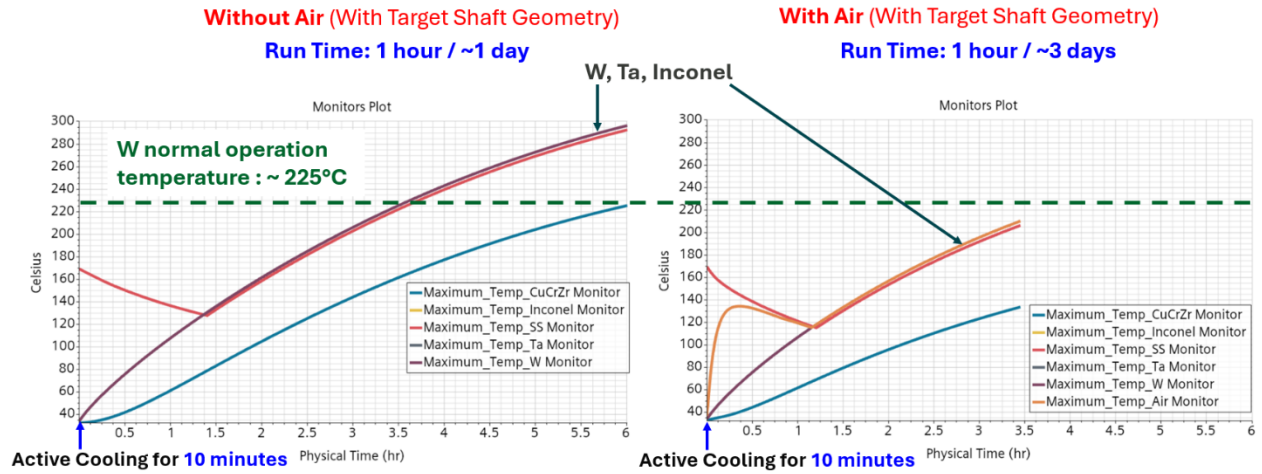


Figure 88. Temperature history of the target segment under decay heat with and without air.

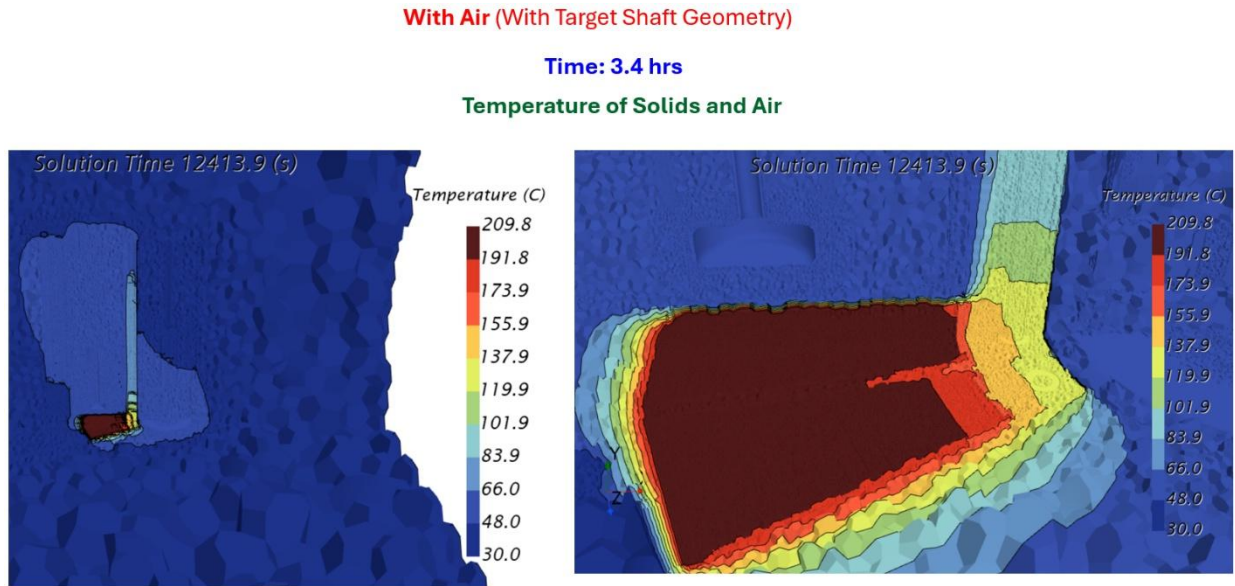


Figure 89. Temperature distribution in the target segment at $t = 3.4$ hours after beam shutdown.

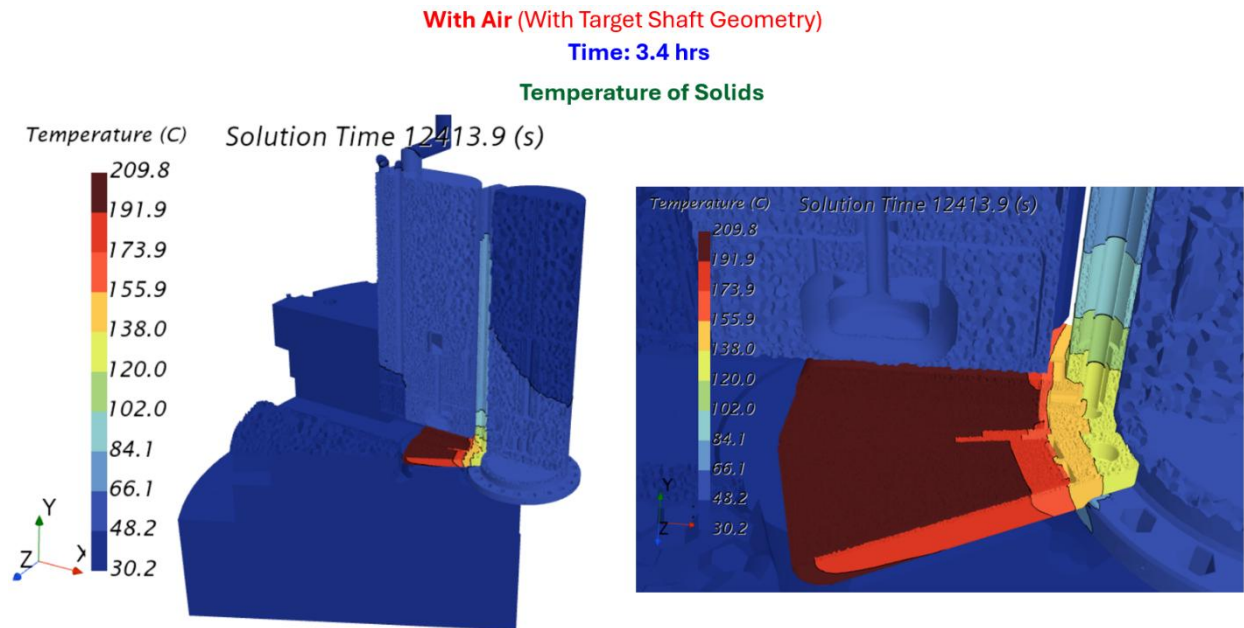


Figure 90. Temperature distribution in the target segment at $t = 3.4$ hours after beam shutdown (air domain hidden).

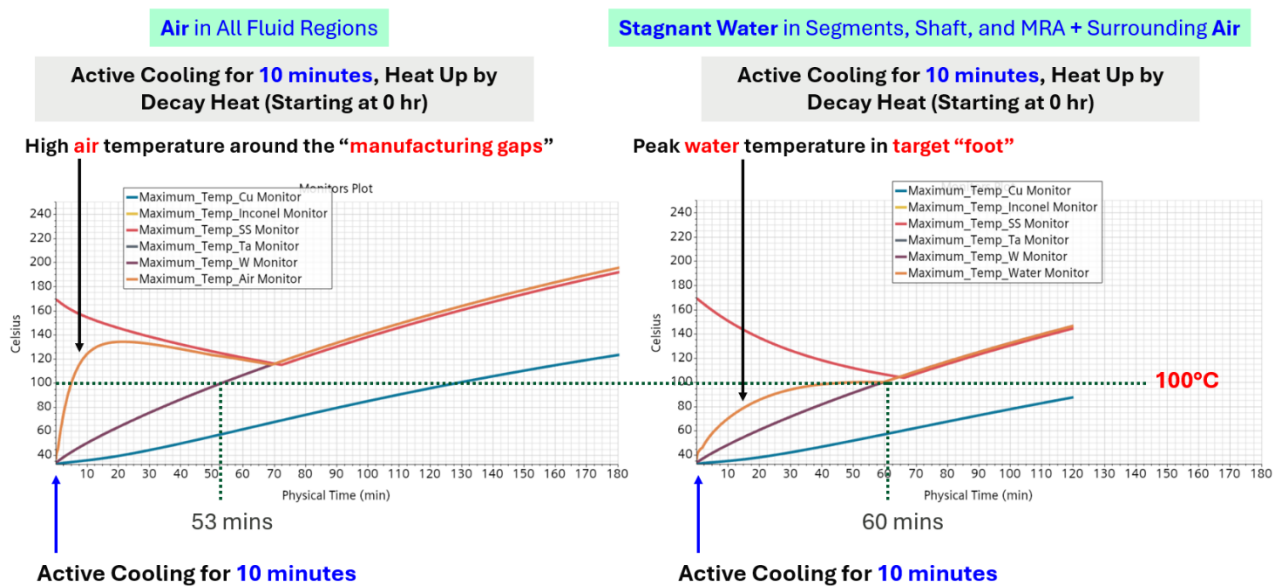


Figure 91. Comparison of target segment temperatures with air and with stagnant water in the segments, shaft, and MRA.

Stagnant Water in Segments, Shaft, and MRA + Surrounding Air

Active Cooling for 10 minutes, Heat Up by Decay Heat (Starting at 0 hr)

1 hr

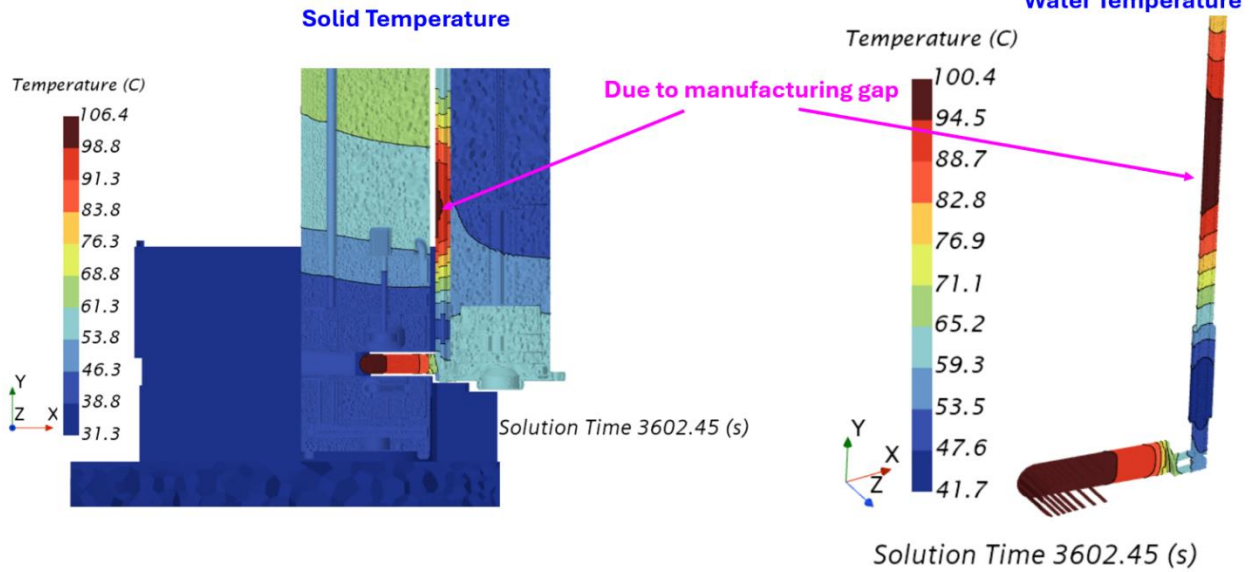


Figure 92. Temperature distribution at = 1 hour, following 10 minutes of active cooling applied to the target segments.

Stagnant Water in Segments, Shaft, and MRA + Surrounding Air

Active Cooling for 10 minutes, Heat Up by Decay Heat (Starting at 0 hr)

Active Cooling for 8 hours, Heat Up by Decay Heat (Starting at 8 hrs)

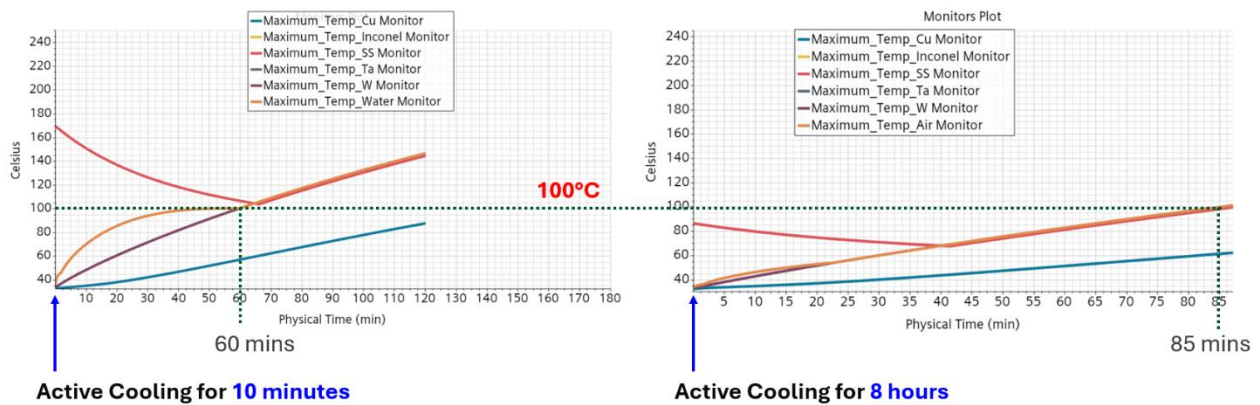


Figure 93. Comparison of target segment temperatures with 10 minutes and 8 hours of active cooling (7.5 GPM).

6.5 AIR COOLING OF A SINGLE TARGET SEGMENT

Prior to developing a full CV air-cooling configuration for decay heat removal from all 20 target segments, a single-segment airflow analysis was performed to establish bounding estimates of the required flow rate, local convective velocities, and mesh resolution requirements. This approach provides a controlled framework for understanding the fundamental heat transfer behavior while minimizing geometric and flow distribution complexities inherent in the full assembly.

The simulation domain (Figure 94 and Figure 95) consists of a localized air volume extracted from the CV surrounding a single target segment, rather than the full CV air volume. The domain includes one representative target segment along with nearby geometric features that define the immediate flow passages, such as portions of the target shaft interface and adjacent structural boundaries. This localized extraction preserves key geometric constraints, including small clearances such as the 2 mm gap between the target segment and the shaft (Figure 95), which could influence local flow behavior.

It should be noted that this approach does not capture global flow redistribution across the full set of 20 target segments. Instead, the extracted air volume imposes **artificial lateral confinement**, effectively restricting cross-flow and limiting interaction with neighboring segments. As a result, the model tends to maintain higher local velocities near the target surface than would be expected in the full CV configuration. This simplification is intentional and is used to establish a **bounding (optimistic) estimate of local convective cooling performance**, while retaining sufficient geometric fidelity to avoid nonphysical flow acceleration or unrealistic channeling within the immediate vicinity of the target segment.

Air is introduced through a 30 mm diameter circular duct directed toward the nose region of a representative target segment (Figure 94). This configuration approximates an idealized impinging jet condition and is intentionally selected to evaluate the upper bound of achievable convective heat transfer. The primary objective is to determine the airflow required to remove 150 W of decay heat from a single target segment, corresponding to approximately 8 hours of decay following beam shutdown. To simplify the analysis, steady-state simulations were performed assuming a constant 150 W heat head load, rather than modeling the time-dependent decay heat behavior.

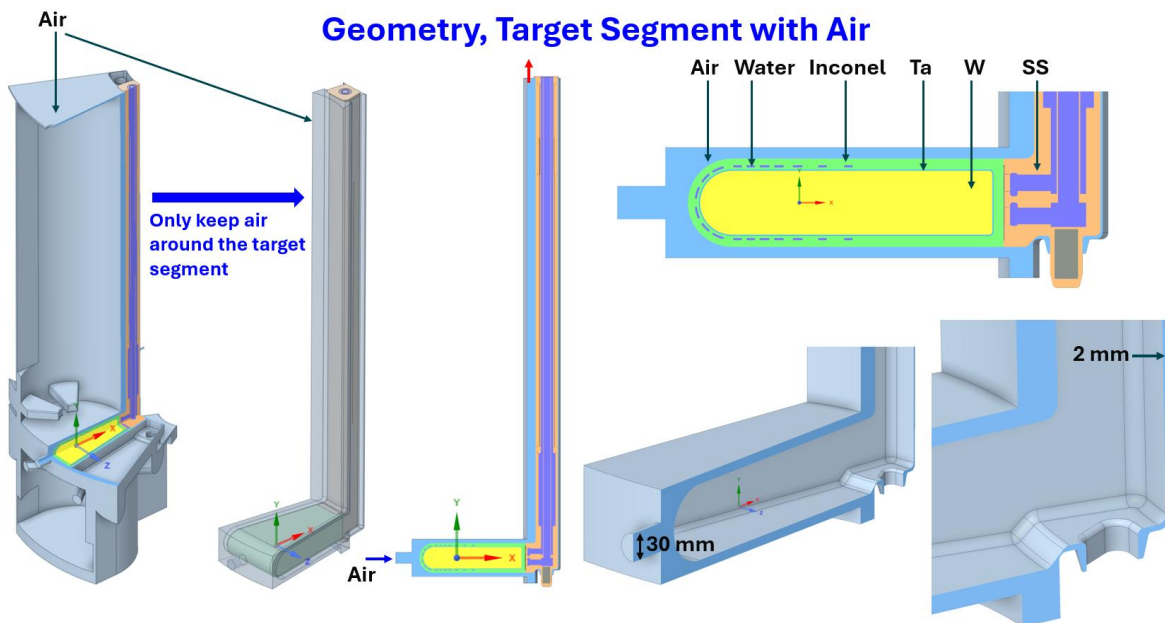


Figure 94. Simulation domain of a single target segment and the surrounding air domain.

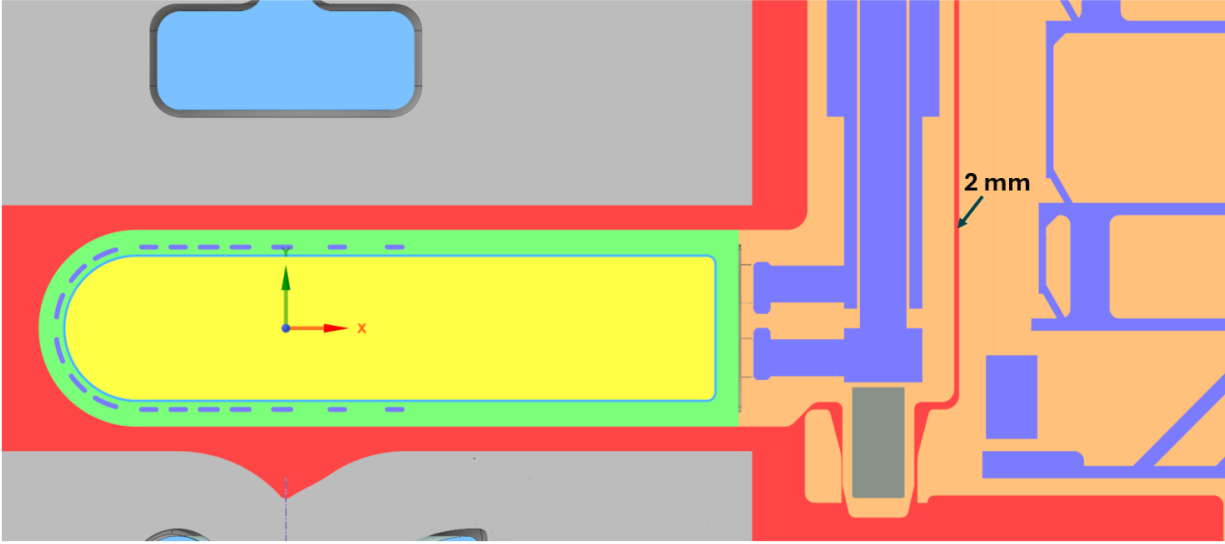


Figure 95. Geometry showing the 2 mm air gap between the target segments and the shaft.

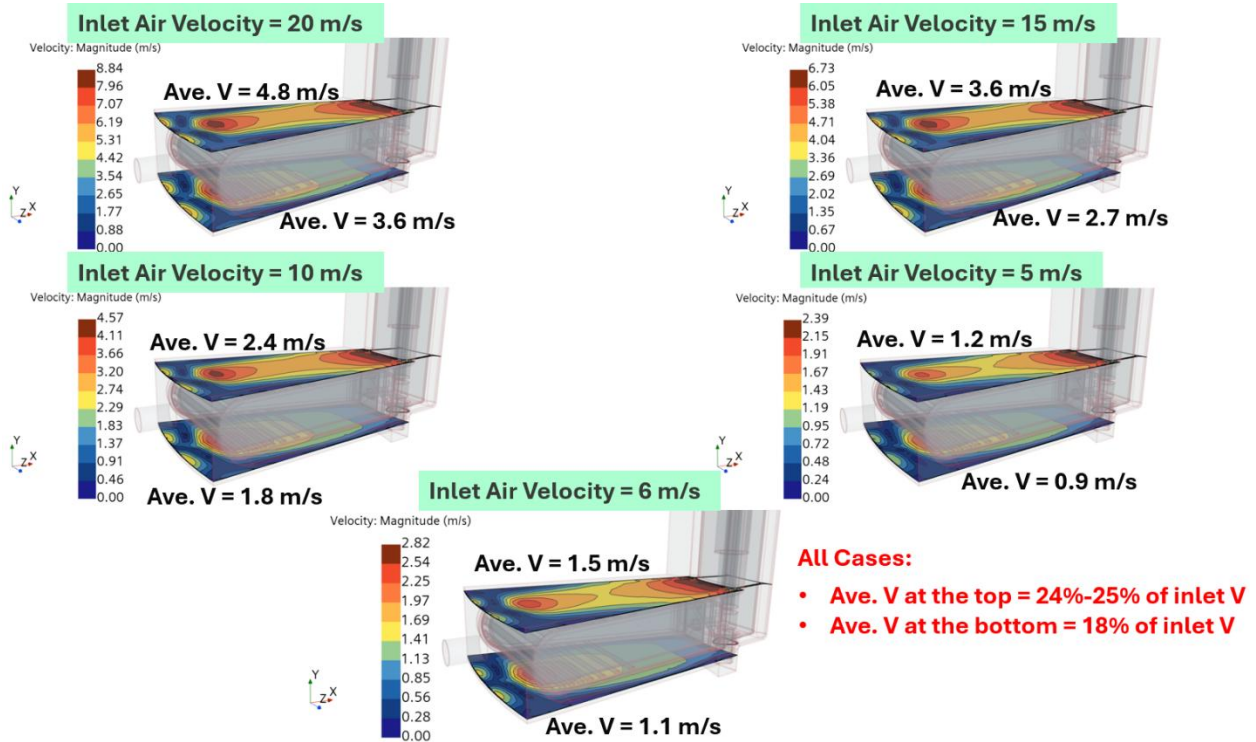


Figure 96. Velocity profiles at the top and bottom of the target segment for different inlet velocities.

A parametric set of simulations was conducted over a range of inlet velocities and temperatures. The resulting velocity distributions at the top and bottom planes of the target segment are presented in Figure 96. The results (Figure 97) indicate that an inlet velocity of 6 m/s, corresponding to a volumetric flow rate of 9 cfm at 22.22 °C (72 °F), is sufficient to limit the peak target block temperature to 96 °C. The associated temperature field and flow streamlines (Figure 98 and Figure 99) demonstrate effective cooling localized near the impingement region, with flow spreading over the target surface.

Steady State with 150 W of Decay Heat (8hrs) in Tungsten Block

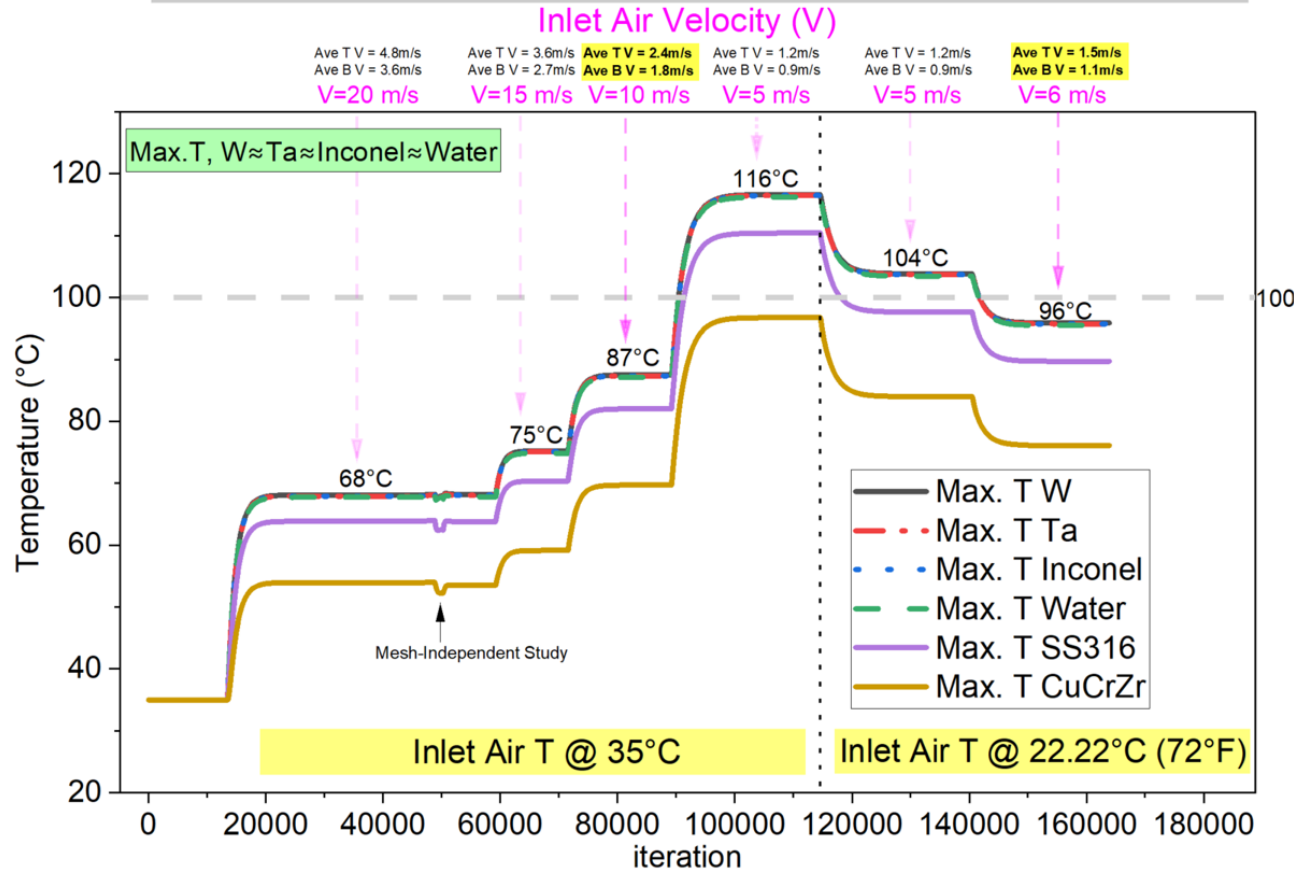


Figure 97. Peak target temperature under different inlet air velocities and temperatures.

Inlet Air Velocity = 6 m/s (Flow Rate: 9 cfm)

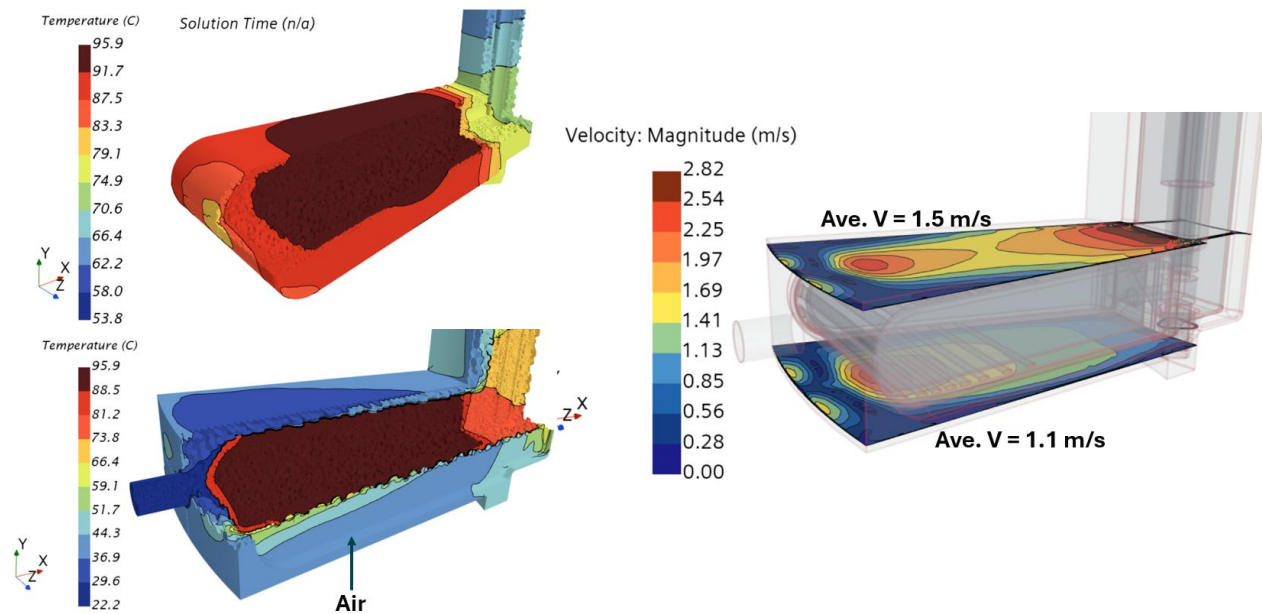


Figure 98. Temperature distribution and flow velocity field at an inlet flow rate at 9 cfm.

