



08/10 – 08/12, 2026

FDR - STS Target Thermal Hydraulic Analysis

Min-Tsung Kao

Second Target Station



U.S. DEPARTMENT
of **ENERGY**

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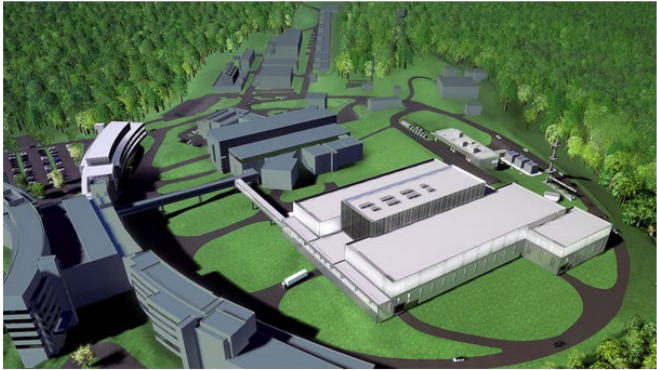


- **Charge Question 2:**
Has the design been shown to meet the requirements?
- **Charge question 3:**
Do DACs and other supporting documentation adequately support the final design?
- **Question 5:**
Is the design sufficiently mature to proceed with finalizing the procurement package?

Related Documents

S03020000-DAC10003

Second Target Station Project: CFD Analysis for Target Assembly



Min-Tsung Kao
April 2026

Draft. Document has not been reviewed and approved for public release.



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0000019063

Blowdown Analysis of the STS Target Assembly



Min-Tsung Kao
July 2026

Draft. Document has not been reviewed and approved for public release.



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Outline

- Geometry
- Requirements
- Simulation Assumptions
- Day 2: Target Segment Analysis
- Day 3: Target Assembly Analysis
- Requirement Verification
- Conclusion

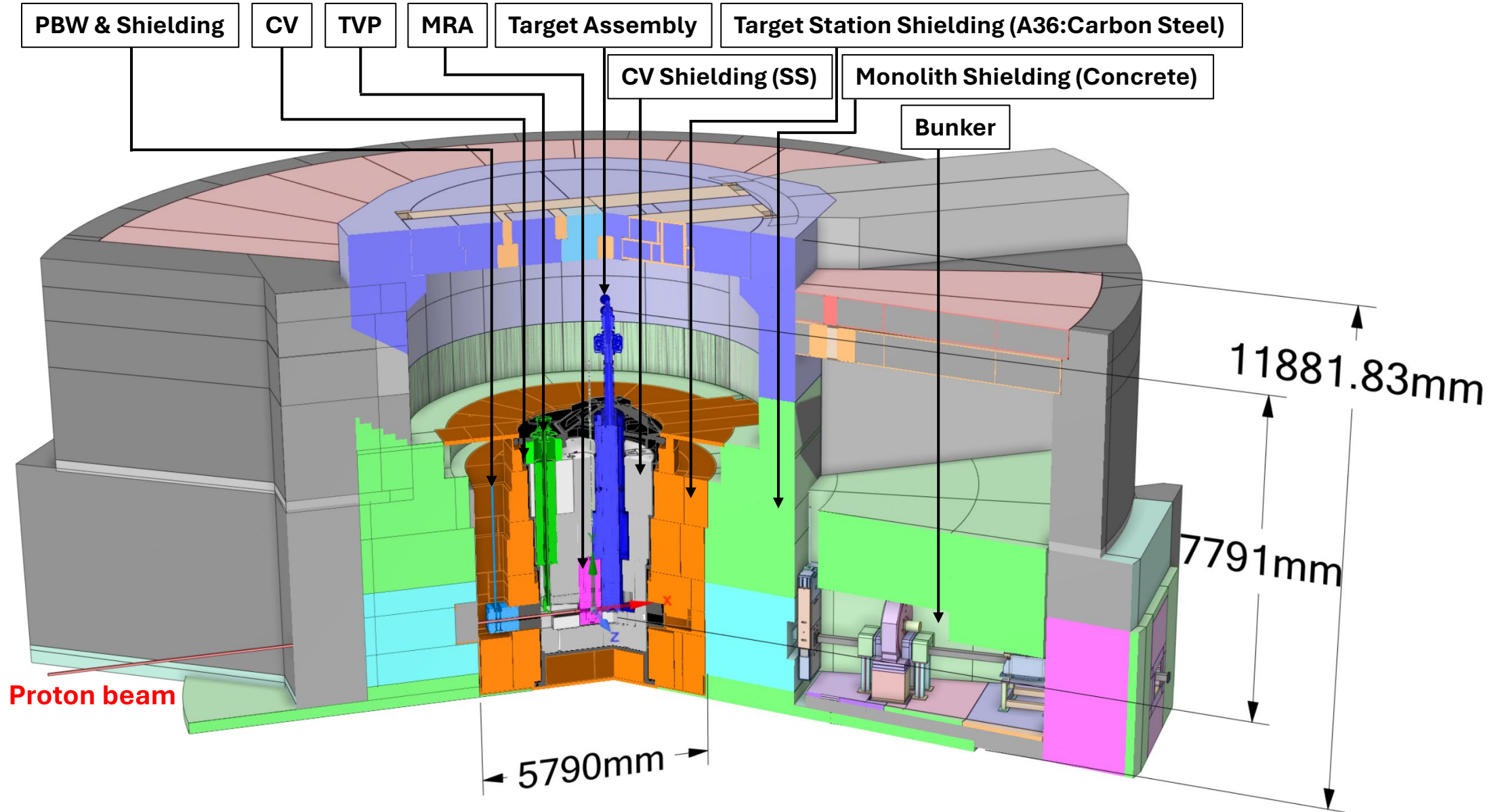
Day 2 : Target Segment Analysis

- Geometry
- Mesh, Boundary Conditions, Heat Load
- Results
 - **700 kW & 7.5 GPM**: Nominal, Over-Focused, Offset, and Diffused Beams (**Requirement**)
 - Increased Beam Power (**900 kW**) or Reduced Flow Rate (**5.71GPM**) (**Sensitivity of Design**)
 - **Maintenance Temperature (Beam Off)**
 - Decay Heat
 - Under Reduced Flow Rate (0.1 & 0.2 GPM) (**Steady State**)
 - Immediately after Shutdown **with Active Internal** Water Cooling (7.5GPM) (**Transient**)
 - Loss of Cooling
 - ❑ **Without Active** Cooling (**Transient**)
 - ❑ **Preliminary External** Air-Cooling Analysis (**Steady State**)
 - ❖ **Air-cooling for a single segment** ← lower-bound estimate of required flow rate
 - ❖ **Air-cooling for the entire target disk (20 segments)** ← pressure drop required for sufficient flow

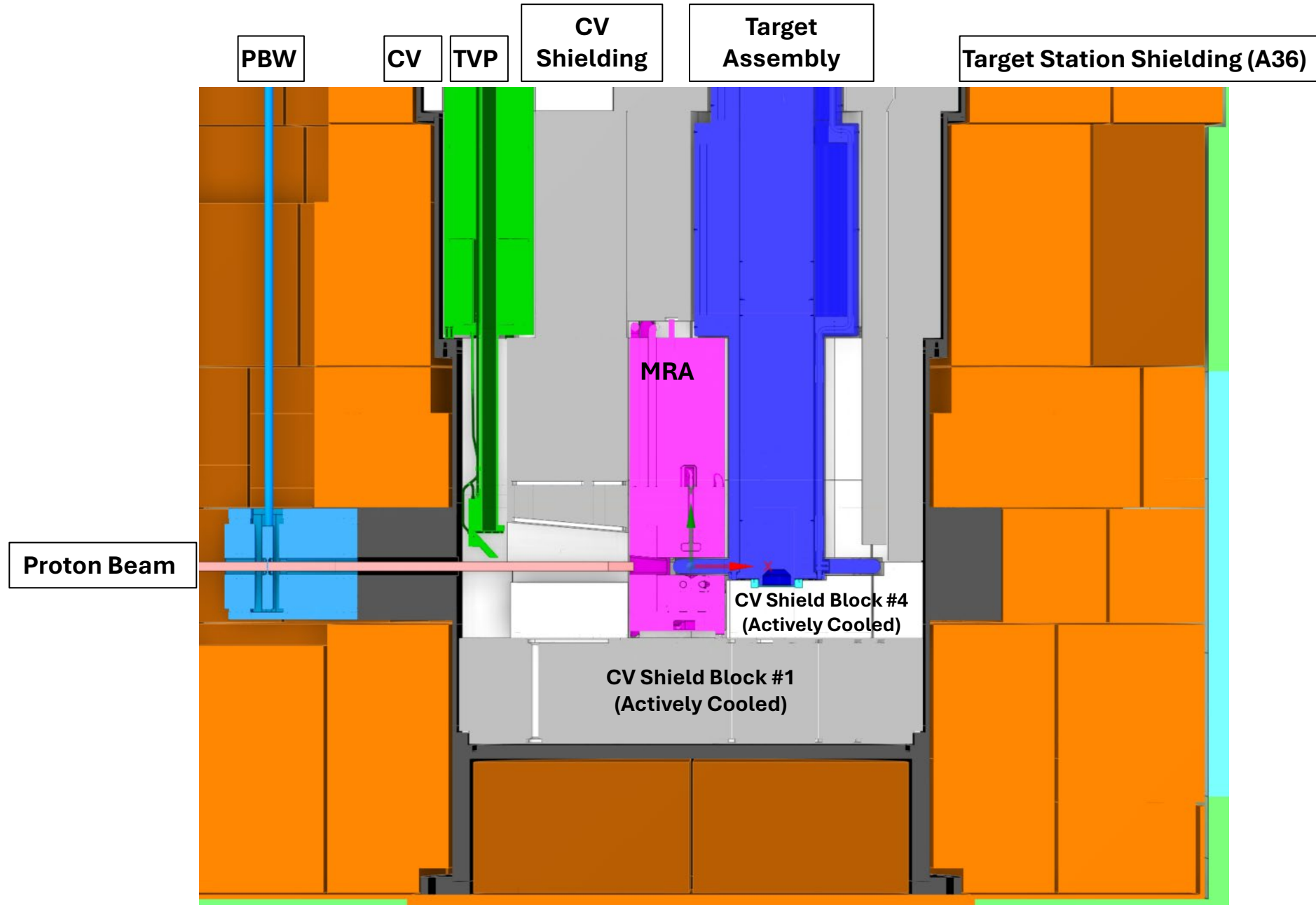
Day 3 : Target Assembly Analysis

- Geometry
- Results
 - **Target Shaft** : Nominal, Over-Focused, Offset, and Diffused Beams
 - **Target Assembly**
 - Total pressure drop (**Requirement**)
 - Flow balance – Target Drive → 20 Segments & Shaft
 - **Blowdown Analysis**
 - Case 1 – Air Purge of Water in a Single Target Segment
 - Case 2 – Air Purge of Water in the Whole Target Assembly

Relative location of the Target Assembly in STS



Proton Beam and Target Assembly



Target Assembly, Geometry

07/30/2026

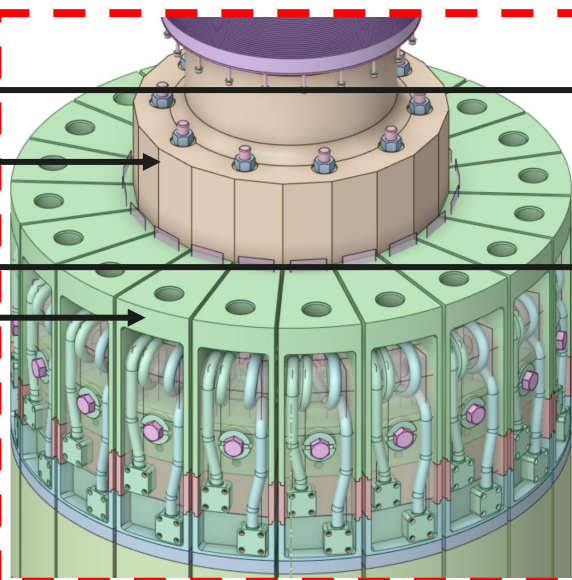
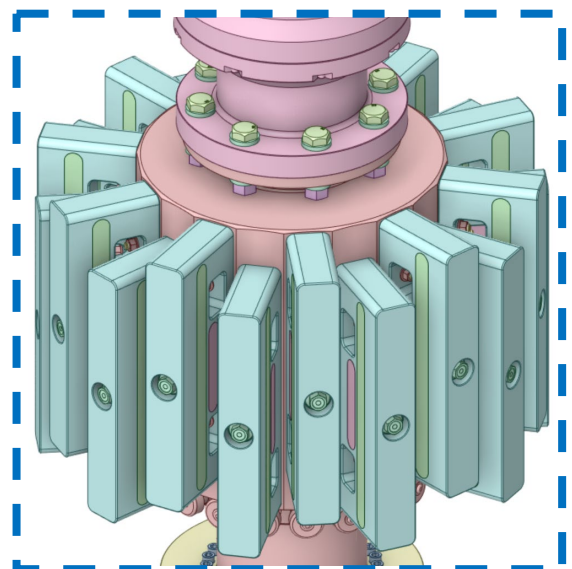
FDR

Valve/Manifold
Assembly

Segment-to-
Crown Interface

Target Shaft
(Crown)

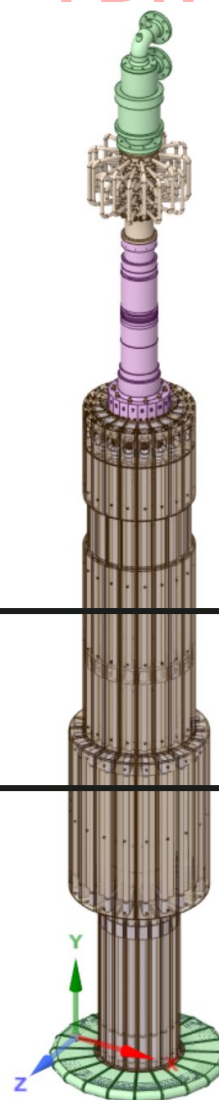
Target
Segment



12/18/2025

10% of report

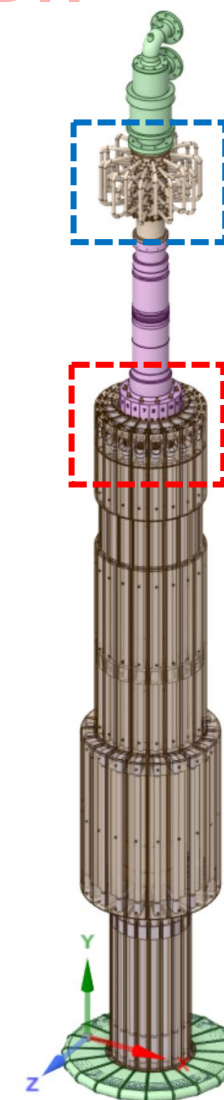
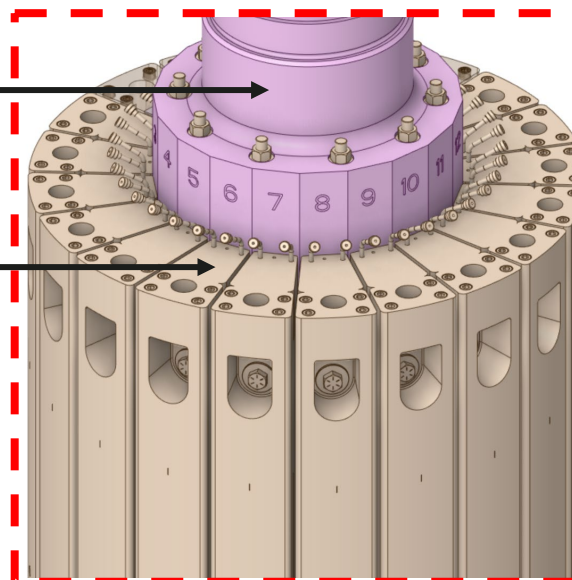
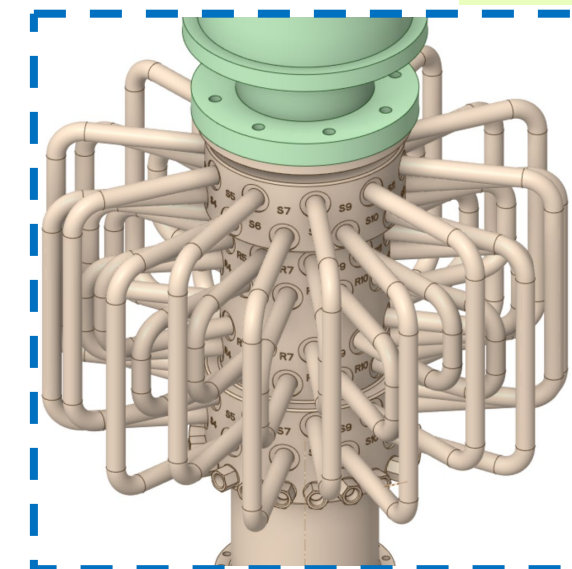
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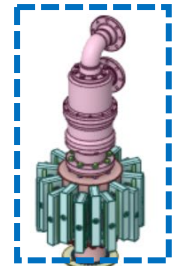
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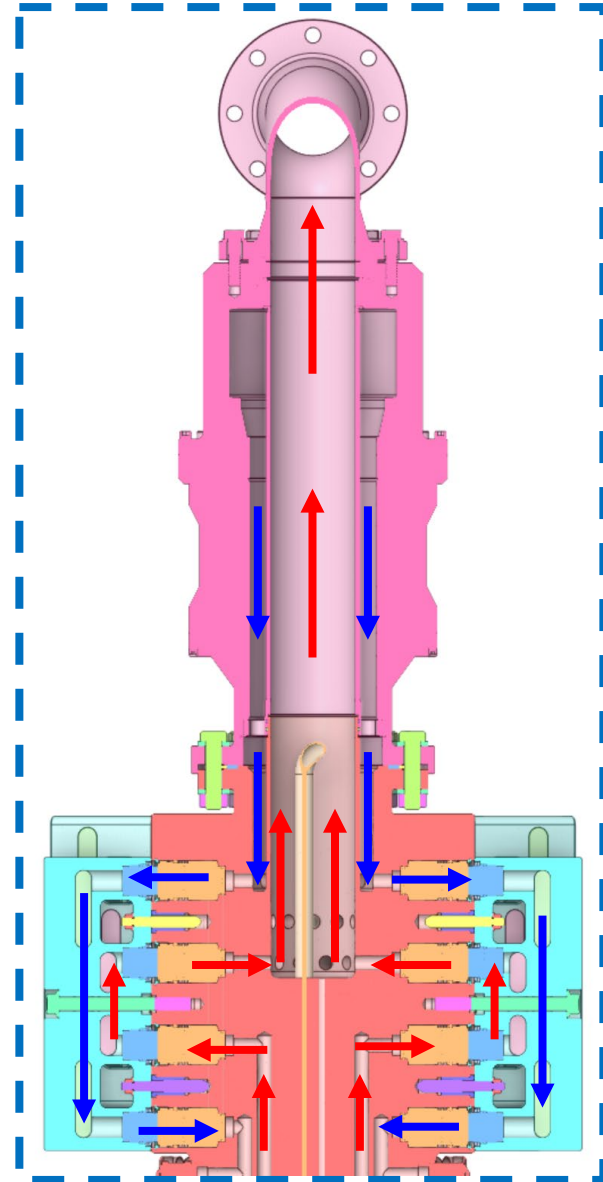
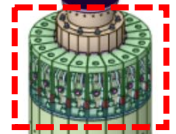
Target Assembly, Geometry

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FDR



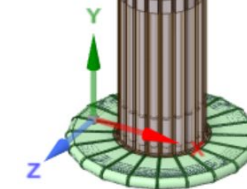
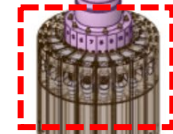
Valve/Manifold
Assembly



12/18/2025

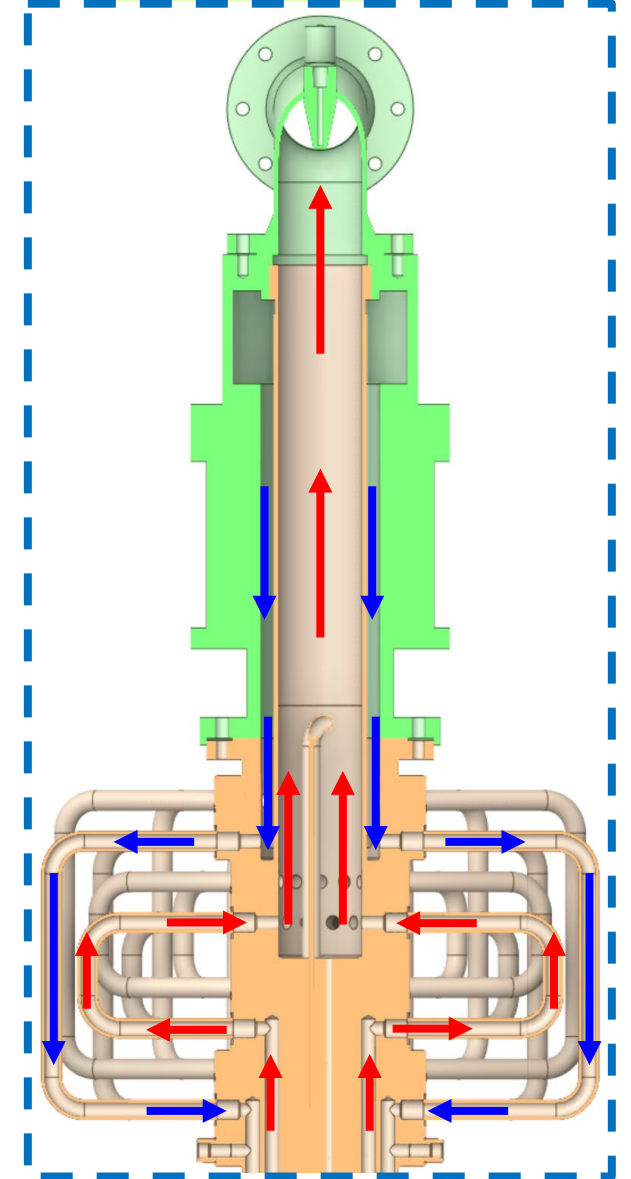
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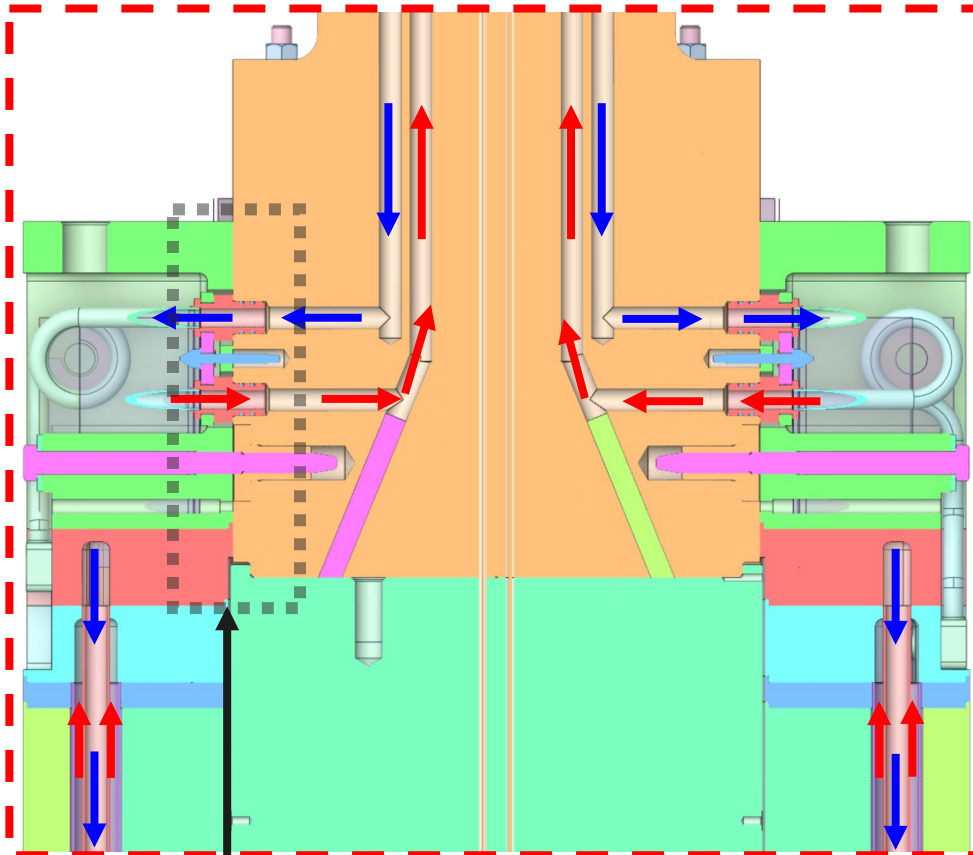
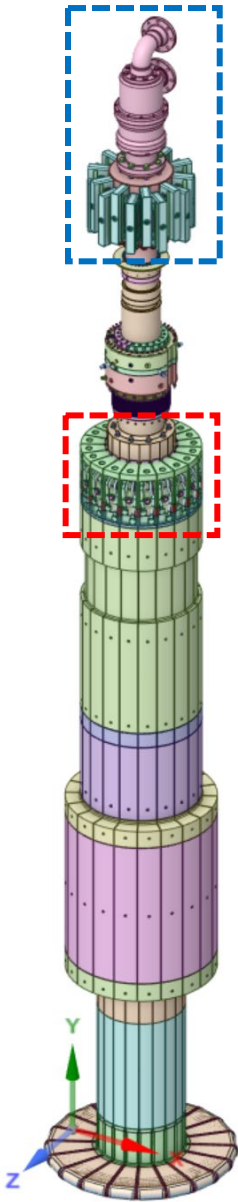
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Target Assembly, Geometry

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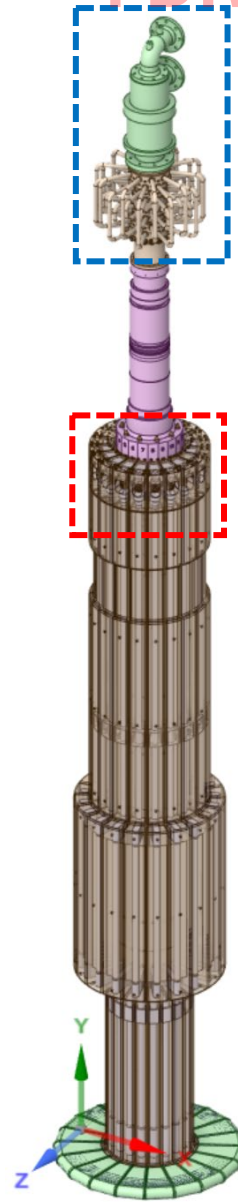
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Segment-to-Crown Interface

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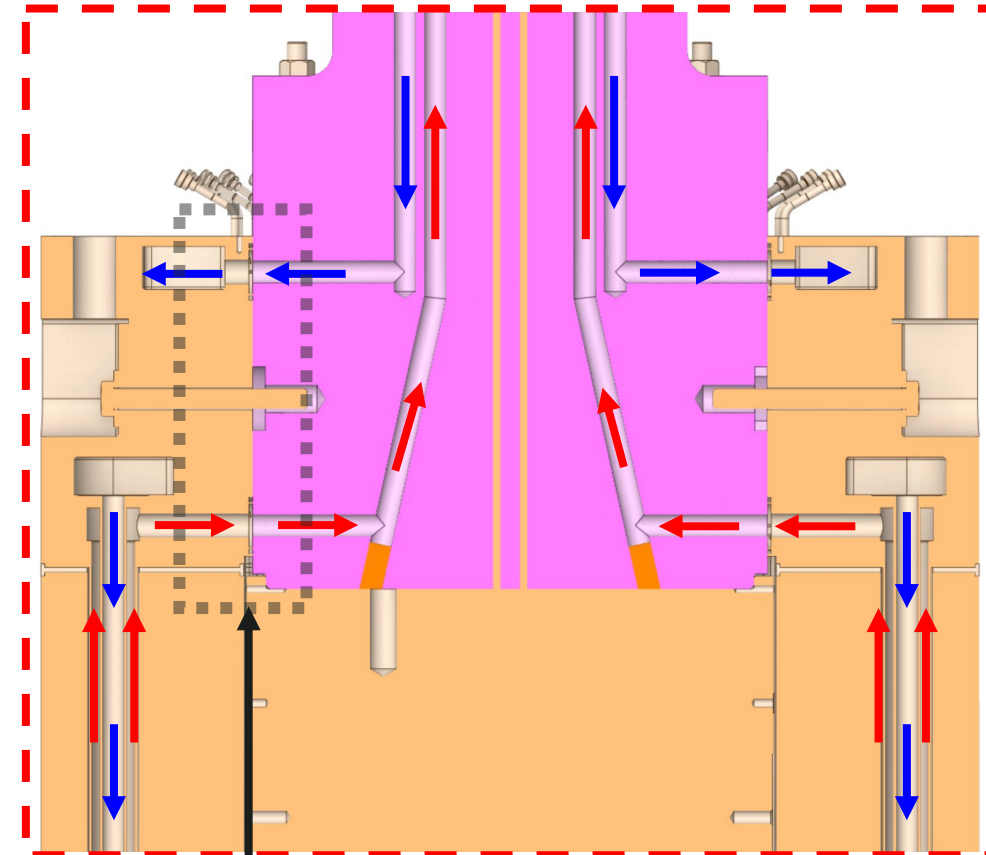


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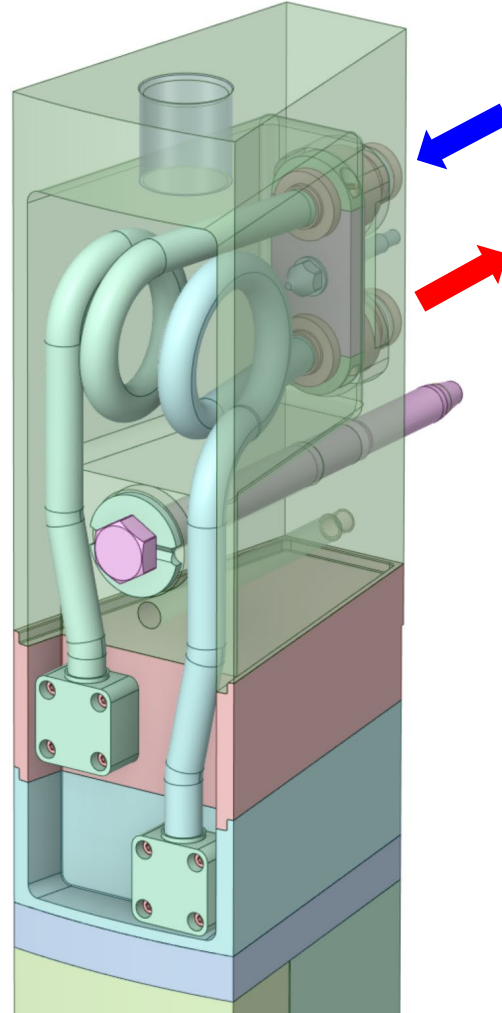
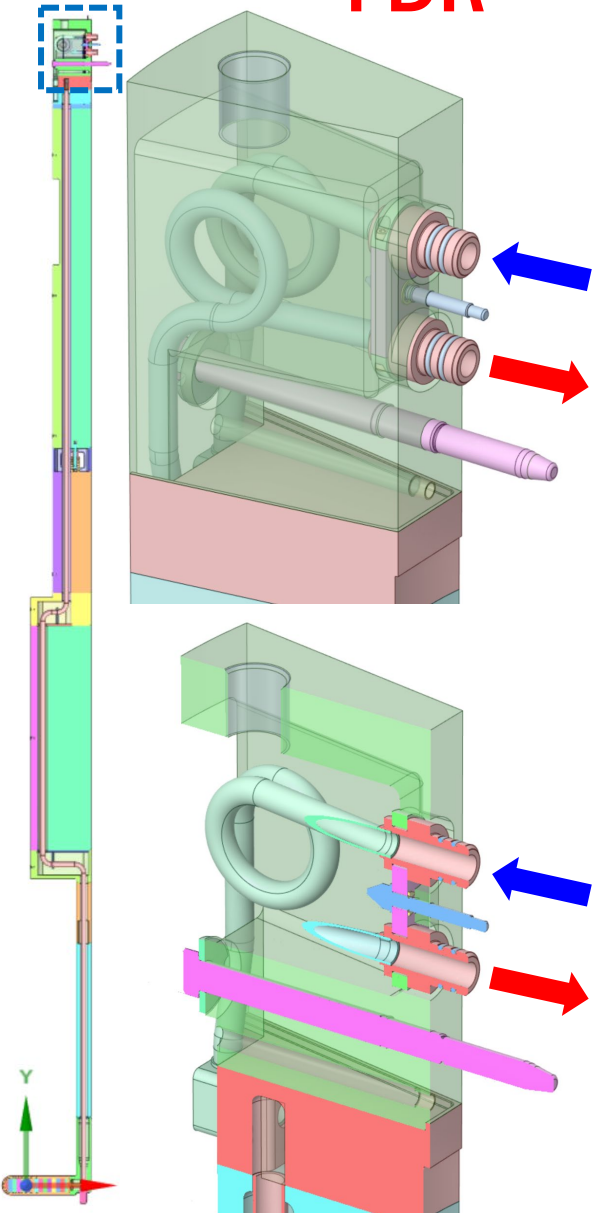


Segment-to-Crown Interface

Target Segment, Geometry

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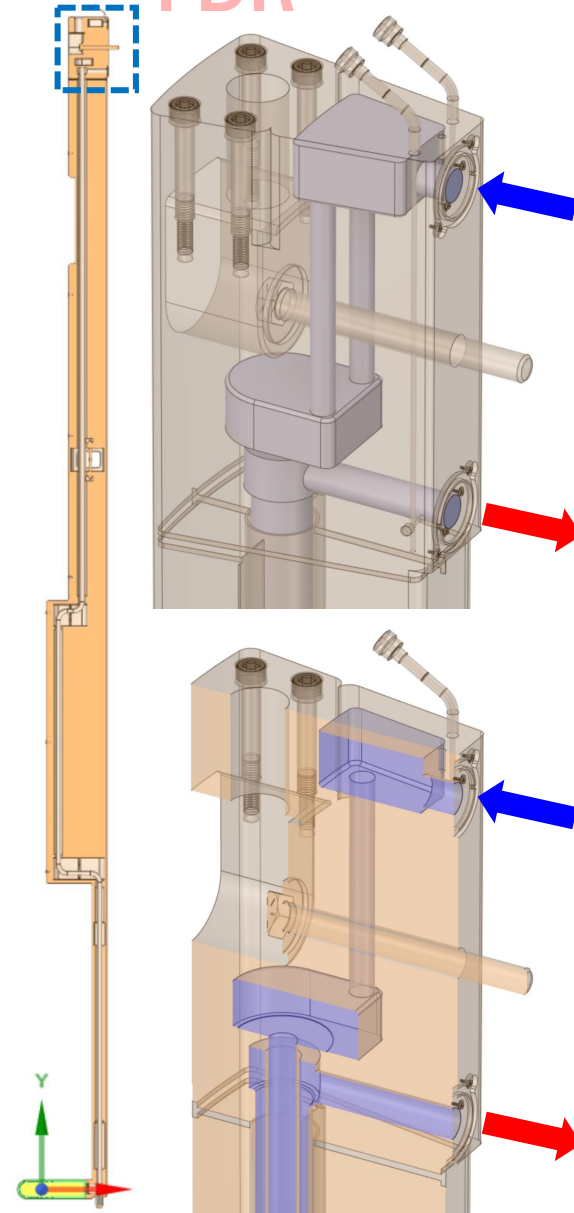
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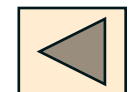
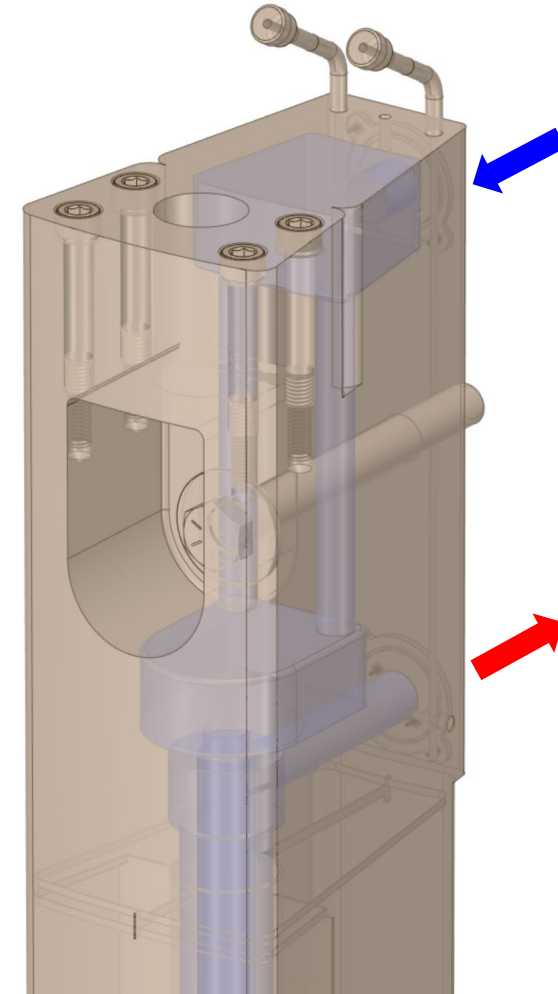
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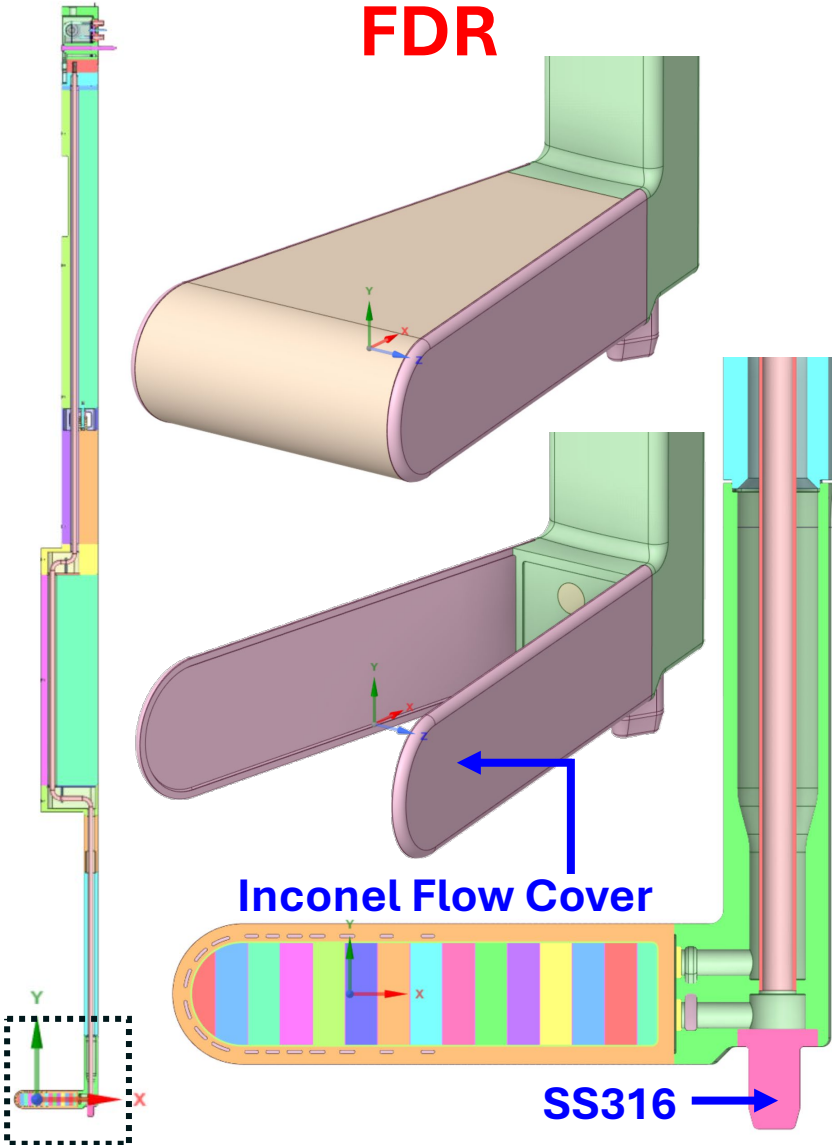
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Target Segment, Geometry

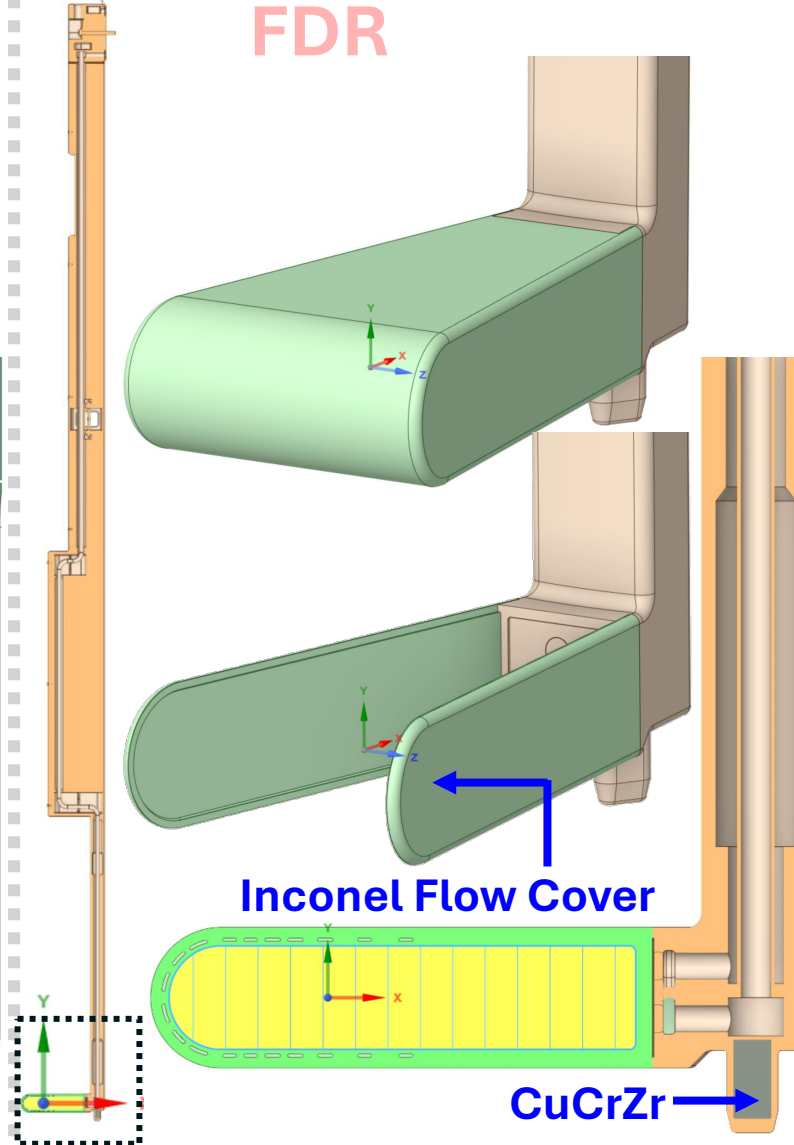
07/30/2026

FDR



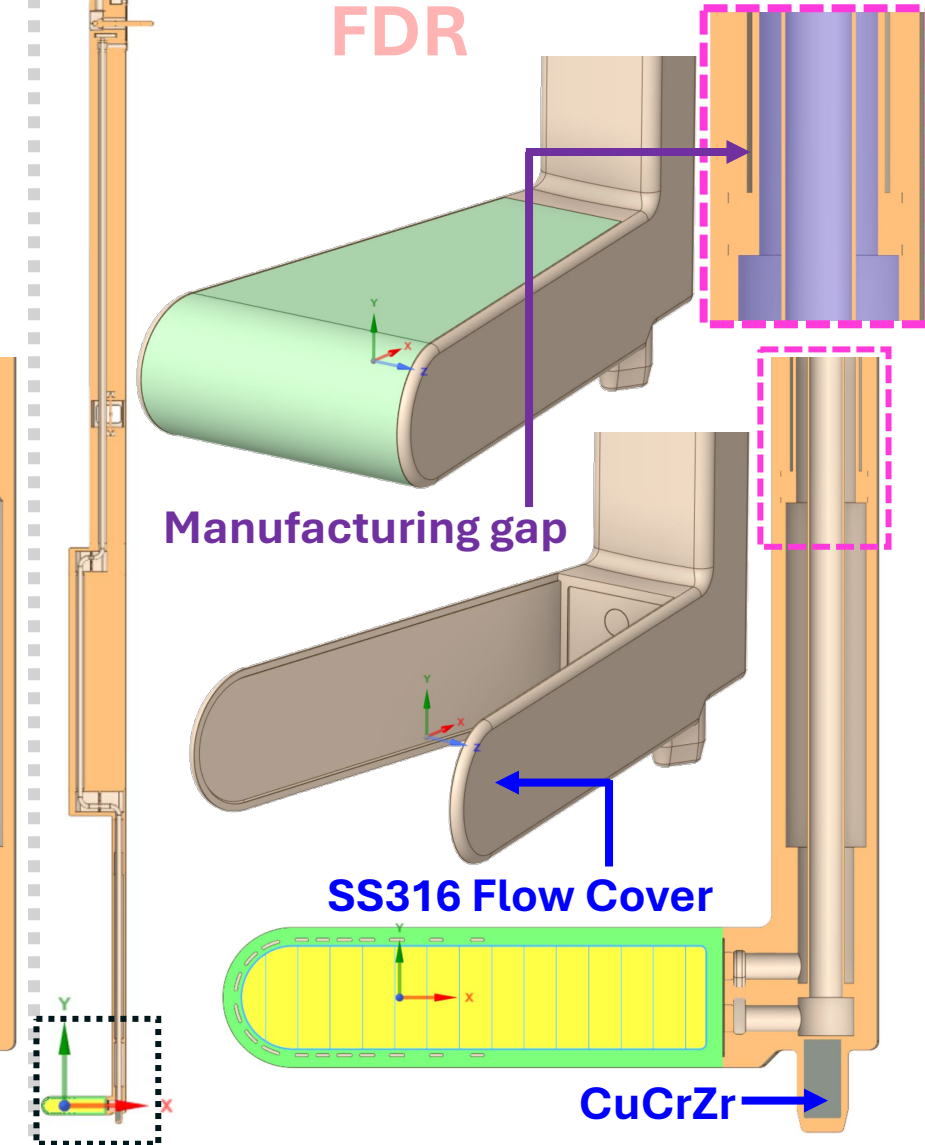
12/18/2025 10% of report

FDR



08/12/2025 90% of report

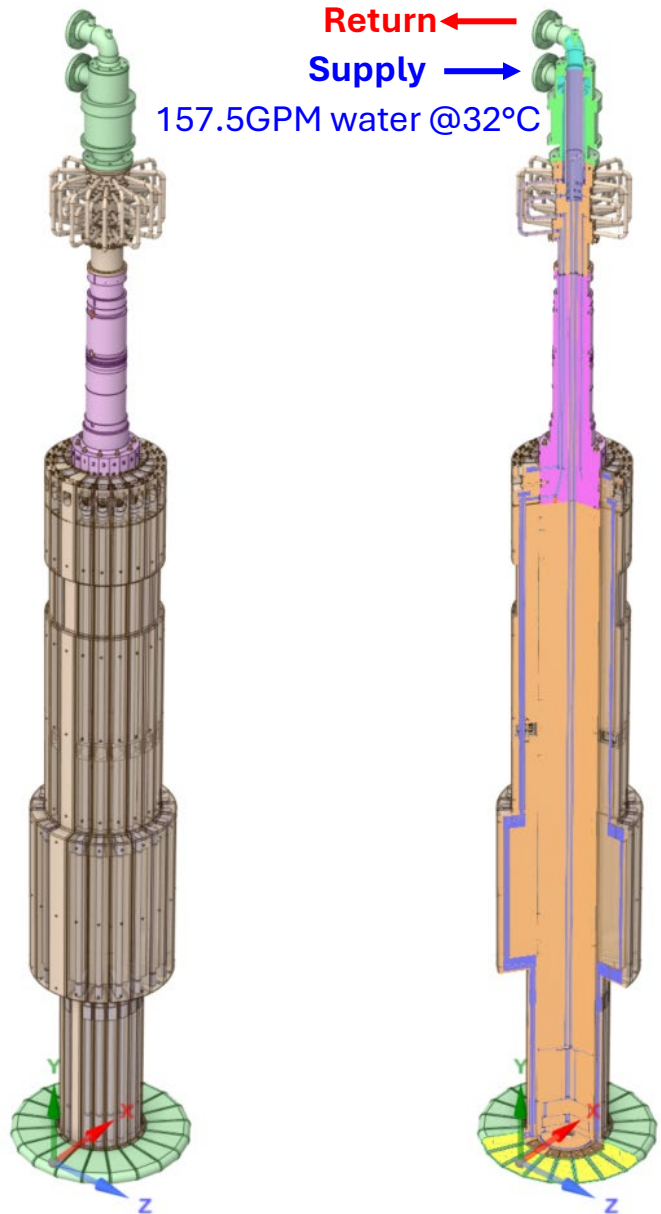
FDR



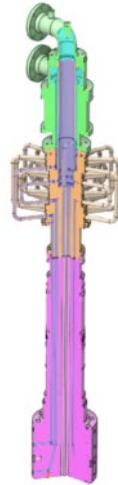
Target Assembly, Geometry

08/12/2025

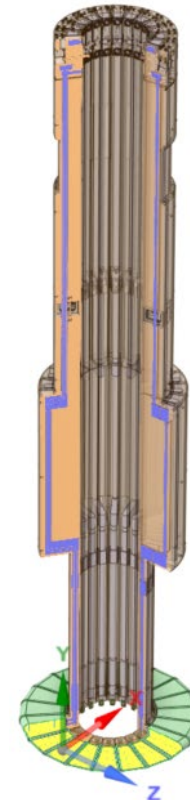
Target Assembly



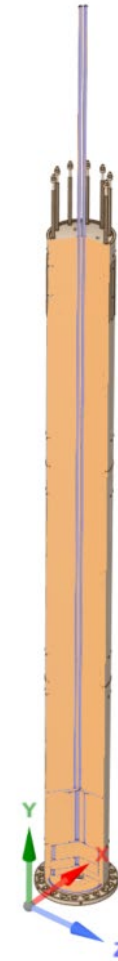
Target Drive



Segments



Shaft



Requirements

Requirements and status will be indicated by

- Pass 
- Fail 
- Not evaluated 

Thermal Hydraulics Requirements Discussed in This Presentation:

Codebeamer Tracker and Link	Requirement
Target Assembly Requirement 1487 https://sts-req.ornl.gov:8443/cb/issue/1487	The system shall have a pressure drop less than 14.5 psi (100 kPa).
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 target Drive shall have a pressure drop of less than 6 psi (42 kPa) at 157.45 gpm (596 L/min).
Shaft Requirement 1691 https://sts-req.ornl.gov:8443/cb/issue/1691	The shaft shall have a pressure drop of less than 6 psi (62 kPa) at 7.5 gpm (28.4 L/min).
Prevent Boling Requirement 1567 https://sts-req.ornl.gov:8443/cb/issue/1567	The target cooling water shall be single-phase (liquid).

Soft Requirement and Assumption

• Soft Requirement (Verified in Day 3: Target Assembly Analysis)

- **Flow balance**: Inlet flow from the **target drive** **uniformly** distributes to 20 **target segments** (20 x 7.5 GPM) and the **target shaft** (1x 7.5 GPM).
- This implies **similar pressure drop** for a **target segment** and the **shaft**

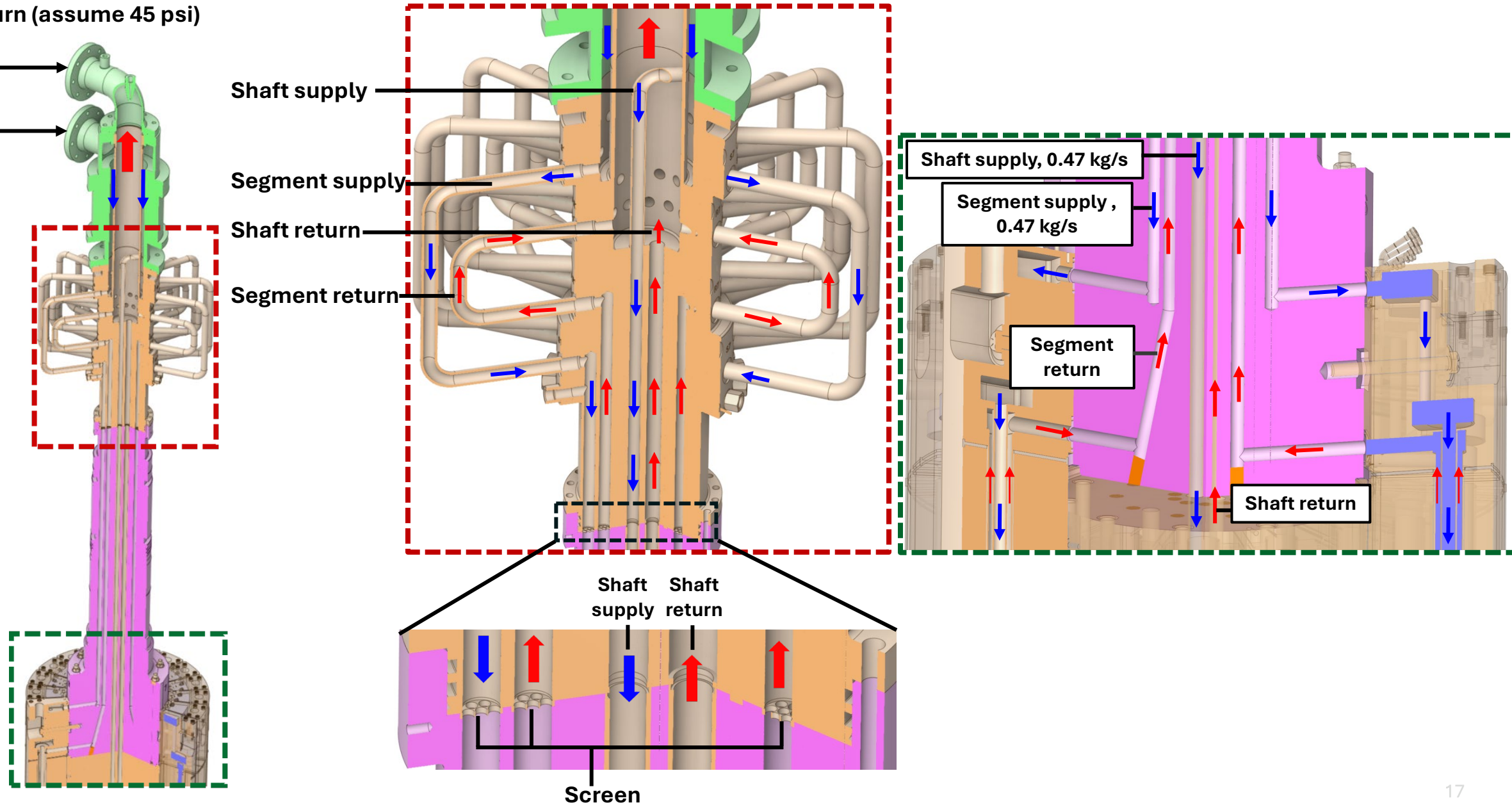
• Assumption

- Instead of a single big CFD model for the whole target assembly, individual components, the **segment** and the **shaft**, are **studied separately**.
 - For faster design evolutions to meet the design requirements
- Target segment: Rotating at 45 RPM
- Target shaft: Rotating at 45 RPM
- **Uniform inlet** mass flow rate for the **target segment** and **shaft**

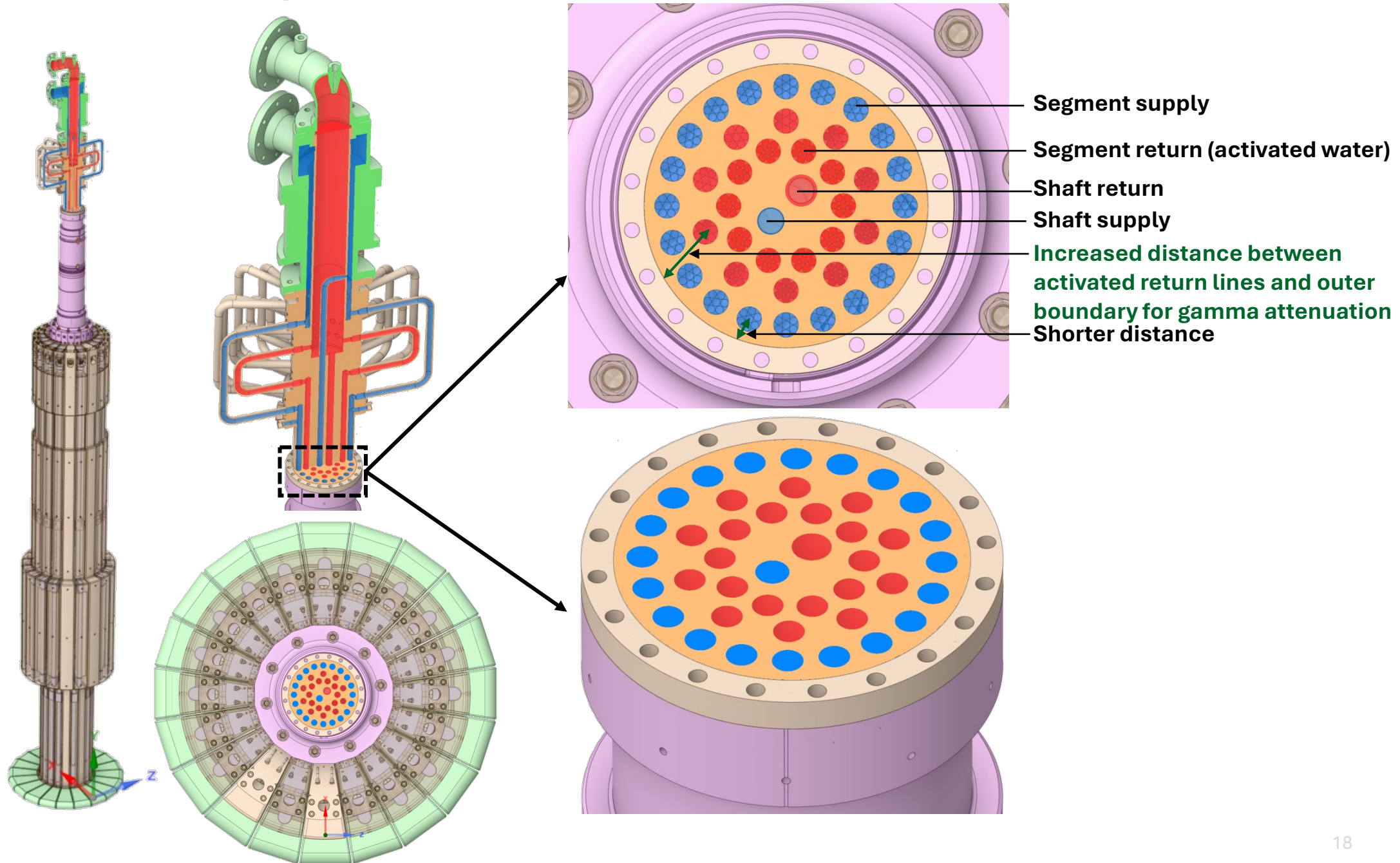
Target Assembly, Flow Direction and Assumption

Supply (32.22°C (90°F) water, 9.87 kg/s (157.5 GPM) = 0.47 kg/s (7.5 GPM)*20 segments + 0.47 kg/s (7.5 GPM) shaft)

Return (assume 45 psi)

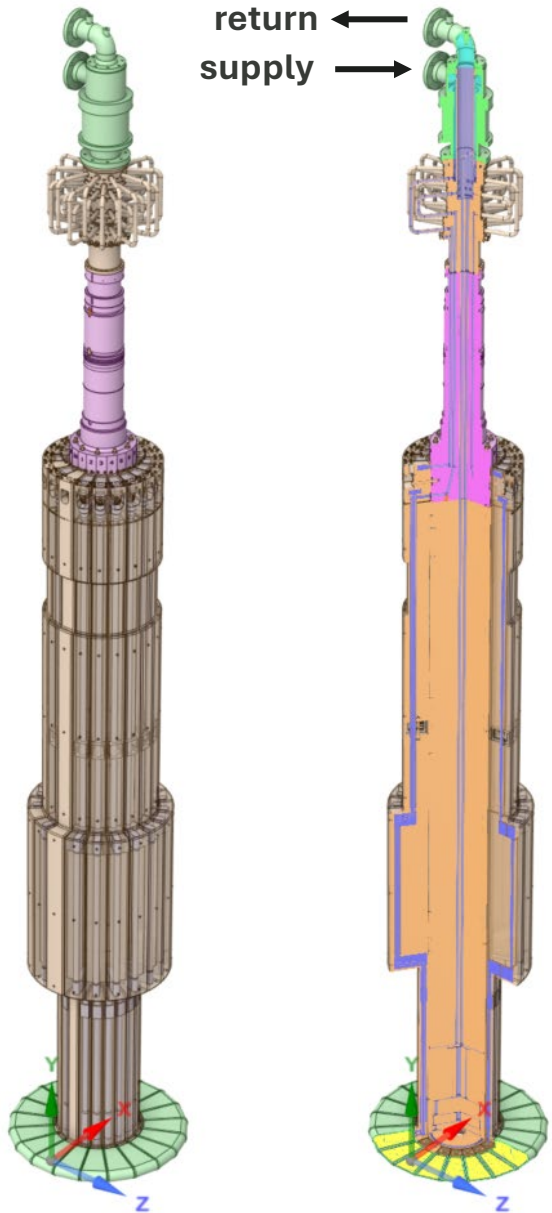


Target Assembly, Flow Direction

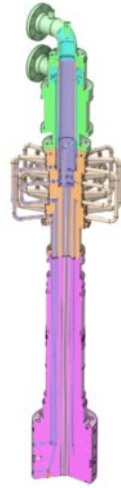


Day 3

Target Assembly

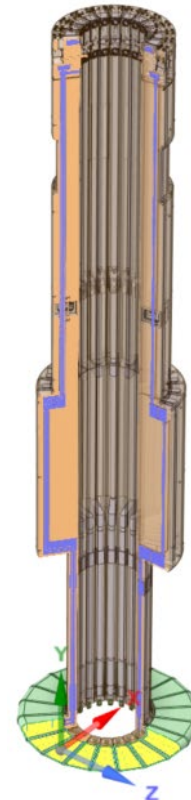


Target Drive



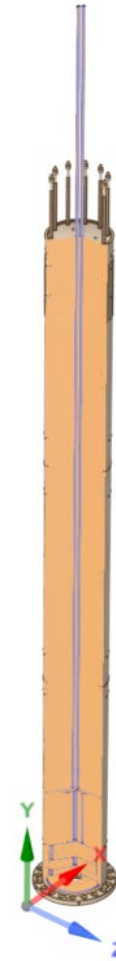
Day 2

Segments



Day 3

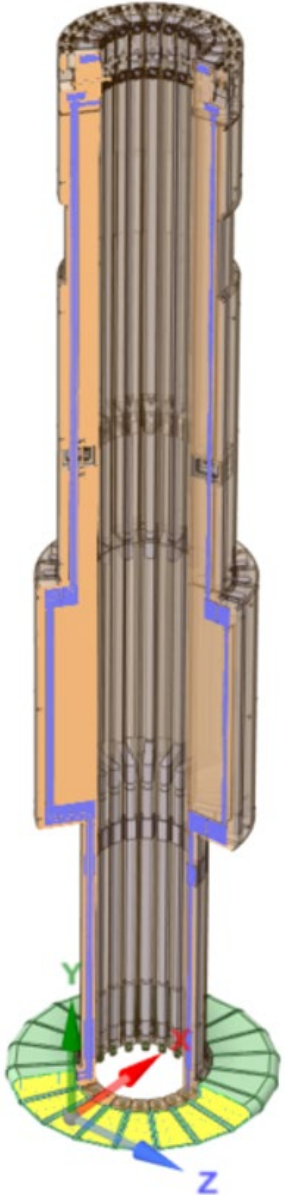
Shaft



Day 2 : Target Segment Analysis

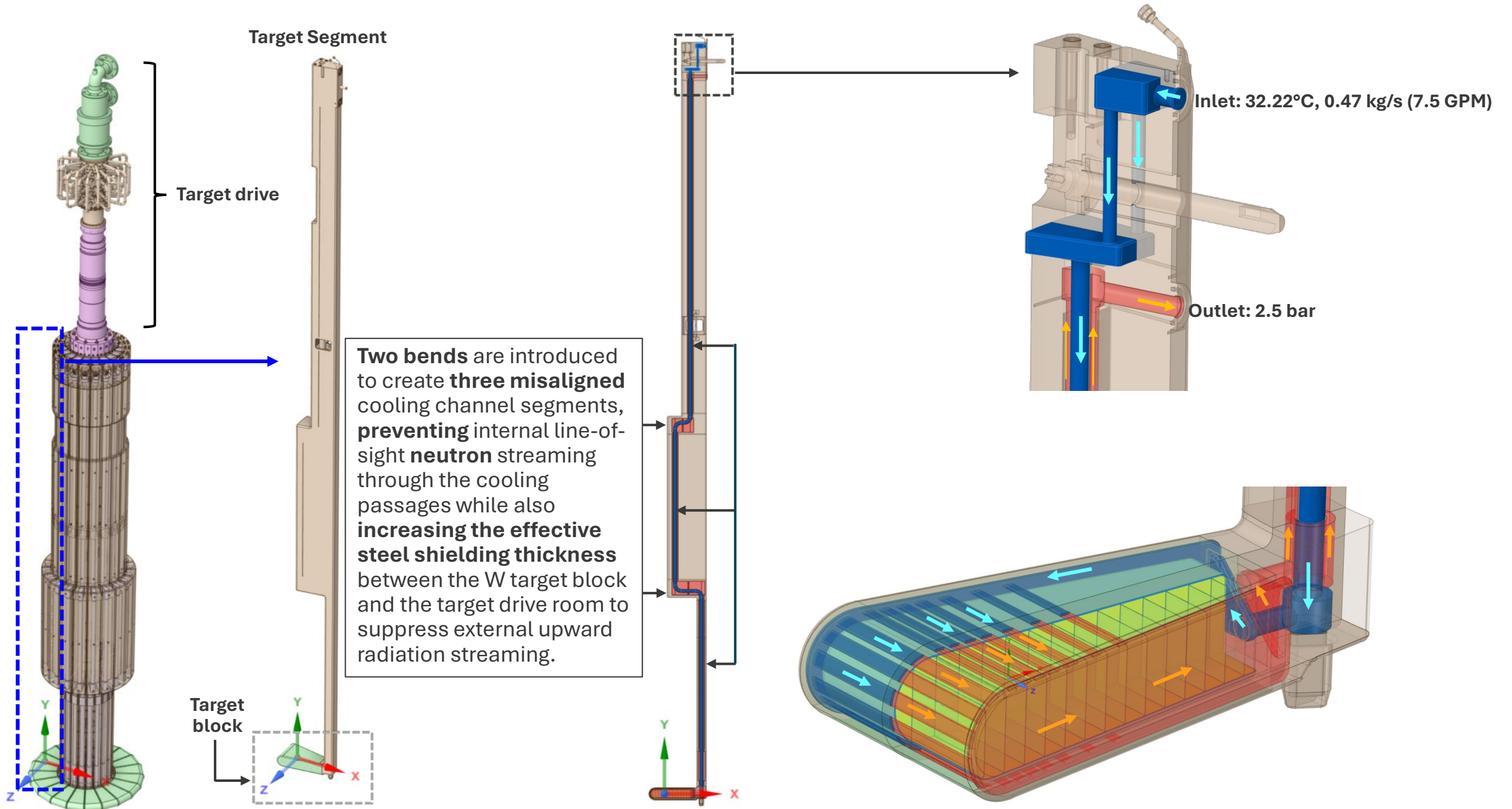
- Geometry
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 - **Maintenance Temperature (Beam Off)**
 - Decay Heat
 - Under Reduced Flow Rate (0.1 & 0.2 GPM) (**Steady State**)
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 - ❖ **Air-cooling for a single segment** ← lower-bound estimate of required flow rate
 - ❖ **Air-cooling for the entire target disk (20 segments)** ← pressure drop required for sufficient flow

Day 2 : Target Segment Analysis

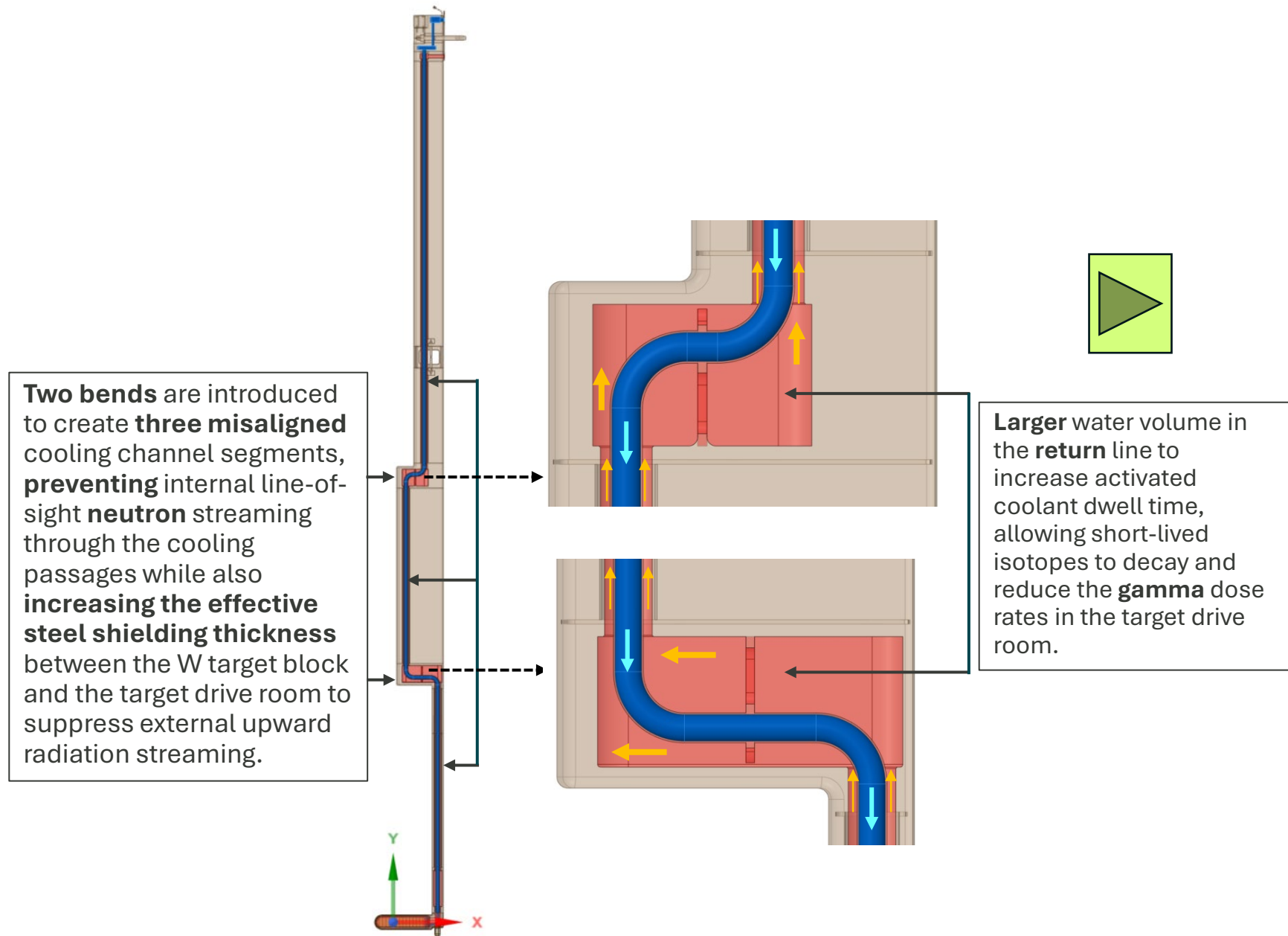


ID	Codebeamer Tracker and Link	Requirement
1602	Target Segment Requirement 1602	The segment shall have a pressure drop less than 9 psi at 7.5 gpm .
	https://sts-req.ornl.gov:8443/cb/issue/1602	
1567	Prevent Boling Requirement 1567	The target cooling water shall be single-phase (liquid).
	https://sts-req.ornl.gov:8443/cb/issue/1567	

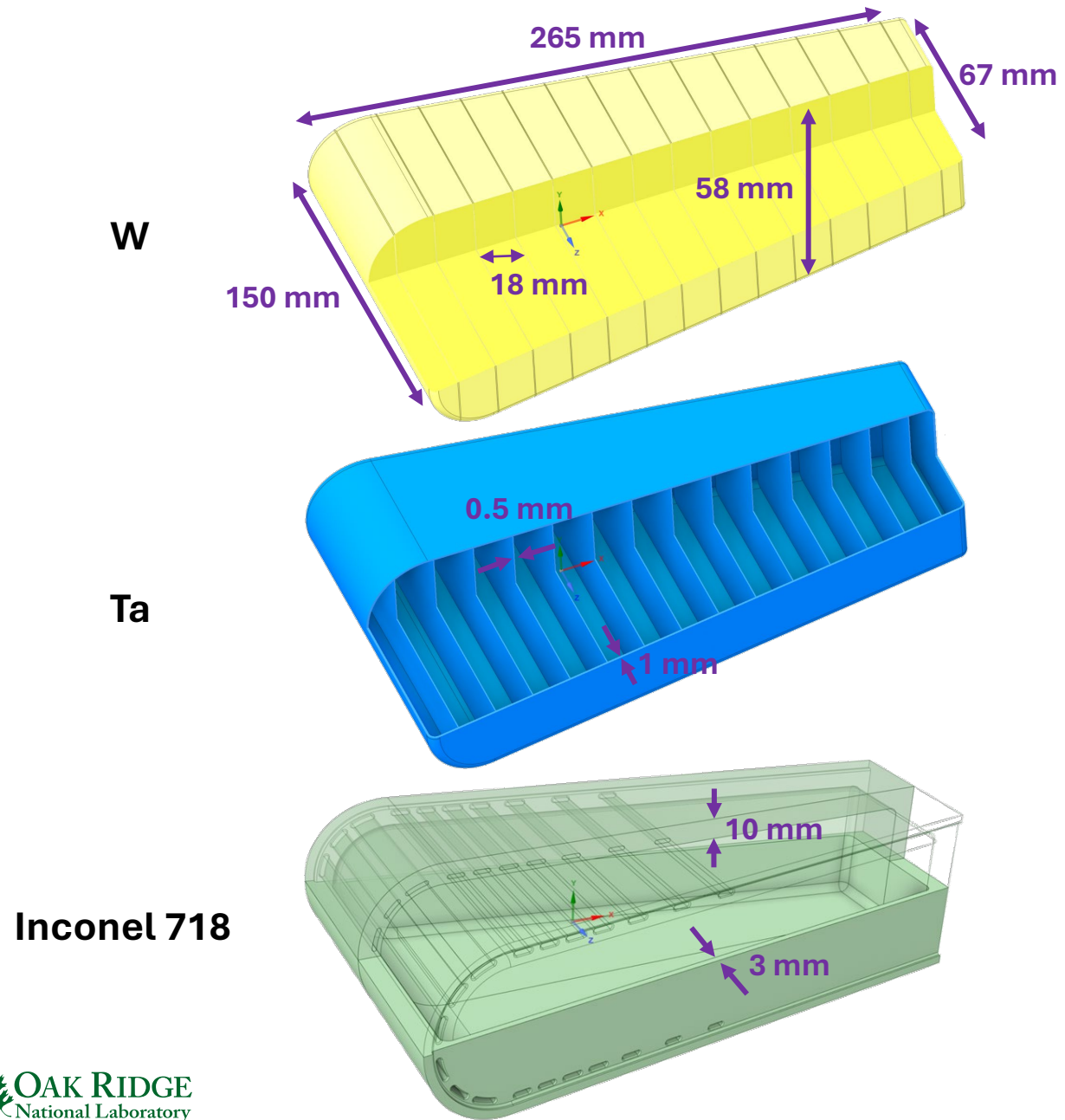
Target Segment, Geometry



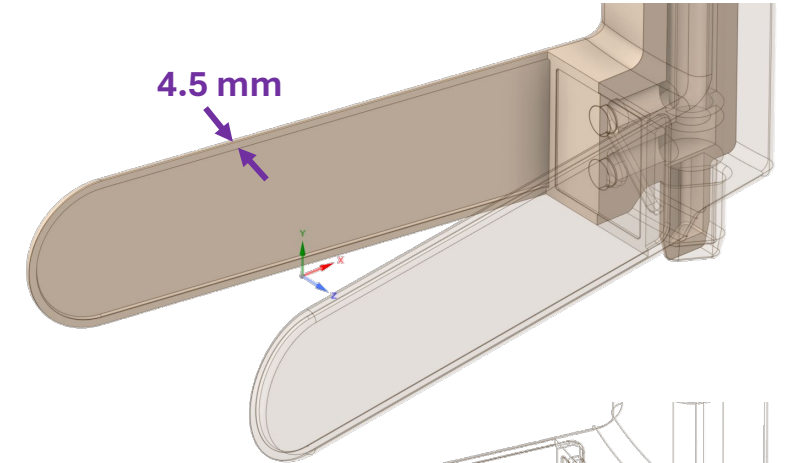
Target Segment, Geometry



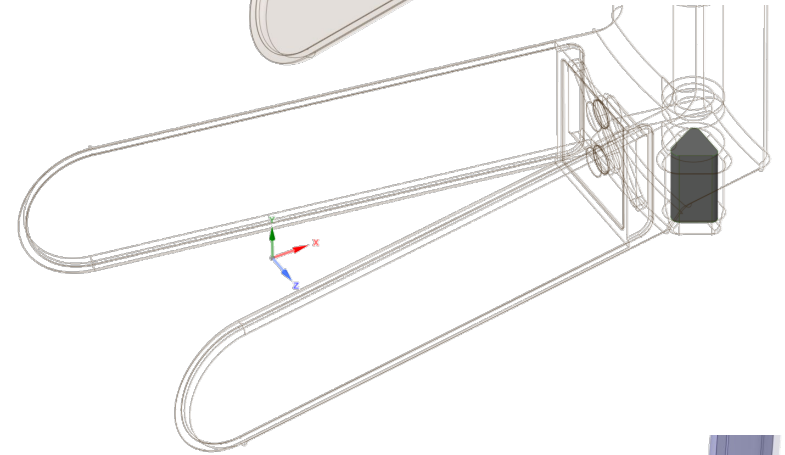
Target Segment, Geometry



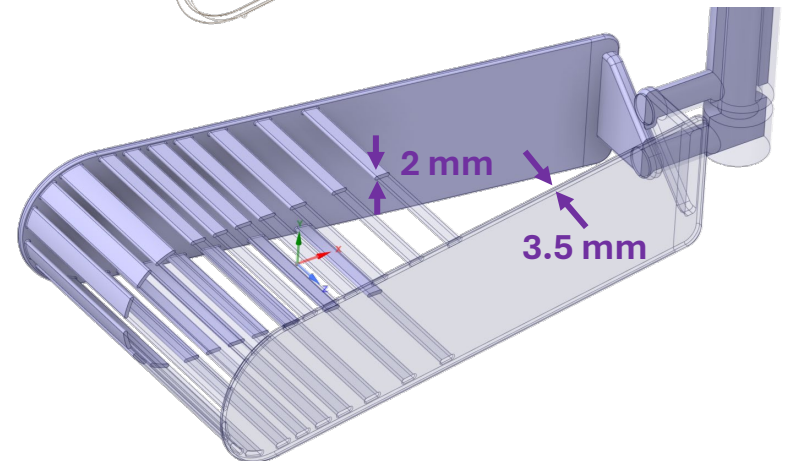
SS



CuCrZr



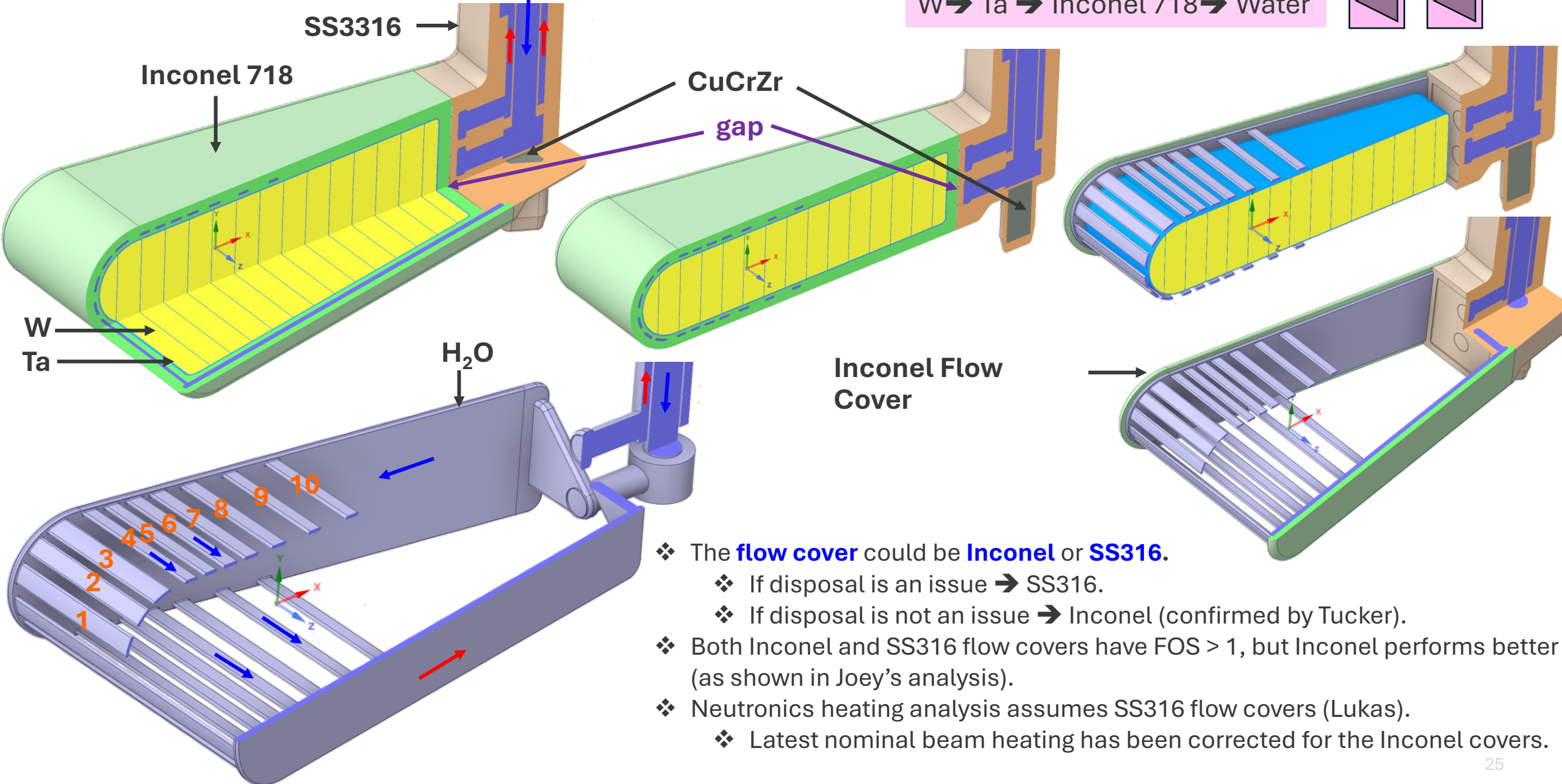
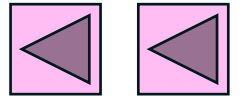
Water



Target Segment, Geometry

32.22°C (90°F) 0.47 kg/s (7.5 GPM)

W → Ta → Inconel 718 → Water



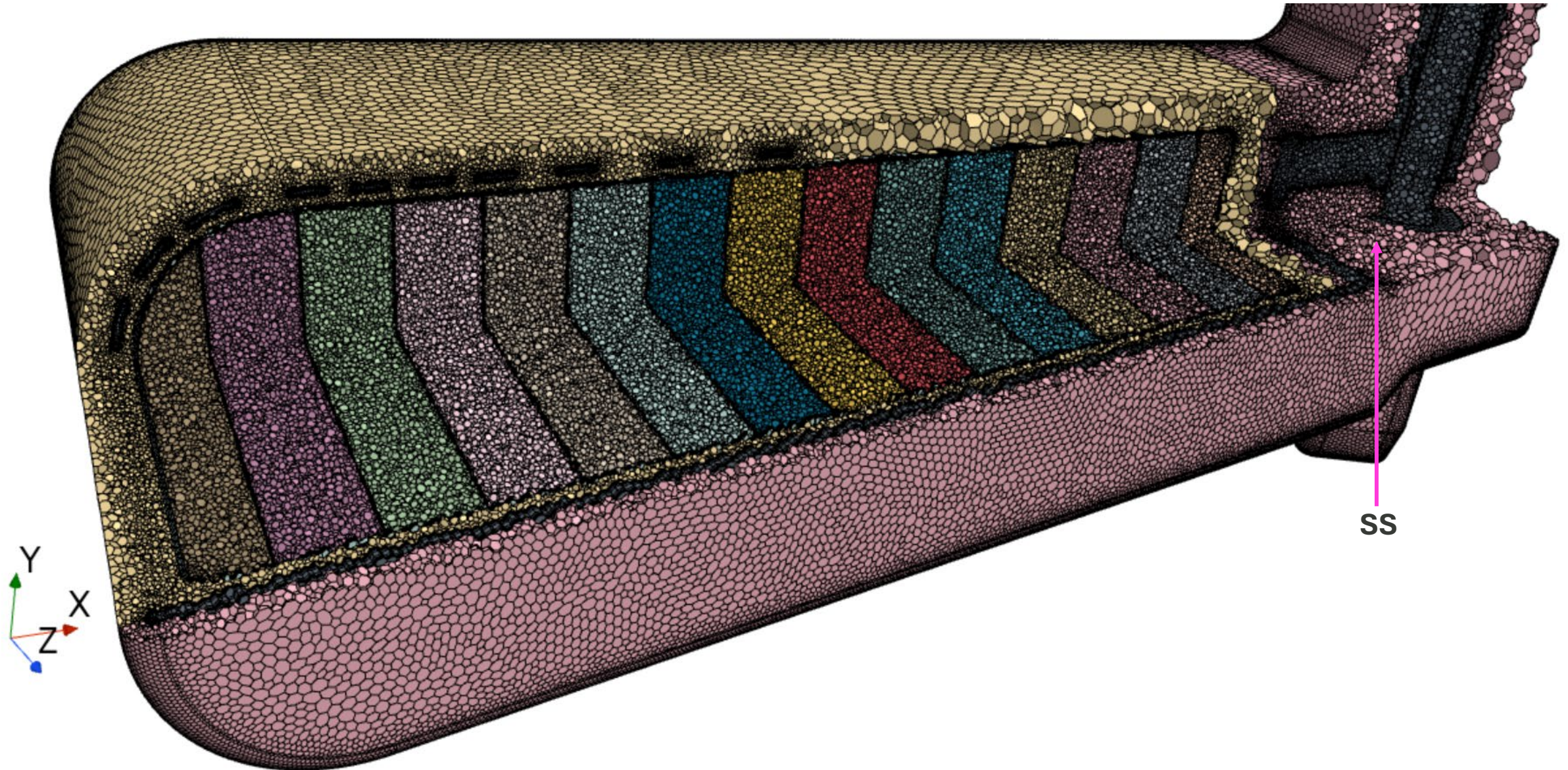
- ❖ The **flow cover** could be **Inconel** or **SS316**.
 - ❖ If disposal is an issue → SS316.
 - ❖ If disposal is not an issue → Inconel (confirmed by Tucker).
- ❖ Both Inconel and SS316 flow covers have FOS > 1, but Inconel performs better (as shown in Joey's analysis).
- ❖ Neutronics heating analysis assumes SS316 flow covers (Lukas).
 - ❖ Latest nominal beam heating has been corrected for the Inconel covers.

