Preliminary STS Upper Reflector Thermal Hydraulic Analysis

Min-Tsung Kao
Jim Janney

6/21/2023

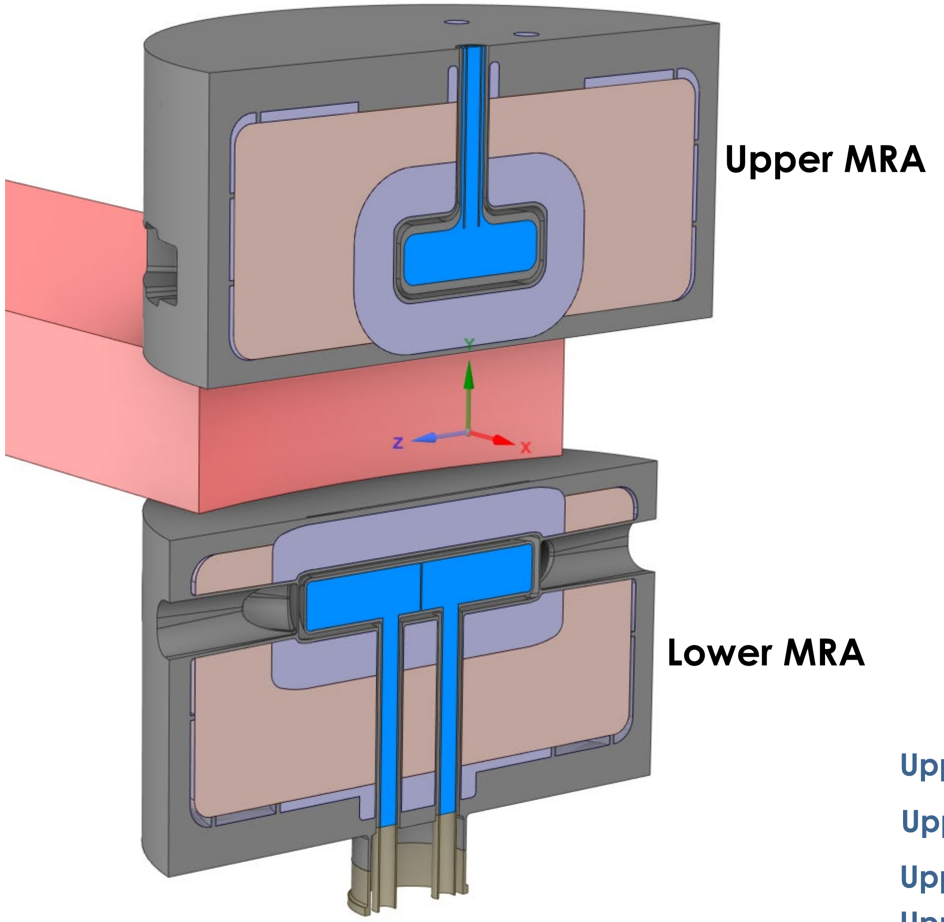
Background

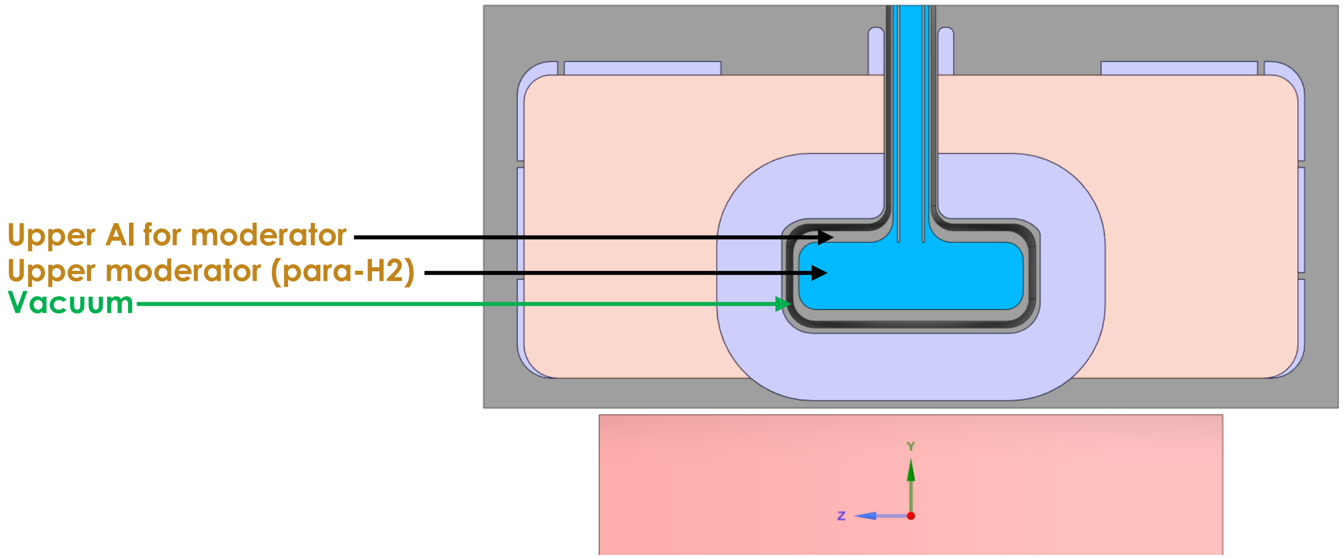
- Previous MRA analysis (2020) done by Elvis (Elvis E Dominguez-Ontiveros) applied bounding curves for the heating. Bounding curve is a more conservative method, and the heating was overestimated by about a factor of 2.
- MRA geometry has been updated by Jim Janney and Ken Gawne since 2020.
- New heat sources were obtained from the MCNP energy deposition calculations done by Lukas Zavorka.
- The new MCNP calculations with Attila4MC unstructured mesh provide higher fidelity of heating results.
- Additional heating from 27Al(n,g)28Al reaction is also included in the new MCNP heating calculations.