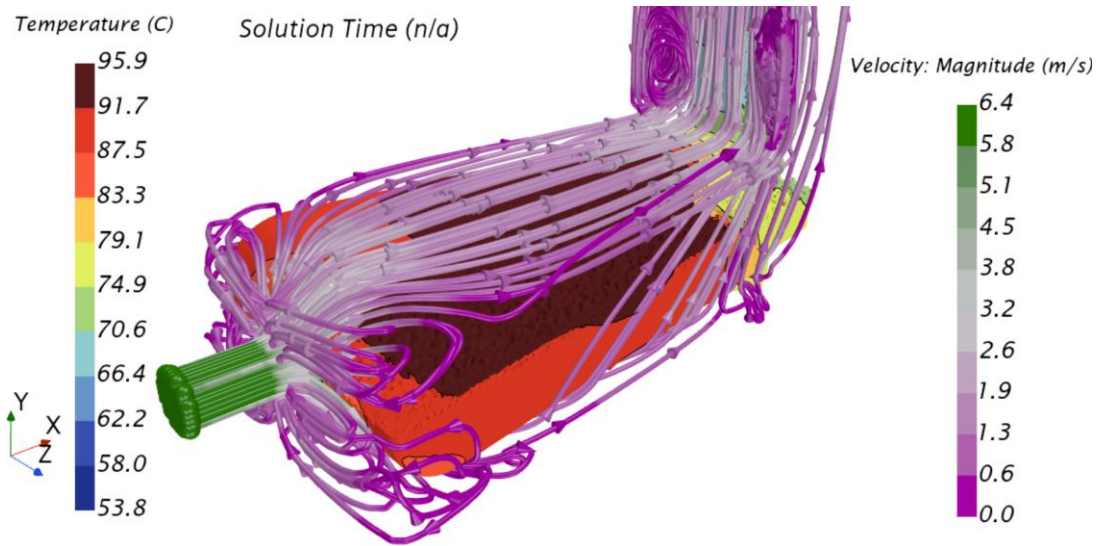


Figure 99. Air streamlines around the target block at an inlet flow rate at 9 cfm.

Extrapolation of this result to all 20 target segments yields a nominal total flow requirement of 180 cfm. However, this estimate is considered a **non-conservative lower bound** for several reasons:

1. Artificial Flow Confinement in Single-Segment Model

In the present model, the surrounding air volume effectively behaves as a set of “invisible walls” (Figure 94), constraining the flow and maintaining high local velocities adjacent to the target surface. This confinement enhances convective heat transfer and does not accurately represent the more open and competing flow paths present in the full CV geometry.

2. Limited Flow Access to Narrow Gaps

In the actual STS configuration, the inter-segment spacing is 5 mm (Figure 4). These narrow gaps present significant hydraulic resistance, making it unlikely that a meaningful fraction of the bulk airflow will penetrate and cool the lateral surfaces of the target segments. As a result, the side cooling observed in the single-segment model is expected to be overpredicted.

3. Infeasibility of Distributed Impinging Jets

The assumed impinging jet configuration cannot be practically implemented for all 20 target segments. In particular, the segment located directly below the MRA cannot accommodate a jet aligned with the proton beam axis due to geometric and operational constraints (Figure 2). Therefore, the highly effective localized cooling observed at the target nose in this analysis represents an idealized condition rather than a realizable system design.

4. Flow Redistribution in Full-System Configuration

In the full CV, airflow will preferentially follow paths of least resistance, primarily over the top and bottom regions of the target array rather than through constrained side gaps. This redistribution will reduce local velocities near critical heat-generating regions unless significantly higher bulk flow rates are provided.

Based on these considerations, the actual airflow required for adequate decay heat removal is expected to be substantially higher than 180 cfm. Rather than relying solely on total flow rate, local velocity criteria provide a more robust design metric. As shown in Figure 98, the minimum required air velocities to remove 150 W of decay heat are approximately 1.5 m/s over the top surface and 1.1 m/s over the bottom surface of a target segment. These values should be interpreted as **minimum local velocity targets** for subsequent full-system design and optimization. These velocity targets are used as design criteria to evaluate whether candidate CV air flow configurations provide sufficient local cooling under realistic flow distribution conditions.

6.6 AIR COOLING OF THE ENTIRE TARGET ASSEMBLY¹¹

Figure 100 shows a simplified geometry within the CV, including the TVP, MRA, target assembly, and all shielding blocks. The air volume within the CV was then extracted to ensure all meaningful gaps that could affect airflow distribution are retained. As shown in Figure 101, sheet metal covers are introduced over the gaps between CV shielding blocks to act as flow directors, guiding airflow closer to the target blocks and enhancing the cooling performance.

The simulation domain for the steady-state thermal analysis includes the air volume and the lower portion of all 20 target segments, as shown in Figure 102. As shown in Figure 103, the 6-inch (152.4 mm) outlet is located at the lower portion of the CV and is connected to the 10 mm clearance gap between shielding blocks, which serves as a primary flow path for air exiting the system.

Airflow through the STS core vessel and target assembly is driven by a combination of inlet and outlet pressure boundary conditions, selected to represent the intended operational ventilation scenario. Air enters the CV through a 6-inch (152.4 mm) diameter inlet duct at a temperature of 22.22 °C (72 °F), corresponding to ambient high-bay conditions. At the outlet, a negative pressure boundary is applied to simulate the suction effect of the Hot Off-Gas (HOG) system, which draws air downward through the CV and target assembly. This arrangement ensures that convective flow proceeds from the top to the bottom, removing decay heat from the target segments while preventing the upward transport of potentially activated air. Maintaining downward airflow is critical to limit the release of radioactive particulates or contaminated air into the target drive room or high-bay areas, where personnel access is required for maintenance and other operations. The imposed pressure difference is selected to provide realistic flow velocities over the target surfaces, while the combination of controlled inlet temperature and suction at the HOG outlet ensures that the thermal and convective behavior of the air is representative of steady-state operational conditions.

For modeling simplicity, within each target segment, the 20 tungsten blocks and the 0.5 mm tantalum interlayers are combined and represented as a single equivalent tungsten block with a total decay heat source of 150 W. This equivalent block is enclosed by the tantalum cladding, Inconel shroud, and stainless-steel structural components. The primary objective of this analysis is to estimate the required pressure drop needed to drive sufficient airflow for the decay heat removal from all 20 target segments (3 kW total = 150 W × 20).

¹¹ Geometry file: https://windchill-prod.ornl.gov:8443/Windchill/app/#ptcl/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792CFD_CAD/Air_Cooling.zip

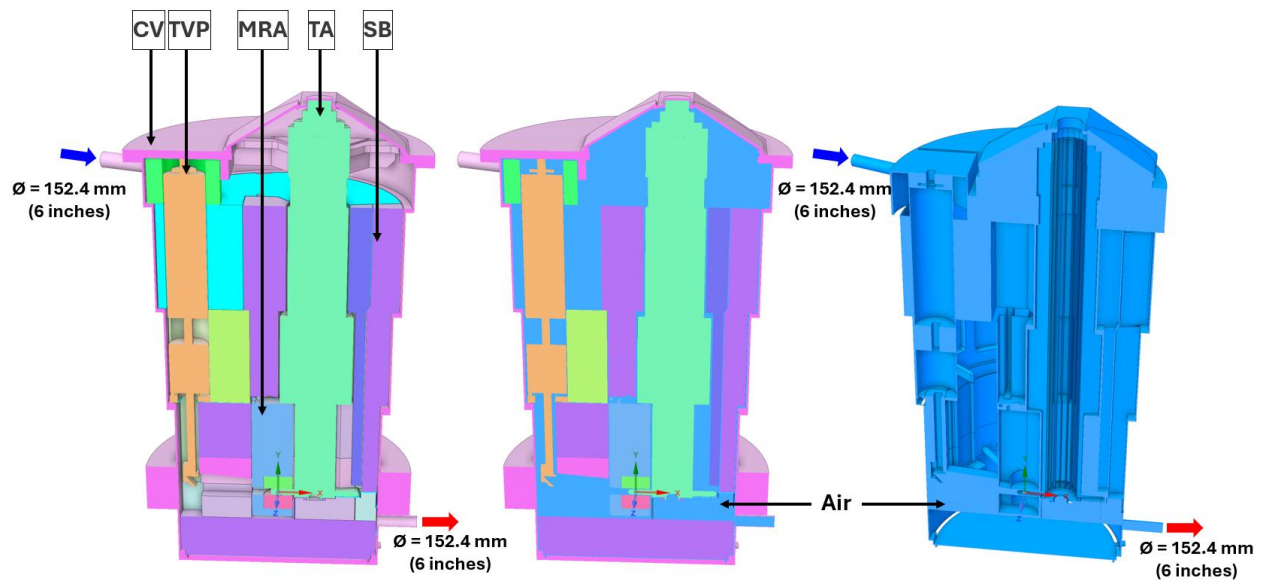


Figure 100. Air volume within the CV.

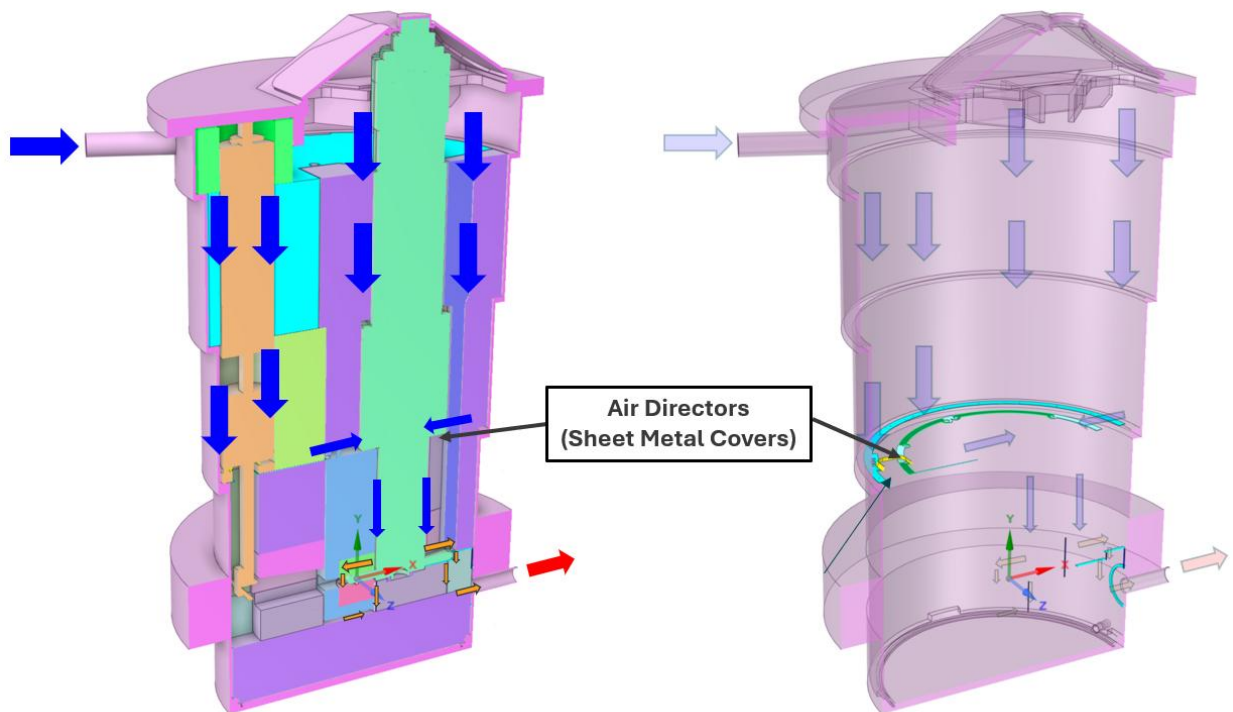


Figure 101. Air directors.

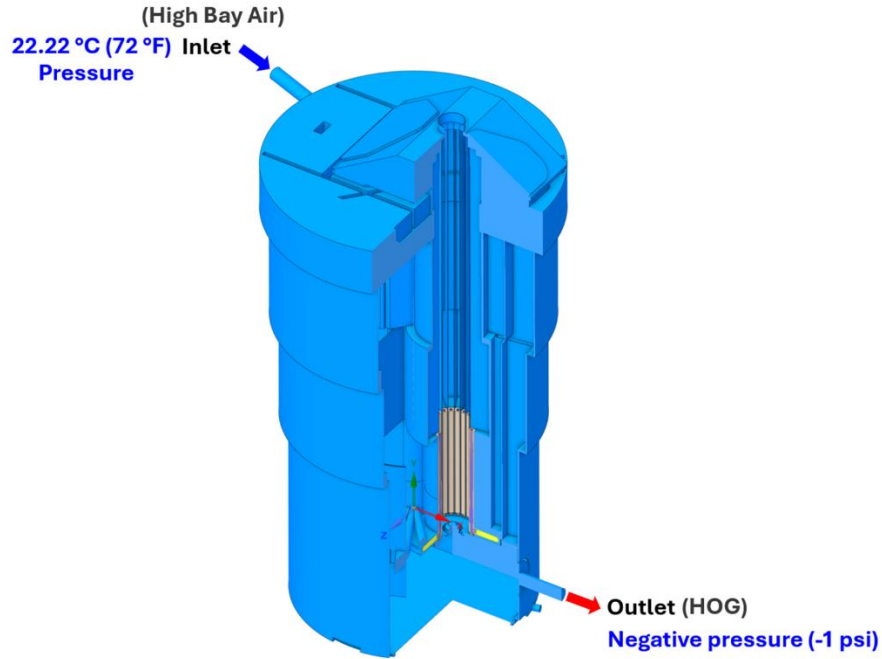


Figure 102. Simulation domain: air and all 20 target segments.

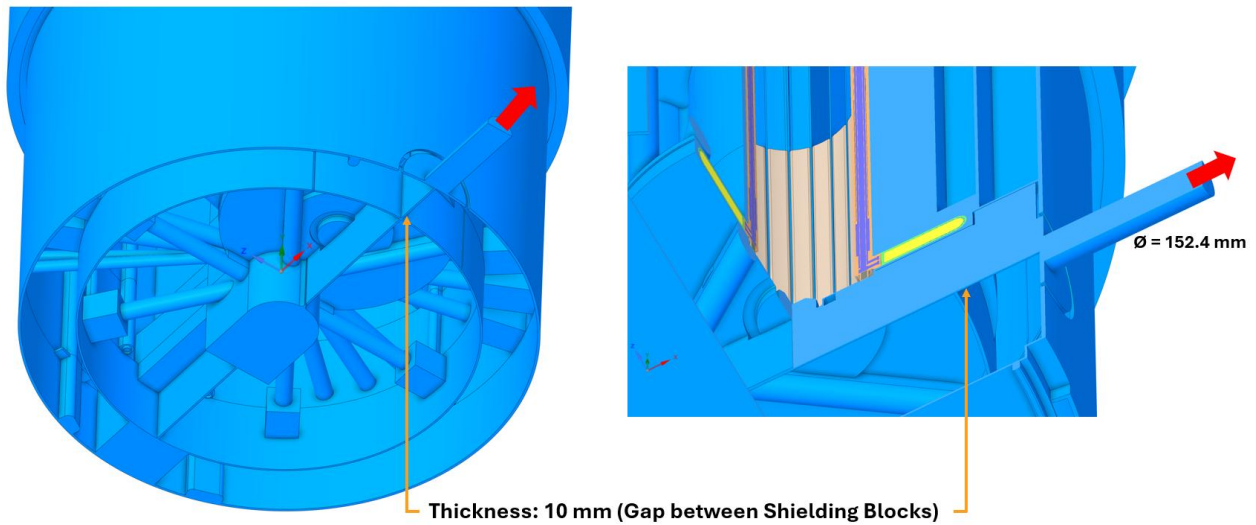


Figure 103. Air volume in the vicinity of the outlet.

The airflow velocity distributions corresponding to pressure drops of 0.2 psi, 0.4 psi, and 1.0 psi are shown in Figure 104, Figure 105, and Figure 106, respectively. With pressure drops of 0.2–0.4 psi, the velocities over the top and bottom surfaces of the target blocks remain below 1.10–1.4 m/s, which is lower than the minimum target velocities identified in the previous section. As shown in Figure 106, with a pressure drop of 1.0 psi (corresponding to an airflow rate of approximately 500 cfm), the air velocity around the target blocks is generally above 1.5 m/s, although some regions farther from the outlet remain below 1.1–1.4 m/s.

The corresponding temperature distribution is shown in Figure 107. Under a 1.0 psi pressure drop, the majority of the target blocks can be maintained below 120 °C; however, six blocks exhibit peak

temperatures up to 130 °C, primarily due to reduced local airflow in regions farther from the outlet. As shown in Figure 107, the current configuration—with the outlet located at the lower side of the CV—produces a highly non-uniform velocity distribution. Regions near the outlet experience velocities exceeding 2.5 m/s, resulting in lower peak temperatures (55–76 °C), whereas regions farther from the outlet experience velocities below 1.0 m/s.

An earlier design iteration featuring an outlet located at the bottom center of the target wheel produced a more uniform velocity distribution, maintaining peak temperatures near 90 °C under a 1.0 psi pressure drop. However, this configuration is not feasible due to geometric and system integration constraints.

The primary **limitations** of this air-cooling approach are as follows:

- (1) The airflow path depends on the full assembly of shielding blocks, MRA, and target structures; removal of any components during maintenance disrupts the designed flow path and reduces cooling effectiveness.
- (2) Several critical flow paths rely on narrow (10 mm) clearance between shielding blocks (e.g., Figure 103), which may be sensitive to installation tolerances or deformation during seismic events, potentially degrading airflow performance.

Forced Air Flow for Decay Heat Removal (8 hrs, 150W*20 Segments = 3 kW)

Air flow Rate = ~230 cfm , pressure drop = 0.2 psi

Geometry: 01/2026

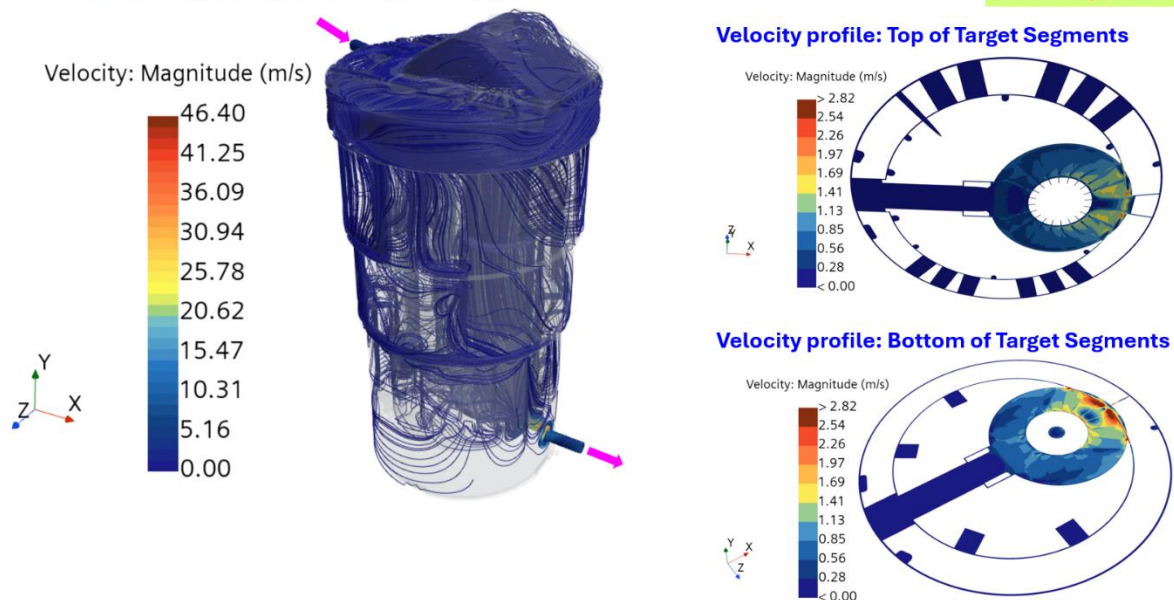


Figure 104. Velocity distribution over the top and bottom surfaces of the target segments with a pressure drop of 0.2 psi.

Forced Air Flow for Decay Heat Removal (8 hrs, 150W*20 Segments = 3 kW)

Air flow Rate = 321 cfm , pressure drop = 0.4 psi

Geometry: 01/2026

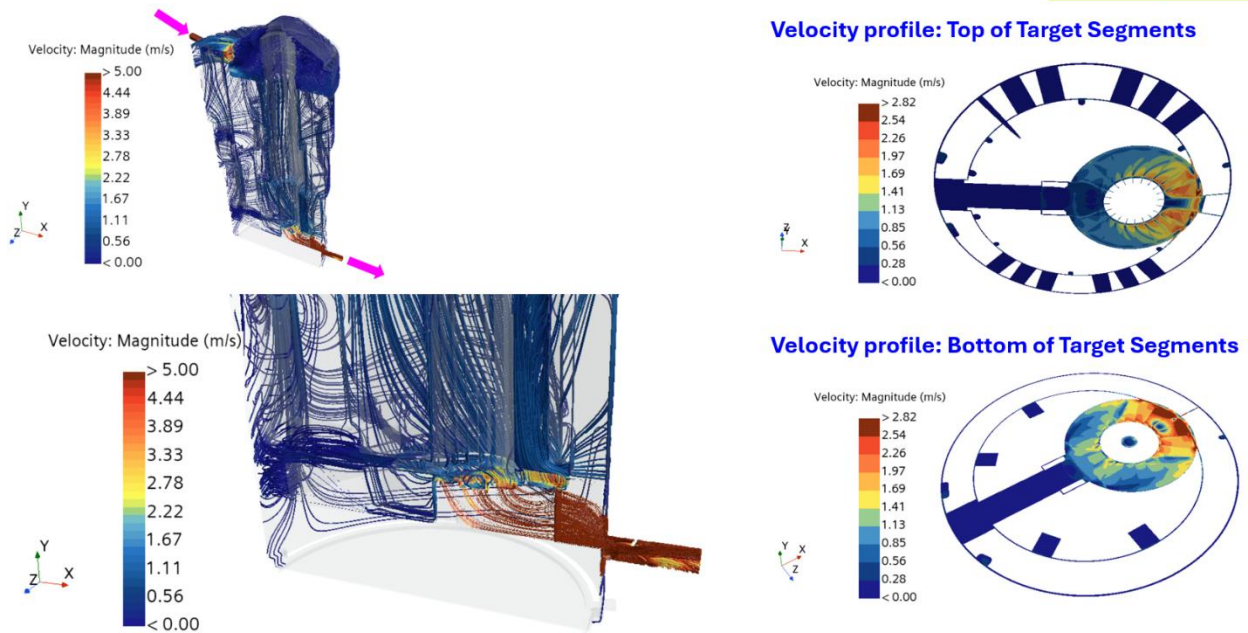


Figure 105. Velocity distribution over the top and bottom surfaces of the target segments with a pressure drop of 0.4 psi.

Forced Air Flow for Decay Heat Removal (8 hrs, 150W*20 Segments = 3 kW)

Air flow Rate = ~526 cfm , pressure drop = 1.0 psi , Peak Target Temperature = 130°C

Geometry: 01/2026

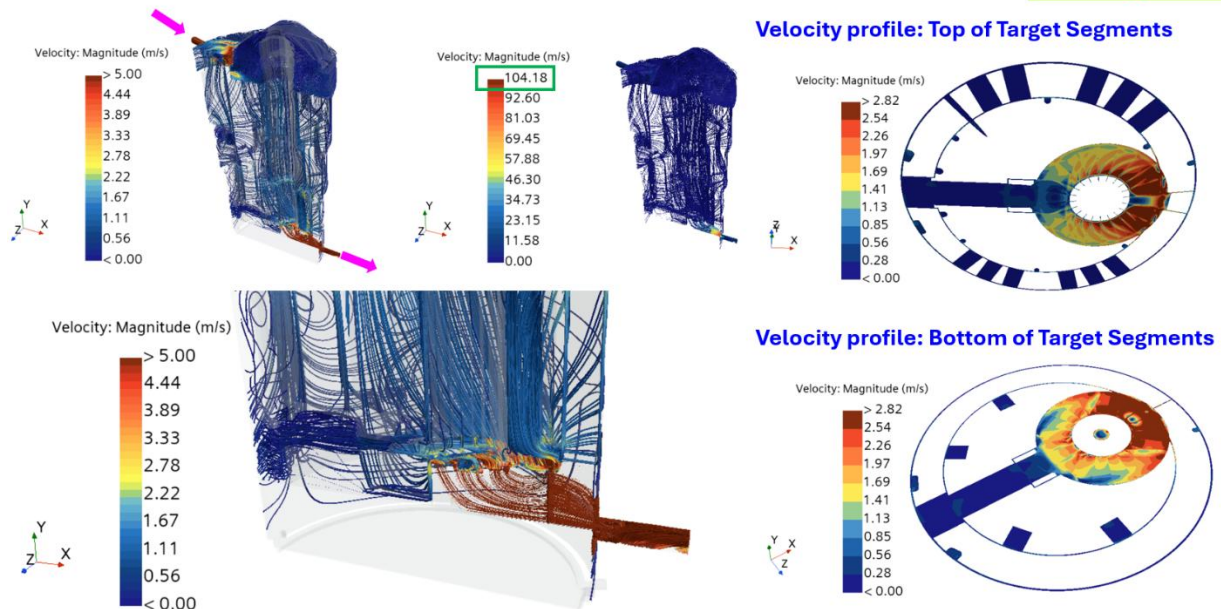


Figure 106. Velocity distribution over the top and bottom surfaces of the target segments with a pressure drop of 1.0 psi.

Forced Air Flow for Decay Heat Removal (8 hrs, 150W*20 Segments = 3 kW)

Air flow Rate = ~526 cfm , pressure drop = 1.0 psi , Peak Target Temperature = 130°C

Geometry: 01/2026

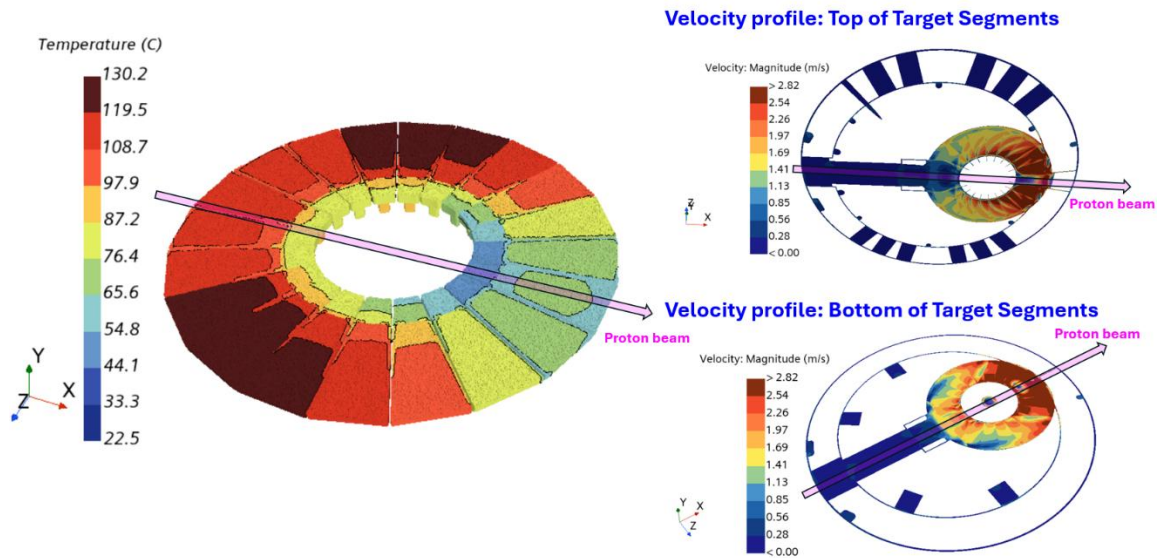


Figure 107. Temperature distribution of the target blocks and corresponding velocity distribution with a pressure drop of 1.0 psi.