Material Property

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
Cu (irradiated)	368	8950	385	N/A
Inconel 718	11.4	8190	435	N/A
SS 316	14.58	7969	486.1	N/A
CuCrZr	323.4	8890	376	N/A
H ₂ O	0.620271	997.561	4181.72	8.89E-04

- CuCrZr was no longer in the latest FDR design but 90% of results in this presentation came from the model with CuCrZr.

Target Segment, Mesh Configuration



Number of meshes: 15,018,873

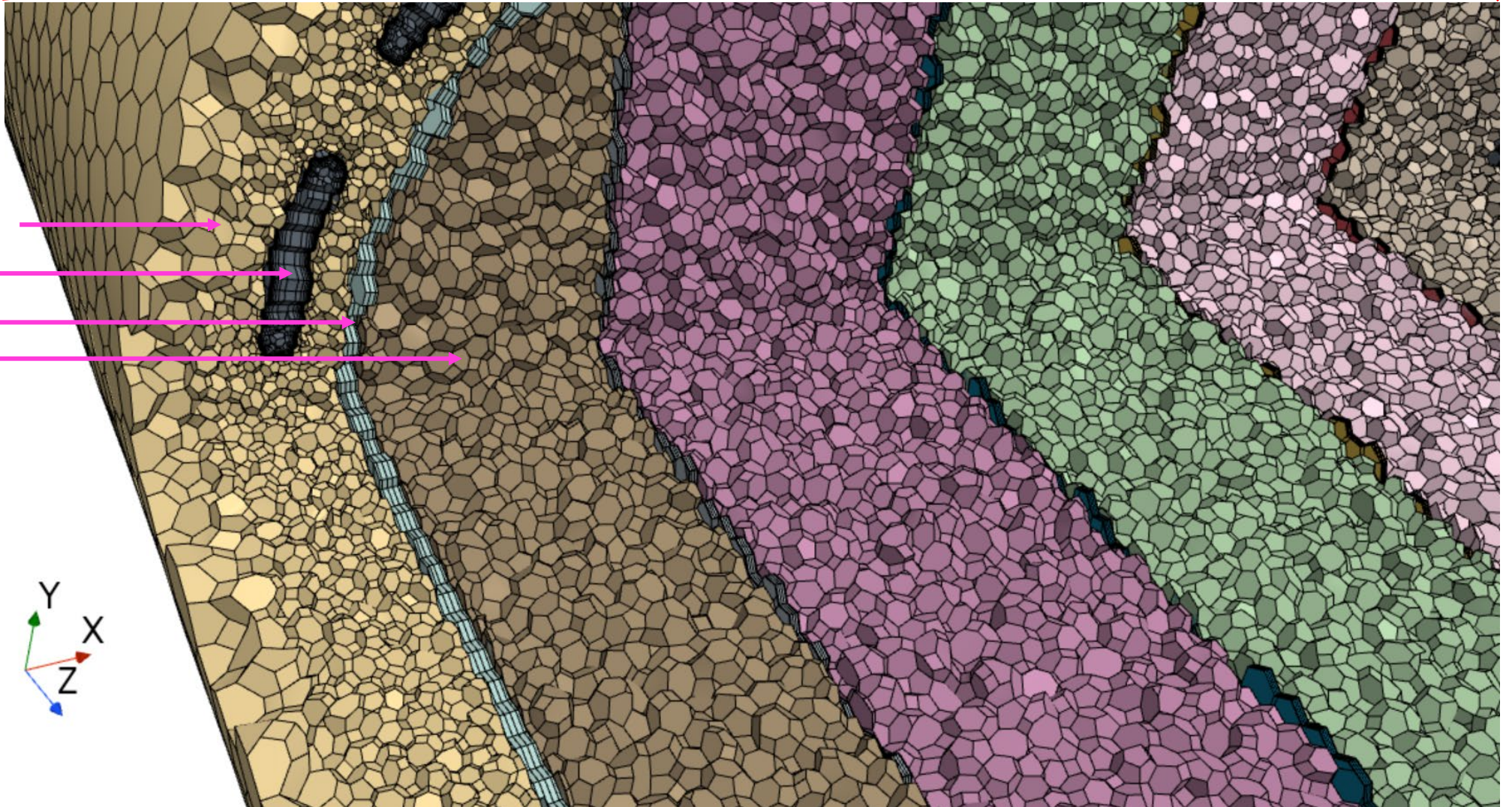
Target Segment, Mesh Configuration

Inconel 718

Water

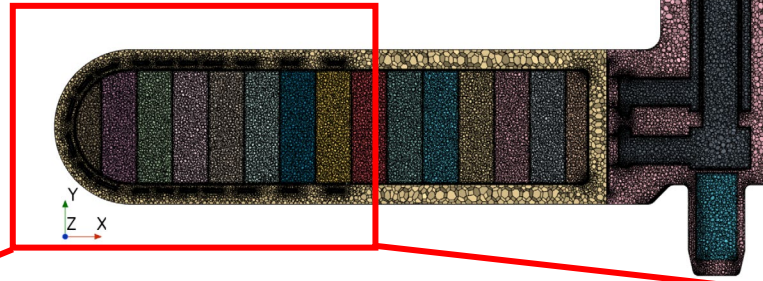
Ta

W

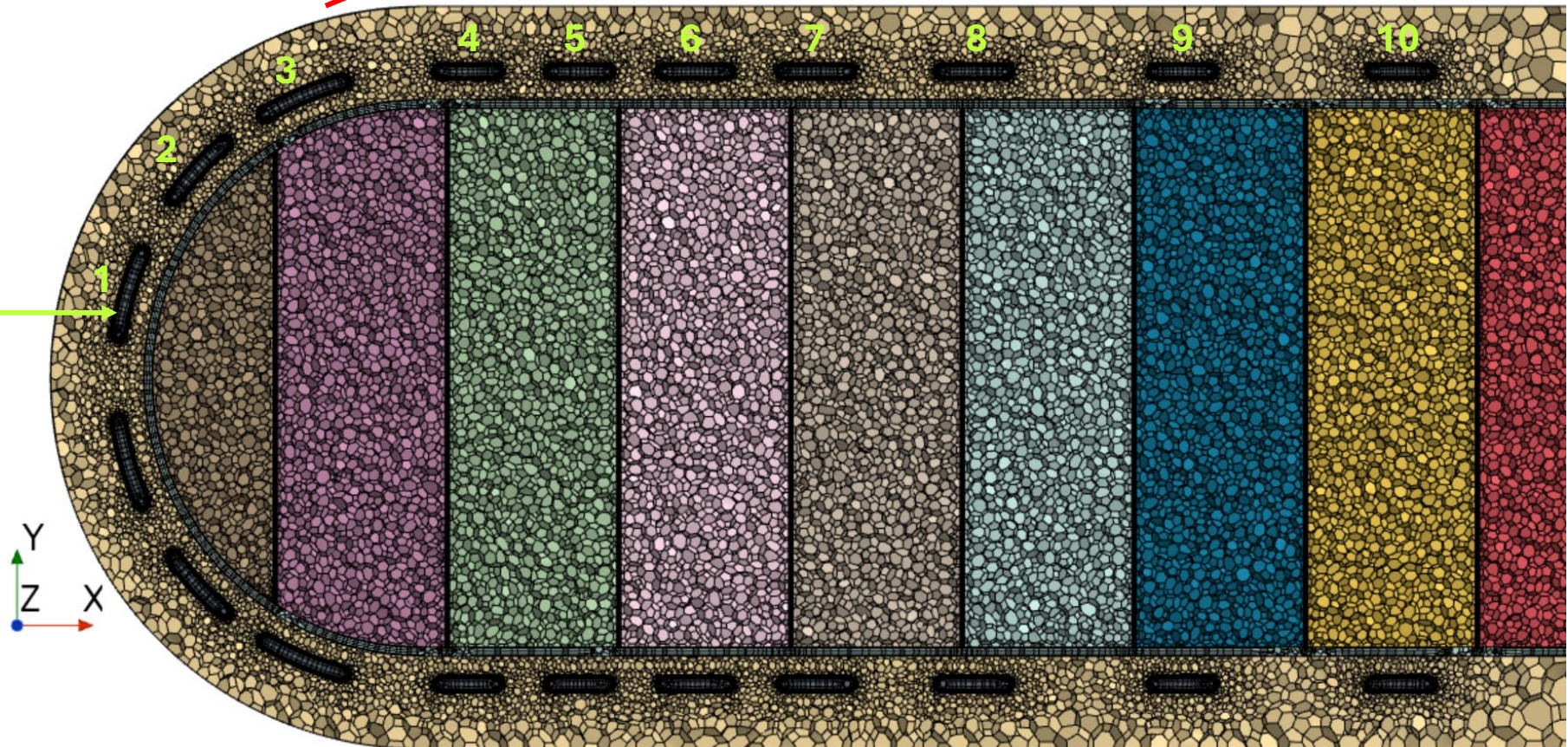


Number of meshes: 13,835,365

Target Segment, Mesh Configuration

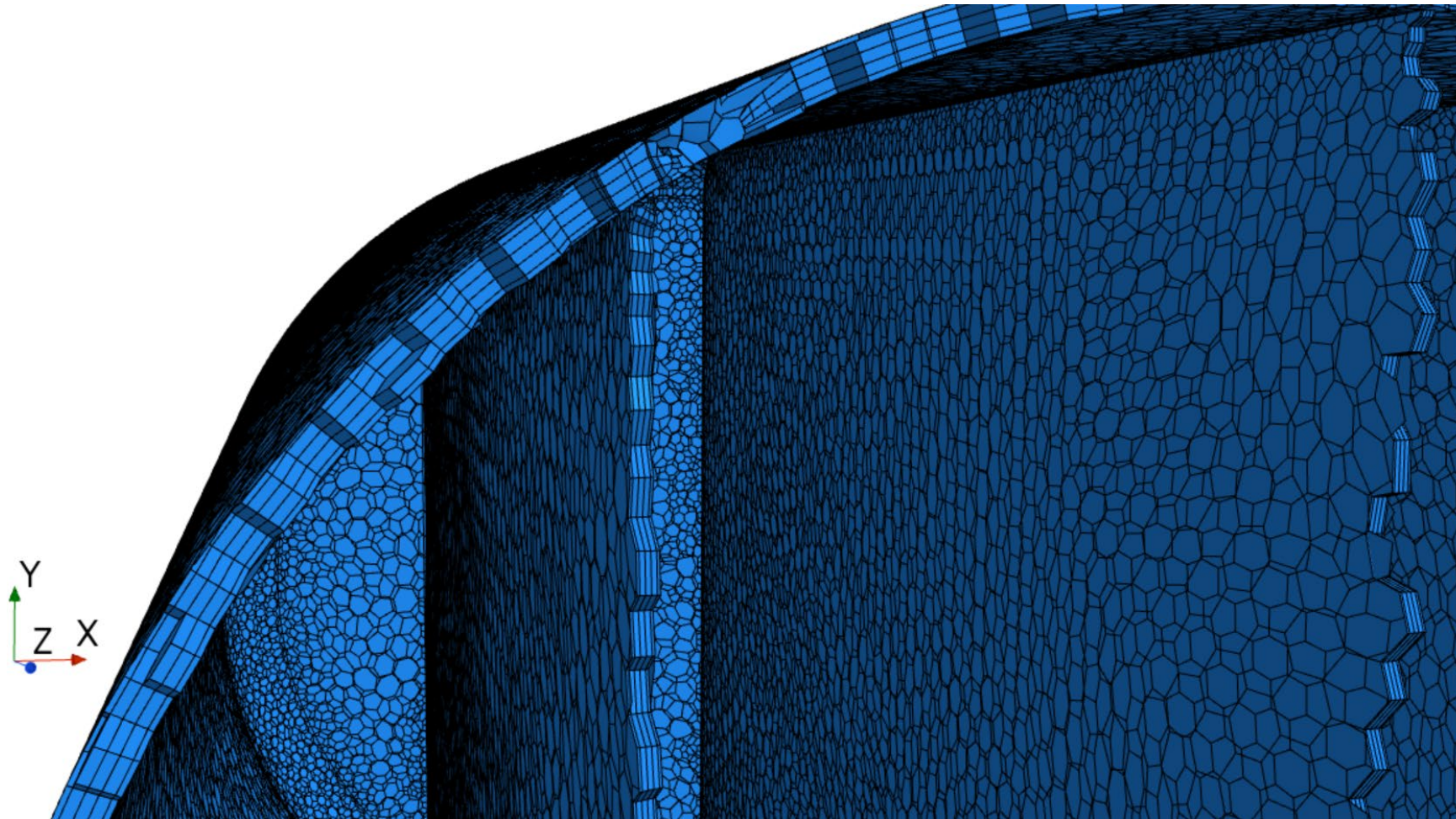


Cooling Channel



Target Segment, Mesh Configuration

water

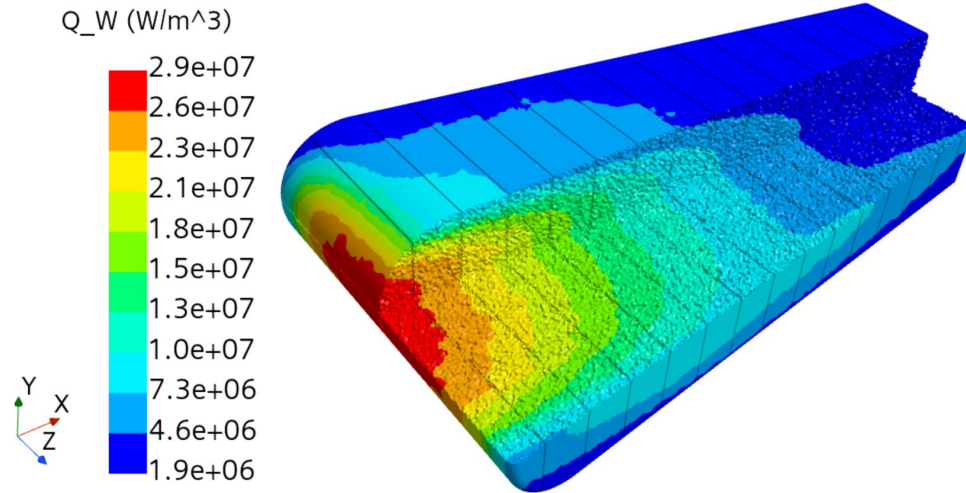


Target Segment, Heat Source

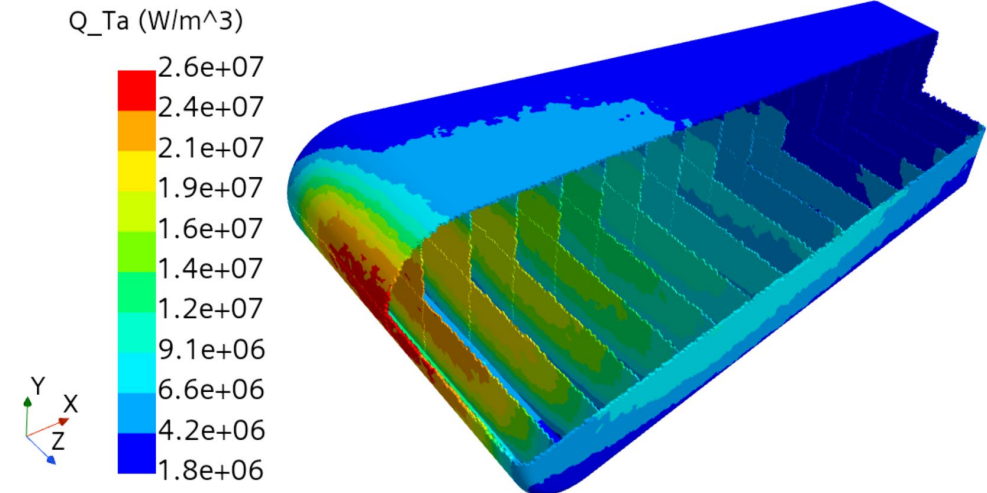
Nominal Beam

Heat Source Calculation done by Lukas Zavorka

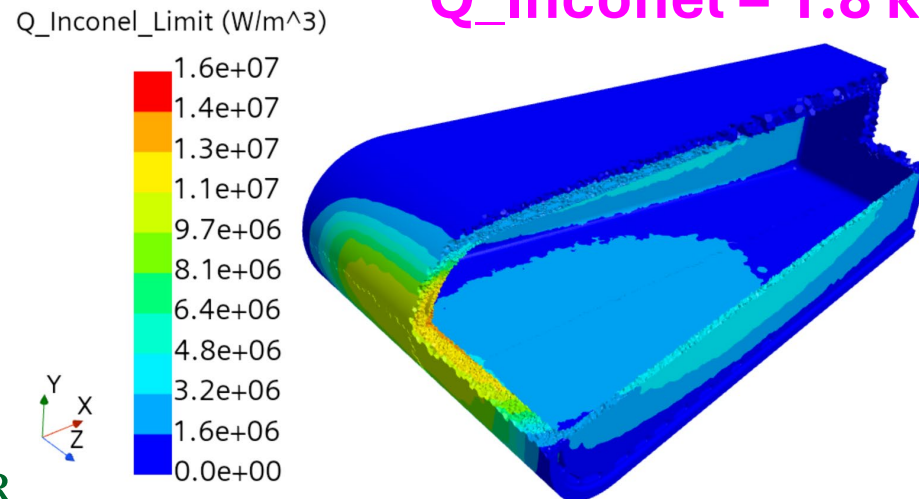
$Q_W = 14.6 \text{ kW}$



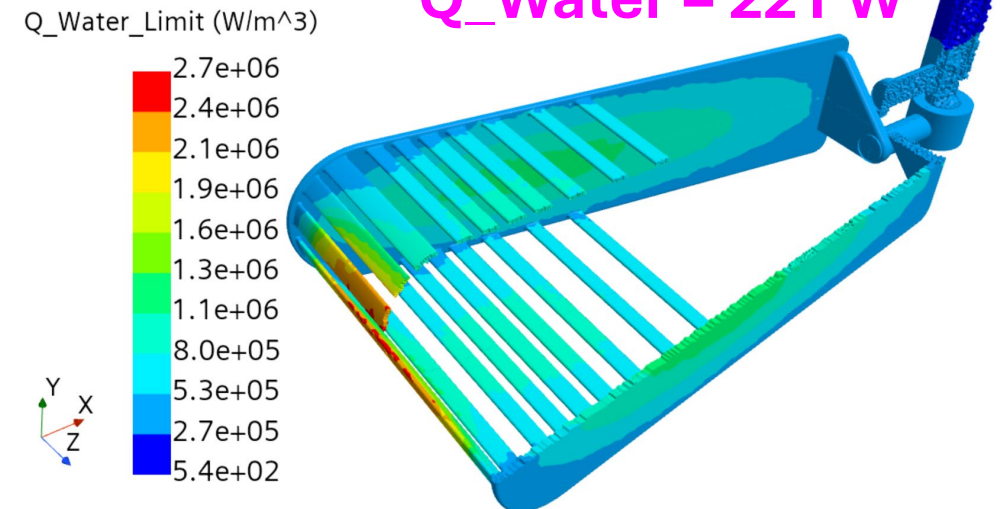
$Q_{Ta} = 877 \text{ W}$



$Q_{Inconel} = 1.8 \text{ kW}$



$Q_{Water} = 221 \text{ W}$



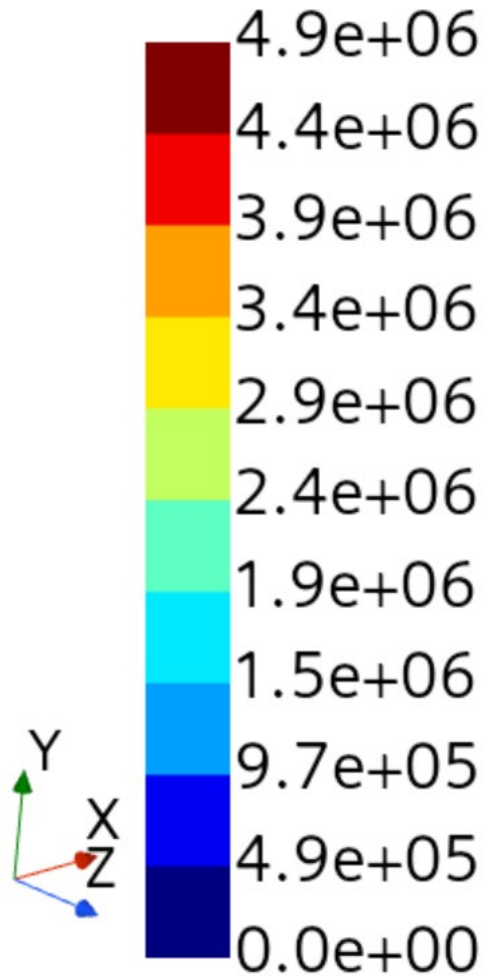
Target Segment, Heat Source

Nominal Beam

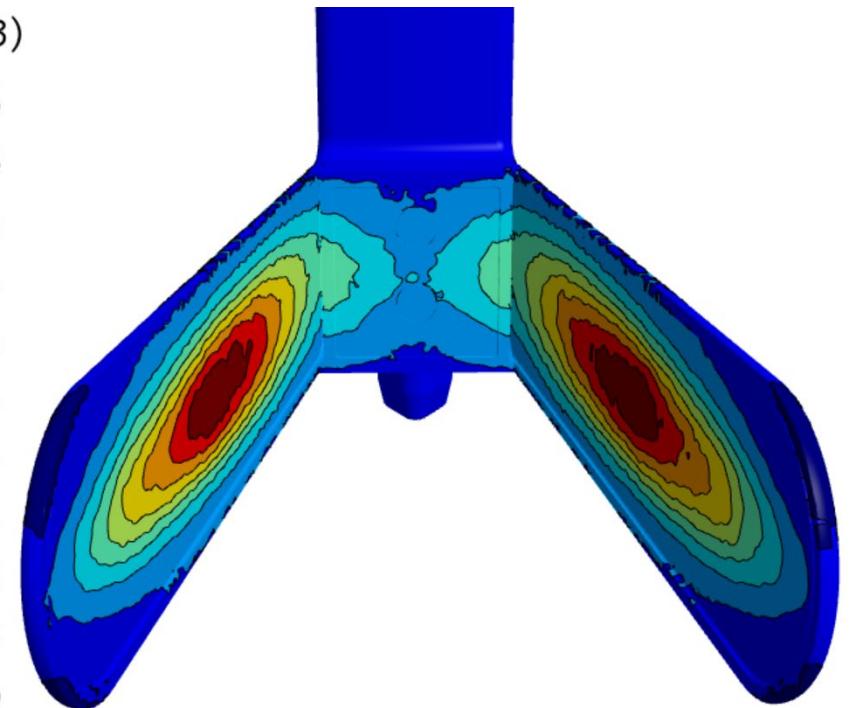
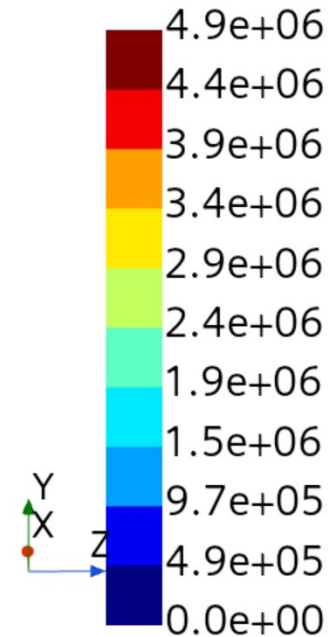
Heat Source Calculation done by Lukas Zavorka

$$Q_{SS316} = 1380 \text{ W}$$

$Q_{SS_Limit} \text{ (W/m}^3\text{)}$



$Q_{SS_Limit} \text{ (W/m}^3\text{)}$

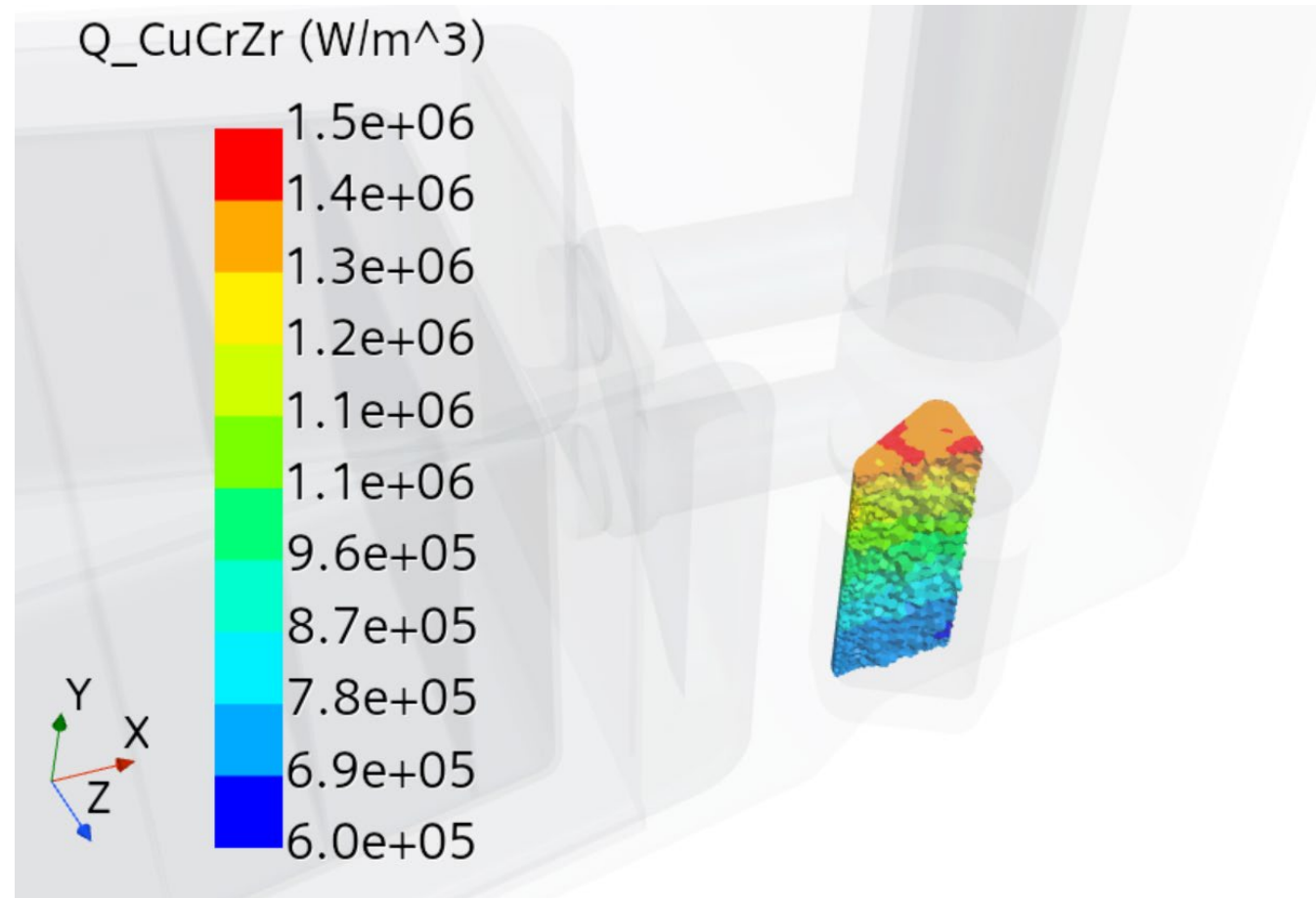


Target Segment, Heat Source

Nominal Beam

Heat Source Calculation done by Lukas Zavorka

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



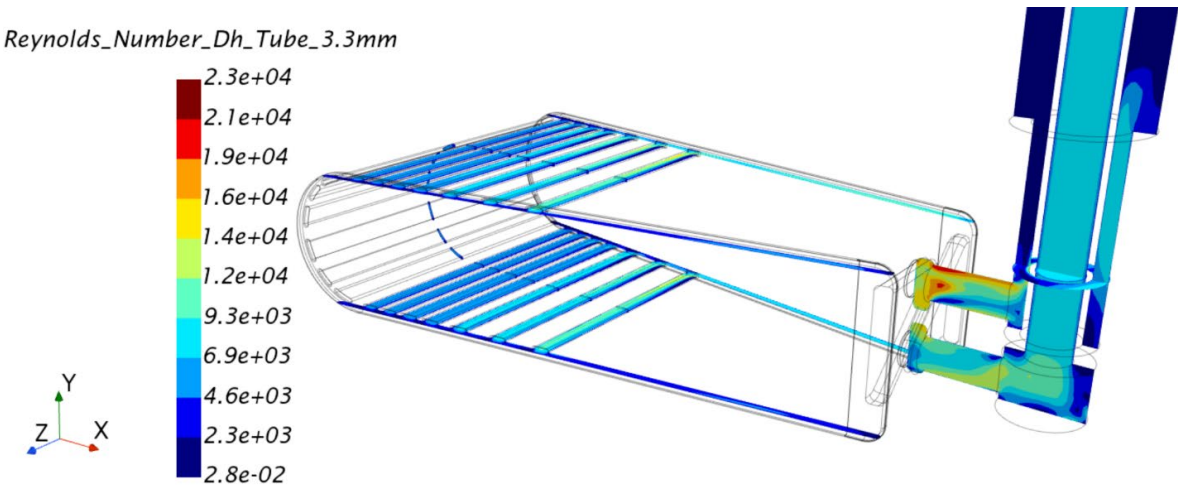
Steady State Heat Transfer Analysis for Target Segment, Solver and Boundary Conditions

Solver

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

↑
Pressure at the target block elevation

Reynolds Number in Target Segment



Target Segment, Heat Source Summary

Nominal Beam

12/18/2025

Latest Design

Inconel 718 Flow Covers		
Material	Heat (W)	%
W	14,643	77.4
Ta	874	4.6
Inconel	2,245	11.9
SS	952	5.0
Water	215	1.1
Total	18,929	100.0

1 segment → 18.9 kW = **2.7%** of 700 kW

20 segments → 378.6 kW = **54.1%** of 700 kW

08/12/2025

Previously Design Documented in FDR Report

SS316 Flow Covers		
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	0.1
Total	18,905	100.0

Target Segment, Water Pressure

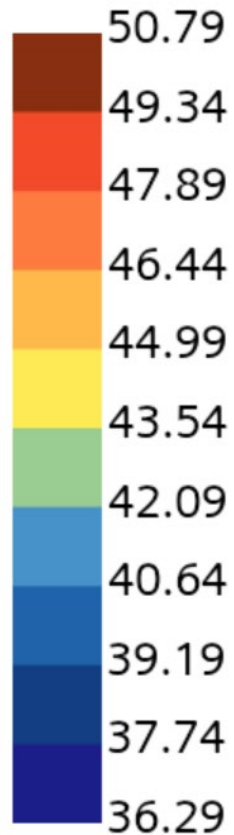
ID	Codebeamer Tracker and Link	Requirement
1602	Target Segment Requirement 1602	The segment shall have a pressure drop less than 9 psi at 7.5 gpm.
	https://sts-req.ornl.gov:8443/cb/issue/1602	

1602

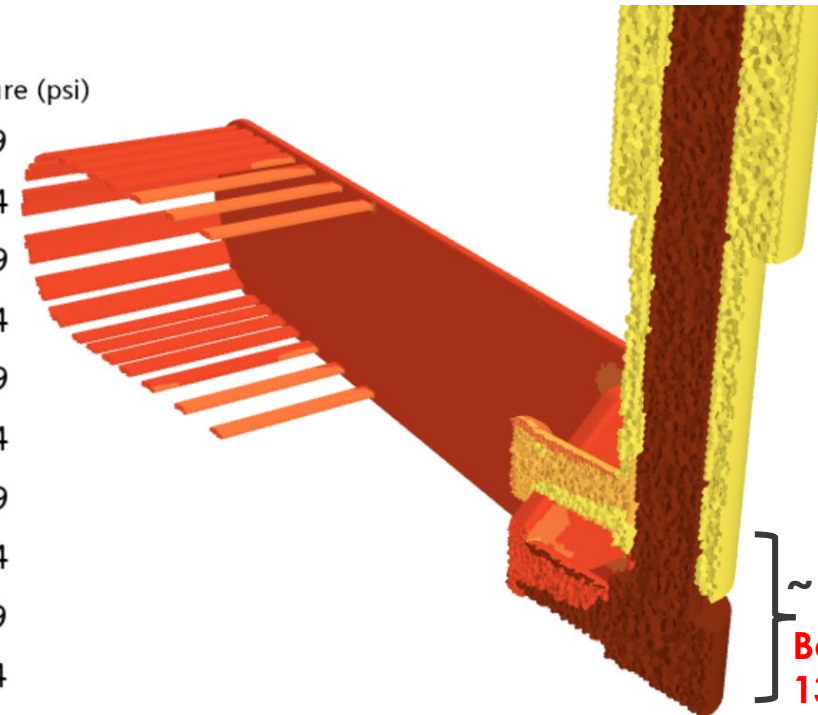
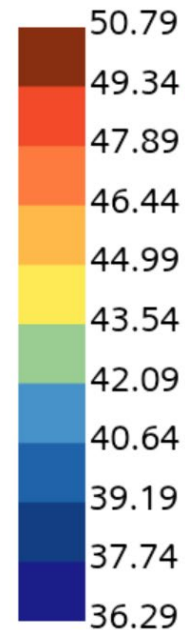
$$\Delta P_{inlet-outlet} = 0.58 \text{ bar} (= 58.0 \text{ kPa} = 8.42 \text{ psi} = 0.57 \text{ atm})$$

Absolute Total Pressure (psi) ← Inlet (0.47 kg/s, 32.22°C) (7.5 GPM)

→ Outlet



Absolute Total Pressure (psi)



~ 3 bar

Boiling temperature:
133.5°C

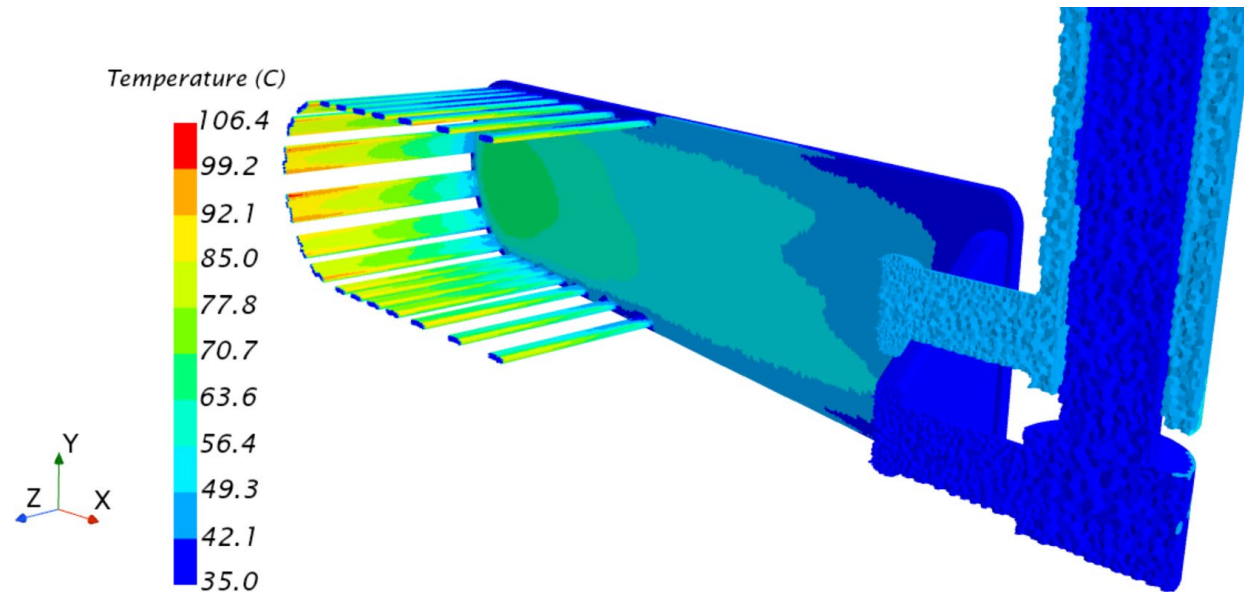
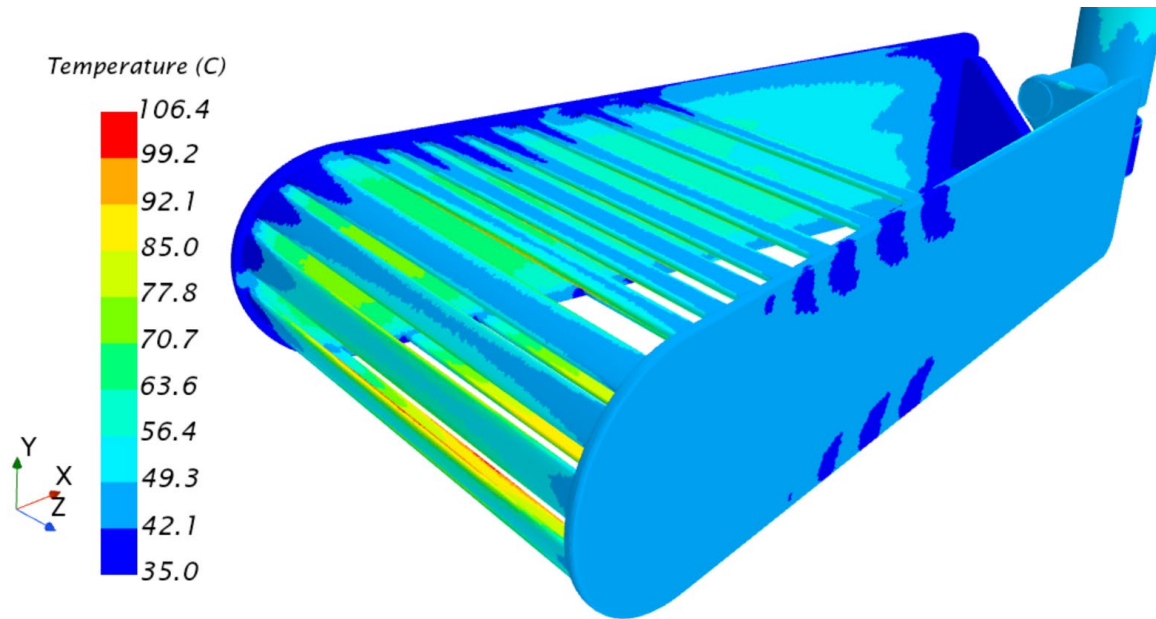
Target Segment, Water Temperature

Nominal Beam

ID	Codebeamer Tracker and Link	Requirement
1567	Prevent Boling Requirement 1567	The target cooling water shall be single-phase (liquid) .
	https://sts-req.ornl.gov:8443/cb/issue/1567	

1567

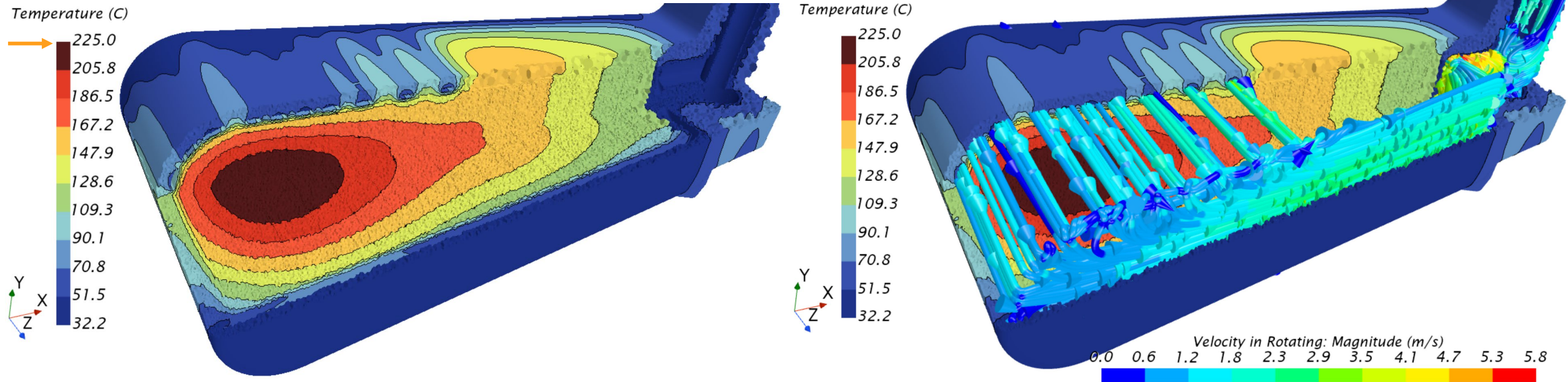
Peak : 106.4°C (Boiling point, 133.5°C @ 3bar)



Target Segment, Temperature

Nominal Beam

SS316 Flow Covers



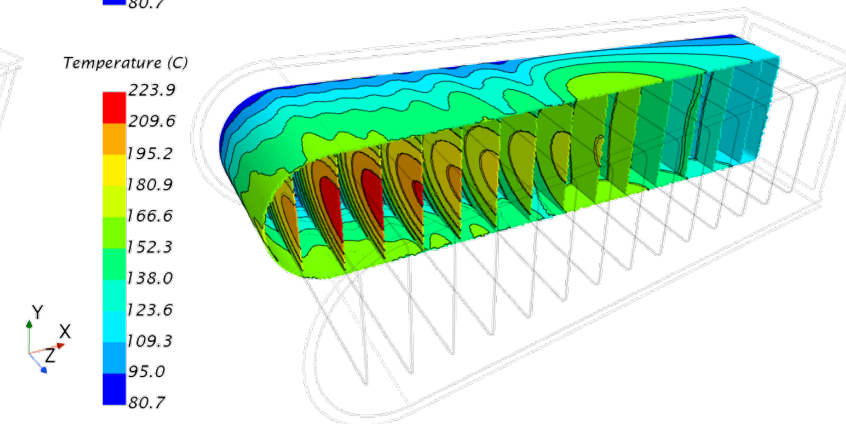
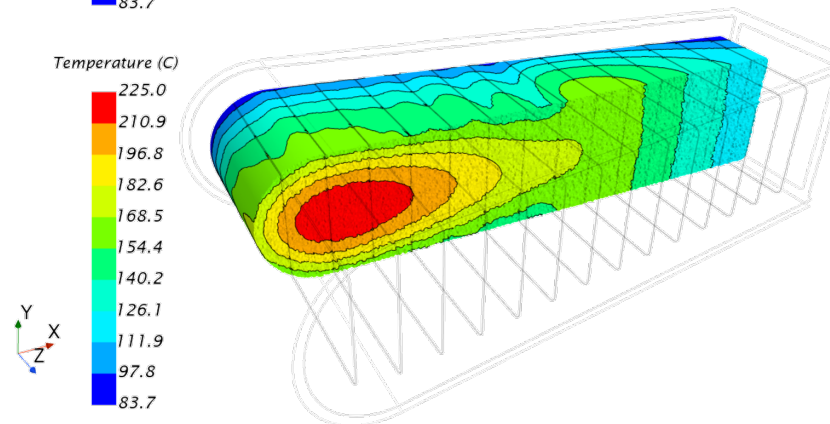
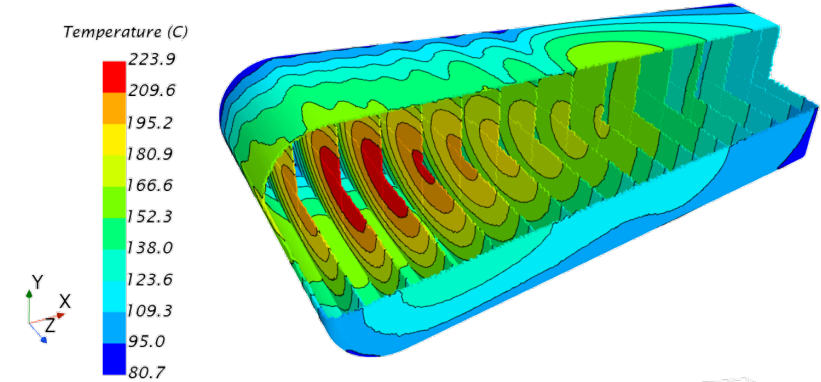
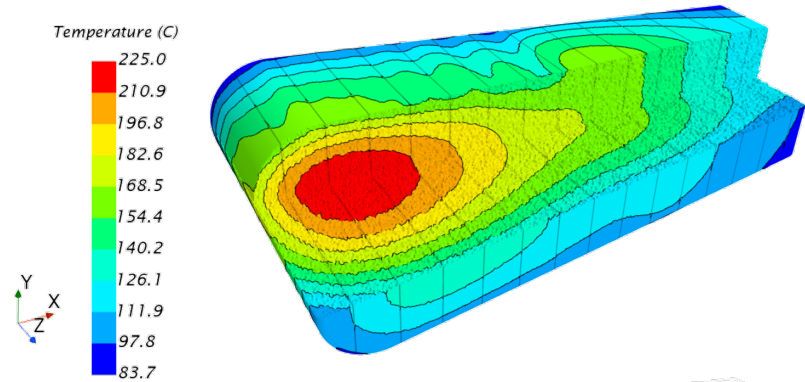
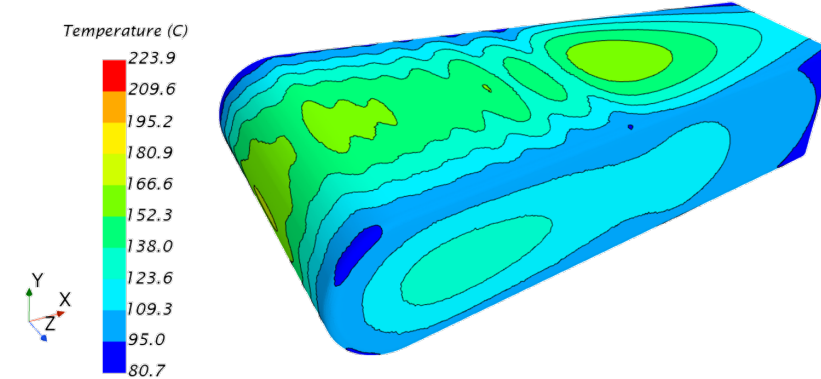
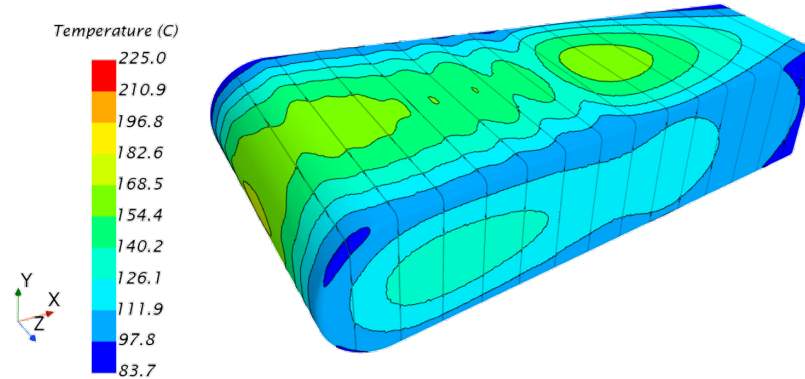
Target Segment, Temperature

Nominal Beam

SS316 Flow Covers

W Temperature
Peak 225.0 °C

Ta Temperature
Peak 223.9 °C

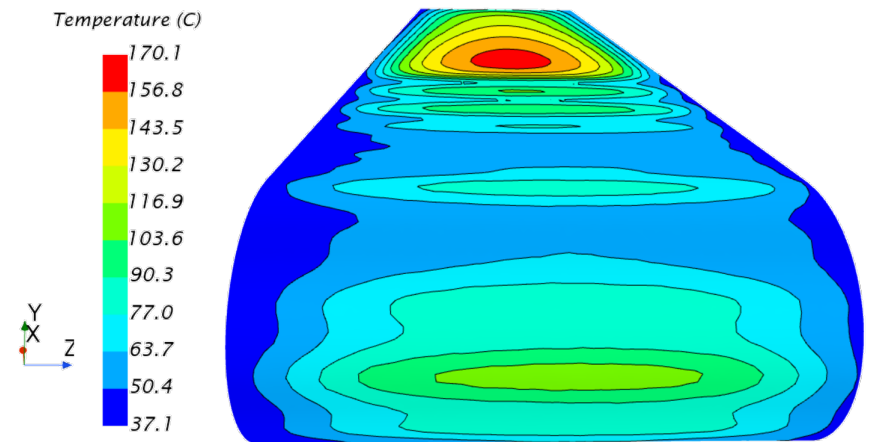
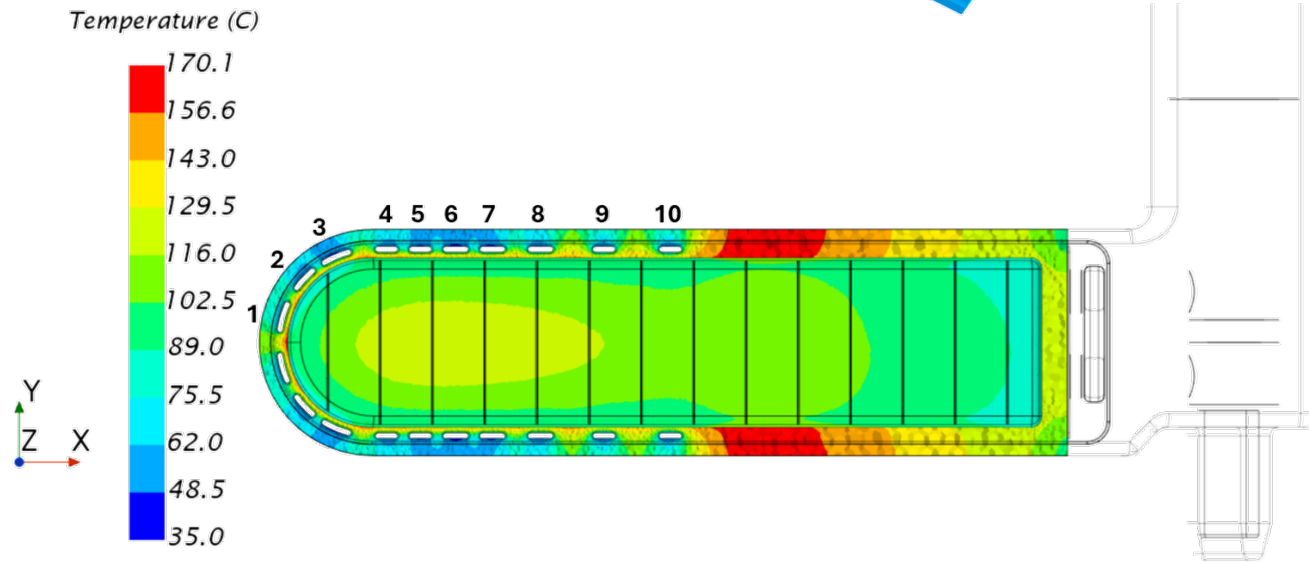
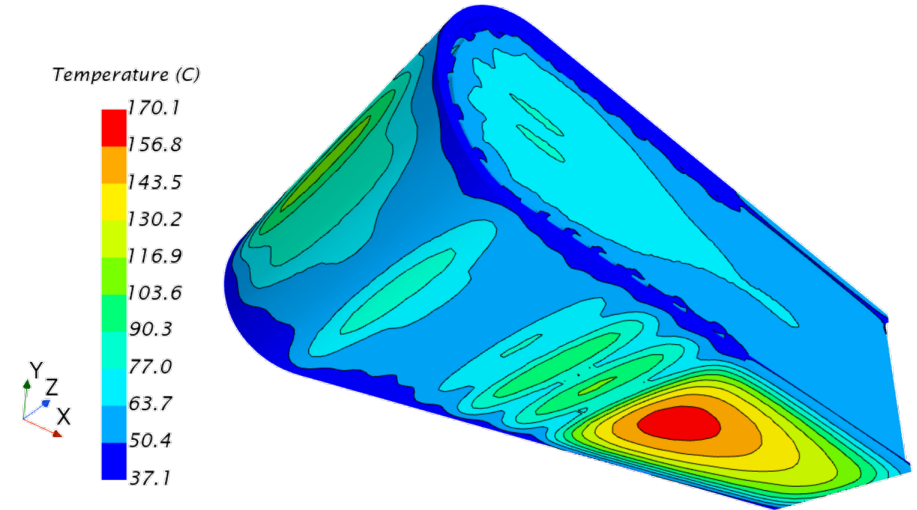
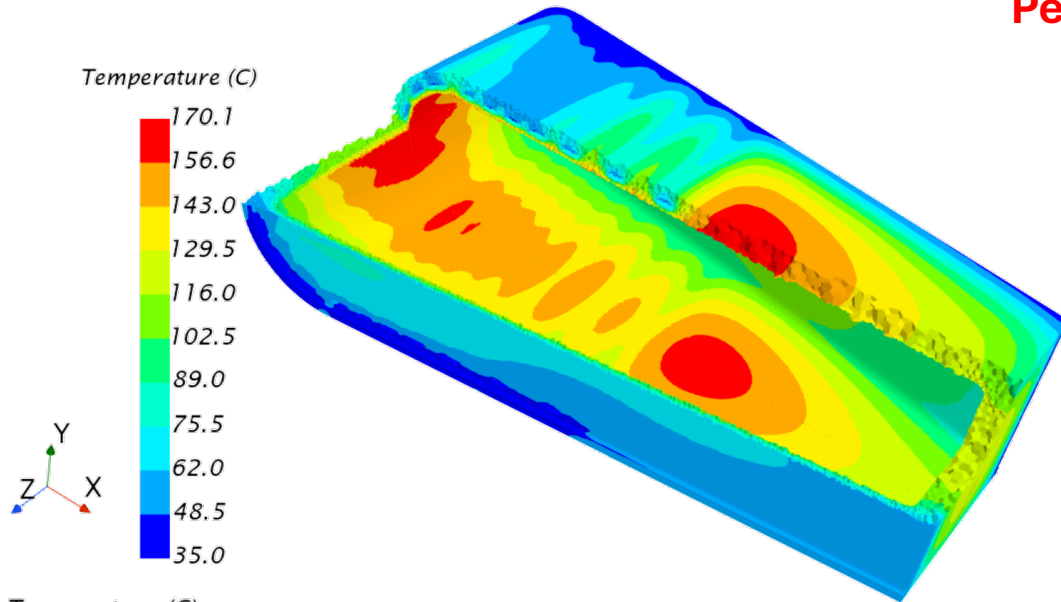


Target Segment, Temperature

Inconel Temperature
Peak 170.1 °C

Nominal Beam

SS316 Flow Covers



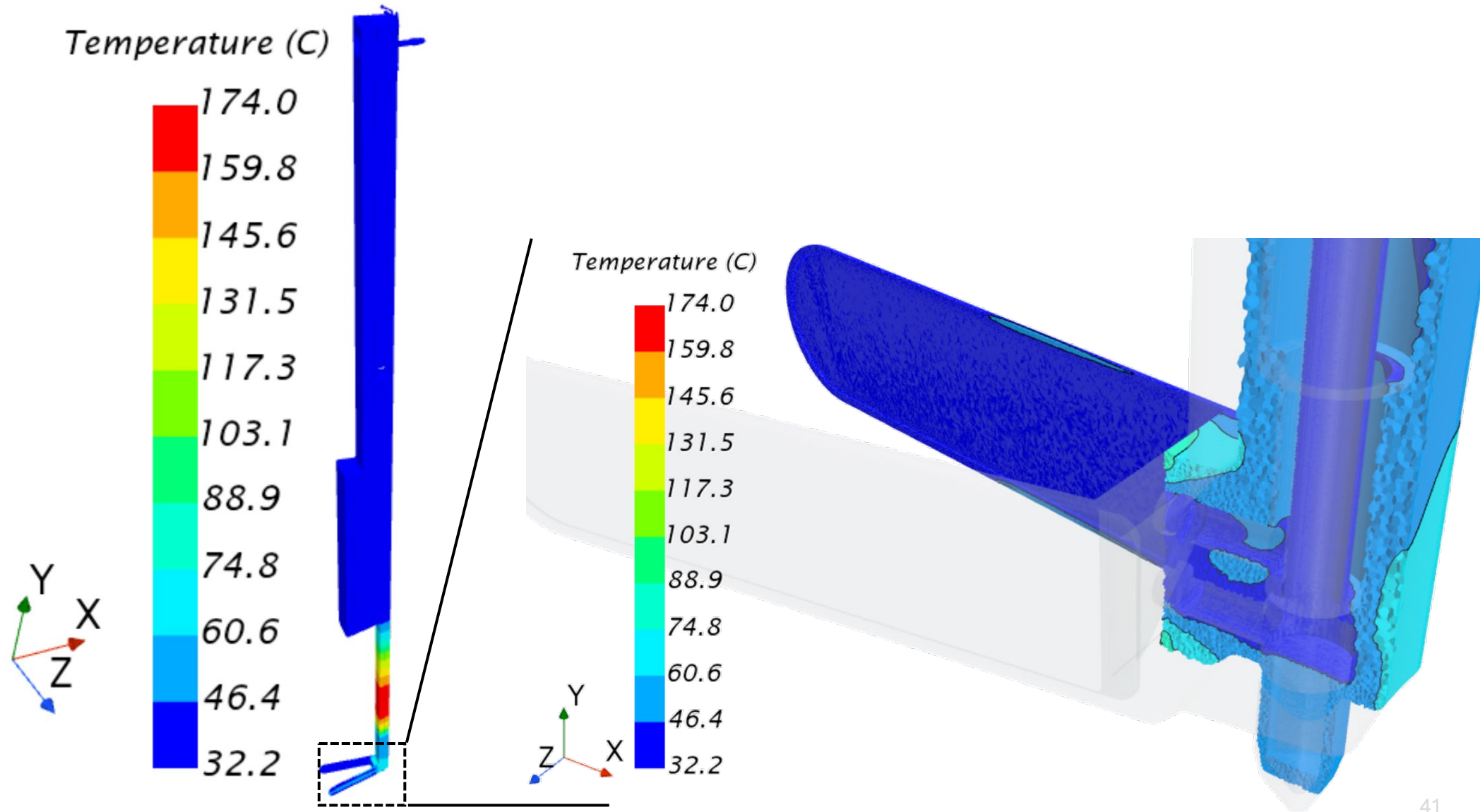
Target Segment, Temperature

Nominal Beam

SS316 Flow Covers

SS316 Temperature

Peak 174.0 °C



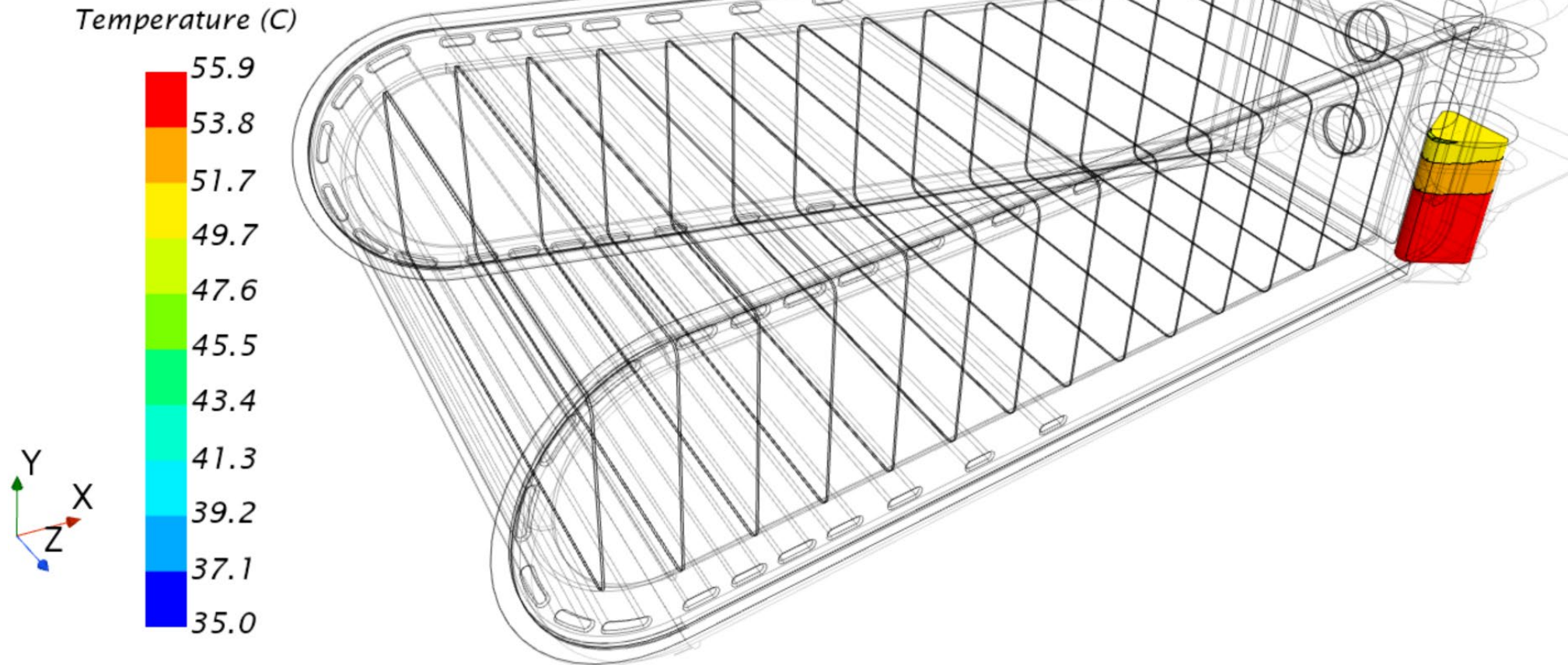
Target Segment, Temperature

Nominal Beam

SS316 Flow Covers

CuCrZr Temperature

Peak 55.9 °C

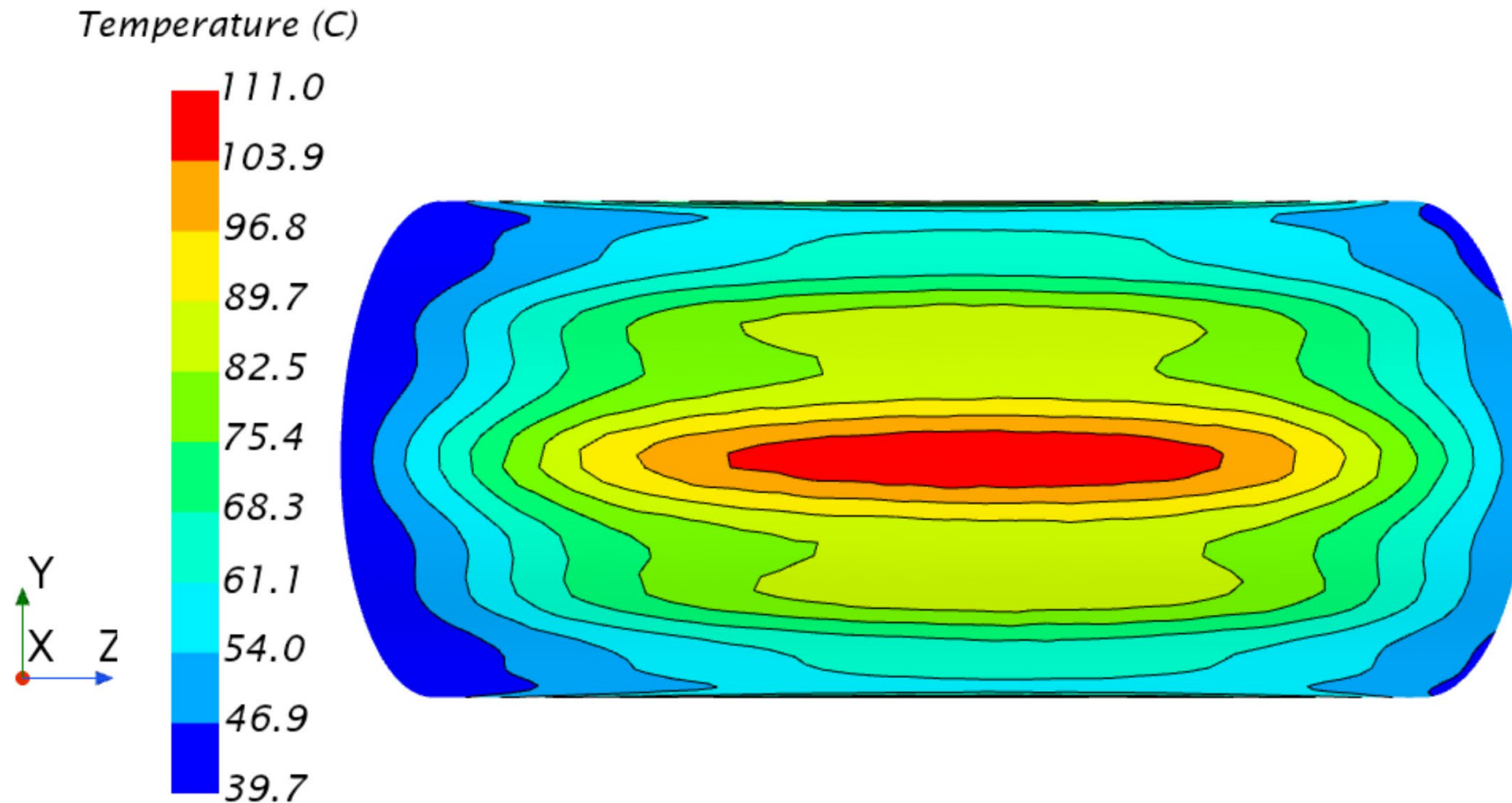


Target Segment, Front Surface Temperature (Inconel)

Nominal Beam

SS316 Flow Covers

Peak 110.0 °C



- Temperature profile that the **TVP** (Target Viewing Periscope) should see

Day 1 : Target Segment Analysis

- Results

- **700 kW & 7.5 GPM**: Nominal, Over-Focused, Offset, and Diffused Beams (**Requirement**)
- Increased Beam Power (900 kW) or Reduced Flow Rate (5.71 GPM) (Sensitivity of Design)
- Maintenance Temperature (Beam Off)

Beam-on-Target Load

The standard beam conditions to be considered for evaluating target fatigue life are to be considered below:

1. 714kW beam, at 54cm². This beam loading represents a 10% over focusing of the beam beyond the maximum extents defined in the interface sheet. A 10% allowance is provided to account for indirect diagnostic capability of the beam footprint during operations.
2. 700kW beam, nominal focused at 60cm²per [52]
3. 700kw beam, diffusely spread to 90cm²per [52]

Case		Beam Loads						Body Loads			Water			State
ID	Case	Power kW	Peak Density ^a 10 ¹⁰	Name	Offset v/h, mm	Pulses 10 ⁸	Trips 10 ⁵	Grav	Rot	Accel	Temp °C	Flow gpm	Press psi	State
A	Nominal	700	5.2	60cm ²	0/0	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL ^{bd}
B	Nominal-corner	700	5.2	60cm ²	7.08/8.5	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL ^{bd}
C	Nominal-low flow	700	5.2	60cm ²	0/0	1.35	1.25	Y	Y	N	32.2	5.24	36	WOL ^{bd}
D	Overfocused	714	5.5	57cm ²	0/0	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL ^{bd}
E	Diffuse	700	3.23	95cm ²	0/0	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL ^{bd}

^a 10¹⁰ protons/pulse/mm²

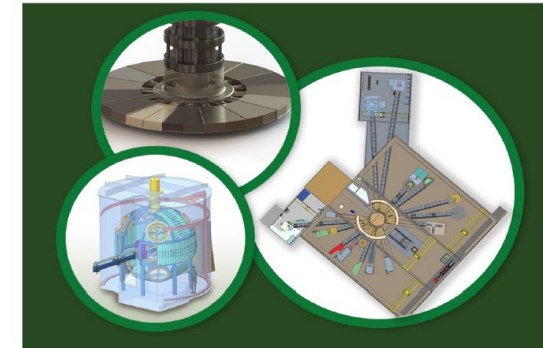
^b Worst of Life material conditions (irradiated elastic modulus and thermal conductivity, but not strength)

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

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

Figure 59. Beam-on-Target Load Combinations

Second Target Station Target Assembly Design Description



Aaron Jacques
Lukas Bearden
Joseph B. Tipton, Jr.

July 31, 2026

Approved for public release.
Distribution is unlimited.