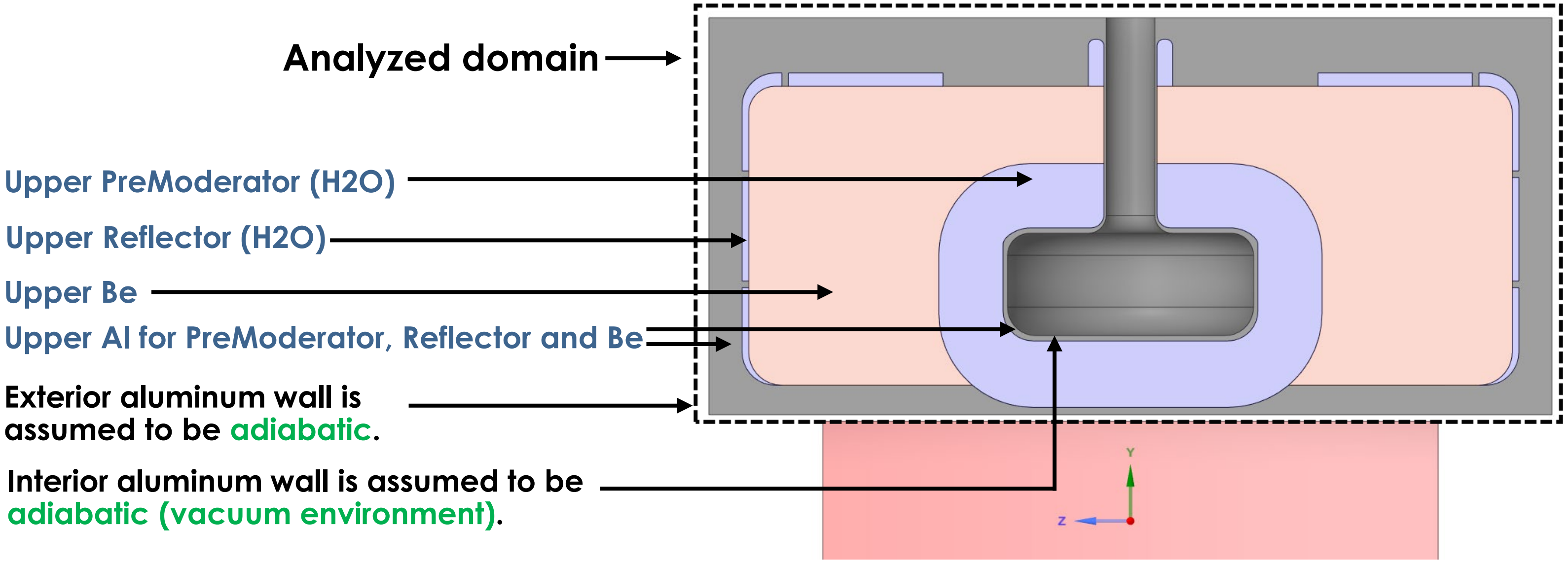
Background

- This thermal-hydraulic analyses were performed to demonstrate that the current MRA design (without moderators, which were done in separate analyses and the results were also documented in a separate presentation) can meet the following requirements.
- Requirements
  - Pressure drop < 15 psi
    - Low pressure drop allows flexibility for CMS design
  - Maximum water temperature < 100°C
    - No water boiling
  - Maximum Aluminum temperature < 100°C
  - Maximum Beryllium temperature < 100°C

Geometry of Upper MRA





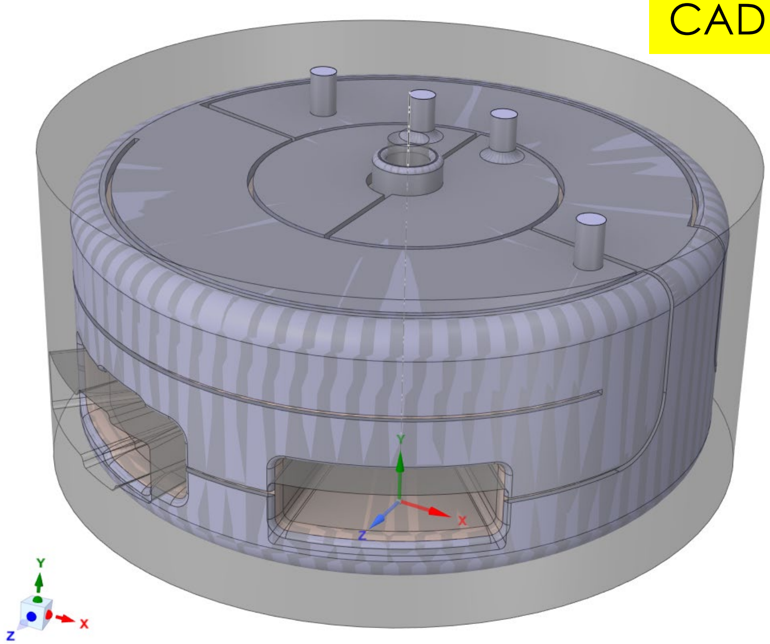


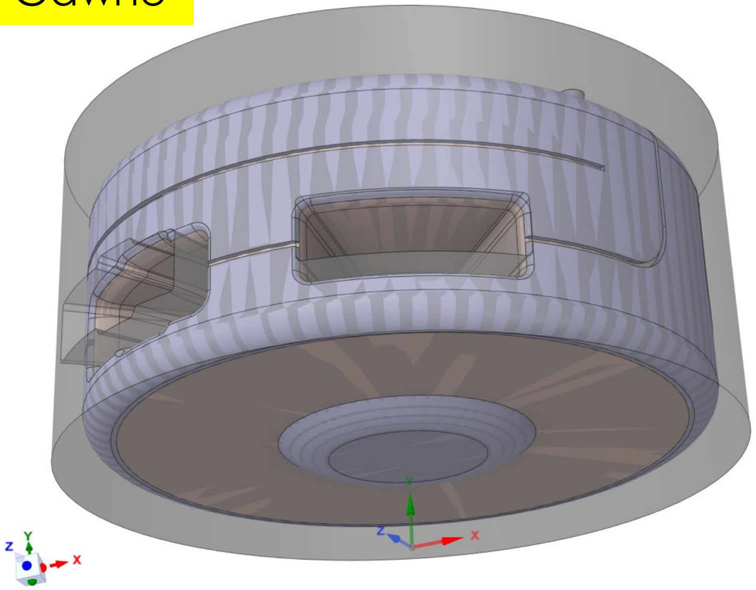
Steady State Heat Transfer Analysis for Upper MRA, Geometry

Link to the CAD

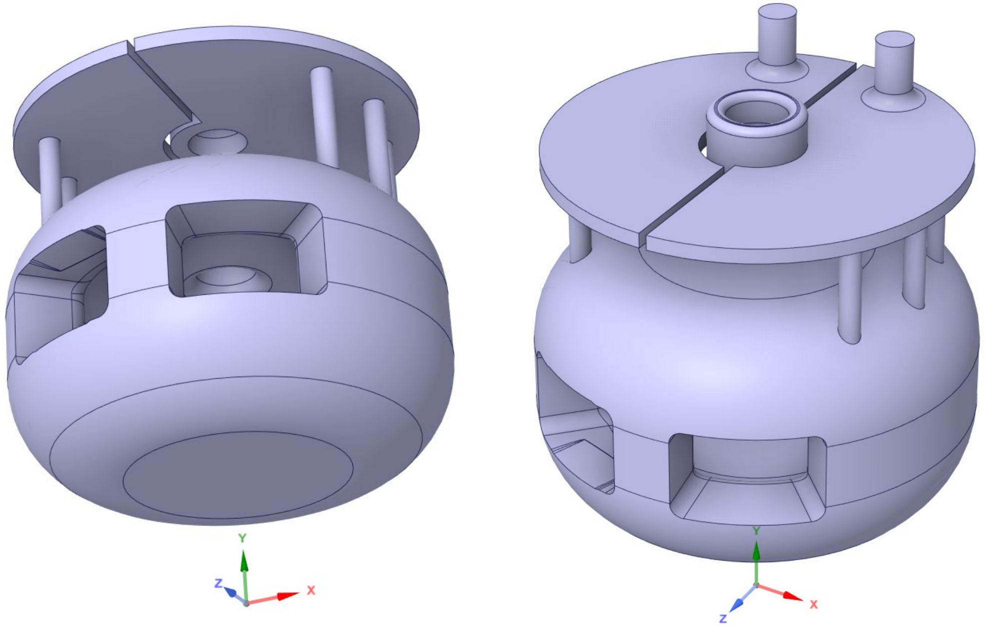
https://ornl.sharepoint.com/sites/sts/targetsystems/Shared%20Documents/Forms/AllItems.aspx?id=%2Fsites%2Fsts%2Ftargetsystems%2FShared%20Documents%2FS%2E03%2E02%20Target%20Assembly%2F99%5FSANDBOX%2FKAO%2F2023%2FCFD%5FSTS%5FMRA%2F0%5FSummary%2FPreliminary%20STS%20Upper%20Reflector%20Thermal%20Hydraulic%20Analysis%2FCAD%5FModel%2F2022%5F12%5F09%5FMRA%5FUpper%5FReflector&viewid=9be9bc88%2D5a13%2D48c7%2D9fff%2Dd22f94ffdeb5