7. PRESSURE DROP AND FLOW BALANCE OF THE TARGET ASSEMBLY¹²

As indicated in Section 3, the pressure drop across the target assembly is governed by both the geometric hydraulic resistance and the imposed inlet flow conditions. Previous analyses of the target shaft and target segments were performed separately, with pressure drops evaluated under the assumption of uniform inlet flow conditions. However, this assumption does not account for the complex flow field, including vortex structures, that develops at the inlets of the target shaft and the 20 target segments. Furthermore, in the absence of an active control system to regulate flow distribution, the actual flow rate entering each component is determined solely by its hydraulic resistance. Consequently, flow imbalance may occur, potentially leading to insufficient cooling in certain target segments. Therefore, this section evaluates the total pressure drop across the full target assembly and examines how the total inlet flow rate of 157.5 GPM is distributed among individual components, in order to assess the validity of the 7.5 GPM inlet flow rate assumption used in previous sections.

As shown in Figure 108, the supply and return channels of the target assembly are vertically aligned in the FDR design. The assembly consists of both stationary and rotating components (rotation rate: 45 RPM). Accordingly, the coolant domain in the CFD model is divided into a stationary region (laboratory reference frame) and a rotating region, with a rotating reference frame defined at ($x = 0.483$ m, $y = 0$, $z = 0$). In addition, screens (or strainers) are incorporated into the cooling system to prevent particulate matter from entering narrow cooling channels, thereby avoiding flow blockage, maldistribution, and potential local overheating. These screens introduce additional hydraulic resistance and are therefore included in the CFD analysis.

For an inlet flow rate of 157.5 GPM, an outlet reference pressure of 45 psi, and a rotation rate of 45 RPM, the total pressure drop across the target assembly is 13.58 psi, as shown in Figure 109. The mass flow rates in the target shaft and the 20 target segments are evaluated on the cross-sectional planes shown in Figure 110, and are summarized in Figure 111 and Table 20. The total flow rate obtained from these planes does not exactly match the prescribed inlet flow rate of 157.5 GPM. This discrepancy does not indicate a violation of mass conservation, which is strictly enforced at the control-volume level in the CFD solver. Instead, the difference arises from interpolation of the velocity field onto the post-processing planes. The relative flow distribution among components is obtained directly from the CFD results, and the corresponding flow rates are normalized to the total inlet flow rate of 157.5 GPM, as summarized in Table 20. Figure 112 shows the mass conservation monitor, where the inlet and outlet mass flow rates are both approximately 9.87 kg/s (157.5 GPM), with a difference of 2×10^{-6} kg/s, confirming that mass conservation is satisfied.

As illustrated in Figure 108, coolant enters horizontally through a single inlet, flows downward along the shell side to the interface between the stationary and rotating regions, and is then distributed to the target shaft and the 20 target segments. This flow path (single inlet → shell side → stationary/rotating interface → 21 outlets (inlets of the shaft and the 20 segments)) and resulting inlet velocity distributions differ significantly from the uniform inlet flow assumptions used in the separate target shaft and target segment analyses, where a flow rate of 7.5 GPM was prescribed for each component (Chapter 0 and Chapter 5). As indicated in Table 20, the actual flow rates entering individual target segments are not identical (though relatively uniform) and are slightly lower than 7.5 GPM, whereas the flow rate entering the target shaft is significantly higher, at 13.28 GPM (APPENDIX G). This difference arises primarily from variations in hydraulic resistance between the shaft and the segments, as discussed in Chapter 0 and

¹² Geometry file: <https://windchill-prod.ornl.gov:8443/Windchill/app/#ptcl/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792>
CFD_CAD/Target_Assembly_Total_Pressure_Drop.zip

Chapter 5. The minimum flow rate entering a target segment is 7.14 GPM (0.447 kg/s), which is 4.8% lower than the assumed value of 7.5 GPM (0.47 kg/s).

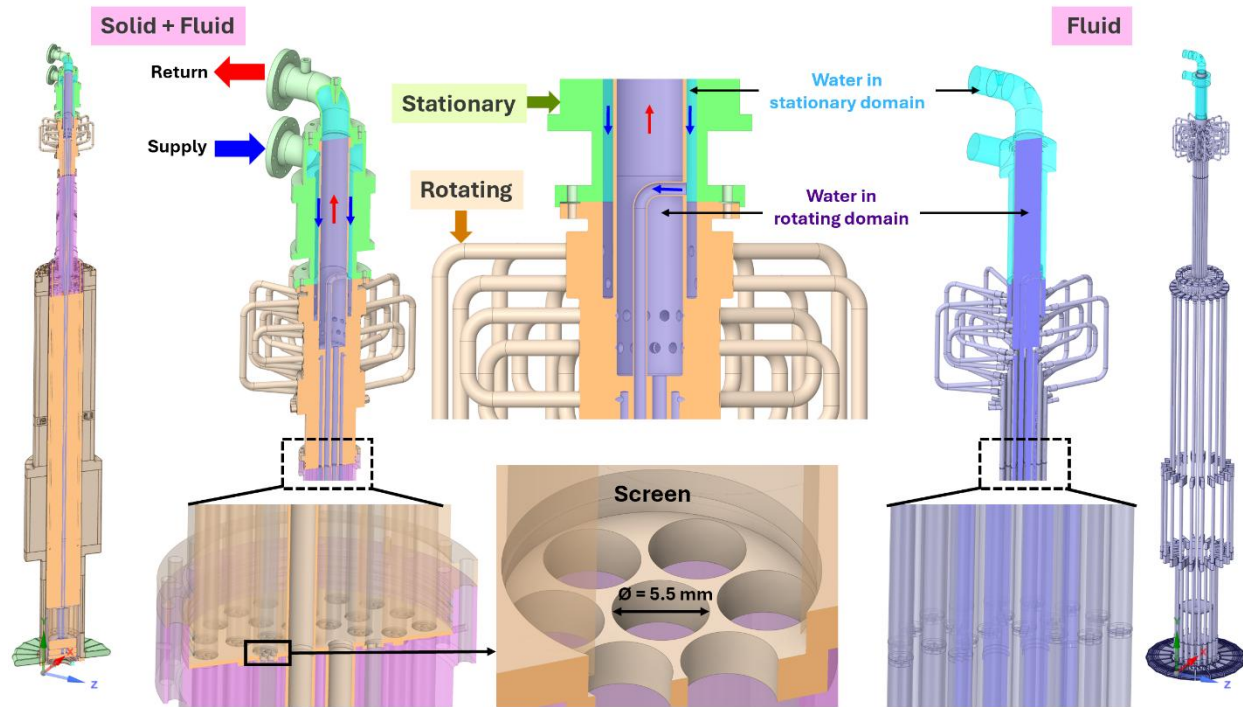


Figure 108. Simulation domain of the target assembly.

$$\Delta P_{\text{inlet-outlet}} = 0.94 \text{ bar} (= 93.6 \text{ kPa} = \mathbf{13.58 \text{ psi}} = 0.92 \text{ atm})$$

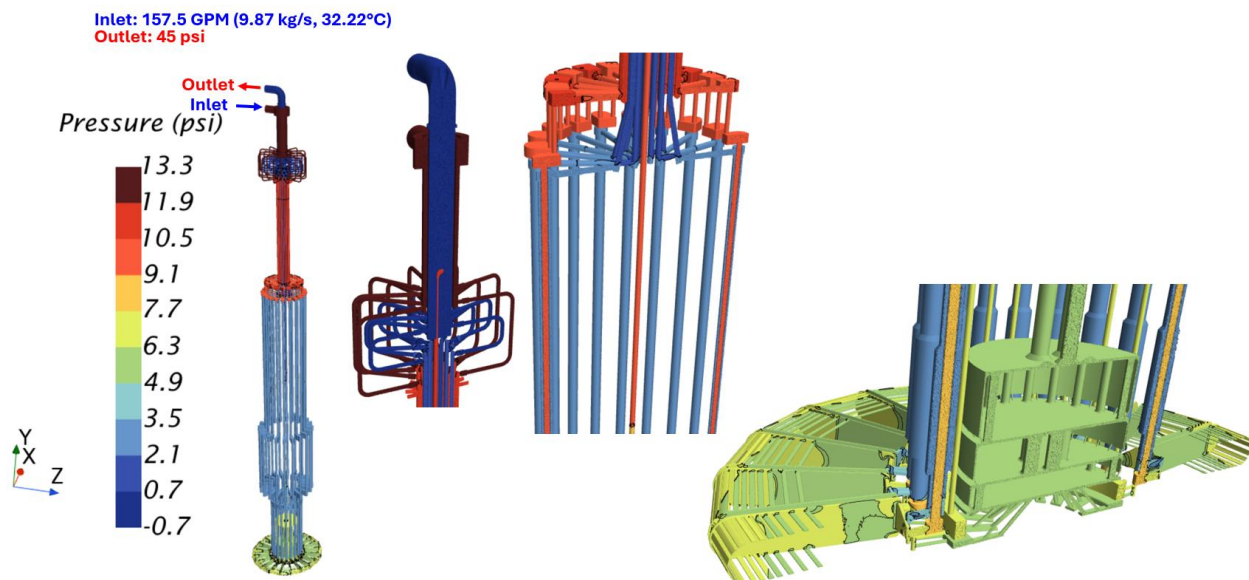


Figure 109. Pressure distribution in the Target Assembly.

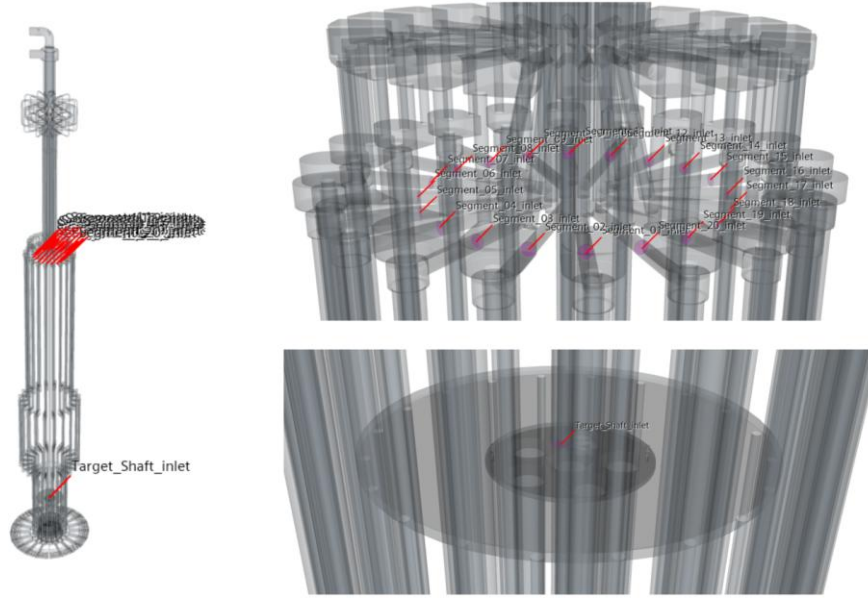


Figure 110. Cross-sectional planes used to evaluate channel mass flow rates.

Table 20. Mass flow rate in the 20 target segments and the shaft.

Flow Balance Analysis: Average = 4.76 % (=100%/21)					
Component	CFD Results (Post-Processing Planes)			Mass-Conservation-Corrected Flow Rate	
	Mass Flow Rate (kg/s)	GPM	%	Mass Flow Rate (kg/s)	GPM
segment_01	0.439	7.01	4.58	0.452	7.21
segment_02	0.442	7.05	4.60	0.454	7.25
segment_03	0.440	7.02	4.58	0.452	7.22
segment_04	0.439	7.01	4.58	0.452	7.21
segment_05	0.440	7.02	4.58	0.453	7.22
segment_06	0.438	6.99	4.57	0.451	7.20
segment_07	0.439	7.01	4.58	0.452	7.21
segment_08	0.441	7.03	4.60	0.454	7.24
segment_09	0.437	6.97	4.56	0.450	7.18
segment_10	0.435	6.94	4.53	0.447	7.14
segment_11	0.437	6.98	4.56	0.450	7.18
segment_12	0.441	7.04	4.60	0.454	7.24
segment_13	0.439	7.00	4.58	0.452	7.21
segment_14	0.439	7.01	4.58	0.452	7.21
segment_15	0.439	7.01	4.58	0.452	7.21
segment_16	0.441	7.03	4.60	0.454	7.24
segment_17	0.438	6.98	4.56	0.450	7.19
segment_18	0.440	7.03	4.59	0.453	7.23
segment_19	0.439	7.00	4.57	0.451	7.20
segment_20	0.440	7.02	4.59	0.453	7.22
Target_Shift	0.808	12.90	8.43	0.832	13.28
Sum	9.59	153.04		9.870	157.5

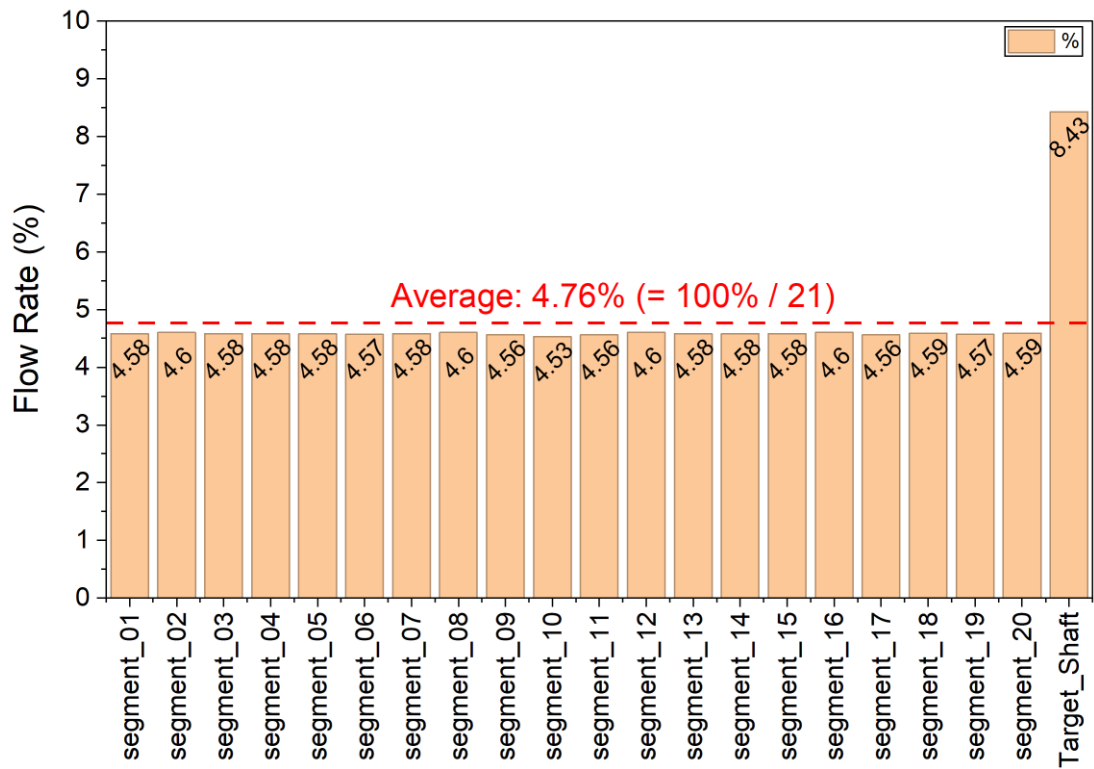


Figure 111. Mass flow rate.

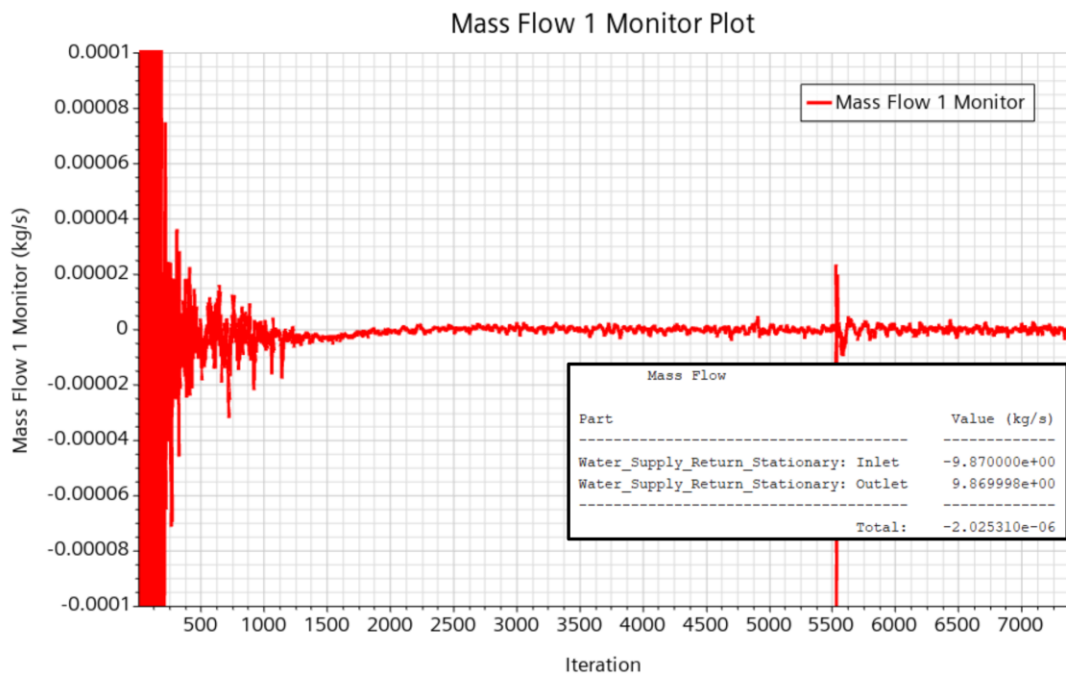


Figure 112. Mass conservation monitor.

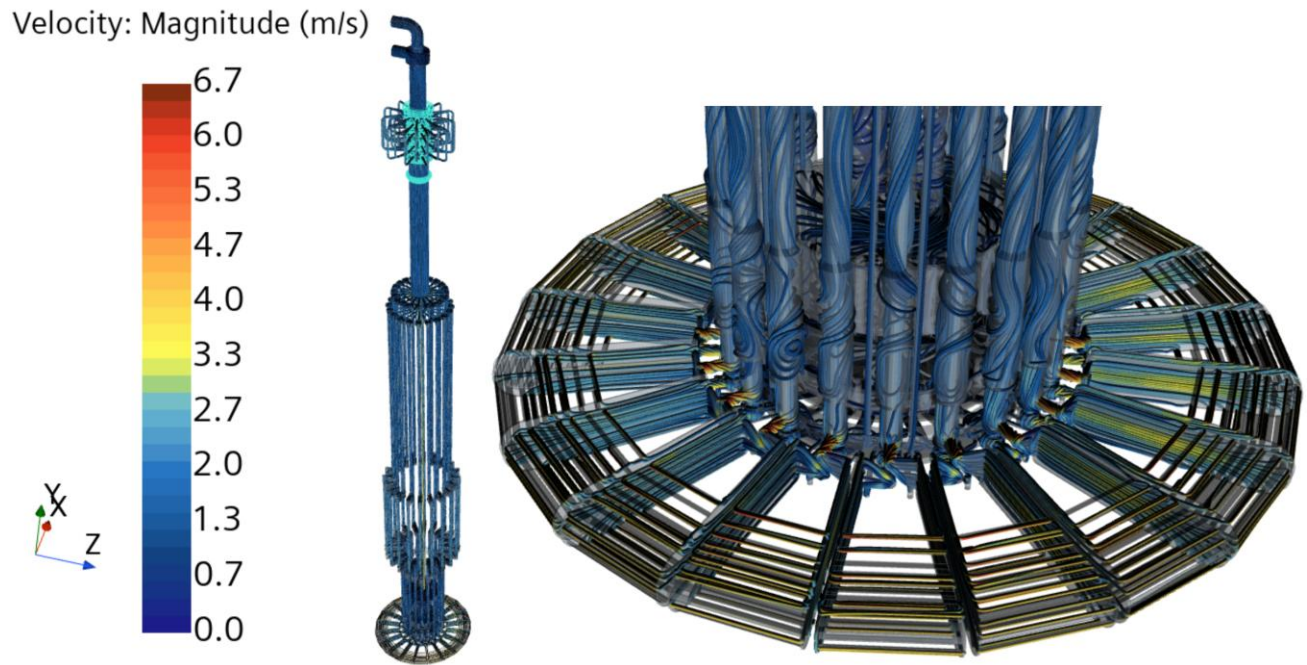


Figure 113. Flow streamlines.

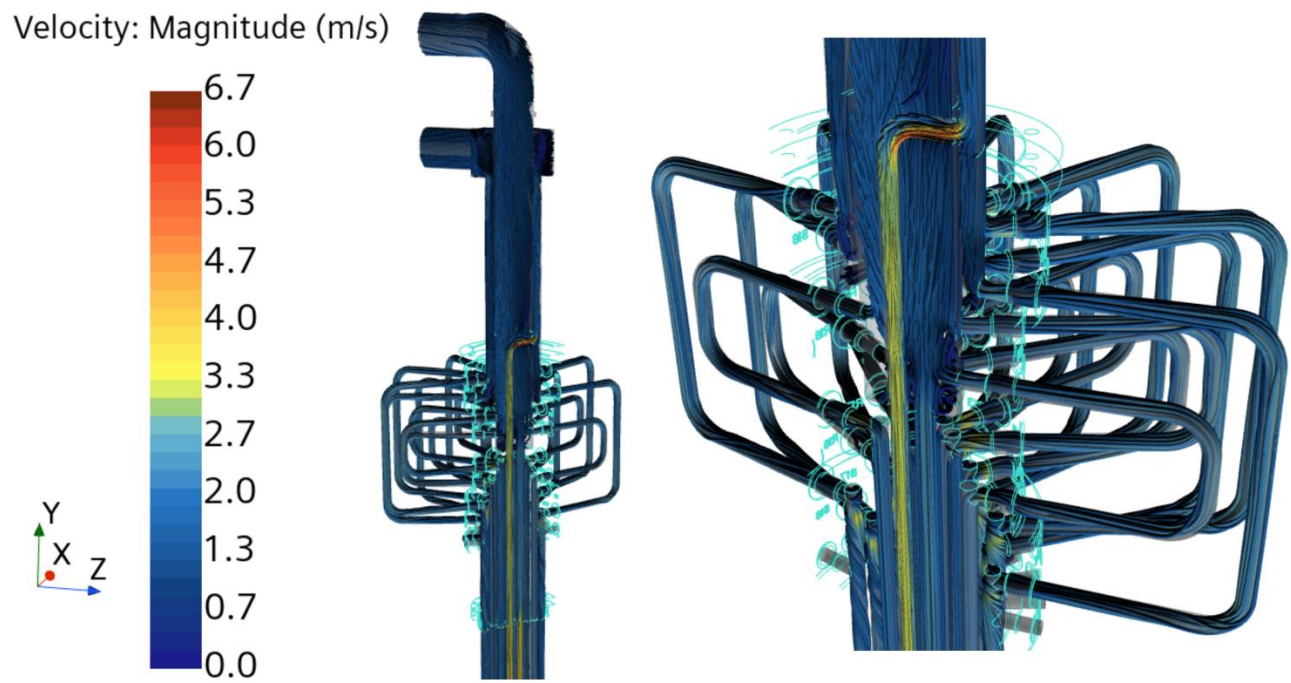


Figure 114. Flow streamlines near the inlet regions.

The temperature distribution in the target segment under the reduced flow rate condition (7.14 GPM, worst case) is shown in Figure 115. A comparison of peak temperatures between the nominal (7.5GPM) and reduced (7.14 GPM) flow rates is presented in Table 21. It should be noted that the target segment considered in this section incorporates Inconel 718 (instead of SS316) flow covers, a modified lower SS316 leg design to reduce the previously observed high temperature (~174 °C in Figure 30), and excludes the CuCrZr component in the segment pin to simplify manufacturing. As a result, the peak temperatures reported in Table 21 differ slightly from those presented in Table 6 and Table 8.

A key finding of this integrated analysis is that the peak temperature within the target core remains relatively insensitive to flow rate variations. Despite the 4.8% flow maldistribution observed in the system-level model, separate single-segment analysis confirms that peak temperatures vary by only 2–3 °C.

The insensitivity is attributed to two primary factors:

- **Strategic Cooling Placement for Contamination Control:** To prevent the release of activation products into the water system, the cooling channels are intentionally located within the Inconel 718 shroud rather than in direct contact with the tantalum cladding (W → Ta → Inconel 718 → water). This creates a robust physical barrier between the coolant and the highly activated tantalum-clad tungsten core. In contrast, if the coolant were in direct contact with the high-conductivity tantalum cladding, the peak temperature would be more sensitive to variations in convective flow conditions.
- **Thermal Insulation of the Inconel 718 Shroud:** Because the cooling channels are housed in Inconel 718—which has a lower thermal conductivity (11.4 W/m-K, Table 1) than stainless steel (14.58 W/m-K)—the shroud effectively acts as a thermal insulator. This high conductive resistance effectively "shields (decouples)" the internal target components from fluctuations in the convective cooling at the water interface, making the internal temperature field less dependent on the exact flow rate.

This behavior is consistent with the results from the 900 kW cases discussed in Section 4.7 and suggests that significantly higher flow rates would be required to achieve further temperature reduction under elevated beam power conditions.

Overall, the system-level CFD results demonstrate that inlet flow configuration has a measurable impact on both pressure drop and flow distribution within the target assembly. Despite moderate flow imbalance, the resulting variation in target segment temperature remains limited, indicating that the current design maintains adequate thermal performance under realistic operating conditions

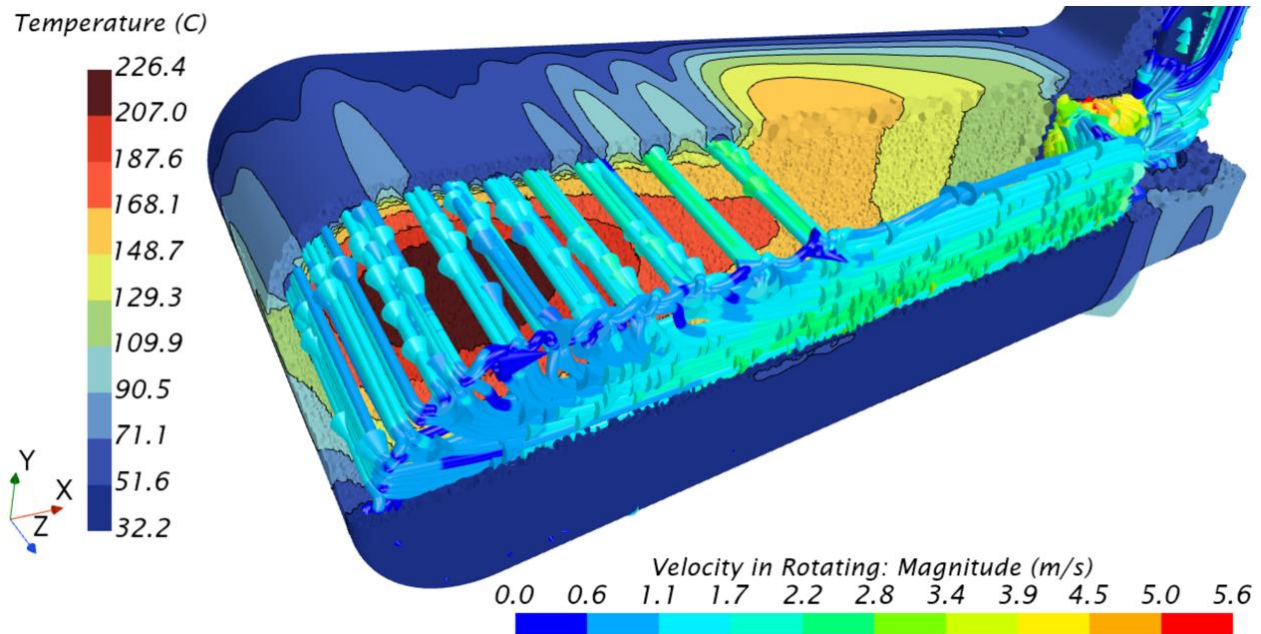


Figure 115. Steady-state temperature distribution in the target segment with Inconel 718 flow covers and a modified lower SS316 leg design at a reduced flow rate of 7.14 GPM due to flow imbalance.¹³

Table 21. Comparison of peak temperatures for the target segment with Inconel 718 flow covers and a modified lower SS316 leg design at nominal (7.5 GPM) and reduced (7.14 GPM) flow rates under a 700 kW nominal beam.

Material	Peak Temperature (°C) (700 kW Nominal Beam)		
	7.5 GPM (0.47 kg/s)	7.14 GPM (0.447 kg/s)	Difference (°C)
Tungsten	224.6	226.4	1.8
Tantalum	223.4	225.3	1.9
Inconel 718	169.6	171.7	2.1
SS 316	109.4	109.8	0.4
H ₂ O	106.1	108.6	2.5

¹³ Heat Source file: https://windchill-prod.ornl.gov:8443/Windchill/app/#ptcl/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792CFD_Heat_Sources/1_Nominal_Beam_With_Inconel_Flow_Covers
 Geometry file: https://windchill-prod.ornl.gov:8443/Windchill/app/#ptcl/tcomp/infoPage?oid=VR%3Awt.doc.WTDocument%3A850350792CFD_CAD/Target_Segment_Inconel_Flow_Cover.zip

8. REQUIREMENT SATISFACTION

Satisfactions of thermal hydraulics requirements documented on Codebeamer are summarized in Table 22.