OAK RIDGE
National Laboratory

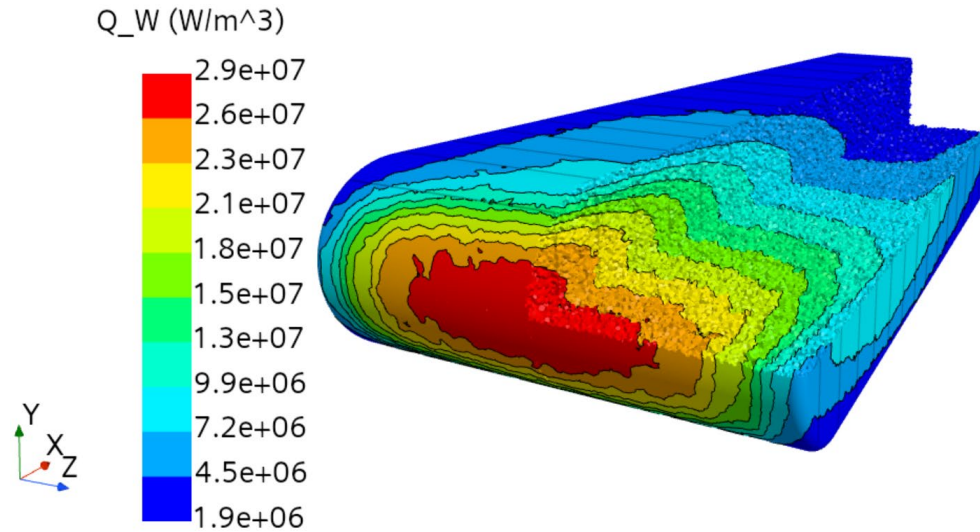
ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

Target Segment, Tungsten Heat Source

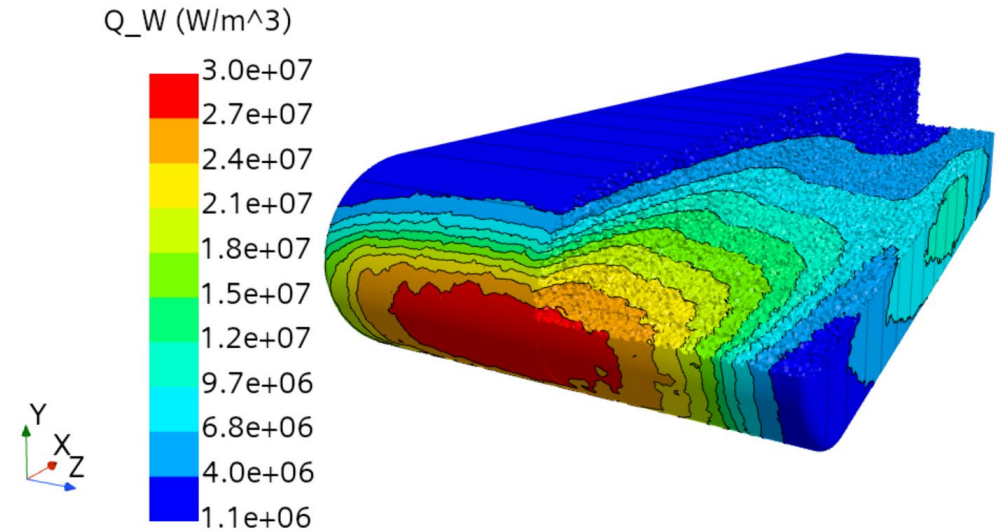
SS316 Flow Covers

Heat Source Calculation done by Lukas Zavorka

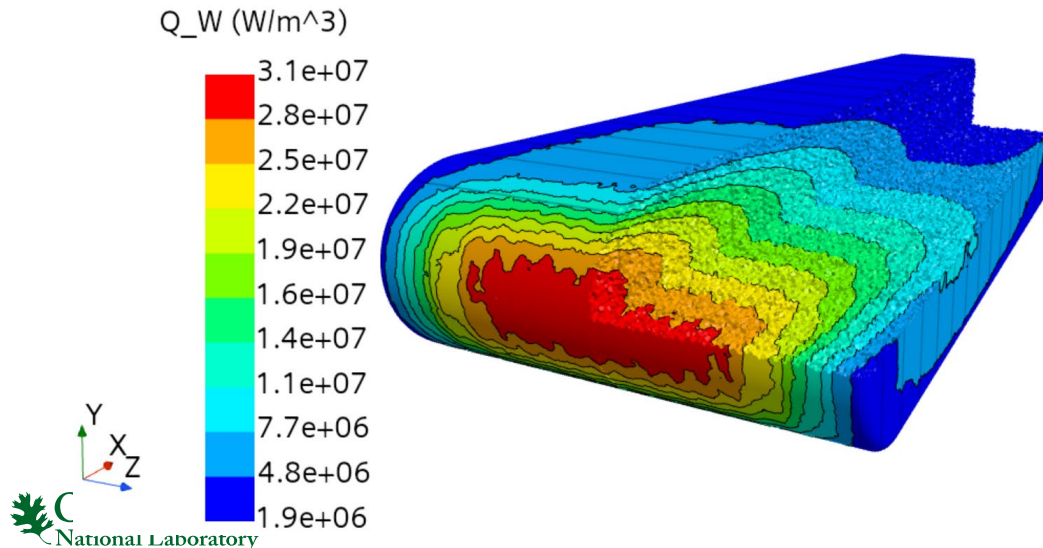
Nominal Beam



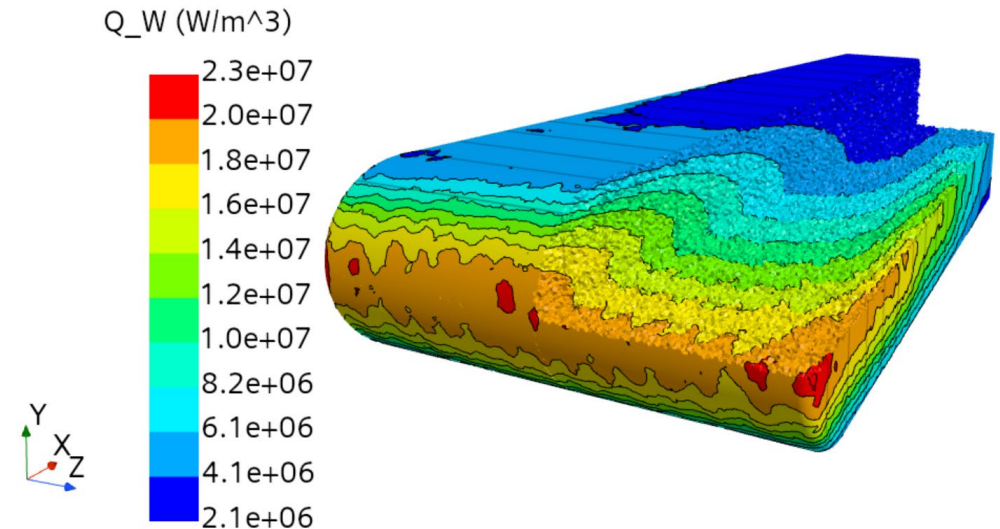
Offset Beam (Down: 0.85cm ; left: 1.2 cm)



Over-Focused Beam



Diffused Beam

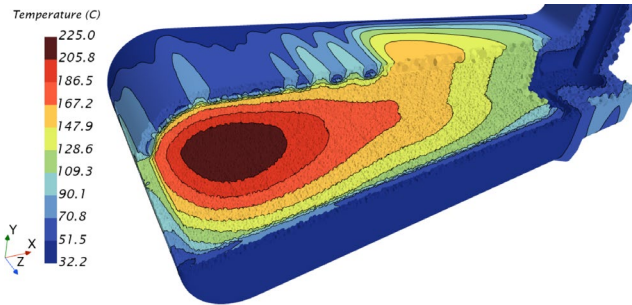


Target Segment, Tungsten Heat Source

SS316 Flow Covers

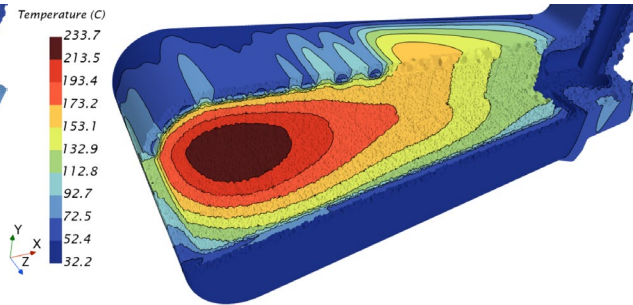
Nominal Beam

Peak: 225°C



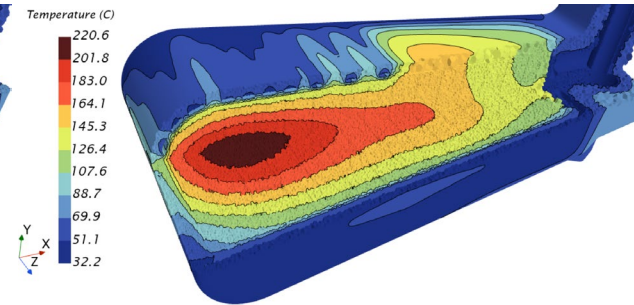
Over-Focused Beam

Peak: 233.7°C



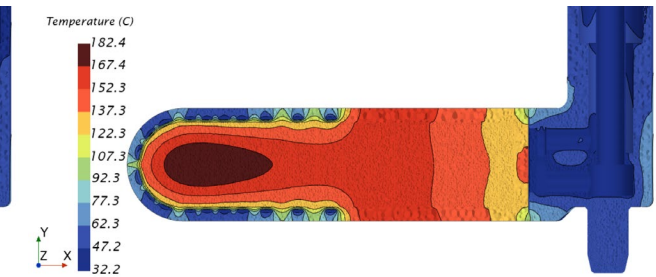
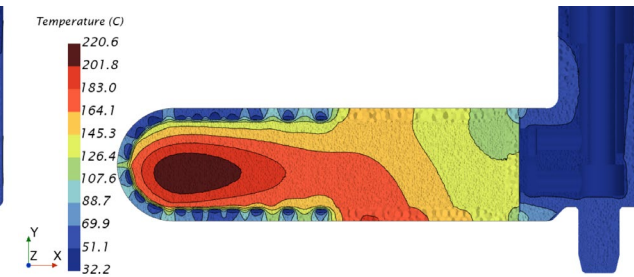
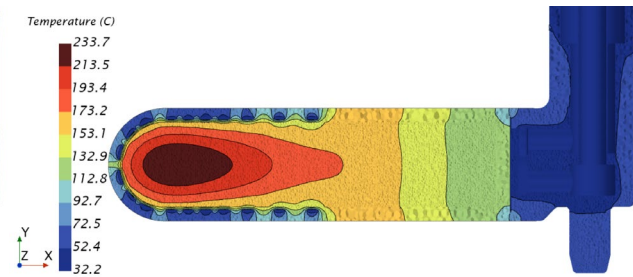
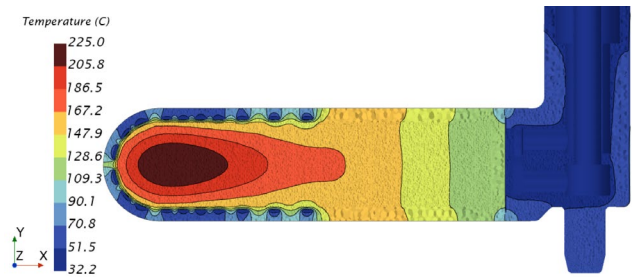
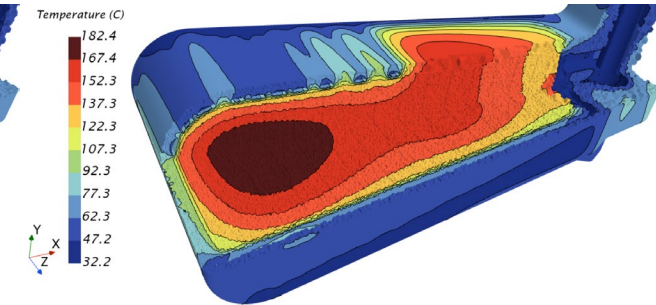
Offset Beam
(Down: 0.85cm ; left: 1.2 cm)

Peak: 220.6°C



Diffused Beam

Peak: 182.4°C

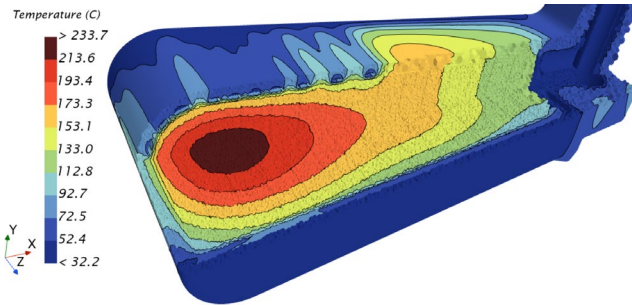


Target Segment, Tungsten Heat Source

SS316 Flow Covers

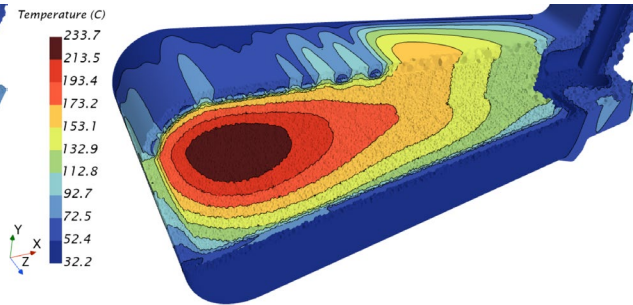
Nominal Beam

Peak: 225°C



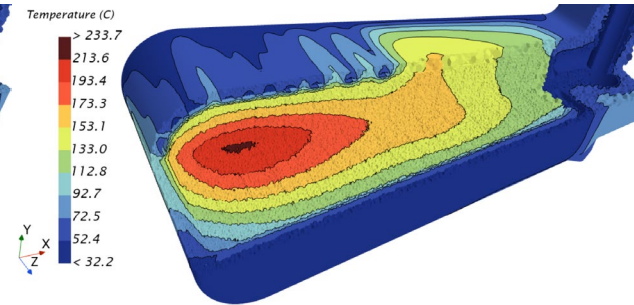
Over-Focused Beam

Peak: 233.7°C



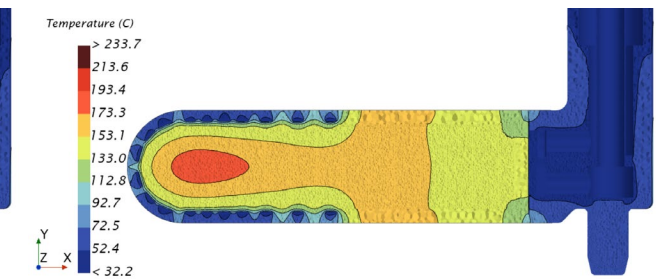
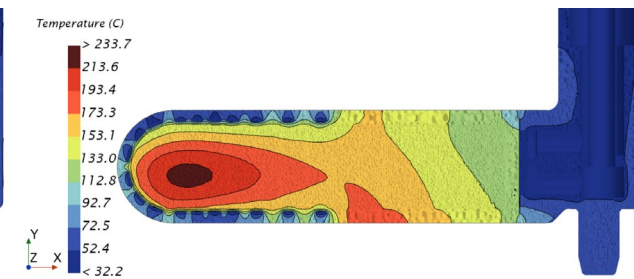
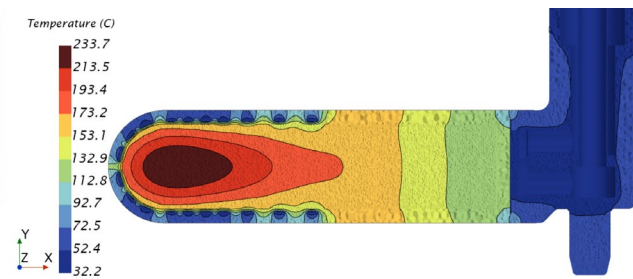
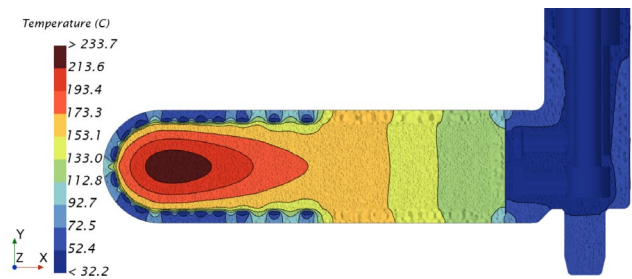
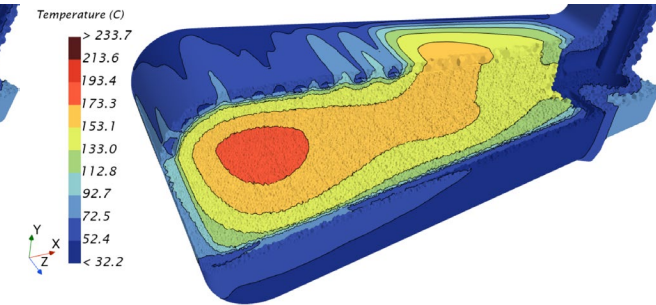
Offset Beam
(Down: 0.85cm ; left: 1.2 cm)

Peak: 220.6°C



Diffused Beam

Peak: 182.4°C



Target Segment, Peak Temperature under Various Beam Profiles

SS316 Flow Covers

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

Day 2 : Target Segment Analysis

- **Results**

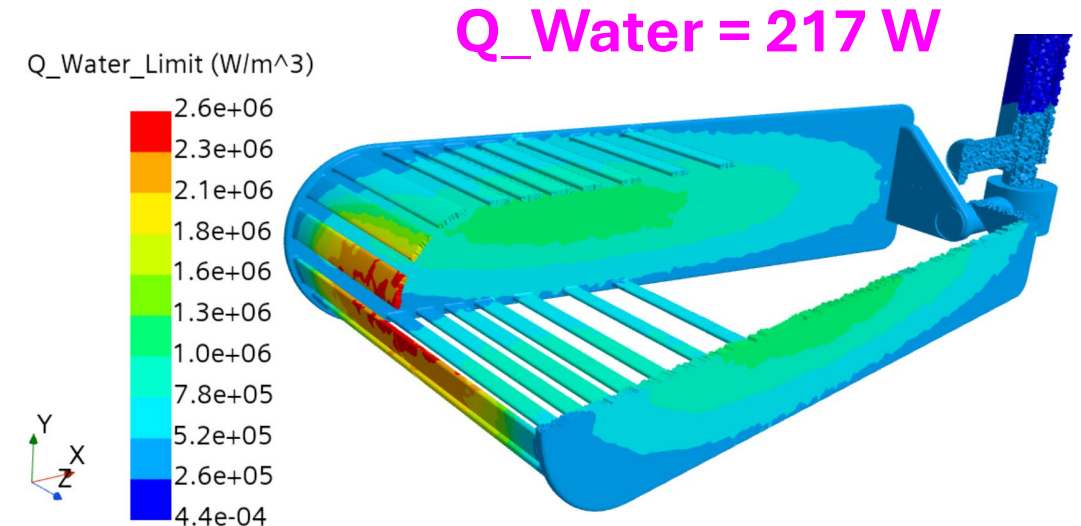
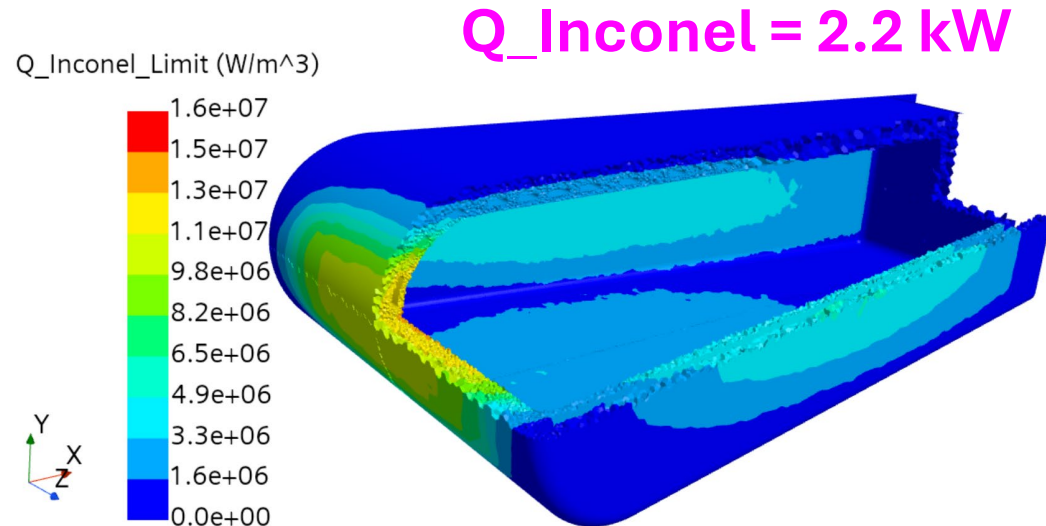
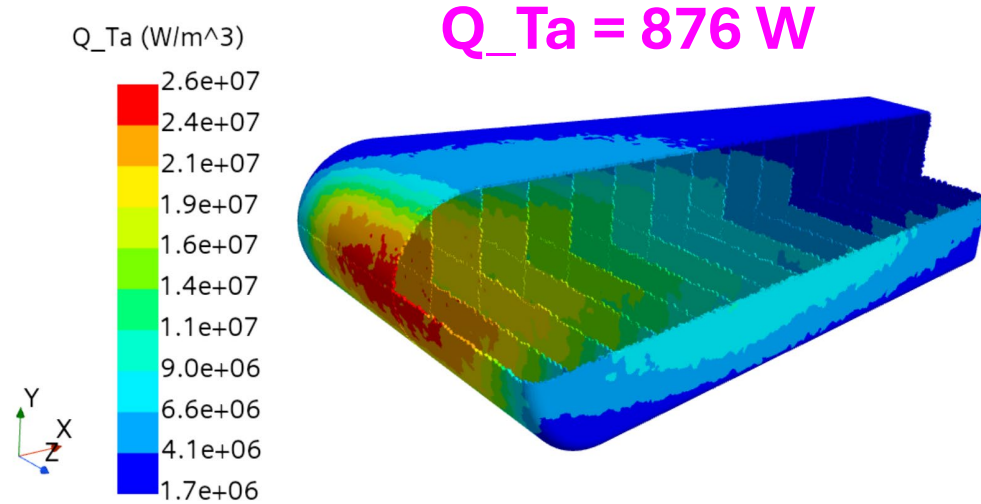
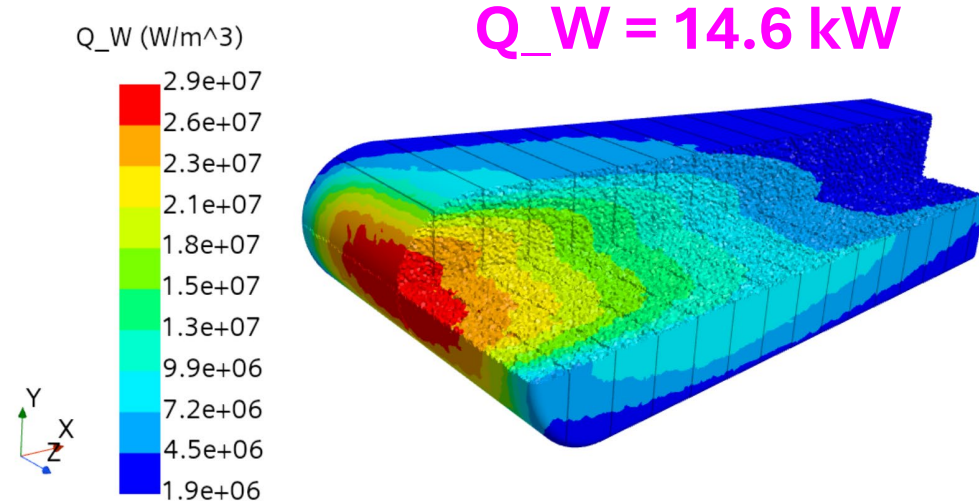
- 700 kW & 7.5 GPM: Nominal, Over-Focused, Offset, and Diffused Beams (Requirement)
- Increased Beam Power (**900 kW**) or Reduced Flow Rate (**5.71GPM**) (**Sensitivity of Design**)
- Maintenance Temperature (Beam Off)

Steady State Heat Transfer Analysis for Target Segment, Heat Source

Heat source calculation done by Lukas Zavorka

Inconel Flow Covers

Nominal Beam, 700 kW



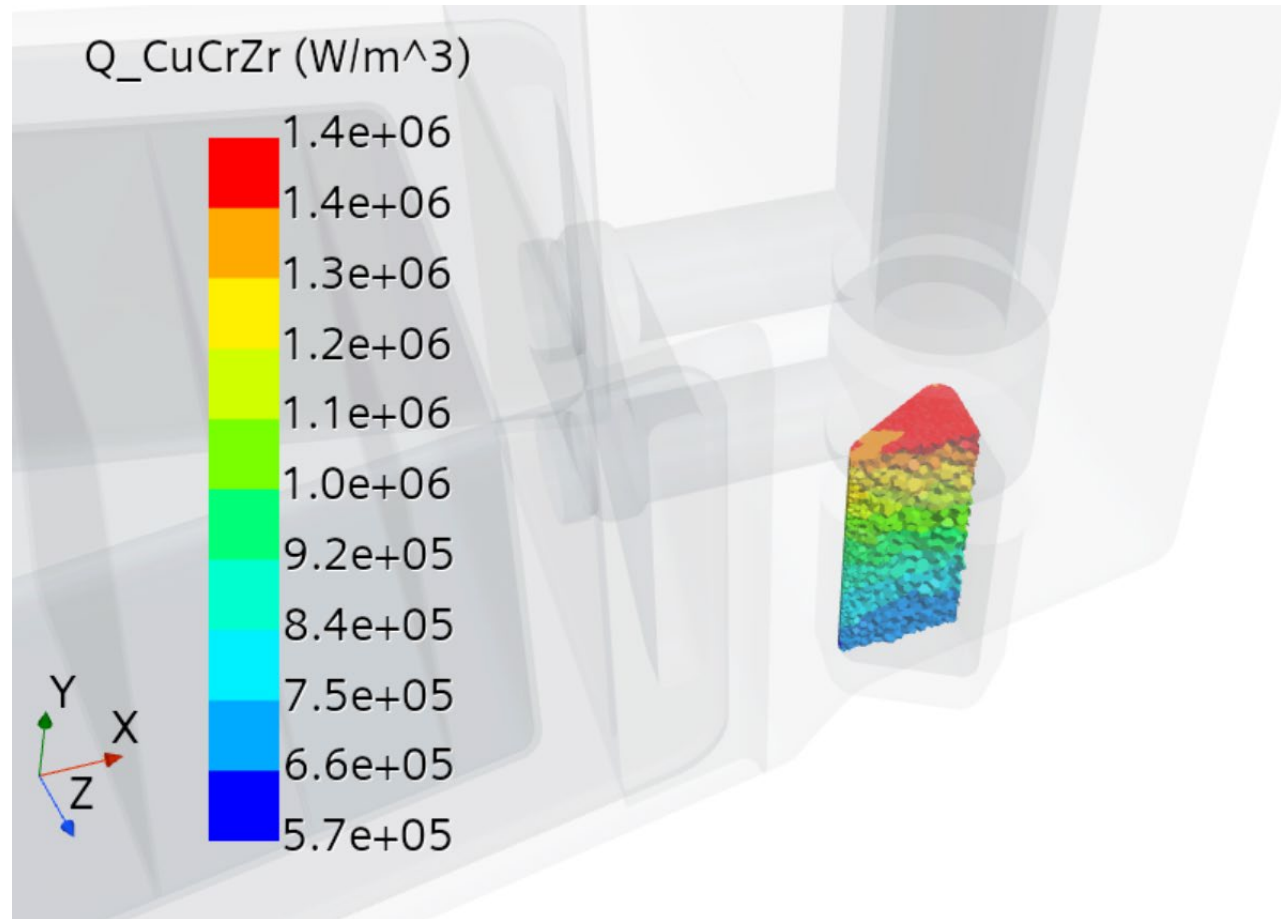
Steady State Heat Transfer Analysis for Target Segment, Heat Source

Heat source calculation done by Lukas Zavorka

Inconel Flow Covers

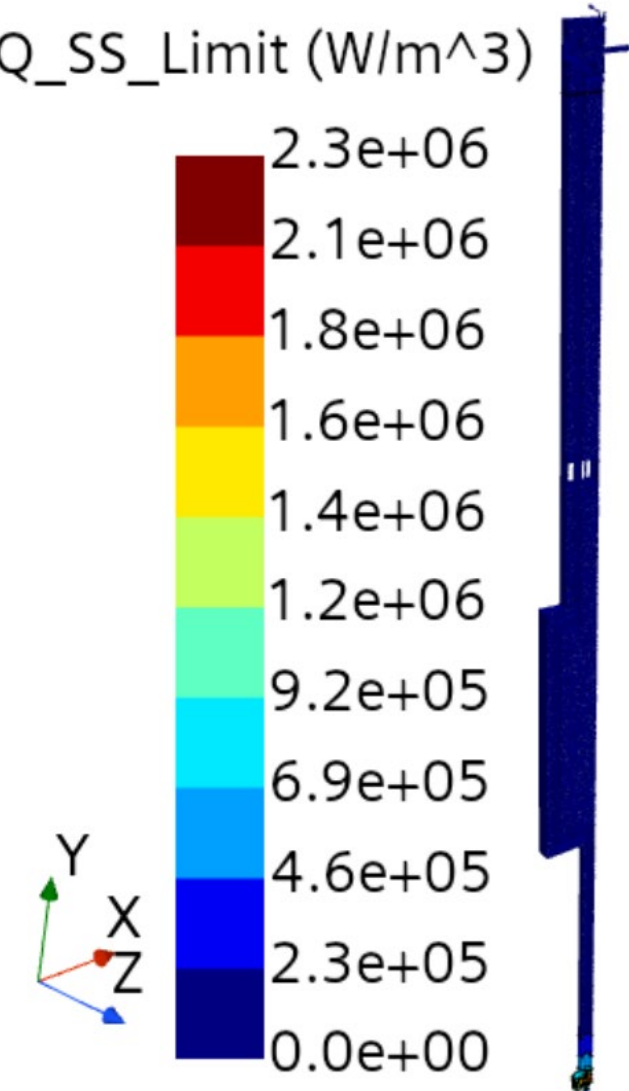
Nominal Beam, 700 kW

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



$Q_{\text{SS316}} = 923 \text{ W}$

$Q_{\text{SS_Limit}}$ (W/m^3)

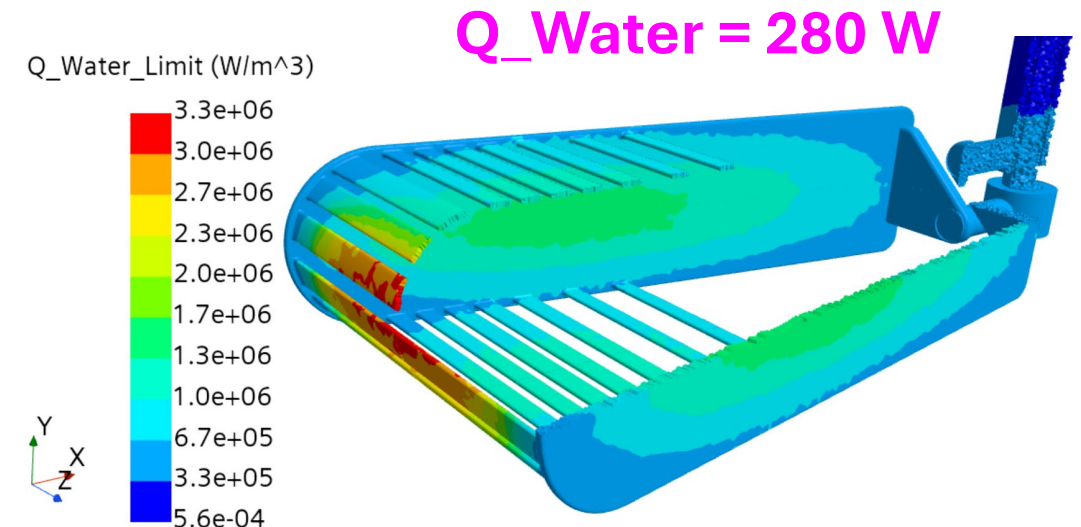
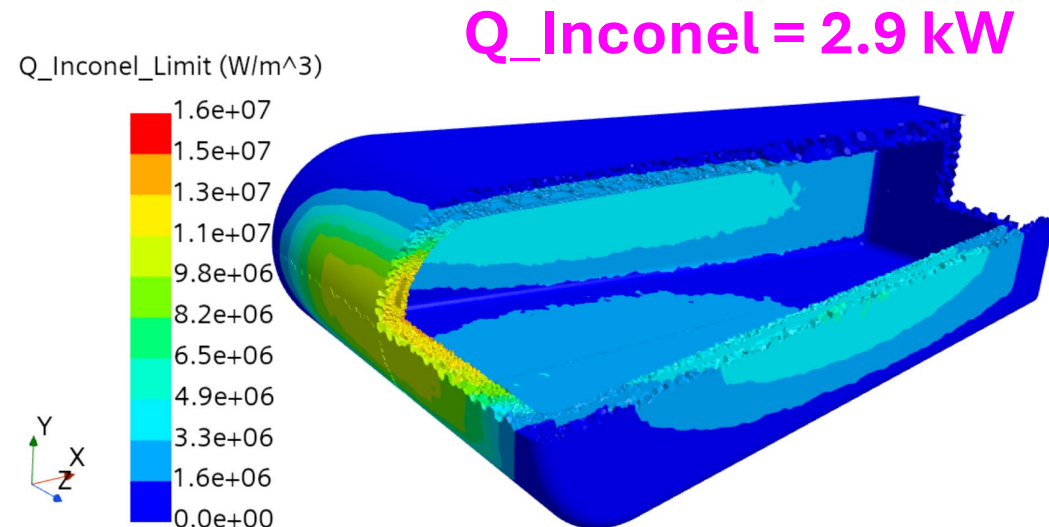
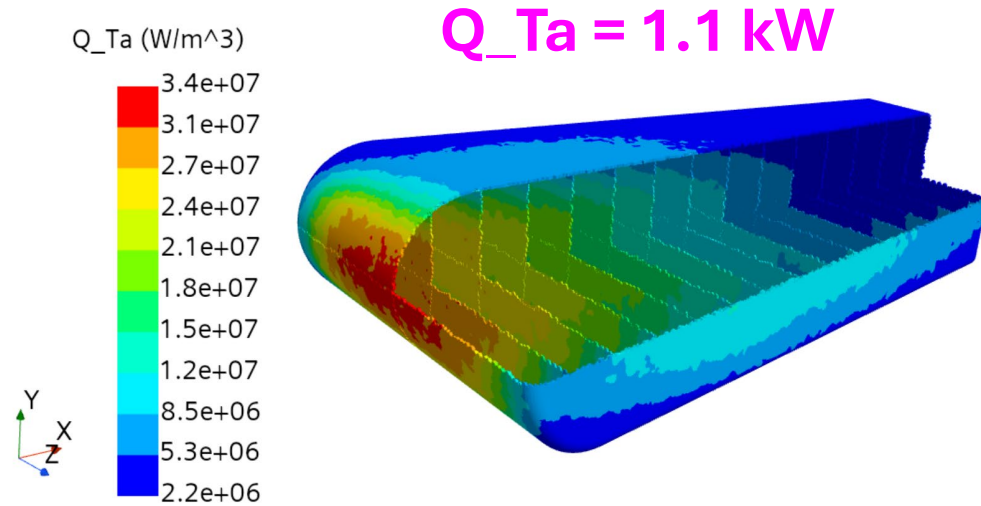
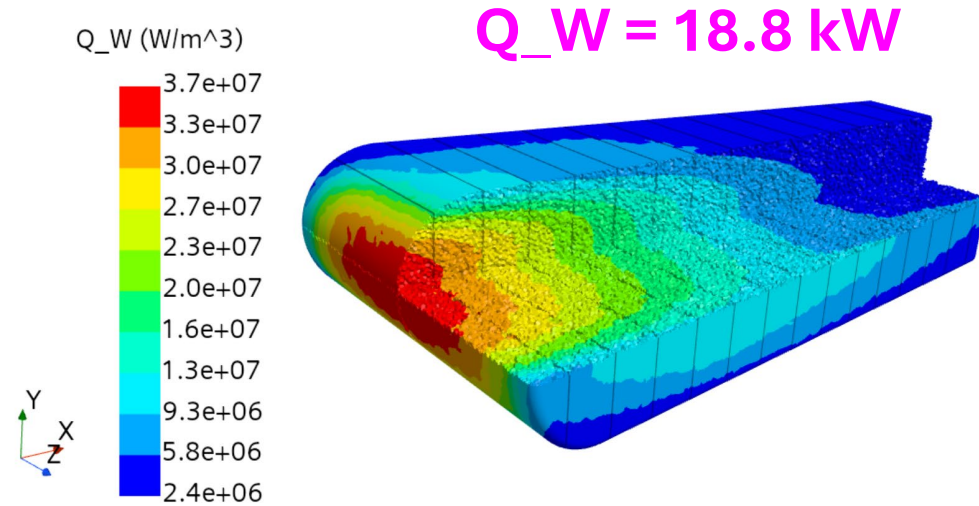


Steady State Heat Transfer Analysis for Target Segment, **Heat Source**

Heat sources scaled by a factor $f = 900/700$

Inconel Flow Covers

Nominal Beam, 900 kW



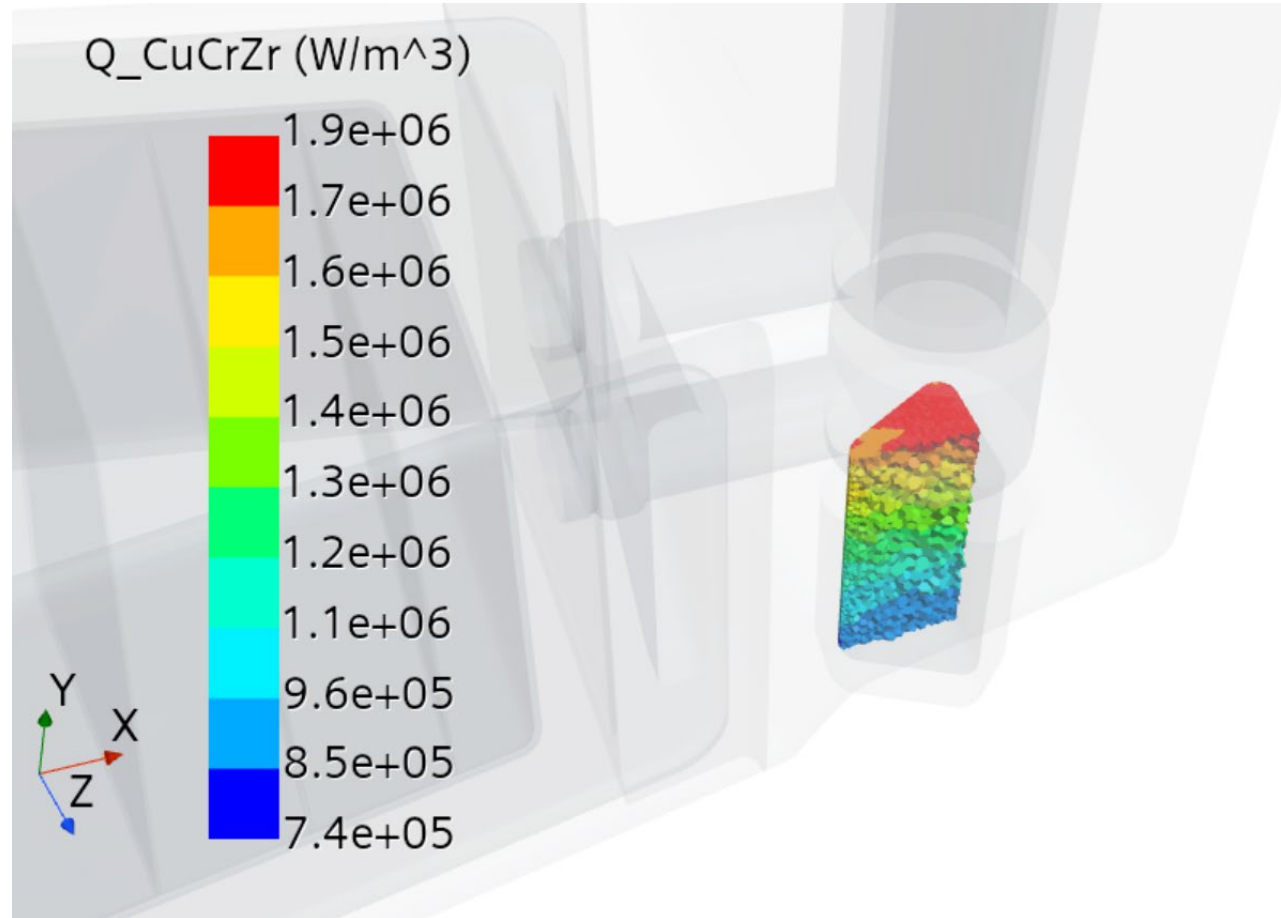
Steady State Heat Transfer Analysis for Target Segment, **Heat Source**

Heat sources scaled by a factor $f = 900/700$

Inconel Flow Covers

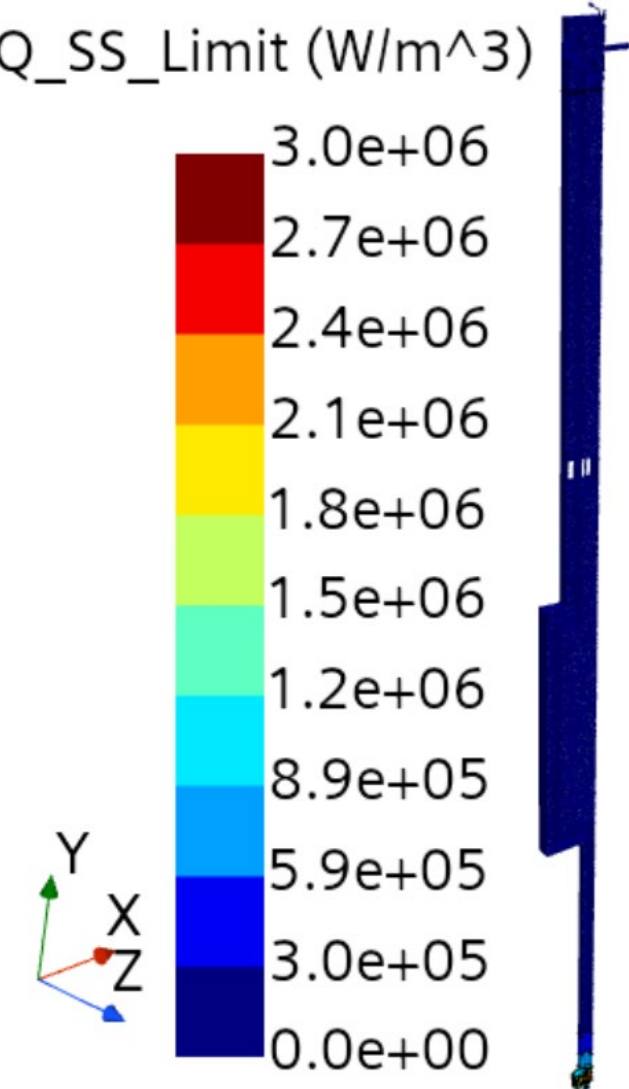
Nominal Beam, 900 kW

$Q_{\text{CuCrZr}} = 20 \text{ W}$



$Q_{\text{SS316}} = 1.2 \text{ kW}$

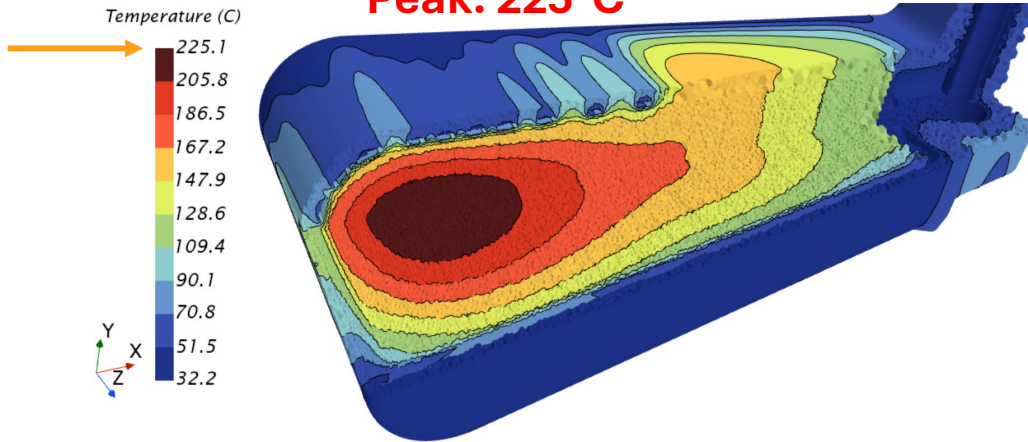
$Q_{\text{SS_Limit}} (\text{W/m}^3)$



Steady State Heat Transfer Analysis for Target Segment, Temperature

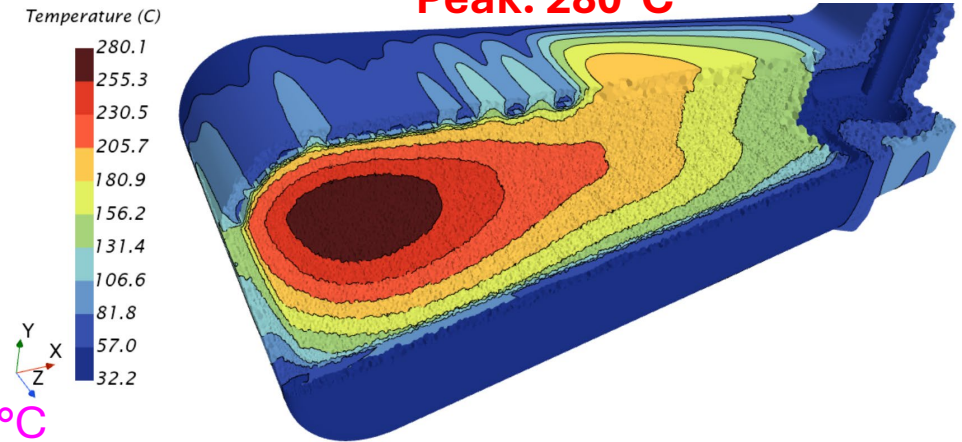
700 kW; 7.5 GPM (Normal Operation)

Peak: 225°C



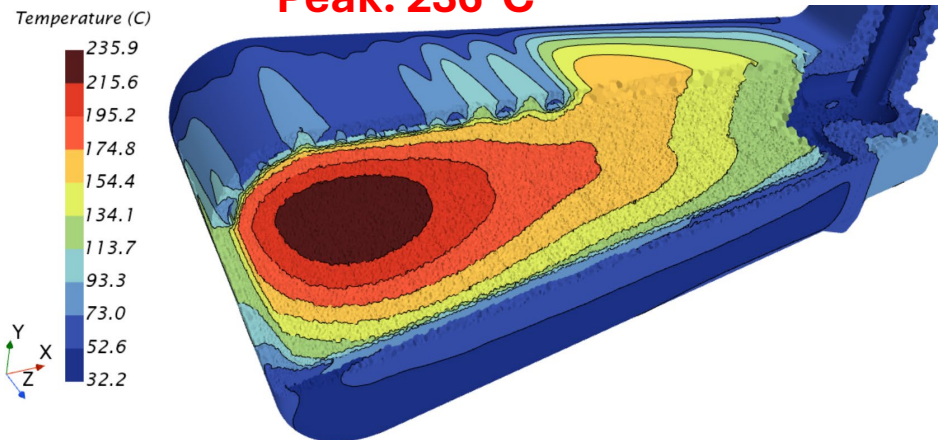
900 kW; 7.5 GPM

Peak: 280°C



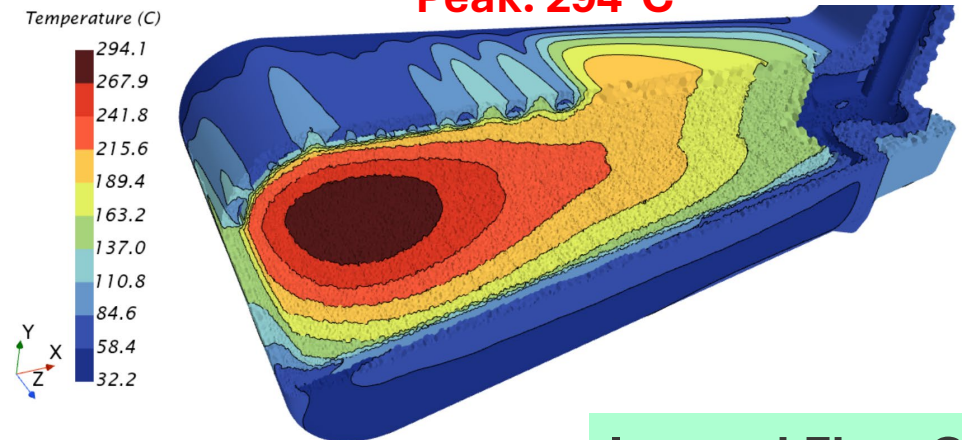
700 kW; 5.71 GPM (76%)

Peak: 236°C



900 kW; 5.71 GPM (76%) (Additional Case)

Peak: 294°C

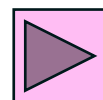
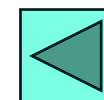


11-14°C

55-58°C

Inconel Flow Covers

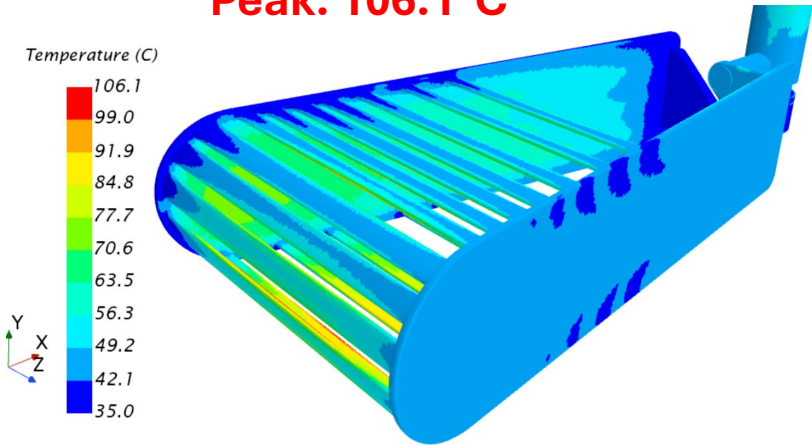
- Impact of power (700 kW → 900 kW, **29%** increase): **55-58°C**
- Impact of flow rate (7.5 GPM → 5.71 GPM, **24%** reduction): **11-14°C**



Steady State Heat Transfer Analysis for Target Segment, Water Temperature

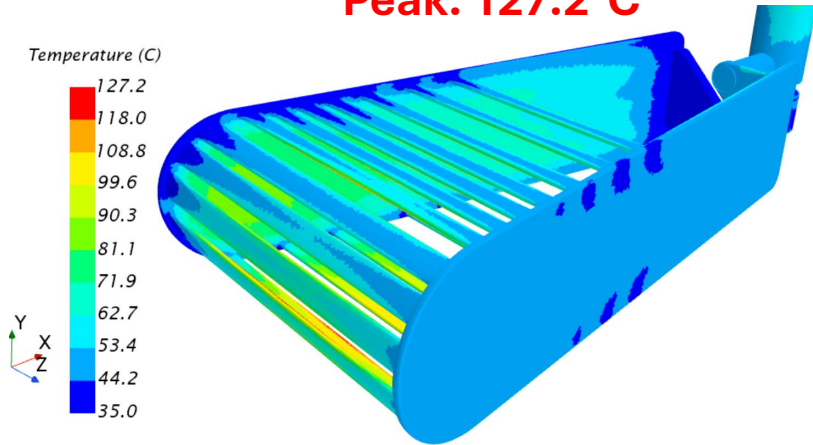
700 kW; 7.5 GPM (Normal Operation)

Peak: 106.1°C



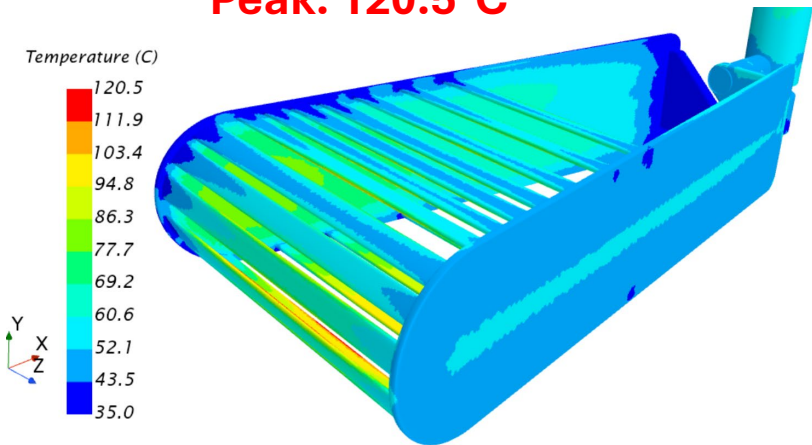
900 kW; 7.5 GPM

Peak: 127.2°C



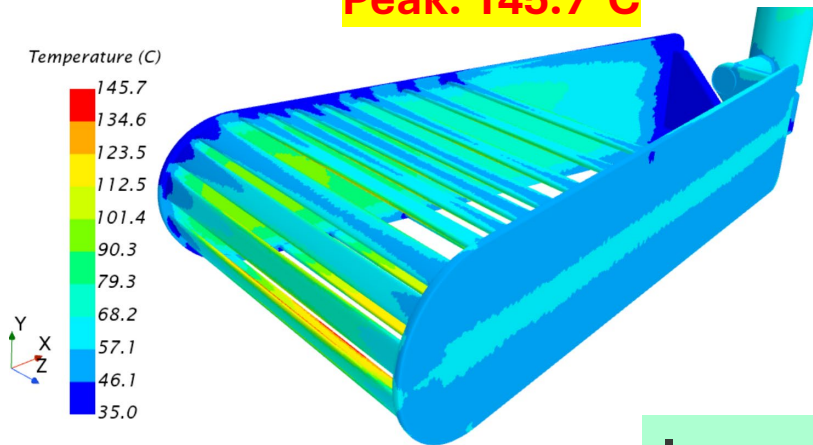
700 kW; 5.71 GPM (76%)

Peak: 120.5°C



900 kW; 5.71 GPM (76%) (Additional Case)

Peak: 145.7°C



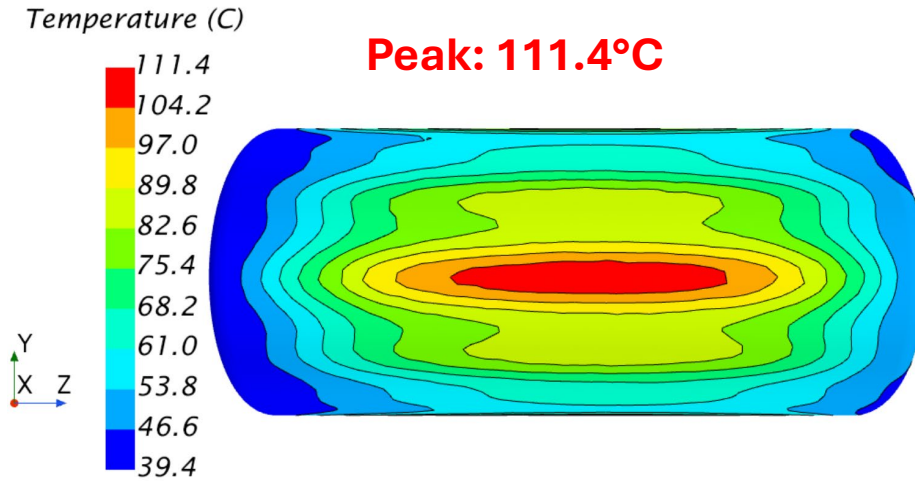
Boiling Point @ 3 bar: 133.5 °C

Inconel Flow Covers

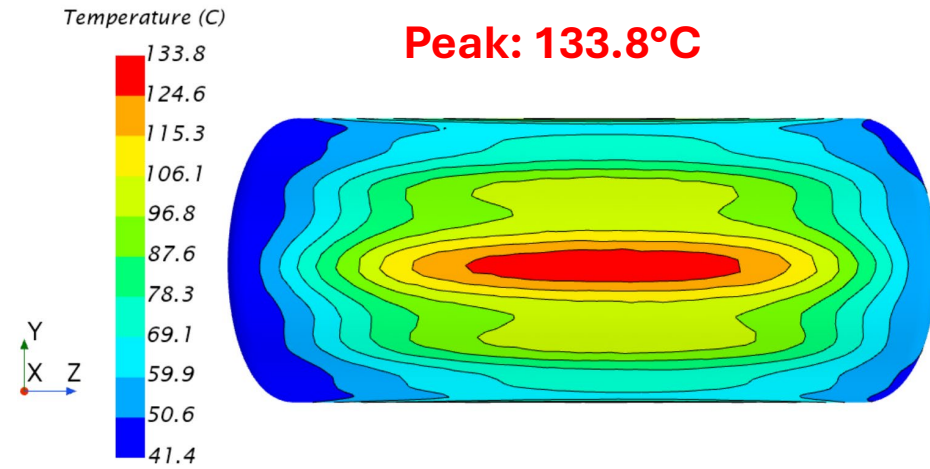
Steady State Heat Transfer Analysis for Target Segment, **Front Surface Temperature**

Inconel Flow Covers

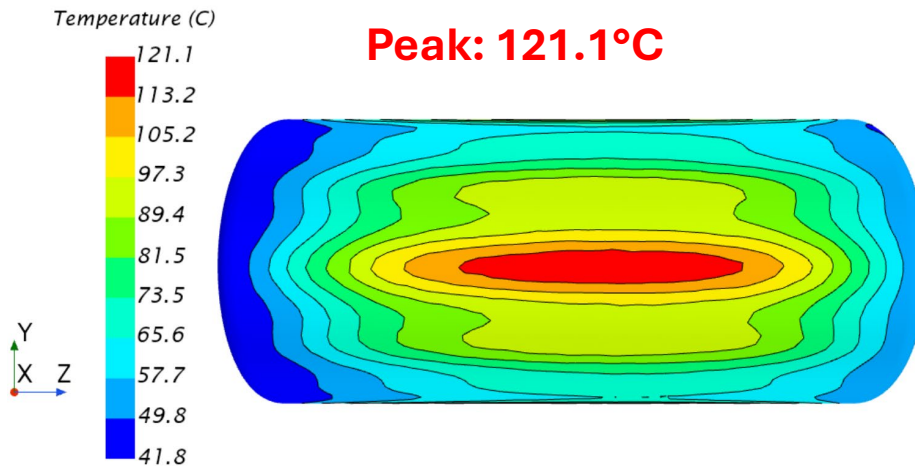
700 kW; 7.5 GPM (Normal Operation)



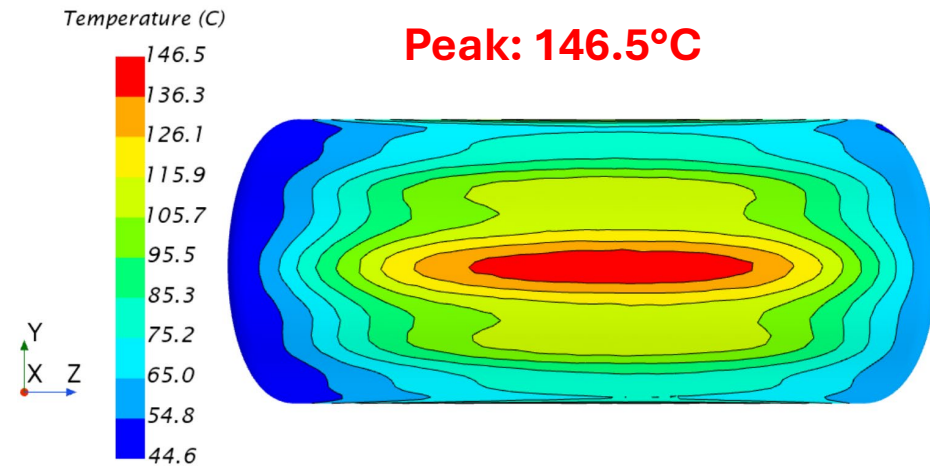
900 kW; 7.5 GPM



700 kW; 5.71 GPM (76%)



900 kW; 5.71 GPM (76%) (Additional Case)



- Temperature profile that the **TVP** (Target Viewing Periscope) should see

Summary of the Analyses for Increased Beam Power (900 kW) or Reduced Flow Rate (5.71GPM)

Heat Source

Inconel Flow Covers

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

Peak Temperature

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

Summary of the Analyses for Increased Beam Power (900 kW) or Reduced Flow Rate (5.71GPM)

Inconel Flow Covers

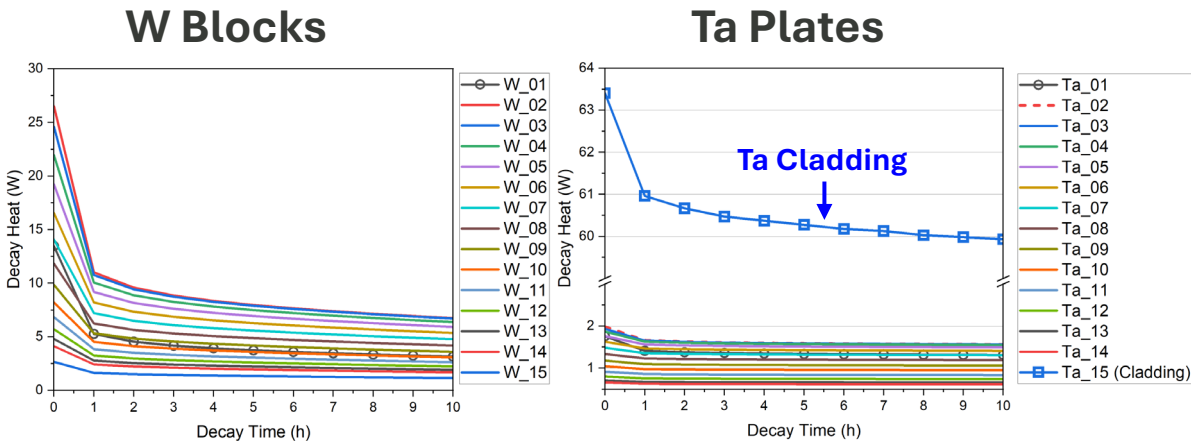
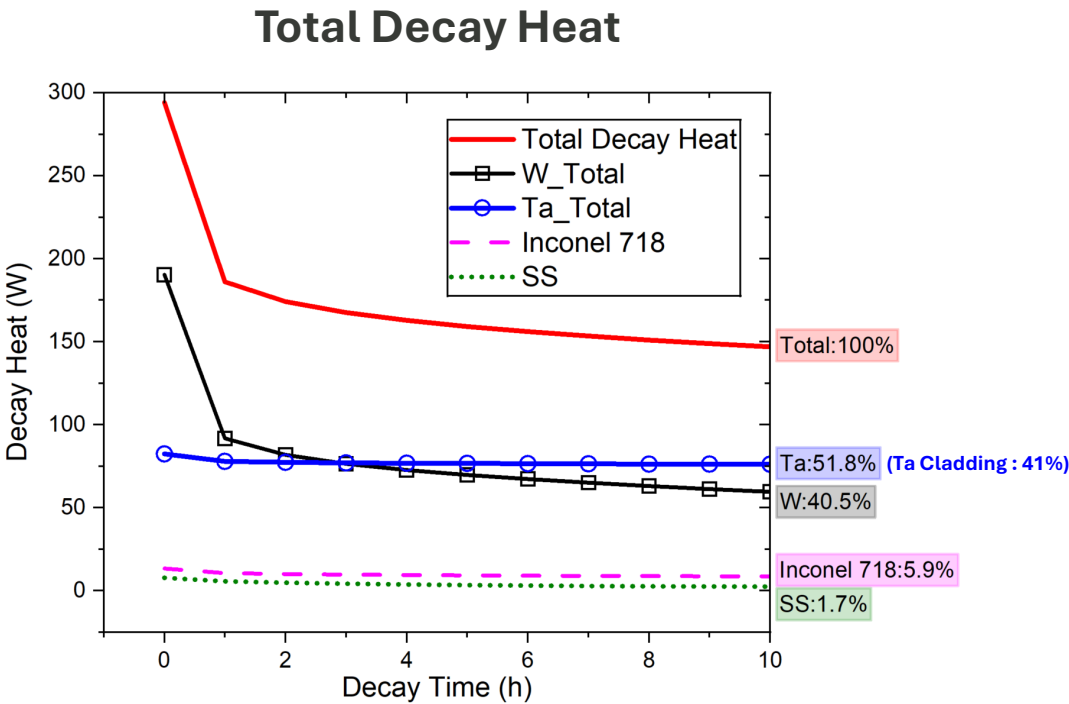
- The heat transfer analysis was conducted for the target segment using 700 kW (nominal) and 900 kW (29% increase) proton beams. The analysis considered both the nominal coolant flow rate of 7.5 GPM and a reduced flow rate of 5.71 GPM (24% reduction) resulting from a cooling-loop malfunction.
- At 700 kW beam power, the peak tungsten temperature is 225 °C. Increasing the beam power to 900 kW raises the peak temperature by 55 °C, reaching 280 °C under the nominal 7.5 GPM flow rate.
- At 900 kW beam power with the reduced flow rate of 5.71 GPM, the peak tungsten temperature increases further to 294 °C. The peak water temperature reaches 145.7 °C, which exceeds the water boiling point at 3 bar (the pressure at the target block elevation) by 12 °C.
- The reduction in **flow rate (24%)** increases the peak target segment temperature by approximately **11–14 °C**. In contrast, the **29%** increase in **beam power** (to 900 kW) results in a substantially larger temperature rise of **55–58 °C**.

Day 2 : Target Segment Analysis

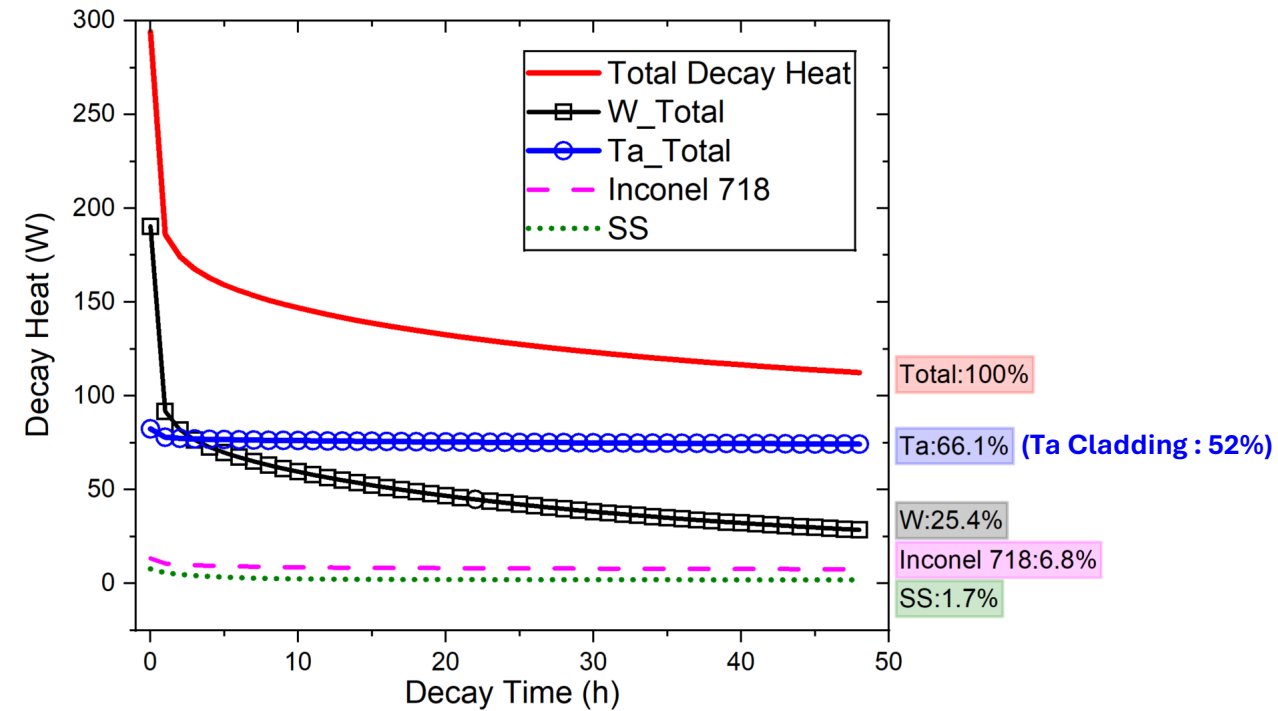
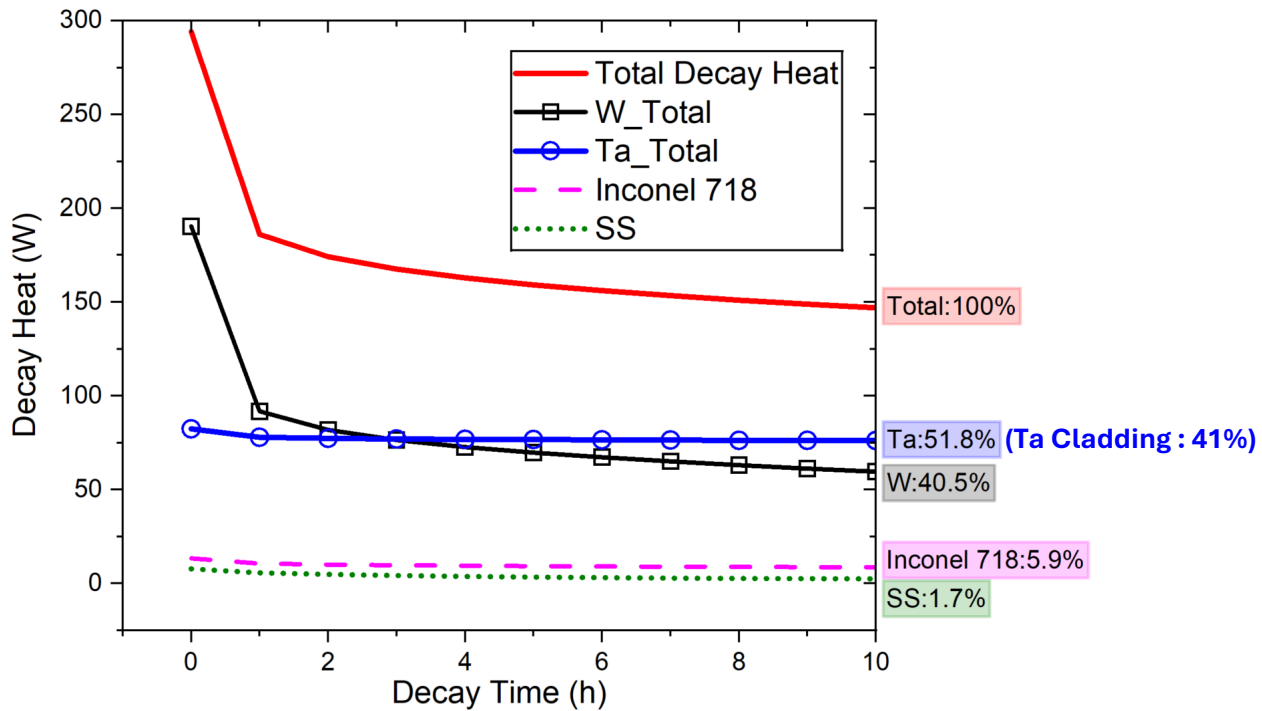
- **Results**

- 700 kW & 7.5 GPM: Nominal, Over-Focused, Offset, and Diffused Beams (Requirement)
- Increased Beam Power (900 kW) or Reduced Flow Rate (5.71 GPM) (Sensitivity of Design)
- **Maintenance Temperature (Beam Off)**
 - **Decay Heat**

Decay Time (h)	W_Total (W)	Ta_Total (W)	Inconel 718 (W)	SS (W)	Total Decay Heat (W)	W (%)	Ta (%)	Inconel 718 (%)	SS (%)	Sum (%)
0	190.46	82.47	13.41	7.80	294.15	64.8	28.0	4.6	2.7	100
1	91.81	77.92	10.69	5.75	186.17	49.3	41.9	5.7	3.1	100
2	81.86	77.39	10.14	4.86	174.26	47.0	44.4	5.8	2.8	100
3	76.50	77.07	9.79	4.23	167.59	45.6	46.0	5.8	2.5	100
4	72.75	76.89	9.52	3.75	162.90	44.7	47.2	5.8	2.3	100
5	69.80	76.73	9.30	3.39	159.22	43.8	48.2	5.8	2.1	100
6	67.30	76.58	9.14	3.10	156.12	43.1	49.1	5.9	2.0	100
7	65.10	76.48	9.00	2.89	153.46	42.4	49.8	5.9	1.9	100
8	63.11	76.35	8.88	2.72	151.06	41.8	50.5	5.9	1.8	100
9	61.27	76.26	8.78	2.59	148.91	41.1	51.2	5.9	1.7	100
10	59.58	76.18	8.70	2.48	146.95	40.5	51.8	5.9	1.7	100
11	57.98	76.10	8.63	2.40	145.12	40.0	52.4	5.9	1.7	100
12	56.49	75.98	8.56	2.34	143.37	39.4	53.0	6.0	1.6	100
13	55.06	75.91	8.51	2.29	141.76	38.8	53.5	6.0	1.6	100
14	53.71	75.84	8.46	2.25	140.25	38.3	54.1	6.0	1.6	100
15	52.42	75.81	8.41	2.21	138.86	37.8	54.6	6.1	1.6	100
16	51.20	75.74	8.37	2.19	137.50	37.2	55.1	6.1	1.6	100
17	50.02	75.68	8.33	2.17	136.19	36.7	55.6	6.1	1.6	100
18	48.89	75.61	8.29	2.15	134.94	36.2	56.0	6.1	1.6	100
19	47.82	75.54	8.26	2.13	133.75	35.8	56.5	6.2	1.6	100
20	46.78	75.48	8.22	2.12	132.60	35.3	56.9	6.2	1.6	100
21	45.79	75.41	8.19	2.10	131.49	34.8	57.4	6.2	1.6	100
22	44.83	75.40	8.16	2.09	130.48	34.4	57.8	6.3	1.6	100
23	43.91	75.33	8.13	2.08	129.46	33.9	58.2	6.3	1.6	100
24	43.02	75.27	8.10	2.08	128.47	33.5	58.6	6.3	1.6	100
25	42.16	75.21	8.08	2.07	127.51	33.1	59.0	6.3	1.6	100
26	41.34	75.19	8.05	2.06	126.64	32.6	59.4	6.4	1.6	100
27	40.54	75.13	8.03	2.05	125.75	32.2	59.7	6.4	1.6	100
28	39.77	75.07	8.00	2.05	124.89	31.8	60.1	6.4	1.6	100
29	39.03	75.06	7.98	2.04	124.10	31.4	60.5	6.4	1.6	100
30	38.31	75.00	7.95	2.03	123.30	31.1	60.8	6.5	1.6	100
31	37.61	74.94	7.93	2.03	122.51	30.7	61.2	6.5	1.7	100
32	36.94	74.93	7.91	2.02	121.80	30.3	61.5	6.5	1.7	100
33	36.29	74.87	7.89	2.02	121.06	30.0	61.8	6.5	1.7	100
34	35.66	74.81	7.87	2.01	120.34	29.6	62.2	6.5	1.7	100
35	35.05	74.80	7.85	2.01	119.70	29.3	62.5	6.6	1.7	100
36	34.46	74.74	7.83	2.00	119.03	29.0	62.8	6.6	1.7	100
37	33.88	74.73	7.81	2.00	118.42	28.6	63.1	6.6	1.7	100
38	33.33	74.67	7.79	1.99	117.78	28.3	63.4	6.6	1.7	100
39	32.79	74.61	7.77	1.99	117.16	28.0	63.7	6.6	1.7	100
40	32.27	74.60	7.75	1.98	116.60	27.7	64.0	6.6	1.7	100
41	31.76	74.54	7.73	1.98	116.01	27.4	64.3	6.7	1.7	100
42	31.27	74.53	7.72	1.97	115.49	27.1	64.5	6.7	1.7	100
43	30.79	74.48	7.70	1.97	114.93	26.8	64.8	6.7	1.7	100
44	30.33	74.42	7.68	1.97	114.39	26.5	65.1	6.7	1.7	100
45	29.87	74.41	7.67	1.96	113.91	26.2	65.3	6.7	1.7	100
46	29.44	74.35	7.65	1.96	113.40	26.0	65.6	6.7	1.7	100
47	29.01	74.34	7.63	1.95	112.94	25.7	65.8	6.8	1.7	100
48	28.60	74.29	7.62	1.95	112.45	25.4	66.1	6.8	1.7	100

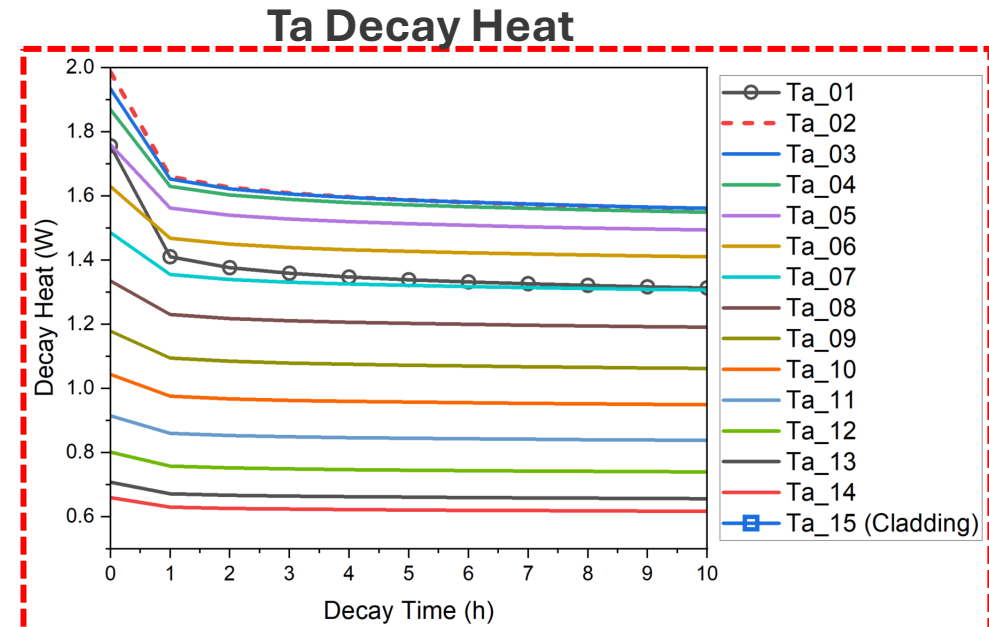
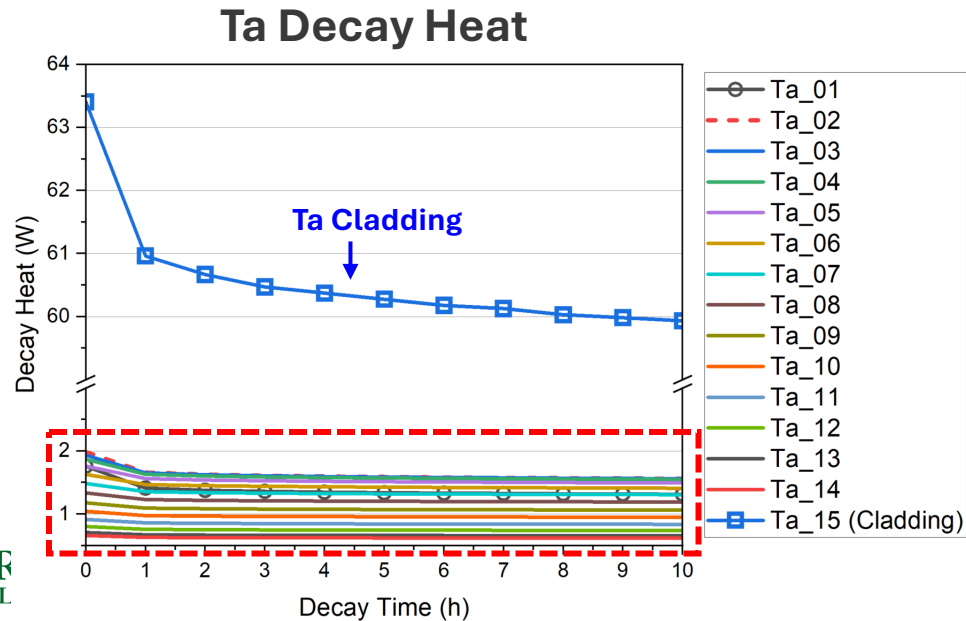
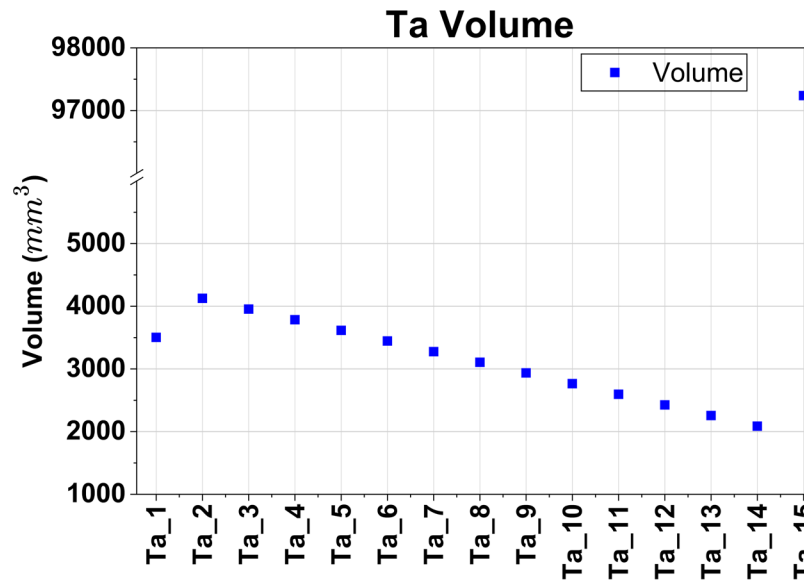
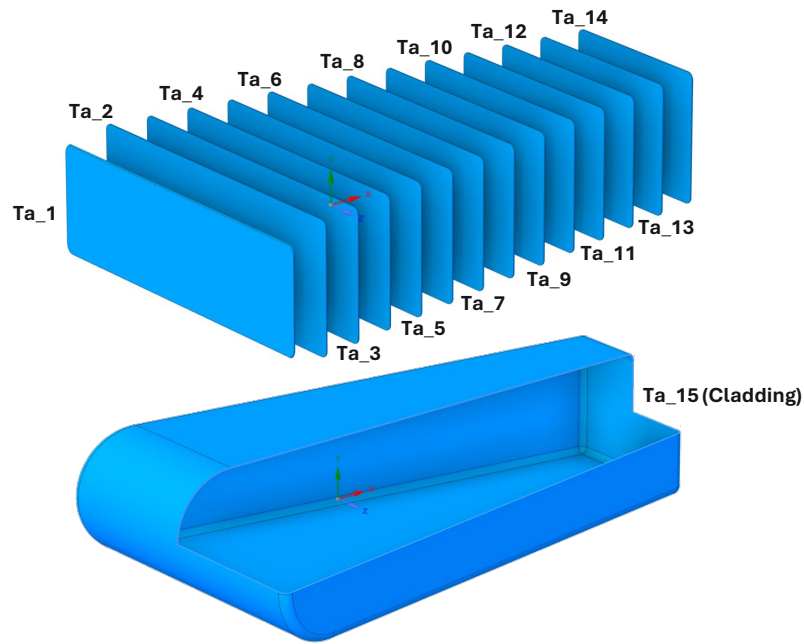


Target Segment, Decay Heat

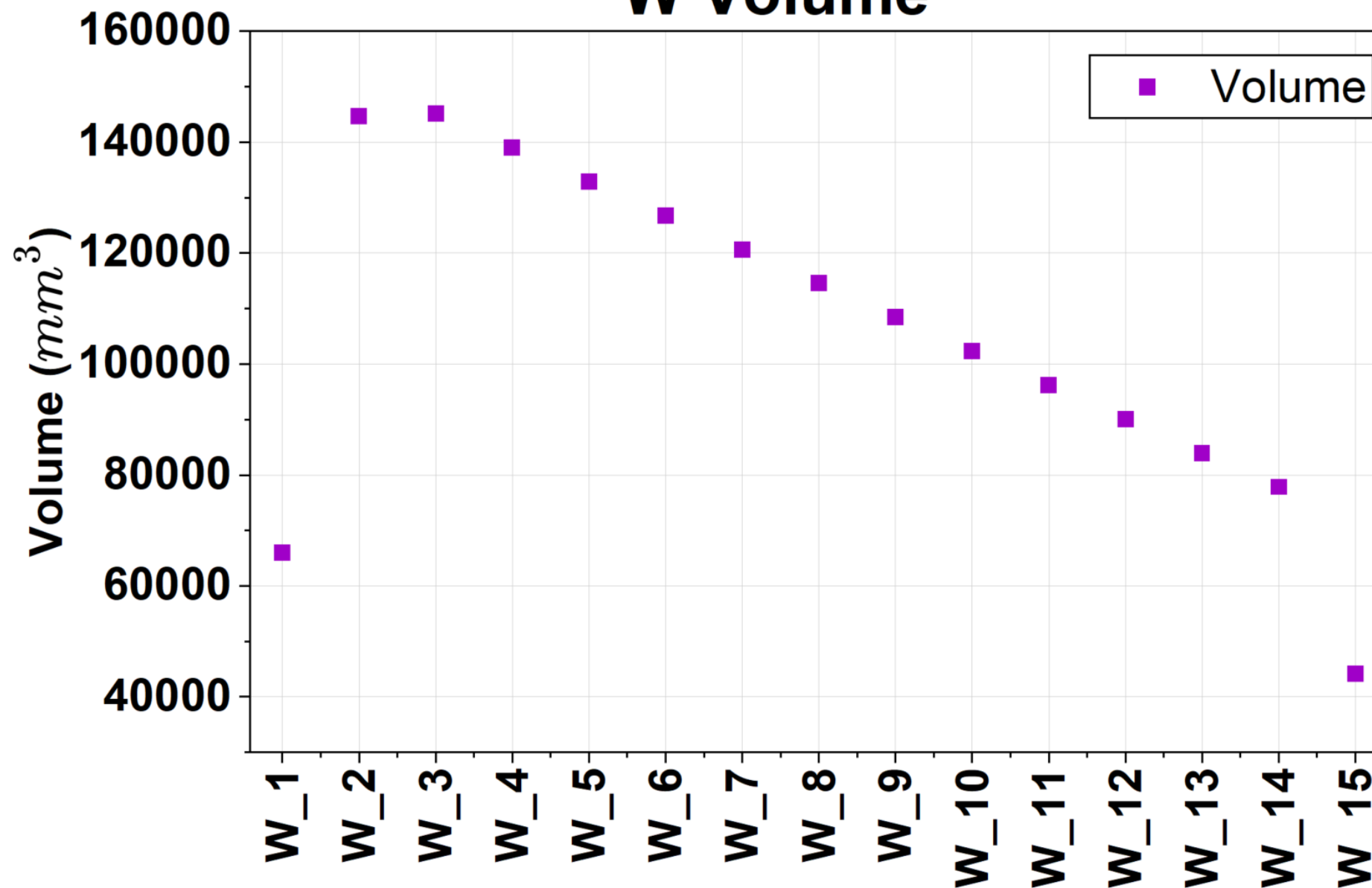


- More than **half** of the decay heat comes from the **Ta cladding** after **48 hours**.