CAD model from Ken Gawne

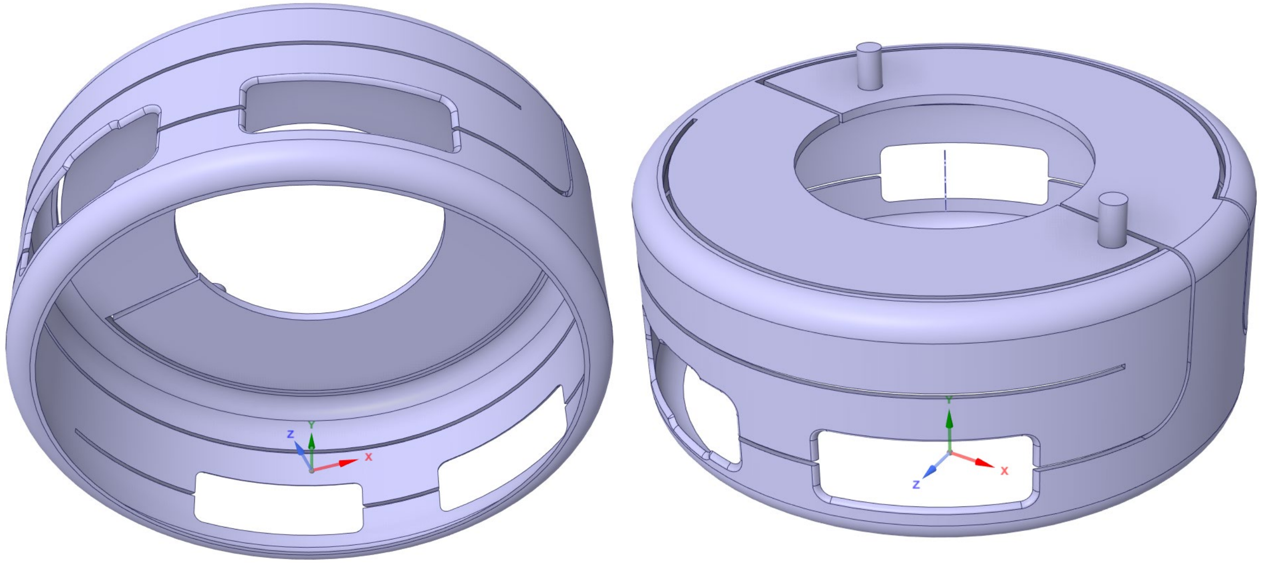




Upper PreModerator (H_2O)



Upper Reflector (H_2O)

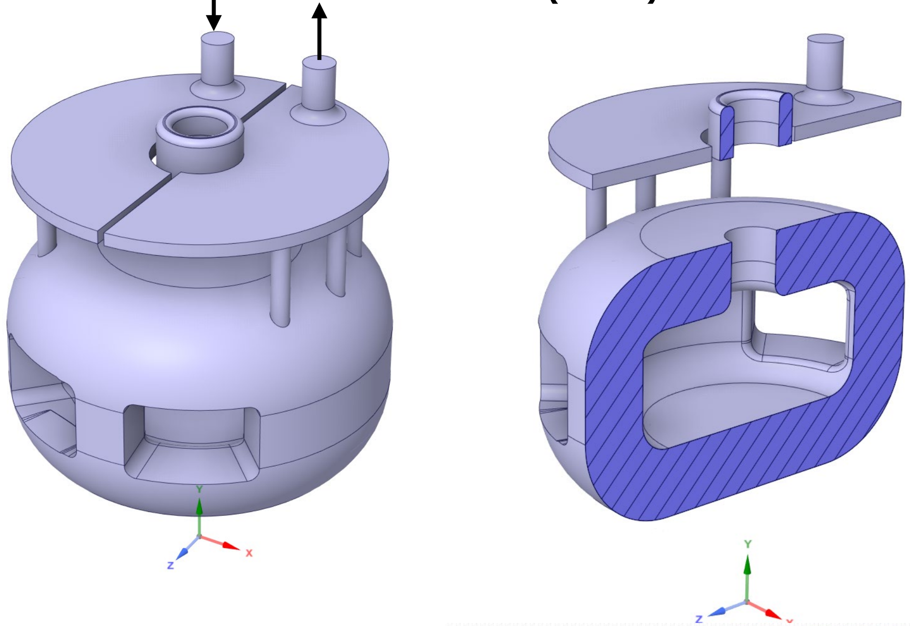


Steady State Heat Transfer Analysis for Upper MRA, Geometry

Upper PreModerator (H_2O)

PreModerator inlet (0.47 kg/s, 35°C H_2O)

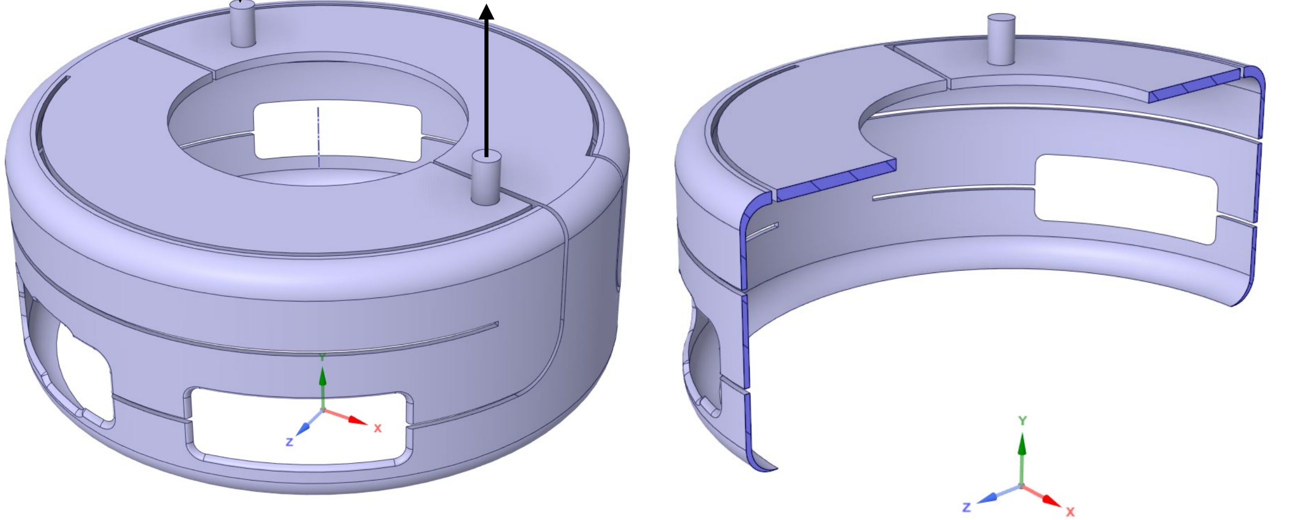
PreModerator outlet (1 atm)