Table 22. Requirement satisfaction of target assembly.

Codebeamer Tracker and Link	Requirement	CFD Result	Status
Target Assembly Requirement 1487 https://sts-req.ornl.gov:8443/cb/issue/1487	System pressure drop shall not exceed 14.5 psi. (100 kPa)	13.6 psi	Pass
Segment Requirement 1602 https://sts-req.ornl.gov:8443/cb/issue/1602			
Drive Requirement 1644 https://sts-req.ornl.gov:8443/cb/issue/1644	The segment shall have a pressure drop less than 9 psi (62 kPa) at 7.5 gpm (28.4 L/min).	9.0 psi	Pass
Shaft Requirement 1691 https://sts-req.ornl.gov:8443/cb/issue/1691	The target Drive shall have a pressure drop of less than 6 psi (42 kPa) at 157.45 gpm (596 L/min).	4.6 psi at 157.5 gpm	Pass
	The shaft shall have a pressure drop of less than 6 psi (62 kPa) at 7.5 gpm (28.4 L/min).	4.9 psi	Pass

9. SUMMARY TABLES

The following tables summarize the key results for the final STS target design, compiled from Table 6, Table 8, Table 10, Table 18, and Table 21. The results are representative of the final configuration, as only minor geometric variations exist among the simulation models.

Table 23. Comparison of peak temperatures for the target segment at assumed (7.5 GPM) and actual (7.14 GPM) flow rates under a 700 kW nominal beam.

Material	Peak Temperature (°C) (700 kW Nominal Beam)		
	7.5 GPM (0.47 kg/s)	7.14 GPM (0.447 kg/s)	Difference (°C)
Tungsten	224.6	226.4	1.8
Tantalum	223.4	225.3	1.9
Inconel 718	169.6	171.7	2.1
SS 316	109.4	109.8	0.4
H ₂ O	106.1	108.6	2.5

Table 24. Peak temperatures in target segment under various beam powers, coolant flow rates, and beam profiles.

Material	Peak Temperature (°C)						
	Nominal (700 kW, 7.5 GPM)	Over-Focused (714 kW, 7.5 GPM)	Offset (700 kW, 7.5 GPM)	Diffused (700 kW, 7.5 GPM)	900 kW, 7.5 GPM	700 kW, 5.71 GPM	900 kW, 5.71 GPM
Tungsten	224.6	233.7	220.6	182.4	280.1	235.9	294.1
Tantalum	223.4	232.5	219.3	181.4	278.6	235.0	292.9
Inconel 718	169.6	176.6	184.2	162.7	209.3	182.3	225.1
SS 316	109.4	Table 6 ¹⁴	Table 6	Table 6	Table 8	Table 8	Table 8
H ₂ O	106.1	109.8	110.2	90.7	127.2	120.5	145.7

Table 25. Peak temperatures in target segment under beam-off conditions (maintenance temperature)

Material	Peak Temperature (°C)			
	0-hour decay heat (294.15 W)		8-hour decay heat (151.06 W)	
	0.1 GPM	0.2 GPM	0.1 GPM	0.2 GPM
Tungsten	99.0	54.5	67.0	44.3
Tantalum	99.0	54.5	67.0	44.3
Inconel 718	99.0	54.5	67.0	44.3
SS 316	97.9	53.0	66.4	43.4
H ₂ O	98.8	53.9	66.8	43.9

¹⁴ The SS316 geometry in Table 6 and Table 8 includes manufacturing gaps that result in elevated SS316 temperatures. These gaps were eliminated in the final design.

Table 26. Peak temperatures in target shaft under different beam profiles (7.5 GPM flow rate)

Beam Profile	Peak SS316 Temperature (°C)	Peak Water Temperature (°C)
Nominal	114.0	81.0
Over-Focused	112.5	79.2
Offset	154.6	81.0
Diffused	122.9	79.4

10. CONCLUSION

A comprehensive CFD study of the Second Target Station (STS) Target Assembly at Oak Ridge National Laboratory (ORNL) was conducted to evaluate thermal-hydraulic performance under nominal and off-normal conditions. The analysis provides detailed insight into pressure drop characteristics, flow distribution, cooling effectiveness, and transient thermal behavior for both individual target segments and the full assembly under maintenance conditions.

The total pressure drop across the target assembly was determined to be approximately 13.6 psi, with individual contributions of 9.0 psi (APPENDIX A, Table 27) across a single target segment, 4.6 psi across the target drive, and 4.9 psi across the target shaft¹⁵. Local geometric features, particularly abrupt flow-area transitions in the target foot, were found to significantly influence pressure drop, highlighting the importance of smooth flow-path design to minimize hydraulic losses.

Thermal analyses indicate that under nominal operating conditions (700 kW beam power and 7.5 GPM per segment), peak temperatures in the target segments are 224.6 °C (tungsten), 223.4 °C (tantalum), 169.6 °C (Inconel 718), 109.4 °C (SS316), and 106.1 °C (water). The peak water temperature of 106.1 °C is safely below the boiling point of 133.5 °C at the operating pressure of 3 bar at the target block elevation, ensuring single-phase flow. Sensitivity studies (Chapter 7) indicate that minor flow maldistribution among the 20 segments has a negligible effect on peak temperatures, with variations of only 2–3 °C. This insensitivity is attributed in part to the low thermal conductivity of the Inconel 718 shroud and the strategic placement of cooling channels.

The impact of different beam profiles (nominal, over-focused, offset, and diffused) on cooling performance was also evaluated. The absence of cooling channels in the rear half of the Inconel 718 shroud leads to increased temperature gradients under offset beam conditions, with peak Inconel temperatures reaching 184.2 °C.

Under off-normal conditions, including increased beam power (900 kW) or reduced coolant flow (5.71 GPM), peak temperatures increase significantly. With coolant flow maintained at 7.5 GPM and beam power increased to 900 kW, the peak tungsten temperature rises to 280 °C, and the peak water temperature increases to 127.2 °C. Although this is 6.3 °C below the boiling point, the effective thermal margin may be reduced to 1.3 °C when accounting for potential ± 5 °C temperature oscillations associated with transient pulsed heating (based on earlier STS target studies with 700 kW proton beam). Given the absence of experimental validation, uncertainties in the numerical model (e.g., turbulence modeling) may be comparable to this reduced thermal margin (~ 1.3 °C); therefore, the potential for localized boiling cannot be excluded.

Air-cooling analyses demonstrate that post-shutdown and maintenance scenarios can be managed using forced airflow. For the full 20-segment assembly, a pressure-driven airflow system providing approximately 500 CFM with a pressure drop on the order of 1 psi is required to maintain acceptable temperature limits. However, due to geometric constraints of the current STS configuration, direct air

¹⁵ For the assumed flow conditions, each target segment is assigned a flow rate of 7.5 GPM, and the target shaft is also assigned a flow rate of 7.5 GPM. The pressure drops reported herein are therefore based on these prescribed flow rates for individual components, rather than a coupled flow distribution between parallel paths. In the actual system, the target segments and target shaft operate as parallel flow paths, and the resulting flow split would differ from the assumed values due to differences in hydraulic resistance, while maintaining an equal pressure drop across each path under steady-state conditions. A more detailed discussion of the coupled flow distribution is provided in Chapter 7.

cooling of the target segments is not feasible. Instead, an indirect cooling approach is adopted, in which high-bay air (approximately 7 m above the target wheel) is directed downward. This approach relies on sheet metal covers to close gaps among the CV shielding blocks and guide airflow to the target location. Its effectiveness depends on maintaining critical flow paths, including the 10 mm installation clearance, which may be susceptible to blockage or misalignment.

Overall, the current design **meets thermal and hydraulic performance requirements** under **nominal conditions**, while identified sensitivities and uncertainties highlight the need for further validation and potential design refinement under off-normal and maintenance scenarios.

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APPENDIX A: MESH INDEPENDENT STUDY

Results from multiple mesh configurations were compared to ensure sufficient spatial resolution for accurately capturing the peak temperatures and pressure drop in the target segment, while maintaining acceptable numerical error and computational cost. Figure 116 presents the mesh configurations used in the mesh-independence study, and Figure 117 shows a detailed view of the mesh in critical regions (cooling channel, tungsten blocks, and tantalum plates), highlighting local refinement differences among the meshes. The total number of elements for Mesh_1, Mesh_2, Mesh_3, and Mesh_4 are 2.4, 7.7, 8.4, and 13.1 million, respectively. The Mesh_4 (finest) solution is used as the reference for error estimation.

The peak temperatures and pressure drop in the target segment (7.5 GPM flow rate) for each mesh configuration are summarized in Table 27, with the corresponding percentage errors relative to Mesh_4 presented in Table 28. The errors in the predicted peak temperatures are below 3% for Mesh_2 through Mesh_4, indicating good convergence with mesh refinement. For the pressure drop, the difference between the coarsest (Mesh_1) and finest (Mesh_4) meshes is approximately 3%. Although Mesh_2 provides reasonably accurate predictions for bulk quantities, a finer mesh is required to adequately resolve temperature gradients for subsequent thermal stress analysis. Therefore, Mesh_4 is considered sufficiently refined, and its results are used for the Target Assembly FDR report.

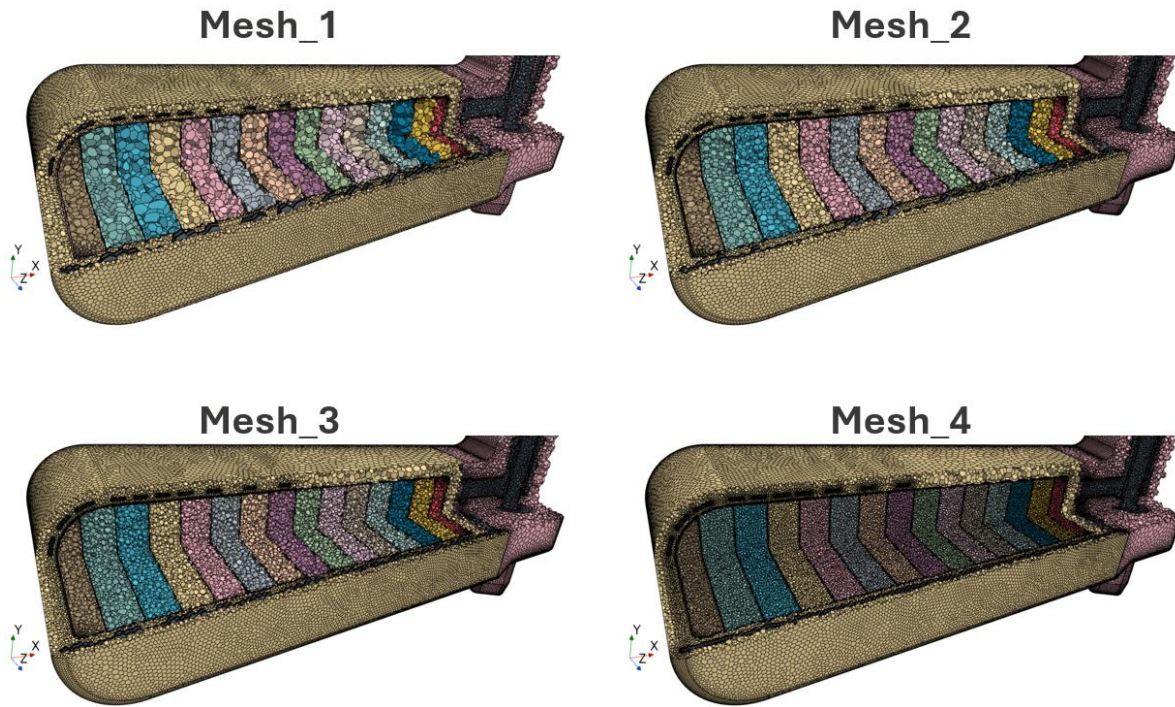


Figure 116. Computational meshes employed in the mesh-independence study, comprising four refinement levels: Mesh_1 (coarsest) to Mesh_4 (finest).

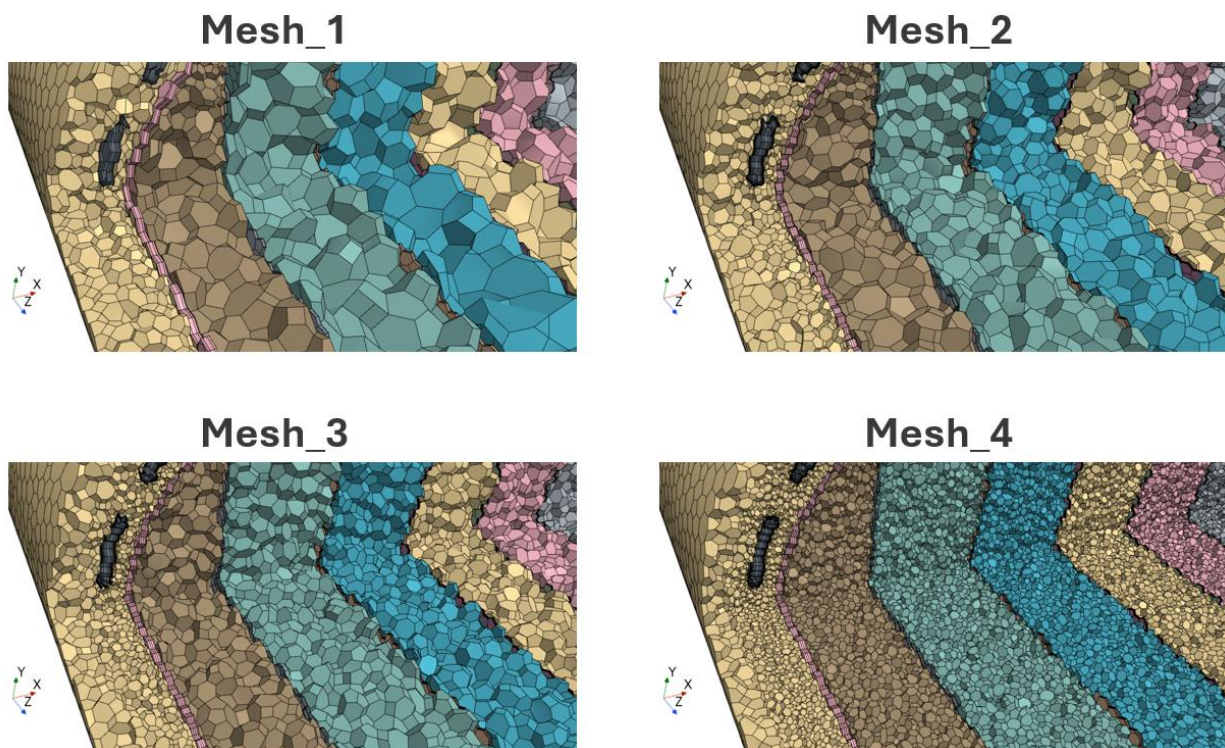


Figure 117. Detailed view of the mesh in key regions (cooling channel, tungsten blocks, and tantalum plates), illustrating local refinement variations among the mesh configurations.

Table 27. Peak temperatures and pressure drop obtained from the mesh-independence study for M1 (coarsest) through M4 (finest) (7.5 GPM flow rate).

Mesh	W (°C)	Ta (°C)	Inconel 718 (°C)	SS316 (°C)	Water (°C)	ΔP (psi)
M1	228.90	227.94	174.39	111.14	116.01	9.33
M2	226.85	225.65	171.97	109.89	108.55	8.84
M3	225.64	224.40	170.40	109.88	108.21	8.85
M4	224.56	223.41	169.61	109.37	106.13	9.05

Table 28. Relative percentage errors in peak temperature and pressure drop for each mesh with respect to the finest mesh (M4), computed for the target segment (7.5 GPM flow rate).

Mesh	W (%)	Ta (%)	Inconel 718 (%)	SS316 (%)	Water (%)	ΔP (%)
M1	1.93	2.03	2.82	1.61	9.31	3.08
M2	1.02	1.00	1.39	0.48	2.28	2.40
M3	0.48	0.44	0.47	0.47	1.96	2.31
M4	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX B: INCONEL SHROUD WITH REAR COOLING CHANNELS

As described in Section 4.2, the latest STS target segment design does not include cooling channel passages in the top and bottom regions of the rear portion of the Inconel 718 shroud. This configuration results in a higher temperature gradient in the central region of the shroud, as shown in Figure 118 (based on an earlier STS target design), and may lead to elevated thermal stress in this area. This section evaluates the impact of introducing additional rear cooling channels to reduce temperature gradients and explains why such modifications were ultimately not incorporated into the final design.

Figure 119 illustrates the rear cooling channel configurations considered in this study.

- Case 0: Baseline design without rear cooling channels (reference case).
- Case 1: Addition of three 8-mm-wide rear cooling channels.
- Case 2: Addition of three rear cooling channels with widths of 4 mm, 2 mm, and 1 mm.
- Case 3: Modification of the 10th channel in Case 0 from 8 mm to 5 mm, with three additional rear channels of 4 mm, 3 mm, and 3 mm.

The coolant (water), target block, and Inconel shroud temperature distributions are presented in Figure 120, Figure 122, and Figure 123, respectively, while the corresponding pressure distributions are shown in Figure 121. As indicated in Figure 121, the pressure drop in the target foot remains approximately 5 psi for all configurations, largely independent of the added rear channels. This behavior is expected, as the additional channels are arranged in parallel with the existing cooling passages. The distribution of coolant flow among individual channels (Figure 124) is governed by channel location (proximity to the inlet, i.e., short-circuit flow effects) and hydraulic resistance (channel size).

In Case 1, the three additional 8-mm rear channels are comparable in size to the existing rear channels in Case 0. Because these channels are located close to the coolant inlet, a short-circuit flow pattern develops, resulting in preferential flow through the rear channels and reduced flow to the hotter front (nose) region. As shown in Figure 120 and Figure 124, the peak coolant temperature increases from 106.4 °C (Case 0) to 117.2 °C (Case 1) due to reduced cooling in the front region.

Consistent with this trend, Figure 122 shows that the peak tungsten temperature increases from 225 °C (Case 0) to 231.1 °C (Case 1), while Figure 123 indicates that the peak Inconel shroud temperature increases from 170.1 °C (Case 0) to 178.8 °C (Case 1). Although the additional channels significantly reduce the temperature gradient observed in Case 0, the overall increase in peak temperatures is attributed to the reduced coolant flow reaching the front region.

In Case 2, the added rear channels are reduced in size (4 mm, 2 mm, and 1 mm), resulting in higher hydraulic resistance. This configuration maintains adequate cooling in the rear (lower heat load) region while minimizing flow diversion from the front channels. However, the inclusion of very small channels (1—2 mm) introduces potential stress concentration concerns and increases manufacturing complexity.

In Case 3, the smallest channels are increased to 3 mm to mitigate stress concentration, while still limiting short-circuit flow and improving temperature uniformity relative to Case 0. Despite these advantages, the 3-mm channels remain challenging to manufacture, and the additional cooling passages increase the volume of activated water during operation.

The addition of rear cooling channels in the Inconel 718 shroud was evaluated to reduce temperature gradients and associated thermal stresses. Although these modifications improved temperature uniformity, they also led to flow maldistribution, increased peak coolant temperature, and introduced manufacturability constraints and additional activated coolant volume. Therefore, **the baseline design without rear cooling channels is selected for the final configuration**, as it provides a more **practical balance** among thermal performance, structural integrity, manufacturability, and operational considerations, despite not being optimal from a heat transfer perspective.

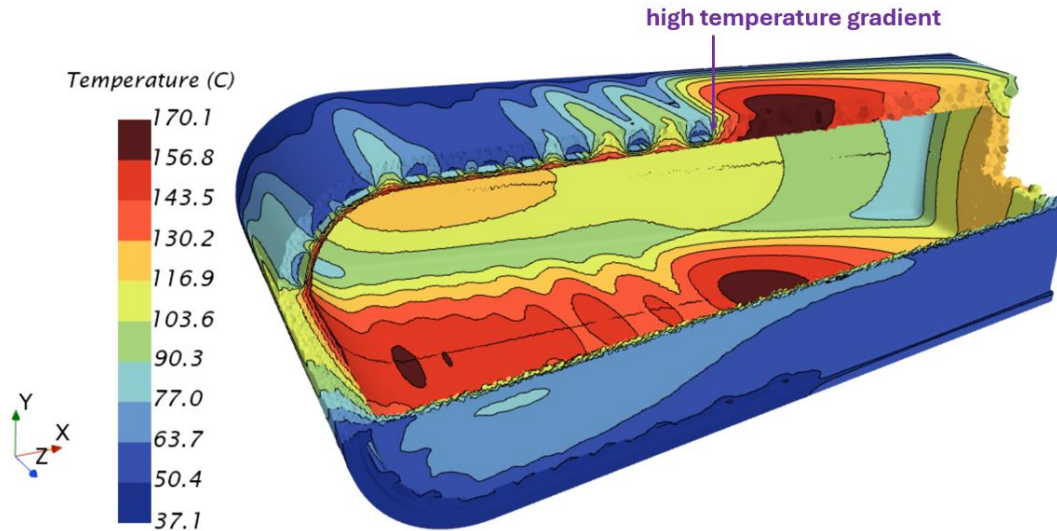


Figure 118. Temperature distribution in the Inconel 718 shroud without rear cooling channels.

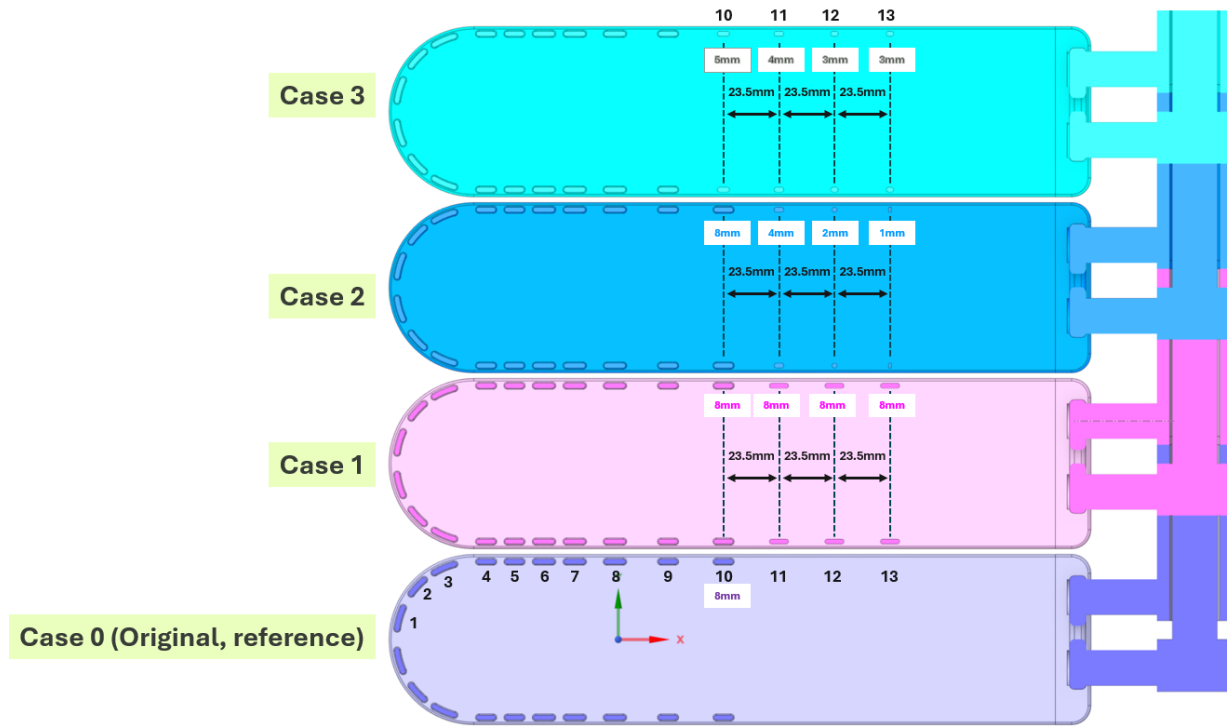


Figure 119. Rear cooling channel configurations evaluated for the Inconel 718 shroud.

Water Temperature Boiling temperature @ 3 bar: 133.5°C

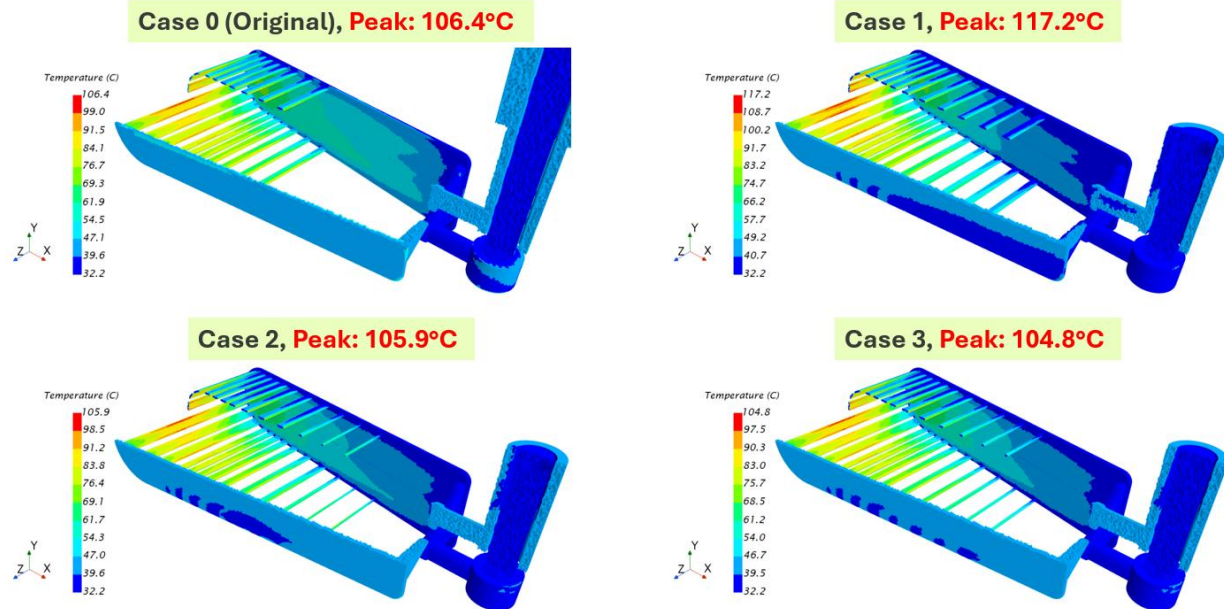


Figure 120. Coolant (water) temperature distribution for the different Inconel shroud cooling channel designs.

Pressure Distribution

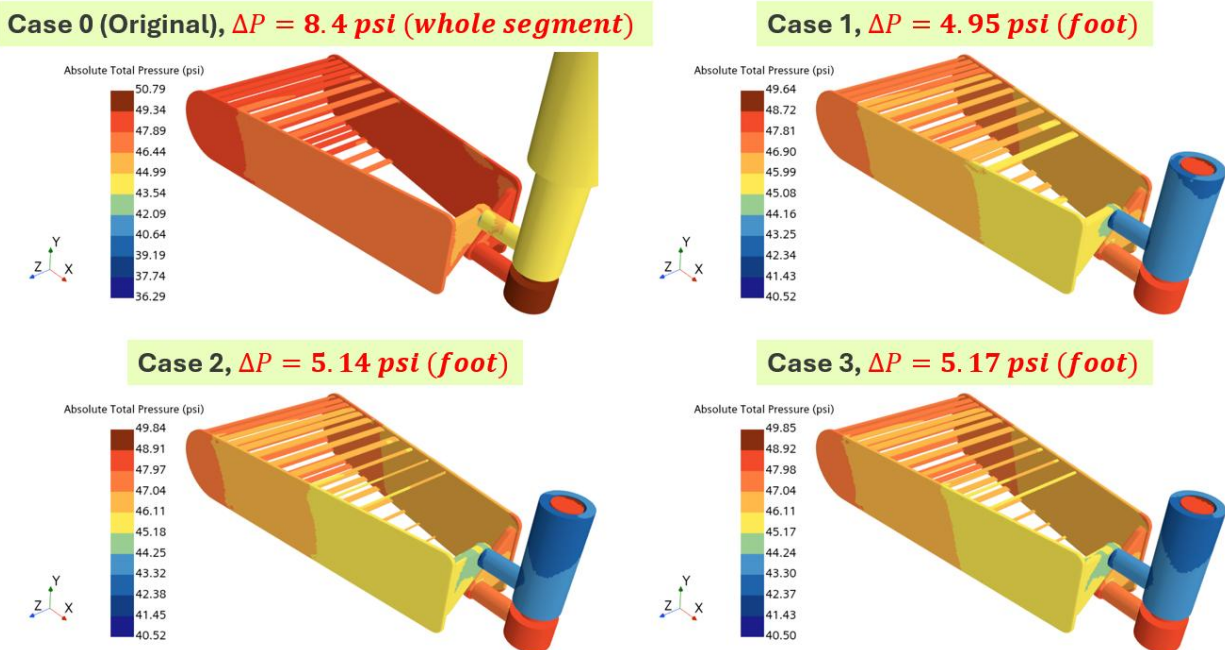


Figure 121. Pressure distribution in the coolant for the different Inconel shroud cooling channel designs..