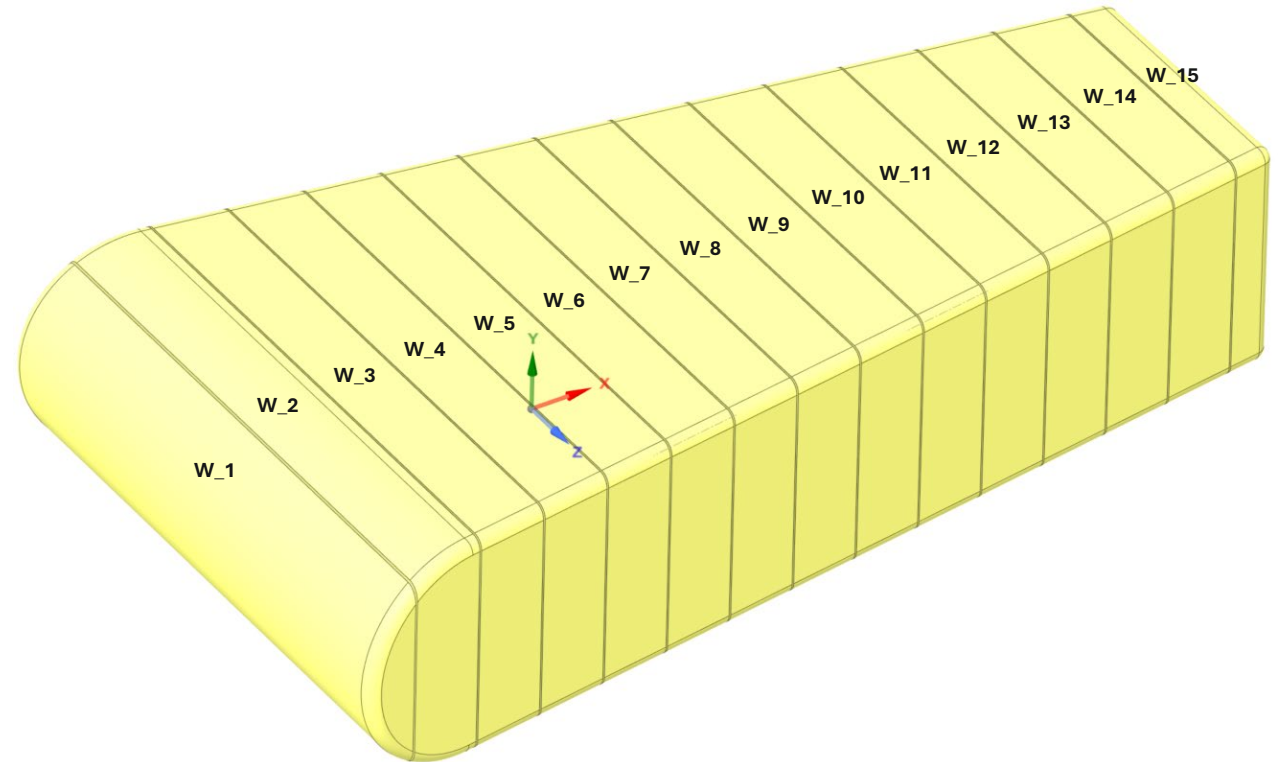
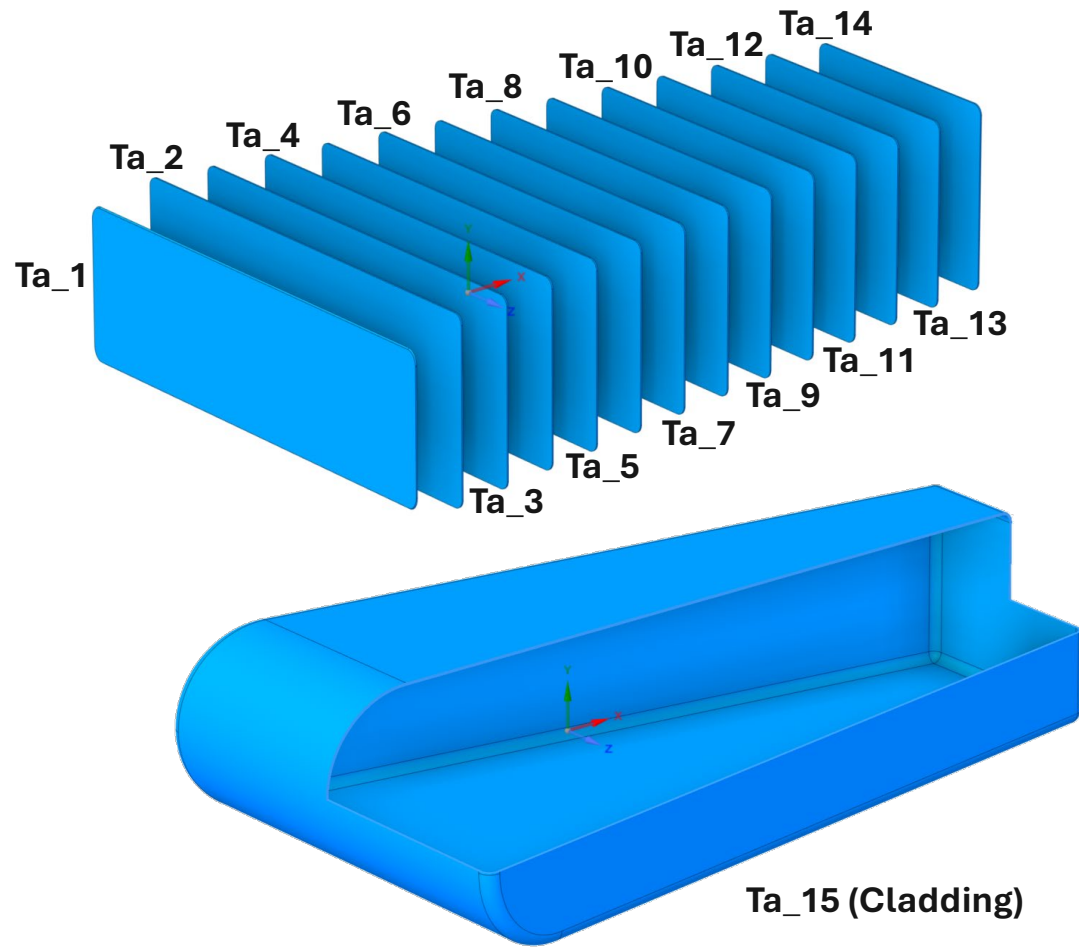
Target Segment, Decay Heat



W Volume



Target Segment, Decay Heat



Target Segment, Curve Fitting of Decay Heat

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

t: Time (hr)

Q(t): Decay Heat (W)

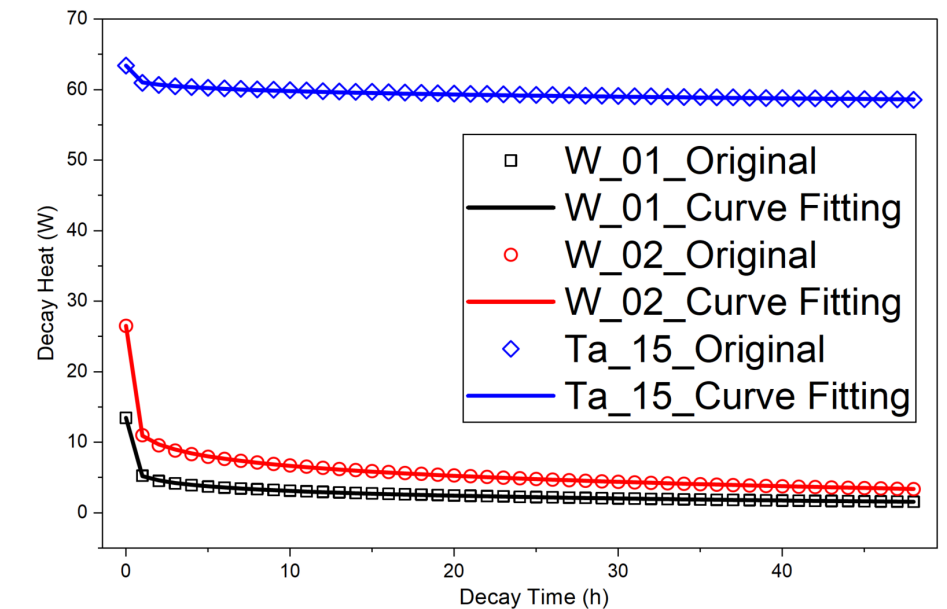
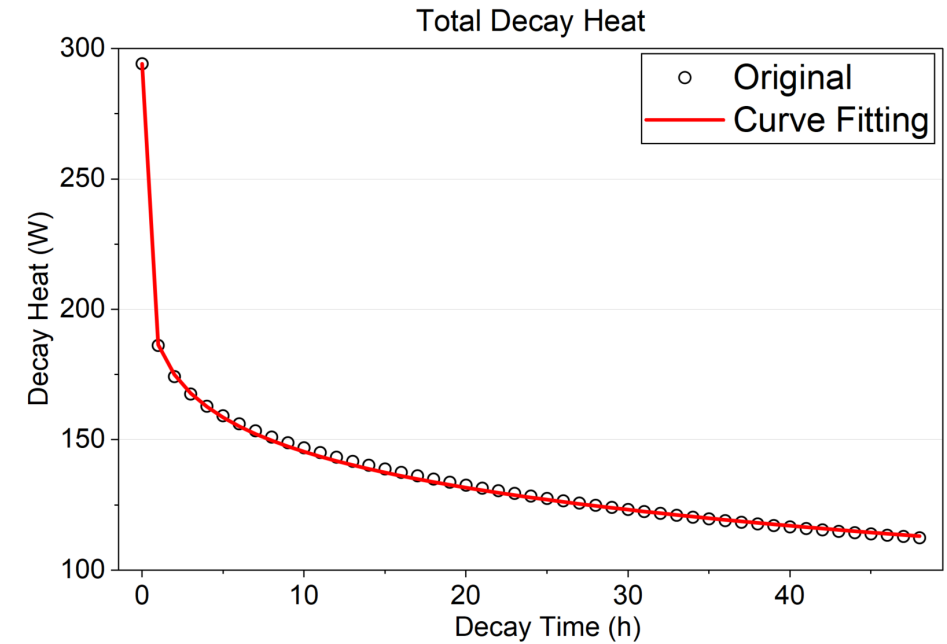
Decay Heat Curve Fitting for W Blocks (0 - 48 h)				
	a	b	c	d
W_01	13.470100	0.1522375	178.7338	-12.92346
W_02	26.530210	0.1394696	8832.380	-44.44535
W_03	24.600190	0.1248932	39809310	-113.1218
W_04	21.949380	0.1229845	1.815886E+11	-279.6004
W_05	19.227910	0.1304583	1.618474E+11	-282.3464
W_06	16.546400	0.1378560	1.393388E+11	-277.9442
W_07	14.075220	0.1448328	1.199227E+11	-267.5152
W_08	11.834780	0.1518518	1.048015E+11	-254.9775
W_09	9.854363	0.1580361	8.704426E+10	-234.2990
W_10	8.204309	0.1640910	6.964257E+10	-212.9572
W_11	6.834851	0.1687723	5.856978E+10	-189.3069
W_12	5.704993	0.1734061	5.037057E+10	-169.1832
W_13	4.805256	0.1774867	4.291028E+10	-150.2996
W_14	4.125306	0.1830665	3.573420E+10	-139.3851
W_15	2.665320	0.2010891	2.213105E+10	-117.5808

Decay Heat Curve Fitting for Ta Plates (0 - 48 h)				
	a	b	c	d
Ta_01	1.759998	0.2534509	1.049262	1.0563440
Ta_02	1.989998	0.2631361	1.203649	1.3141120
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	1.630006	0.2656174	4.122176	1.2348500
Ta_07	1.490014	0.2005294	164.5168	0.9893797
Ta_08	1.339997	0.1979418	162.8491	0.9305302
Ta_09	1.179953	0.1389281	2502151000	-0.7307162
Ta_10	1.040007	0.3244036	5.069228	0.8771060
Ta_11	0.909990	0.1499774	1566836000	-0.3779287
Ta_12	0.800002	0.1723137	1465150000	-0.8313612
Ta_13	0.709793	0.1666562	1300966000	-0.5388245
Ta_14	0.659716	0.2054816	1057661000	-1.2820630
Ta_15 (Cladding)	63.401960	0.1827662	48666410000	-153.01190

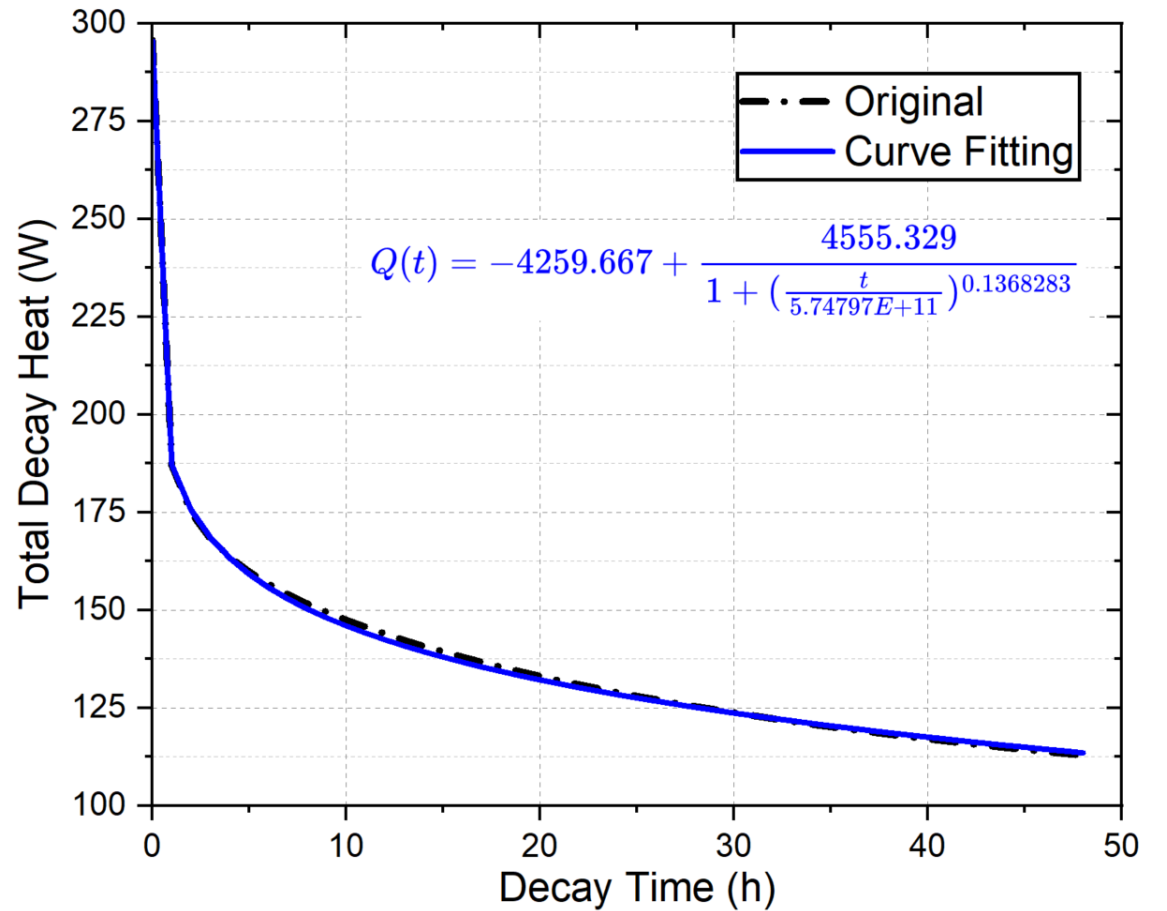
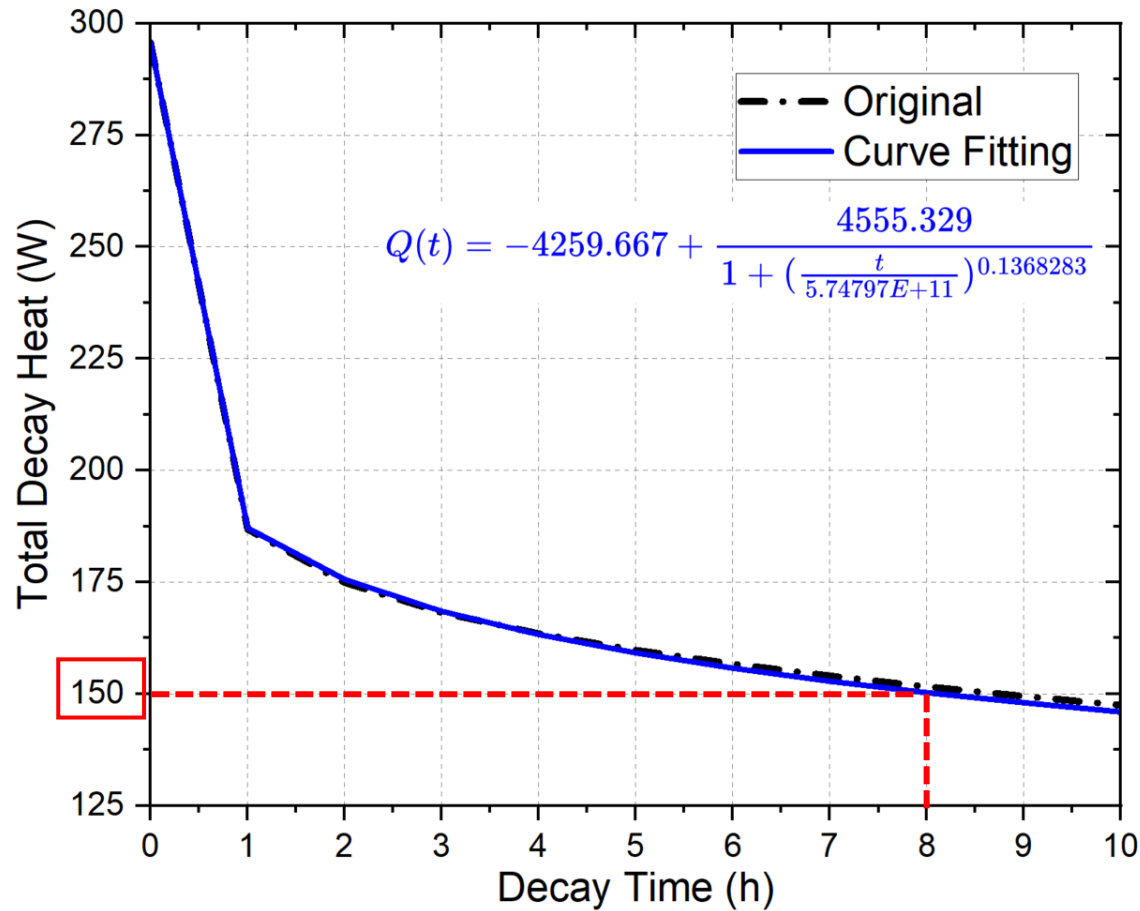
Decay Heat Curve Fitting for Inconel 718 and SS (0 - 48 h)				
	a	b	c	d
Inconel 718	13.40937	0.4894982	2.92127	6.143613
SS	7.783984	1.113557	1.97162	1.727172

Target Segment, Decay Heat: Comparison between Original Data and Curve Fitting Data

Decay Time (h)	Original: Total Decay Heat (W)	Curve Fit: Total Decay Heat (W)	Difference (W)	%
0	294.15	294.09	0.05	0.018
1	186.17	186.44	-0.27	0.147
2	174.26	174.99	-0.73	0.420
3	167.59	167.88	-0.29	0.173
4	162.90	162.68	0.23	0.139
5	159.22	158.58	0.64	0.403
6	156.12	155.18	0.94	0.601
7	153.46	152.27	1.19	0.776
8	151.06	149.73	1.33	0.878
9	148.91	147.47	1.43	0.961
10	146.95	145.44	1.51	1.026
11	145.12	143.59	1.53	1.055
12	143.37	141.88	1.49	1.039
13	141.76	140.30	1.46	1.028
14	140.25	138.84	1.41	1.007
15	138.86	137.46	1.40	1.007
16	137.50	136.17	1.32	0.964
17	136.19	134.95	1.24	0.908
18	134.94	133.80	1.14	0.848
19	133.75	132.70	1.05	0.785
20	132.60	131.65	0.94	0.712
21	131.49	130.65	0.84	0.641
22	130.48	129.70	0.78	0.599
23	129.46	128.78	0.68	0.524
24	128.47	127.90	0.57	0.444
25	127.51	127.05	0.46	0.364
26	126.64	126.23	0.41	0.324
27	125.75	125.44	0.31	0.249
28	124.89	124.68	0.21	0.170
29	124.10	123.94	0.17	0.135
30	123.30	123.22	0.08	0.062
31	122.51	122.52	-0.01	0.012
32	121.80	121.85	-0.05	0.039
33	121.06	121.19	-0.13	0.108
34	120.34	120.56	-0.21	0.176
35	119.70	119.93	-0.23	0.195
36	119.03	119.33	-0.30	0.254
37	118.42	118.74	-0.32	0.270
38	117.78	118.16	-0.38	0.325
39	117.16	117.60	-0.44	0.376
40	116.60	117.05	-0.45	0.383
41	116.01	116.51	-0.50	0.430
42	115.49	115.99	-0.49	0.428
43	114.93	115.47	-0.54	0.469
44	114.39	114.97	-0.58	0.503
45	113.91	114.47	-0.56	0.494
46	113.40	113.99	-0.59	0.522
47	112.94	113.52	-0.57	0.509
48	112.45	113.05	-0.60	0.534



Target Segment, Total Decay Heat

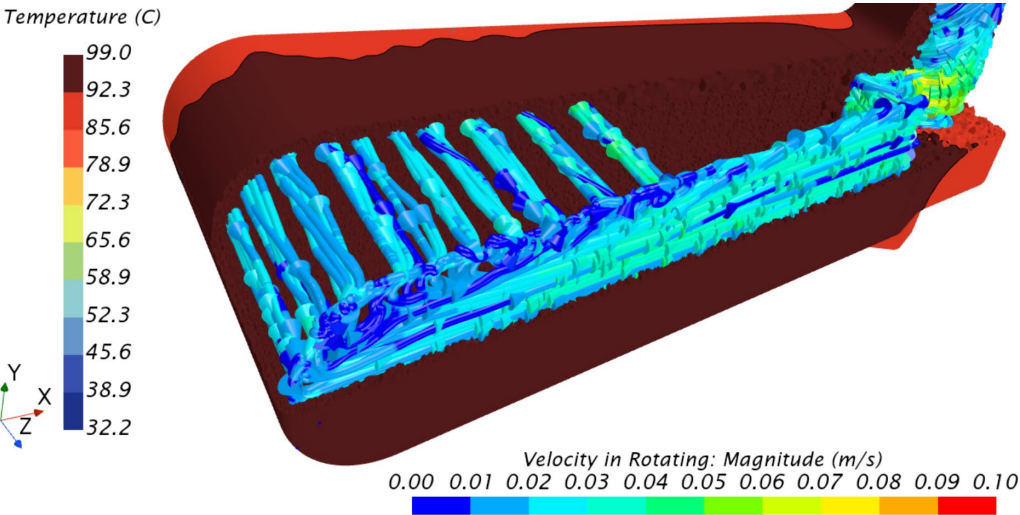


Day 2 : Target Segment Analysis

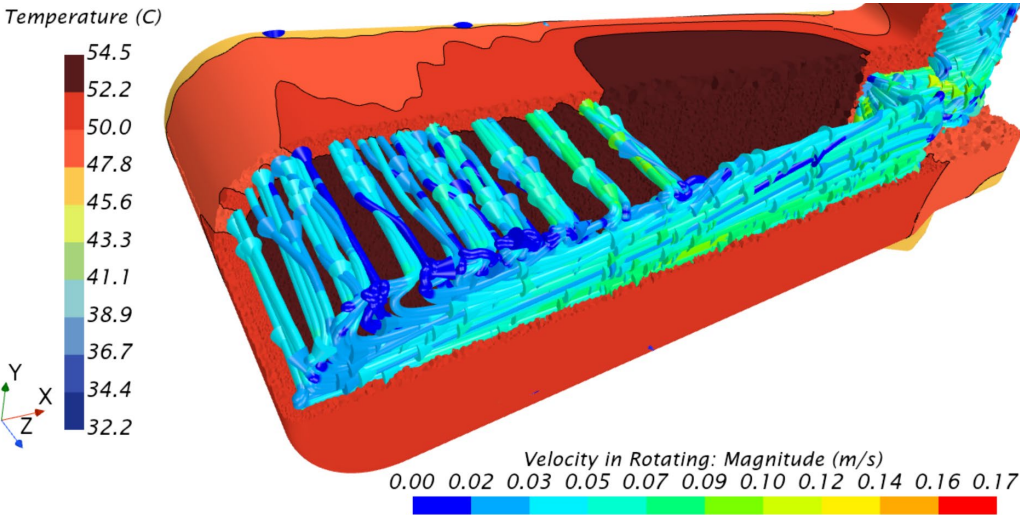
- Results
 - **Maintenance Temperature**
 - Decay Heat
 - **Under Reduced Flow Rate (0.1 & 0.2 GPM)**

Maintenance Temperature of Target Segment under Reduced Flow Rates

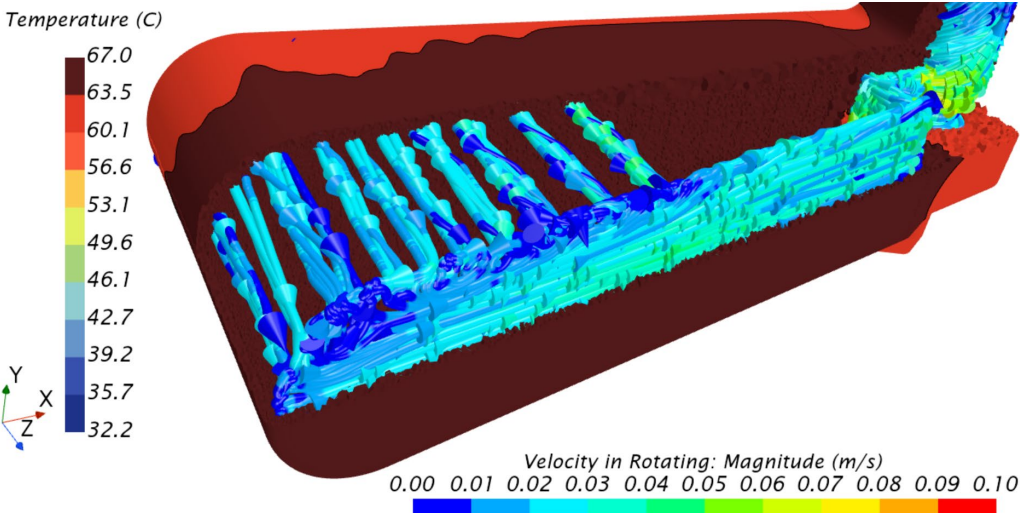
0-hour decay heat: 294.15 W; 0.1 GPM



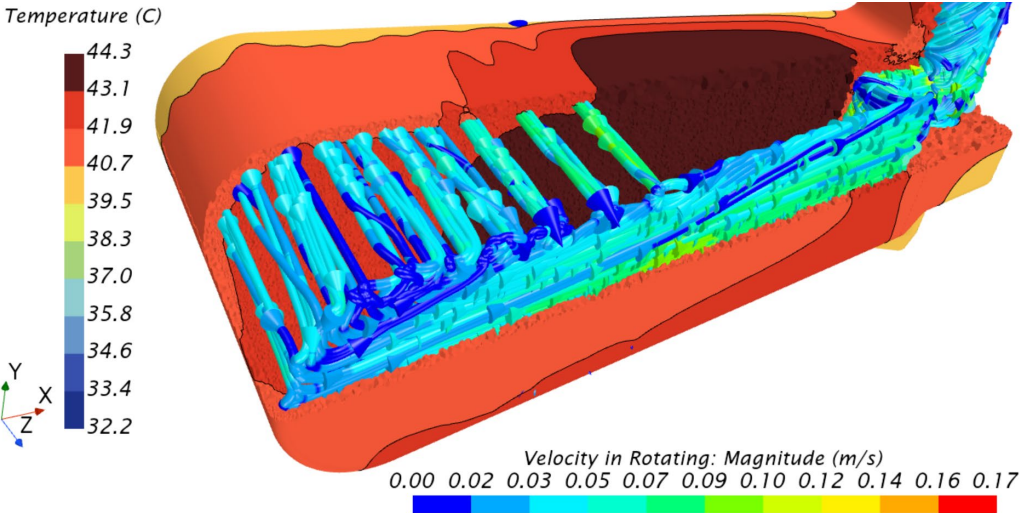
0-hour decay heat: 294.15 W; 0.2 GPM



8-hour decay heat: 151.06 W; 0.1 GPM



8-hour decay heat: 151.06 W; 0.2 GPM



Maintenance Temperature of Target Segment under Reduced Flow Rates

For **Single** target segment

0-hour decay heat: 294.15 W

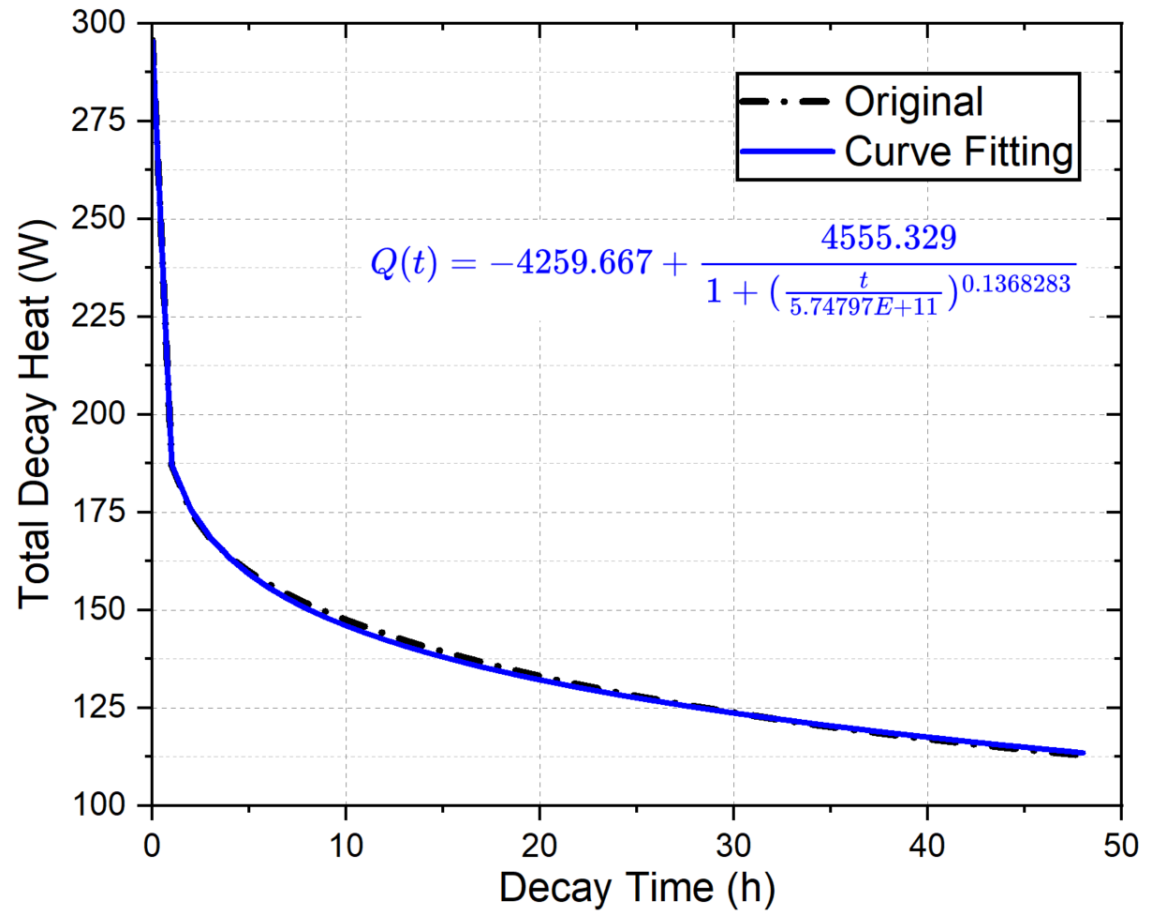
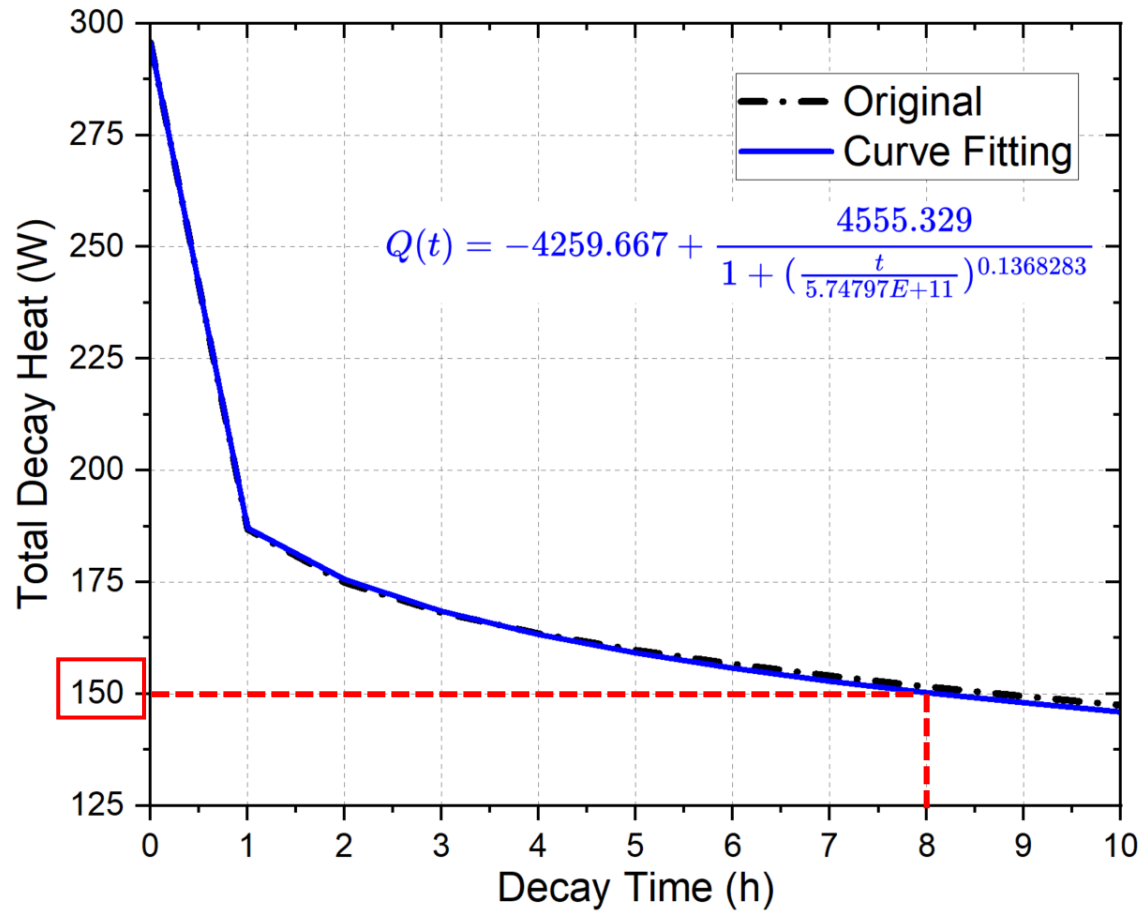
8-hour decay heat: 151.06 W

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

Day 2 : Target Segment Analysis

- Results
 - **Maintenance Temperature**
 - Decay Heat
 - Under Reduced Flow Rate (0.1 & 0.2 GPM)
 - Immediately after Shutdown **with Active Internal** Water Cooling (7.5GPM) **(Transient)**

Target Segment, Total Decay Heat

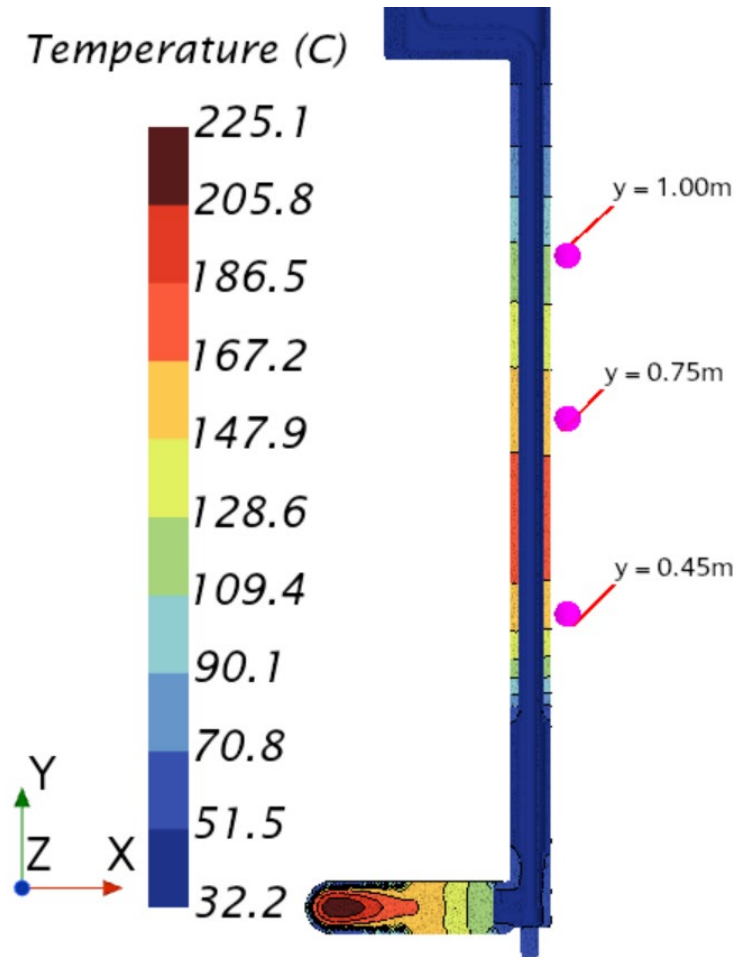


Target Segment, **Steady State**

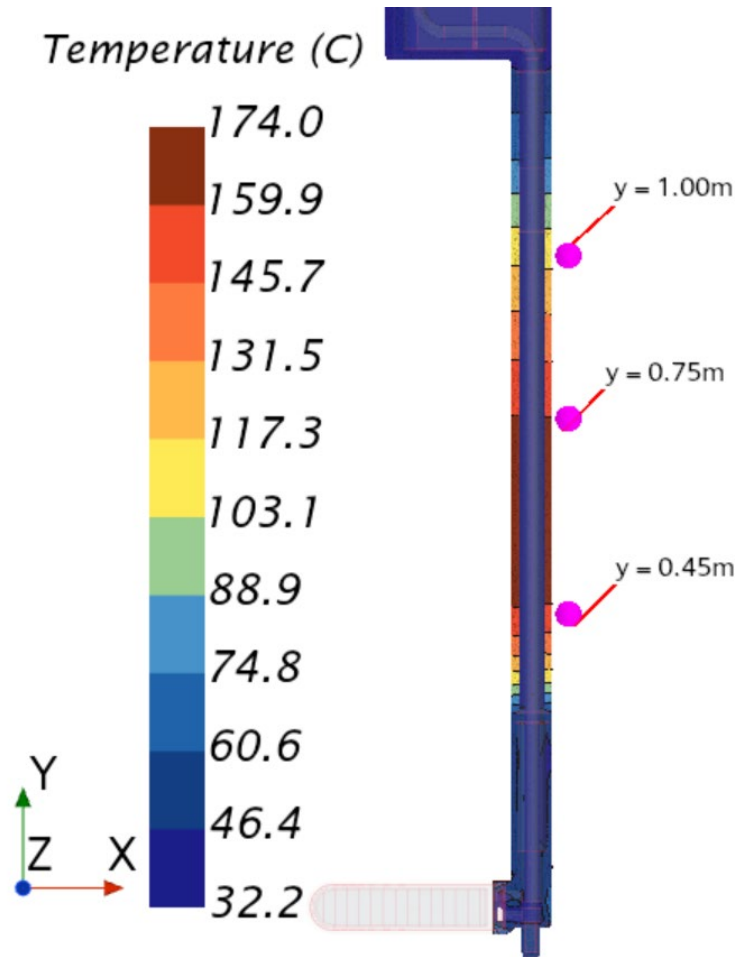
Not FDR Design

Without Thermal Radiation, Nominal Flow Rate (7.5 GPM)

Target Segment Temperature



Stainless Steel Temperature



Target Segment, **Steady State**

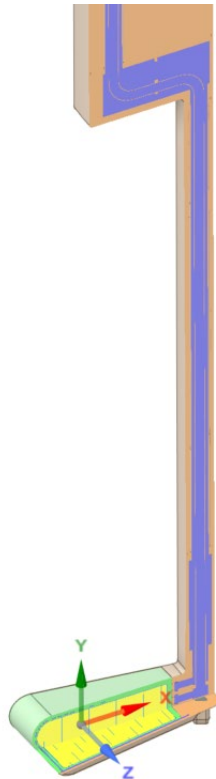
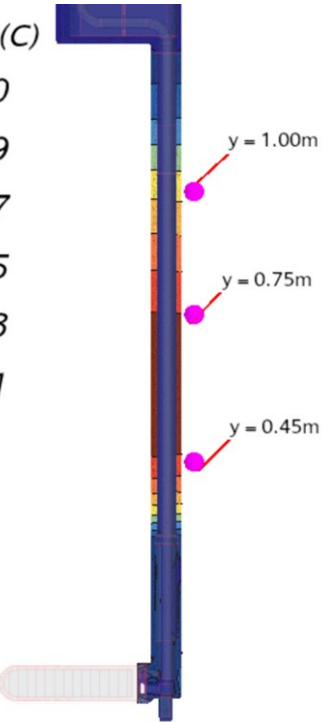
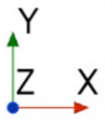
Not FDR Design

Without Thermal Radiation, Nominal Flow Rate (7.5 GPM)

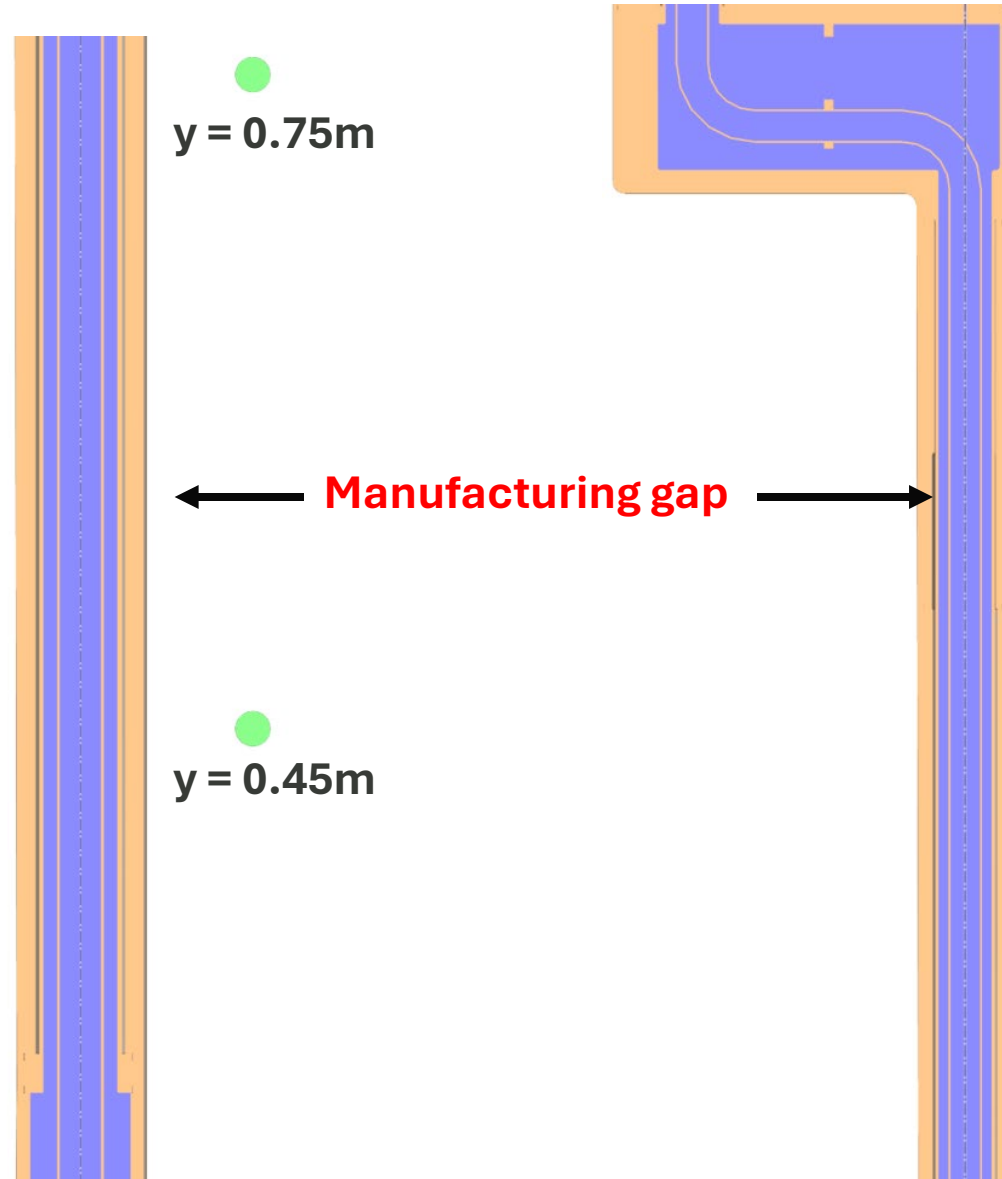
Stainless Steel Temperature

Temperature (C)

174.0
159.9
145.7
131.5
117.3
103.1
88.9
74.8
60.6
46.4
32.2



• $y = 0.75\text{m}$
• $y = 0.45\text{m}$



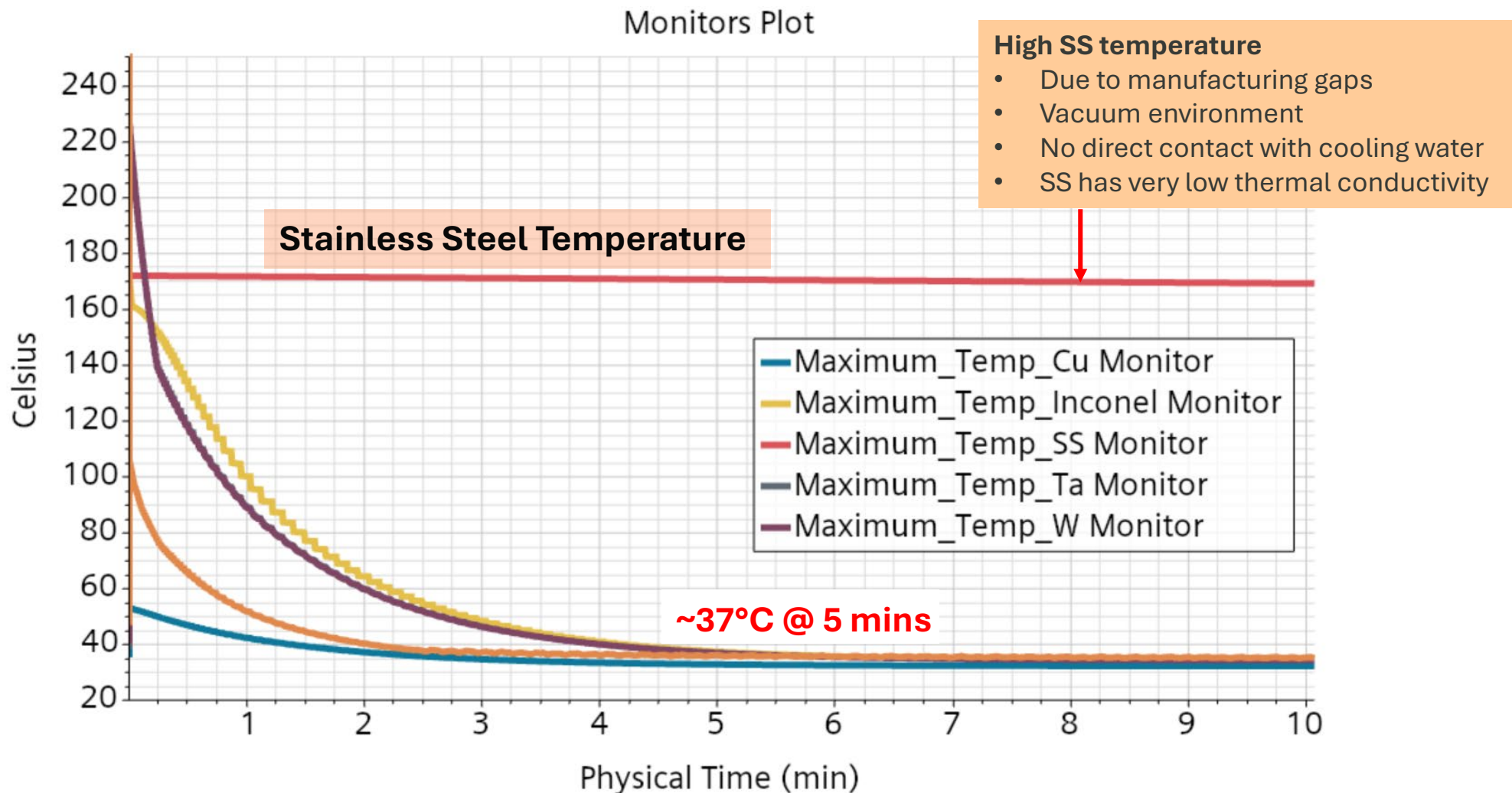
• $y = 0.75\text{m}$

Temperature Profile with Decay Heat (2025), Multiple W Blocks and Ta Plates

Not FDR Design

Without Thermal Radiation, Nominal Flow Rate (7.5 GPM)

Variable Time Step (dt_Max = 5s); Decay Heat: Target Foot Only



- For the beam-off condition, after about **10 minutes** of **active cooling (7.5 GPM)**, the tungsten block can be cooled down to room temperature.

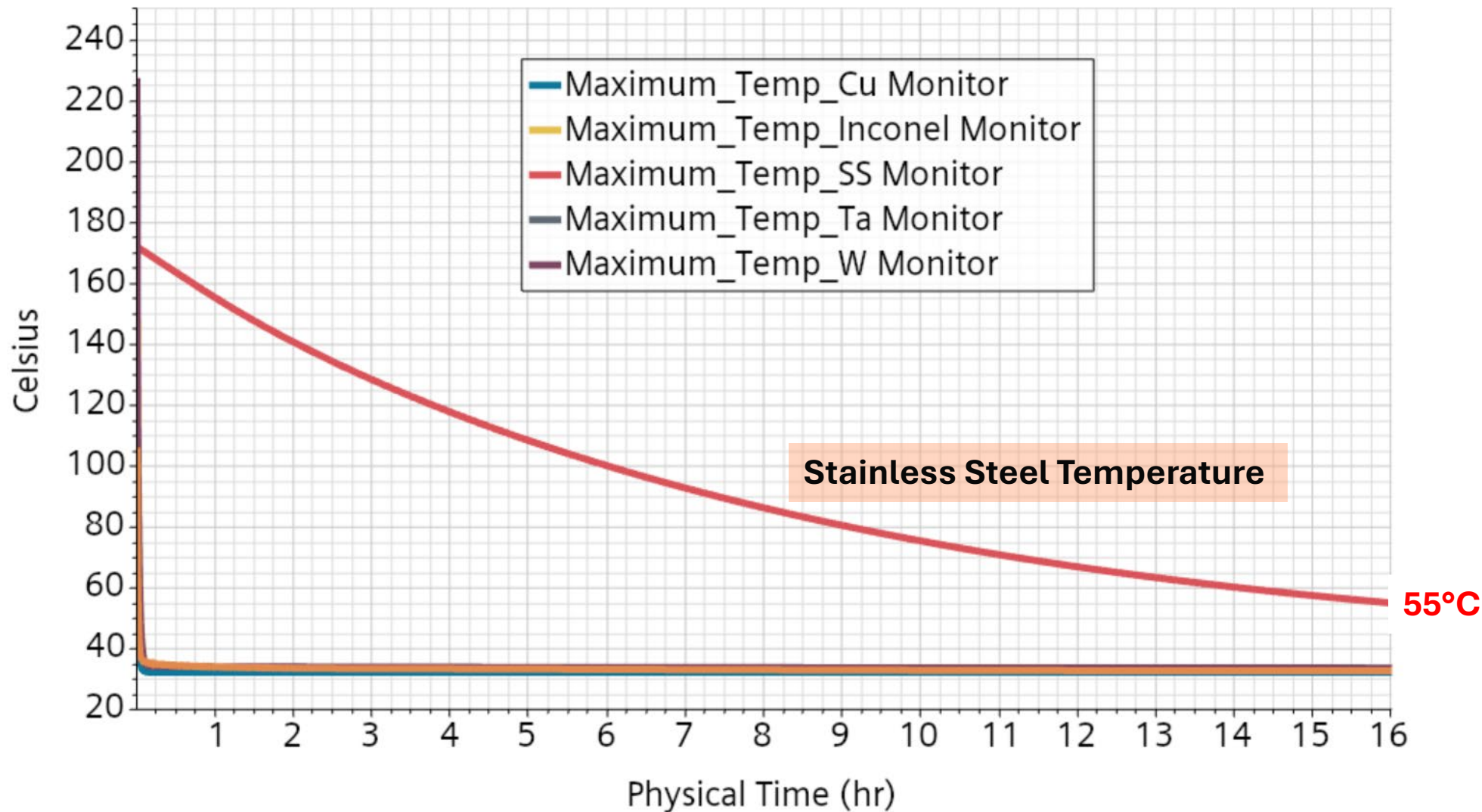
Temperature Profile with Decay Heat (2025), Multiple W Blocks and Ta Plates

Not FDR Design

Without Thermal Radiation, Nominal Flow Rate (7.5 GPM)

Variable Time Step (dt_Max = 5s); Decay Heat: Target Foot Only

Monitors Plot



Temperature Profile with Decay Heat (2025), Multiple W Blocks and Ta Plates

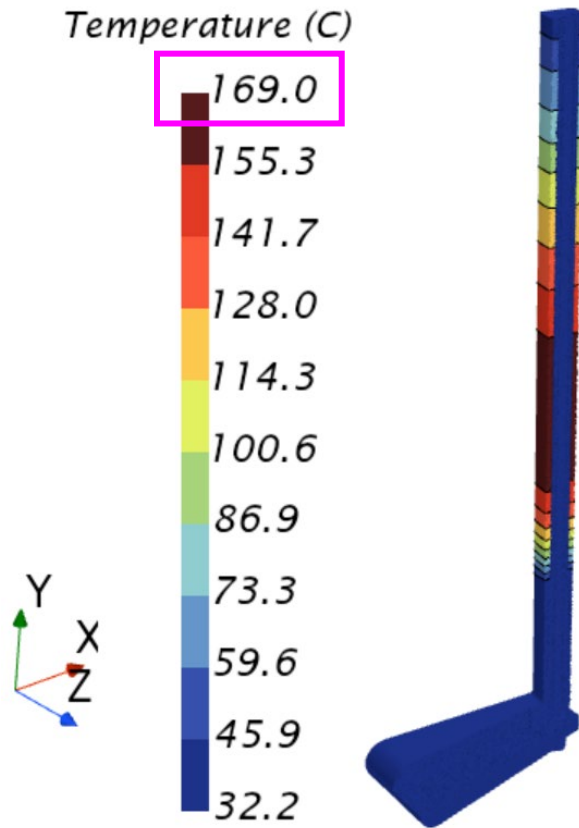
Not FDR Design

Without Thermal Radiation, Nominal Flow Rate (7.5 GPM)

Variable Time Step (dt_Max = 5s); Decay Heat: Target Foot Only

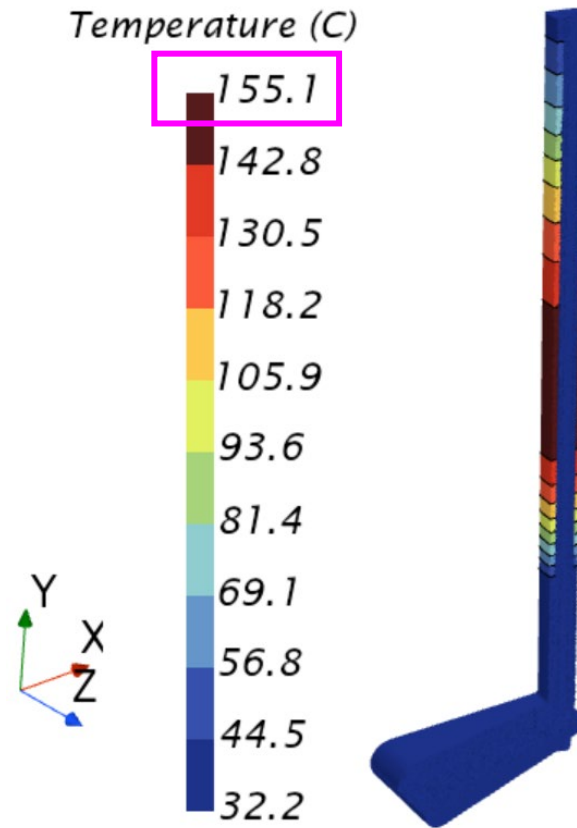
10 mins Peak: 169°C

Solution Time 603.834 (s)



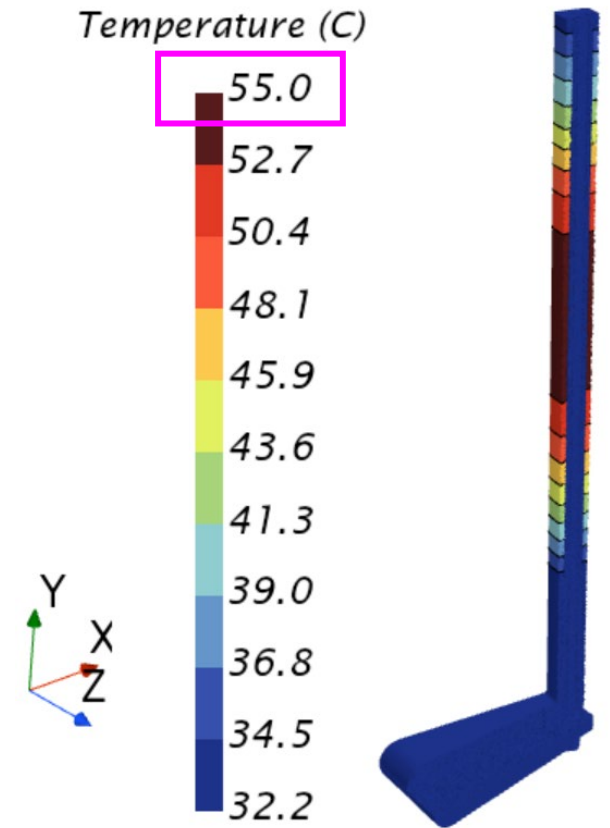
1 hr Peak: 155°C

Solution Time 3604.89 (s)



16 hrs Peak: 55°C

Solution Time 57601.9 (s)



Temperature Profile with Decay Heat (2025), Multiple W Blocks and Ta Plates

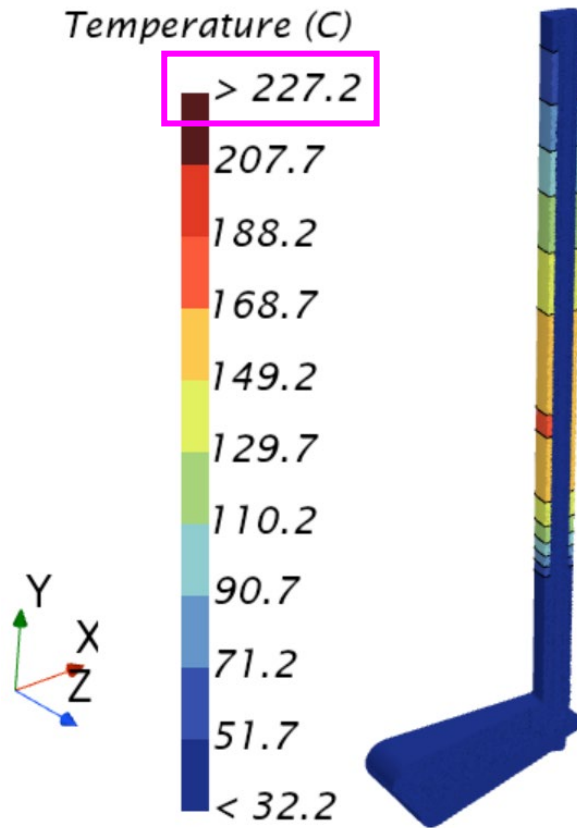
Not FDR Design

Without Thermal Radiation, Nominal Flow Rate (7.5 GPM)

Variable Time Step (dt_Max = 5s); Decay Heat: Target Foot Only

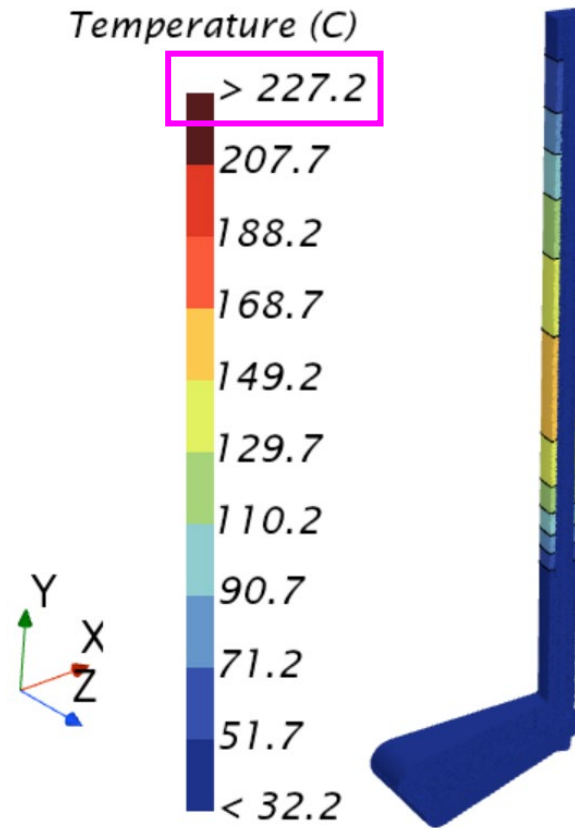
10 mins Peak: 169°C

Solution Time 603.834 (s)



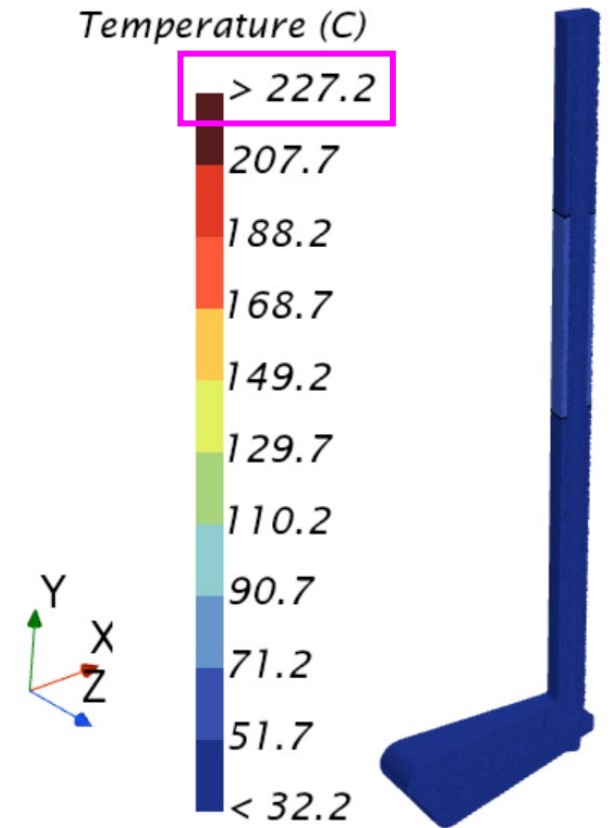
1 hr Peak: 155°C

Solution Time 3604.89 (s)



16 hrs Peak: 55°C

Solution Time 57601.9 (s)



Day 2 : Target Segment Analysis

- **Results**

- **Maintenance Temperature**

- Decay Heat
 - Under Reduced Flow Rate (0.1 & 0.2 GPM) (Steady State)
 - Immediately after Shutdown with Active Internal Water Cooling (7.5GPM) (Transient)
 - **Loss of Cooling**
 - ❑ **Without Active** Cooling **(Transient)**

Maintenance Temperature Simulations, Geometry

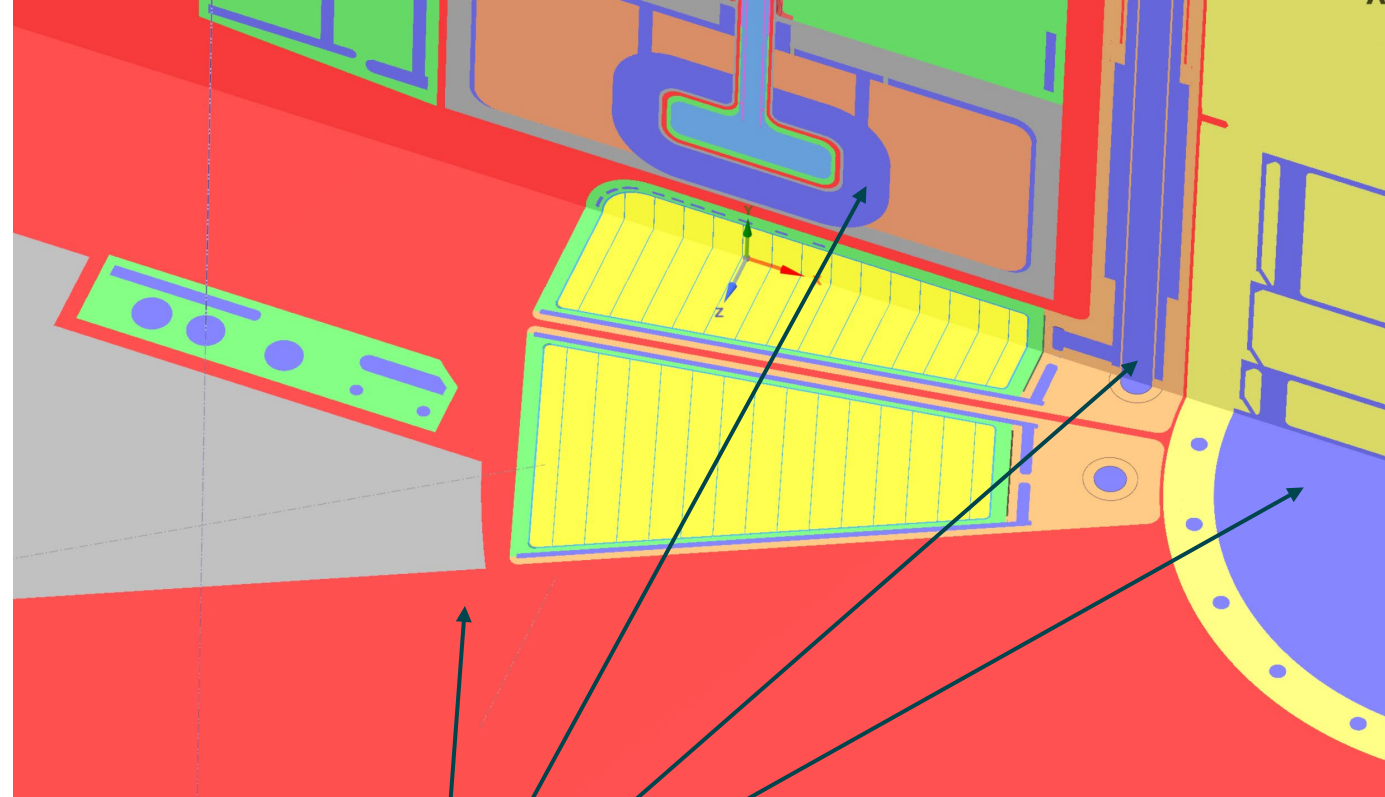
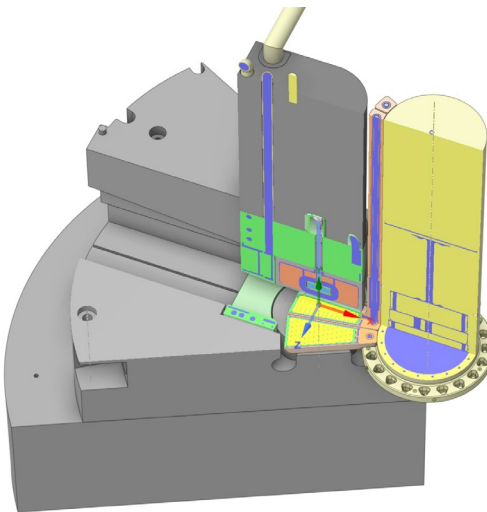
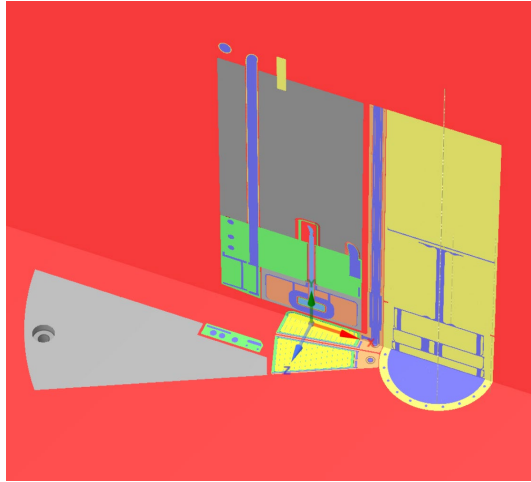
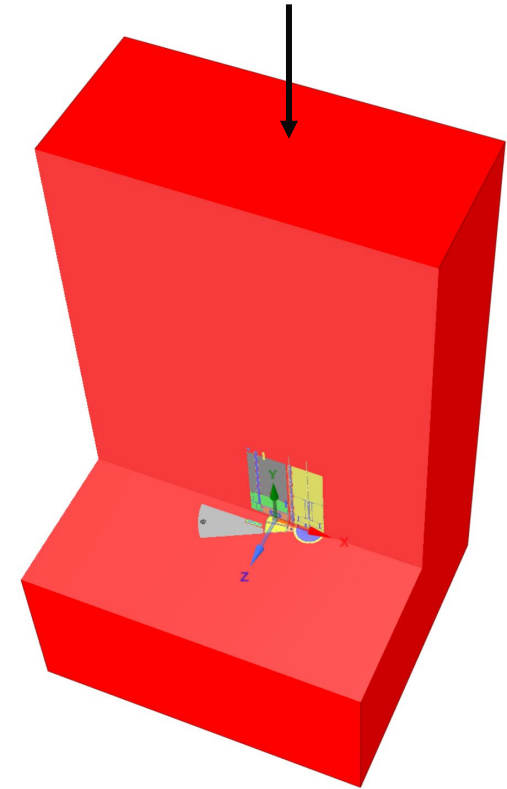
Beam Off, Without Active Cooling, Decay Heat, With Thermal Radiation

Boundary Condition: 30°C Air

- **Shielding blocks** are initially at **32.22 °C**.