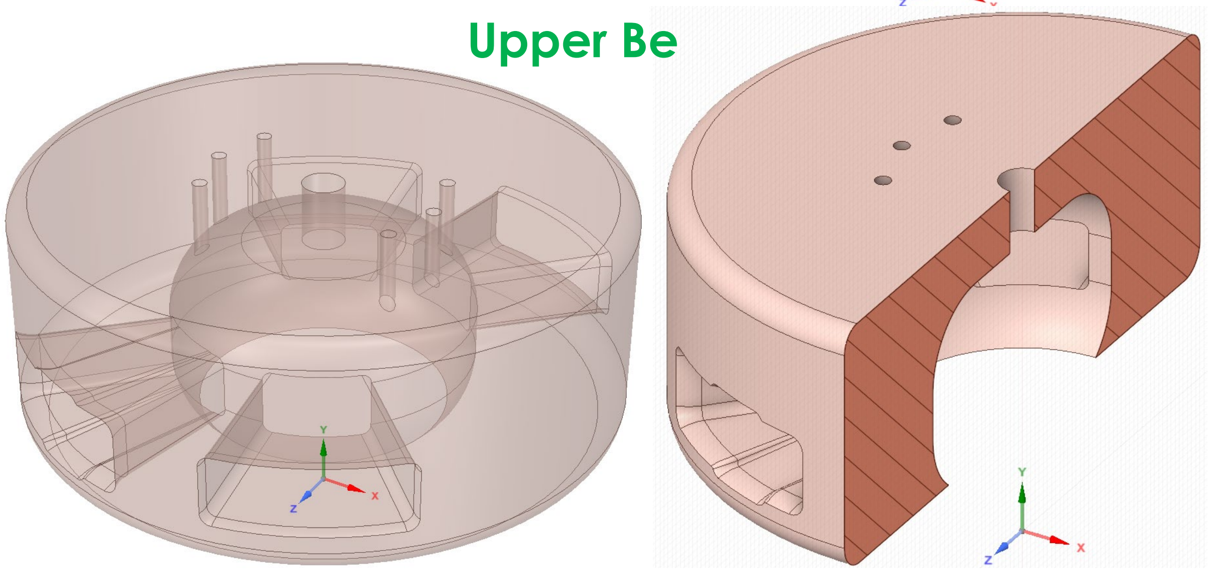
Upper Reflector (H_2O)

Reflector inlet (0.47 kg/s, 35°C H_2O)

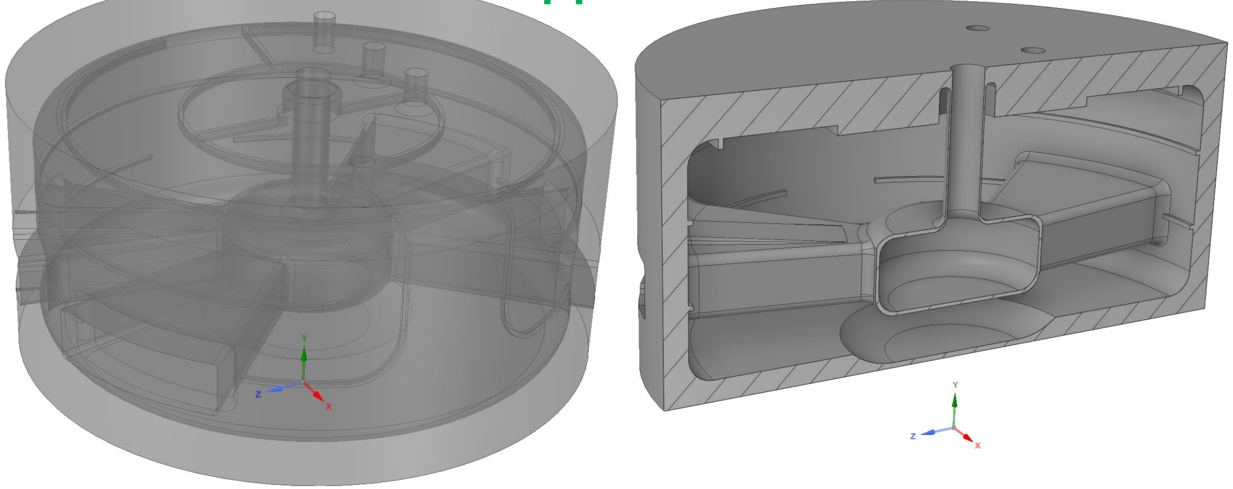
Reflector outlet (1 atm)



Upper Be

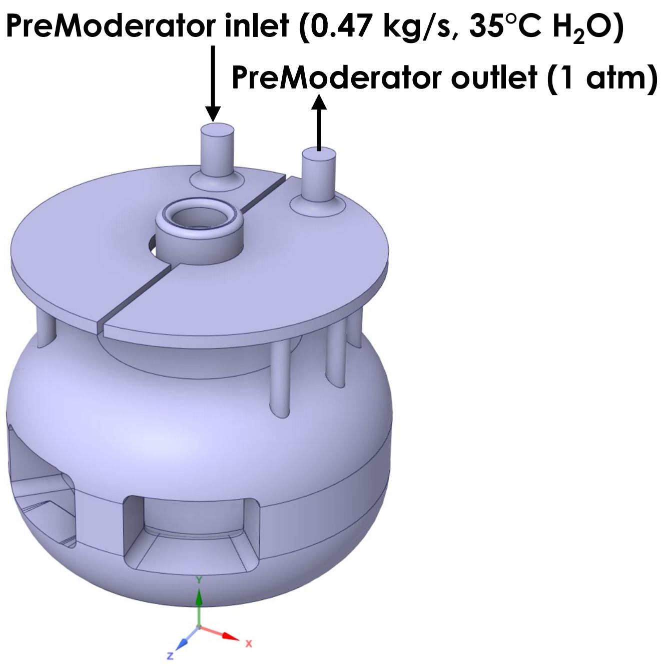


Upper Al

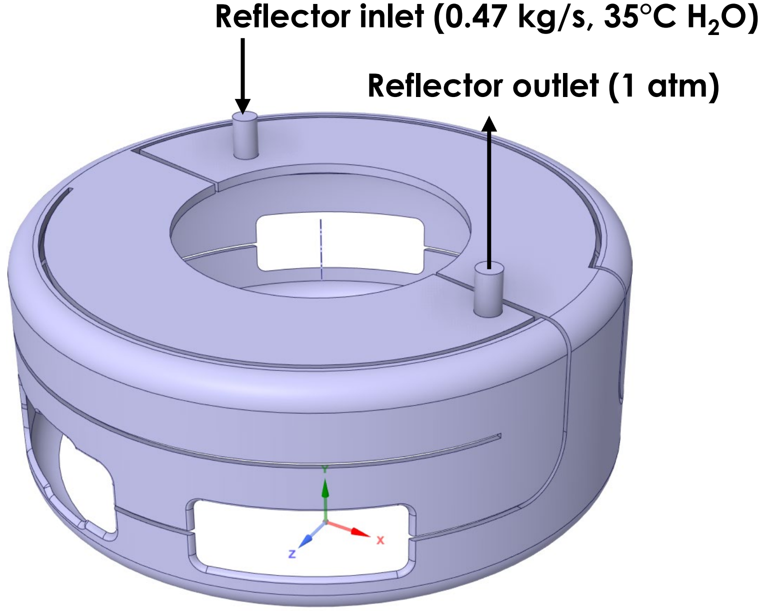


Steady State Heat Transfer Analysis for Upper MRA, Geometry

Upper PreModerator (H_2O)