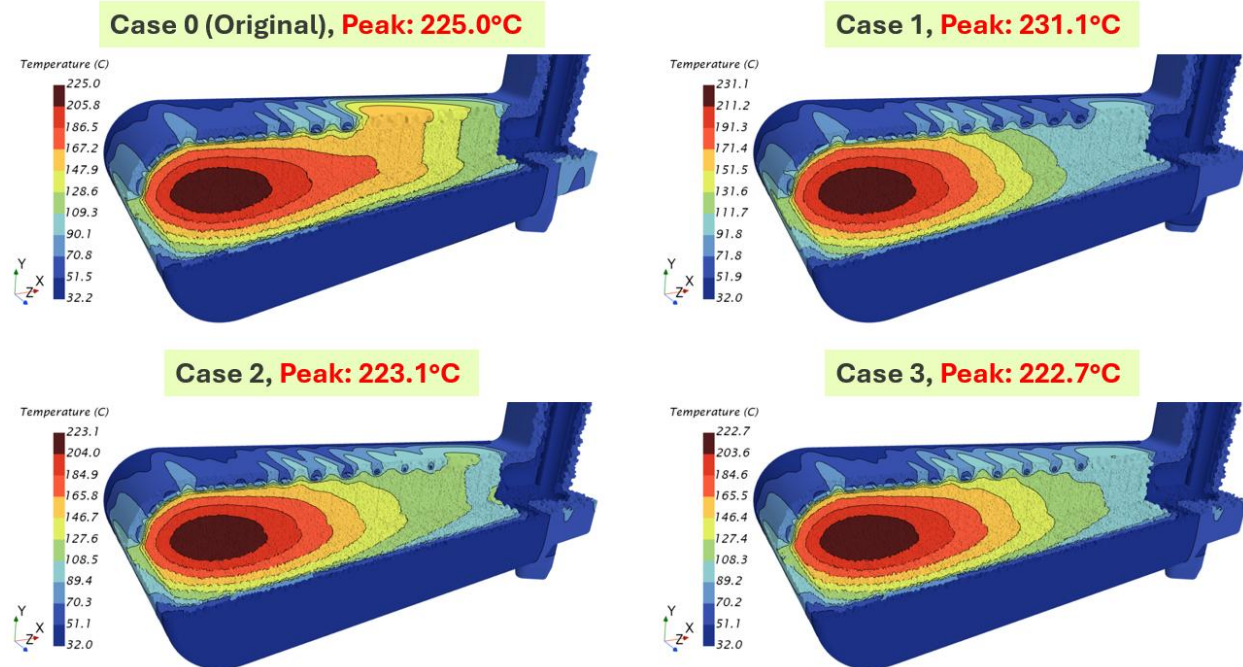


Figure 122. Temperature distribution in the tungsten target blocks for the different Inconel shroud cooling channel designs.

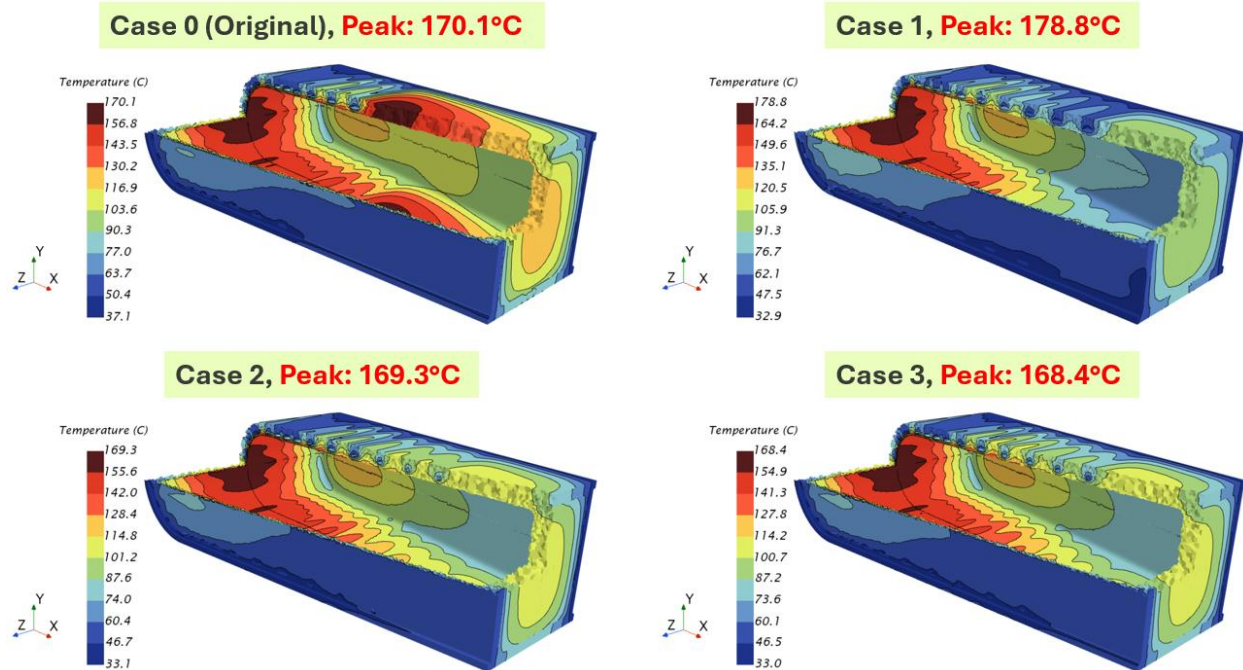


Figure 123. Temperature distribution in the Inconel 718 shroud for the different cooling channel designs.

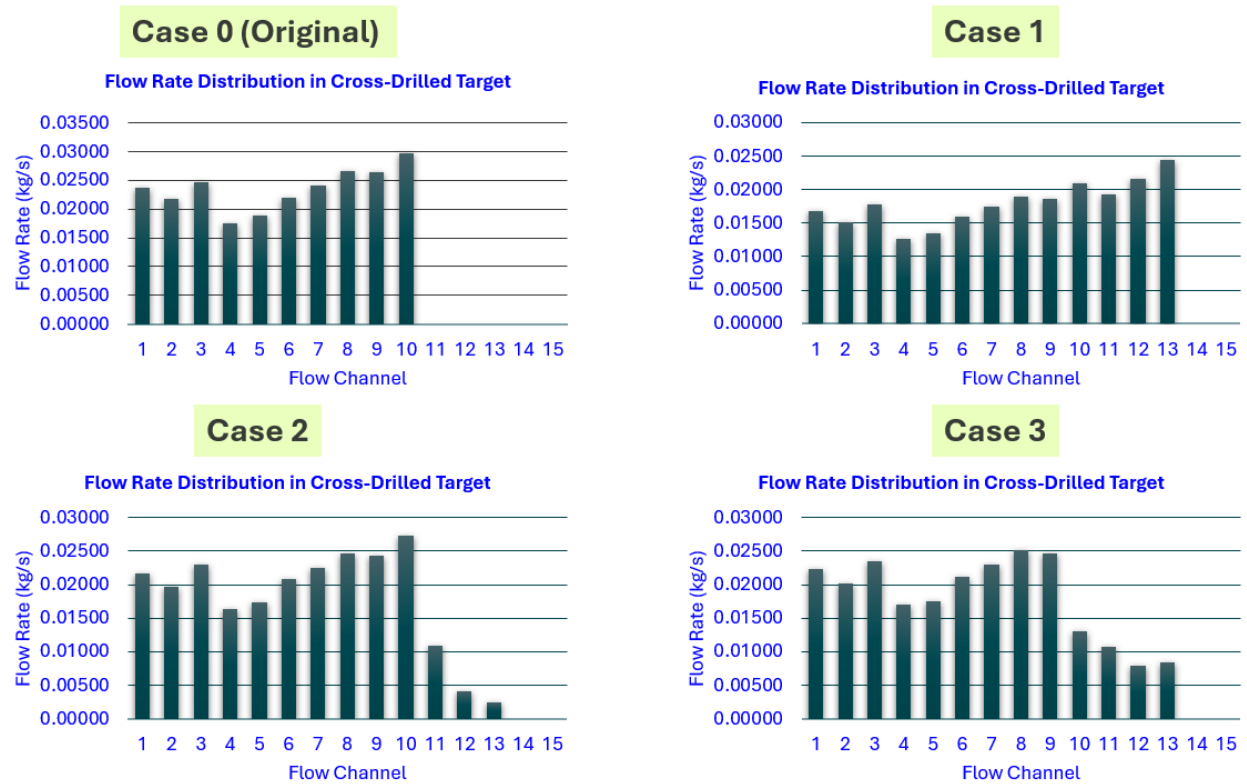


Figure 124. Coolant flow rate distribution among channels for the different Inconel shroud cooling configurations.

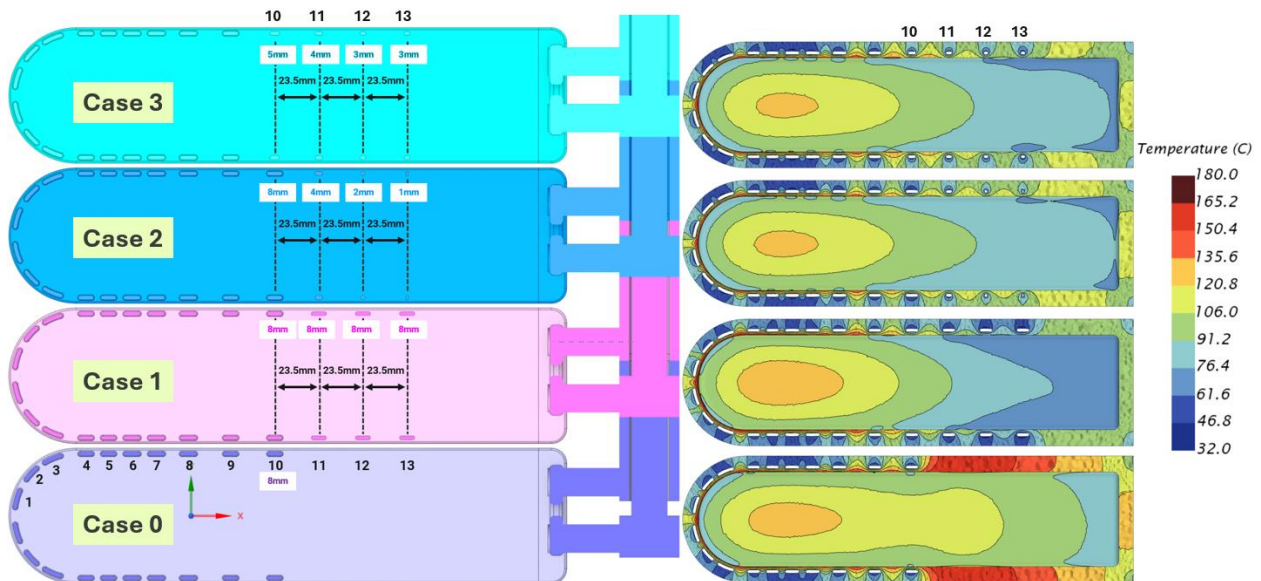


Figure 125. Comparison of Inconel 718 shroud temperature distributions with corresponding rear cooling channel geometries.

APPENDIX C: IMPACT OF CORIOLIS FORCE ON EARLIER STS TARGET

The STS target segments and shaft rotate at 45 RPM. To account for rotational effects, centrifugal and Coriolis forces are included in the CFD simulations by applying a rotating reference frame at ($x = 0.483$ m, $y = 0$, $z = 0$), as shown in Figure 126. The Moving Reference Frame (MRF) is computationally efficient because the governing equations are solved in a rotating coordinate system, eliminating the need to physically rotate the geometry and mesh, as required in the Rigid Body Motion (RBM) method. The RBM approach is computationally expensive due to the need for small time steps to resolve transient behavior. In contrast, the MRF method is sufficient for predicting time-averaged flow fields in the STS rotating target, given the relatively low rotational speed (45 RPM), and is well suited for estimating pressure drop, bulk temperature, and flow distribution under steady-state conditions.

The influence of Coriolis force was more pronounced in earlier flood-cooled target designs. The results in this section are based on those earlier configurations and are intended to illustrate the impact of Coriolis effects and explain why they are less significant in the final STS target design.

Figure 127 compares the velocity distributions in a target block obtained using stationary (laboratory) and rotating reference frames. In the stationary frame, the velocity distribution is symmetric, whereas in the rotating frame, the Coriolis force induces a non-uniform distribution, with higher velocities shifted toward one side of the target block. Flow diverters (Figure 128) can be introduced to guide the coolant and mitigate this asymmetry.

A subsequent “open target” concept was proposed, in which the side walls of the target blocks were removed to allow coolant to flow between adjacent blocks. In this configuration, coolant is not confined to individual targets but can circulate across the entire target wheel. The velocity vectors for this design are shown in Figure 129, where the CFD model includes one full target block and adjacent half-blocks (four-halves model). Although Coriolis effects are still present, flow diverters are no longer required because Coriolis-induced crossflow between neighboring blocks occurs naturally. As a result, the overall velocity distribution is uniform (Figure 129). The velocity field for the full target wheel and the corresponding temperature distribution are shown in Figure 130 and Figure 131, respectively. In this flood-cooled design, the coolant is in direct contact with the tantalum cladding; therefore, the peak coolant velocity was limited to below 2 m/s to minimize erosion of the cladding.

The transition from a monolithic “target wheel (open target)” design to a segmented target configuration (final STS Target Assembly design, Figure 3) was primarily driven by considerations of maintainability, reliability, and operational availability. In the target wheel configuration, all target elements are hydraulically connected, and a localized failure can necessitate replacement of the entire assembly. Such replacement requires extensive remote handling operations, including removal of surrounding components (e.g., MRA and CV shielding blocks), resulting in significant downtime.

In contrast, the segmented target design provides hydraulic and mechanical isolation between individual target segments. This allows failures to be localized, enabling replacement of only the affected segment while maintaining operation of the remaining targets. As a result, the segmented configuration reduces maintenance complexity, minimizes shielding removal, and improves overall system availability. In addition, unlike the flood-cooled design, the **final STS configuration incorporates dedicated cooling channels within the Inconel 718 shroud**. The integrated cooling channels guide the coolant flow within each segment and enforce a uniform velocity field, thereby **minimizing the influence of Coriolis** forces (as illustrated by the streamlines in Figure 113).

Axis direction : (0,1,0)
 Axis origin (0.483 m , 0 , 0)
 Rotation rate: 45 RPM (one revolution in 4/3 seconds)

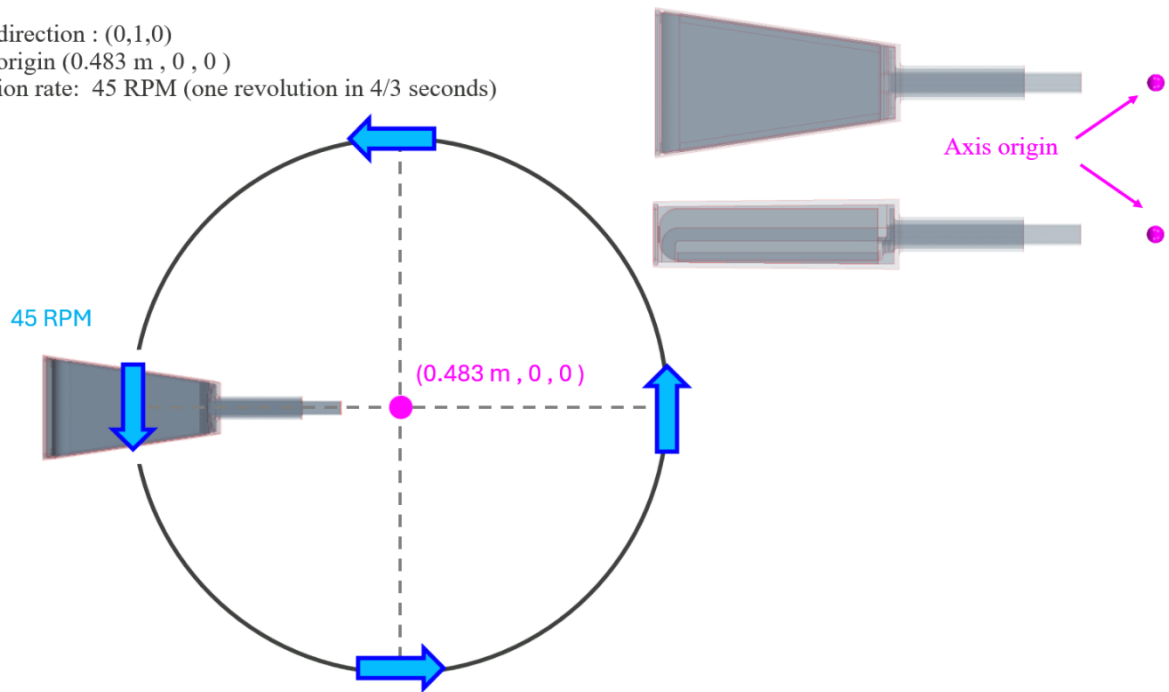


Figure 126. Rotating reference frame used for STS target simulations.

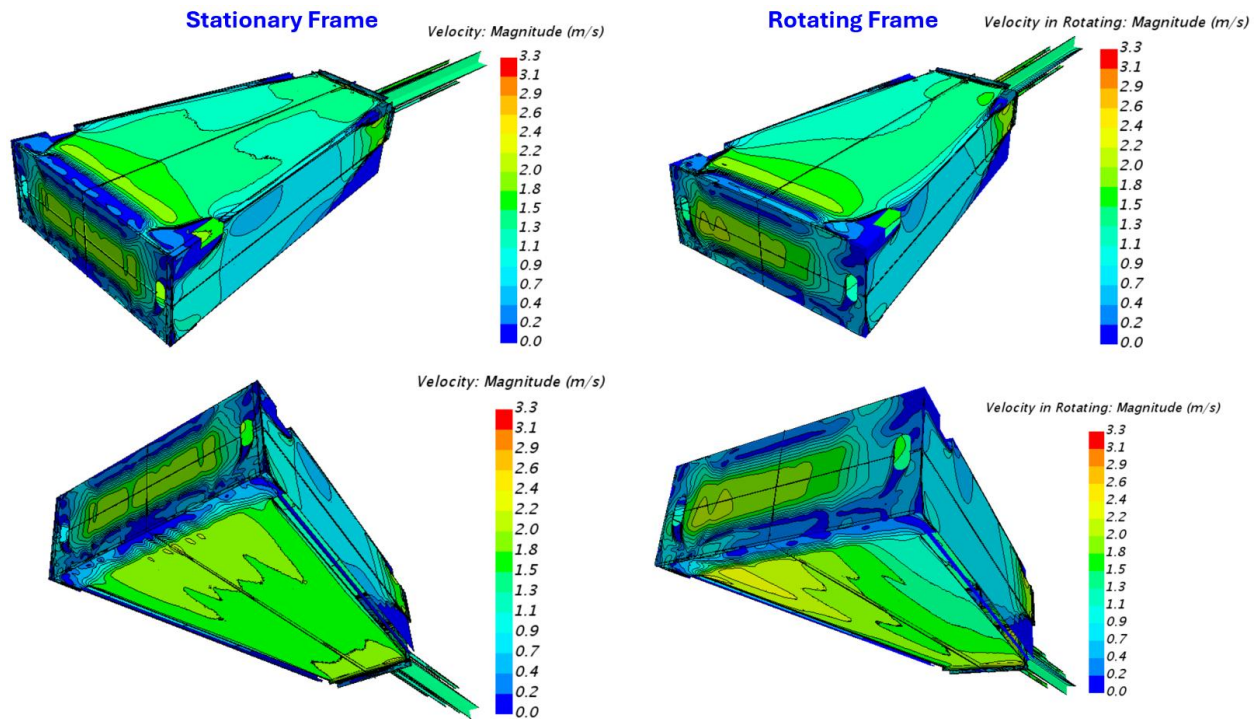


Figure 127. Comparison of velocity distributions in a target block under stationary and rotating reference frames.

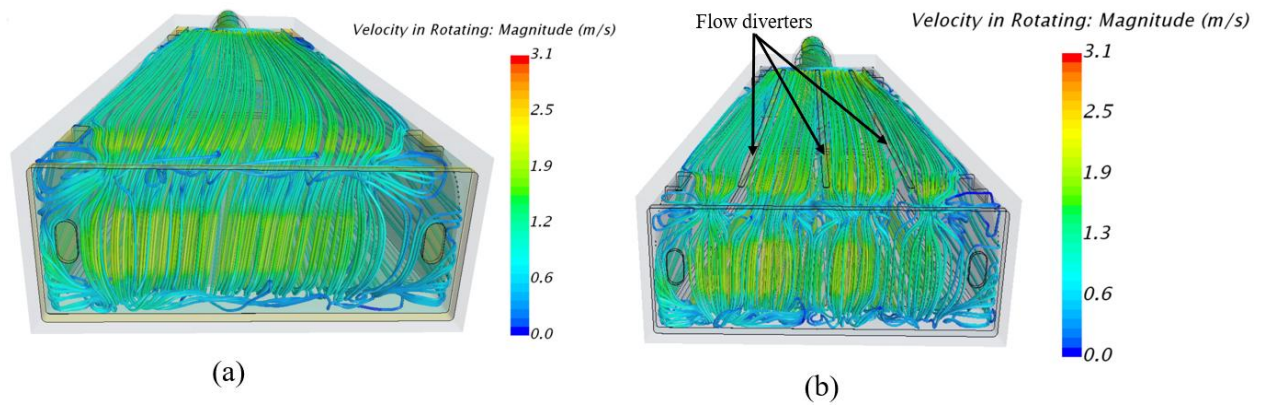


Figure 128. Streamlines (a) without and (b) with flow diverters.

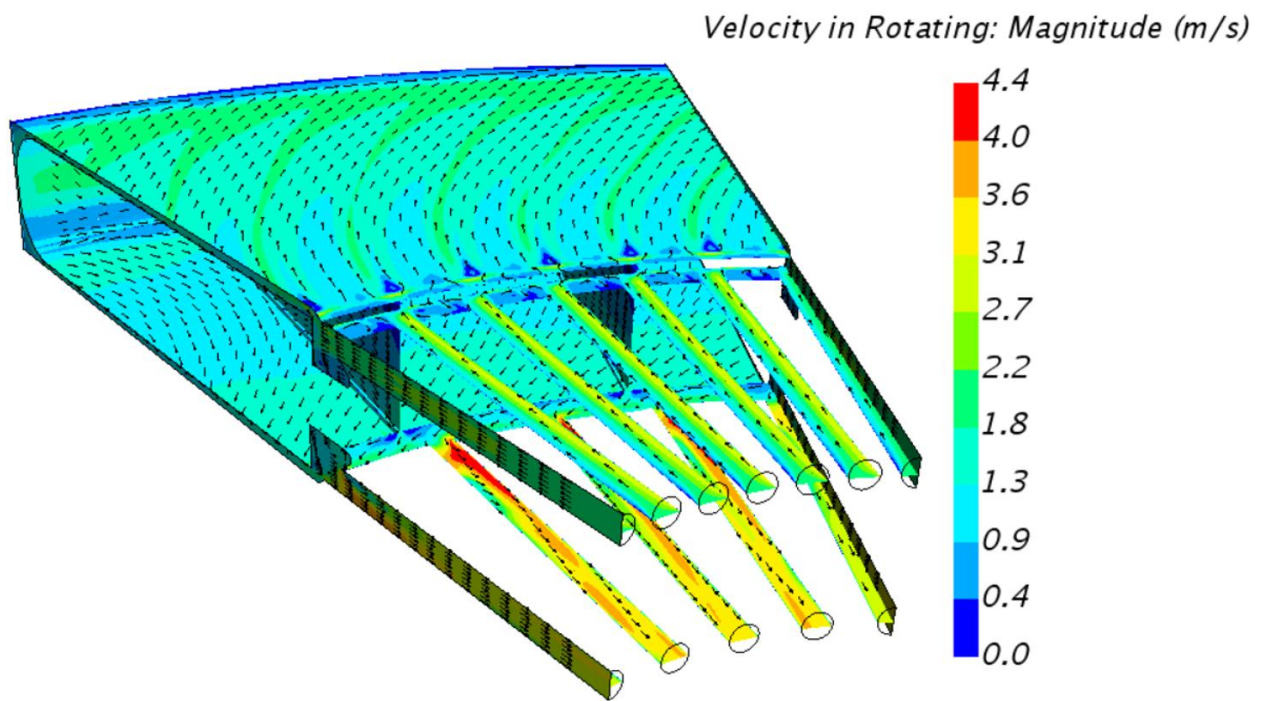


Figure 129. Velocity vectors for the "open target" design (four-halves model, equivalent to two target blocks).

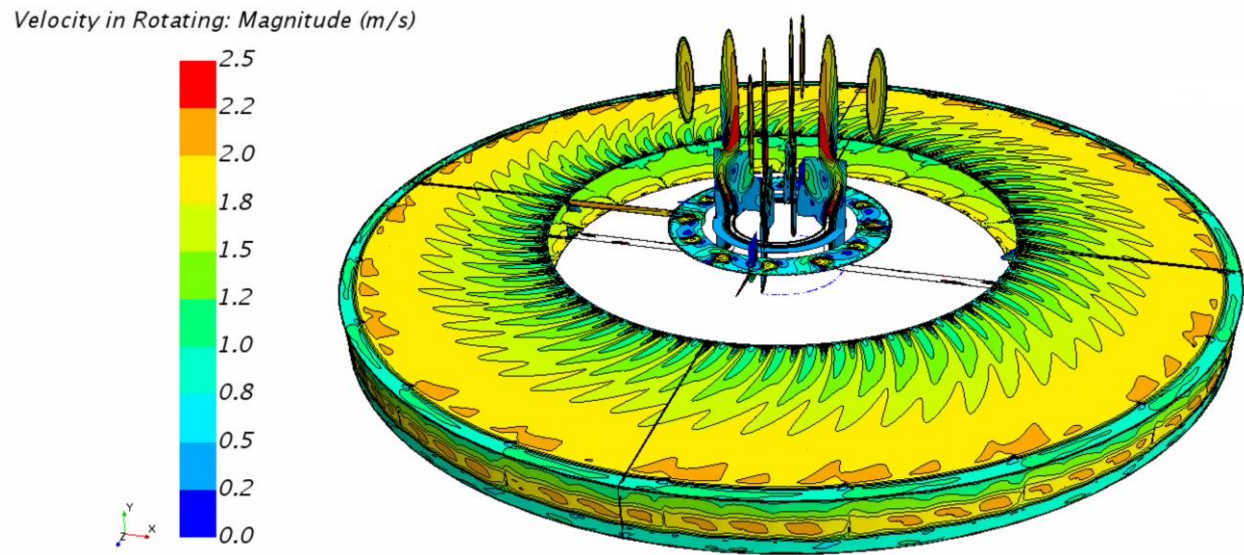


Figure 130. Velocity distribution in the target wheel for the open target design.

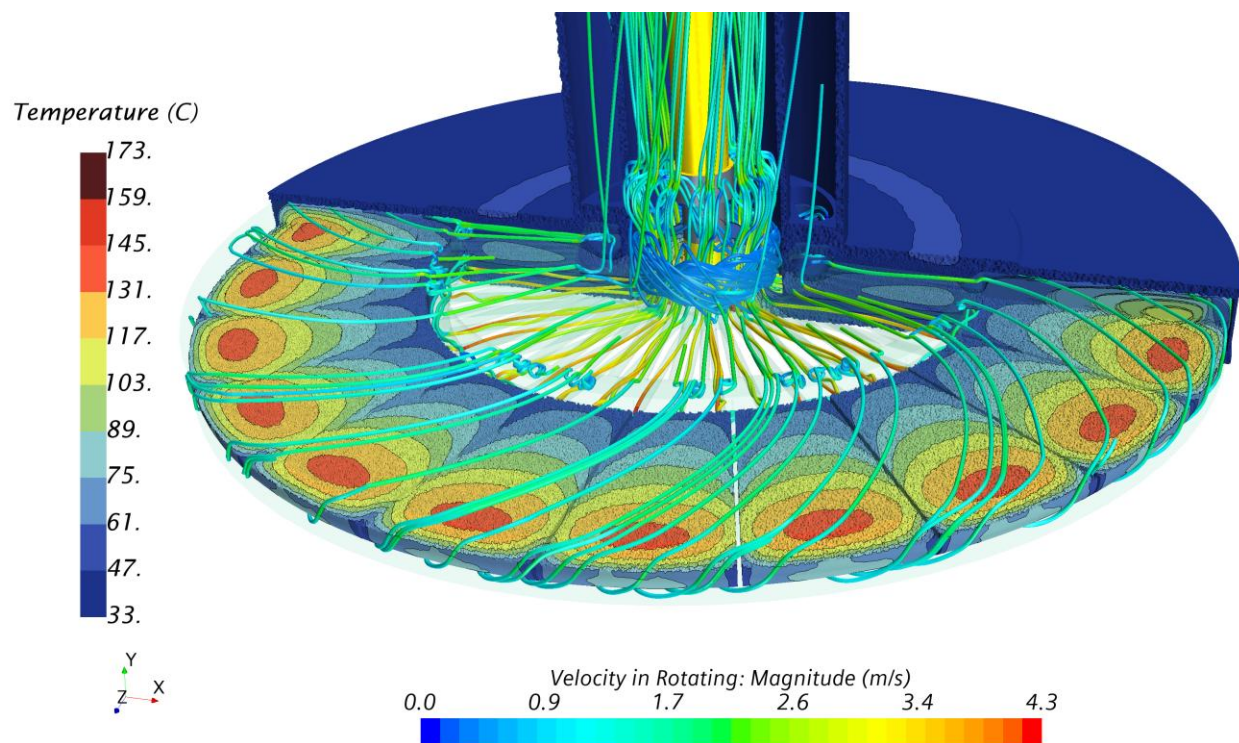


Figure 131. Temperature distribution and streamlines for the open target design.