Without Active Cooling

- The MRA and target shaft are initialized at their steady-state temperatures



Air (water volumes treated as air)

- Air is included in the simulation to account for heat conduction.

Maintenance Temperature Simulations, Initial Condition

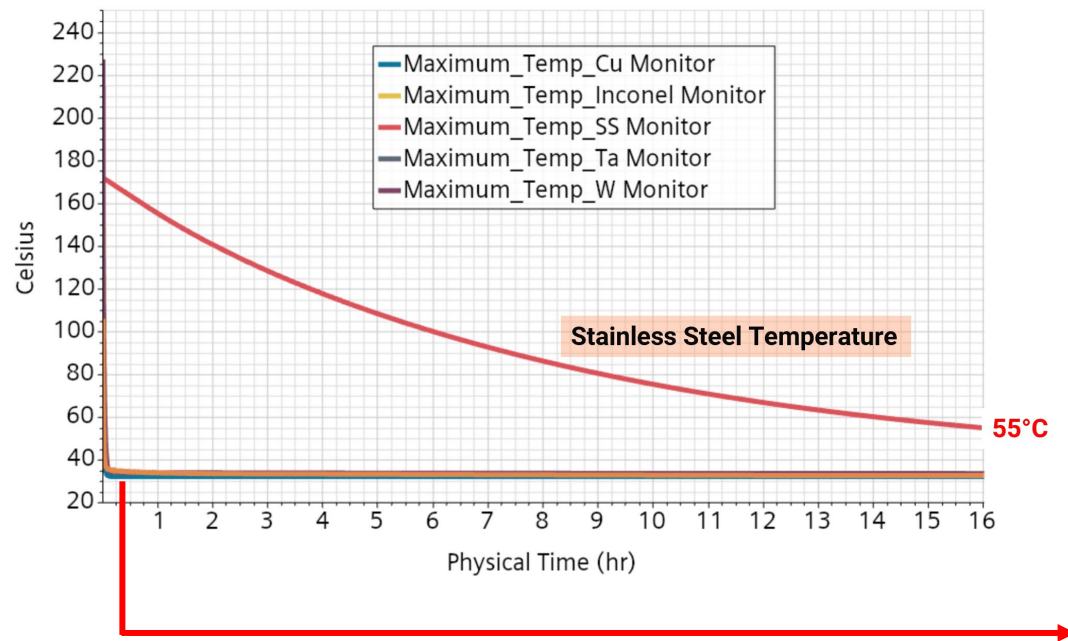
Beam Off ,Without Active Cooling, Decay Heat, With Thermal Radiation

Temperature Profile with Decay Heat (2025), Multiple W Blocks and Ta Plates

Without Thermal Radiation, Nominal Flow Rate (7.5 GPM)

Variable Time Step ($dt_{Max} = 5s$); Decay Heat: Target Foot Only

Monitors Plot

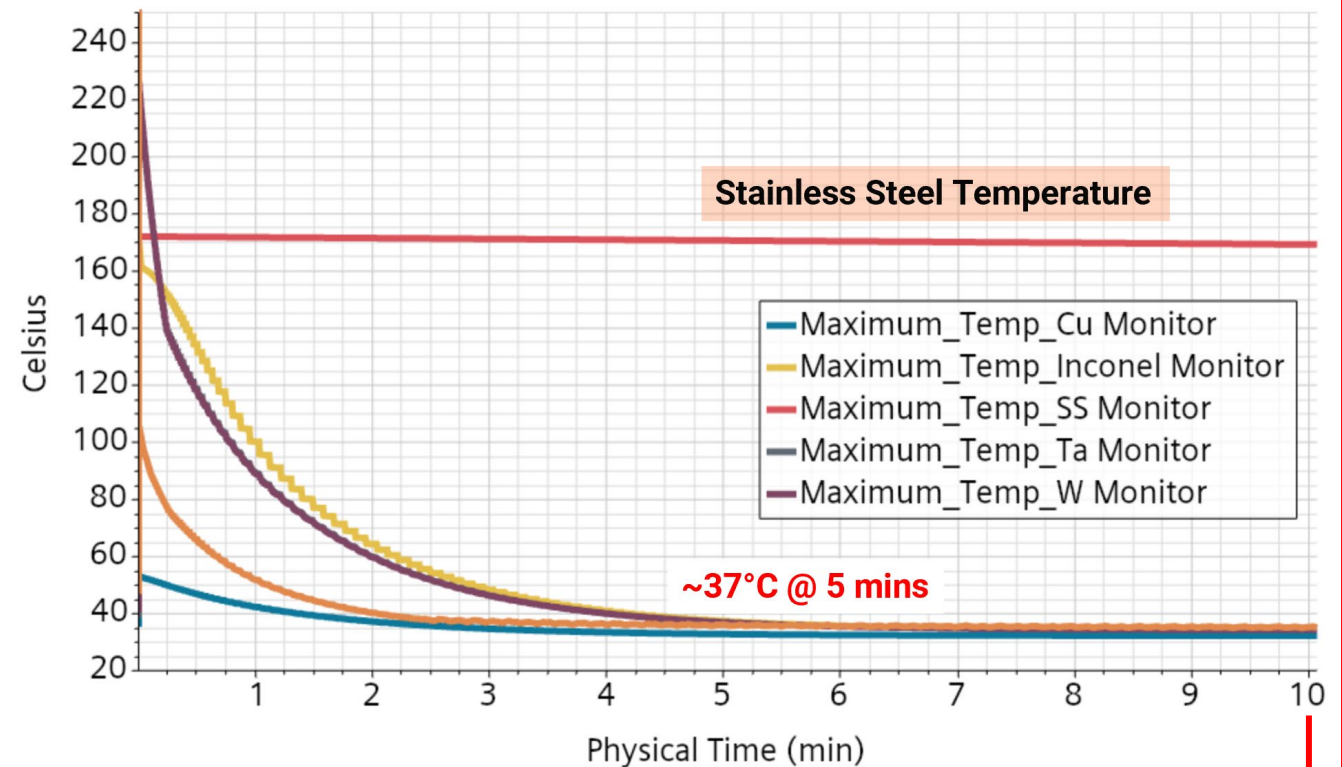


Temperature Profile with Decay Heat (2025), Multiple W Blocks and Ta Plates

Without Thermal Radiation, Nominal Flow Rate (7.5 GPM)

Variable Time Step ($dt_{Max} = 5s$); Decay Heat: Target Foot Only

Monitors Plot



Initial Condition

Without Active Cooling

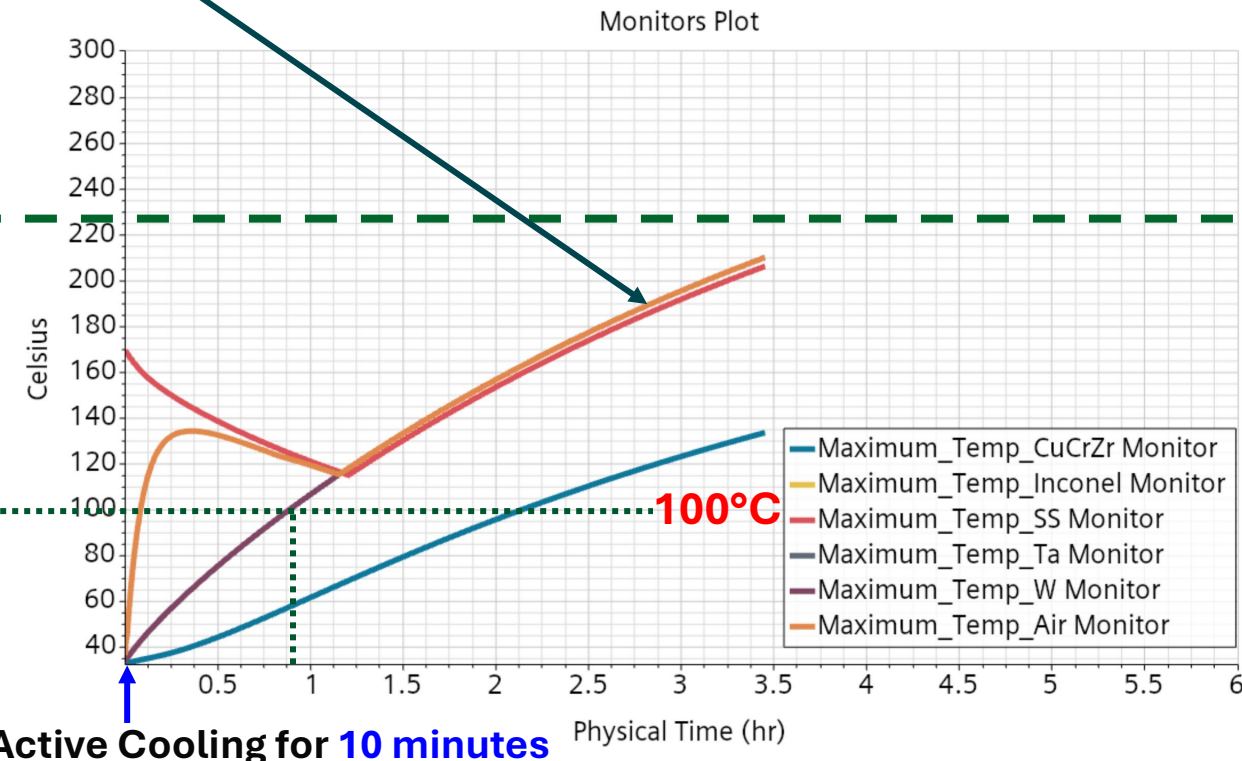
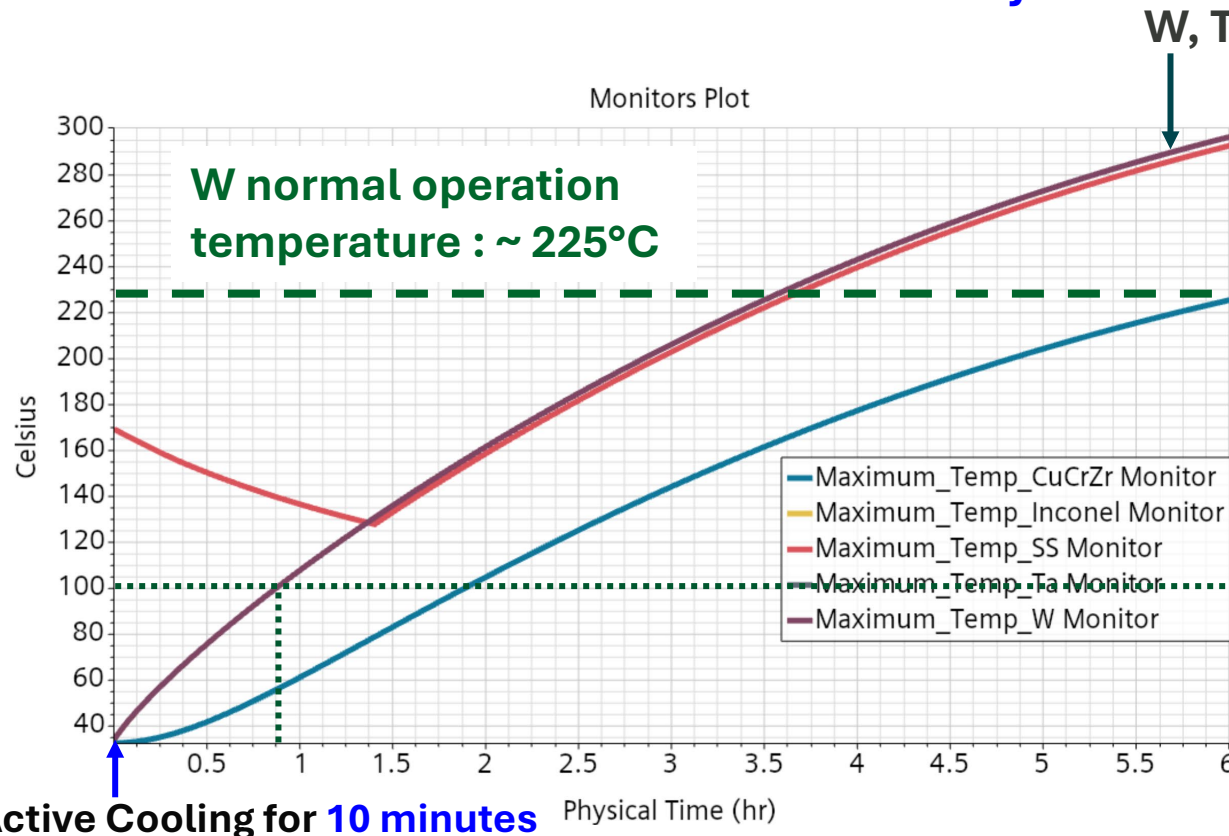
Maintenance Temperature Simulations, Temperature

Without Air/Water (With Target Shaft Geometry)

With Air in all Fluid Domain (With Target Shaft Geometry)

Run Time: 1 hour / ~1 day

Run Time: 1 hour / ~3 days



- Difference between **normal operation** and the case heated up by **decay heat**

▶ • **Normal Operation:** Inconel is much cooler than W and Ta.

▶ • **Decay Heat:** No flowing water, **uniform** temperature for the whole target block (W, Ta, Inconel)

➔ **stress issue** (from Joey's and Tom's simulations)

➔ With a **uniform** temperature profile (**decay heat**), the target block should be maintained **below 100°C—150°C**.

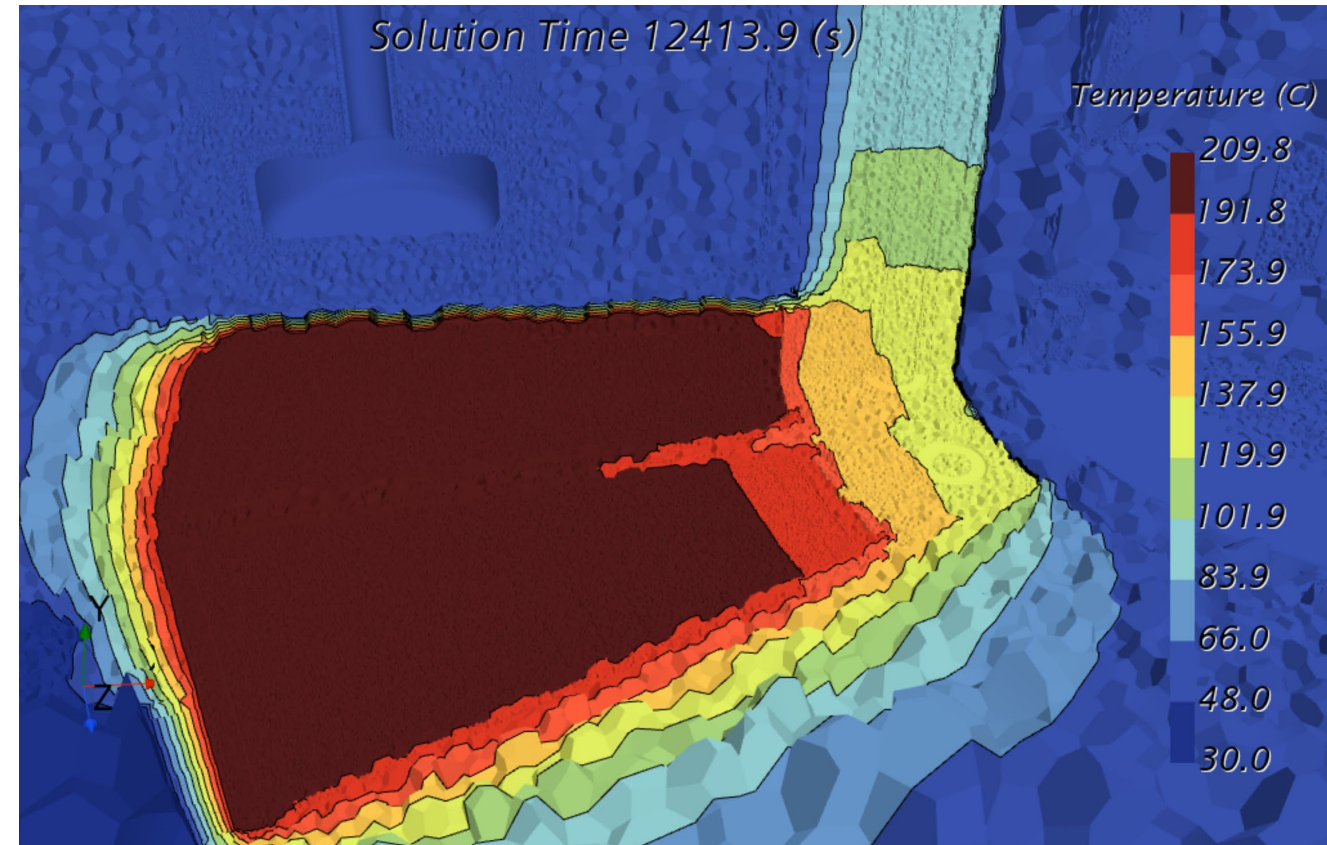
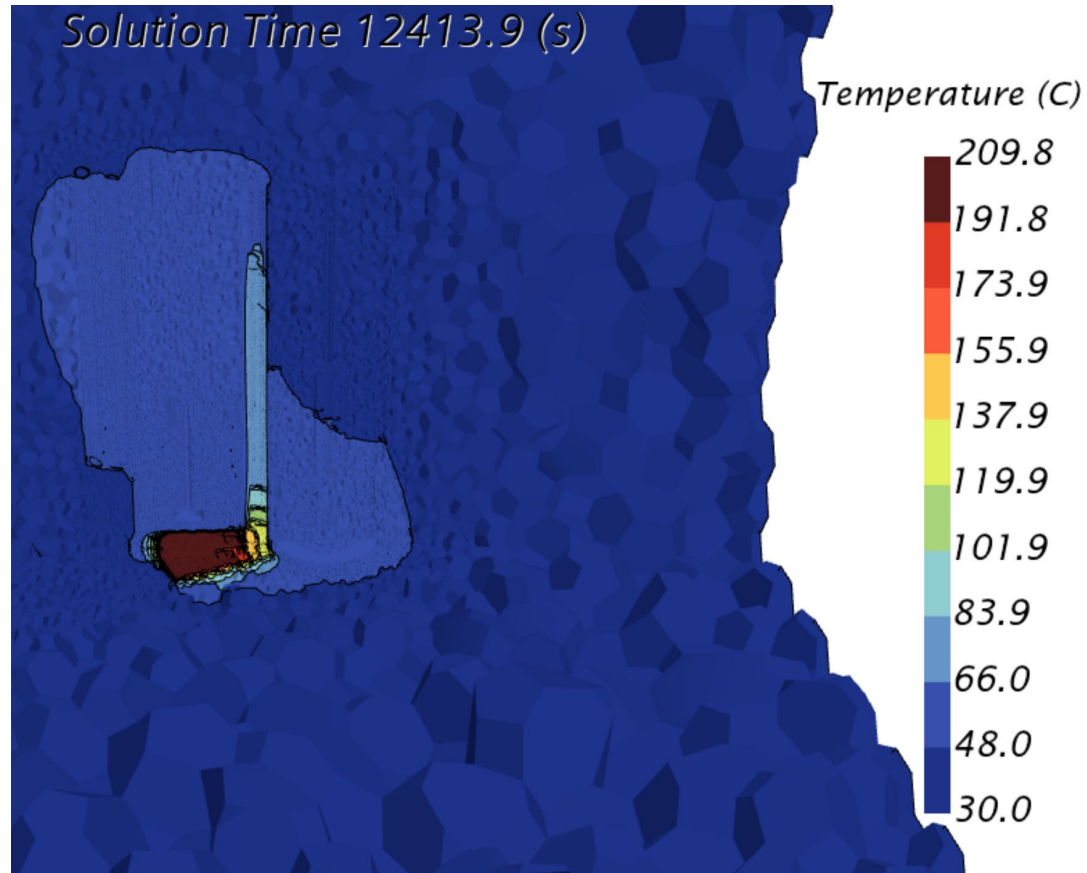
Maintenance Temperature Simulations, Temperature

With Air (With Target Shaft Geometry)

Without Active Cooling

Time: 3.4 hrs

Temperature of Solids and Air



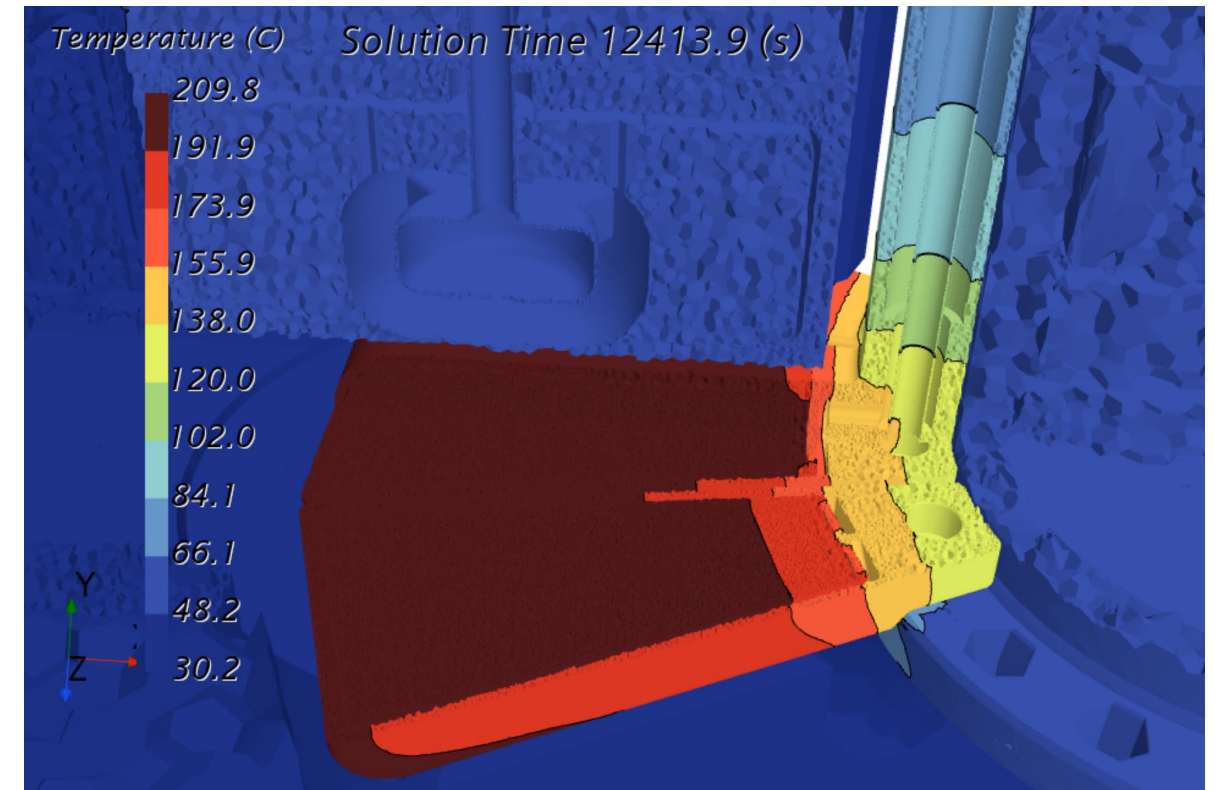
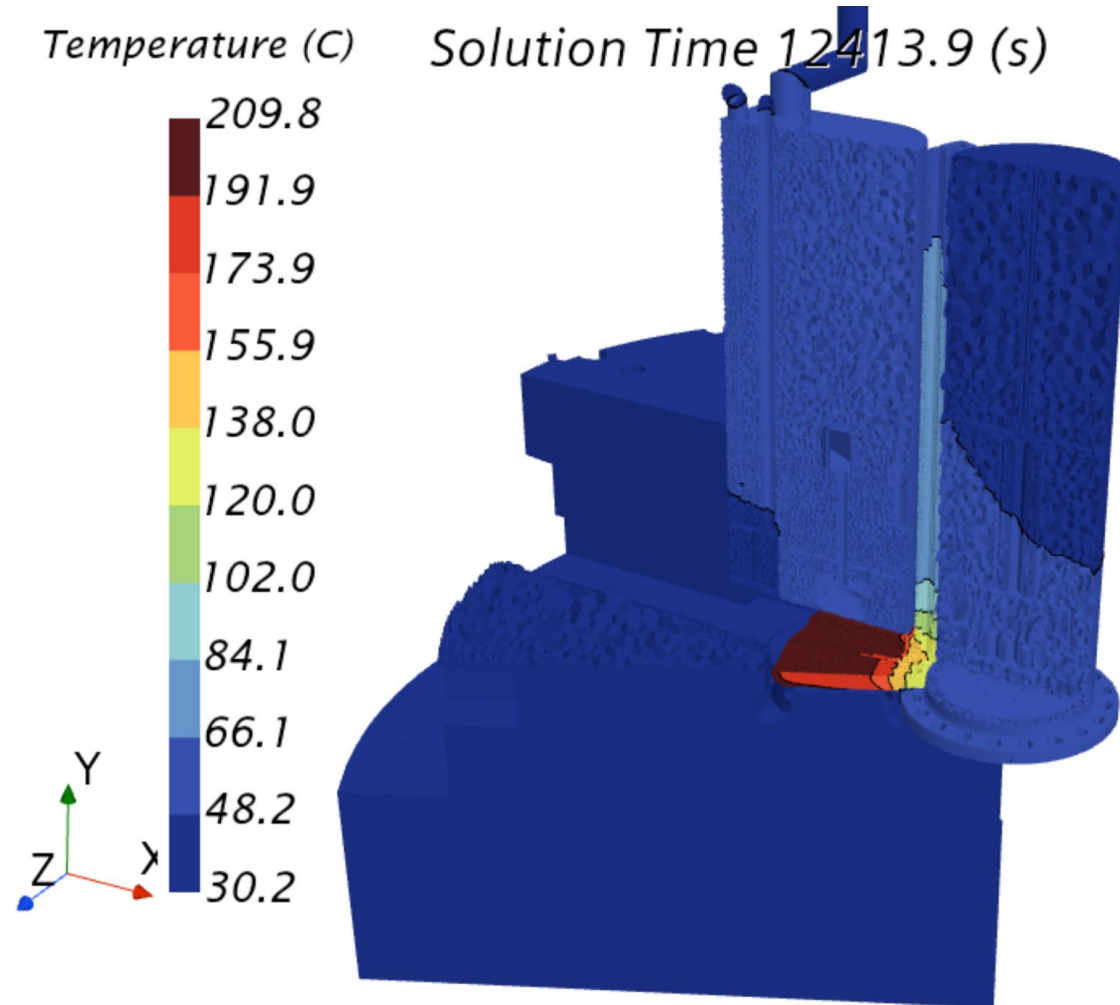
Maintenance Temperature Simulations, Temperature

With Air (With Target Shaft Geometry)

Time: 3.4 hrs

Without Active Cooling

Temperature of Solids

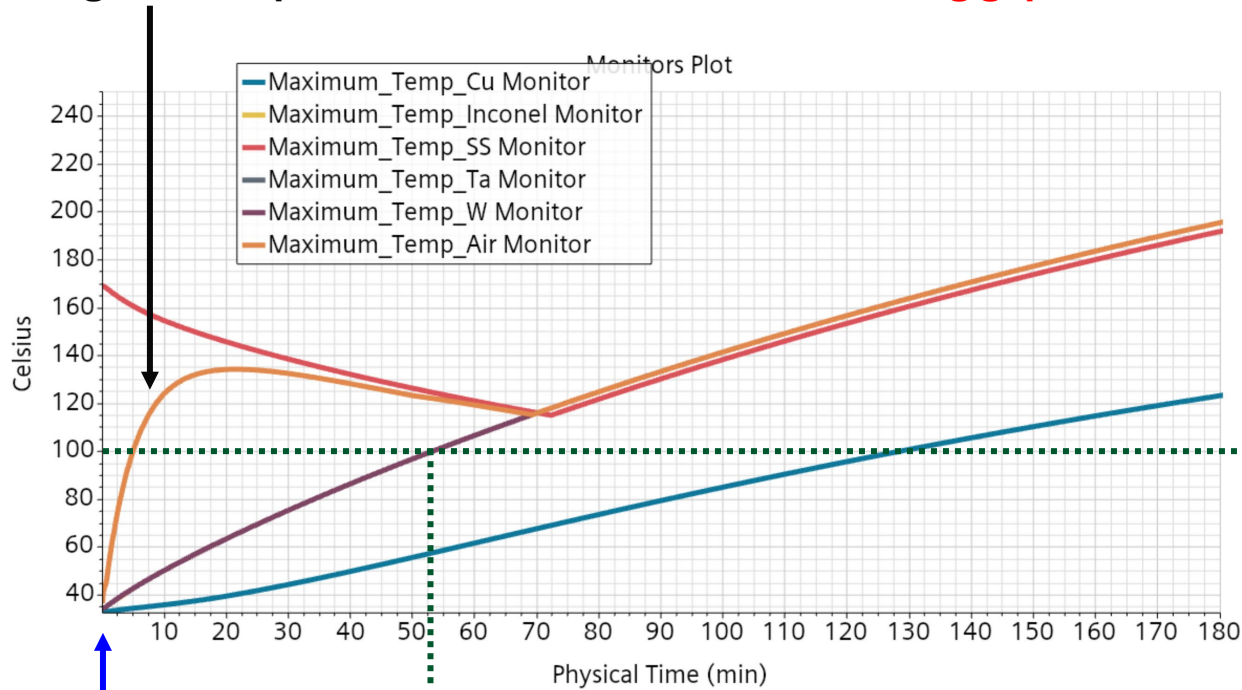


Maintenance Temperature Simulations, Temperature

Air in All Fluid Regions

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

High air temperature around the “manufacturing gaps”



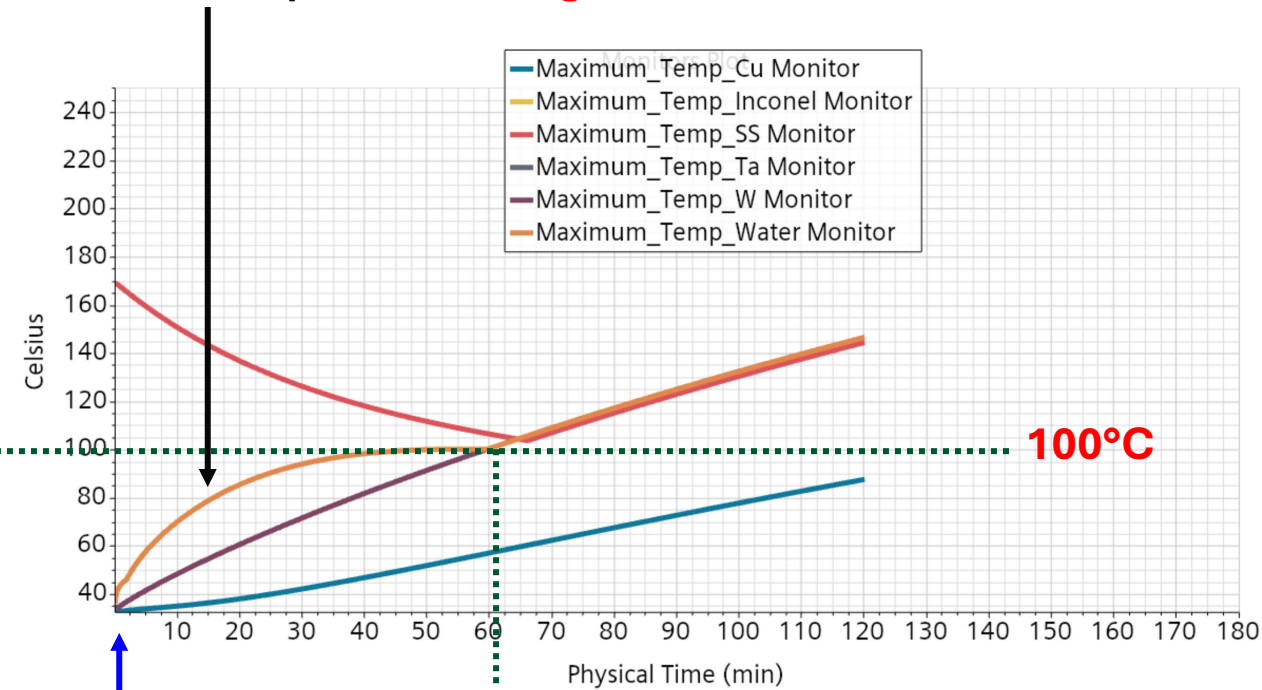
53 mins

Active Cooling for 10 minutes

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

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

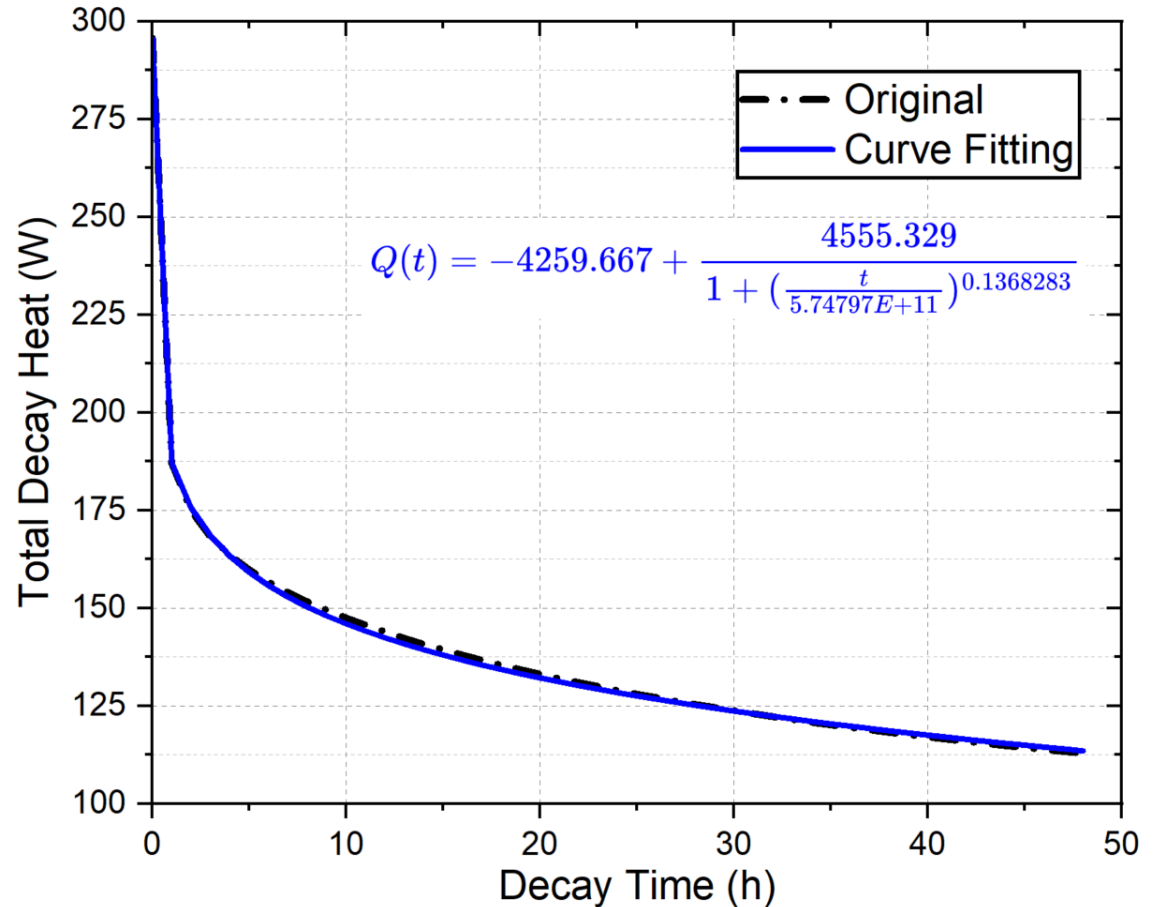
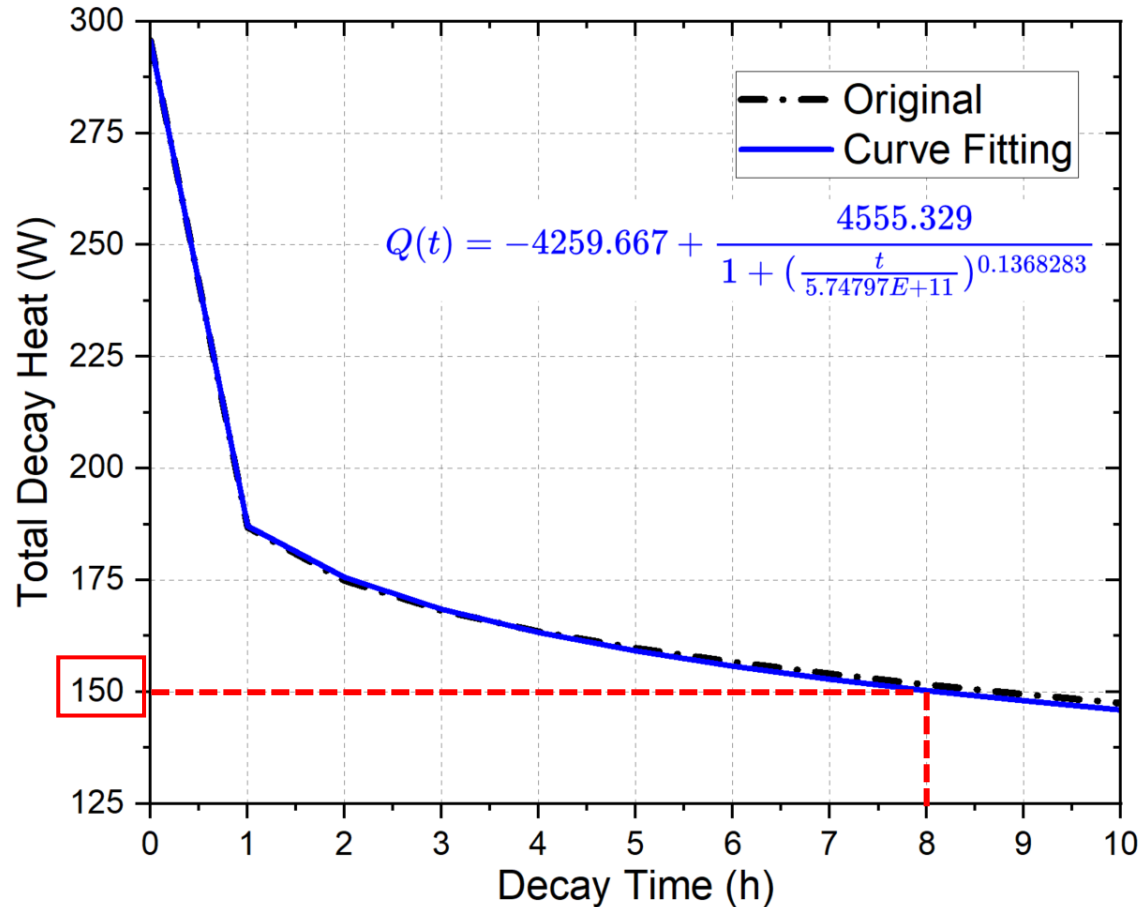
Peak water temperature in target “foot”



60 mins

Active Cooling for 10 minutes

Target Segment, Total Decay Heat



- After **8 hours**, decay heat drops to about **half** of its value at zero minutes.

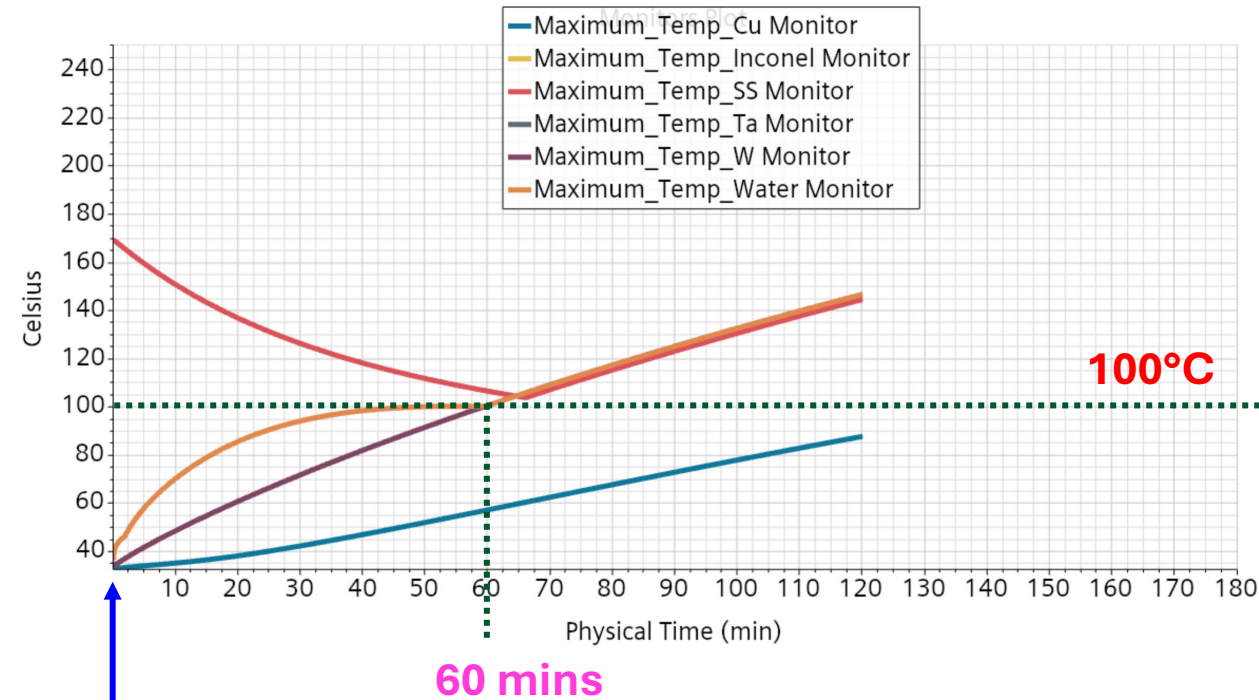
Maintenance Temperature Simulations, Temperature

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

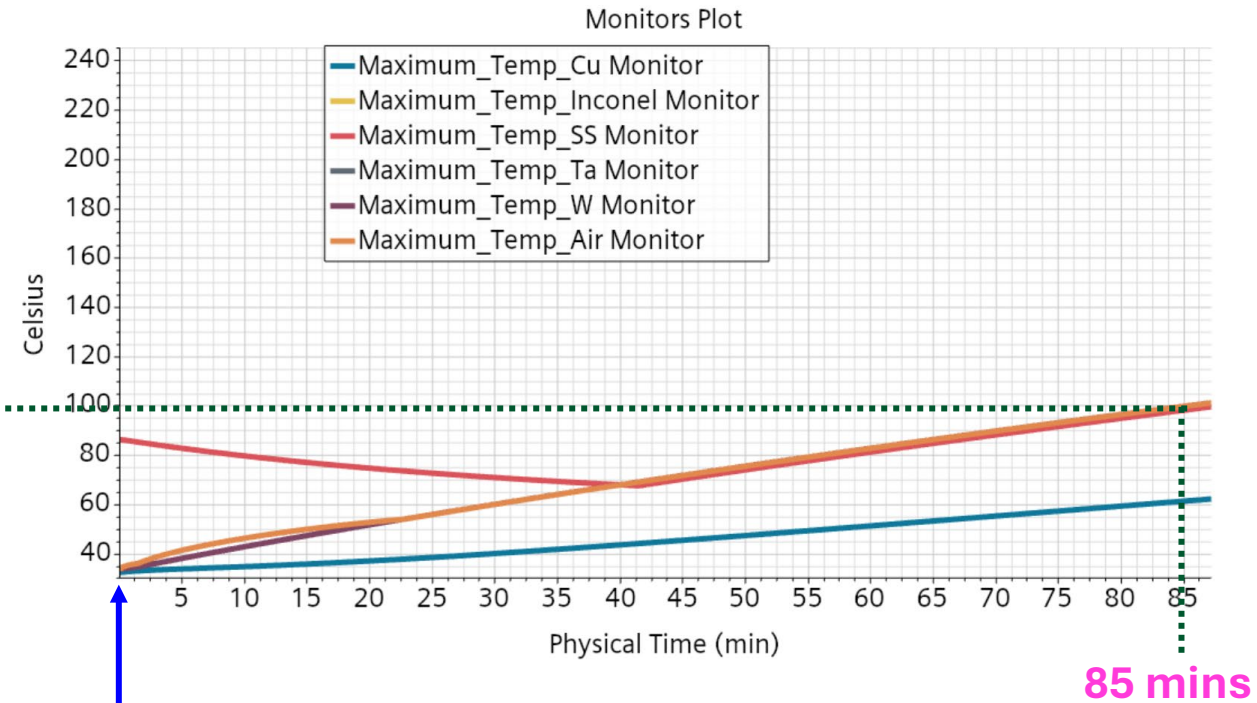
Without Active Cooling

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)



Active Cooling for 10 minutes



Active Cooling for 8 hours

- 60-85 minutes is not enough to perform maintenance.

Maintenance Temperature Simulations, Temperature

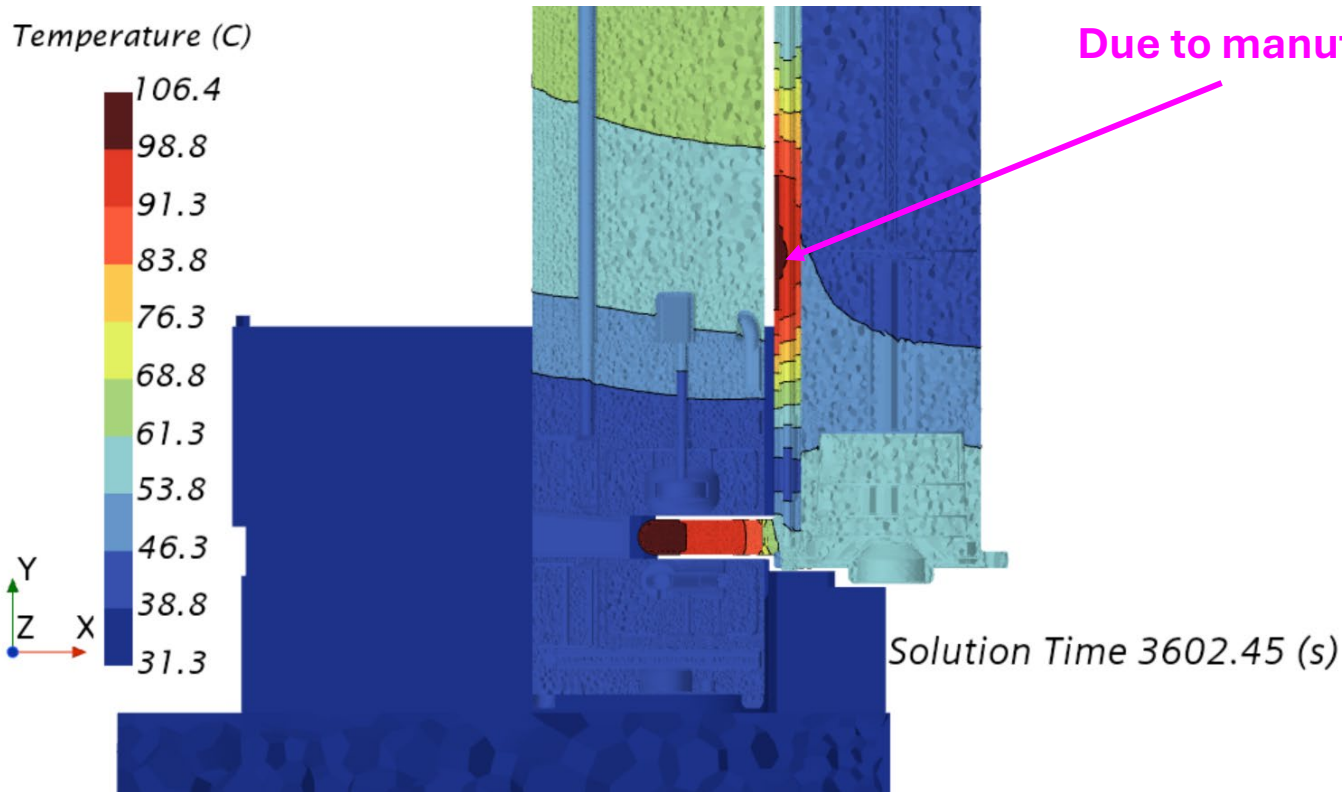
Stagnant Water in Segments, Shaft, and MRA + Surrounding Air

Without Active Cooling

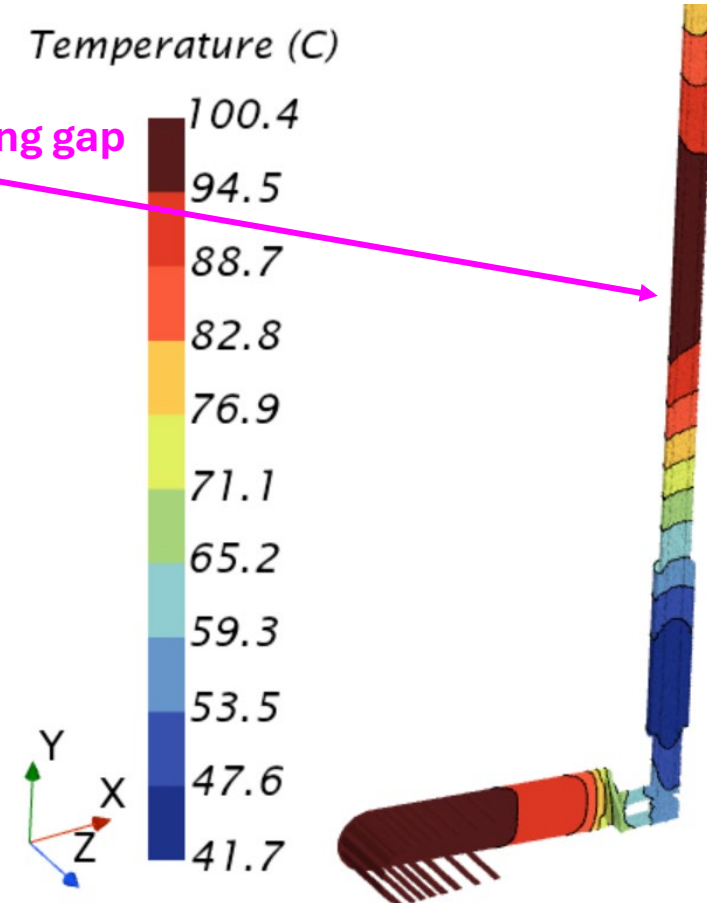
Active Cooling for 10 minutes, Heat Up by Decay Heat (Starting at 0 hr)

1 hr

Solid Temperature



Water Temperature

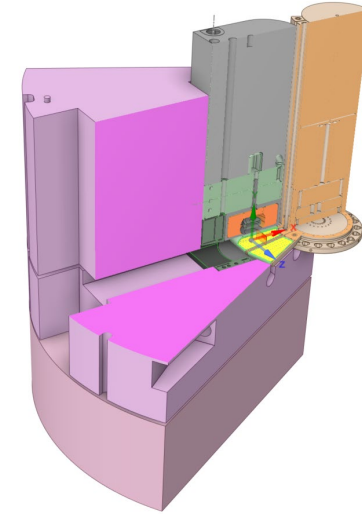


Maintenance Temperature Simulations, Temperature

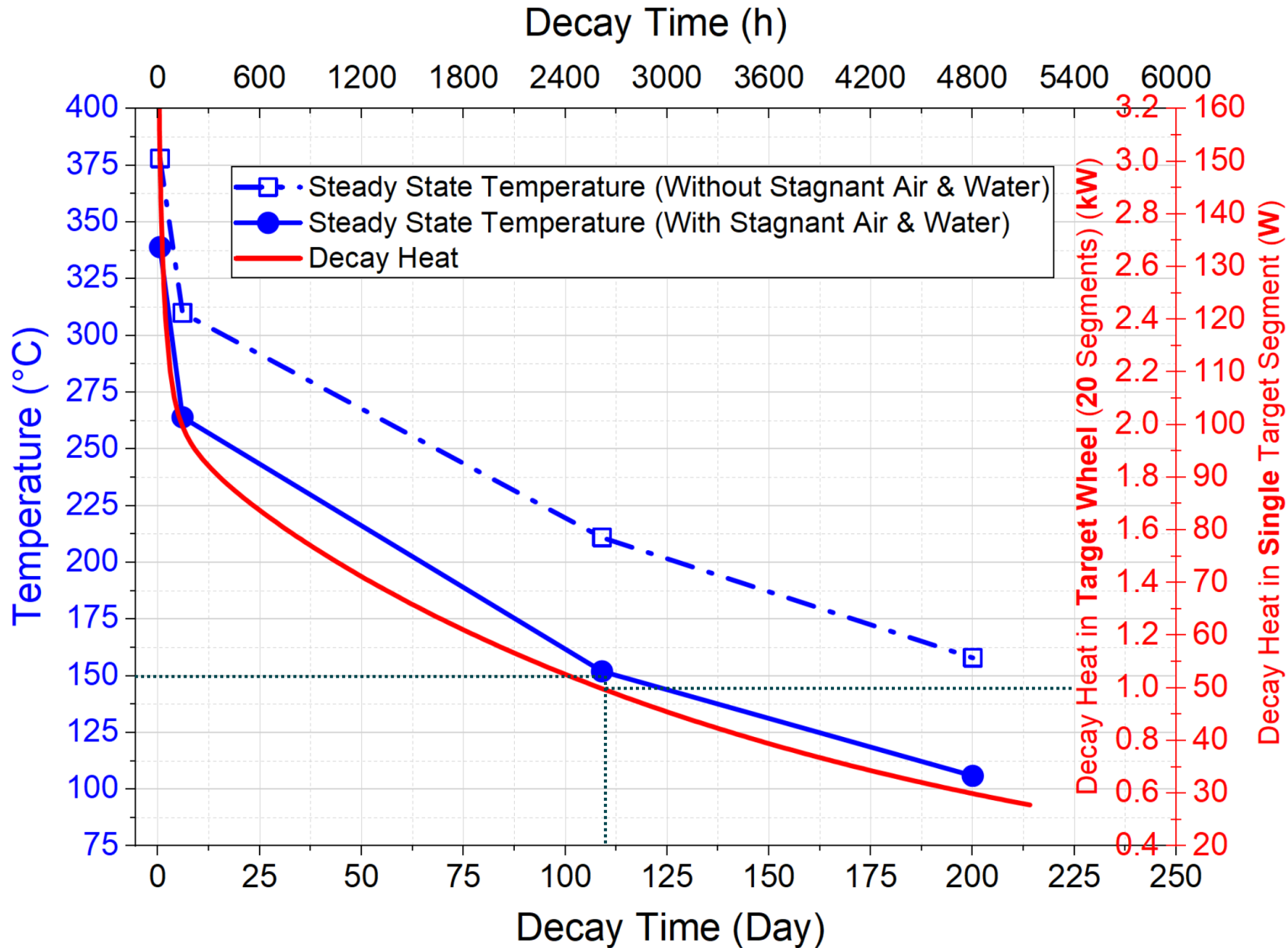
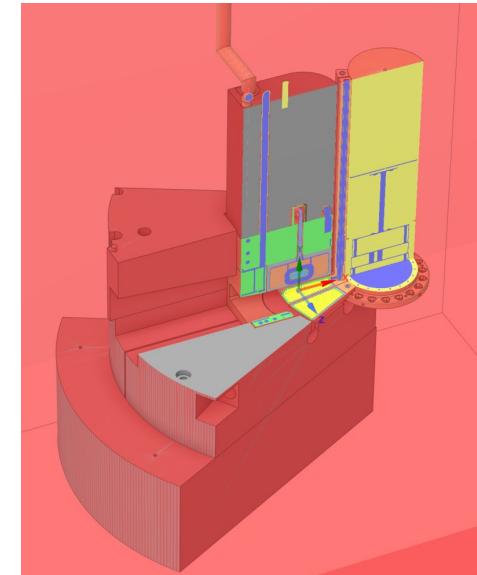
Decay Heat Calculation done by Tucker McClanahan

Without Active Cooling

Without Stagnant Air & Water



With Stagnant Air & Water



Maintenance Temperature Simulations, Temperature

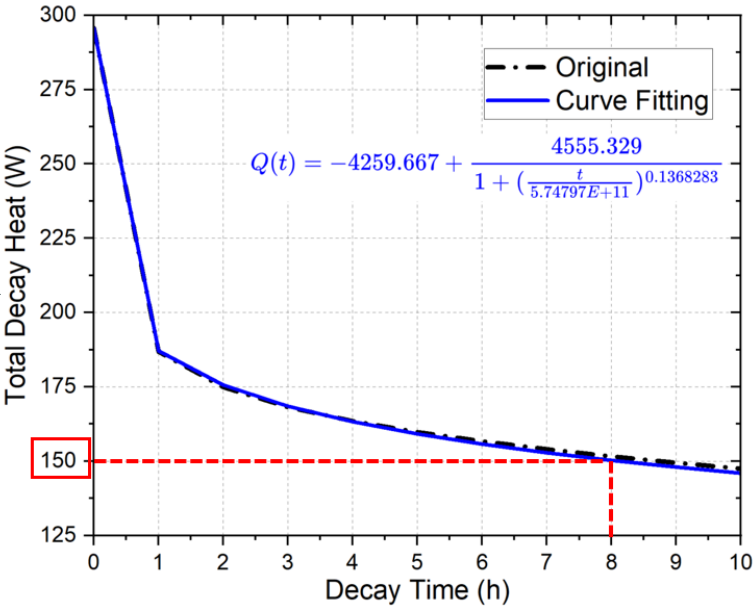
Decay Heat Calculation done by Tucker McClanahan

Without Active Cooling

Single Segment		20 Segments (Target Wheel)		Steady State, No Air ; No Stagnant Water		Steady State, Air & Stagnant Water	
Decay Time (h)	Decay Time (Day)	Decay Heat (W)	Decay Heat (kW)	Temperature (°C)		Temperature (°C)	
12	0.5	150	3	378		339	
144	6	100	2	310		264	
2616	109	50	1	211		152	
4800	200	30	0.6	158		106	

↑
Decay heat (06/12/2026) from a newer target model

Decay heat (07/09/2025) from an older target model →



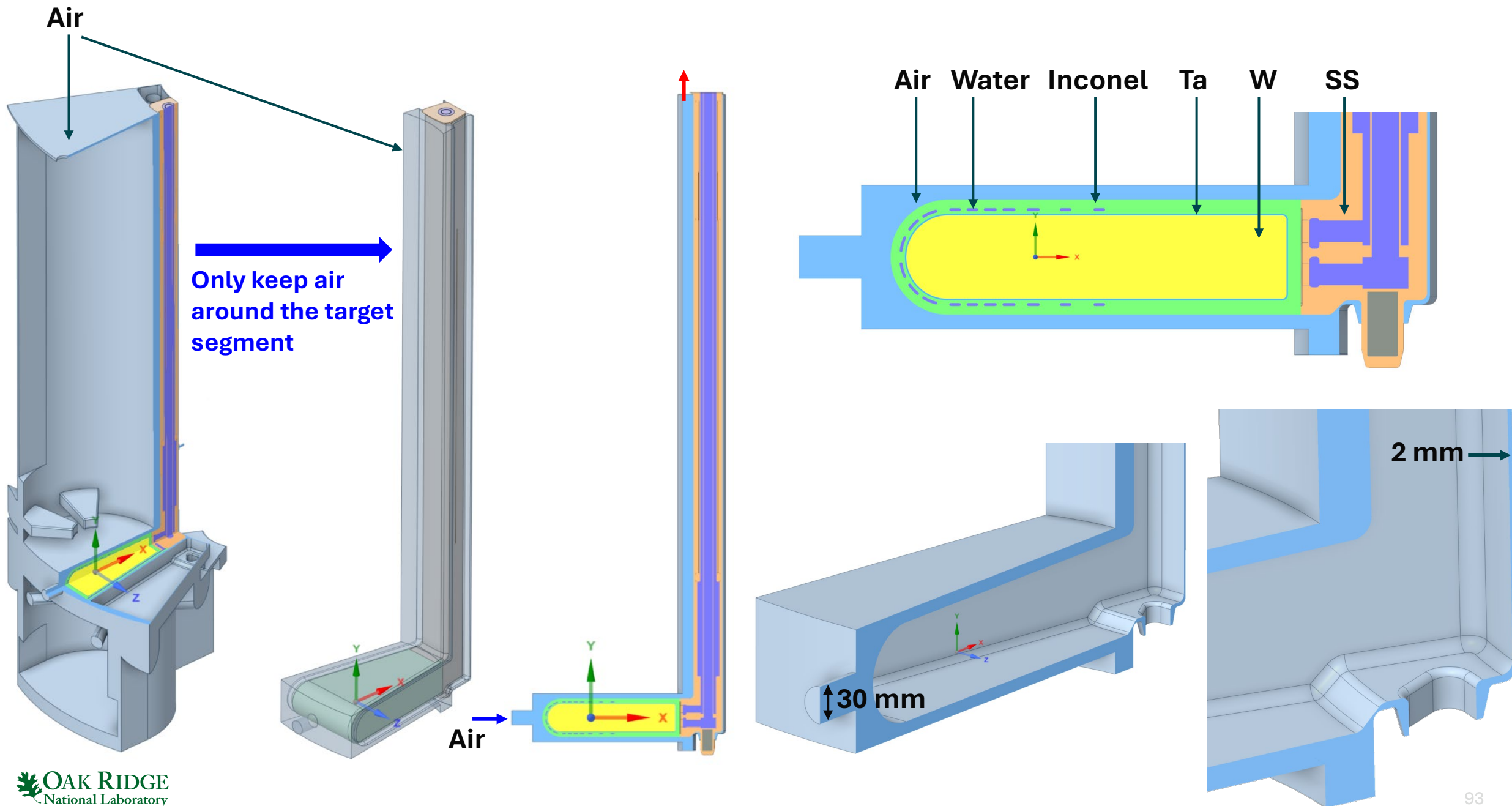
Day 2 : Target Segment Analysis

- **Results**

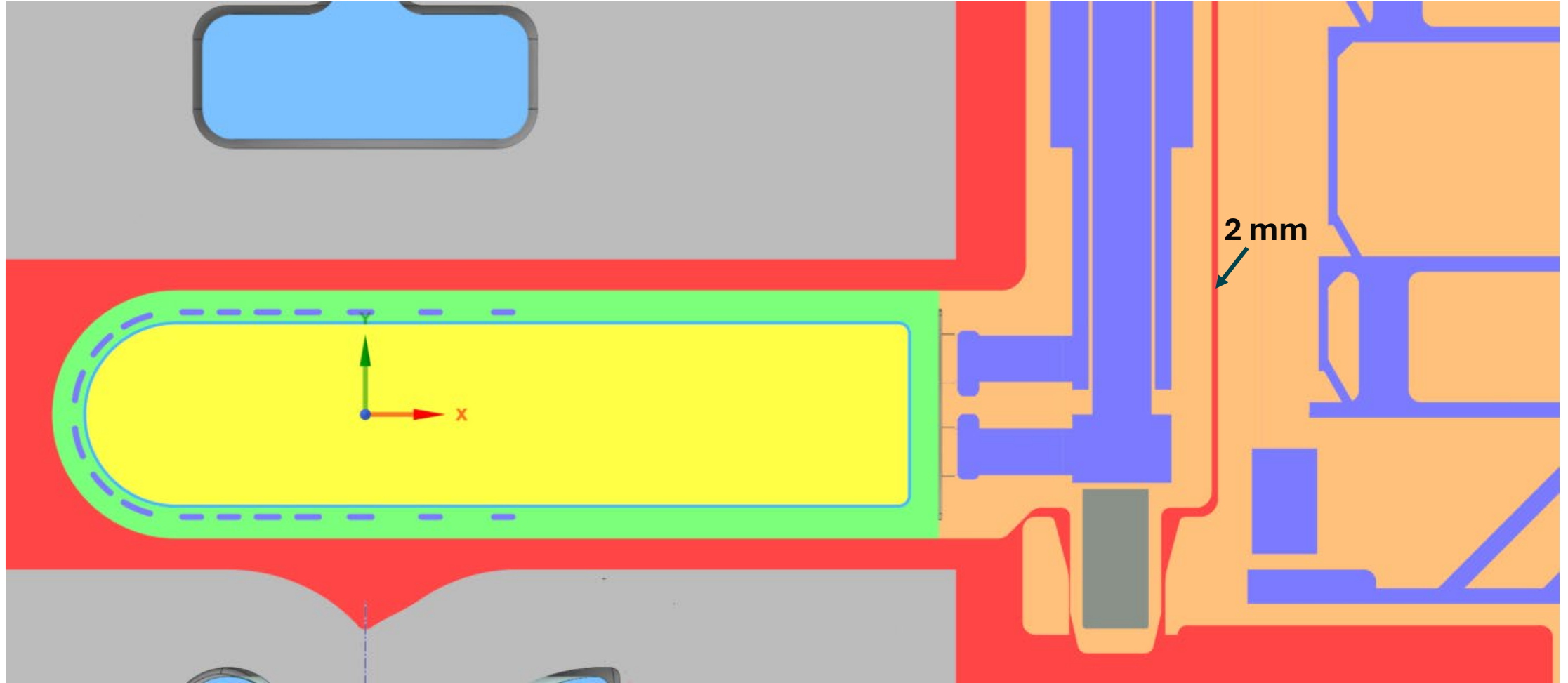
- **Maintenance Temperature**

- Decay Heat
 - Under Reduced Flow Rate (0.1 & 0.2 GPM) (Steady State)
 - Immediately after Shutdown with Active Internal Water Cooling (7.5GPM) (Transient)
 - **Loss of Cooling**
 - ❑ Without Active Cooling (Transient)
 - ❑ **Preliminary External** Air-Cooling Analysis (**Steady State**)
 - ❖ **Air-cooling for a single segment ← lower-bound estimate of required flow rate**

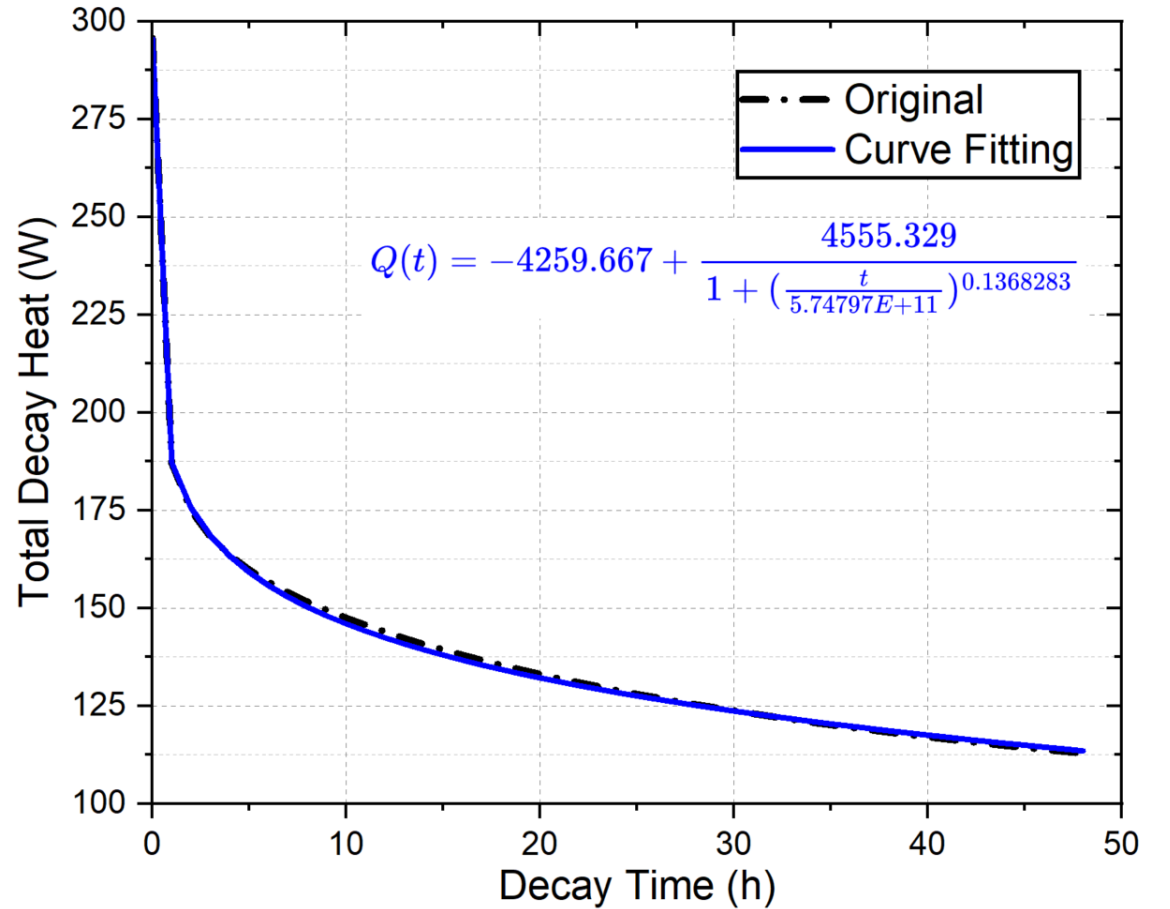
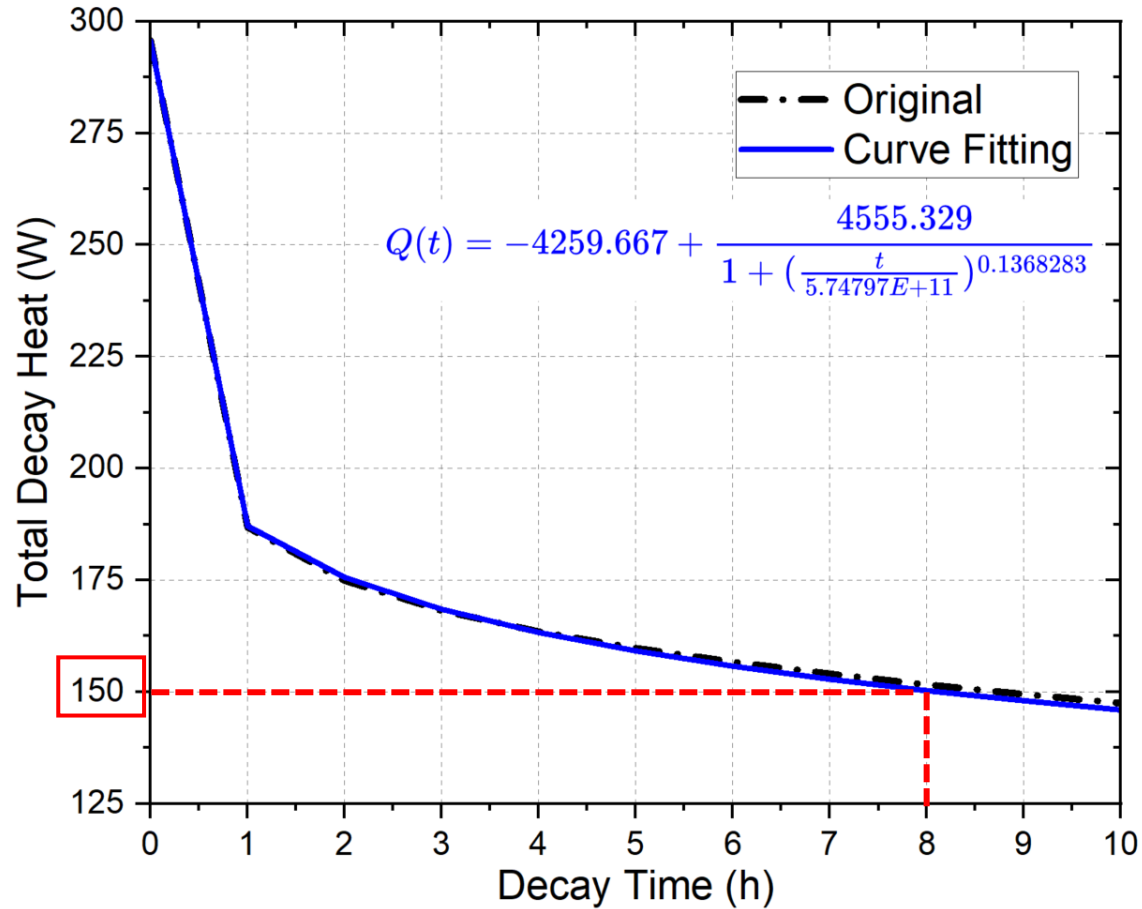
Air Cooling for a Single Segment, **Geometry**



Air Cooling for a Single Segment, Geometry



Decay Heat



Peak Temperature with Various Inlet Air Velocities

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

Inlet Air Velocity (V)