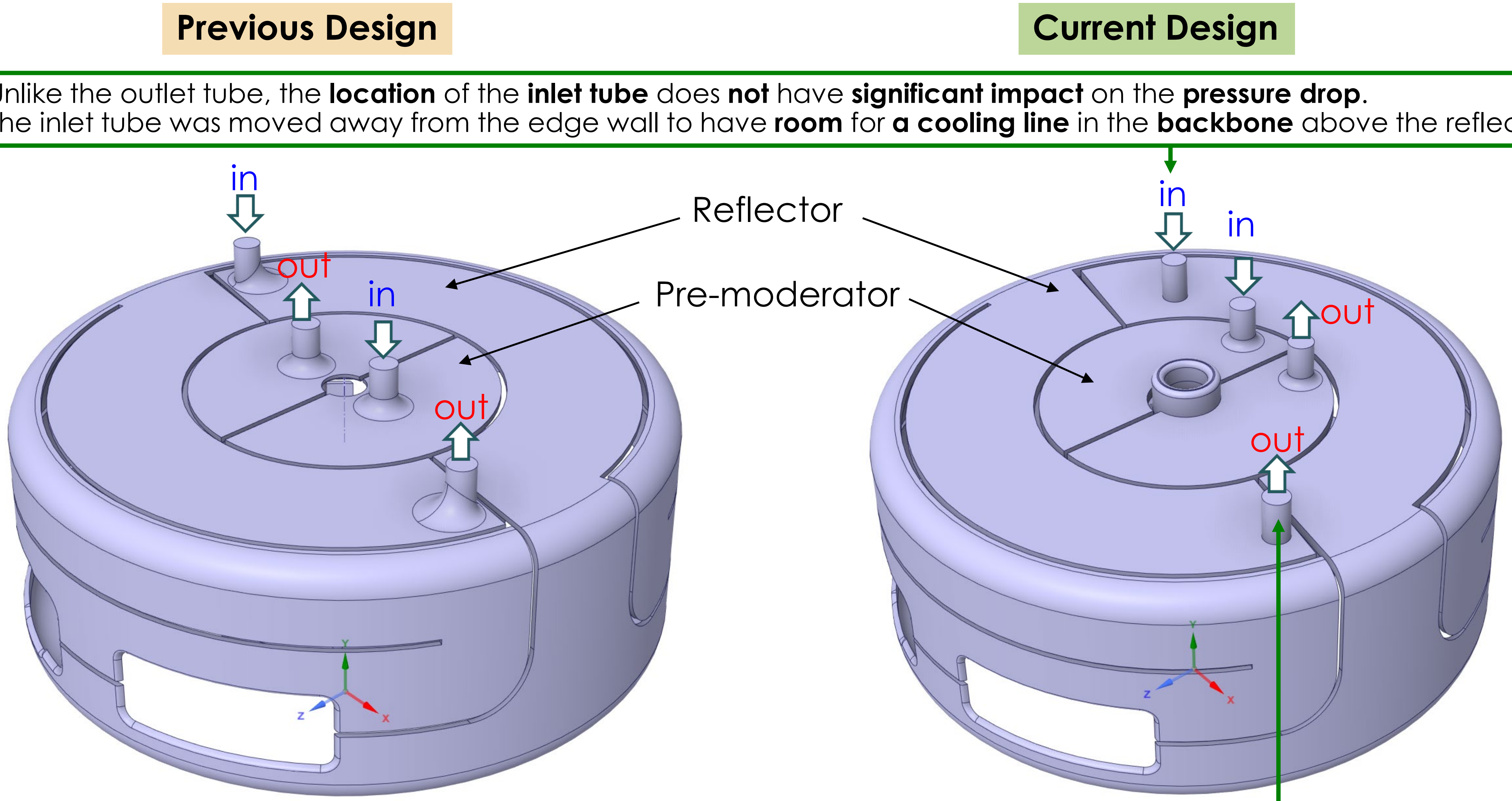
Upper Reflector (H_2O)