APPENDIX D: TRANSIENT HEAT SOURCE ON EARLIER STS TARGET

An earlier rotating STS target disk concept (2019 configuration) comprises 21 target blocks and operates at a rotation rate of 42.86 RPM (1.4 s per revolution). As shown in Figure 18, a single pulse from the 15 Hz proton beam does not deposit energy into only one target block; instead, the deposited energy is distributed across the entire target wheel (21 blocks in the 2019 configuration and 20 blocks in the 2026 configuration). For a given block during one full revolution, it receives energy not only from the pulse directly incident on it but also from pulses that strike neighboring blocks. Over one full revolution, a single block is exposed to contributions from 20 pulses (for the 2026 configuration), although these contributions are not equal. The dominant energy input arises from the pulses centered on the block and the two pulses incident on adjacent blocks, as illustrated in Figure 132. The pulse duration is 0.001 s.

For the 2019 STS target configuration, the analytical solution predicts a temperature rise of 14.3 °C in a target block due to a single proton pulse. In the transient simulation, the predicted temperature rise is 14.294 °C using a time step of 0.001 s (0.6% error) and 14.32 °C using a time step of 0.0001 s (0.42% error). Therefore, a time step of 0.001 s is considered sufficient and is adopted for the transient simulations.

Instead of explicitly modeling individual pulses, an alternative approach is to apply a time-averaged (steady-state) heat source, in which the energy deposited in a single block is averaged over one rotation period. The objective of this section is to compare the results obtained using a transient heat source (individual pulses modeled explicitly) and an equivalent steady-state heat source (all pulses summed and averaged over one period), as the steady-state approach has been used for heat transfer analysis in STS target design development since 2019.

As shown in Figure 133, both fine and coarse meshes were used to ensure mesh-independent results. Figure 134 indicates that the target reaches a quasi-steady thermal state after approximately 100 s. **The peak temperature difference between the transient and equivalent steady-state heat source approach is within ± 5 °C.** Based on this small difference, the equivalent steady-state heat source has been adopted for heat transfer analysis in STS target design development since 2019 to reduce computational cost.

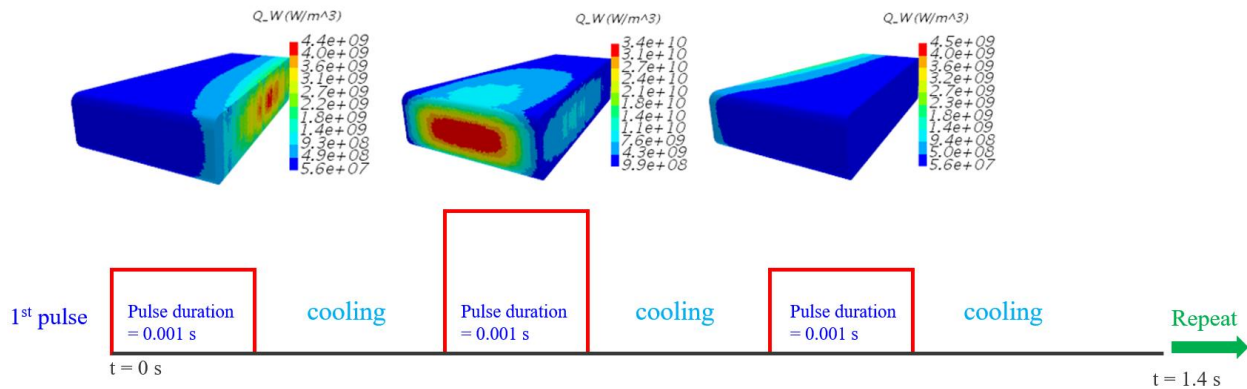


Figure 132. Transient proton beam pulses incident on an individual target segment.

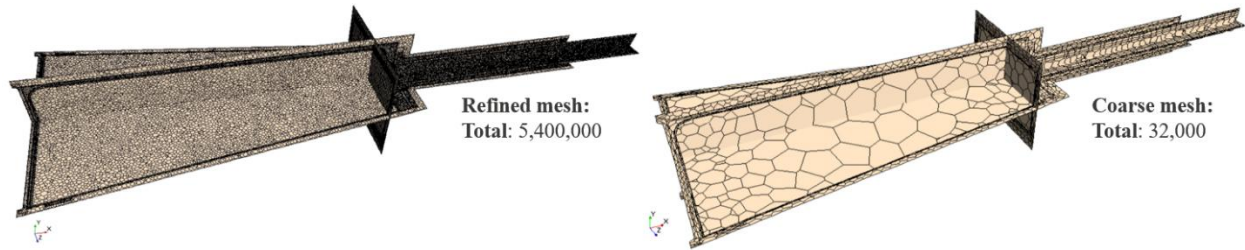


Figure 133. Mesh configurations used for the mesh-independence study.

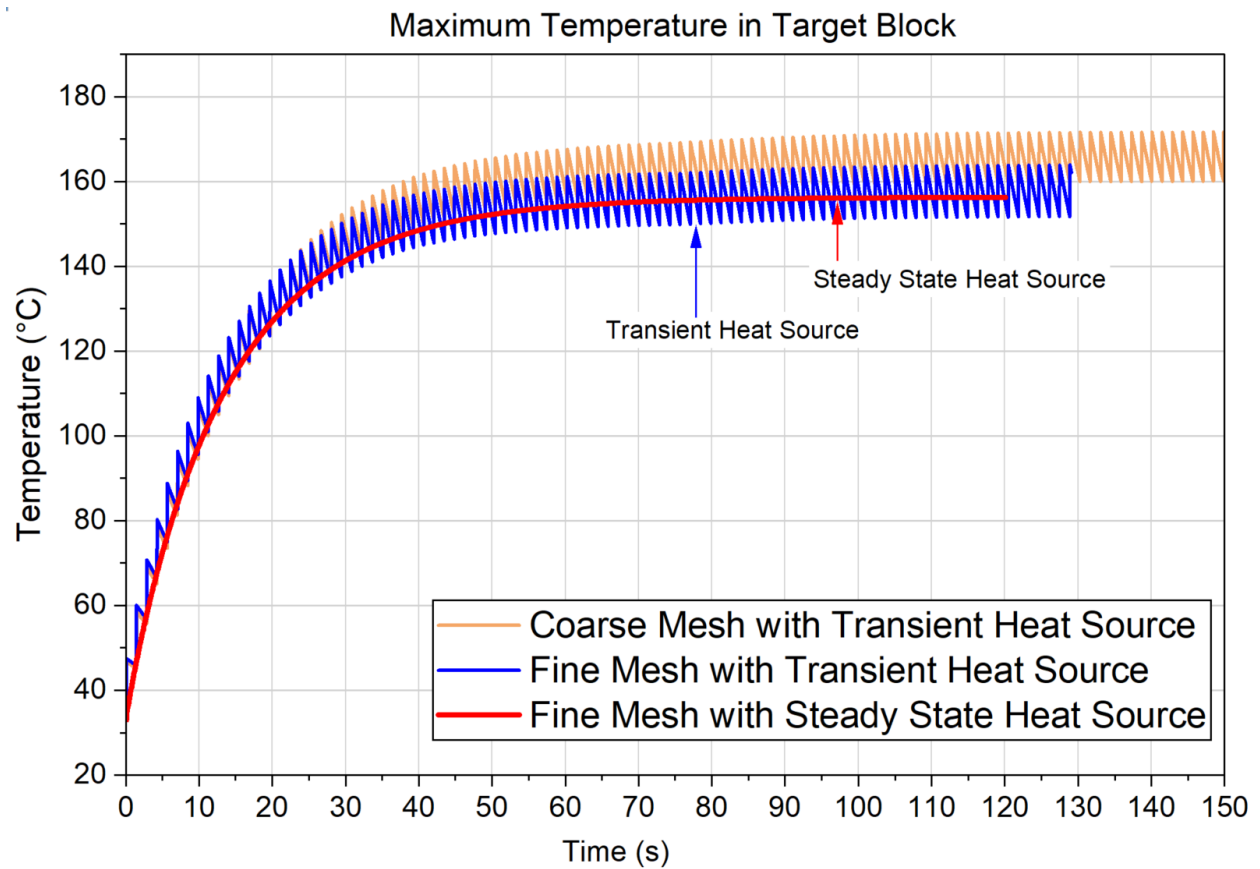


Figure 134. Comparison of peak tungsten temperature between transient and equivalent steady-state heat source approaches.

APPENDIX E: DPA-DEPENDENT THERMAL CONDUCTIVITY OF TUNGSTEN ON EARLIER STS TARGET

The STS target is designed for a 10-years of operation lifetime. During operation, the thermal conductivity of tungsten (W) degrades due to irradiation damage. The thermal conductivity of irradiated tungsten ($k = 87$ W/m-K) is approximately half that of the unirradiated tungsten ($k = 174.9$ W/m-K). Based on MCNP calculations, the displacements per atom (dpa) damage in tungsten blocks after 10 years of operation ranges from approximately 0.7 to 5.7 dpa (Figure 135) for an earlier STS target design, although these results were not formally documented. The dpa distribution for the final STS target design is documented in ([S00000000-CAC10001](#)).

The thermal conductivity of tungsten as a function of temperature and irradiation damage has been reported by Habainy et al. [19] (0, 3.9, and 5.8 dpa) and Roedig et al. [20] (0.2 and 0.6 dpa), as shown in Figure 136. These data indicate that the radiation-induced reduction in thermal conductivity approaches a saturation value of approximately 87 W/m-K for dpa levels above ~ 3.9 dpa. For the earlier STS target design, the operating temperature of tungsten is approximately 130–160 °C; therefore, the data corresponding to the 100 °C in Figure 136, together with the dpa distribution shown in Figure 135, were used to construct a dpa-dependent thermal conductivity model for tungsten (Figure 137).

The temperature distributions obtained using a constant thermal conductivity (87 W/m-K) and a dpa-dependent thermal conductivity model are compared in Figure 138. The difference in predicted peak temperatures is only 0.5–0.7°C. Based on this **negligible difference**, a **constant thermal conductivity value of 87 W/m-K** for the irradiated tungsten was adopted in the CFD analyses for STS target concept development.

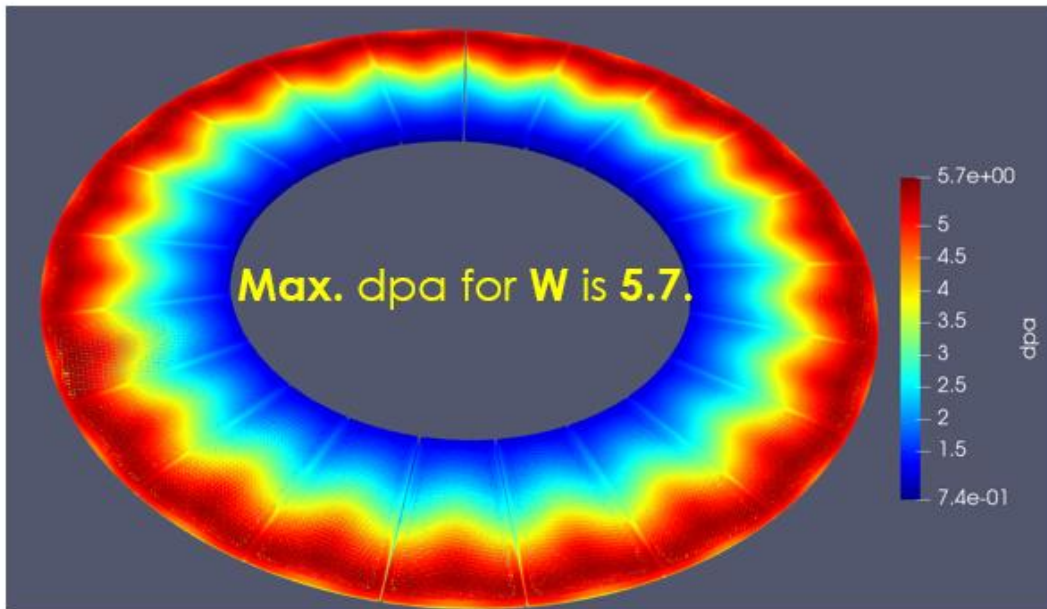


Figure 135. Dpa distribution in tungsten after 10 years of operation.

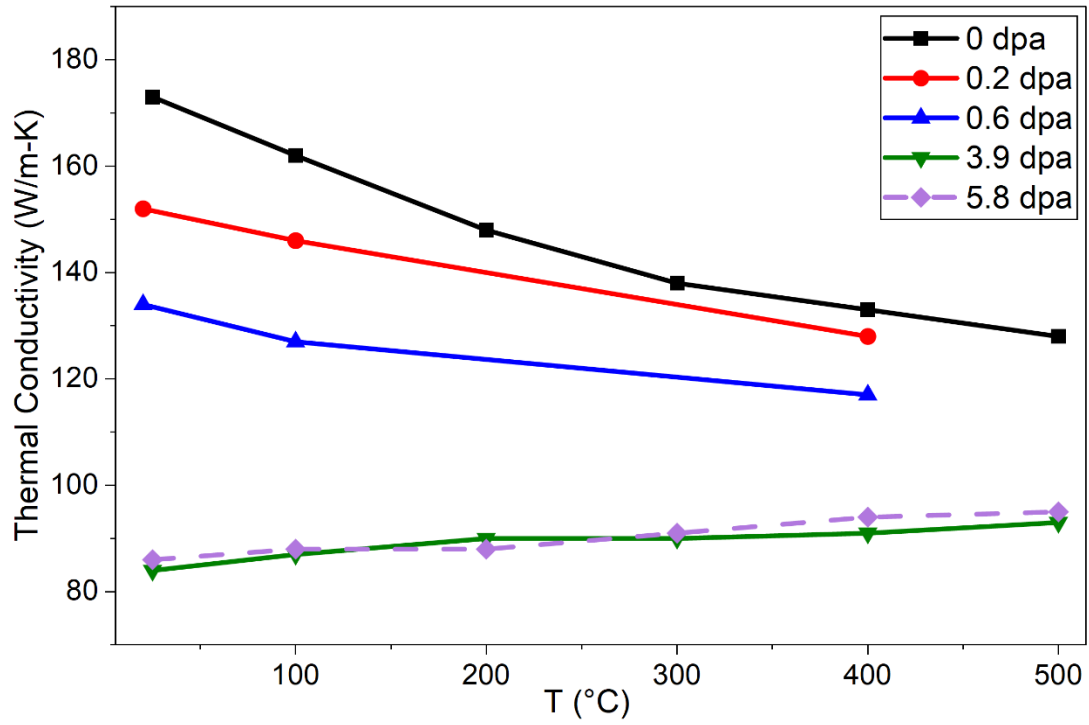


Figure 136. Thermal conductivity of tungsten as a function of temperature and dpa (data from Habainy et al. [19] and Roedig et al. [20]).

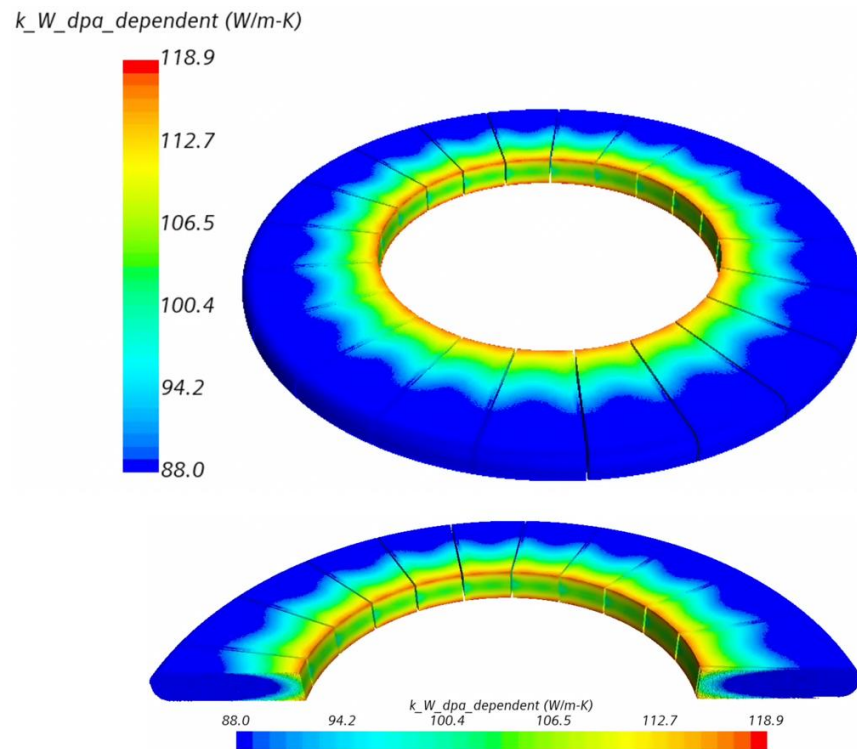


Figure 137. Dpa-dependent thermal conductivity of tungsten used in this study.

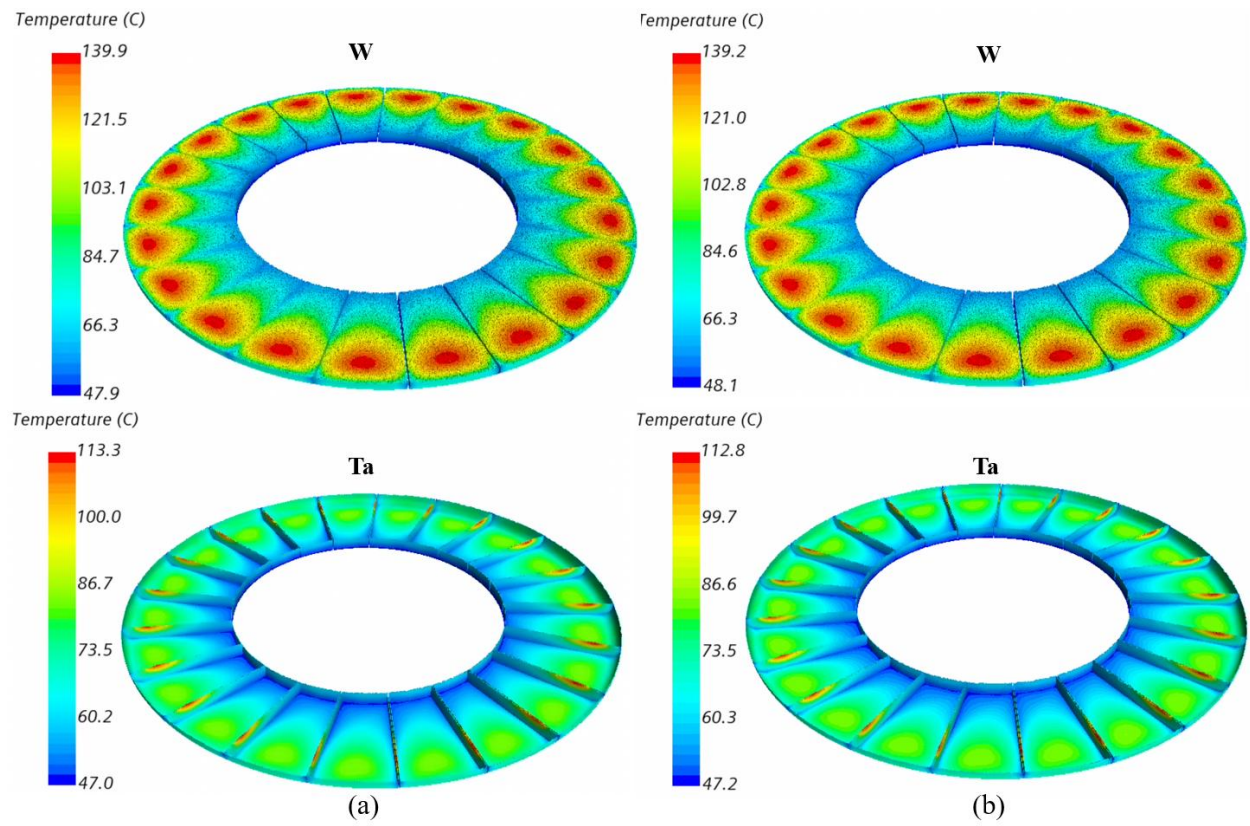


Figure 138. Temperature distributions obtained using (a) constant thermal conductivity (irradiated W, $k = 87 \text{ W/m-K}$) and (b) dpa-dependent thermal conductivity of tungsten.

APPENDIX F: DESIGN WITHOUT COOLING IN TARGET SHAFT FLANGE

An earlier target shaft design (Figure 139) did not incorporate internal cooling circuits within the flange. As a result, the SS316 target shaft flange reached temperatures up to 217 °C, with pronounced temperature gradients concentrated around the circular pockets (used for insertion of the target segment pins), as shown in Figure 140. The elevated temperature is attributed to the flange's proximity to the proton beam, resulting in non-negligible heat deposition (Section 5.3). These temperature gradients arise because the inner circumference of the circular pockets is located close to the cooling channels (Figure 139).

Thermal stress analysis indicates that, under this temperature distribution, the circular pockets deform into oval shapes, leading to a peak von Mises stress of approximately 800 MPa concentrated at the ends of the elongated regions (Figure 141). This stress level significantly exceeds the yield strength of SS316 (252 MPa), indicating unacceptable structural performance.

During the design iteration process, multiple materials—including aluminum, Inconel, CuCrZr and SS316— as well as alternative flange geometries and cooling channel configurations were evaluated. The final design adopts SS316 (consistent with the shaft material) and incorporates internal cooling channels, as shown in Figure 47 and Figure 48. With the inclusion of internal cooling, the temperature distribution around the pockets becomes more uniform, and the maximum temperature is reduced to below 67 °C in the final design (Figure 64 in Section 5.5). These results demonstrate that **internal cooling** of the **flange** is necessary to ensure both **thermal and structural integrity** under operating conditions.

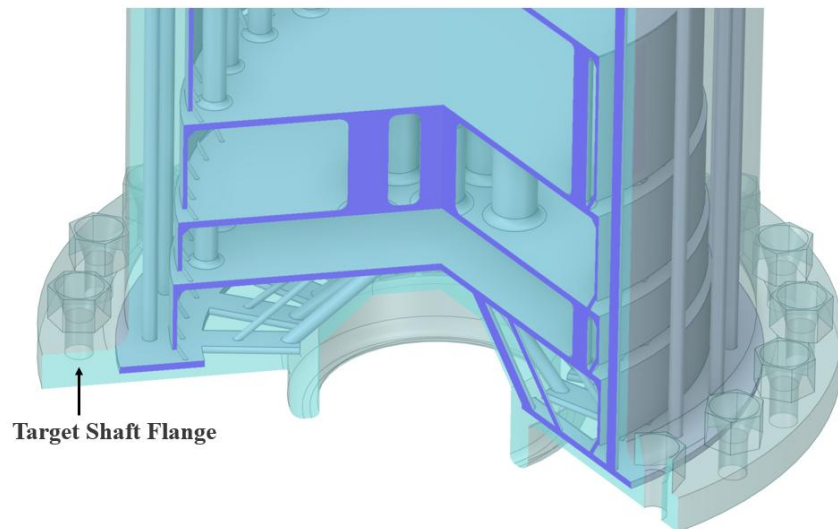


Figure 139. Target shaft configuration without internal cooling circuits in the flange.

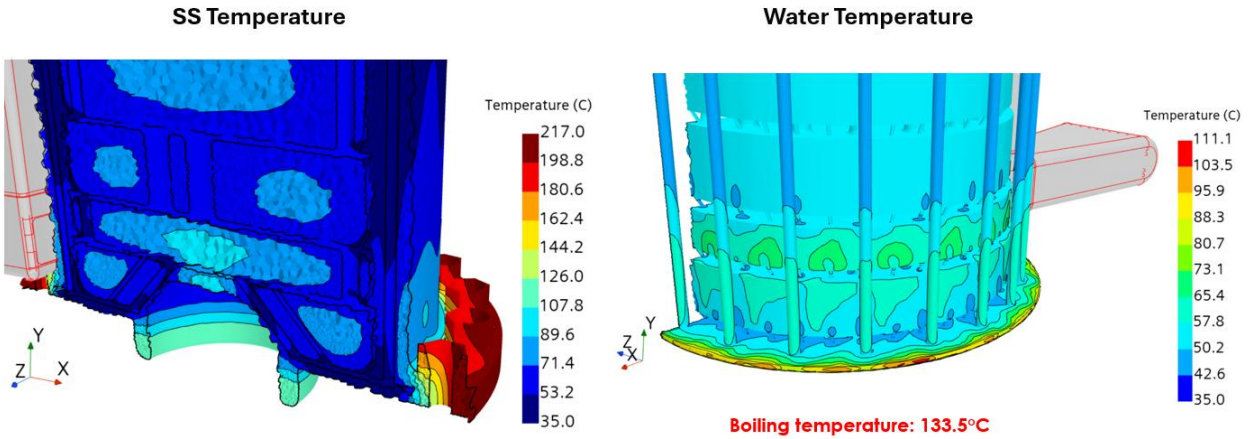


Figure 140. Temperature distributions in stainless steel (SS316) and coolant (water) for the target shaft without internal flange cooling.

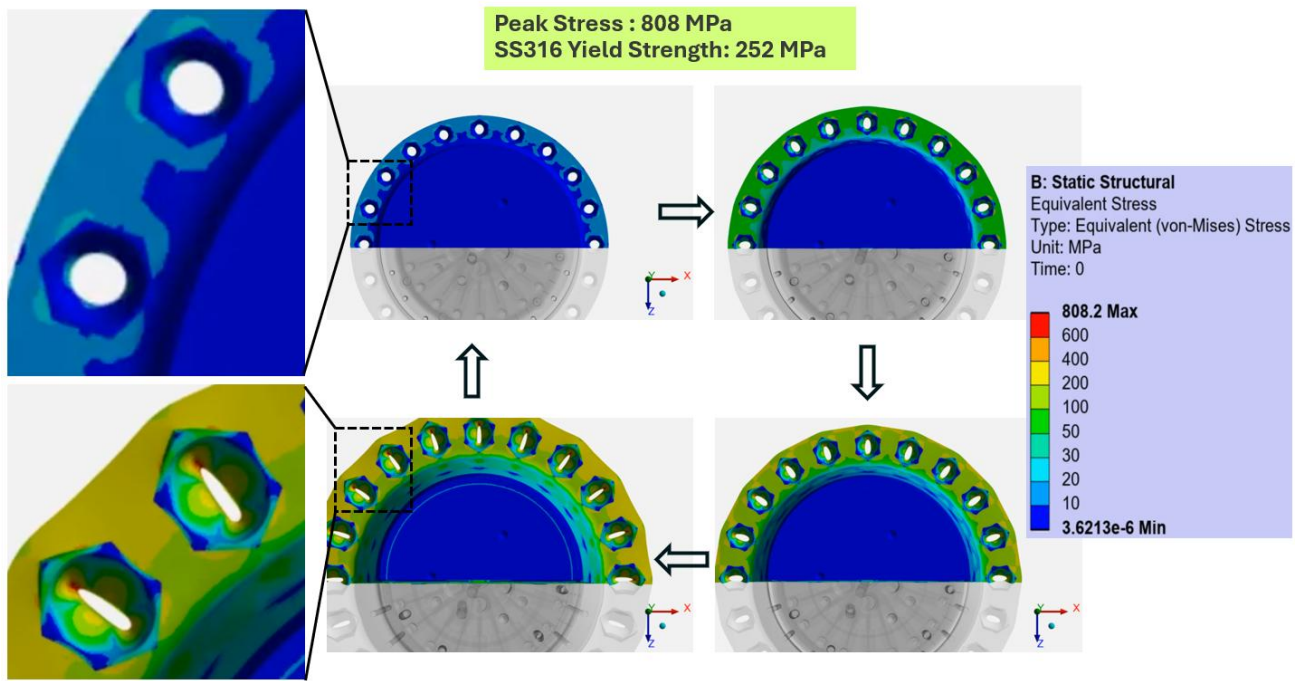


Figure 141. Von Mises stress distribution in the target shaft flange without internal cooling circuits.