Ave T V = 4.8m/s
Ave B V = 3.6m/s

V=20 m/s

Ave T V = 3.6m/s
Ave B V = 2.7m/s

V=15 m/s

Ave T V = 2.4m/s
Ave B V = 1.8m/s

V=10 m/s

Ave T V = 1.2m/s
Ave B V = 0.9m/s

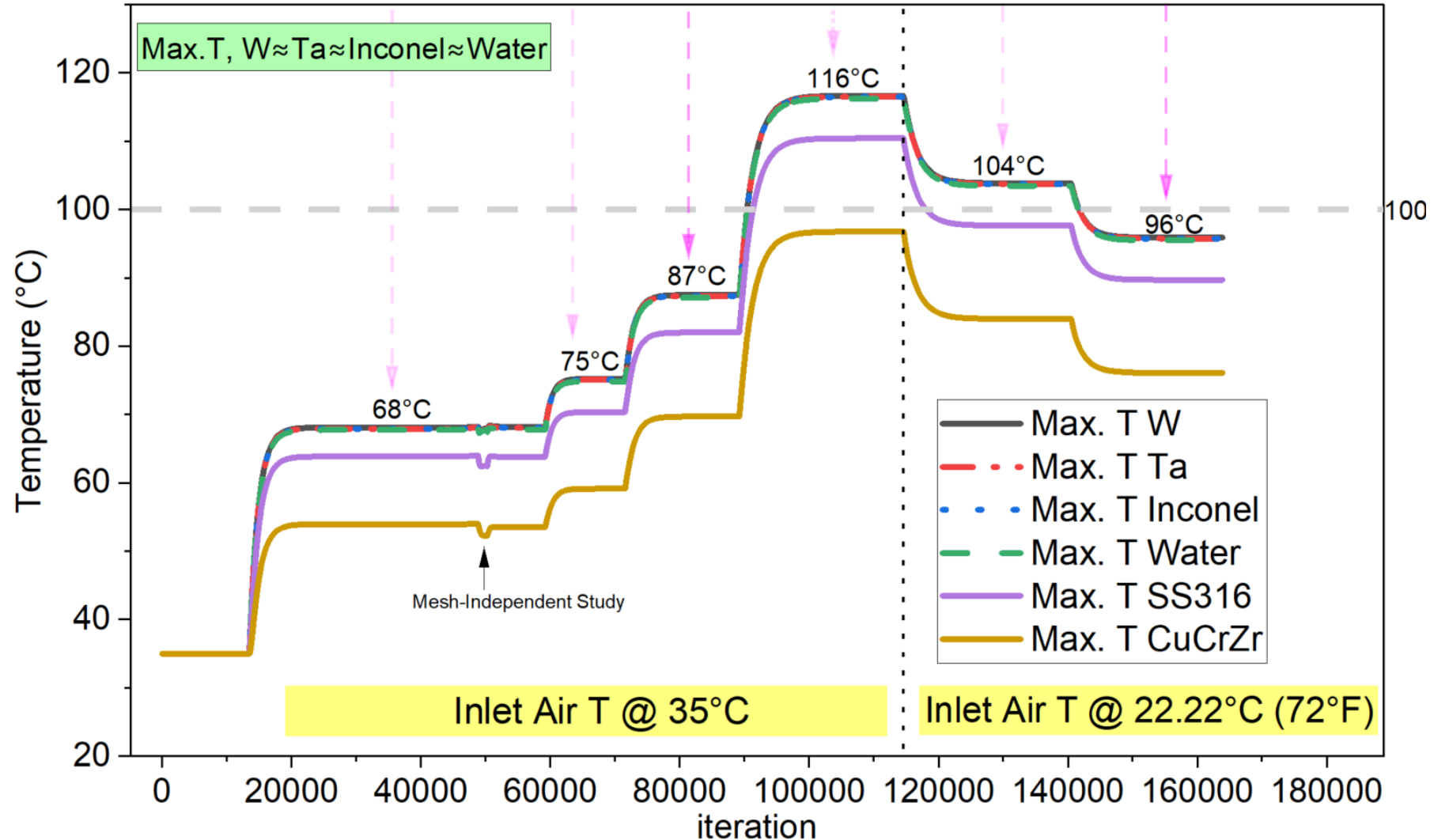
V=5 m/s

Ave T V = 1.2m/s
Ave B V = 0.9m/s

V=5 m/s

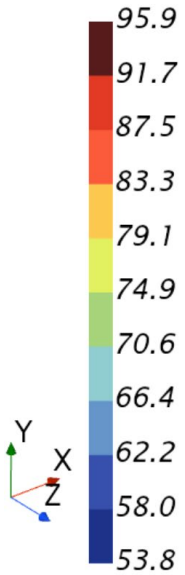
Ave T V = 1.5m/s
Ave B V = 1.1m/s

V=6 m/s

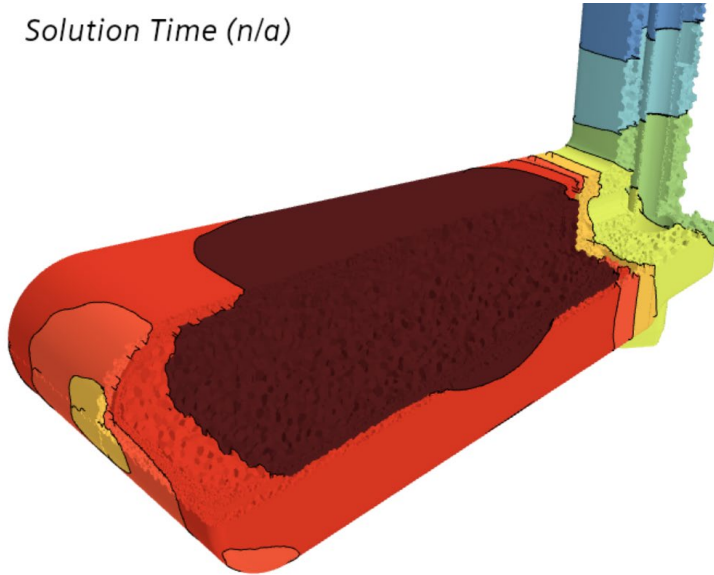


Inlet Air Velocity = 6 m/s (Flow Rate: 9 cfm)

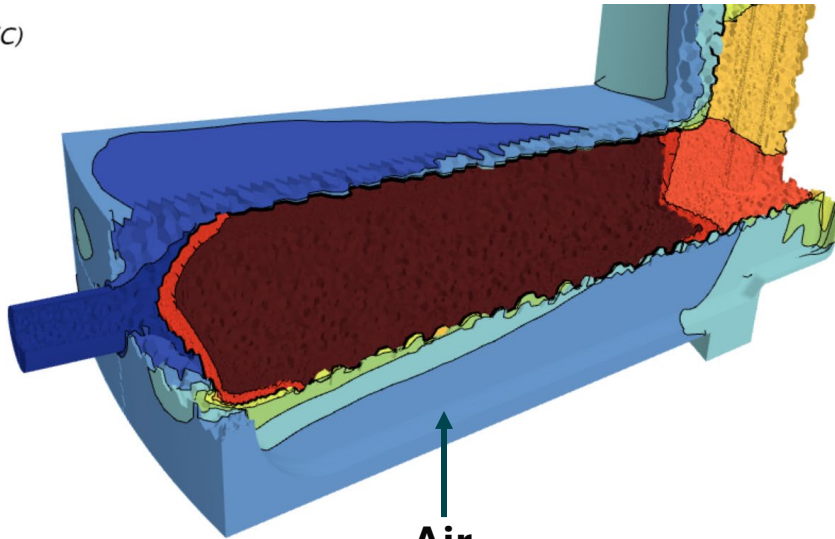
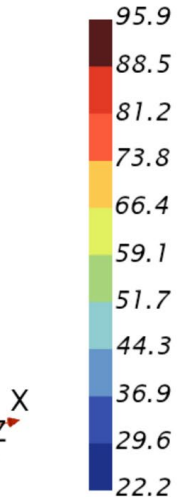
Temperature (C)



Solution Time (n/a)

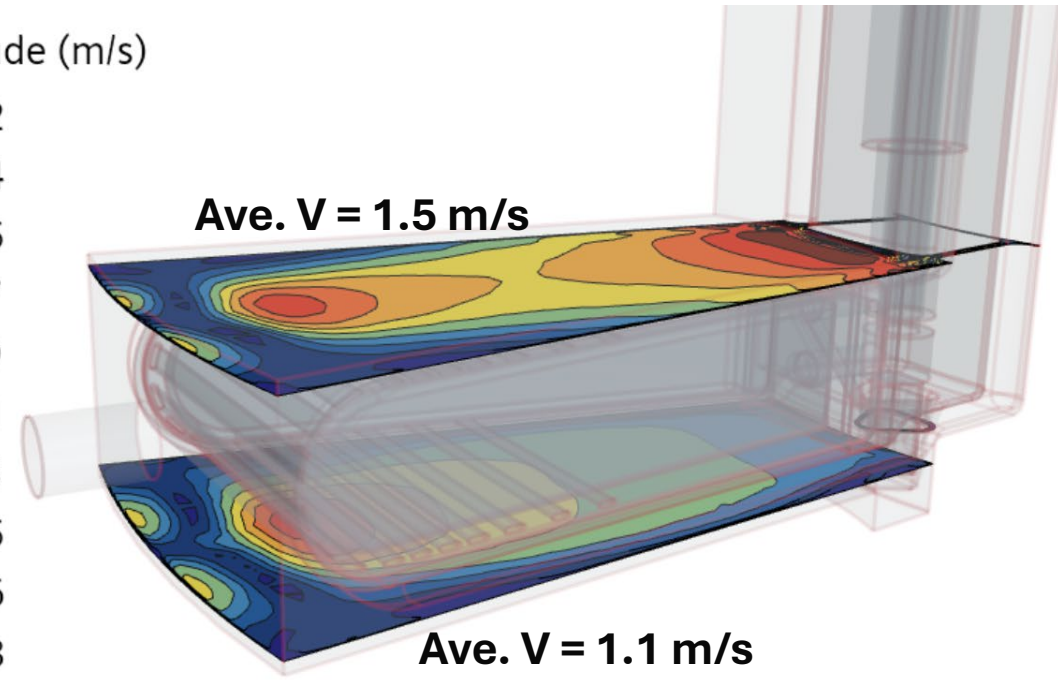
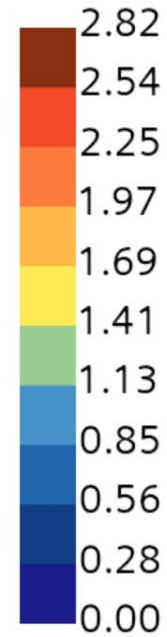


Temperature (C)



Air

Velocity: Magnitude (m/s)



$$D = 30 \text{ [mm]}$$

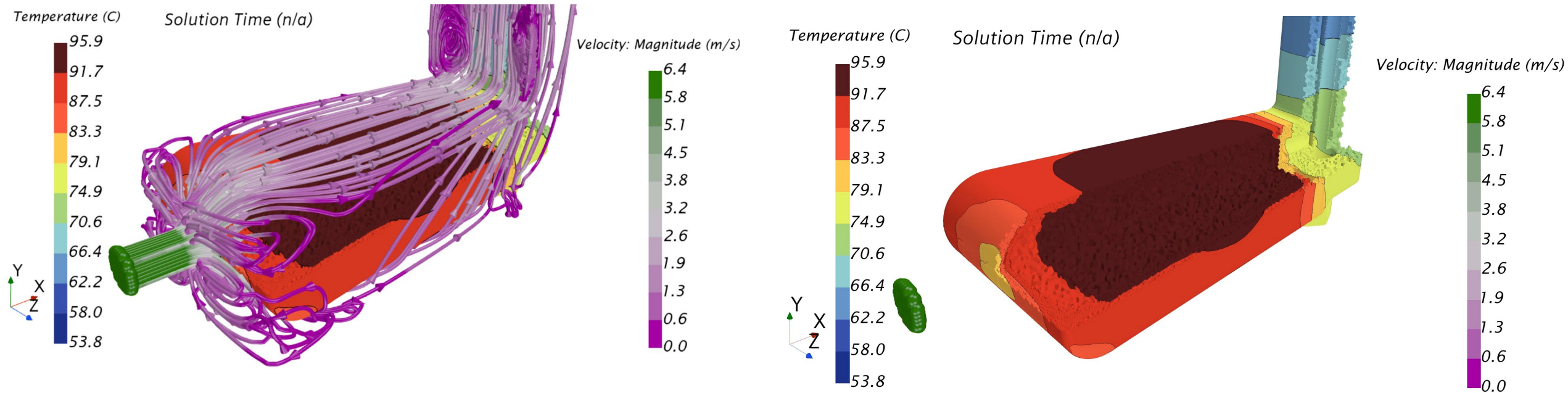
$$A = 0.25 \cdot \pi \cdot D^2 = \text{[mm}^2\text{]} = 706.858347057703 \text{ [mm}^2\text{]}$$

$$V = 6 \left[\frac{\text{m}}{\text{s}} \right]$$

$$F = V \cdot A = \left[\frac{\text{ft}^3}{\text{min}} \right] = 8.99 \left[\frac{\text{ft}^3}{\text{min}} \right]$$

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

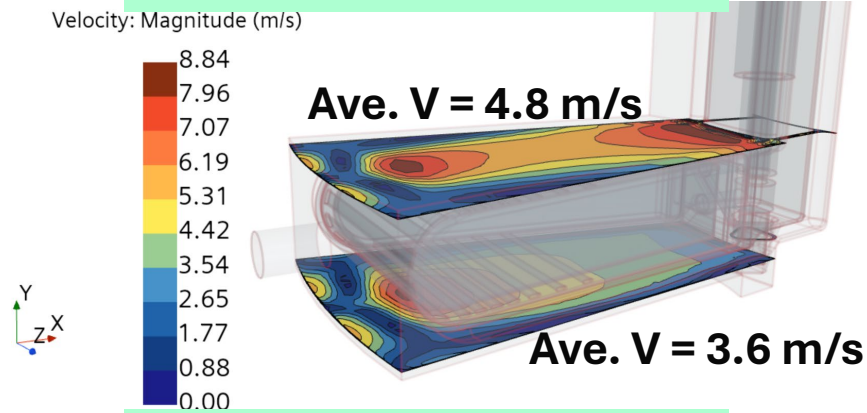
Streamline Animation



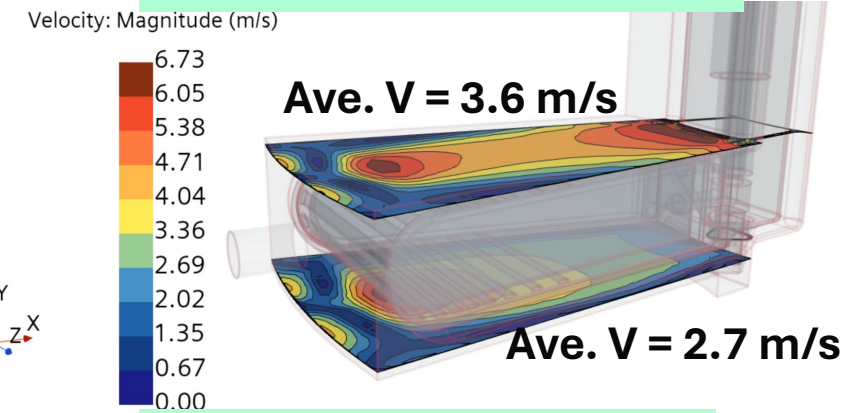
- The **streamline** analysis indicates that the 9 cfm flow rate is a **lower-bound estimate** because the **Single-Segment Model** artificially **confines** the airflow. The surrounding air volume effectively acts as "invisible walls," maintaining high local velocities near the target surface and enhancing convective heat transfer. This behavior does not accurately represent the more open and competing flow paths in the full CV geometry.

Velocity Profile

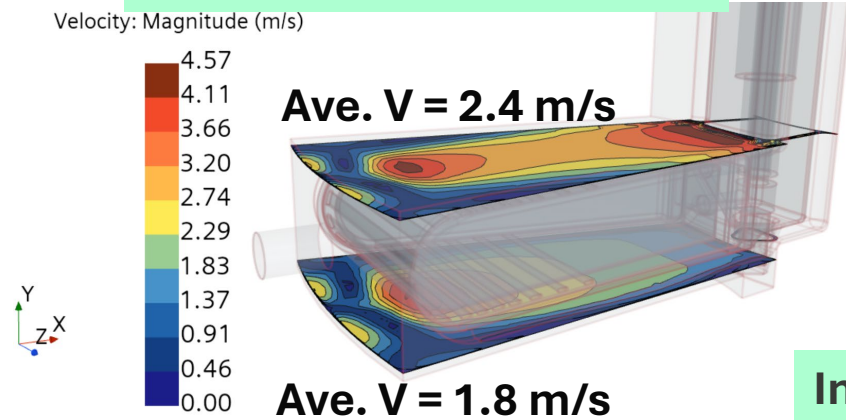
Inlet Air Velocity = 20 m/s



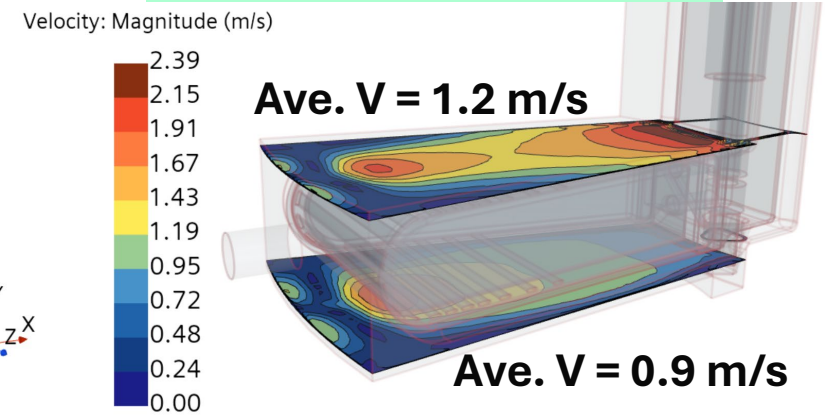
Inlet Air Velocity = 15 m/s



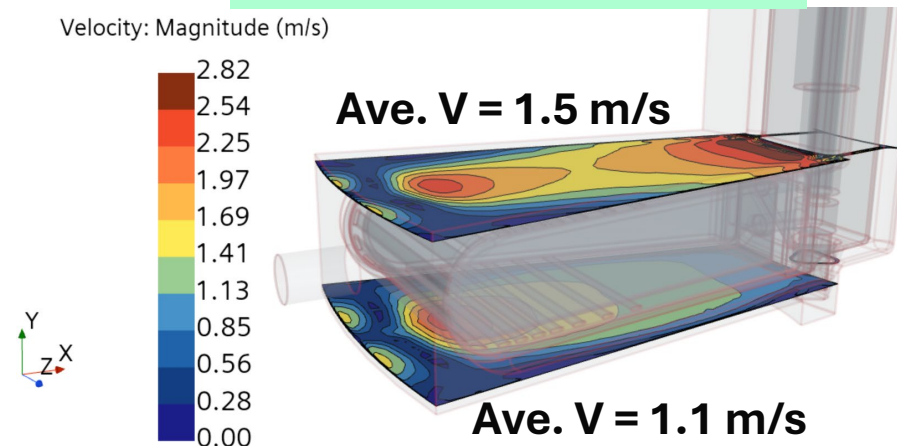
Inlet Air Velocity = 10 m/s



Inlet Air Velocity = 5 m/s



Inlet Air Velocity = 6 m/s



All Cases:

- Ave. V at the top = 24%-25% of inlet V**
- Ave. V at the bottom = 18% of inlet V**

Conclusion of Blowing Air to Cool a Single Target Segment

- Depending on the inlet air temperature, a flow velocity of **1.5 m/s** (for inlet air velocity of **6 m/s at 22.2 °C / 72 °F (9 cfm)**) or **2.4 m/s** (for inlet air velocity of 10 m/s at 35 °C) **around** the target segment is sufficient to maintain its temperature **below 100 °C**.

Day 2 : Target Segment Analysis

- **Results**

- **Maintenance Temperature**

- Decay Heat
 - Under Reduced Flow Rate (0.1 & 0.2 GPM) (Steady State)
 - Immediately after Shutdown with Active Internal Water Cooling (7.5GPM) (Transient)

- **Loss of Cooling**

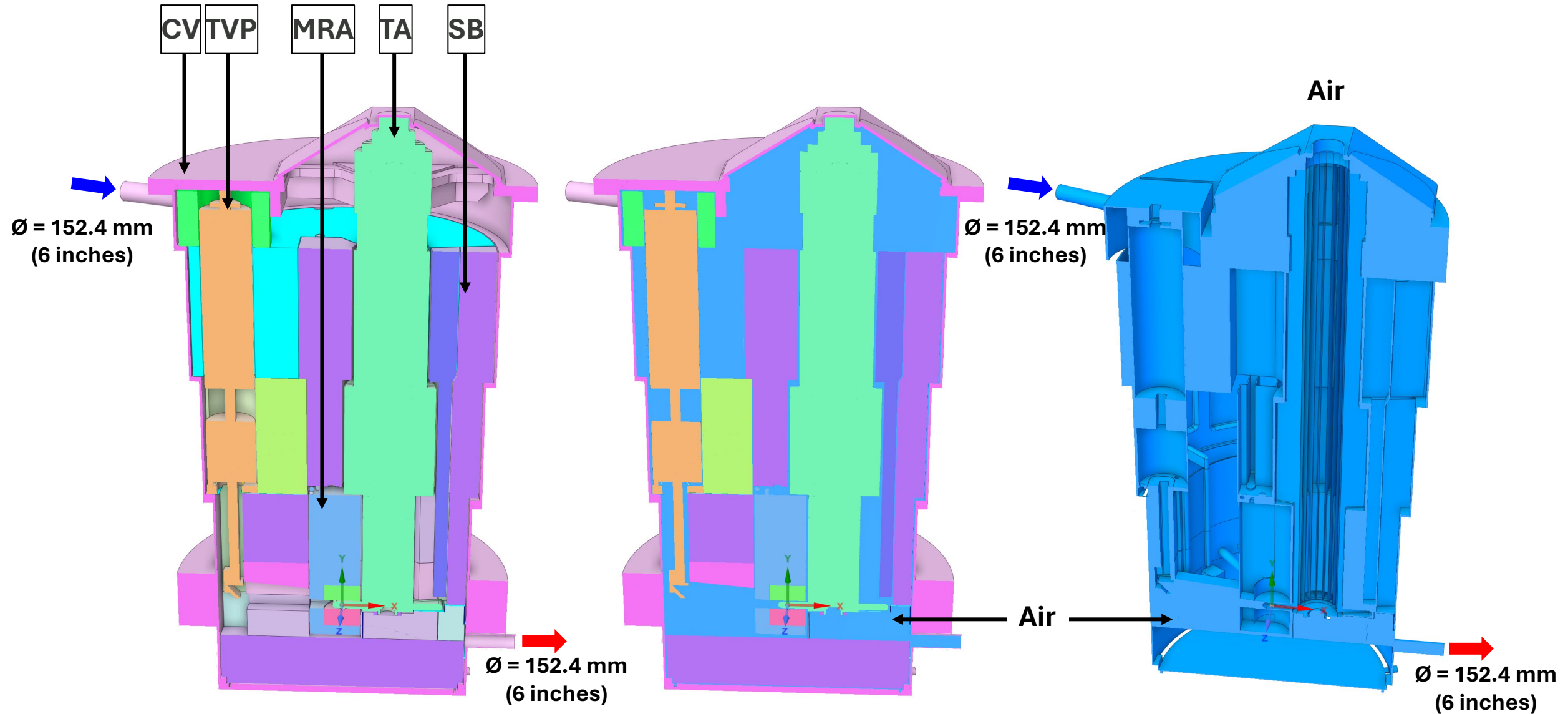
- ☐ Without Active Cooling (Transient)

- ☐ **Preliminary External** Air-Cooling Analysis **(Steady State)**

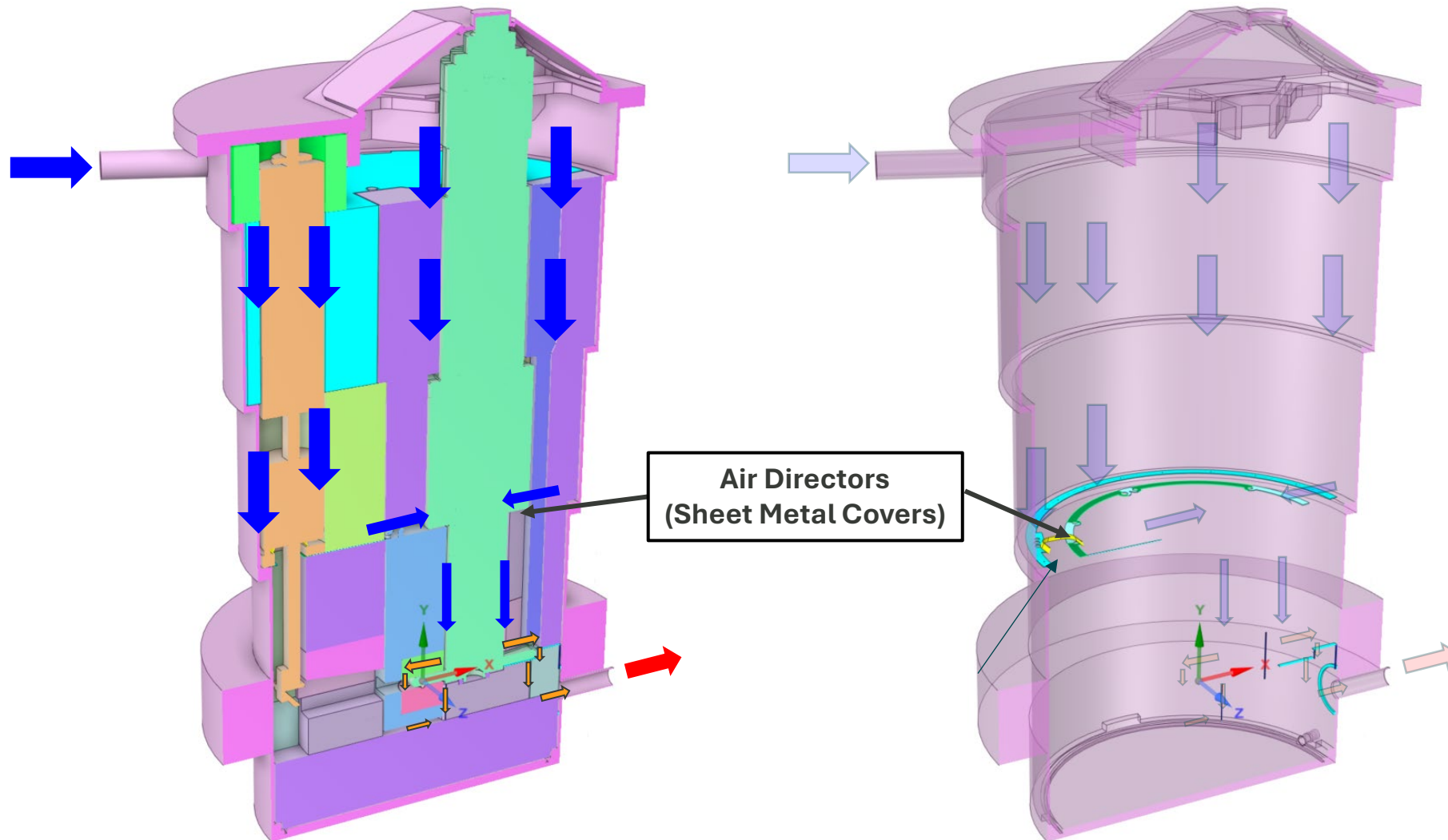
- ❖ Air-cooling for a single segment ← lower-bound estimate of required flow rate

- ❖ **Air-cooling for the entire target disk (20 segments) ← pressure drop required for sufficient flow**

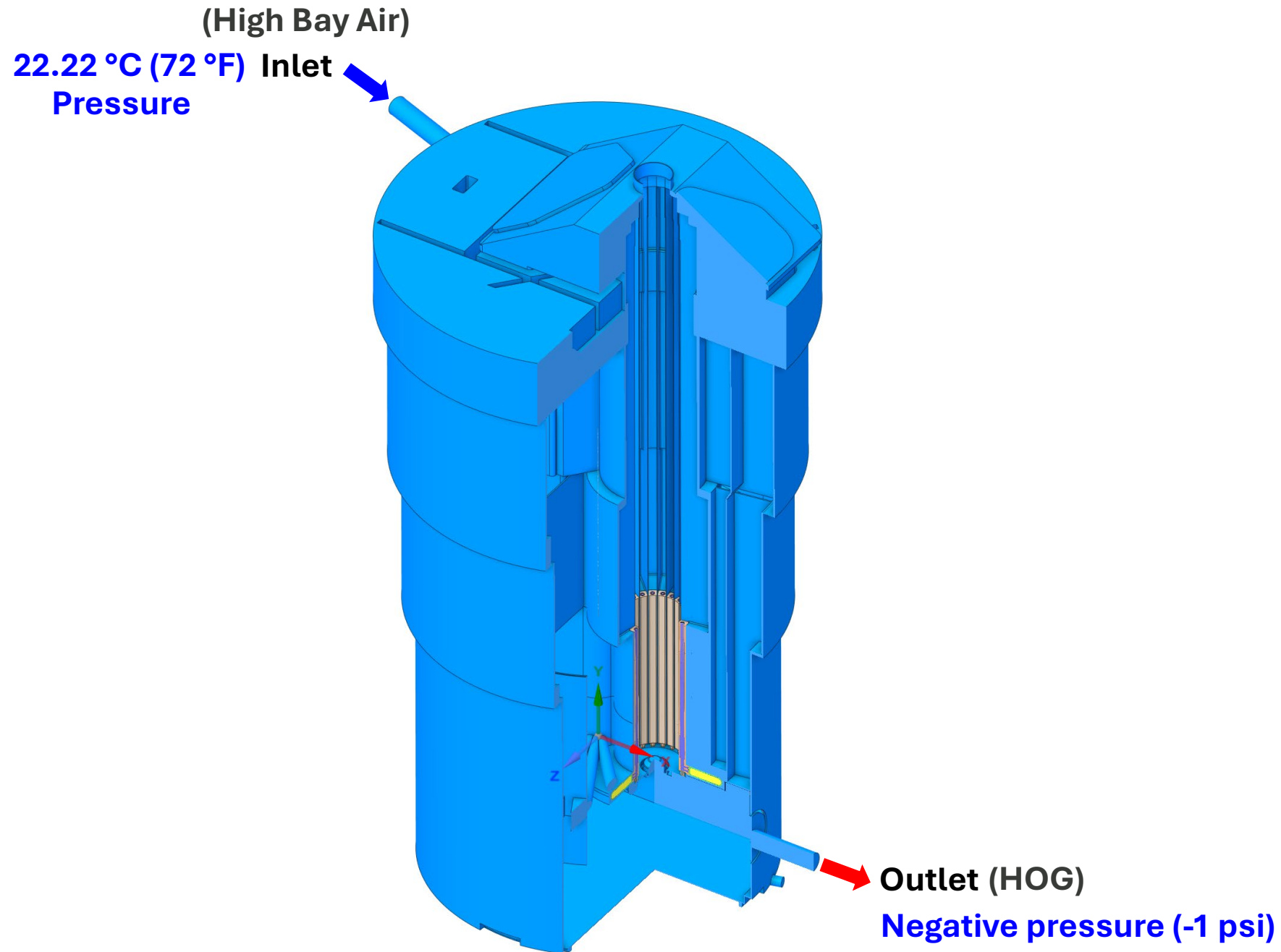
Air Volume within the Core Vessel



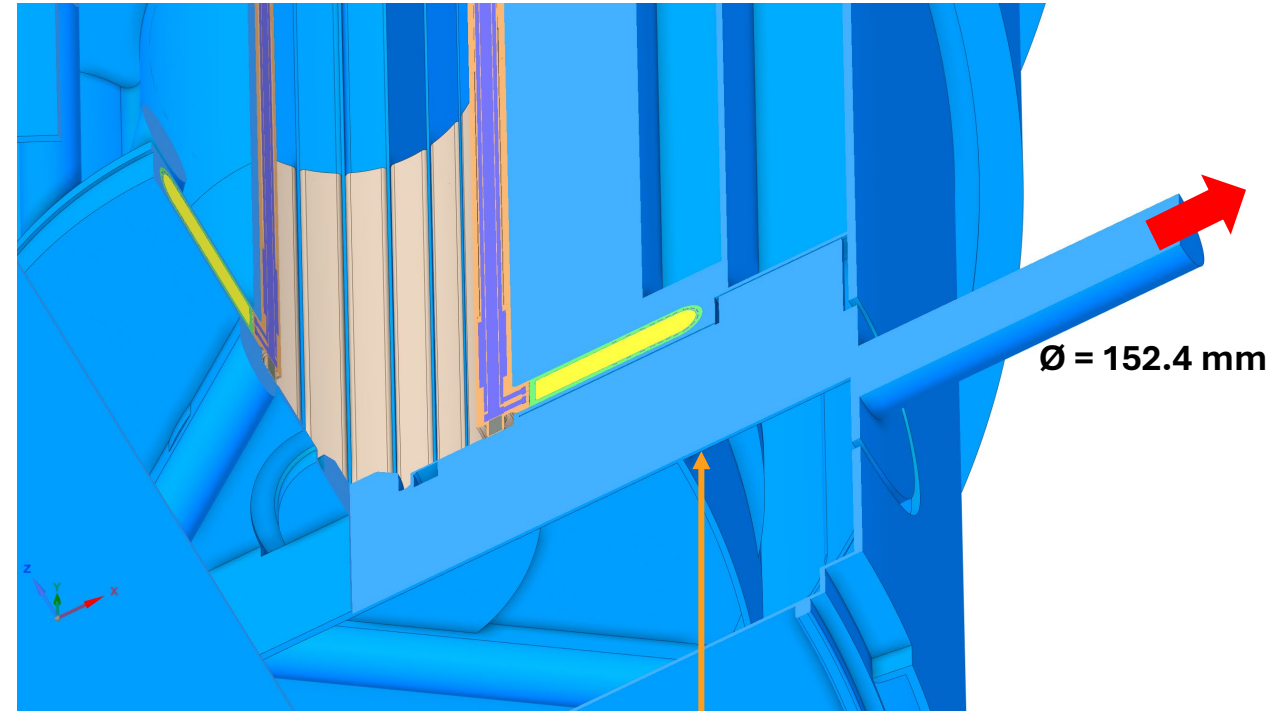
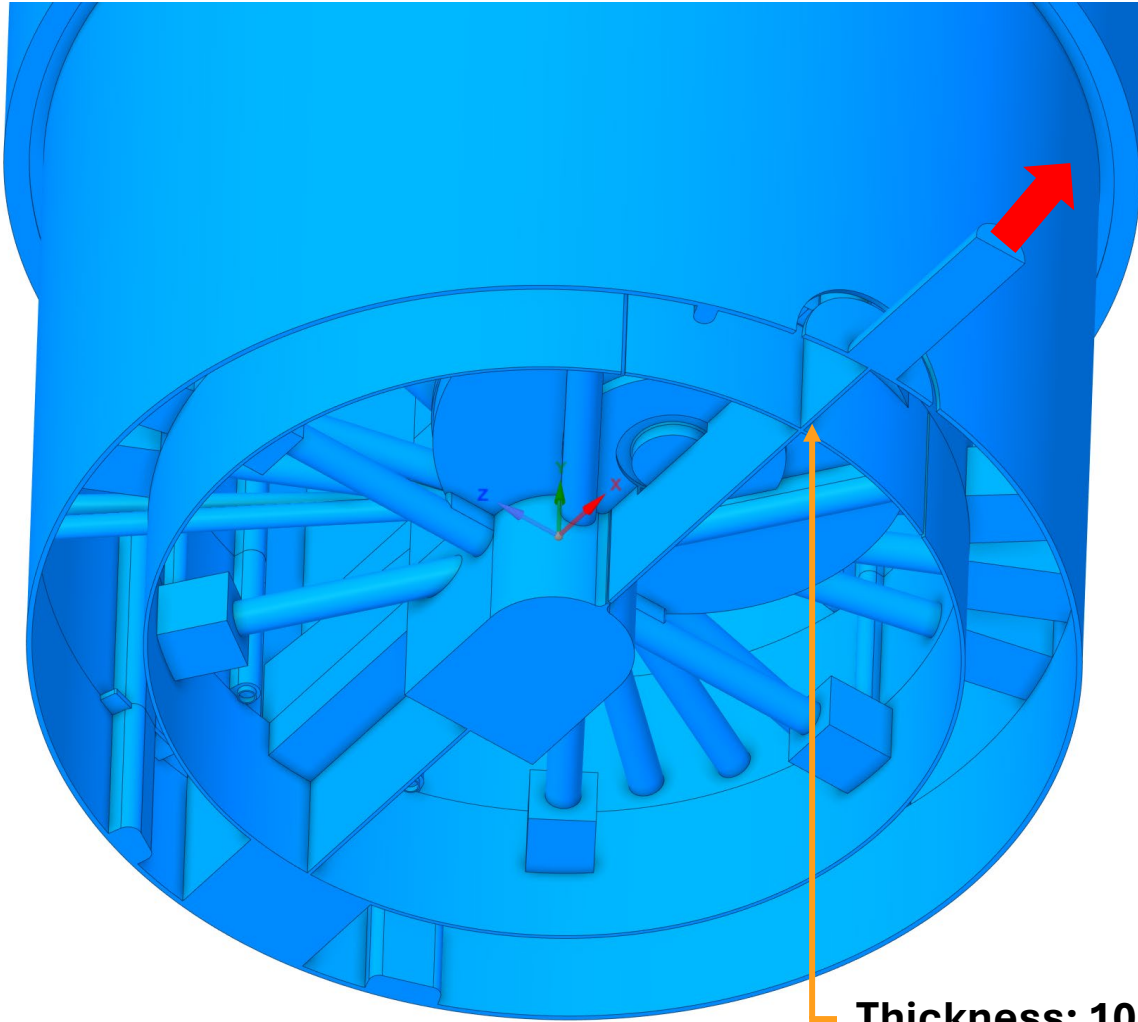
Air Directors



Simulation Domain (Air + 20 Target Segments)



10 mm Gaps between Shielding Blocks

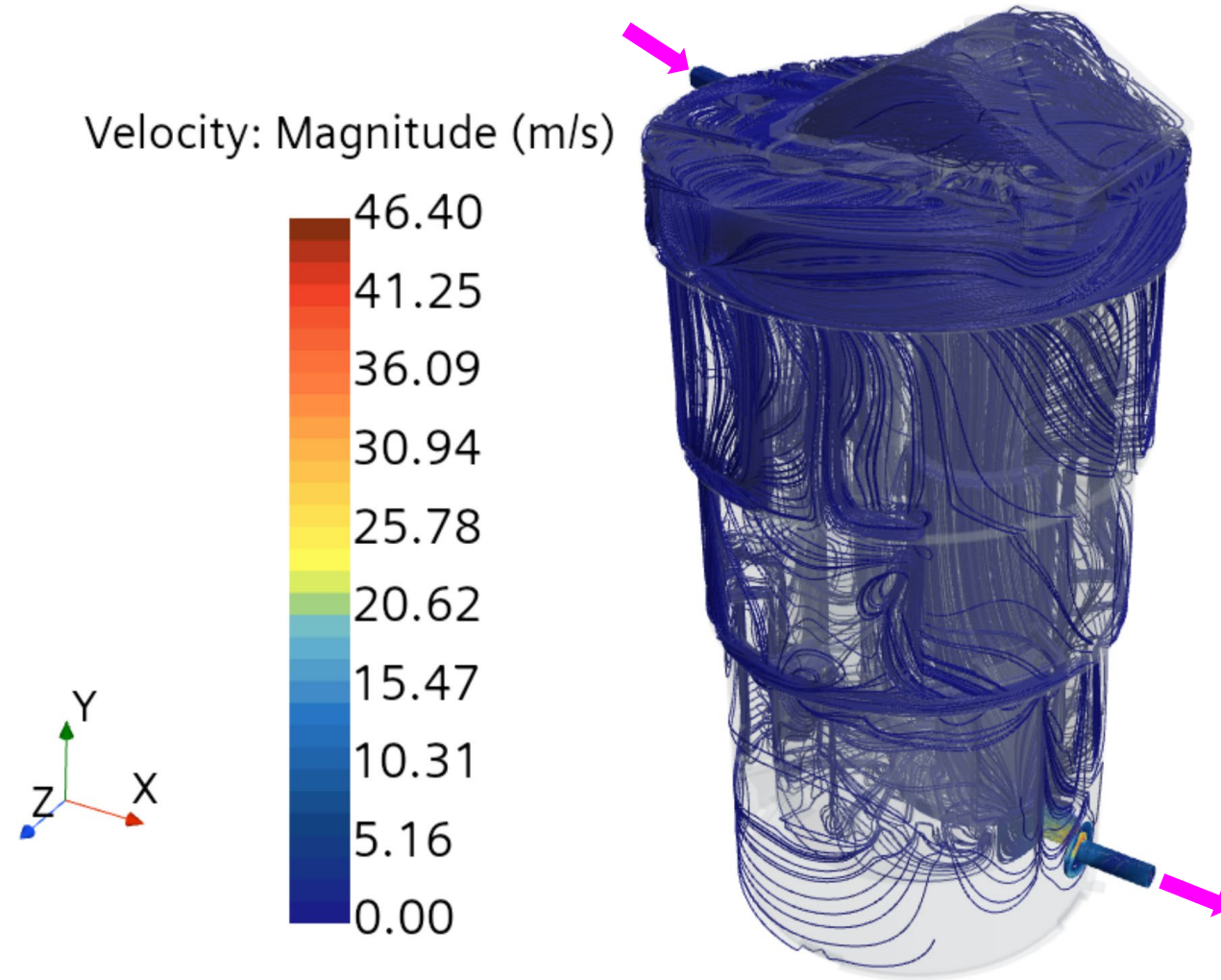


Thickness: 10 mm (Gap between Shielding Blocks)

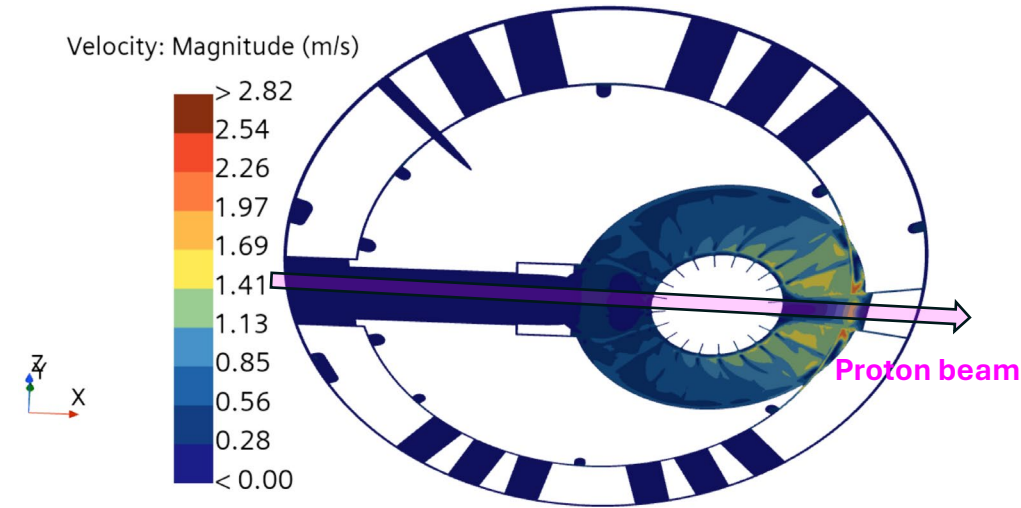
Forced Air Flow for Decay Heat Removal (8 hrs, 150W*20 Segments = 3 kW)

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

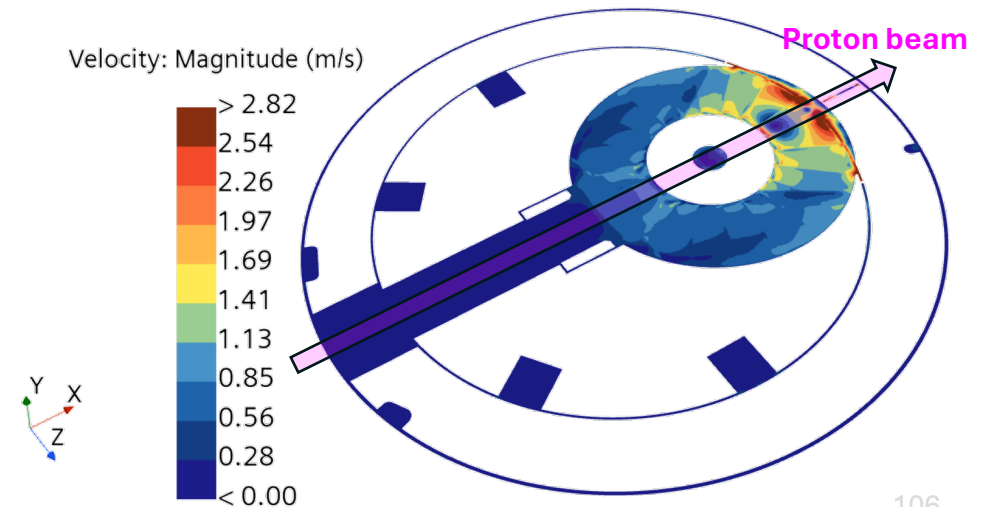
Geometry: 01/2026



Velocity profile: Top of Target Segments



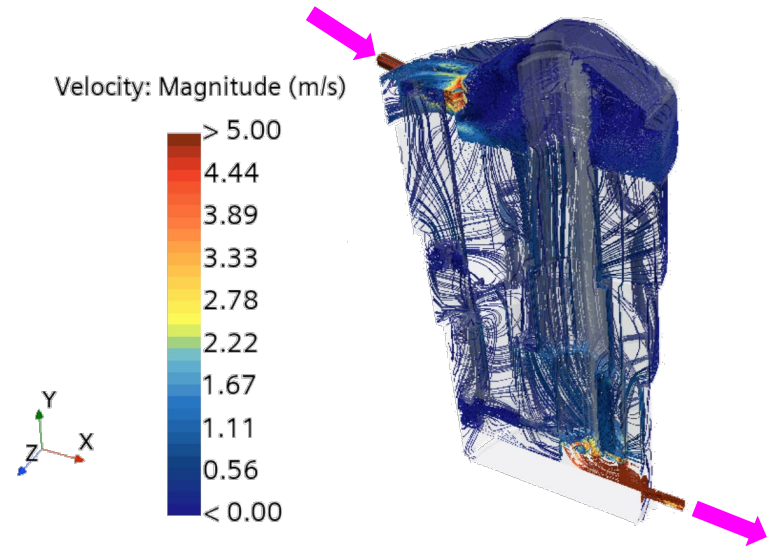
Velocity profile: Bottom of Target Segments



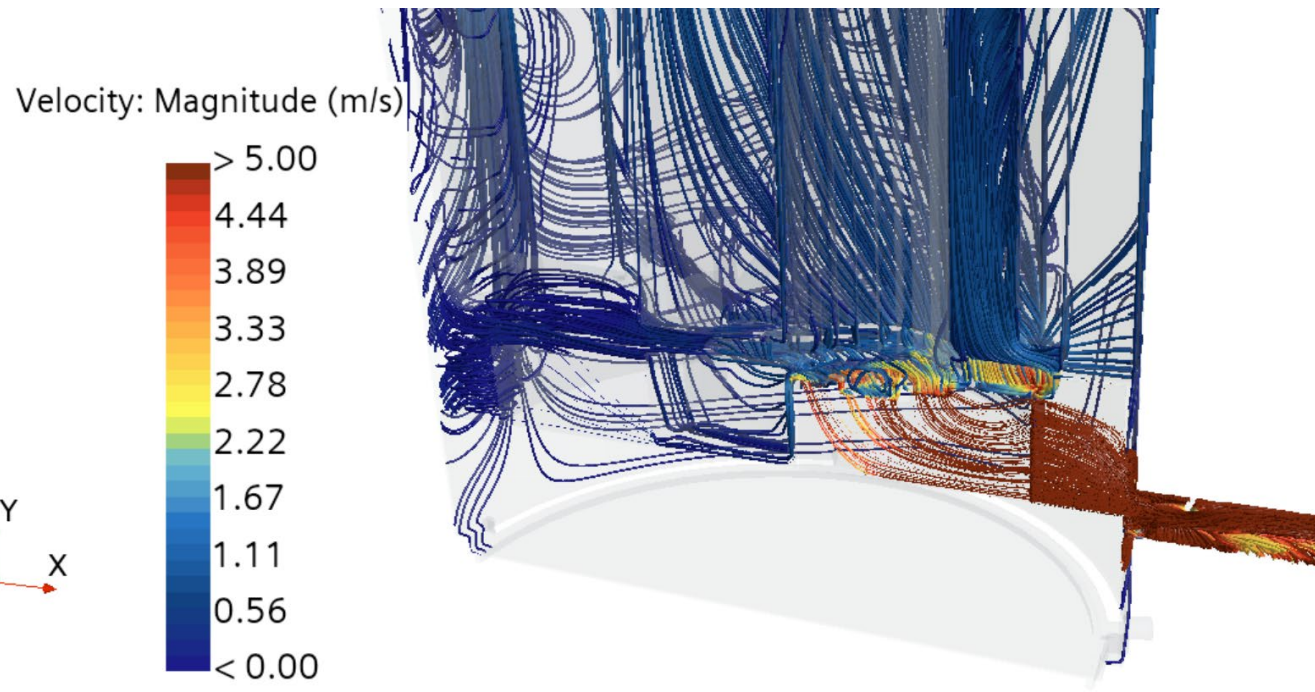
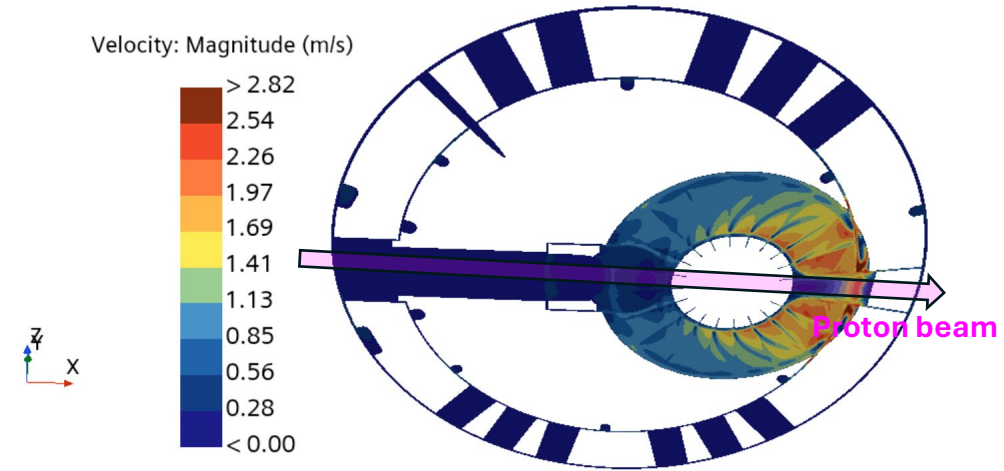
Forced Air Flow for Decay Heat Removal (8 hrs, 150W*20 Segments = 3 kW)

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

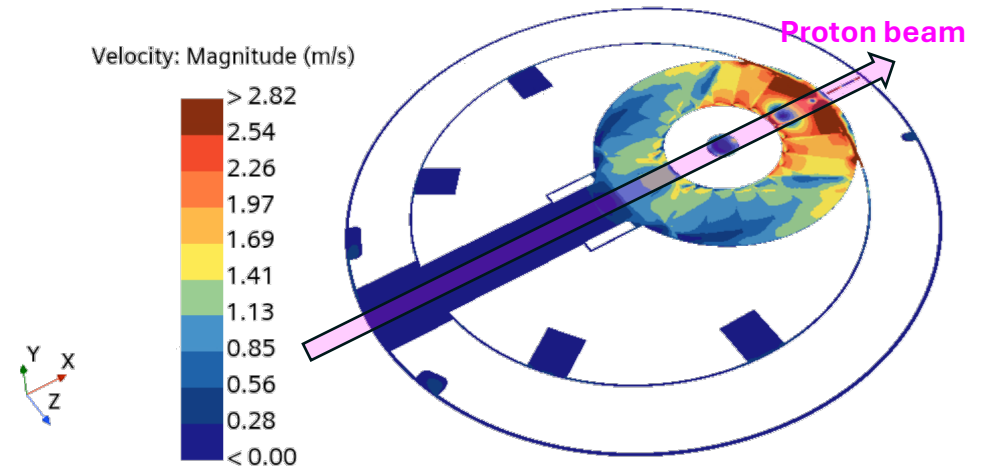
Geometry: 01/2026



Velocity profile: Top of Target Segments



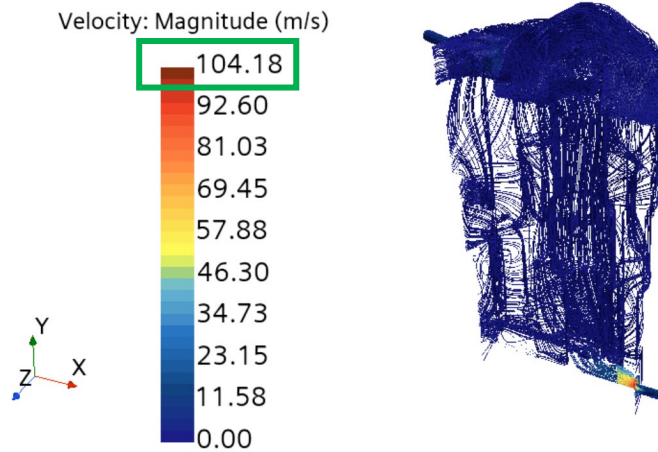
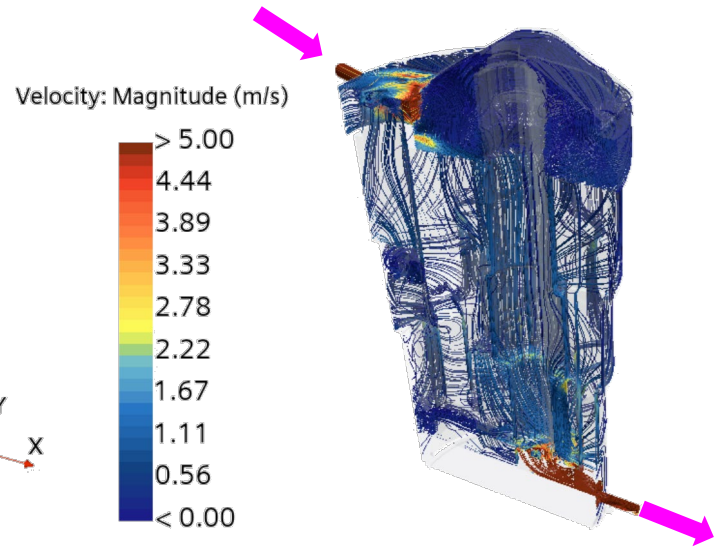
Velocity profile: Bottom of Target Segments



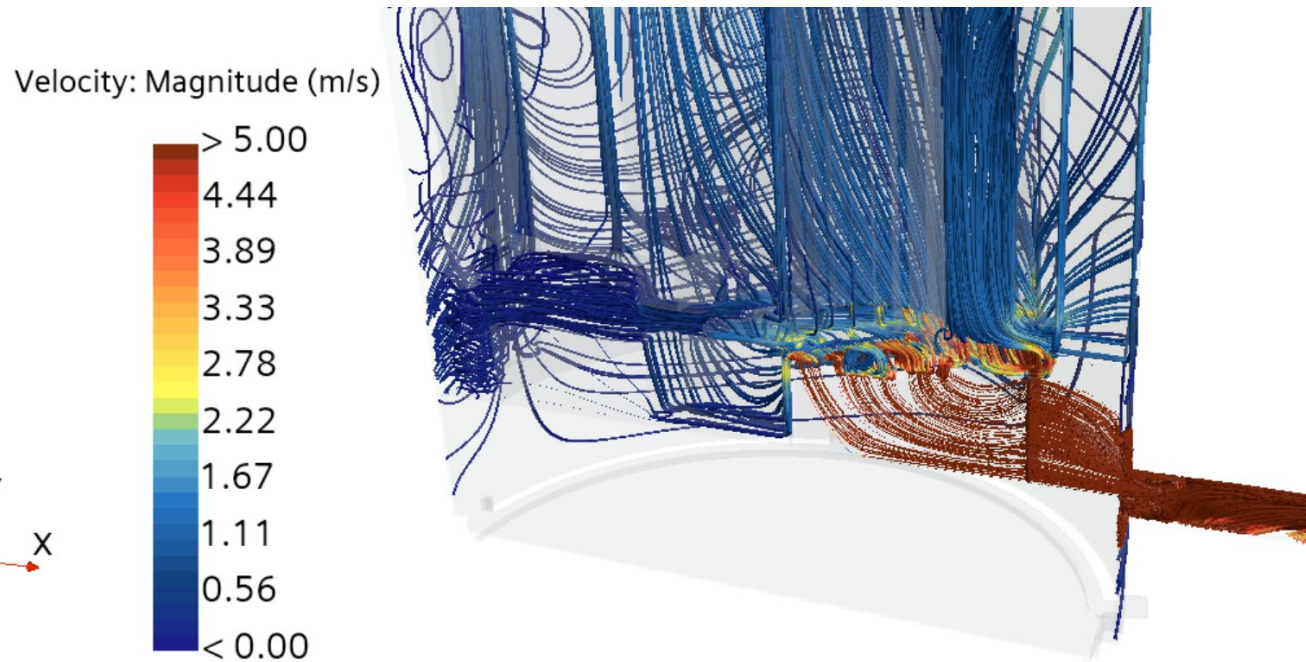
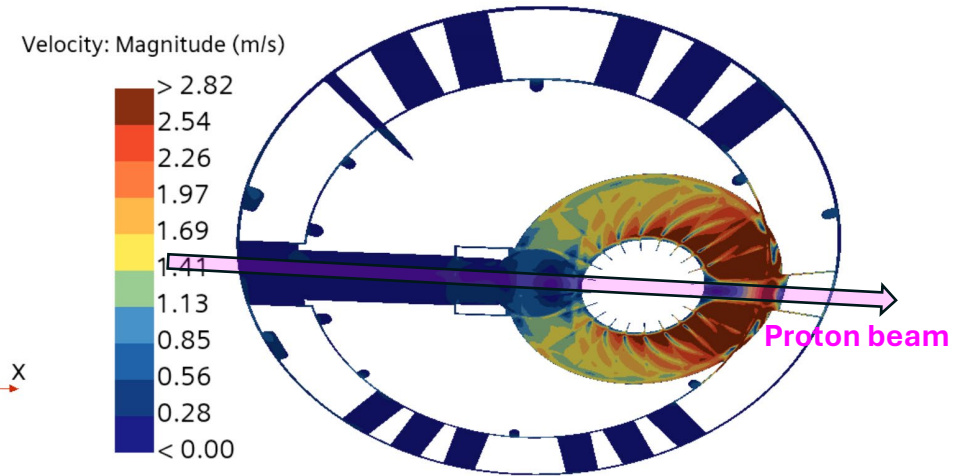
Forced Air Flow for Decay Heat Removal (8 hrs, 150W*20 Segments = 3 kW)

Air flow Rate = ~500 cfm , pressure drop = 1.0 psi , Peak Target Temperature = 130°C

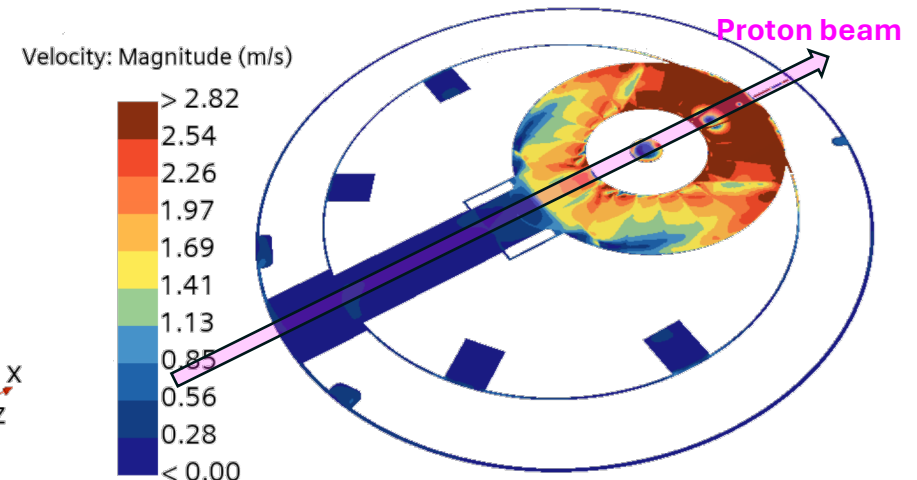
Geometry: 01/2026



Velocity profile: Top of Target Segments



Velocity profile: Bottom of Target Segments

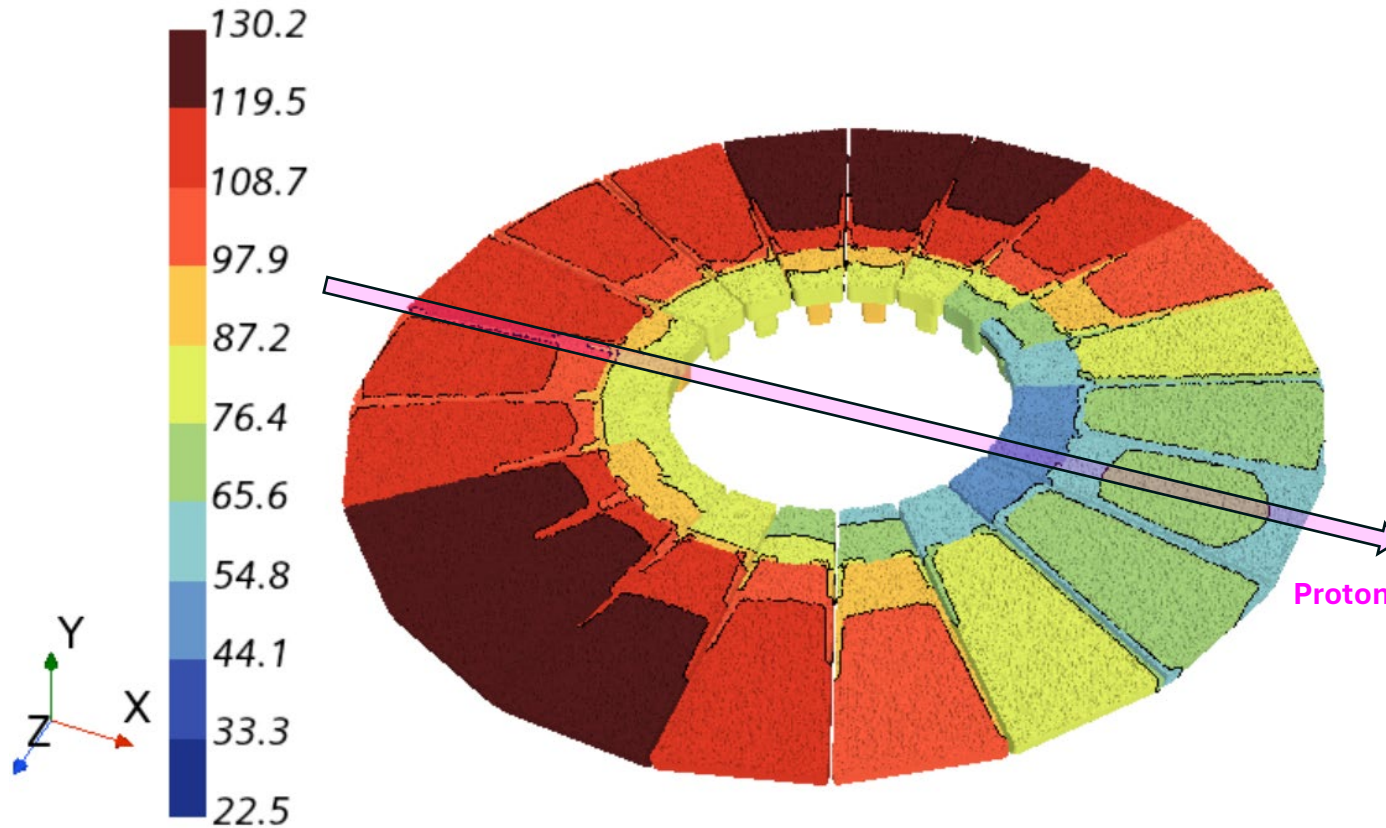


Forced Air Flow for Decay Heat Removal (8 hrs, 150W*20 Segments = 3 kW)

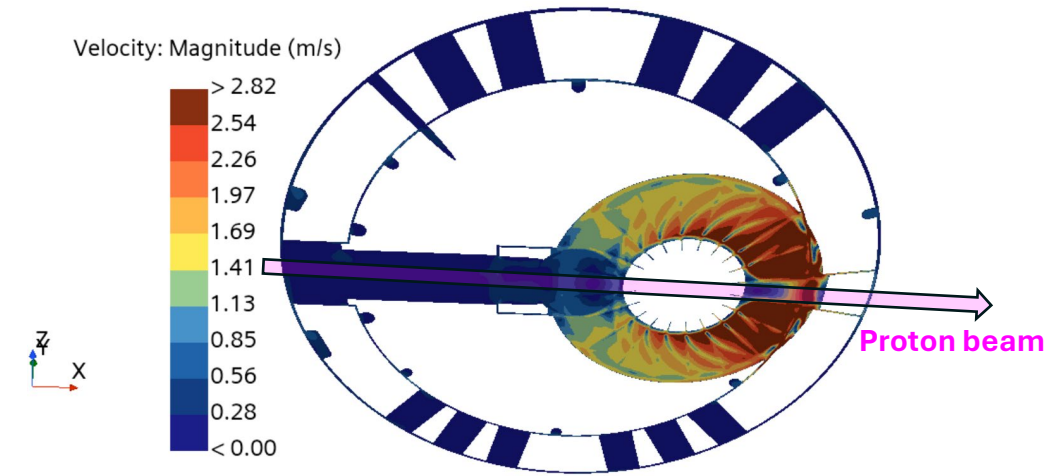
Air flow Rate = ~500 cfm , pressure drop = 1.0 psi , Peak Target Temperature = 130°C

Geometry: 01/2026

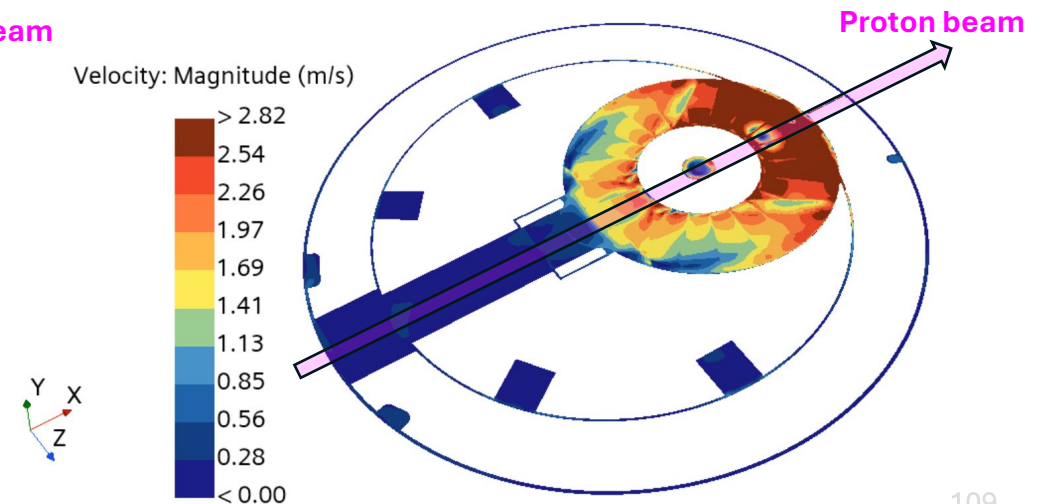
Temperature (C)



Velocity profile: Top of Target Segments

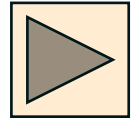


Velocity profile: Bottom of Target Segments



Summary of Target Segment

- The 2 thermal hydraulics requirements are met.
 - Reasonable pressure drop
 - No water boiling



- Additional pressure drop is expected with the updated **segment-to-crow interface (July 2026)**.

ID	Codebeamer Tracker and Link	Requirement	CFD Result	Status
1602	Target Segment Requirement 1602	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
	https://sts-req.ornl.gov:8443/cb/issue/1602			
1567	Prevent Boling Requirement 1567	The target cooling water shall be single-phase (liquid).	No Boiling	Pass
	https://sts-req.ornl.gov:8443/cb/issue/1567			

1602

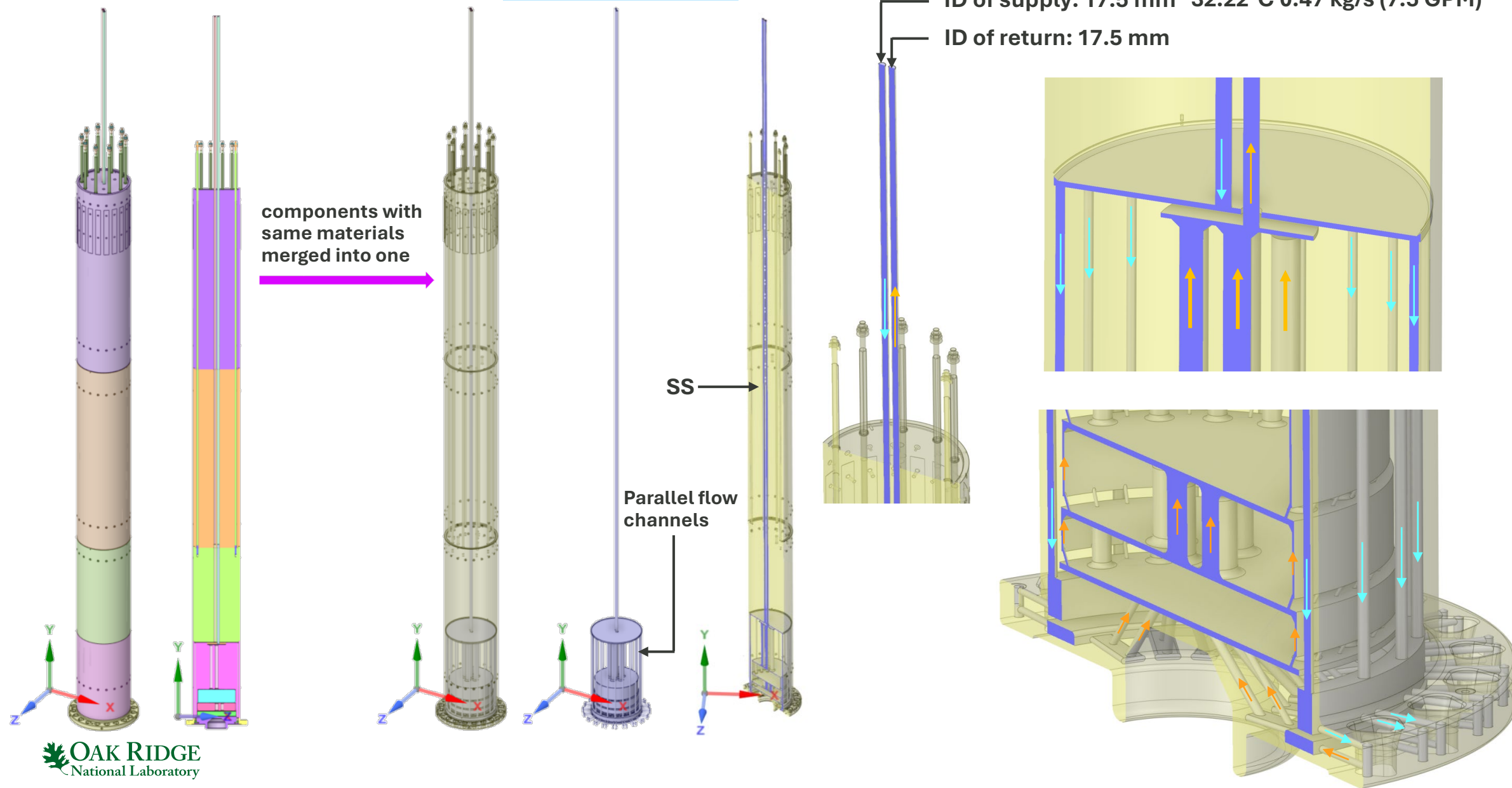
1567

Day 3 : Target Assembly Analysis

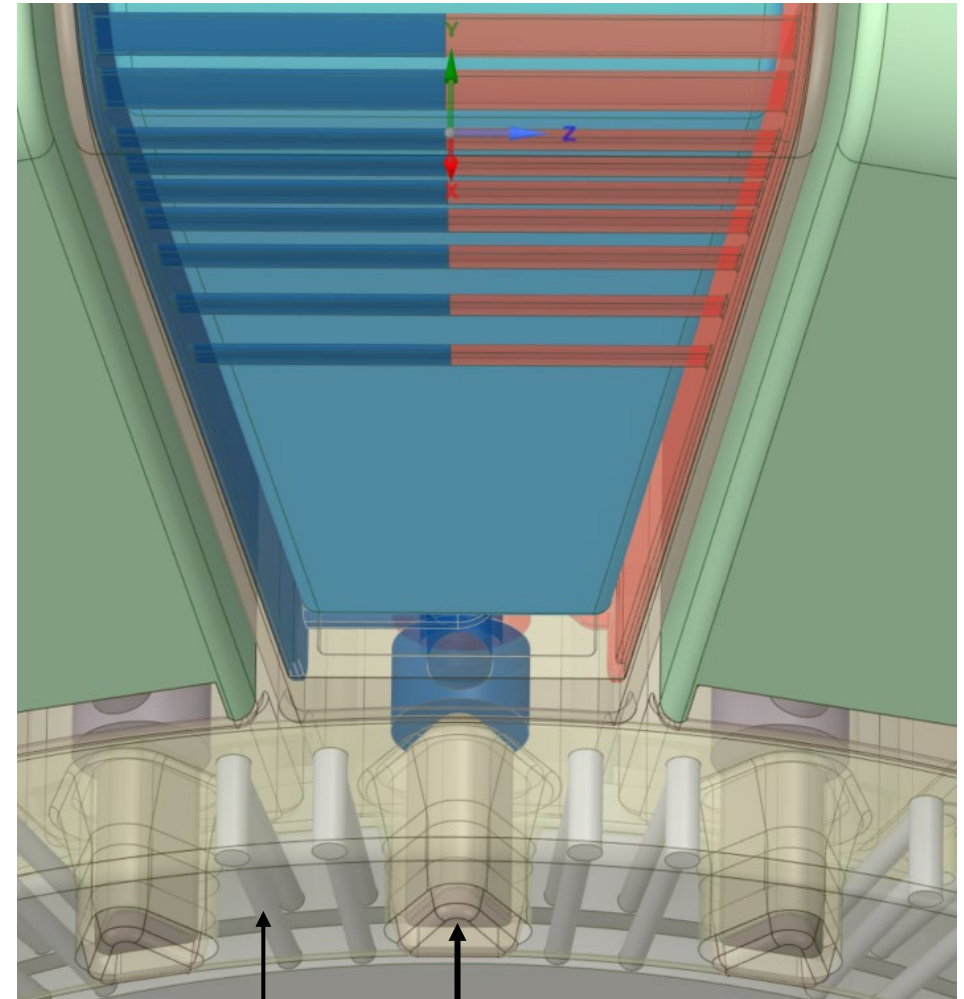
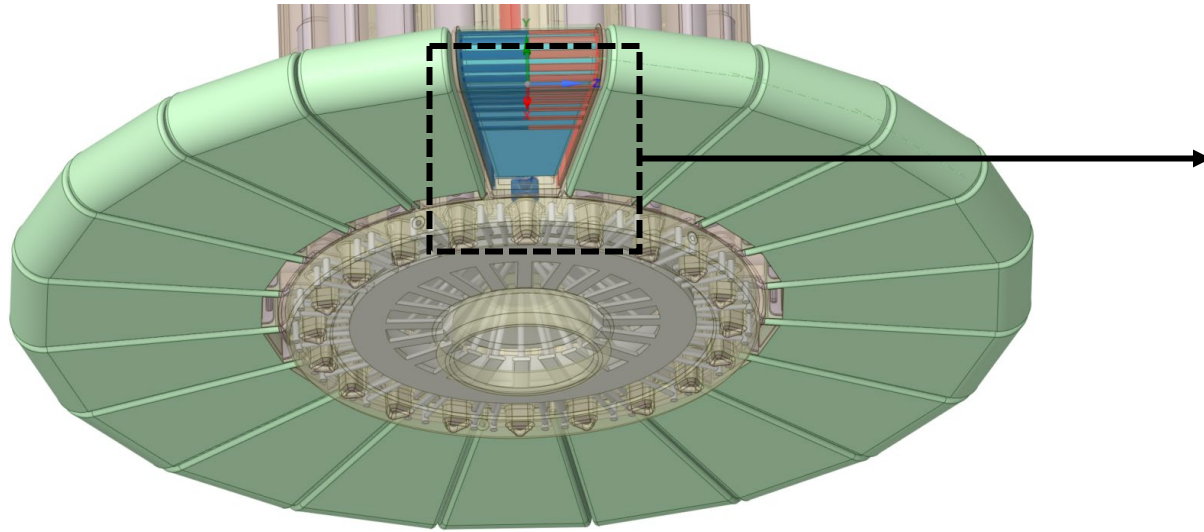
- Geometry
- Results
 - **Target Shaft** : Nominal, Over-Focused, Offset, and Diffused Beams
 - **Target Assembly**
 - Total pressure drop (**Requirement**)
 - Flow balance – Target Drive → 20 Segments & Shaft
 - **Blowdown Analysis**
 - Case 1 – Air Purge of Water in a Single Target Segment
 - Case 2 – Air Purge of Water in the Whole Target Assembly