Part	Volume (mm^3)
Upper PreModerator	1641750.7932
Upper Reflector	782341.6359

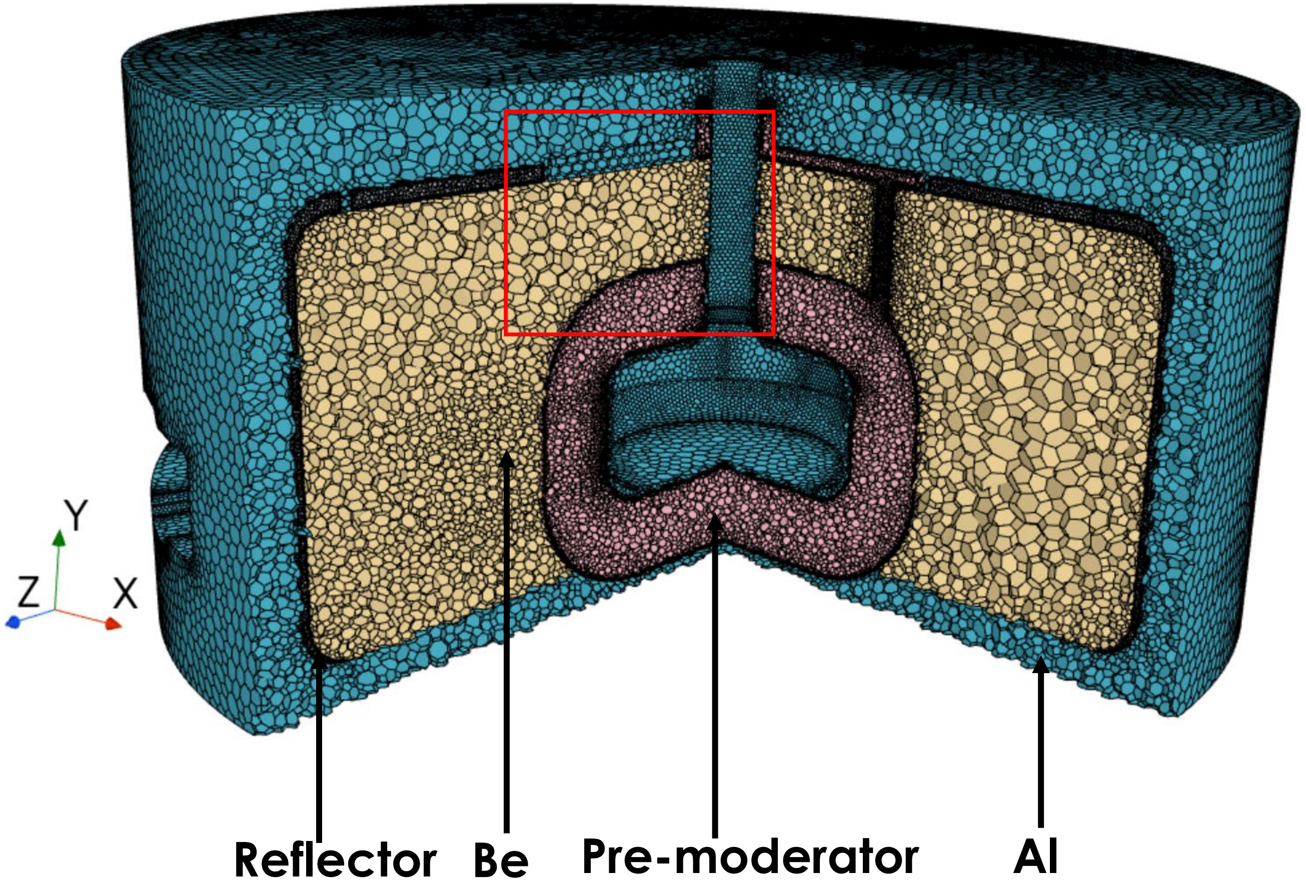
Upper Reflector and Pre-moderator

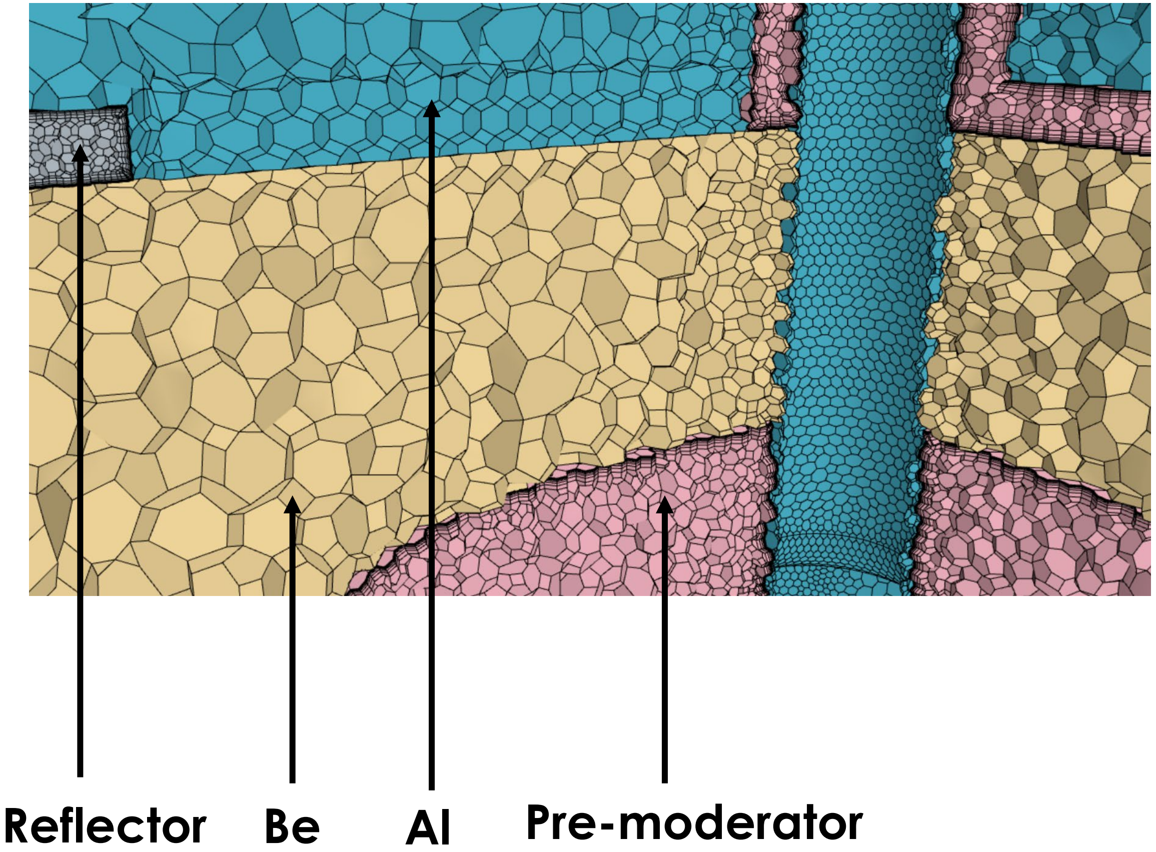
- Unlike the outlet tube, the **location** of the **inlet tube** does **not** have **significant impact** on the **pressure drop**.
- The inlet tube was moved away from the edge wall to have **room** for **a cooling line** in the **backbone** above the reflector.



- **If** this **outlet tube** is **away** from the **edge wall,** a **vortex** would be created.
- **The pressure** at the **vortex** region is very **low** and thus the **pressure drop** (between inlet and outlet) is significantly **high**.
- To **reduce** the **pressure drop**, it is better to have a **uniform flow** at the **outlet** to reduce or to eliminate the vortex region.
- In **current design**, the **outlet tube** is very **close** to the **edge wall** to reduce the strength of the vortex and to **reduce the pressure drop.**

Steady State Heat Transfer Analysis for Upper MRA, Mesh Configuration





Steady State Heat Transfer Analysis for Upper MRA, Mesh Settings

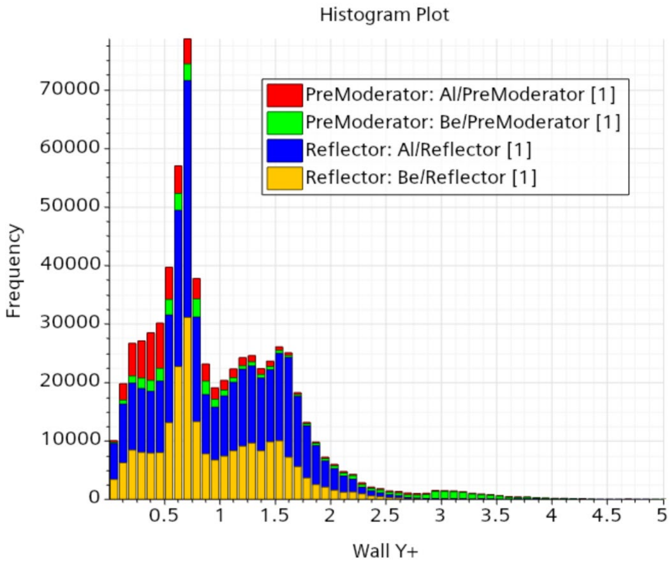
Upper MRA (Without Moderators)				
	Al	**Be**	**PreModerator (H2O)**	**Reflector (H2O)**
Mesh Type	Polyhedral mesh	Polyhedral mesh	Polyhedral mesh	Polyhedral mesh
Base Size (m)	1.00E-02	1.00E-02	4.00E-03	2.00E-03
Target Surface Size (m)	5.00E-03	5.00E-03	2.00E-03	1.00E-03
Minimum Surface Size (m)	1.00E-03	1.00E-03	4.00E-04	2.00E-04
Number of Prism Layers	0	0	8	8
Prism Layer Stretching	0	0	1.5	1.5
Prism Layer Total Thickness (m)	0	0	1.33E-03	7.00E-04
Number of Cells	**2.42E+05**	**1.77E+05**	**1.13E+06**	**5.18E+06**
Total Cells	**6.74E+06**			