APPENDIX G: IMPACT OF ORIFICE PLATES ON TARGET SHAFT PRESSURE DROP

Chapter 7 discusses the flow distribution between the target shaft and the 20 target segments. As summarized in Table 20, when accounting for the hydraulic resistance of all target assembly components, the actual flow rate entering the target shaft is 13.28 GPM, which is significantly higher than the assumed value of 7.5 GPM used in the target shaft CFD analysis presented in Chapter 5. As a result, the nominal flow rate of 7.5 GPM for individual target segments is reduced to approximately 7.14 GPM (a 5% decrease) due to the higher hydraulic impedance of the segments.

Although Table 21 indicates that a 5% reduction in flow rate results in only a 2–3 °C increase in target segment temperature, orifice plates can be introduced at the inlet and outlet of the target shaft to increase its pressure drop and better match that of the target segments, thereby improving flow uniformity across the system. The primary objective of this section is to demonstrate that, while flow balance can be achieved by selecting an appropriate orifice diameter, the pressure drop across the target shaft is highly sensitive to the orifice size and may increase significantly.

This study was conducted using an earlier target shaft configuration featuring a coaxial shell-to-tube flow arrangement, in which coolant enters through the outer annular region and exits through the central tube, as shown in Figure 142. The inlet and outlet geometry of this design are shown in Figure 143 (outlet inner diameter: 30.1 mm). It should be noted that this configuration differs from the final design (inlet and outlet inner diameter: 17.5 mm), shown in Figure 47. The pressure drop across the earlier design is approximately 1.3 psi, which is significantly lower than the 4.9 psi observed in the final design.

Pressure drops for various orifice plate diameters obtained from CFD analyses are summarized in Table 29 and plotted in Figure 144. The CFD results can be curve-fitted using:

$$p \text{ (psi)} = 1.429016 + \frac{32588048.570984}{1 + \left(\frac{D \text{ (mm)}}{0.3936752} \right)^{4.891107}} \quad (3).$$

where D (mm) is the inner diameter of the orifice plate.

As shown in Table 29 and Figure 144, for $D = 15\text{--}30$ mm, the pressure drop across the target shaft remains approximately 1–2 psi. However, when D is reduced below 15 mm, the pressure drop increases rapidly and becomes highly sensitive to further reductions in diameter. For example, decreasing D from 10 mm to 8 mm increases the pressure drop from 6.2 psi to 14.8 psi—comparable to the total pressure drop across the entire target assembly in the final design.

For a simple pipe flow, the relationship between the pressure drop and the pipe diameter can be expressed using the Darcy-Weisbach equation,

$$\Delta P = f \cdot \frac{L}{D} \cdot \frac{\rho V^2}{2} \quad (4),$$

where D is the pipe diameter, L is the pipe length, f is the frictional factor, ρ is the fluid density, and V is average velocity. For a circular pipe, this relationship can be rewritten as,

$$\Delta P = f \cdot \frac{8L\dot{m}^2}{\rho\pi^2 D^5} \quad (5).$$

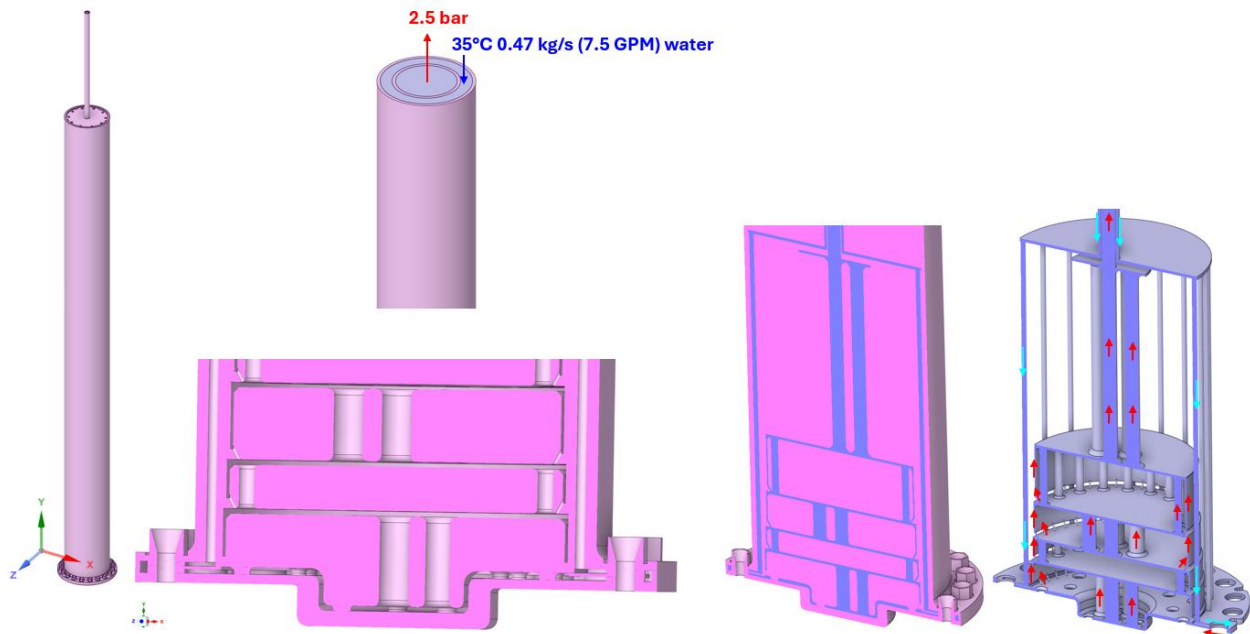


Figure 142. Previous target shaft design with a coaxial annulus-to-core flow configuration.

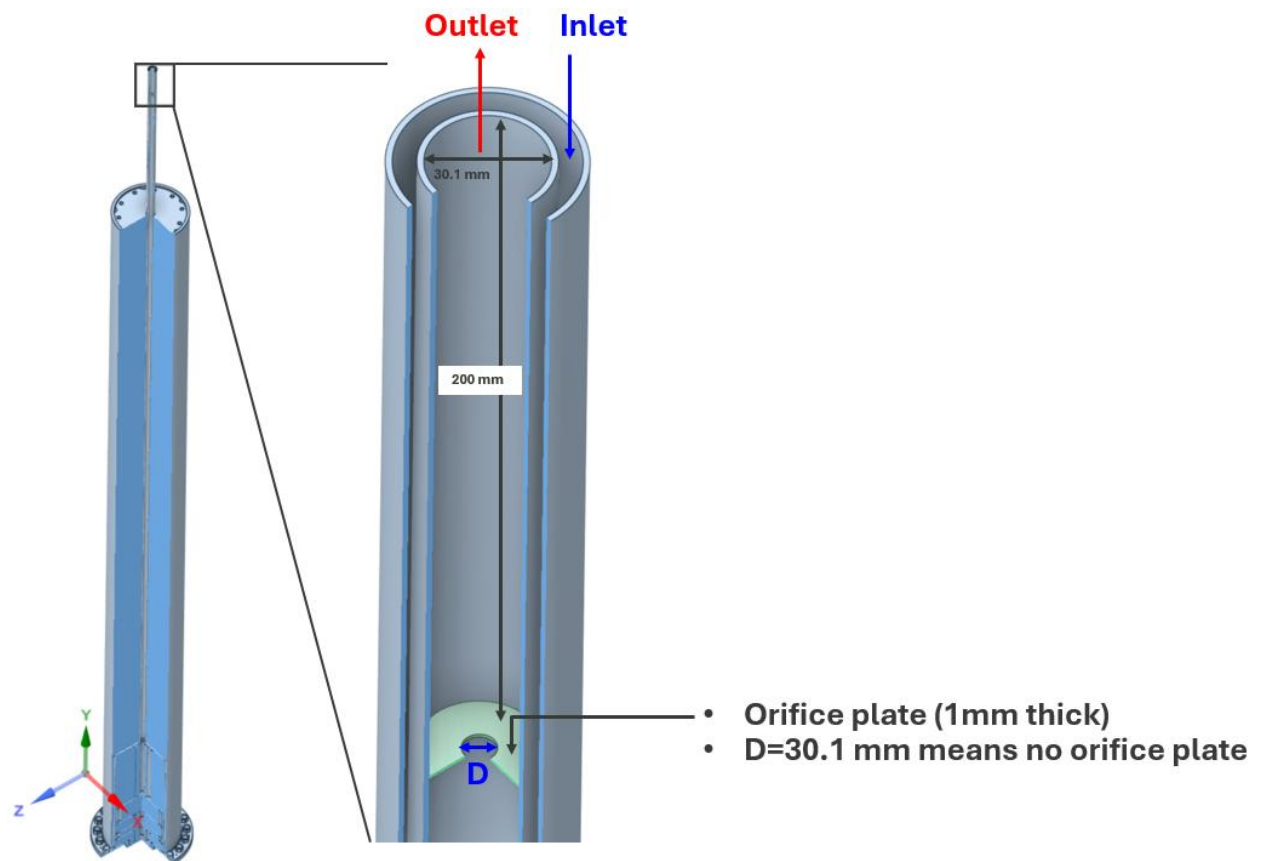


Figure 143. Inlet and outlet regions of the target shaft for the previous design.

Table 29. Pressure drop across the target shaft for various orifice plate diameters.

D (mm)	Pressure Drop (psi) from CFD	Pressure Drop (psi) from Curve Fitting	Difference(psi)
8	14.8	14.5	0.32
8.55	10.4	10.9	0.46
8.7	9.86	10.1	0.23
10	6.2	5.8	0.39
15	2.2	2.0	0.17
20	1.5	1.6	0.08
30.1 (no orifice)	1.3	1.4	0.15

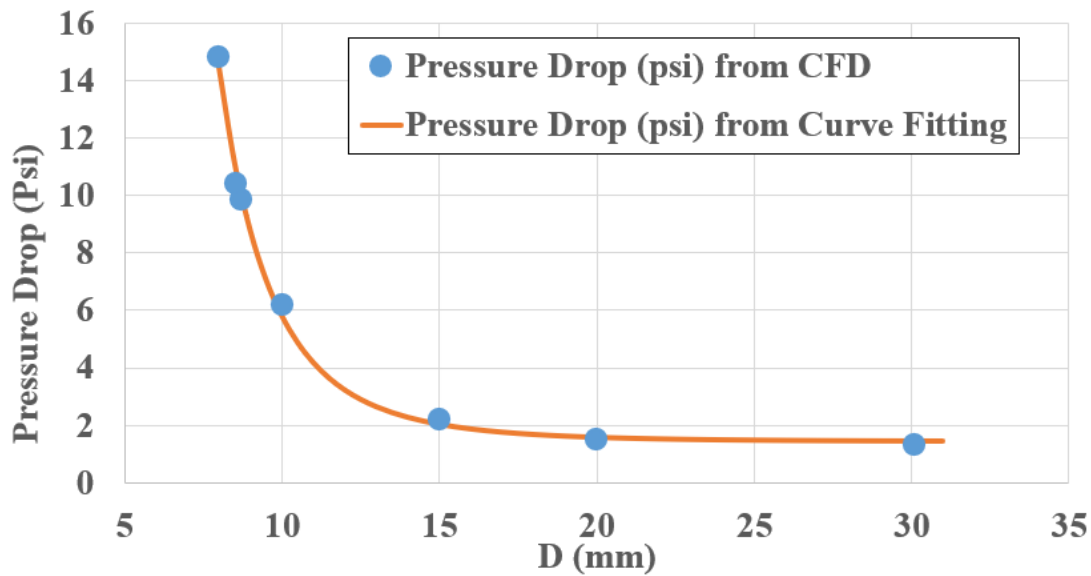


Figure 144. Pressure drop across the target shaft as a function of orifice plate diameter.

The friction factor f is not constant but depends on the Reynolds number (Re). Assuming constant mass flow rate ($\dot{m}$) and turbulent flow ($f \propto Re^{-0.25} \propto D^{0.25}$), the relationship can be approximated as:

$$\Delta P \propto \frac{1}{D^{4.75}} \quad (6).$$

It should be noted that Eq. (6) describes distributed frictional losses associated with changes in pipe diameter (e.g., the return pipe in Figure 143 or the supply and return pipes in Figure 47), rather than localized losses.

For an orifice, the pressure loss is dominated by local effects and can be expressed as:

$$\Delta P = K \cdot \frac{\rho V^2}{2} \quad (7),$$

where K is the loss coefficient (minor or form loss coefficient). Under the assumption of constant mass flow rate, this relationship can be approximated as:

$$\Delta P \propto \frac{1}{D^4} \quad (8),$$

where D is the orifice diameter.

When the orifice diameter is reduced to sufficiently small values (approximately 8–10 mm, as shown in Table 29 and Figure 144), the local loss associated with the orifice dominates the total pressure drop due to the formation of high-velocity jet through the restriction (orifice), as illustrated in Figure 145. As the orifice diameter increases, the contribution of the orifice to the total pressure drop diminishes, and the overall pressure drop asymptotically approaches the baseline hydraulic resistance of the target shaft.

These results indicate that while the hydraulic resistance of the target shaft can be tuned using orifice plates, the **pressure drop is highly sensitive to orifice diameter**, and small reductions in diameter may lead to disproportionately large increases in pressure loss.

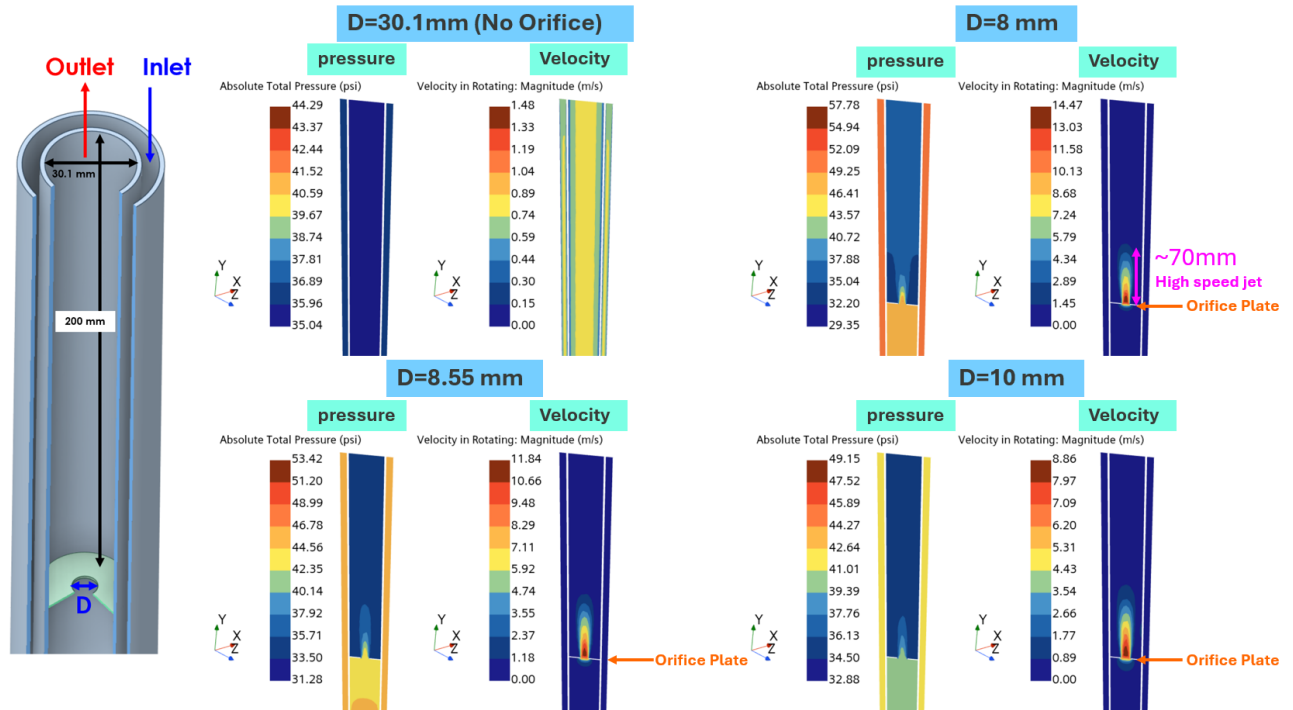


Figure 145. Pressure and velocity distributions near the orifice plate, illustrating jet formation and associated pressure loss.

APPENDIX H: LOSS-OF-COOLANT ANALYSIS FOR TIME-STEP SELECTION

This appendix presents a comparative assessment of mesh resolution and time-step selection for transient heat transfer simulations of several loss-of-coolant (LOC) scenarios. Simulations were performed using both coarse and refined spatial discretizations, with corresponding adjustments to the time stepping parameters to maintain consistent temporal accuracy. For purely heat transfer problems, the time-step requirement is less restrictive than in conventional transient CFD simulations involving fluid flow, as the Courant–Friedrichs–Lewy condition does not impose a stability constraint. Instead, the choice of time step is guided by diffusion-based considerations, commonly expressed through the Fourier number, to ensure that transient thermal behavior is adequately resolved.

The results presented herein quantify the sensitivity of the solution to spatial and temporal discretization and provide **justification** for the mesh and **time-step** parameters adopted in Section 6.4.

All transient simulations presented in this appendix employ a variable (adaptive) time-stepping scheme. The time step is dynamically adjusted to limit the maximum temperature change between successive time steps to 0.5 °C, ensuring adequate temporal resolution of the transient thermal response. In addition, an upper bound is imposed on the time step, with maximum allowable values ranging from 1 s to 200 s, depending on the case considered. These limits are selected to evaluate time-step sensitivity and to establish an appropriate time-step criterion for the analyses presented in Section 6.4.

The thermal radiation modeling settings are consistent with those described in Section 6.4. It should be noted that the initial conditions vary among the hypothetical LOC scenarios considered herein, as the **primary objective** of these analyses is to **access time-step sensitivity** rather than to reproduce a single physical transient.

APPENDIX H.1: Loss-of-Coolant Analysis under Adiabatic Conditions with Multiple Tungsten Blocks

The first hypothetical scenario considers a steady-state target segment subjected to a sudden loss-of-coolant condition under adiabatic assumptions, with no thermal radiation heat removal. The temperature rise is driven solely by decay heat within the tungsten blocks, tantalum plates (including cladding), the Inconel shroud, and stainless-steel components (Section 6.1, Table 14, Table 15, and Table 16). Simulations were performed using both coarse and refined meshes (Figure 146), with time steps of 1 s, 5 s, and 15 s.

A key design (safety) requirement for the STS target is to maintain the tungsten temperature below 800 °C. As shown in Figure 147 and Figure 148, the predicted time to reach 800 °C is approximately 16 hours for both mesh resolutions when a time step of 1 s is used. For the refined mesh, increasing the time step to 5 s and 15 s yields predicted times of 17.4 hours and 25 hours, respectively. For the coarse mesh, the corresponding predictions are 16.5 hours and 20.4 hours.

The results indicate that the solution is **more sensitive to time-step size** than to mesh resolution for this case. At a time step of 15 s, the discrepancy in the predicted time to reach 800 °C between the coarse and refined meshes is 4.6 hours. In comparison, for the refined mesh, increasing the time step from 5 s to 15 s results in a deviation of 7.6 hours (Figure 148).

These findings suggest that **a time step of 5 s** provides an **acceptable balance** between **accuracy** and **computational efficiency**. For the refined mesh, the deviation from the converged solution is limited to 1.4 hours, even under this conservative bounding scenario.

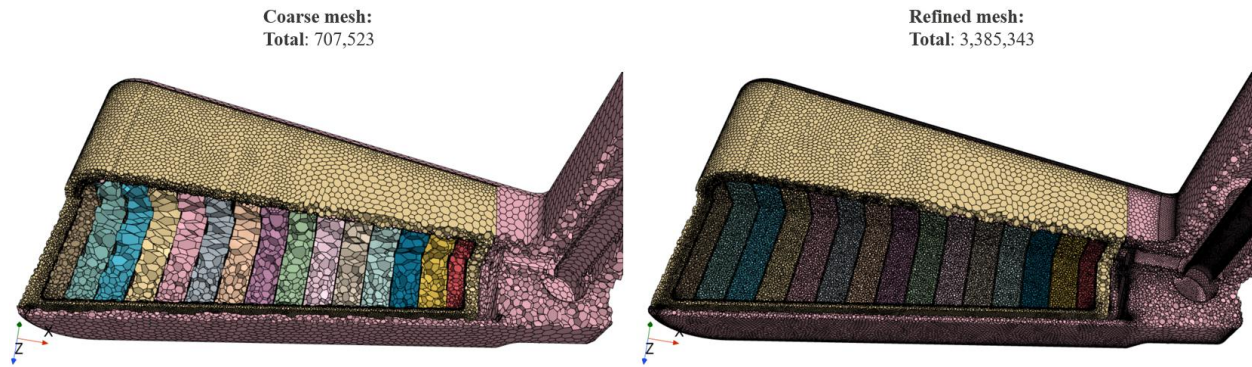


Figure 146. Mesh configurations used for the mesh independence study for the multiple tungsten block configuration.

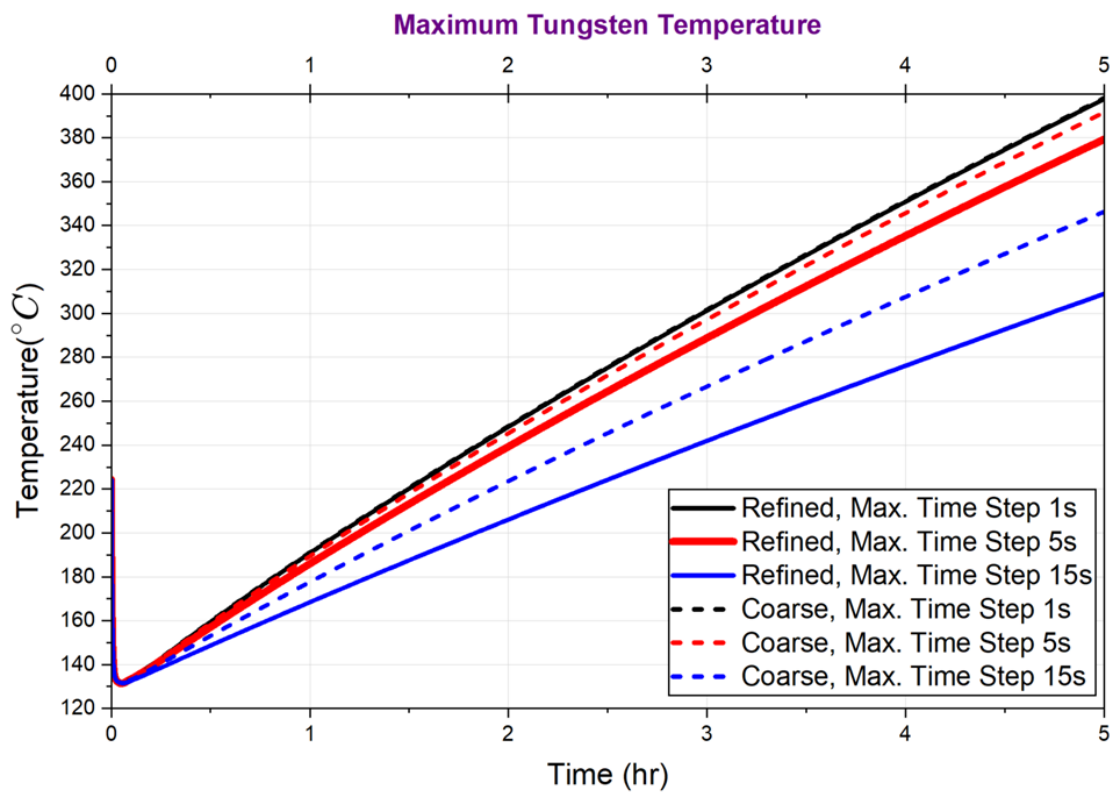


Figure 147. Peak tungsten temperature for the adiabatic target segment case (0-5 hours).

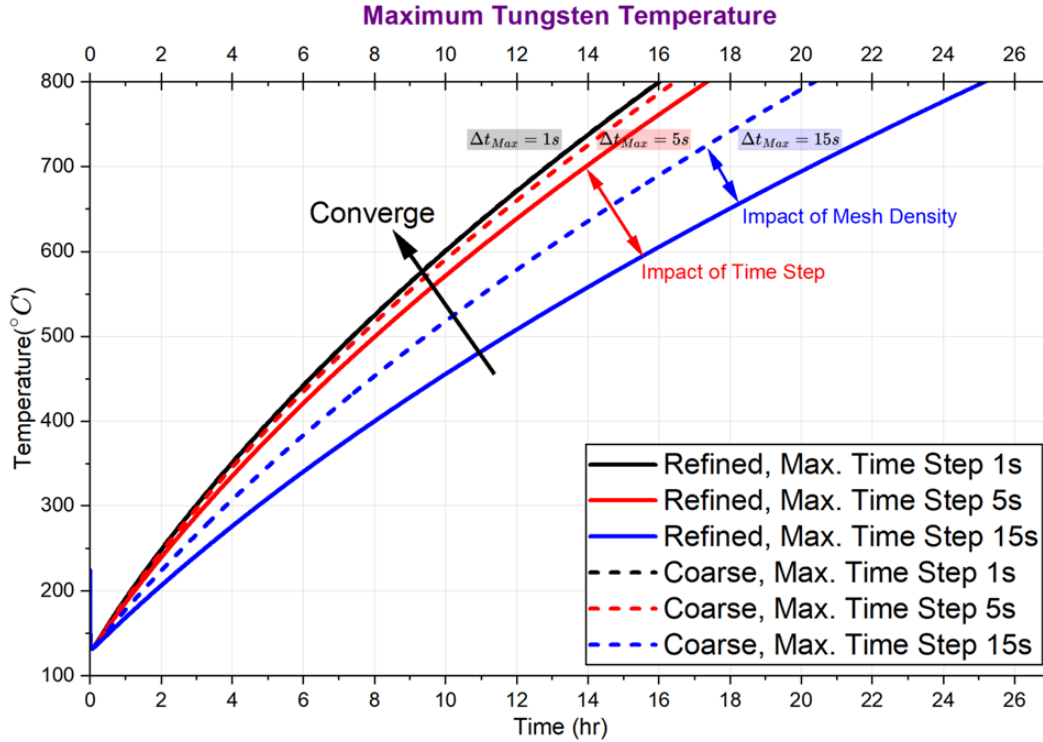


Figure 148. Peak tungsten temperature for the adiabatic target segment case under varying time steps and mesh resolutions.

APPENDIX H.2: Loss-of-Coolant Analysis Including Thermal Radiation with a Monolithic Tungsten Block

The second hypothetical scenario considers a steady-state target segment subjected to the same sudden loss-of-coolant condition, with thermal radiation included as a heat removal mechanism and the environmental temperature set to 65 °C. Consistent with the previous case, adjacent target blocks, the MRA, and CV shielding blocks are excluded from the simulation domain. The domain consists of a single target segment, in which the tungsten blocks and the tantalum interlayers are modeled as a single monolithic tungsten block. The temperature rise is driven solely by decay heat within the monolith (Section 6.1, Eq. (2)). Simulations were performed using both coarse and refined meshes (Figure 149), with time steps of 1 s, 5 s, 15 s, and 200 s.

As shown in Figure 150 and Figure 151, the predicted peak tungsten temperature reaches approximately 261 °C at about 7.5 hours after the loss-of-coolant event for this simplified model. Across all cases, deviations remain within 1.5 °C, indicating that, **for this configuration**, the solution is largely **insensitive** to both **mesh resolution** and **time-step size**.

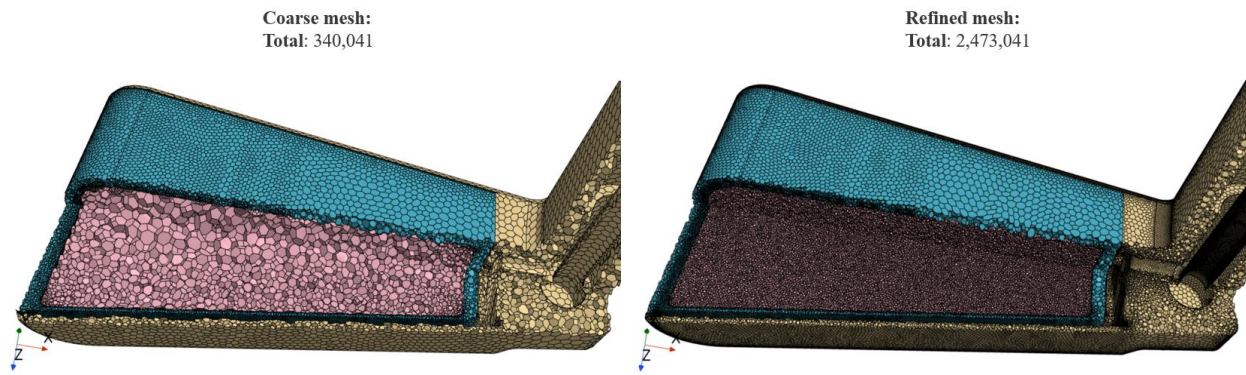


Figure 149. Mesh configurations used for the mesh independence study for the monolithic tungsten block configuration.