Target Shaft, Geometry

Water Volume



Target Shaft, Geometry



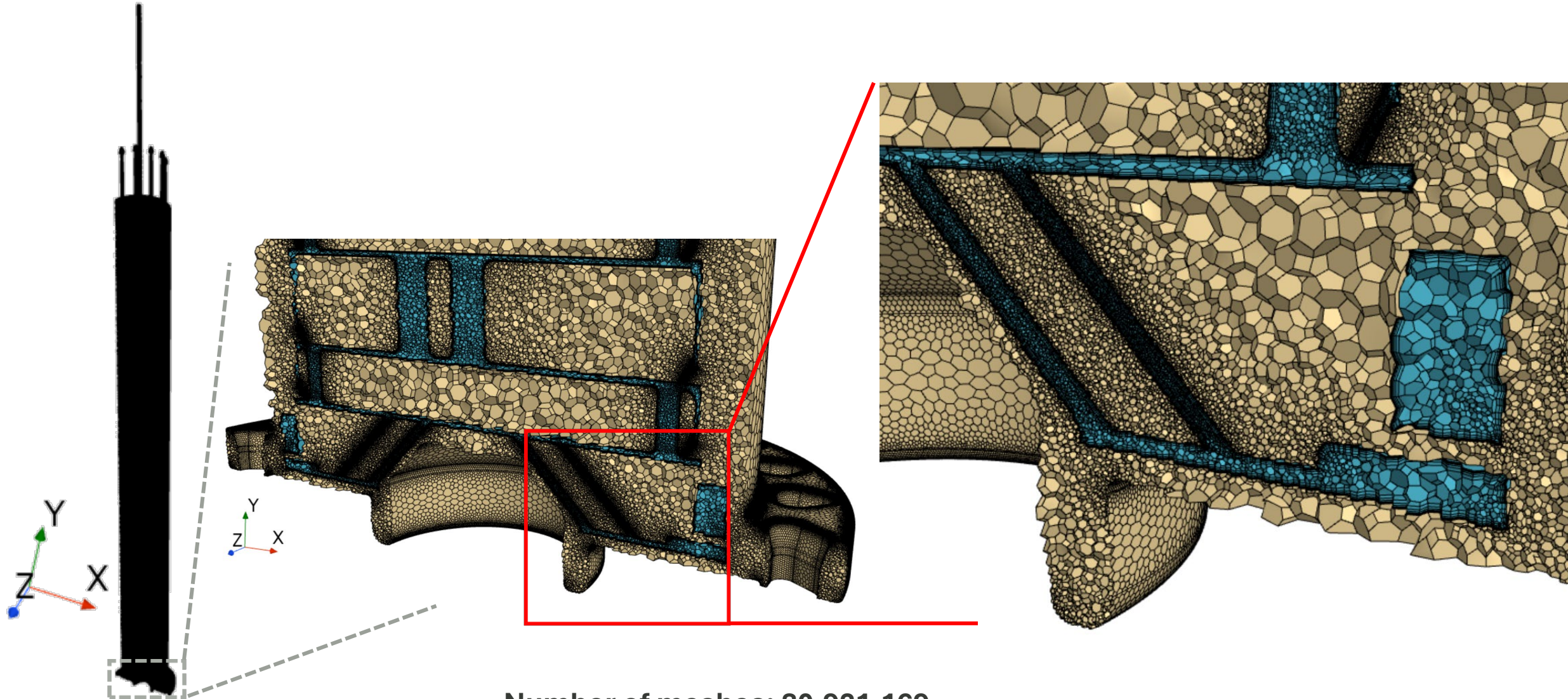
Cooling channels in target shaft

Pocket for target segment pin

Target segment pin



Target Shaft, Mesh Configuration



Number of meshes: 30,921,169

Day 3 : Target Assembly Analysis

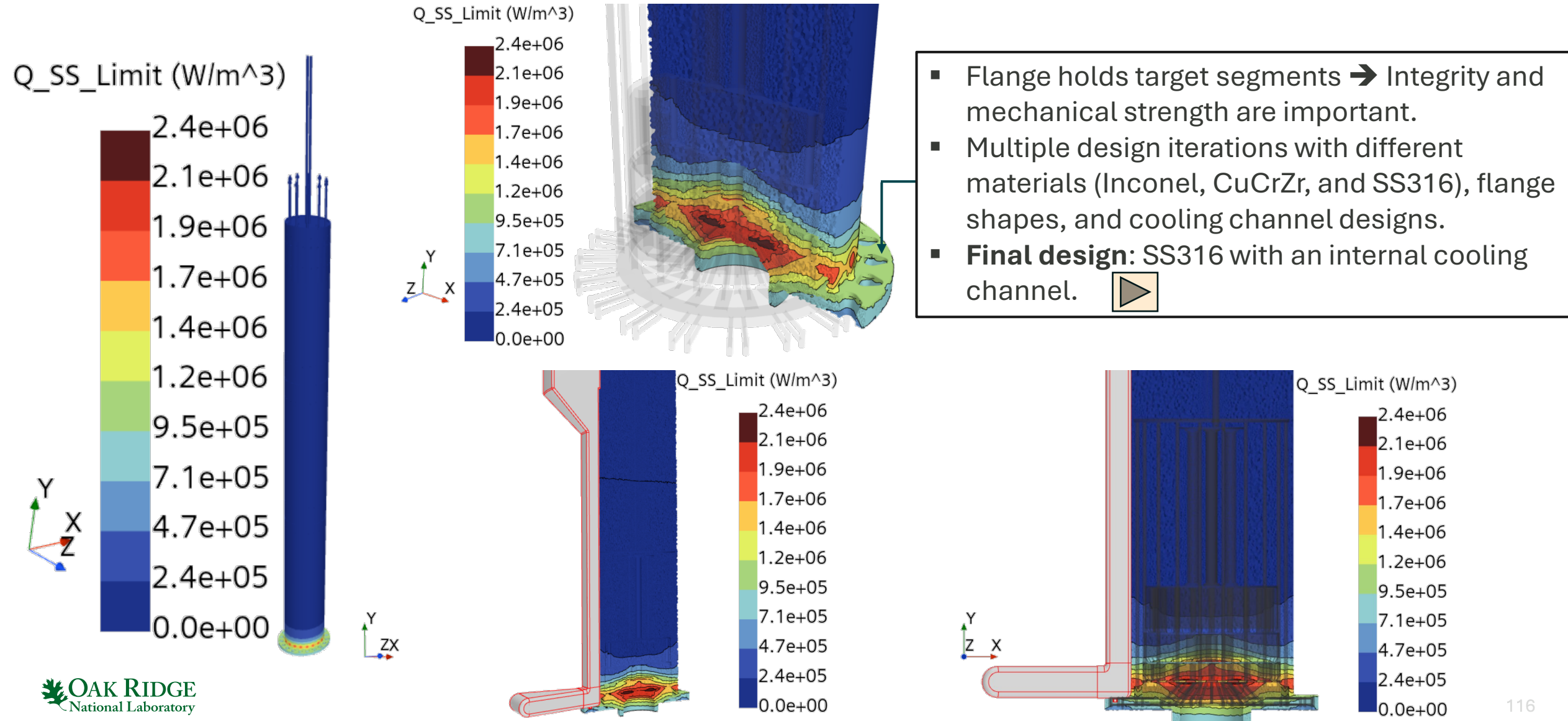
Target Shaft With Nominal, Overfocused, Offset, and Diffused Beams

Target Shaft, Heat Source

Nominal Beam

Heat Source Calculation done by Lukas Zavorka

$Q_{SS} = 32.2 \text{ kW}$ (4.6% of 700 kW)

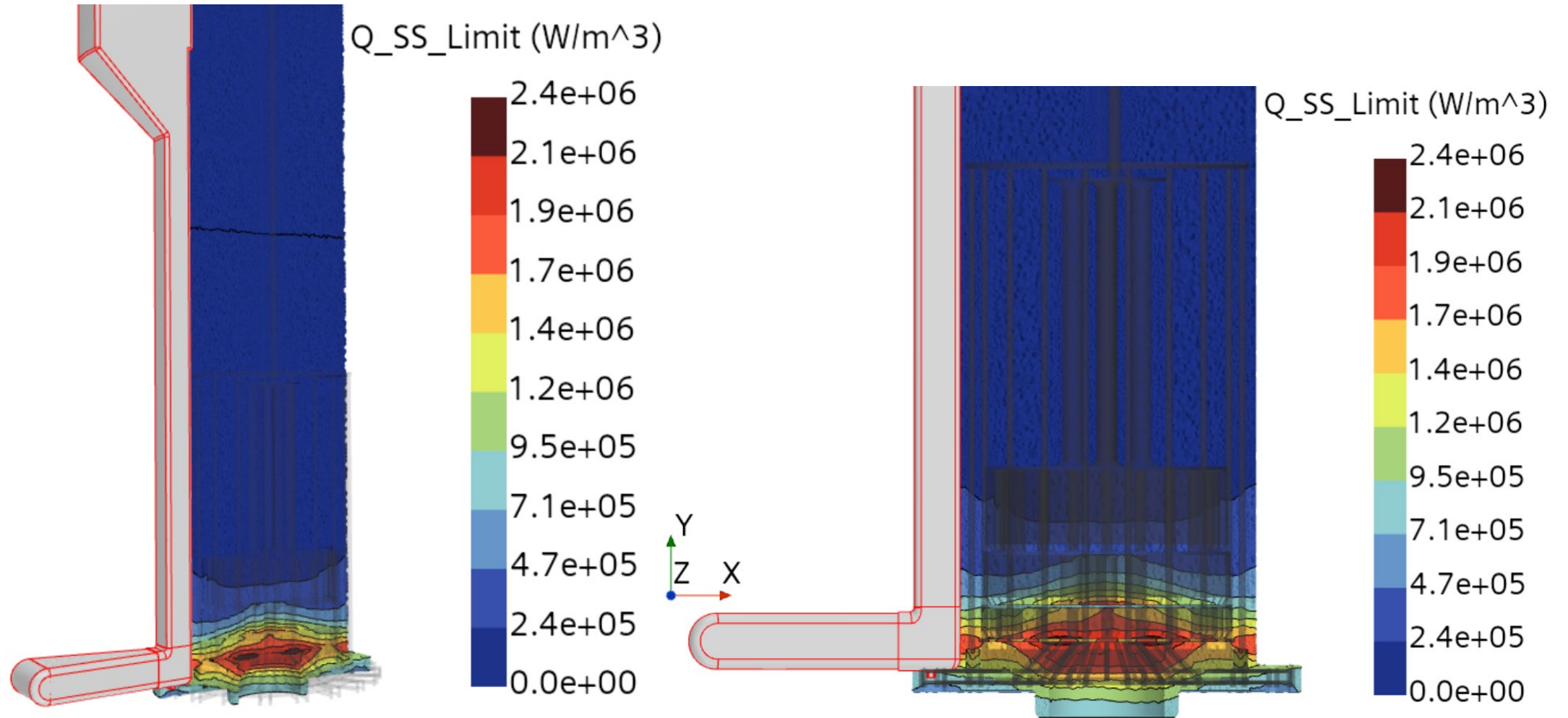


Target Shaft, Heat Source

Nominal Beam

Heat Source Calculation done by Lukas Zavorka

$$Q_{SS} = 32.2 \text{ kW (4.6\% of 700 kW)}$$

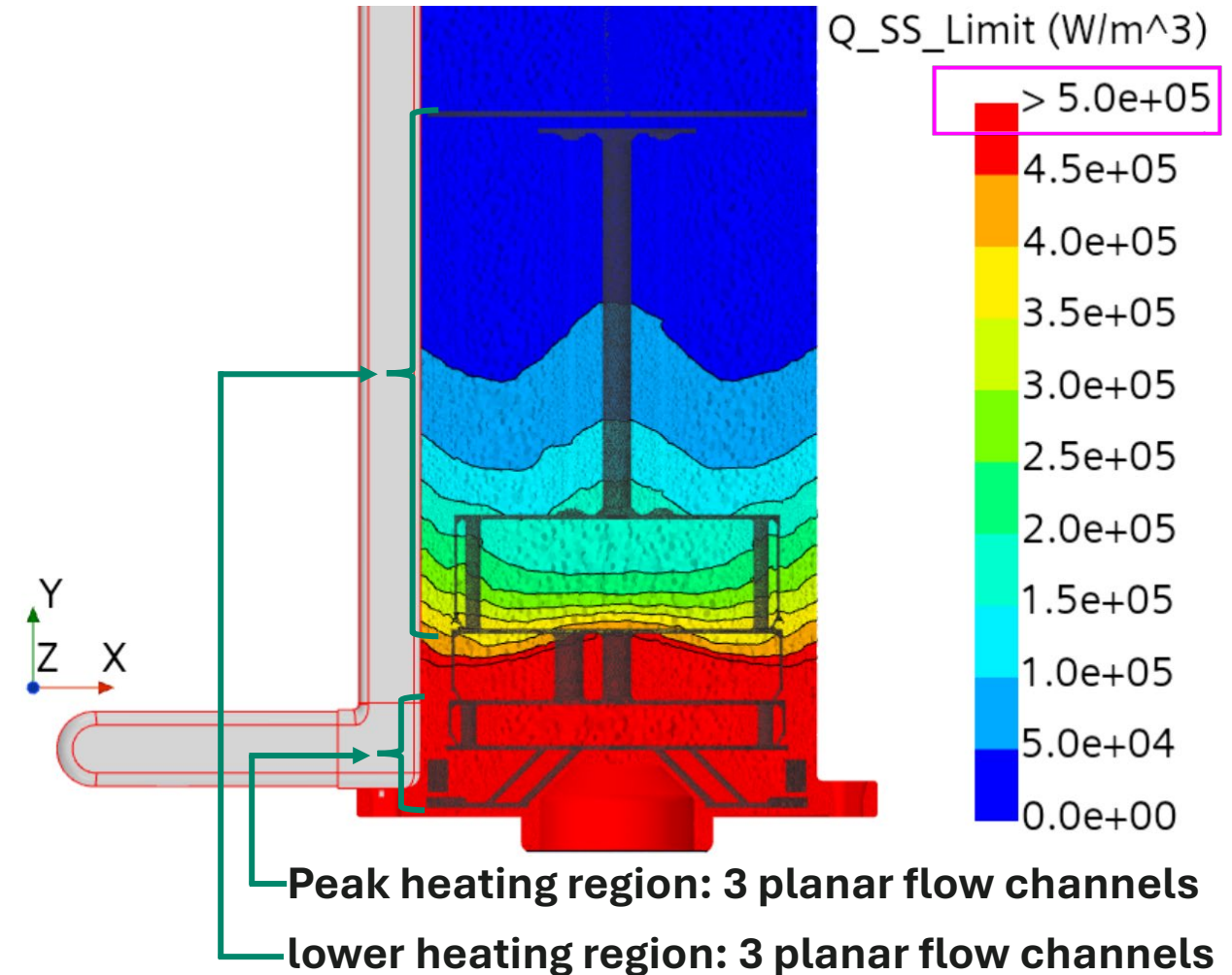
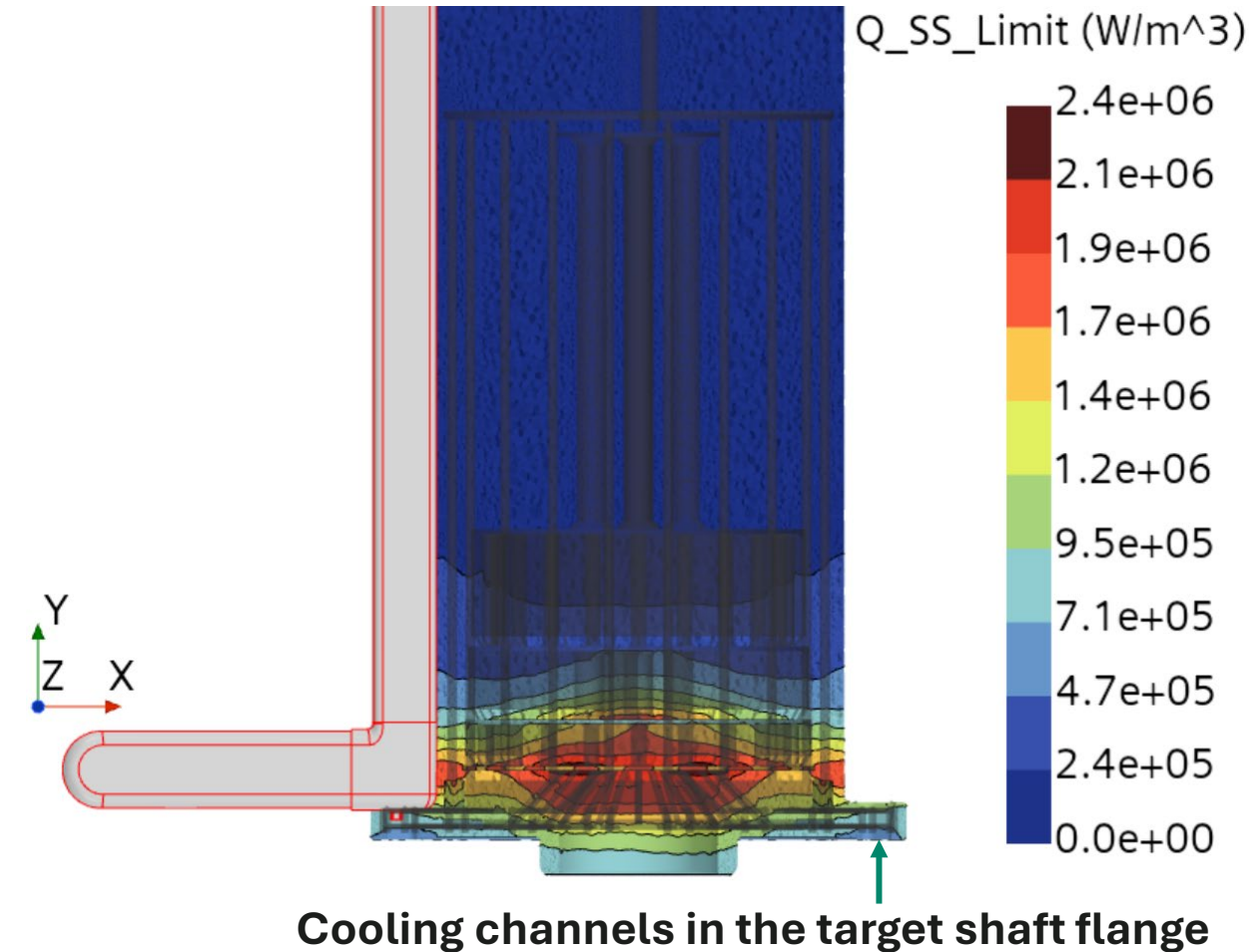


Target Shaft, Heat Source

Nominal Beam

Heat Source Calculation done by Lukas Zavorka

$$Q_{SS} = 32.2 \text{ kW (4.6\% of 700 kW)}$$



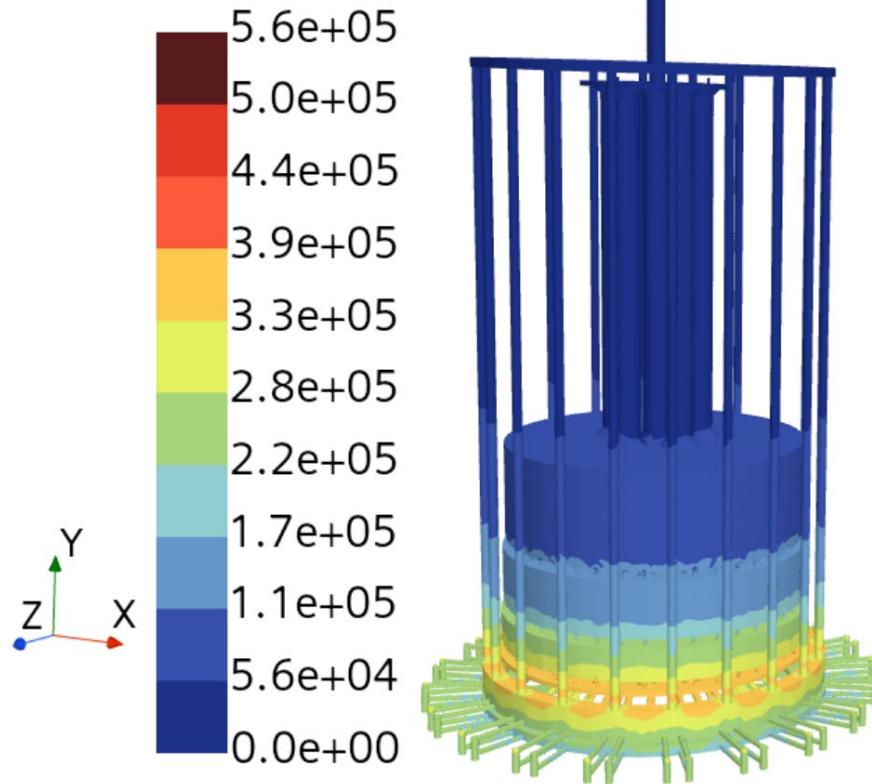
Target Shaft, Heat Source

Nominal Beam

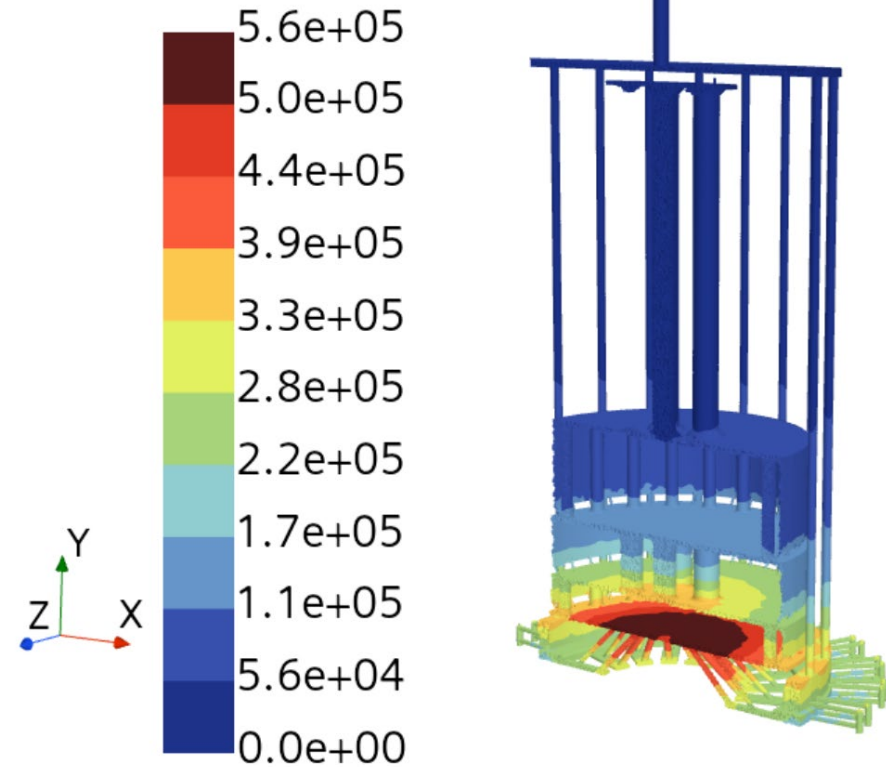
Heat Source Calculation done by Lukas Zavorka

$Q_{\text{Water}} = 1.3 \text{ kW}$

$Q_{\text{Water_Limit}} \text{ (W/m}^3\text{)}$



$Q_{\text{Water_Limit}} \text{ (W/m}^3\text{)}$



Target Shaft, Water Pressure

ID	Codebeamer Tracker and Link	Requirement
1691	Target Shaft Requirement 1691	The shaft shall have a pressure drop of less than 6 psi (62 kPa) at 7.5 gpm (28.4 L/min).
	https://sts-req.ornl.gov:8443/cb/issue/1691	

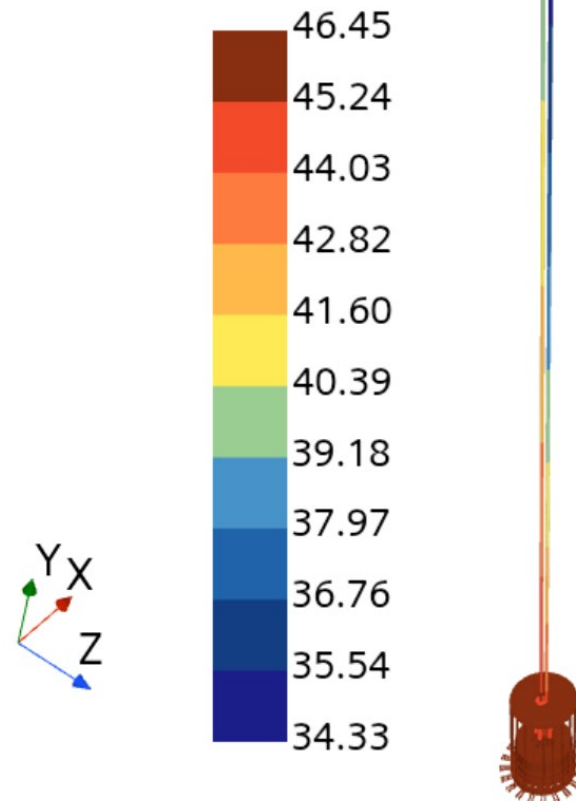
1691

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

Inlet (0.47 kg/s, 32.22°C) Outlet

(7.5 GPM) ↓↑

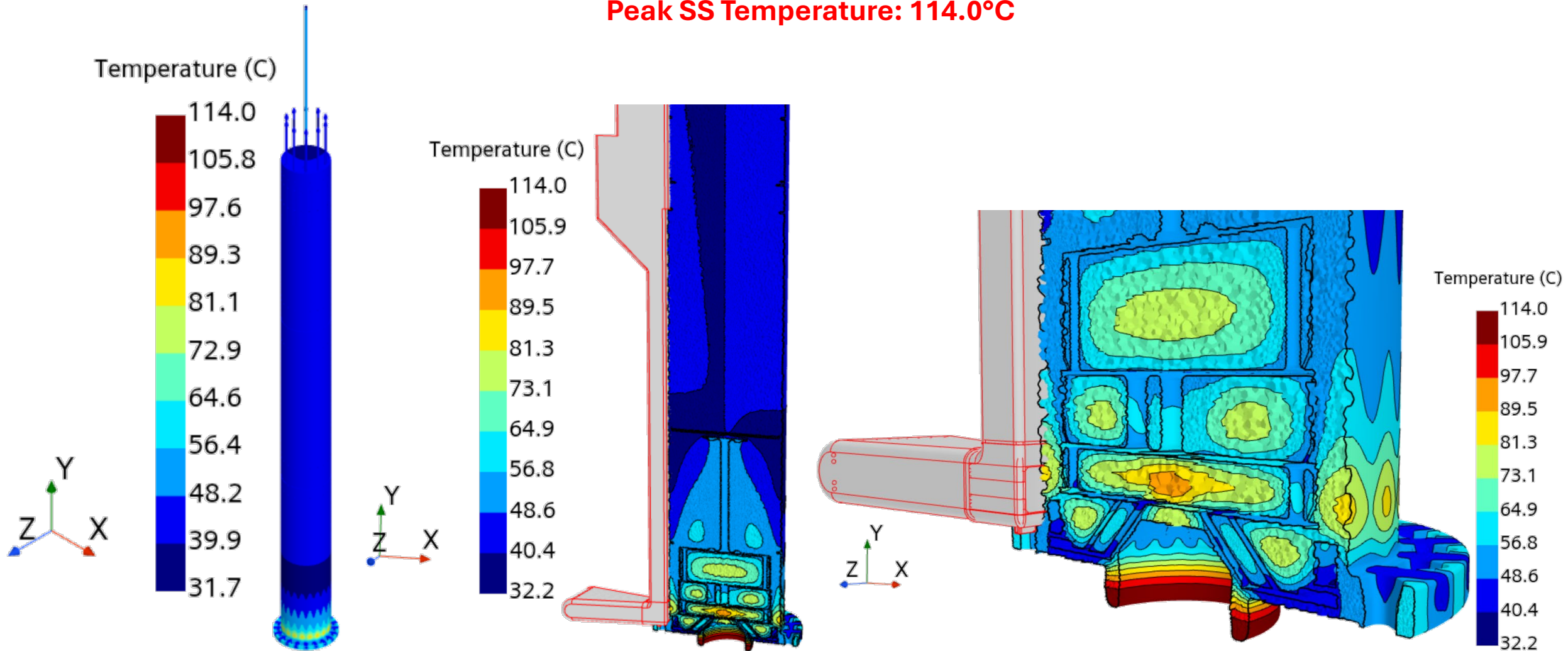
Absolute Total Pressure (psi)



Target Solid Shaft, Temperature

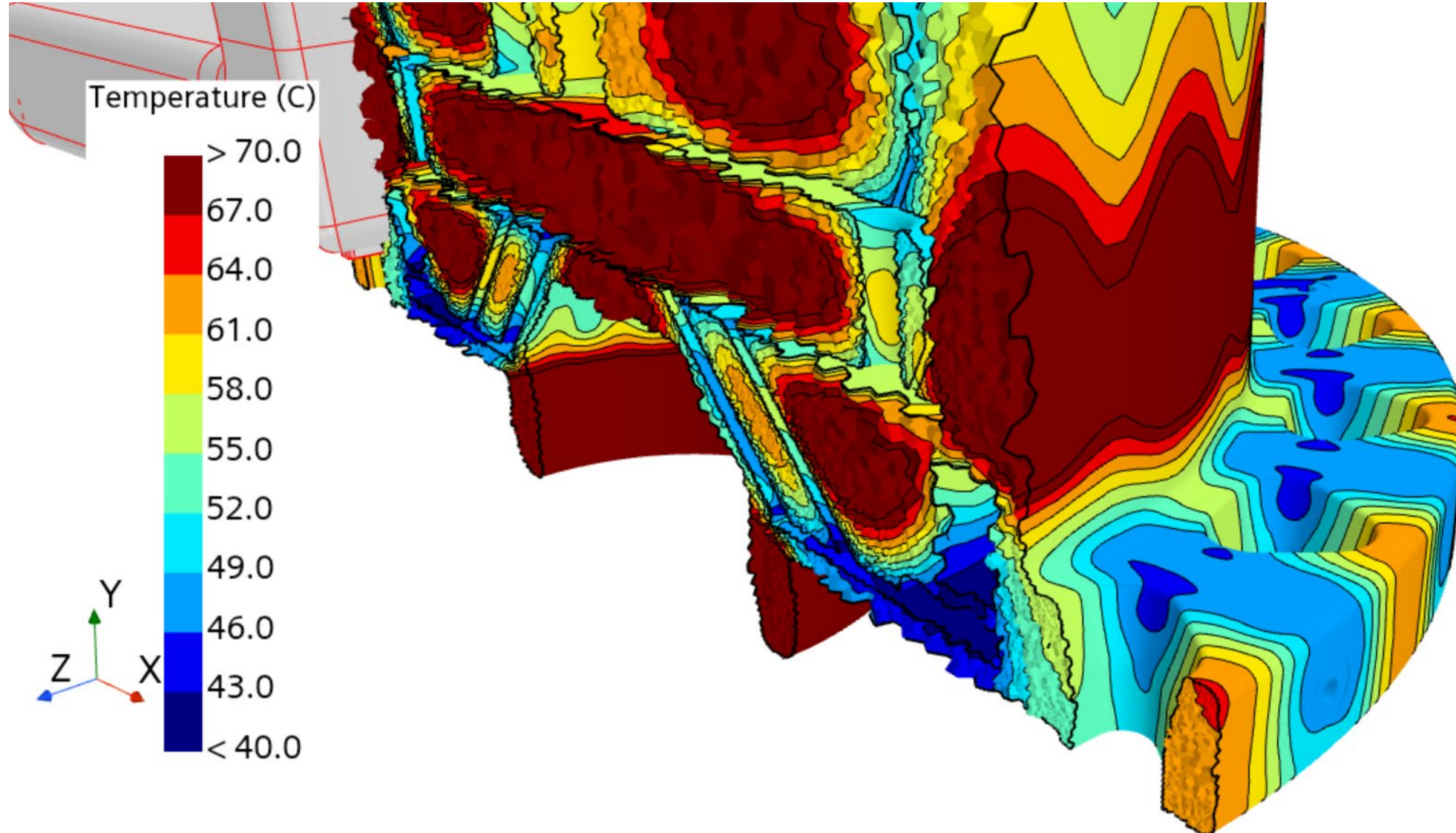
Nominal Beam

Peak SS Temperature: 114.0°C



Target Solid Shaft, Temperature

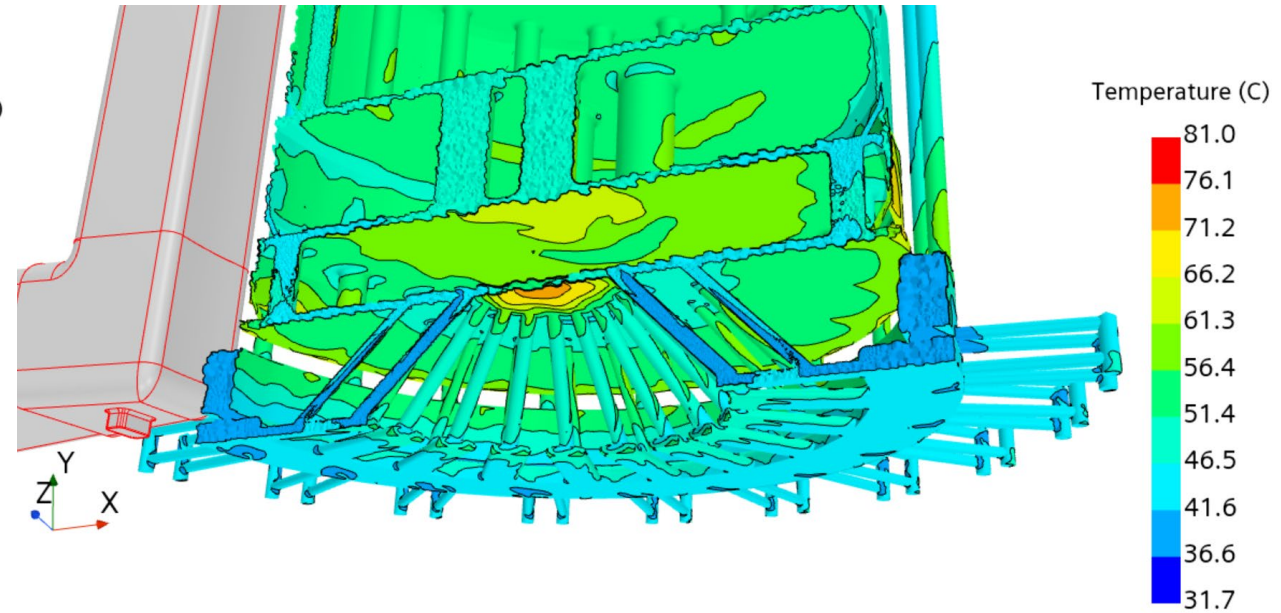
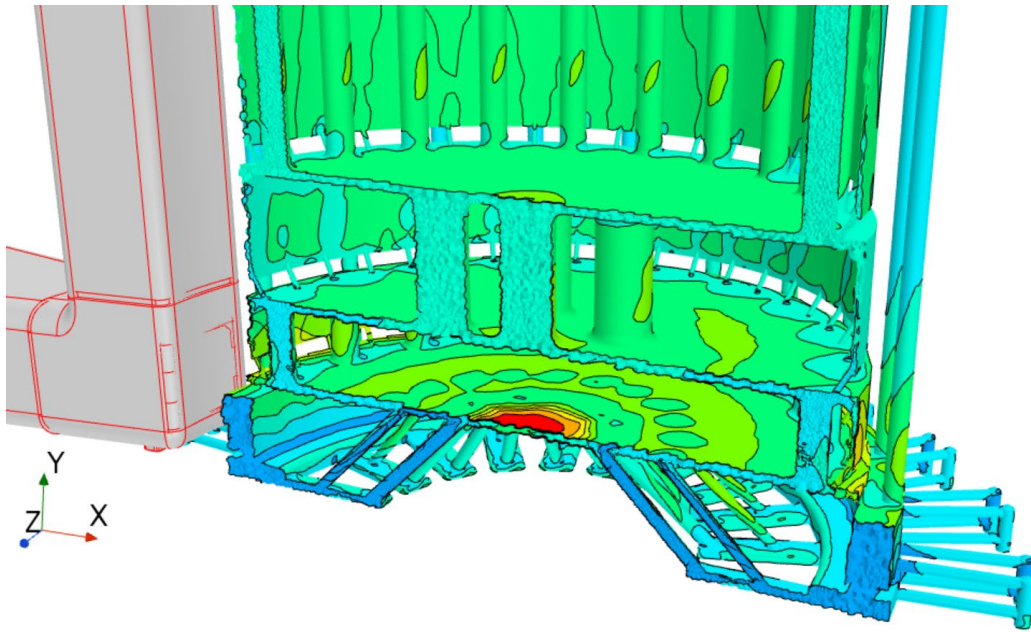
Nominal Beam



Target Shaft, Water Temperature

Nominal Beam

Peak Water Temperature: 81.0°C



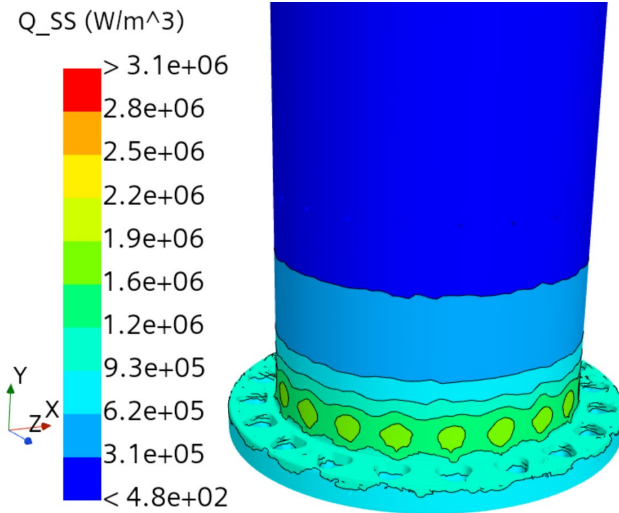
Day 3

Target Shaft With Nominal, Overfocused, Offset, and Diffused Beams

Target Shaft, Heat Source

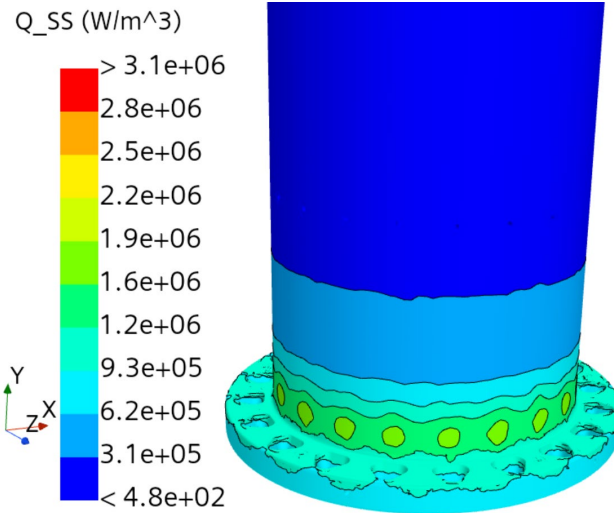
Nominal Beam

$Q_{SS} = 32.2 \text{ kW}$
 $Q_{Water} = 1.3 \text{ kW}$



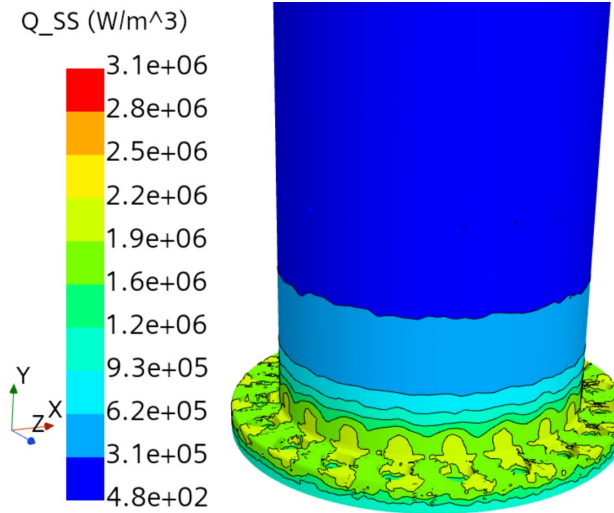
Over-Focused Beam

$Q_{SS} = 31.4 \text{ kW}$
 $Q_{Water} = 1.3 \text{ kW}$



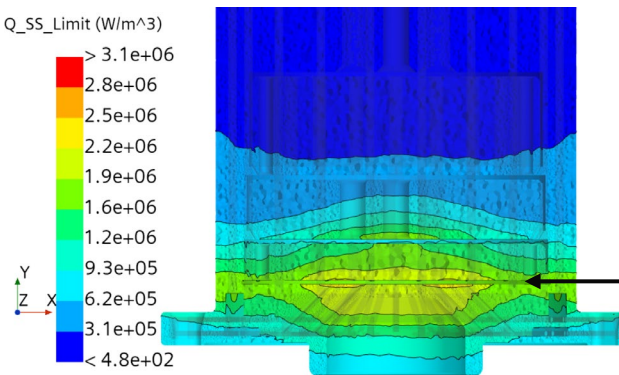
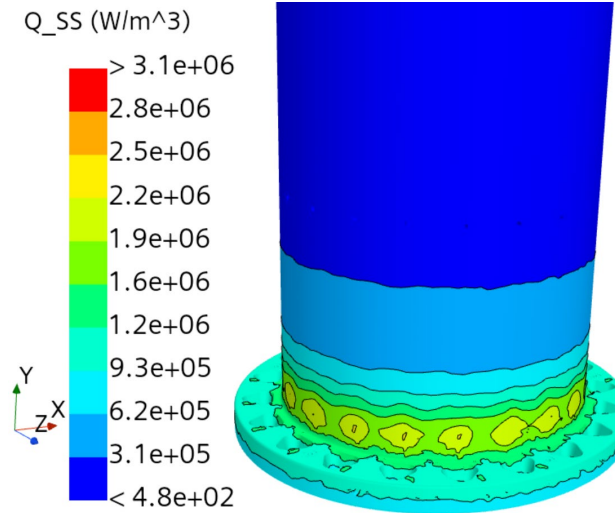
Offset Beam (Down: 0.85cm ; left: 1.2 cm)

$Q_{SS} = 35.1 \text{ kW}$
 $Q_{Water} = 1.4 \text{ kW}$

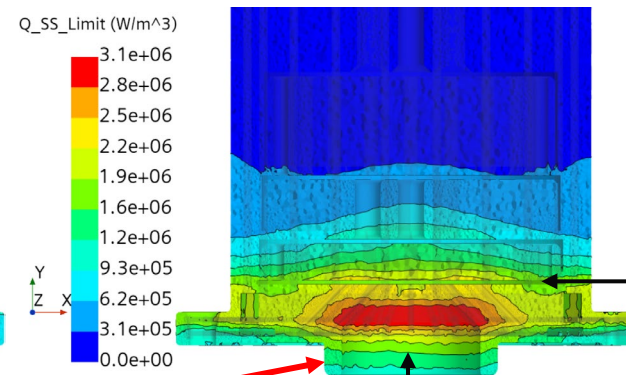
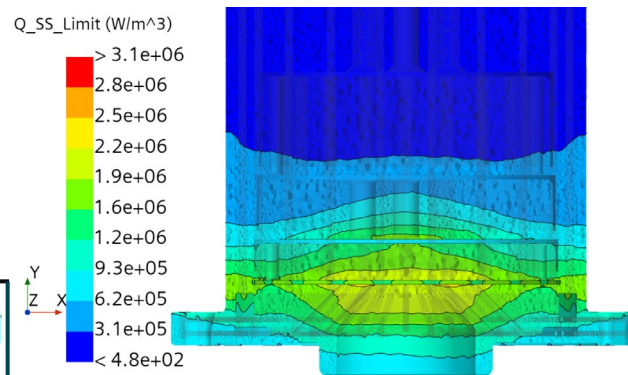


Diffused Beam

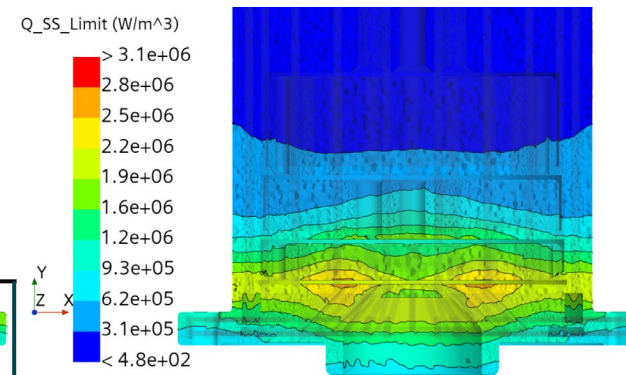
$Q_{SS} = 36.4 \text{ kW}$
 $Q_{Water} = 1.5 \text{ kW}$



Planar cooling channel
through peak heating region



Higer heating, no cooling



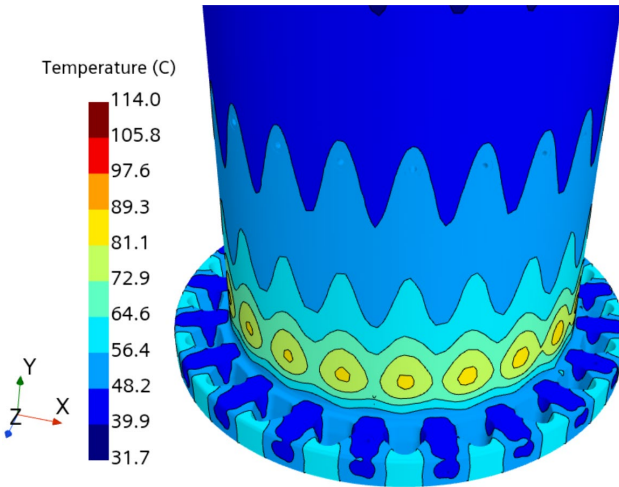
Planar cooling channel

An offset beam deposits more energy in the ring, which lacks designated cooling.

Target Shaft, Temperature

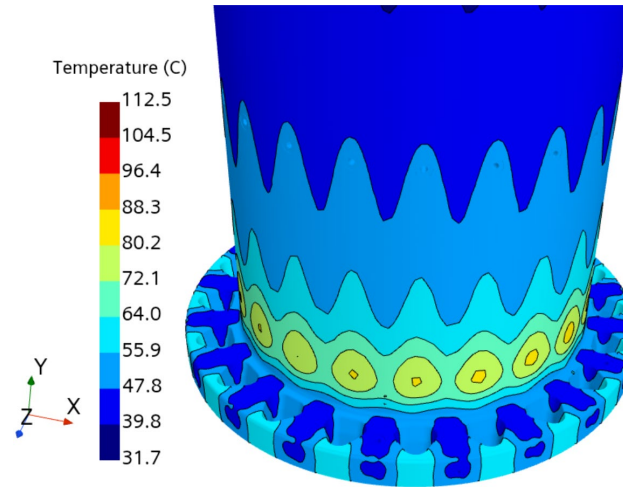
Nominal Beam

Peak: 114°C



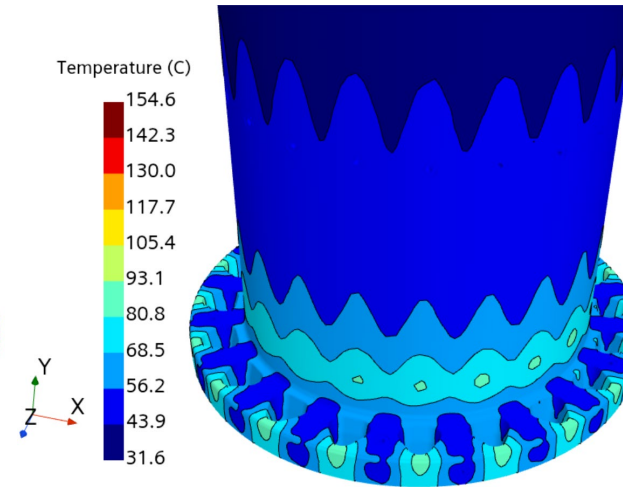
Over-Focused Beam

Peak: 112.5°C



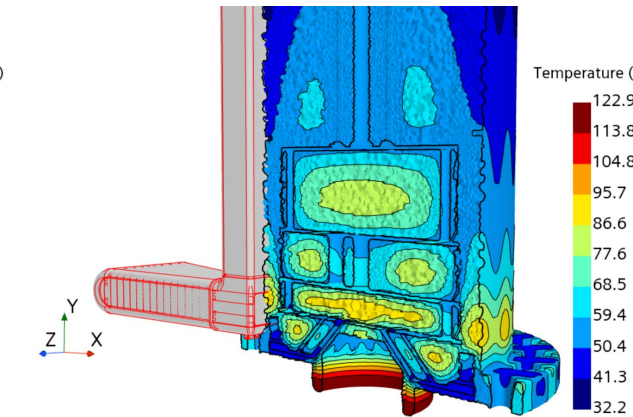
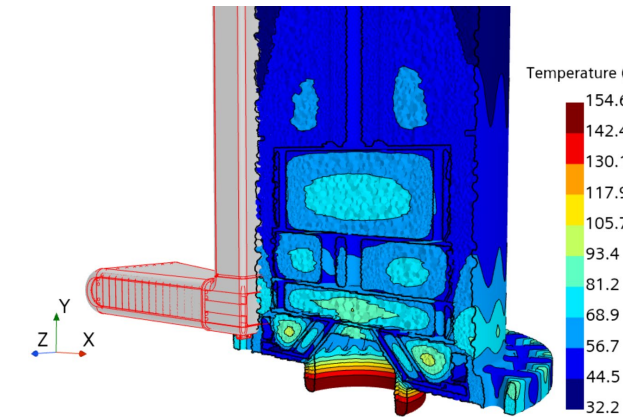
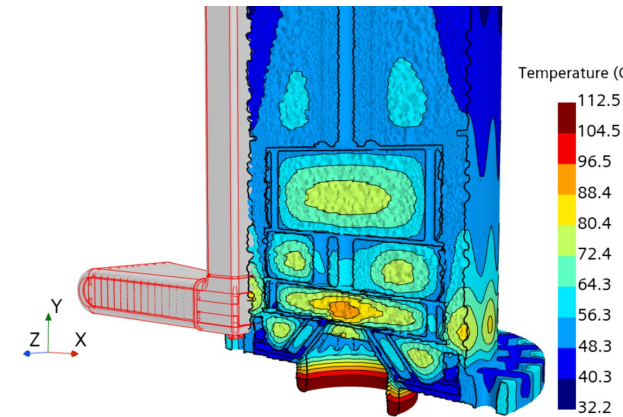
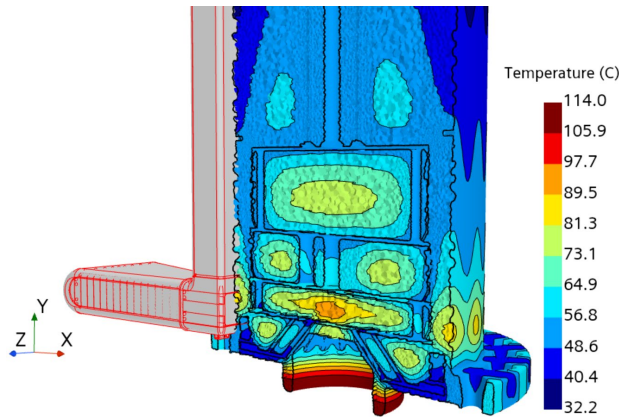
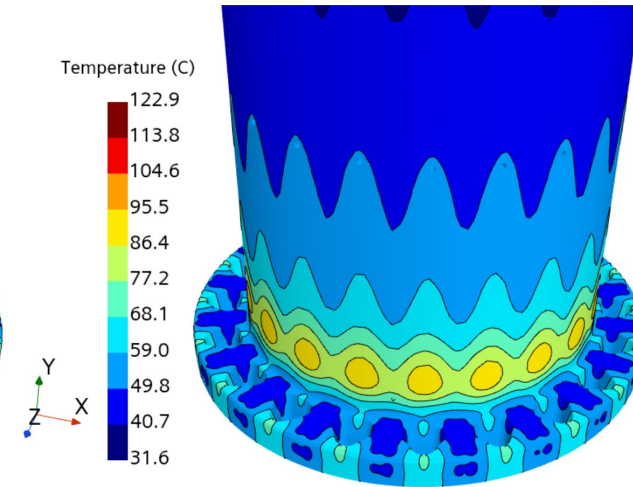
Offset Beam
(Down: 0.85cm ; left: 1.2 cm)

Peak: 154.6°C



Diffused Beam

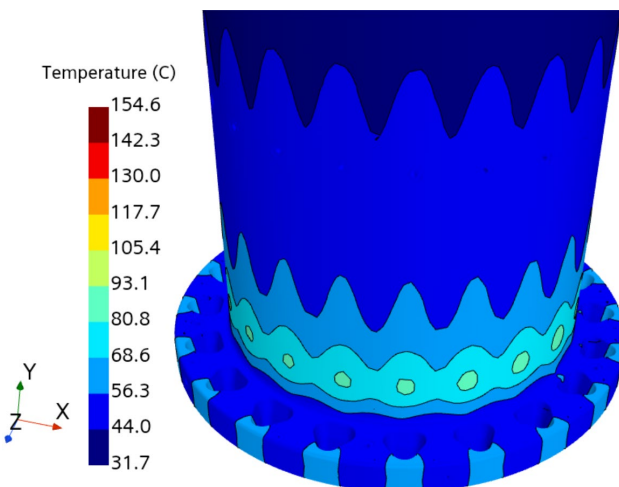
Peak: 122.9°C



Target Shaft, Temperature

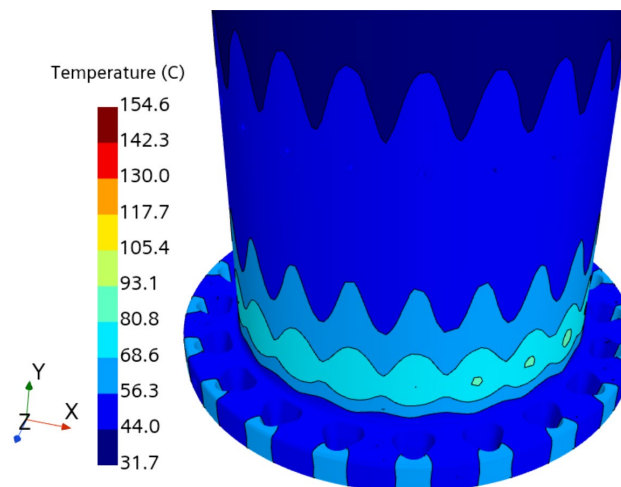
Nominal Beam

Peak: 114°C



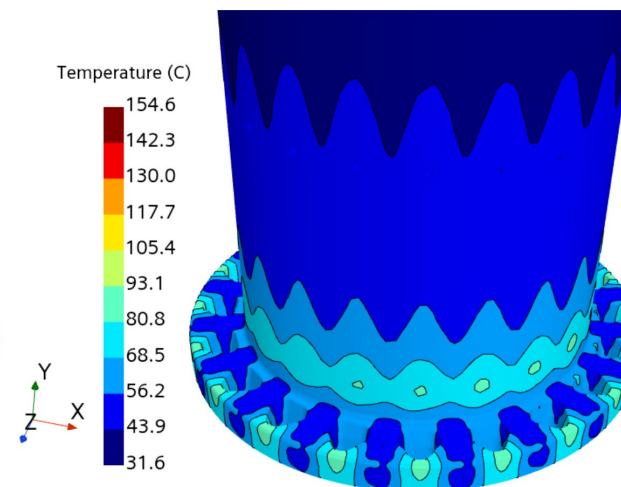
Over-Focused Beam

Peak: 112.5°C



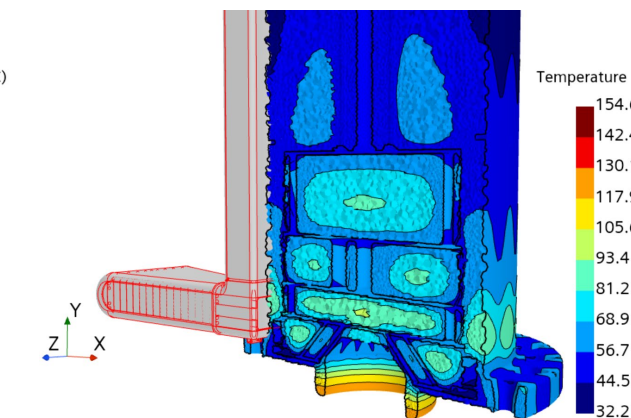
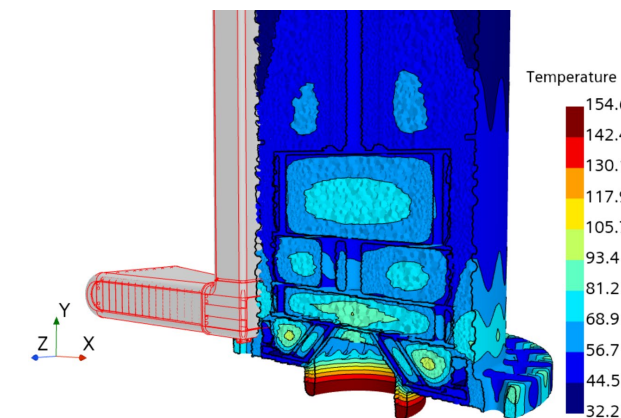
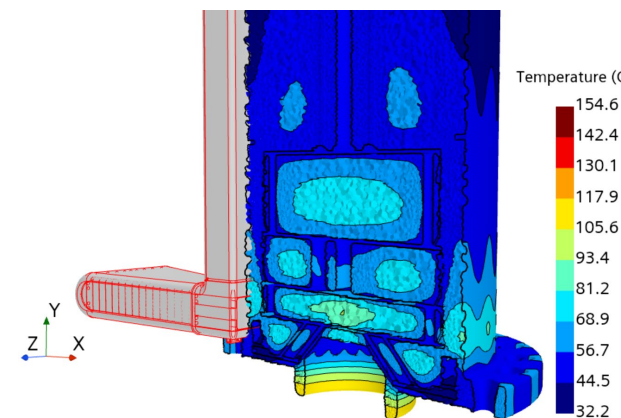
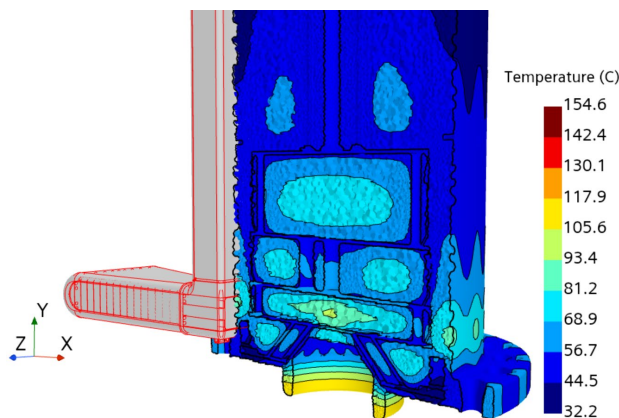
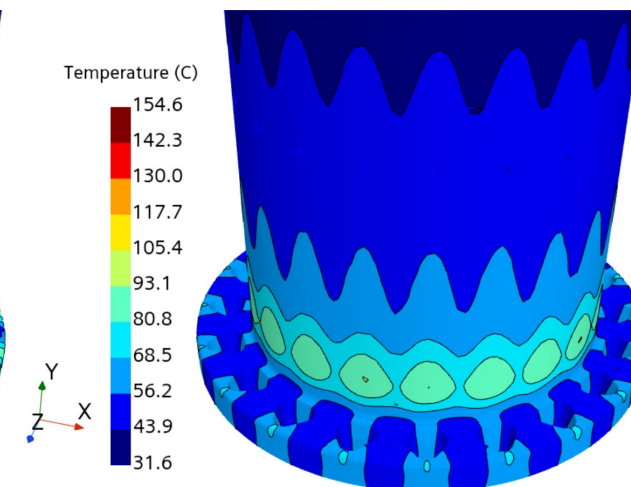
Offset Beam
(Down: 0.85cm ; left: 1.2 cm)

Peak: 154.6°C



Diffused Beam

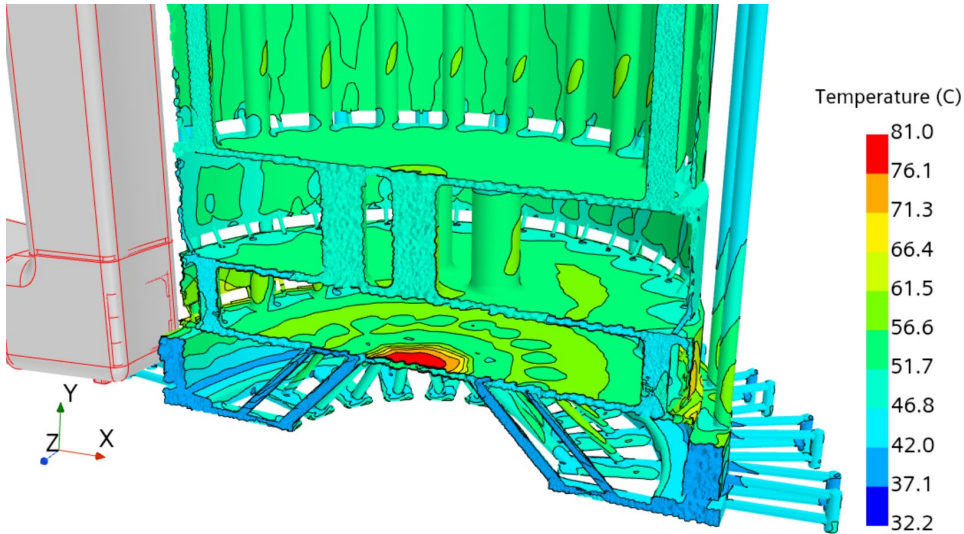
Peak: 122.9°C



Target Shaft, Water Temperature

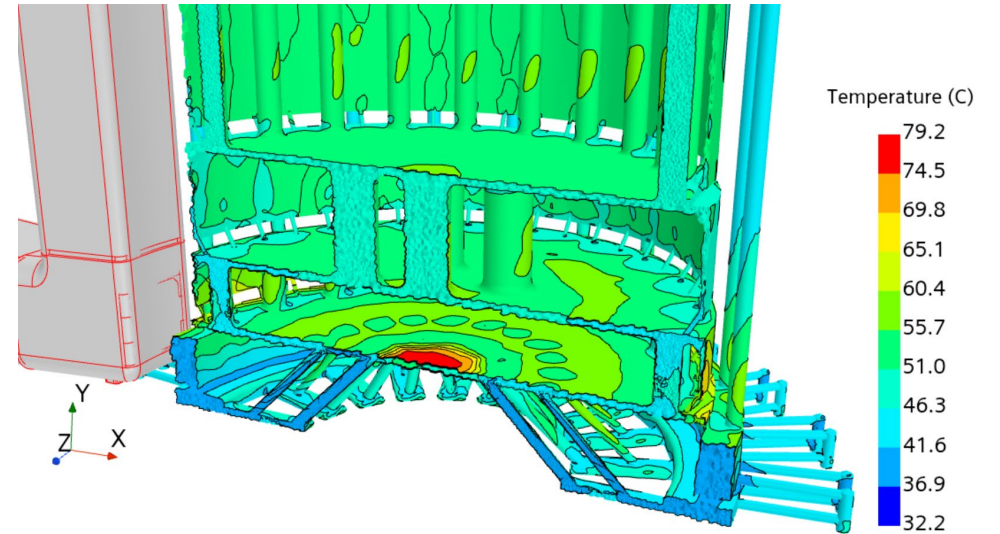
Nominal Beam

Peak: 81°C



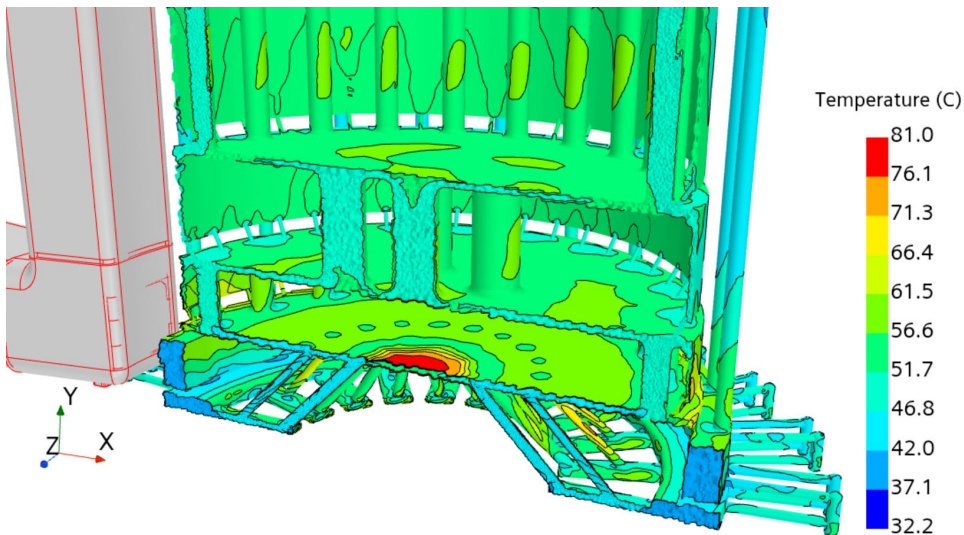
Over-Focused Beam

Peak: 79.2°C



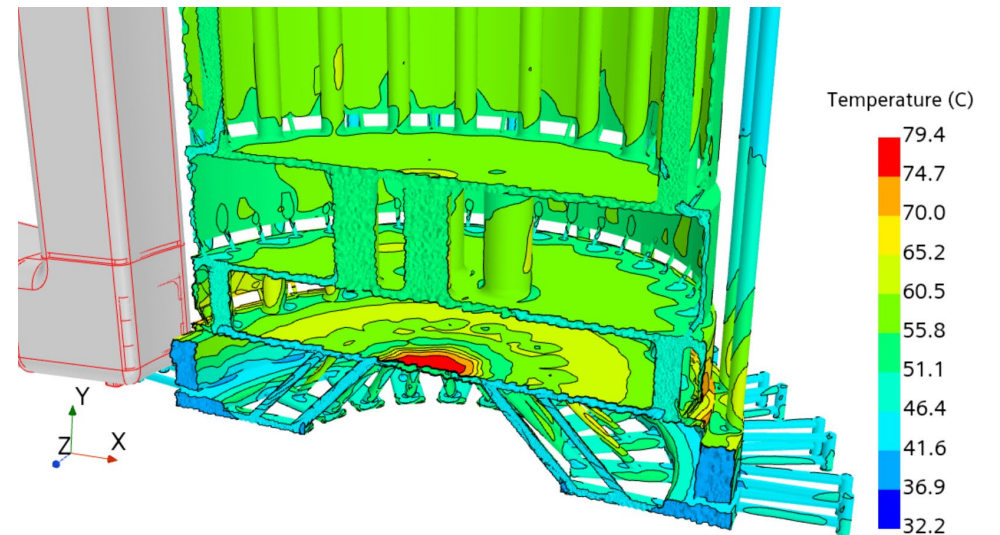
Offset Beam (Down: 0.85cm ; left: 1.2 cm)

Peak: 81°C



Diffused Beam

Peak: 79.4°C

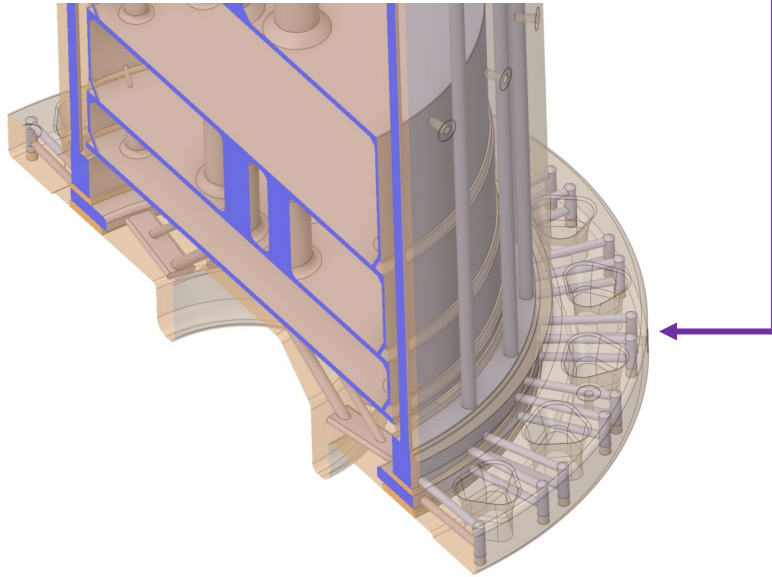


Day 3 : Target Assembly Analysis

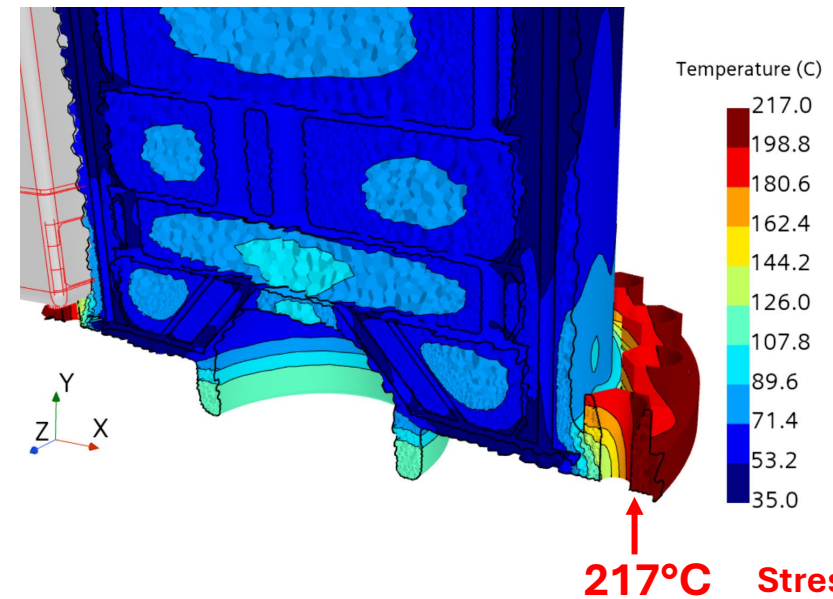
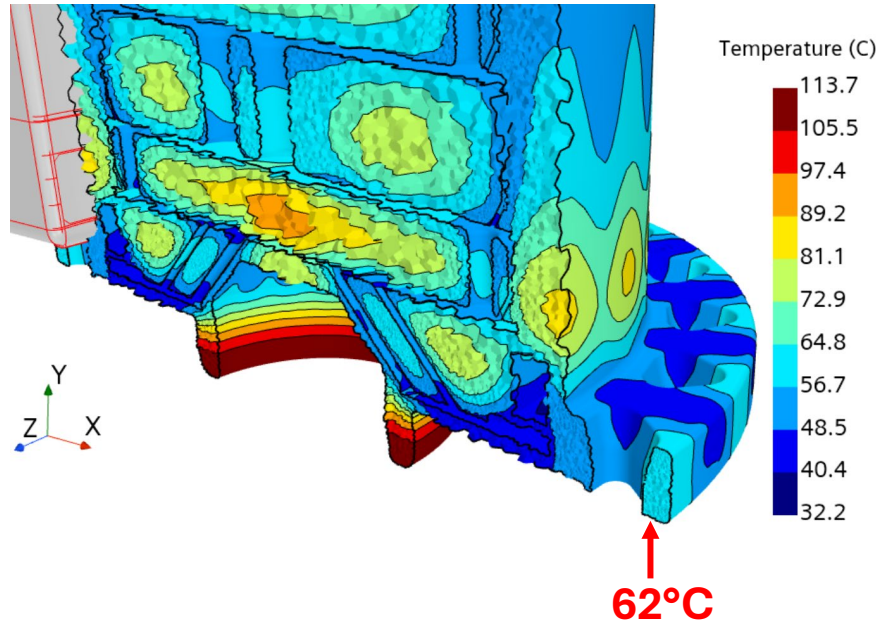
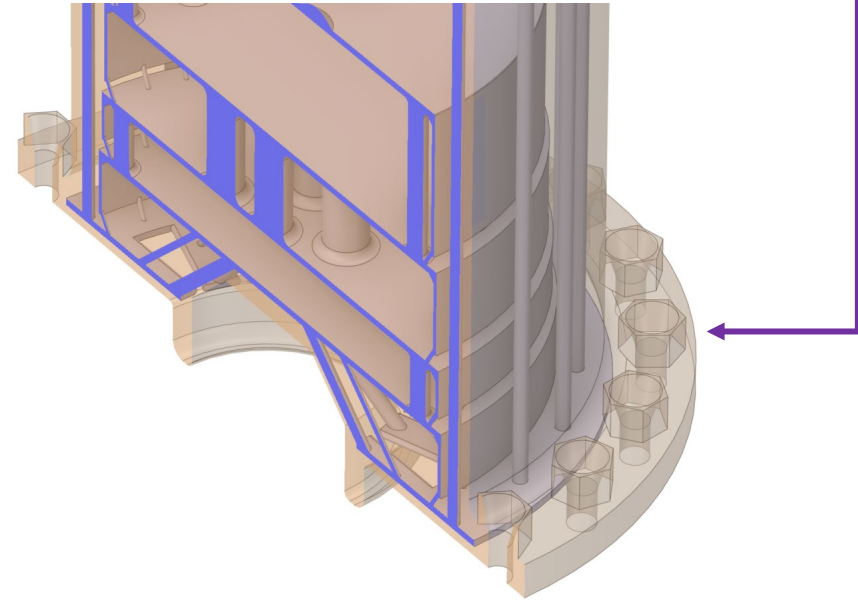
Target Shaft: Impact of Flange Cooling

Target Shaft, Comparison of Target Shaft Flange

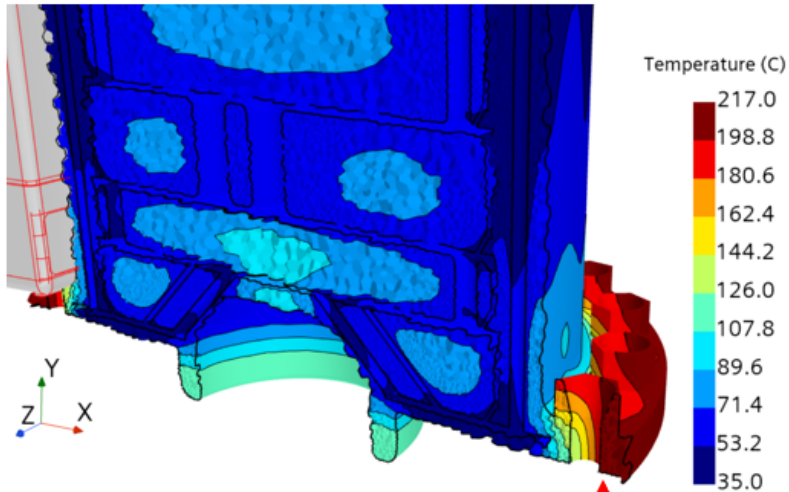
With internal cooling channels



Without internal cooling channels



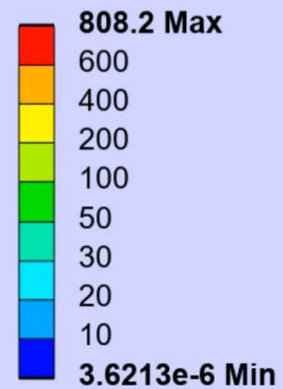
Target Shaft, Target Shaft Flange



217°C Stress issue

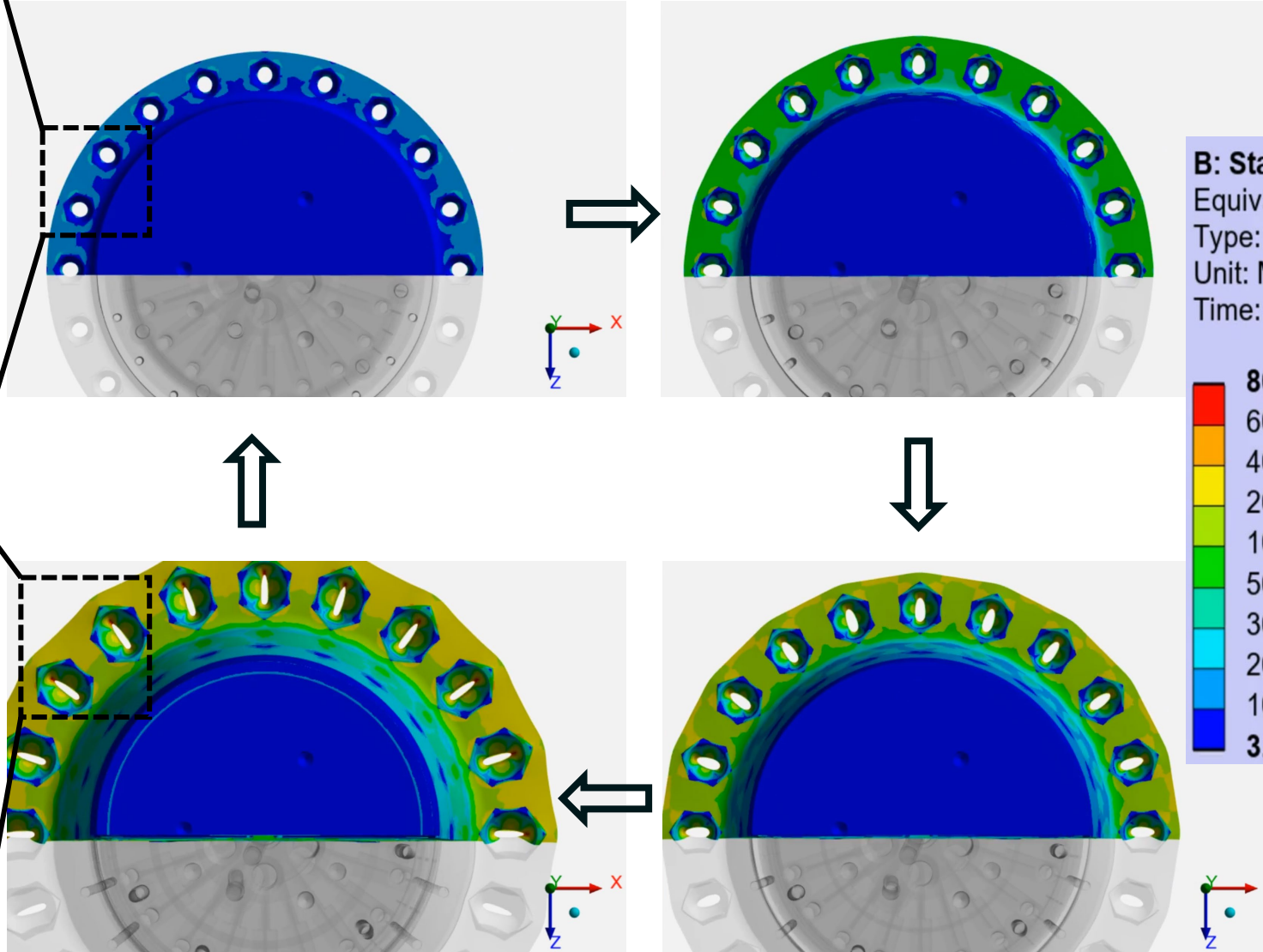
Peak Stress : 808 MPa
SS316 Yield Strength: 252 MPa