CFD Modeling Details

- Simulation software: **Simcenter STAR-CCM+**
- Computer resource: **Libby cluster at ORNL**
  - Compute node:
    - Processors: two 16-core Intel Xeon E5-2683v4
    - 512 GB RAM
  - **1-3 nodes** used
- Solution time: **~ 1 day**
- Flow and Energy model: **Segregated solver**
- Turbulence model: **Realizable k-ε**
- Wall treatment: **Two-layer all y+**
- H2O mass flow rate**: 0.47 kg/s (7.5 gpm)**
- Unirradiated material properties
- Steady state simulation
- H2O inlet temperature: **35°C**
- H2O outlet pressure: **1 atm**
- Heat sources: **MCNP Neutronics (Lukas Zavorka)**

Mesh-Independent Study:
Mesh-independent studies were performed for earlier upper MRA concepts. Similar mesh settings were adopted for the current upper MRA design (without moderator) with 6.7 million cells. One case with 23.5 millions cells was run for the current design. From the results between two mesh configurations, the maximum temperature variations were less than 0.2°C for Al and Be, and less than 0.4°C for H2O. The wall y+ values for the upper MRA are also kept below 5 to ensure that the mesh configuration is appropriate for the usage of the two-layer all y+ wall treatment model in the CFD simulations.

Wall Y+ of Upper MRA



Thermal Properties

Material	Thermal Conductivity, k (W/m-K)	Density, ρ (kg/m^3)	Specific Heat, Cp (J/kg-K)	Viscosity (Pa-s)
Al	167	2800	880	N/A
Be	168	1850	1925	N/A
H2O (PreModerator & Reflector)	0.617	995	4173	7.98E-04

Energy Deposition from Neutronics Calculation (from Lukas Zavorka)

energy deposition data for MRA

Link:

https://ornl.sharepoint.com/sites/sts/targetsystems/Shared%20Documents/Forms/AllItems.aspx?id=%2Fsites%2Fsts%2Ftargetsystems%2FShared%20Documents%2FS%2E03%2E02%20Target%20Assembly%2F1%5FCALCULATIONS%2FCALC%2D016%20%2D%20MRA%2FMRA%5FR5%2FNeutronics&viewid=9be9bc88%2D5a13%2D48c7%2D9fff%2Dd22f94ffdeb5

From: Zavorka, Lukas <zavorkal@ornl.gov>
Sent: Monday, September 12, 2022 1:28 PM
To: Kao, Min-Tsung <kaom@ornl.gov>
Cc: Janney, Jim <janneyjg@ornl.gov>; Remec, Igor <remeci@ornl.gov>
Subject: MRA energy deposition

Min-Tsung,

The energy deposition data for MRA have been uploaded here:

https://ornl.sharepoint.com/sites/sts/targetsystems/Shared%20Documents/Forms/AllItems.aspx?id=%2Fsites%2Fsts%2Ftargetsystems%2FShared%20Documents%2FS%2E03%2E02%20Target%20Assembly%2F1%5FCALCULATIONS%2FCALC%2D016%20%2D%20MRA%2FMRA%5FR5%2FNeutronics&viewid=9be9bc88%2D5a13%2D48c7%2D9fff%2Dd22f94ffdeb5

Format as usual, i.e.,

X(cm), Y(cm), Z(cm), Energy(J/cc/pulse), Rel.error(neutrons and photons only), Volume(cm3)

in the .csv files for individual materials. This includes both MRA and backbone.

Total heating is also stored in “mra_total_numbers.xlsx”, which gives 30.6 kW for MRA and 30.2 kW for backbone. Please check the total numbers if they match your import.

Please let me know if you have any questions about the data or if you find anything suspicious.

Thanks,

Lukas

Additional heating in MRA aluminum due to 27Al(n,g)28Al

Additional heating from the **27Al(n,g)28Al** reaction and **b-decay** in MRA hydrogen and reflector vessel.

Link:

https://ornl.sharepoint.com/sites/sts/targetsystems/Shared%20Documents/Forms/AllItems.aspx?id=%2Fsites%2Fsts%2Ftargetsystems%2FShared%20Documents%2FS%2E03%2E02%20Target%20Assembly%2F1%5FCALCULATIONS%2FCALC%2D016%20%2D%20MRA%2FMRA%5FR5%2FNeutronics&viewid=9be9bc88%2D5a13%2D48c7%2D9fff%2Dd22f94ffdeb5

Additional heating in MRA aluminum due to 27Al(ng)28Al

ZL Zavorka, Lukas
To Kao, Min-Tsung
Cc Janney, Jim; Remec, Igor
You replied to this message on 9/29/2022 8:13 AM.

Reply | Reply All | Forward

Thu 9/29/2022 2:47 AM

Min-Tsung,

Here:

https://ornl.sharepoint.com/sites/sts/targetsystems/Shared%20Documents/Forms/AllItems.aspx?id=%2Fsites%2Fsts%2Ftargetsystems%2FShared%20Documents%2FS%2E03%2E02%20Target%20Assembly%2F1%5FCALCULATIONS%2FCALC%2D016%20%2D%20MRA%2FMRA%5FR5%2FNeutronics&viewid=9be9bc88%2D5a13%2D48c7%2D9fff%2Dd22f94ffdeb5

were uploaded 4 files:

o01g_Al_NG_20K_hydrogen_cyl.csv
o01g_Al_NG_20K_hydrogen_tube.csv
o01g_Al_NG_300K_reflector_cyl.csv
o01g_Al_NG_300K_reflector_tube.csv

with the additional heating from the 27Al(n,g)28Al reaction and b- decay in MRA hydrogen and reflector vessel. (4 files are for tube and cylinder moderator and hydrogen and reflector vessel, as the names indicate). This refers to Igor’s note: Al-27 (n, gamma) Al-28 → decay with e- emission with average energy of ~ 1.247 MeV.

This additional energy deposition is in the format as usual:

X(cm), Y(cm), Z(cm), Energy(J/cc/pulse), Rel.error(neutrons and photons only), Volume(cm3)

and shall be added to the original data for energy deposition in Aluminum. The calculations used the same UM model, meaning that the UM cell coordinates and volumes are the same, and adding the data to the previous set should be straightforward.

This heating in CYL hydrogen vessel is 36.37 W, which is additional 18.97% of the heating. (Agrees well with Igor’s ~20% prediction)
This heating in CYL reflector vessel is 164.73 W, which is additional 3.42% of the heating.
This heating in TUBE hydrogen vessel is 34.73 W, which is additional 23.0% of the heating. (Agrees well with Igor’s ~20% prediction)
This heating in TUBE reflector vessel is 182.93 W, which is additional 3.97% of the heating.

Please let me know if this format is good for you or if you want me to combine this additional heating with the original numbers.