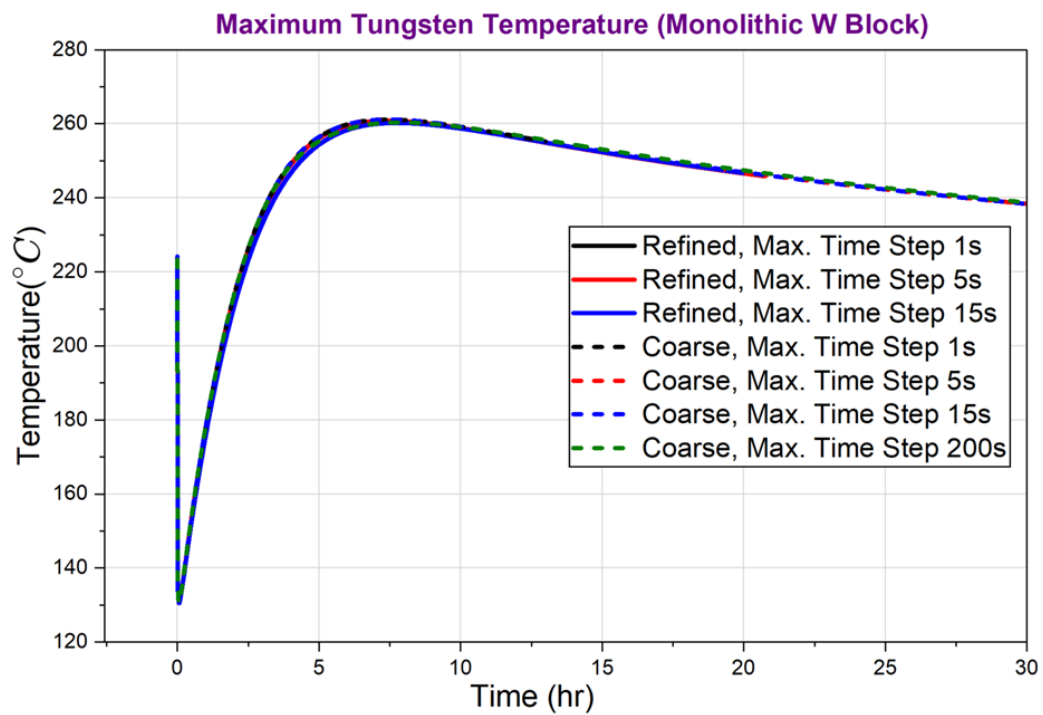


Figure 150. Peak tungsten temperature for the target segment case with thermal radiation (0–30 hours).

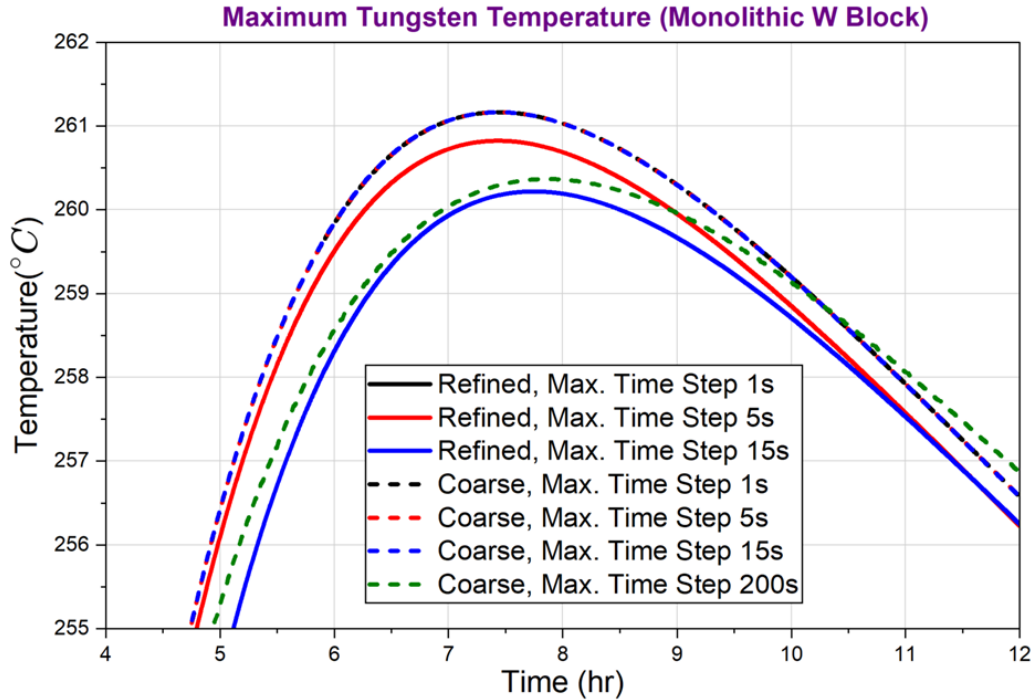


Figure 151. Peak tungsten temperature for the target segment case with thermal radiation under varying time steps and mesh resolutions.

APPENDIX H.3: Loss-of-Coolant Analysis Including Thermal Radiation with Multiple Tungsten Blocks

The third hypothetical scenario considers the same loss-of-coolant condition as in APPENDIX H.2 but includes all tungsten blocks, tantalum interlayers, and tantalum cladding, as shown in Figure 152. The temperature rise is driven by decay heat within the tungsten blocks, tantalum plates (including cladding), the Inconel 718 shroud, and stainless-steel components (Section 6.1, Table 14, Table 15, and Table 16), with thermal radiation serving as the heat removal mechanism (consistent with APPENDIX H.2 but in contrast to APPENDIX H.1).

The primary distinction between the cases in APPENDIX H.2 and APPENDIX H.3 is that the former models a single monolithic tungsten block, whereas the latter **explicitly resolves all tungsten blocks, tantalum layers, and their associated decay heat distributions**. The total decay heat as a function of time is similar in both cases (Figure 79). However, unlike the monolithic configuration in APPENDIX H.2, which exhibits negligible sensitivity to time-step size, the present configuration shows **measurable sensitivity** of the converged solution to **time-step size**, as illustrated in Figure 153 and Figure 154.

For a time step of 15 s, the predicted peak tungsten temperature is 251 °C, occurring at approximately 10.5 hours after the LOC event. In comparison, for a time step of 5 s, the predicted peak tungsten temperature is 255 °C, occurring at approximately 8 hours. These results indicate that a **time step of 5 s is sufficient** to capture the transient thermal response for this configuration. Relative to APPENDIX H.2, the peak tungsten temperature is approximately 6 °C lower, and its occurrence is delayed by 0.5 hours.

Refined mesh:
Total: 2,908,298



Figure 152. Mesh configuration used for the LOC case with multiple tungsten blocks.

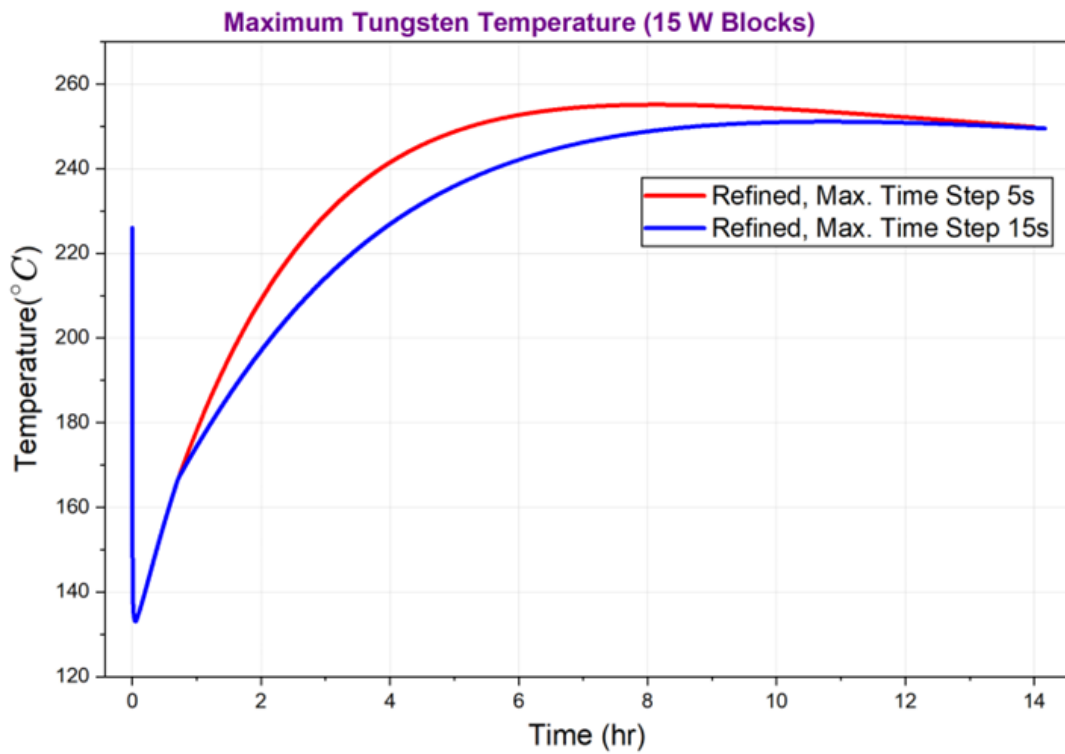


Figure 153. Peak tungsten temperature for the target segment case including thermal radiation under varying time steps (refined mesh).

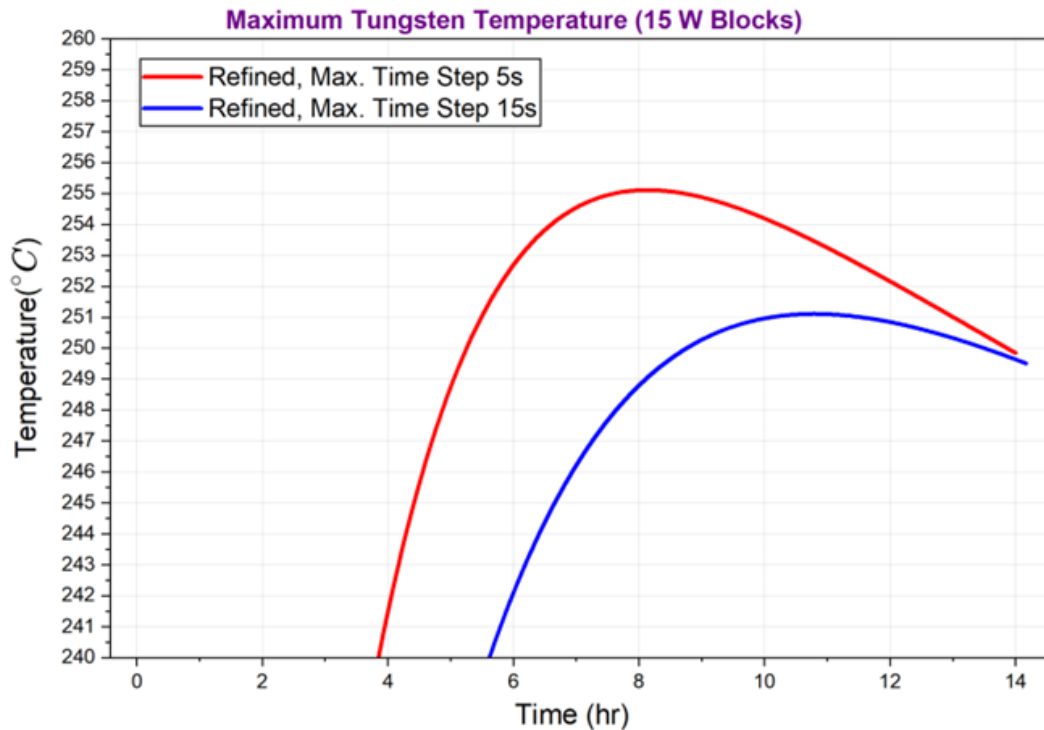


Figure 154. Peak tungsten temperature for the target segment case including thermal radiation under varying time steps (refined mesh, 4–14 hours).

APPENDIX H.4: Loss-of-coolant Analysis Including Thermal Radiation with Target Segments, Target Shaft, CV Blocks, and MRA

In the previous scenarios, the simulation domain was limited to a single target segment, and surrounding components—such as adjacent target segments, the target shaft, the MRA, and CV shielding blocks—were excluded. As a result, their thermal effects, including radiative heating from neighboring target segments (with the same decay heat profiles) and radiative exchange among surrounding surfaces, were not captured.

For the present LOC analysis, the simulation domain is expanded, as illustrated in Figure 155, to include the target block of interest, two neighboring target segments, the target shaft, the MRA, and the corresponding CV shielding blocks. The primary quantity of interest is the temperature of the target block located immediately below the MRA.

The analysis assumes that the target segments are initially at their steady-state temperatures, while the target shaft, MRA, and CV shielding blocks are initialized at 32.22 °C (90 °F). The ambient temperature is set to 35 °C. Immediately following the LOC event, the coolant within the target segments, target shaft, MRA, and CV shielding blocks is assumed to be absent from the simulation domain. Decay heat sources summarized in Table 14, Table 15, and Table 16 are applied to the target segment of interest and its two adjacent segments.

Figure 156 presents results obtained using the refined mesh with variable time stepping, in which the maximum time step is limited to 5 s and 15 s. For a maximum time step of 15 s, the predicted peak tungsten temperature is 345.7 °C, occurring at approximately 18 hours after the LOC event. In comparison, for a maximum time step of 5 s, the predicted peak tungsten temperature is 354 °C, occurring

at approximately 13 hours. These results indicate that a **time step of 5 s is acceptable** to capture the transient thermal response for this configuration.

For comparison, in APPENDIX H.3—where only a single target segment is modeled—the predicted peak tungsten temperature is 255 °C, occurring at approximately 8 hours after the LOC event. In contrast, the present case accounts for radiative heating from adjacent target segments and radiative exchange with surrounding components, resulting in a higher predicted peak temperature of 354 °C and a delayed peak at approximately 13 hours. The inclusion of **surrounding components** therefore increases the predicted peak tungsten temperature by **99 °C** and delays the time to peak by about **5 hours**.

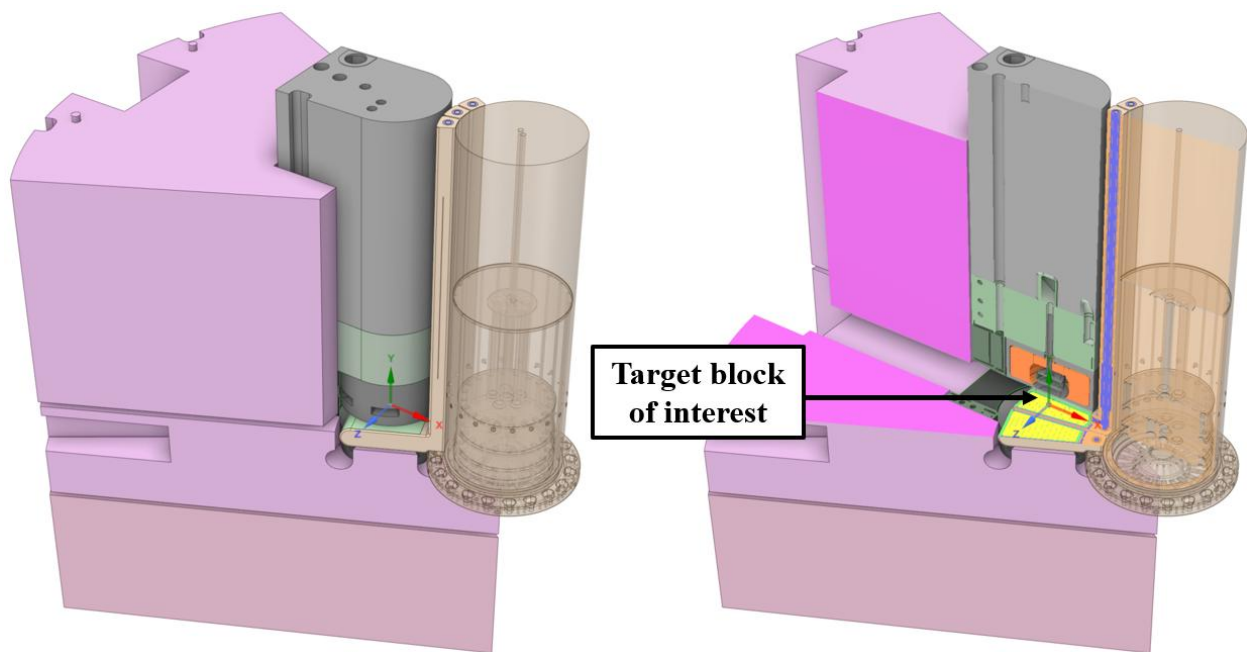


Figure 155. Simulation domain for the LOC case without air.

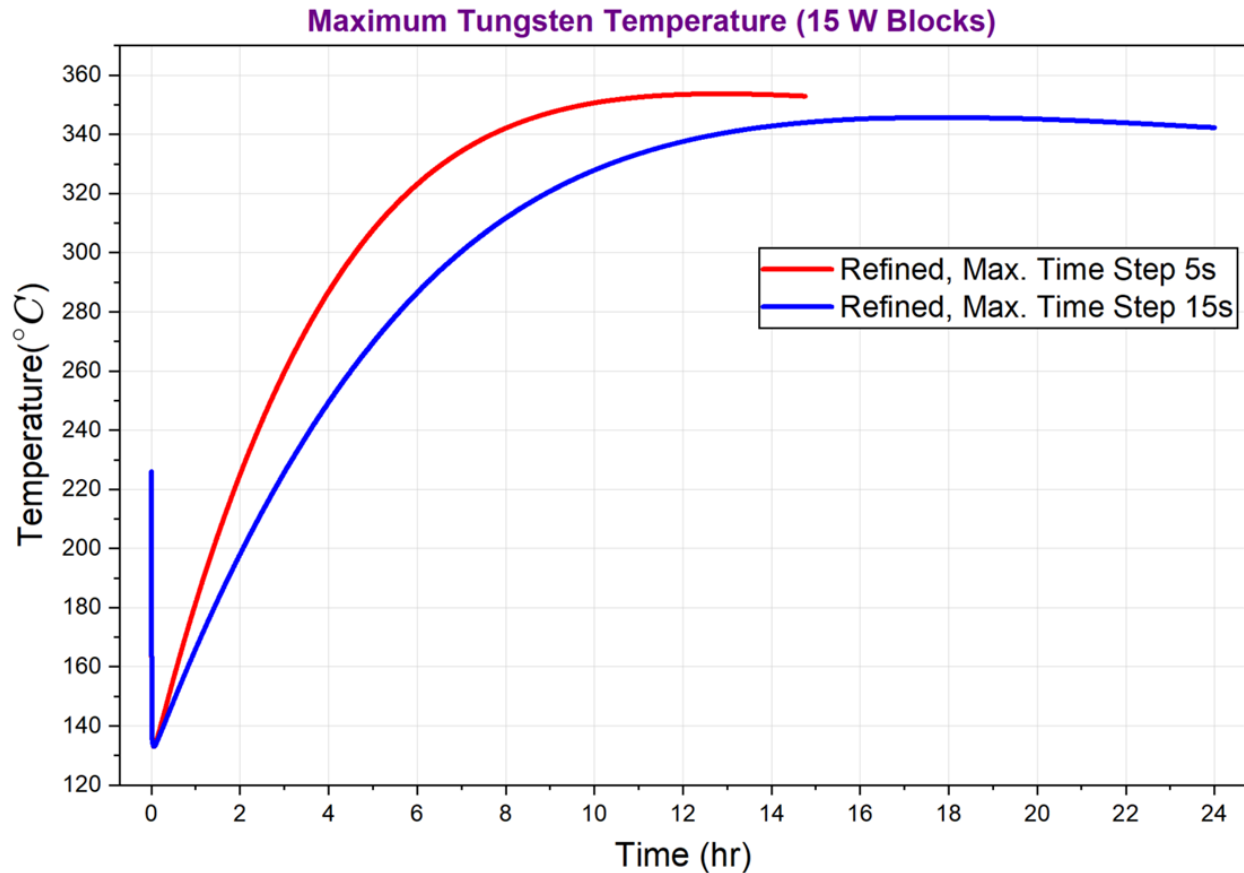


Figure 156. Peak tungsten temperature as a function of time for the configuration including adjacent target segments, target shaft, MRA, and CV shielding Blocks.

APPENDIX H.5: Loss-of-Coolant Analysis Including Thermal Radiation with Target Segments, Target Shaft, CV Blocks, MRA, and the Corresponding Stagnant Water Volumes and Environmental Air

In APPENDIX H.4, the target block of interest and the surrounding mechanical components are included in the simulation domain; however, the water within the MRA, target segments, and target shaft is excluded.

For the LOC analysis in this section, all components in APPENDIX H.4, along with the associated stagnant water volumes and surrounding air, are included in the simulation domain (Figure 157). The air and water regions are modeled to account for heat conduction only; natural circulation and boiling effects in the water are not considered. This LOC scenario is consistent with the case presented in Section 6.4 (Figure 91).

For this analysis, the initial temperature distribution of the target segments corresponds to conditions following 10 minutes of active cooling at a flow rate of 7.5 GPM (per target segment) after beam shutdown. At the end of this cooling period, the target temperature decreases to approximately 34.4 °C. In contrast, the target shaft, MRA and CV shielding blocks are initialized at 32.22 °C (90 °F), and the ambient temperature is set to 30 °C. Decay heat sources summarized in Table 14, Table 15, and Table 16 are applied to the target segment of interest and its two neighboring segments.

The simulation is performed using the refined mesh with a maximum time step of 5 s. The mesh configuration shown in Figure 158 is employed, with a total of approximately 21.86 million cells.

As shown in Figure 159, with the inclusion of air and stagnant water for conductive heat transfer, the predicted peak tungsten temperature is 307.5 °C, occurring at approximately 14 hours after beam shutdown.

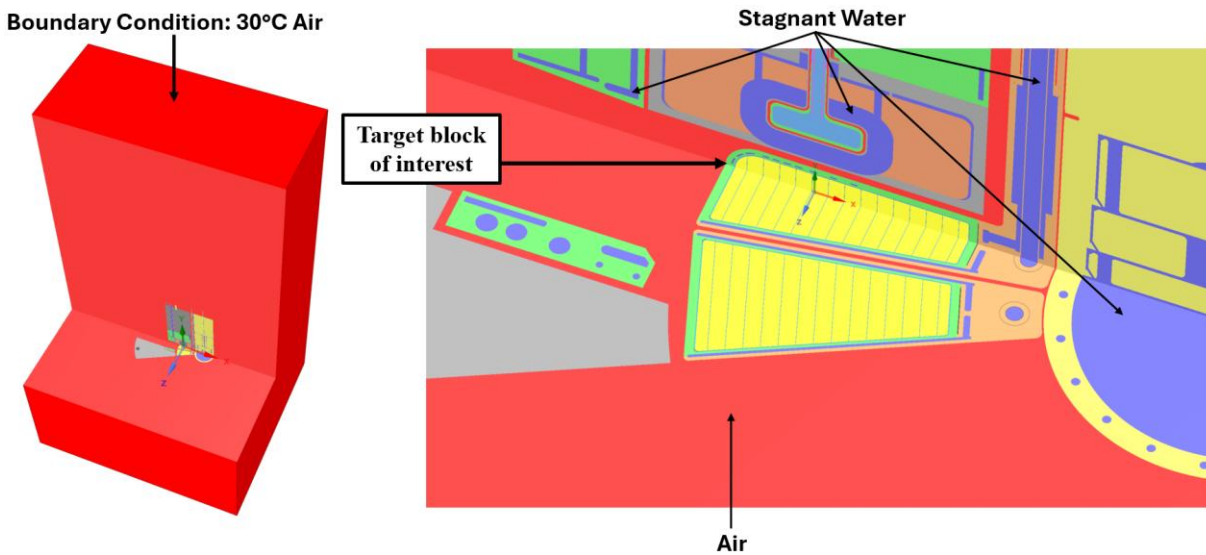
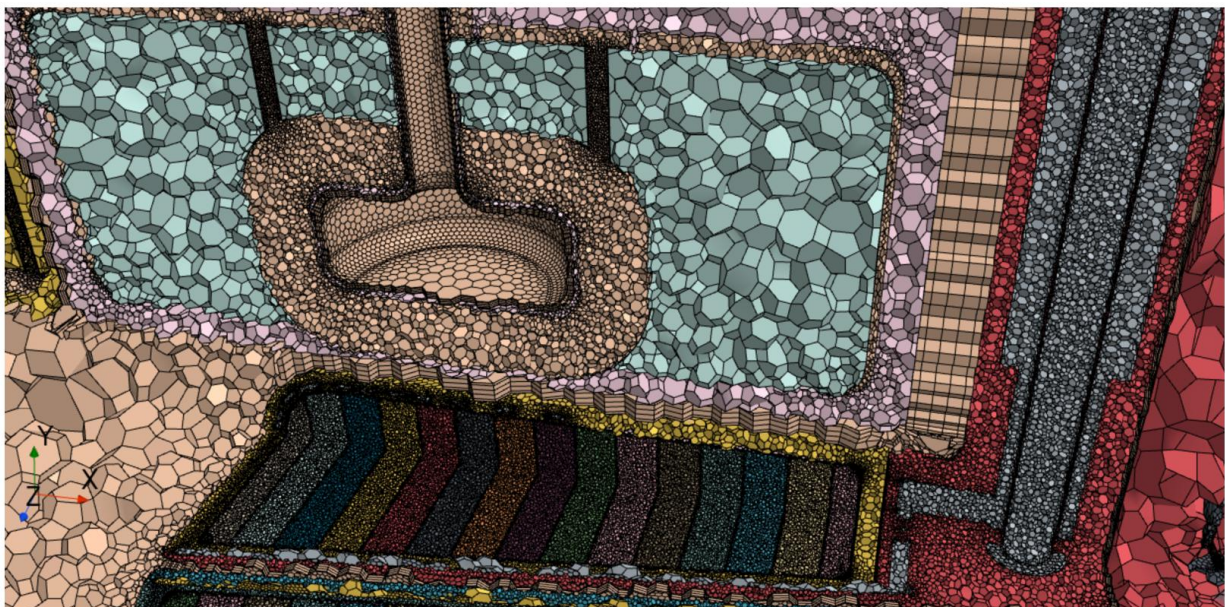


Figure 157. Simulation domain for the LOC case including air and stagnant water.



Number of meshes: 21,862,343

Figure 158. Refined mesh configuration used in the LOC analysis.

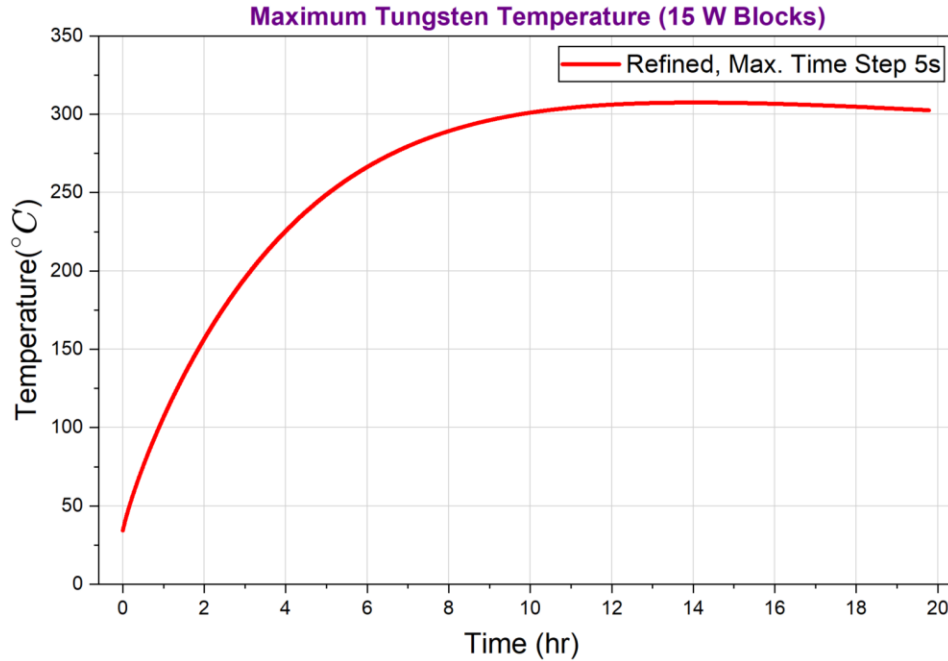


Figure 159. Peak tungsten temperature as a function of time for the configuration including adjacent target segments, target shaft, MRA, CV shielding Blocks, stagnant water, and air within the CV.

The results presented in Appendix H demonstrate that the sensitivity of the transient thermal response to time-step size depends strongly on the underlying physics and model fidelity. The adiabatic case (APPENDIX H.1) represents a conservative bounding scenario, in which the solution exhibits the highest sensitivity to time-step size and therefore governs the time-step selection. In contrast, cases that include thermal radiation and increased geometric complexity (APPENDIX H.2–H.5) show reduced sensitivity due to slower thermal transients and enhanced heat dissipation mechanisms.

Across all scenarios considered, a maximum time step of 5 s, used in conjunction with the adaptive time-stepping scheme ($\Delta T \leq 0.5$ °C), is shown to provide sufficient temporal resolution while maintaining computational efficiency. Larger time steps (e.g., 15 s) introduce non-negligible deviations in the predicted transient response for the more sensitive configurations.

Based on these findings, a **maximum time step of 5 s** is selected for the transient simulations presented in Section 6.4.