B: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 0.42105

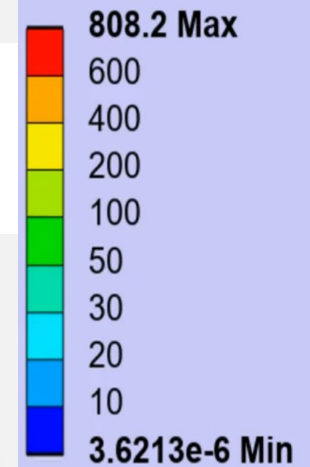


Target Shaft, Target Shaft Flange

Peak Stress : 808 MPa
SS316 Yield Strength: 252 MPa



B: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 0



Day 3 : Target Assembly Analysis

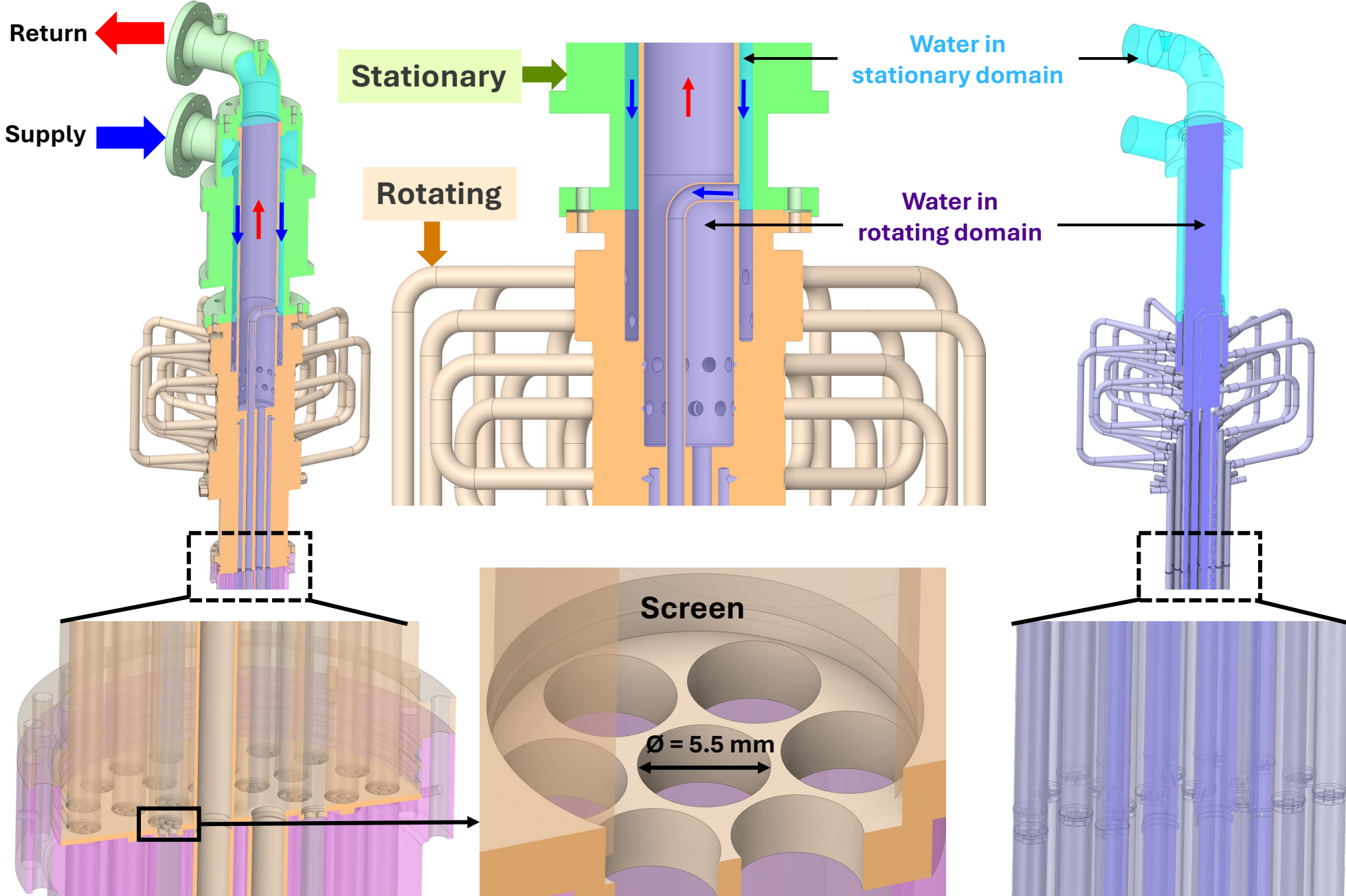
Not the latest FDR design

- **Target Assembly**
 - **Total pressure drop** (**Requirement**)
 - **Flow balance** – Target Drive ➔ 20 Segments & Shaft

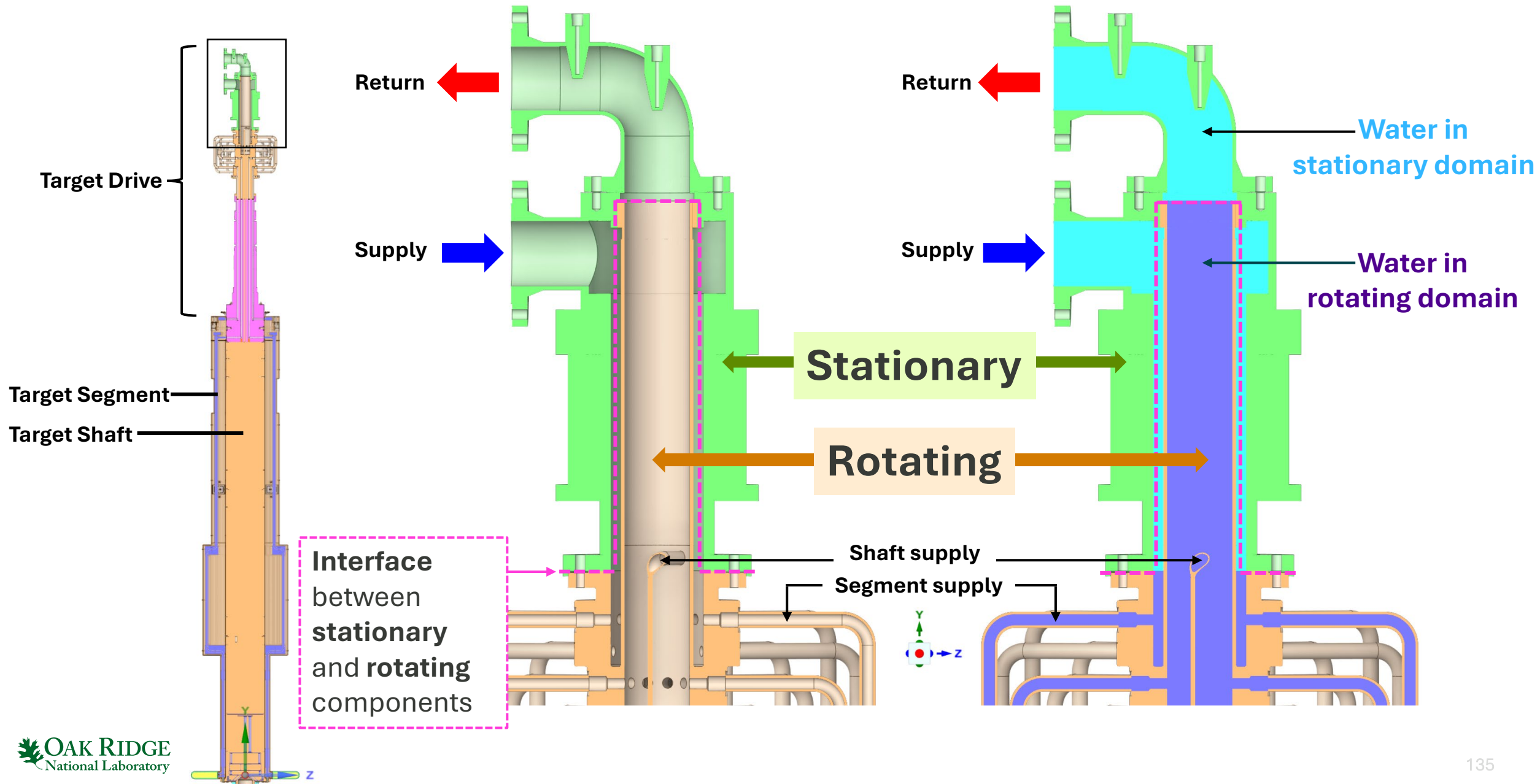
Solid + Fluid

Target Assembly, Geometry

Fluid



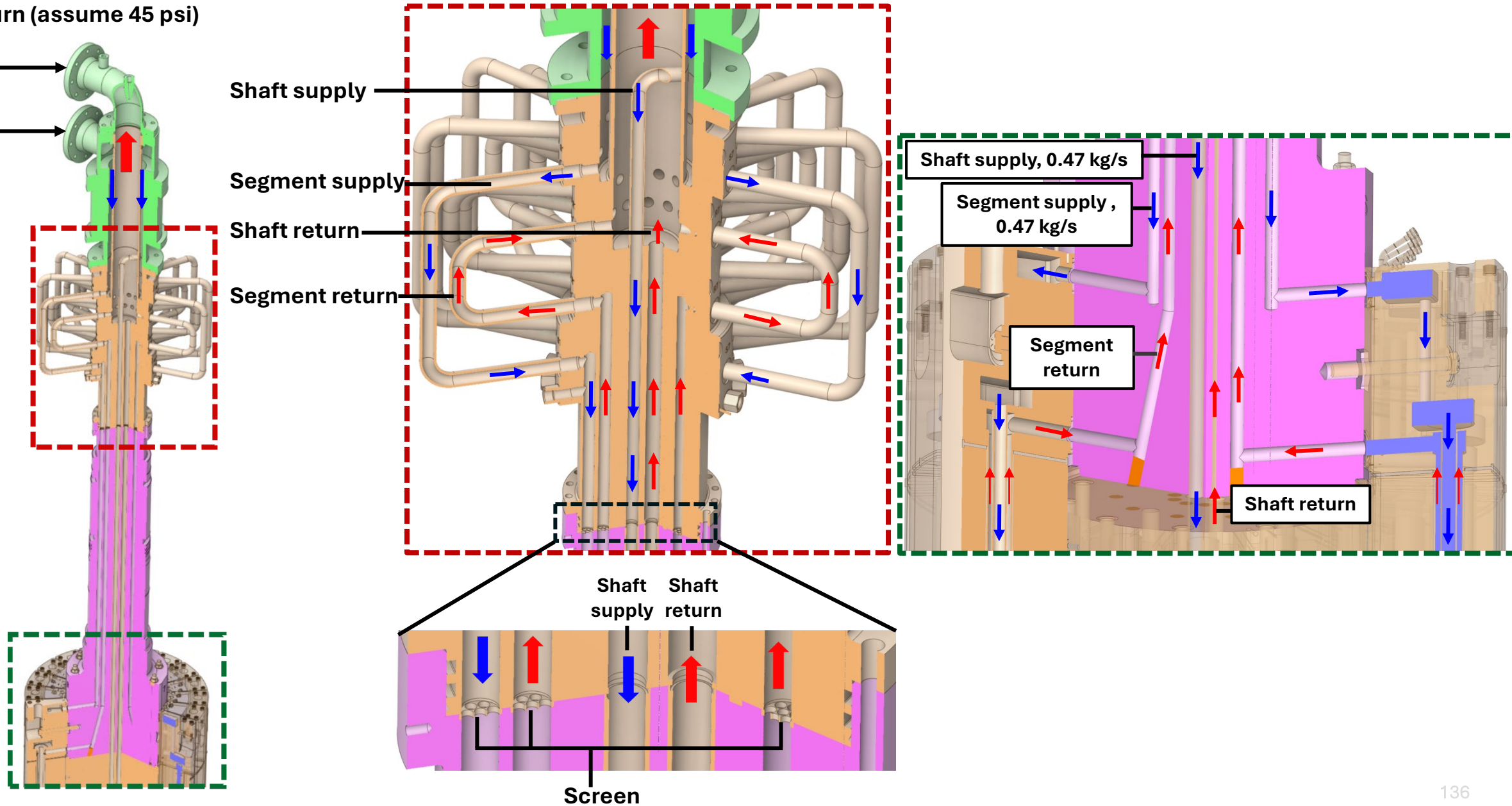
Target Assembly, Geometry



Target Assembly, Flow Direction and Assumption

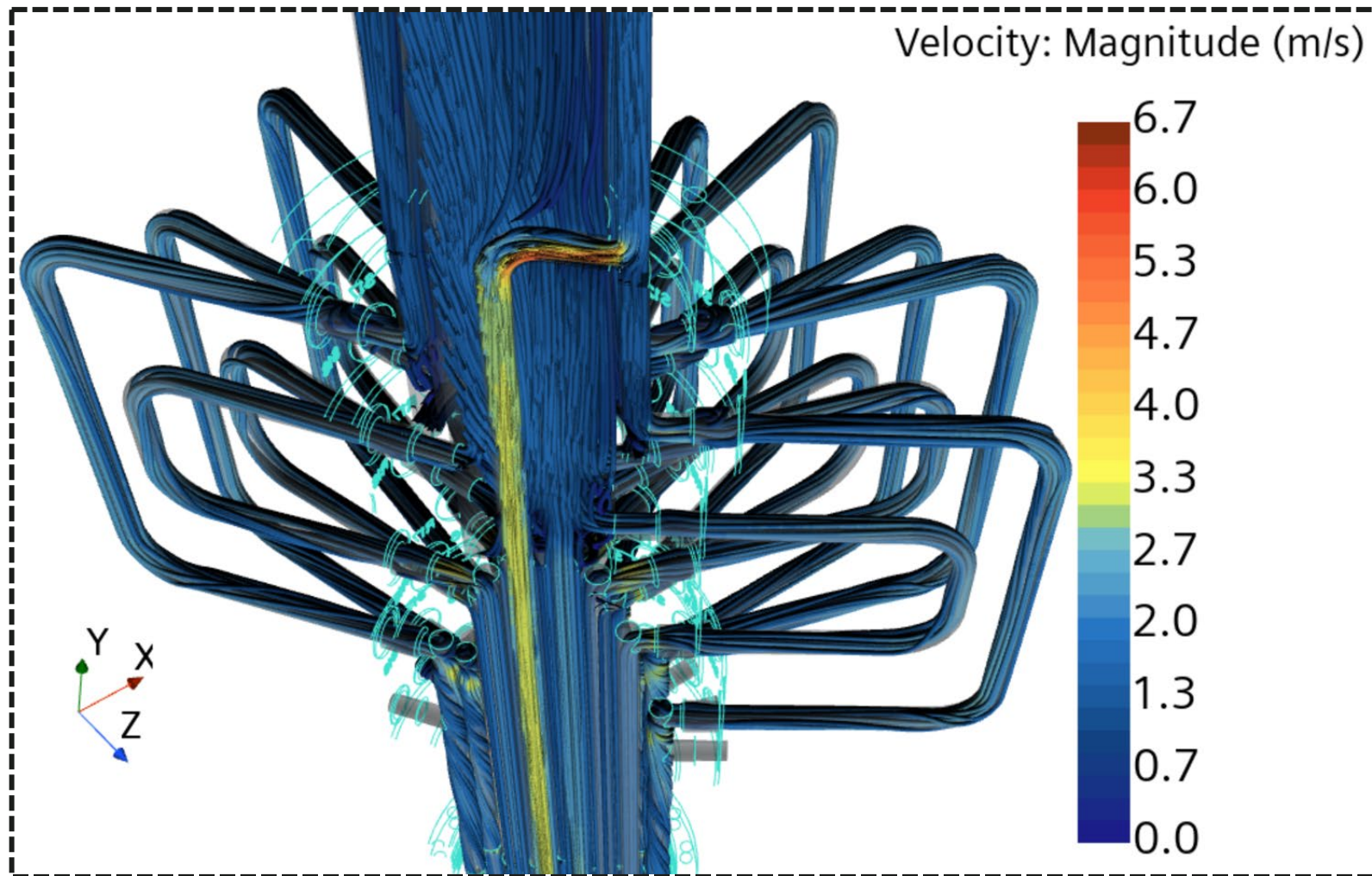
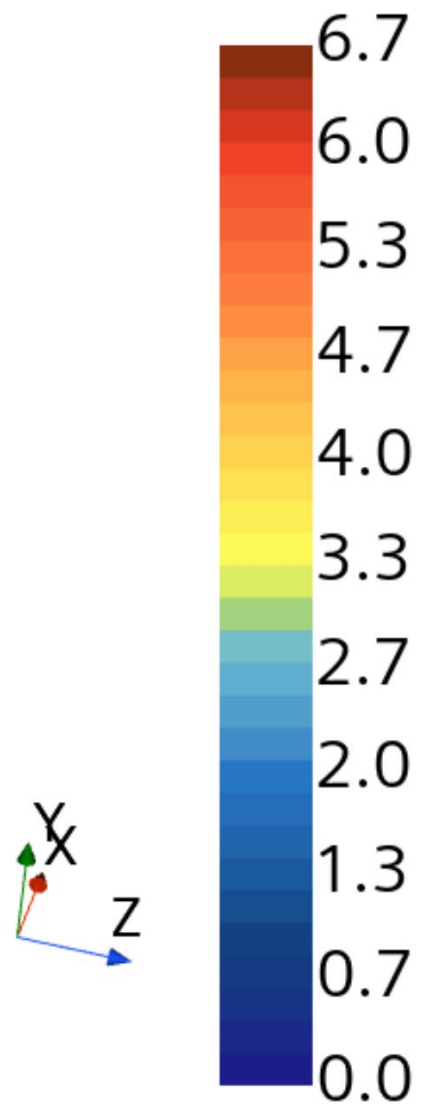
Supply (32.22°C (90°F) water, 9.87 kg/s (157.5 GPM) = 0.47 kg/s (7.5 GPM)*20 segments + 0.47 kg/s (7.5 GPM) shaft)

Return (assume 45 psi)



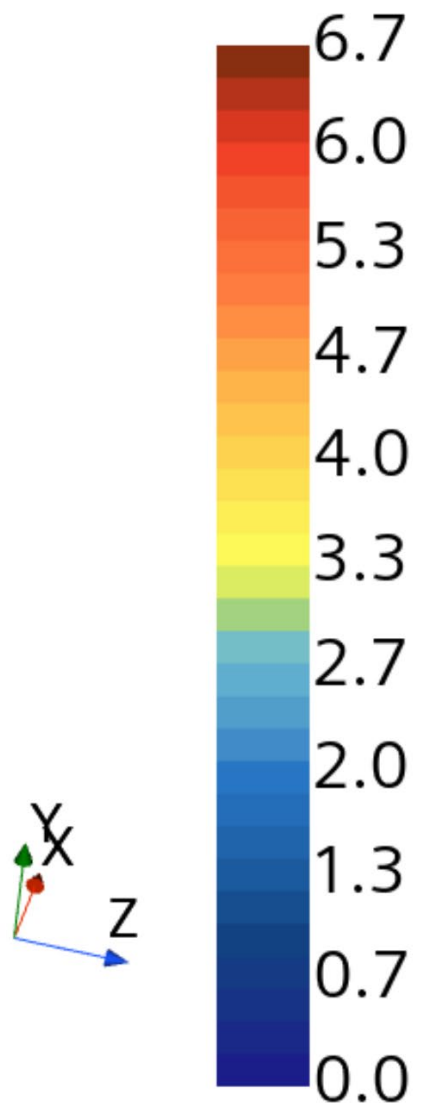
Target Assembly, Streamlines

Velocity: Magnitude (m/s)

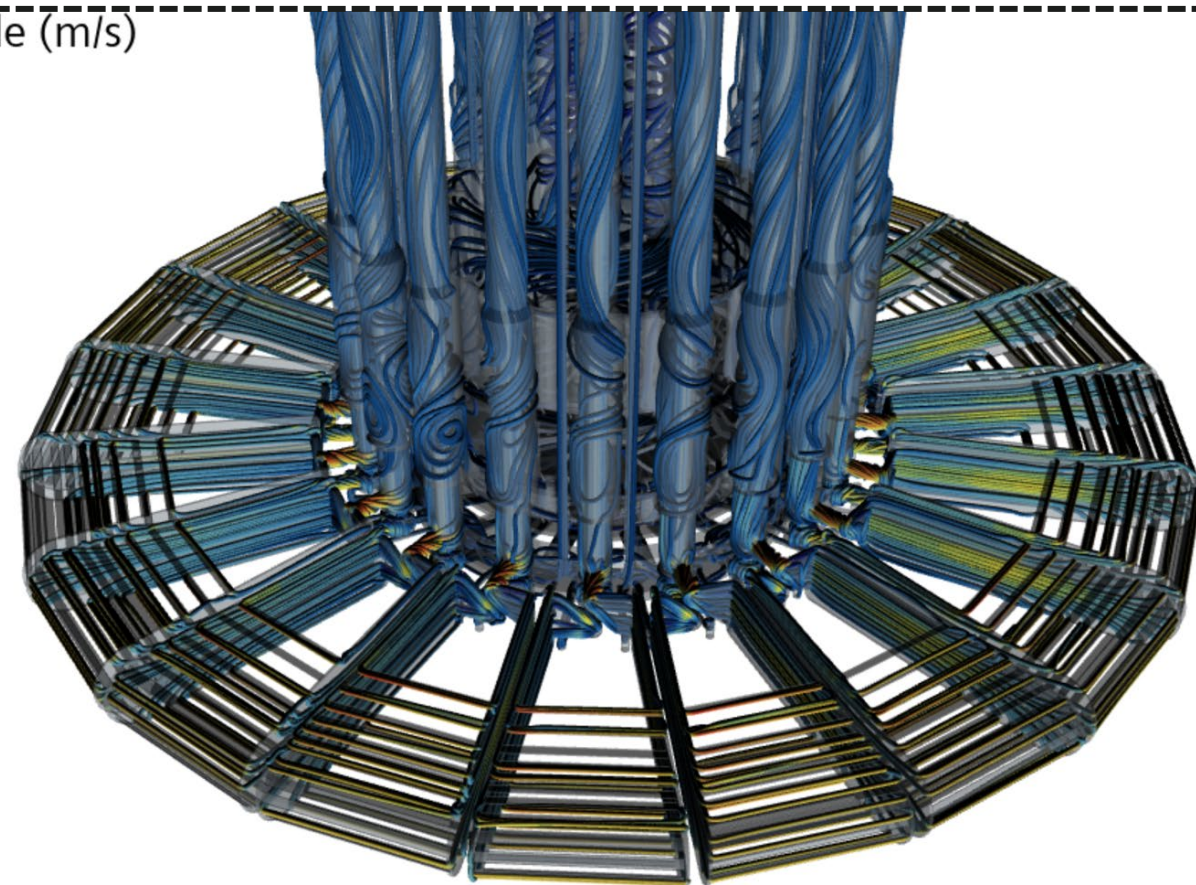
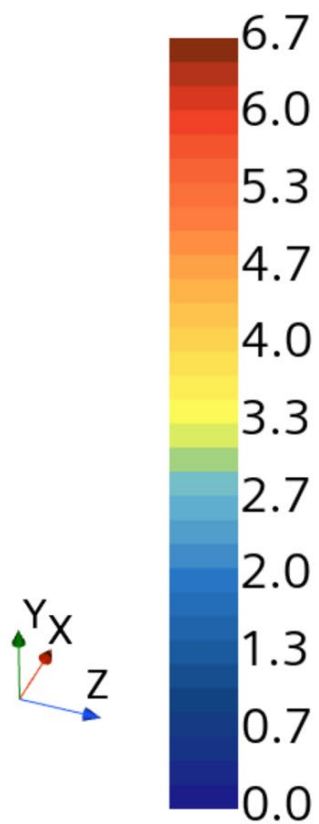


Target Assembly, Streamlines

Velocity: Magnitude (m/s)



Velocity: Magnitude (m/s)



Target Assembly, Water Pressure

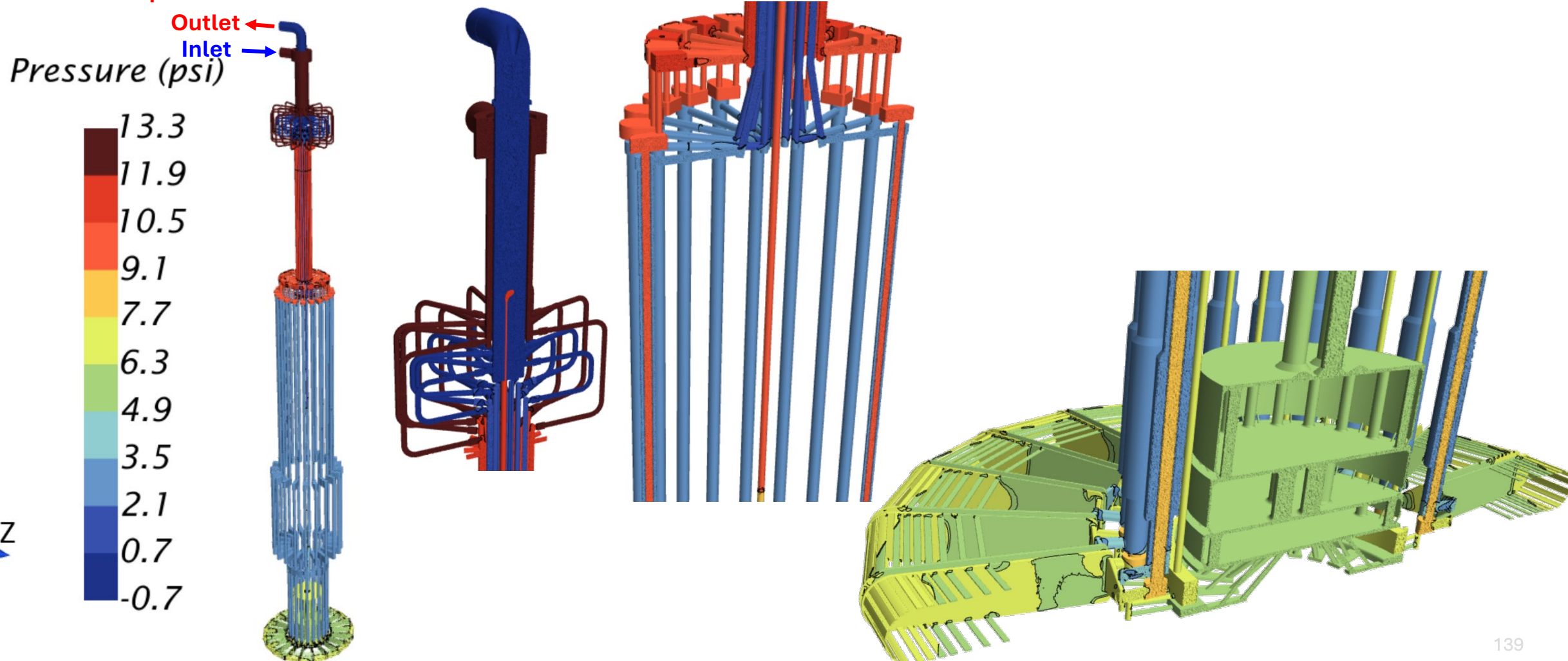
ID	Codebeamer Tracker and Link	Requirement	CFD Result	Status
1487	Target Assembly Requirement 1487	System pressure drop shall not exceed 14.5 psi (100 kPa).	13.6 psi	Pass
	https://sts-req.ornl.gov:8443/cb/issue/1487			

1487

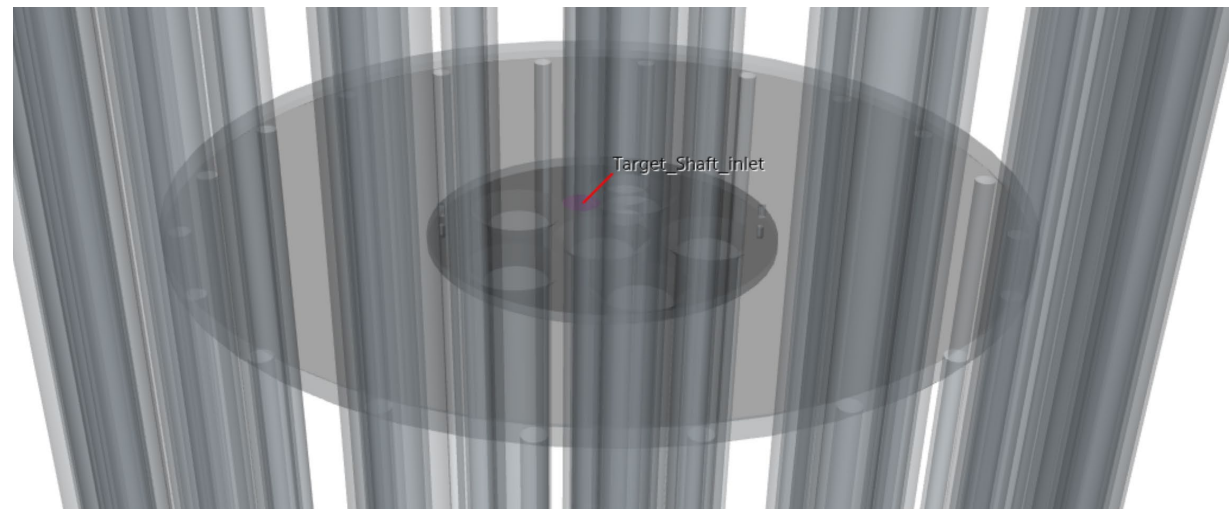
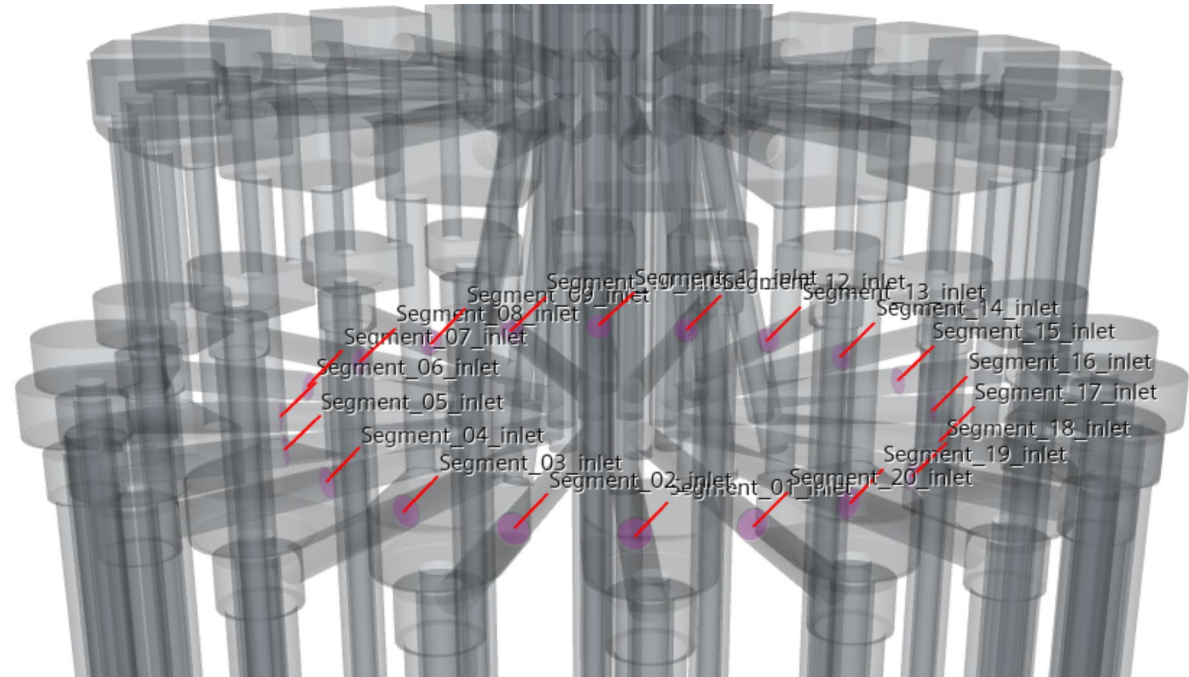
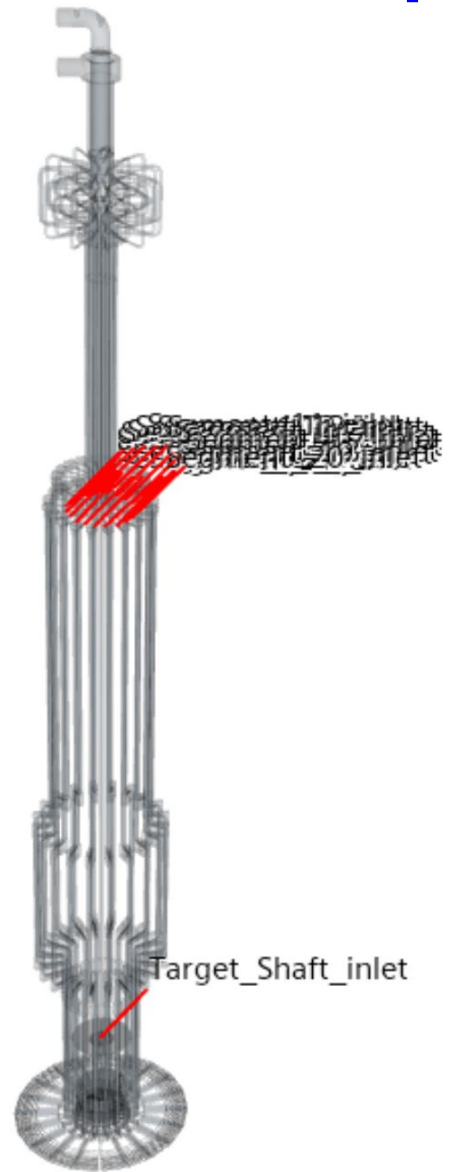
Inlet: 157.5 GPM (9.87 kg/s, 32.22°C)

Outlet: 45 psi

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



Target Assembly, Flow Balance—Cross-Sectional Planes to Measure Flow Rates

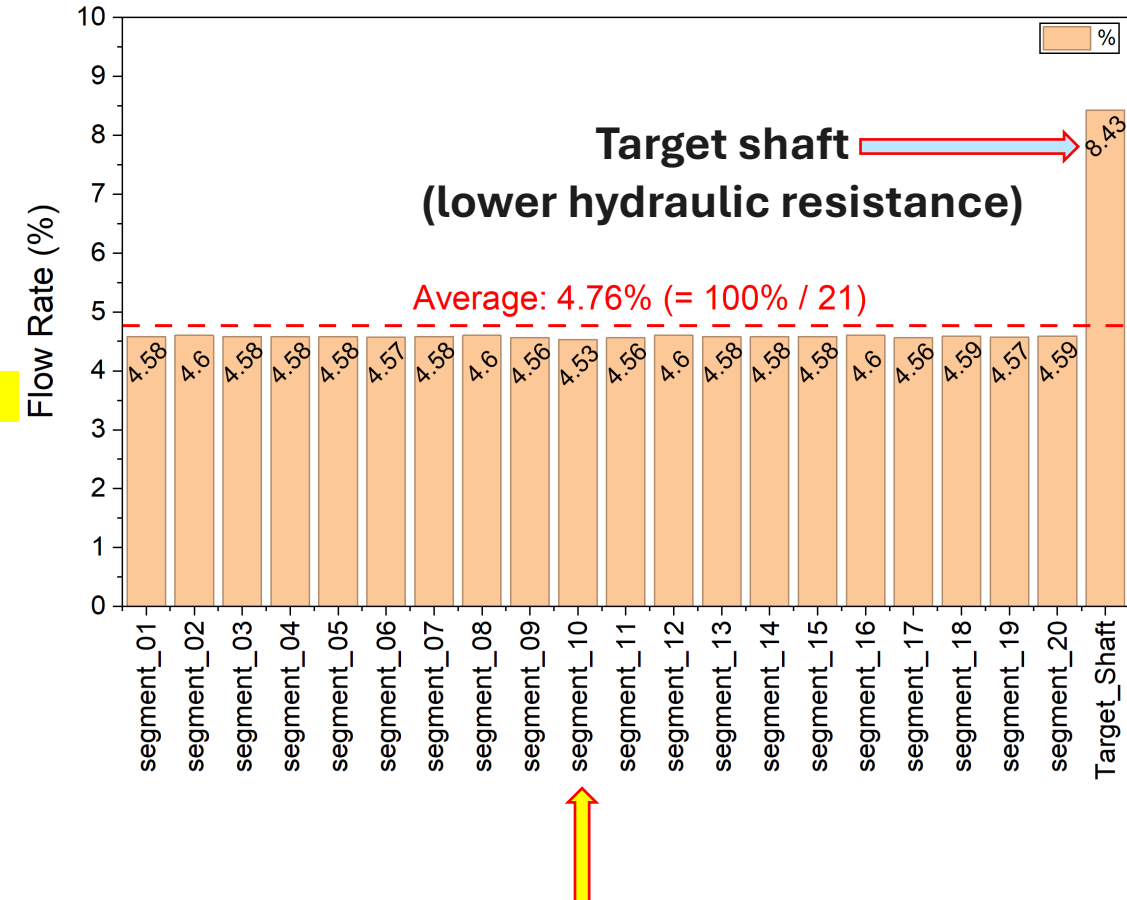


Target Assembly, Flow Balance

Flow Balance Analysis: Average = 4.76 % (=100%/21)

Component	Simulation Results			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 Shaft	0.808	12.90	8.43	0.832	13.28
Sum	9.59	153.04		9.870	157.5

Assumption: **7.5 GPM** for target segment and shaft

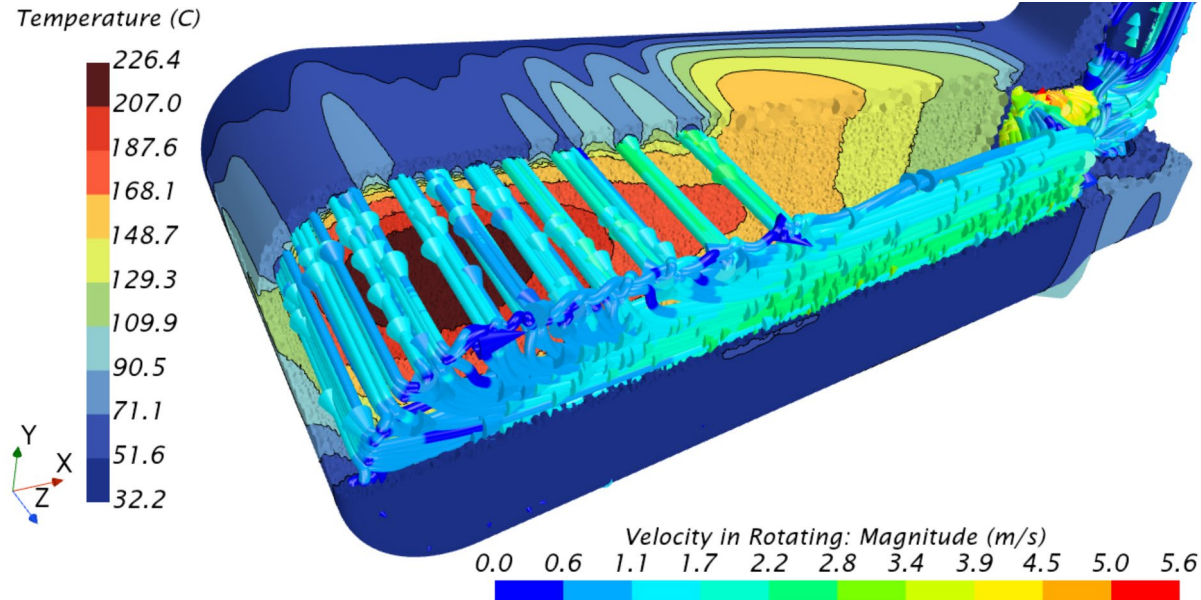


Target Assembly, Flow Balance

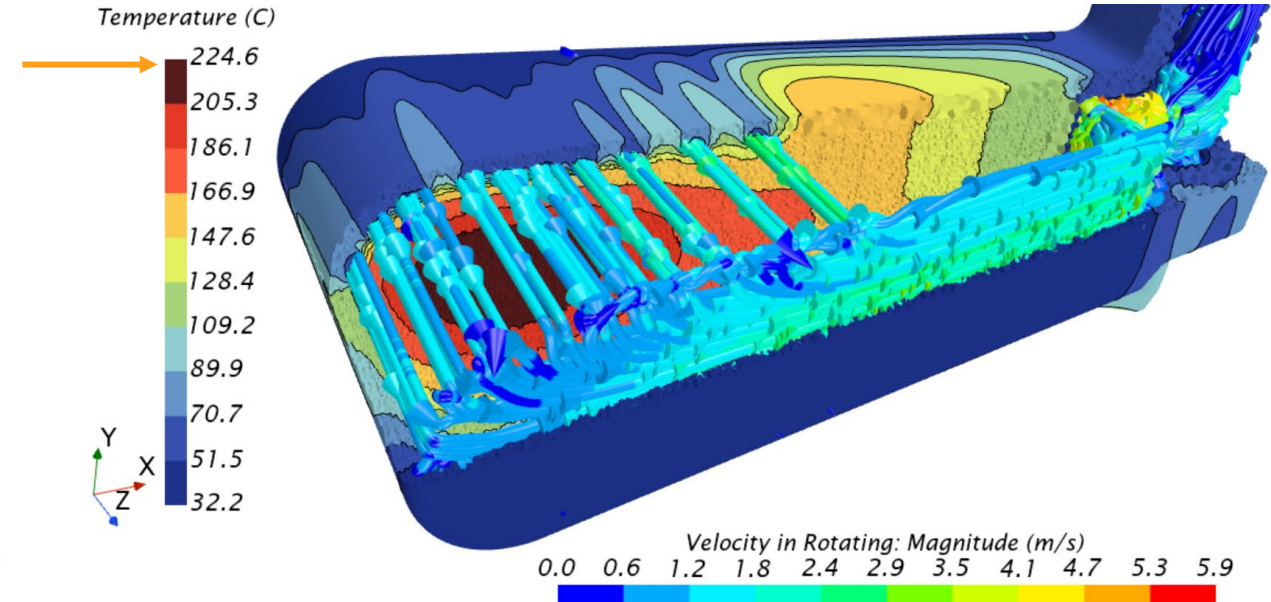
Inconel flow covers & modified lower leg



7.14 GPM (95.2%)



7.5 GPM (100%)



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



Day 2 : Target Assembly Analysis

- **Blowdown Analysis**

- Case 1 – Air Purge of Water in a Single Target Segment
- Case 2 – Air Purge of Water in the Whole Target Assembly

Blowdown Analysis

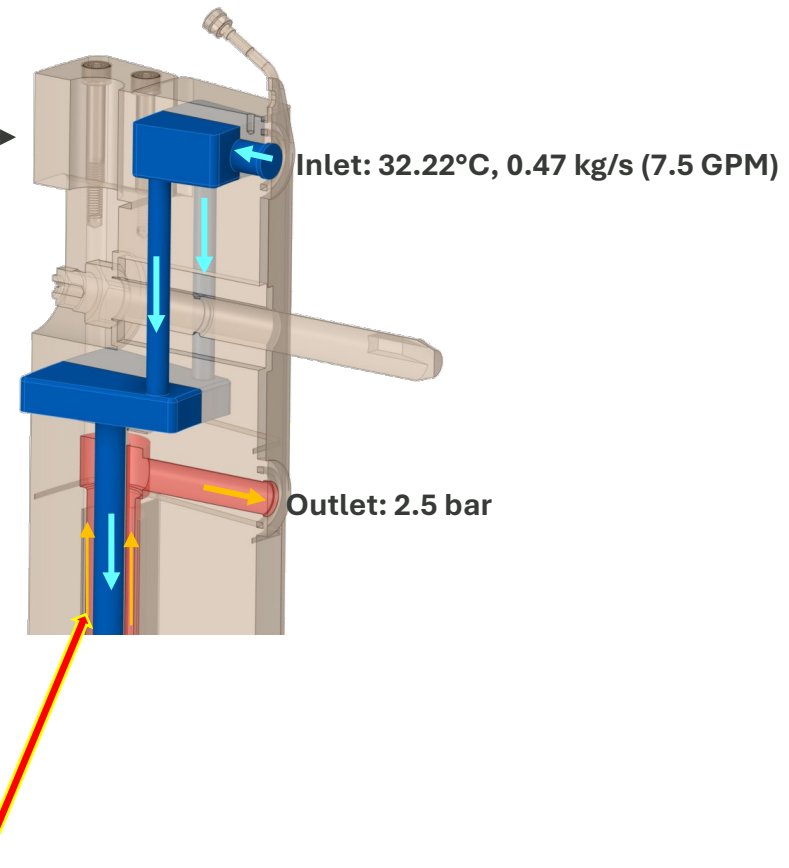
- Maintenance
- Failure
- Replacement

disconnect
disconnect

Proton beam

spallation
reactions

- Neutrons
- Heat
- Activated cooling water (return)



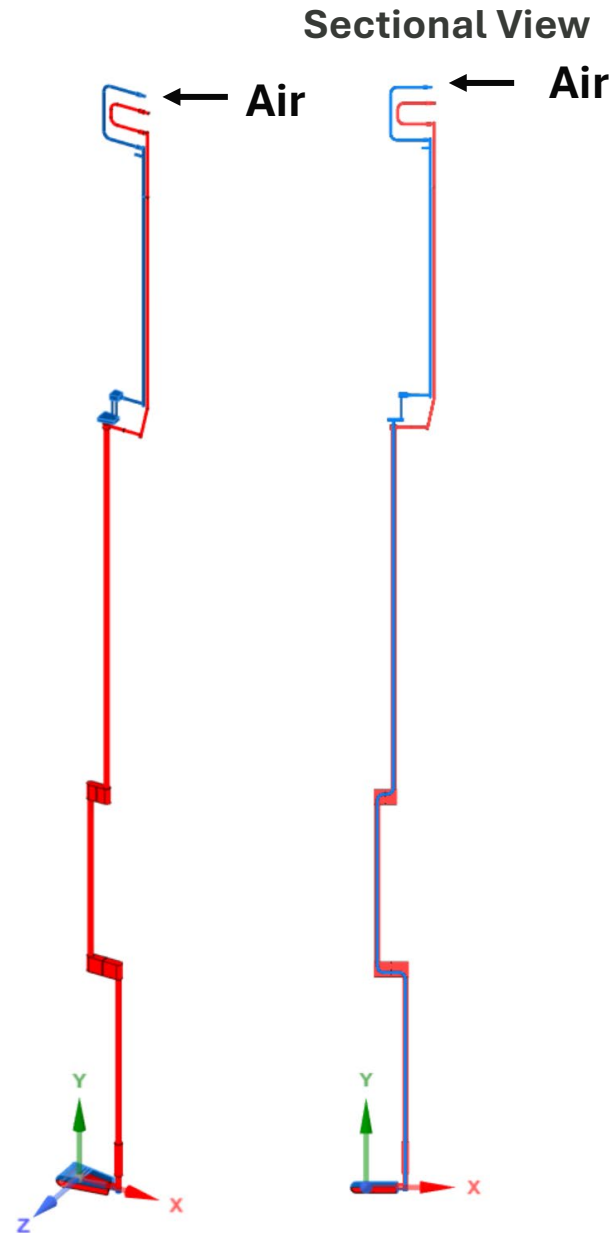
• Objective

- Determine the remaining volume of water after air blowdown;
- Predict the **equilibrium water level** after gravitational redistribution; and
- Verify that the final water level is **below the jumper connection**, thereby preventing leakage of activated cooling water during target segment removal.

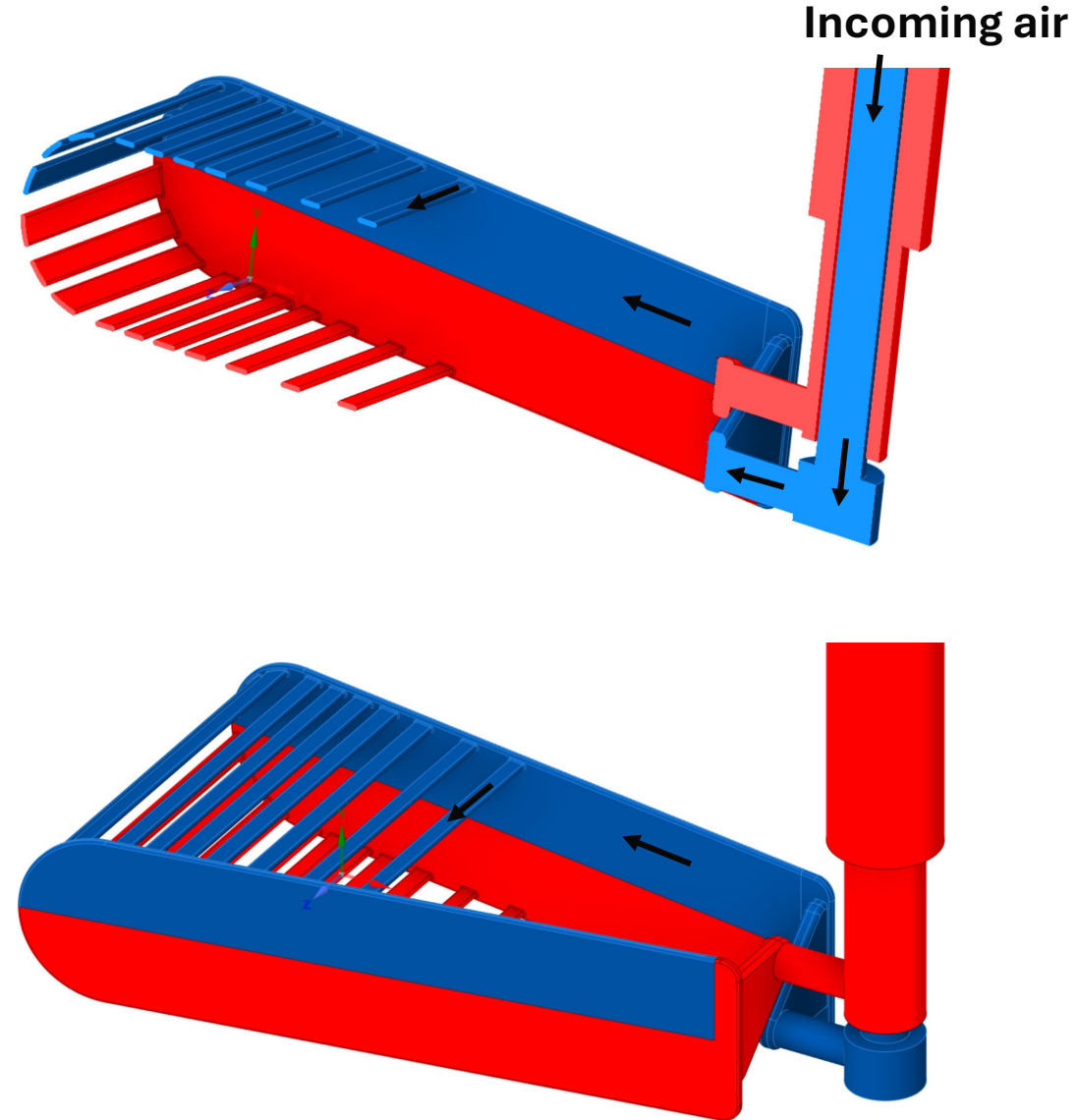
Day 2 : Target Assembly Analysis

- **Blowdown Analysis**
 - **Case 1 – Air Purge of Water in a Single Target Segment**
 - Case 2 – Air Purge of Water in the Whole Target Assembly

Case 1 : Air Purge of Water from Target Segment (Segment 1)



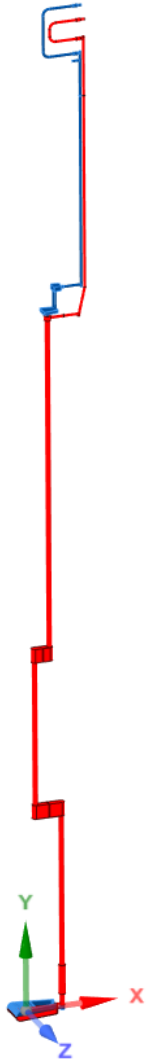
Supply: Air (original water) → Out of the system
Return: Remaining water for equilibrium



Case 1 : Air Purge of Water from Target Segment (Segment 1)

Total fluid

volume: 7150851mm³



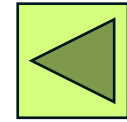
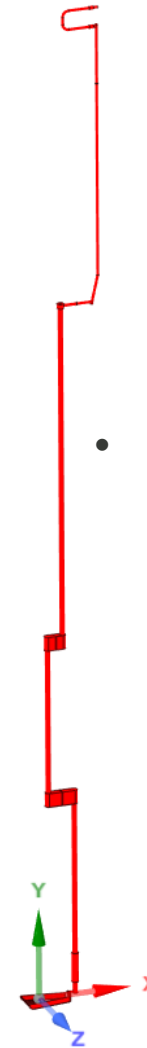
Supply: Air (original water)

Volume: **2470982**mm³



Return: Remaining water for equilibrium

Volume: **4679868**mm³



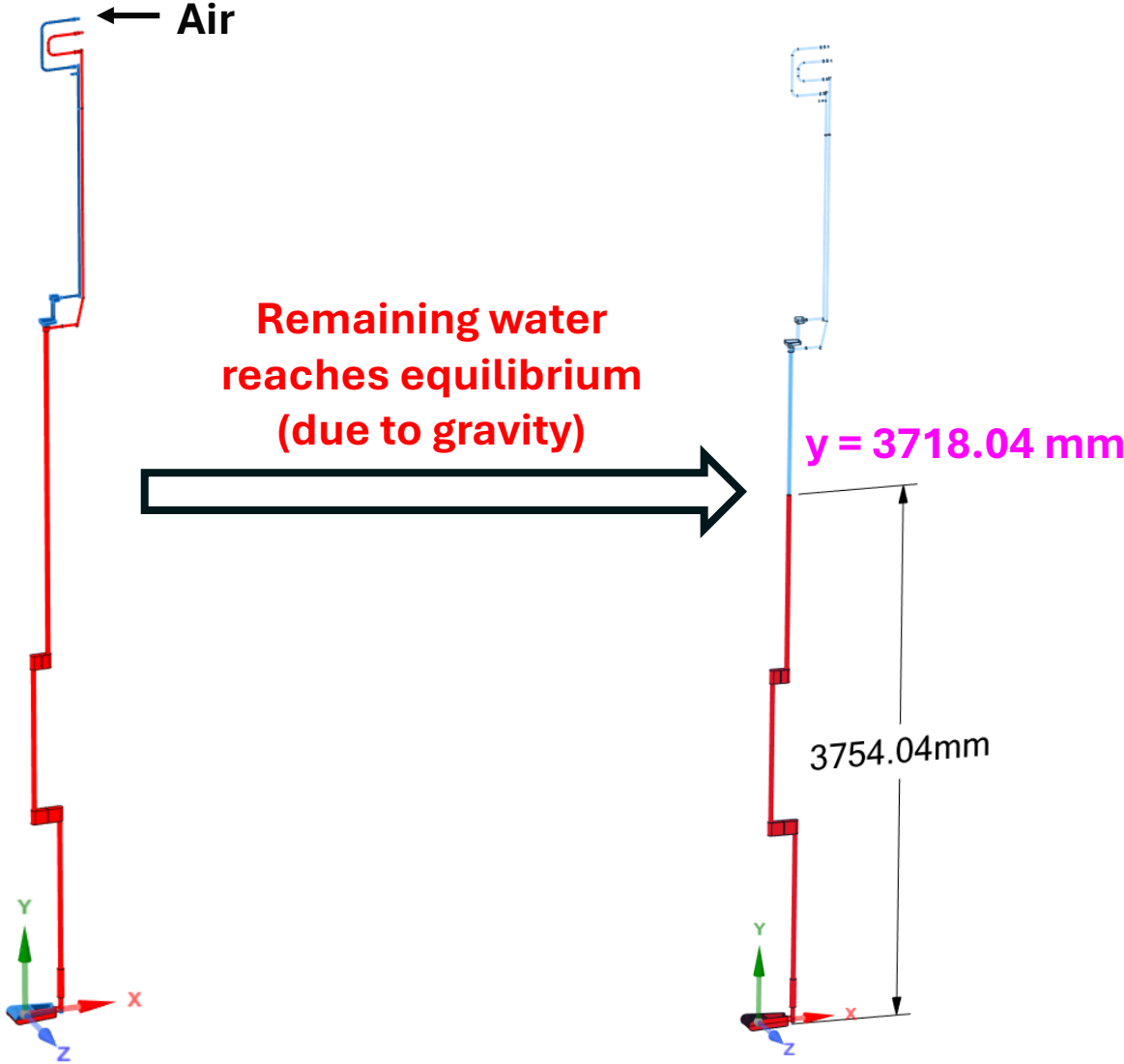
- Return volume is much larger → higher residence time to reduce radiation dose

Case 1 : Air Purge of Water from Target Segment (Segment 1)

Return: Remaining water for equilibrium

Volume: 4679868mm³

Blowdown air for Single Segment					
Segment_1					
Supply Air (mm^3)	2470982.362				
Remaining Water (mm^3)	4679868.361				
Total	7150850.724				
			mm ³		
	Y(mm)	Objective	4679868	Difference	
0	3718		4679831	37	too low
-0.2	3718.2		4679998	-130	too high
-0.1	3718.1		4679915	-46	too high
-0.05	3718.05		4679873	-5	too high
-0.04	3718.04		4679865	4	too low



Day 2 : Target Assembly Analysis

- **Blowdown Analysis**
 - Case 1 – Air Purge of Water in a Single Target Segment
 - **Case 2 – Air Purge of Water in the Whole Target Assembly**

Case 2 : Air Purge of Water from Whole Target Assembly

Total fluid

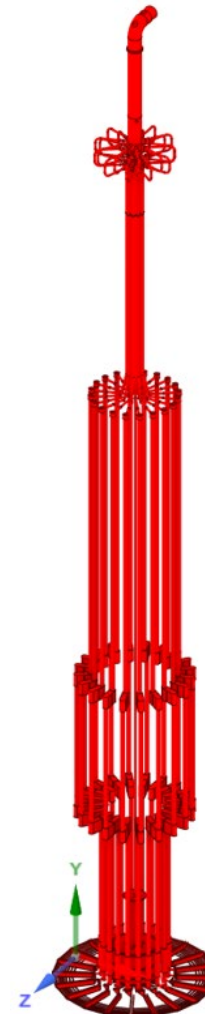
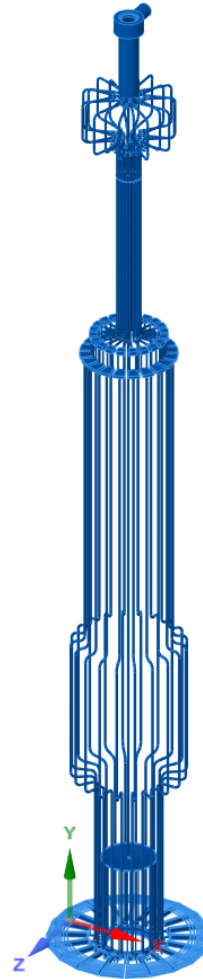
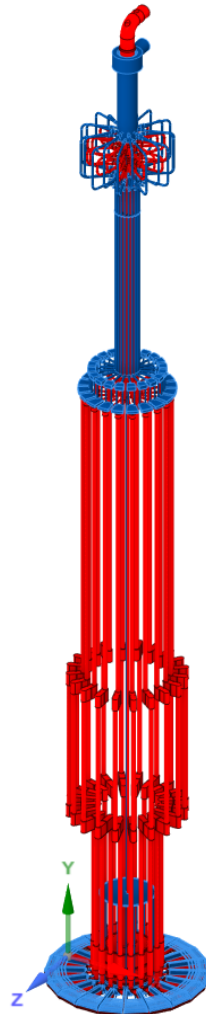
volume: 173113619mm³

Supply: Air (original water)

Volume: 62162223mm³

Return: Remaining water for equilibrium

Volume: 110951396mm³



Case 2 : Air Purge of Water from Whole Target Assembly

Target Shaft

Supply: Air (original water)

Return: Remaining water for equilibrium

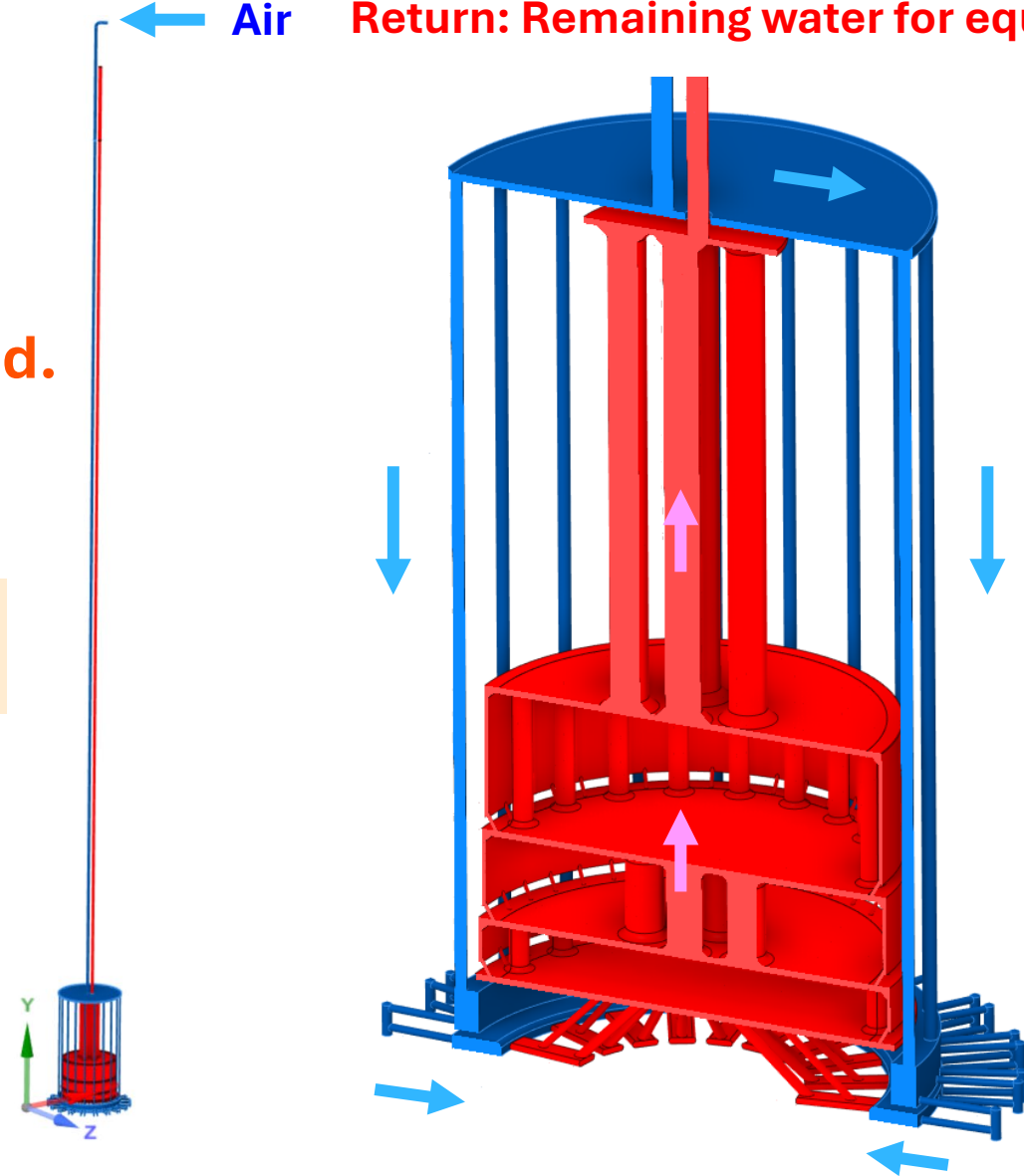
- Bottoms of the target **shaft** and target **segments** are **not** hydraulically **connected**.

1. Blowdown
2. Gravitational Redistribution

Different equilibrium water levels:

- ❖ Target segments
- ❖ Target shaft

Target shaft needs to be analyzed separately.



Case 2 : Air Purge of Water from Whole Target Assembly

Target Shaft

Total fluid

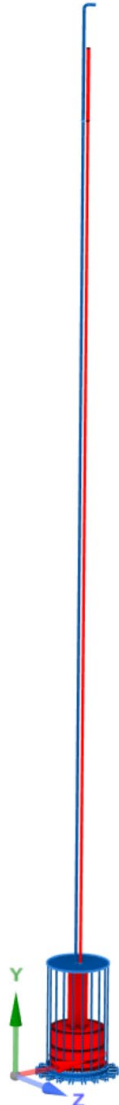
volume: 12042938.416mm³

Supply: Air (original water)

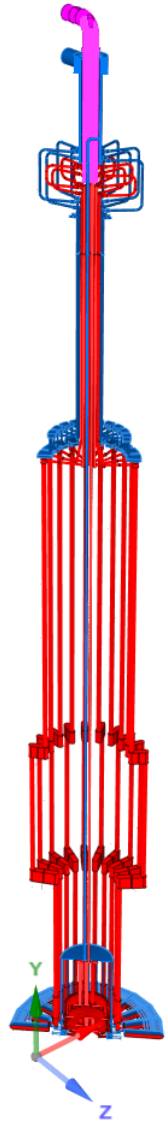
Volume: 4901148.9459mm³

Return: Remaining water for equilibrium

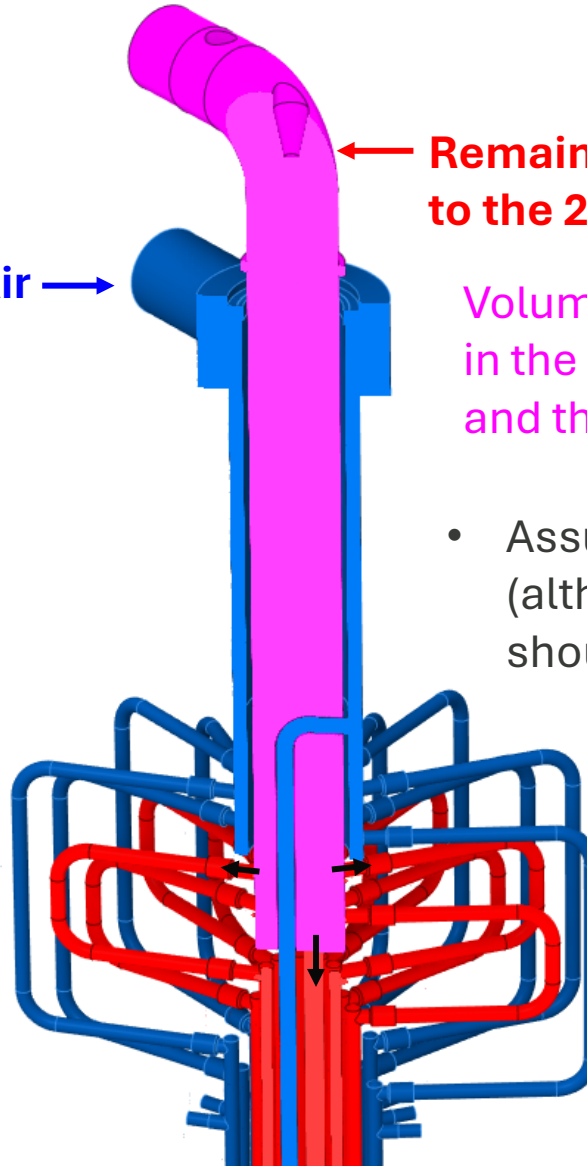
Volume: 7141789.4701mm³



Case 2 : Air Purge of Water from Whole Target Assembly



Supply: Air →



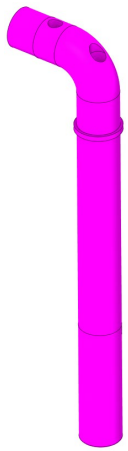
← Remaining water in Target Drive → Flowing back to the 20 segments and shaft (return channels)

Volume: 9917444.2603mm^3 ← This remaining water in the target drive is **redistributed** to the target shaft and the 20 segments.

- Assume it is **equally distributed** to all components (although the shaft has lower flow resistance and should receive more water)

Target **Shaft** and each **segment** receive **additional** water from the target drive:
 $9917444.2603/21 = 472259\text{mm}^3$

Case 2 : Air Purge of Water from Whole Target Assembly



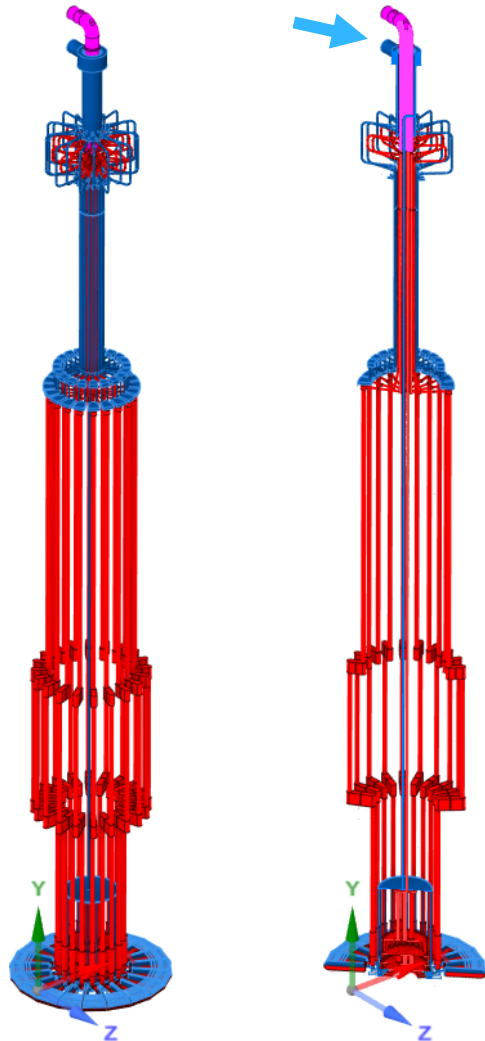
Remaining water in target drive to be redistributed to 20 segments and shaft					
mm ³					
9917444.26					
Each segment and shaft receive (assumed equally, although shaf has lower resistance)					
mm ³					
472259.2505					

Blowdown air for Target Assembly					
Segment 1 receives additional remaining water from the target drive					
Blowdown segment only	Remaining Water (mm ³)	4679868			
Remaining water from drive	Remaining Water (mm ³)	472259			
Total in segment	Remaining Water (mm ³)	5152128		mm ³	
		Y(mm)	Objective	5152128	
	0	3750		4706560	445568
	-782	4500		5333031	-180903
	-382	4100		4998915	153213
	-532	4250		5124206	27922
	-582	4300		5165972	-13844
	-557	4275		5145088	7040
	-567	4285		5153441	-1313
	-564	4282		5150935	1193
	-566.2	4284.2		5152772	-645
	-565.8	4283.8		5152438	-311
	-565.2	4283.2		5151937	191
	-565.43	4283.43		5152129	-2

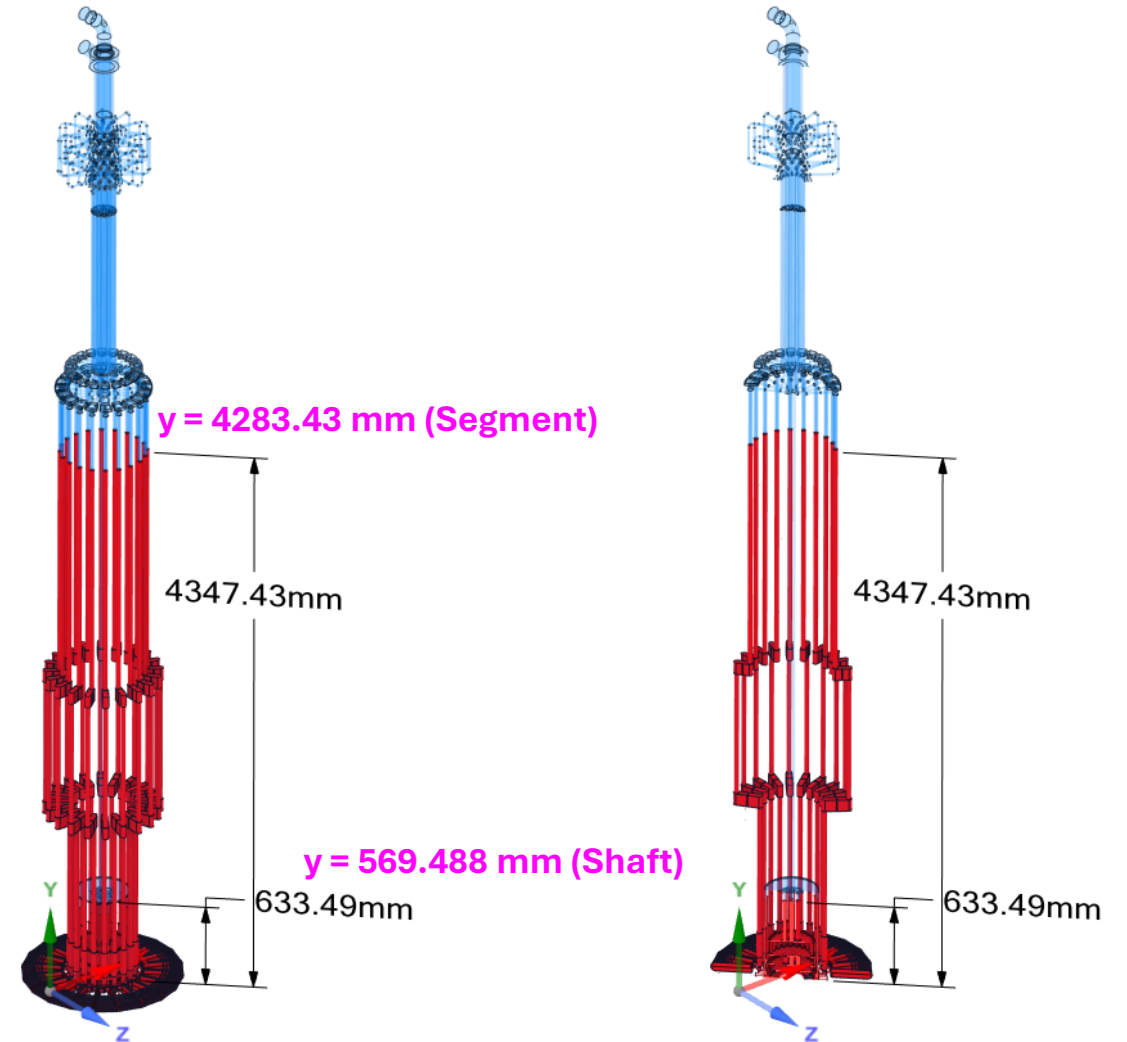
Blowdown air for Target Assembly					
Target Shaft receives additional remaining water from the target drive					
Blowdown shaft only	Remaining Water (mm ³)	7141789			
Remaining water from drive	Remaining Water (mm ³)	472259.3			
Total in shaft	Remaining Water (mm ³)	7614049			
				mm ³	
		Y(mm)	Objective	7614049	
	2750	1000		9097287	-1483238
	3218	500		7210598	403451
	3118	600		7791388	-177339
	3138	580		7675143	-61095
		569.5		7614118	-69
		569.488		7614048	0

Case 2 : Air Purge of Water from Whole Target Assembly

Blowdown Air (Supply)

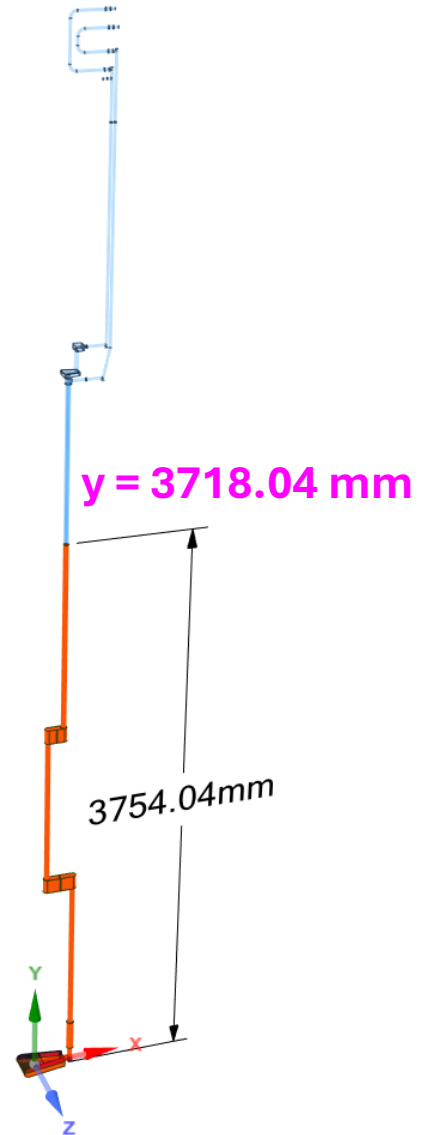


Remaining water
reaches equilibrium

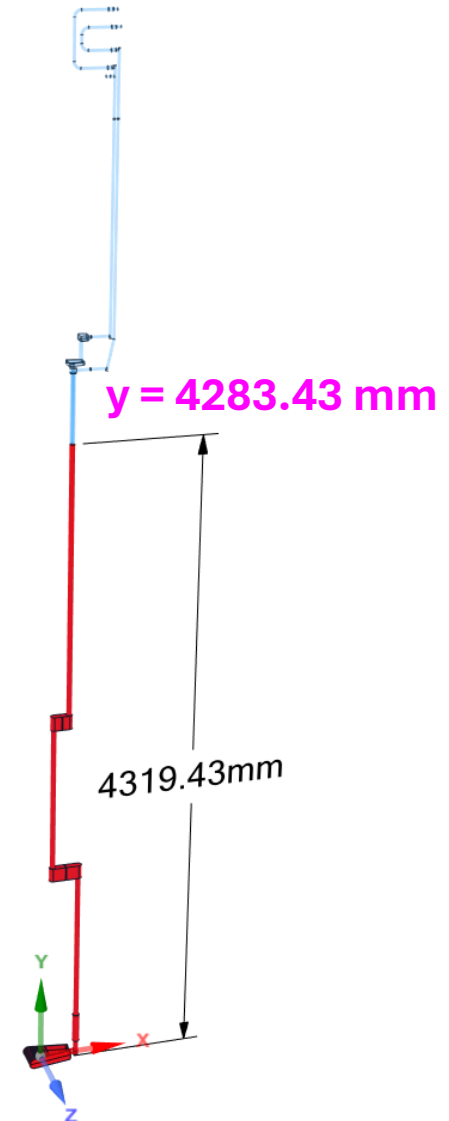


Comparison

Case 1: Blowdown Single Segment



Case 2: Blowdown Target Assembly



Conclusion and Requirement Verification

- The **manifold assembly** and the **segment-to-crown interface** were updated in July 2026 to improve the reliability of the design. The updated design introduces additional **pressure drop** that should be taken into consideration. 
- All thermal-hydraulic requirements are satisfied.
- Flow balance is not an issue for the STS FDR design.

ID	Codebeamer Tracker and Link	Requirement	CFD Result	Status
1487	Target Assembly Requirement 1487	System pressure drop shall not exceed 14.5 psi (100 kPa).	13.6 psi	Pass
	https://sts-req.ornl.gov:8443/cb/issue/1487			
1644	Target Drive Requirement 1644	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
	https://sts-req.ornl.gov:8443/cb/issue/1644			
1602	Target Segment Requirement 1602	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
	https://sts-req.ornl.gov:8443/cb/issue/1602			
1691	Target Shaft Requirement 1691	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
	https://sts-req.ornl.gov:8443/cb/issue/1691			
1567	Prevent Boling Requirement 1567	The target cooling water shall be single-phase (liquid) .	No Boiling	Pass
	https://sts-req.ornl.gov:8443/cb/issue/1567			