Thank you,

Lukas

Heat Sources for CFD calculations were obtained by multiplying the energy deposition by 15Hz.

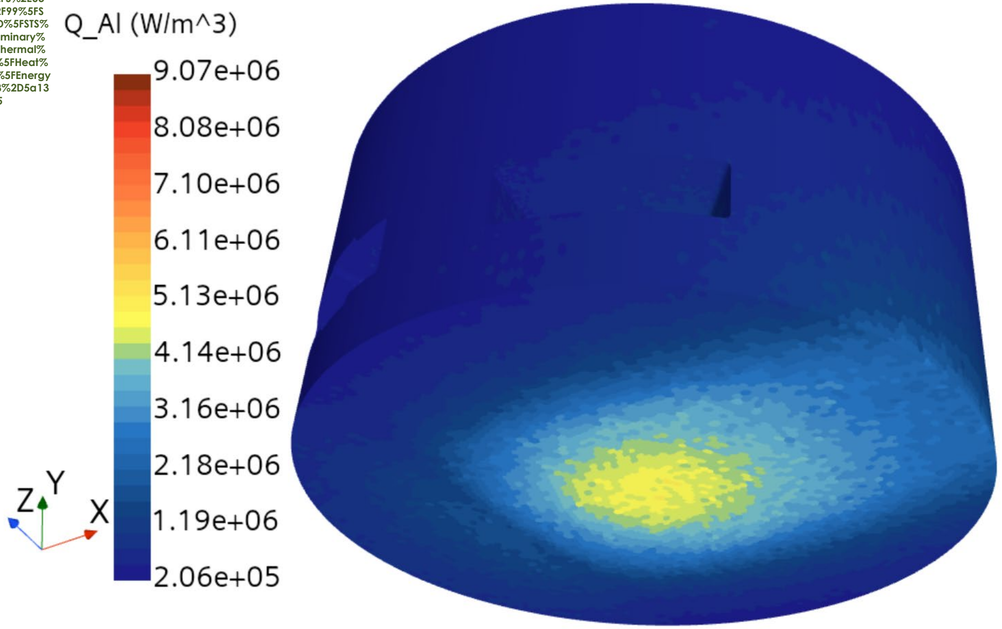
Link: https://ornl.sharepoint.com/sites/sts/targetsystems/Shared%20Documents/Forms/AllItems.aspx?id=%2Fsites%2Fsts%2Ftargetsystems%2FShared%20Documents%2FS%2E03%2E02%20Target%20Assembly%2F99%5FSANDBOX%2FKAO%2F2022%2F0%5FCFD%5FSTS%5FMRA%2FMin%2DTsung%20Kao%5FSTS%5FMRA%5F2022%5F11%5F10%5FLower%5FMRA%5FUpdate%5F1%2FCFD%5FHeat%5FSources&viewid=9be9bc88%2D5a13%2D48c7%2D9fff%2Dd22f94ffdeb5

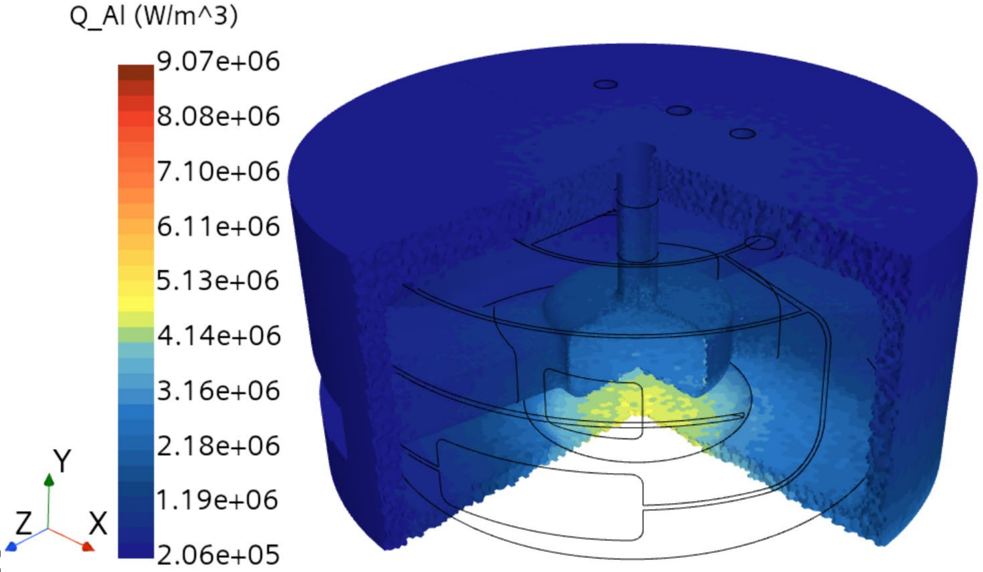
Steady State Heat Transfer Analysis for Upper MRA, Heat Source

Heat source link

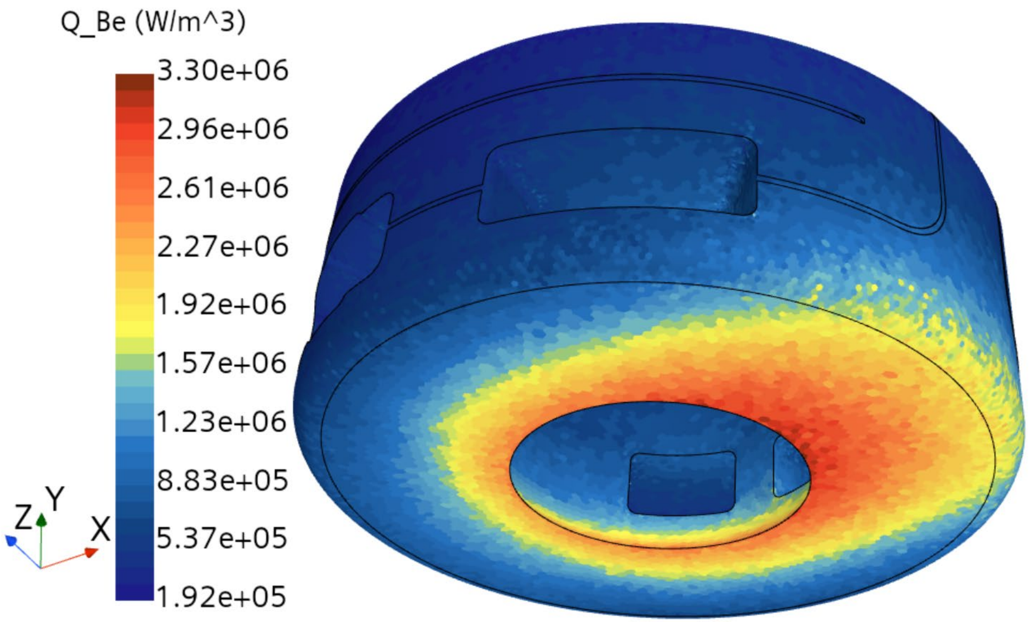
https://ornl.sharepoint.com/sites/sts/targetsystems/Shared%20Documents/Forms/AllItems.aspx?id=%2Fsites%2Fsts%2Ftargetsystems%2FShared%20Documents%2FS%2E03%2E02%20Target%20Assembly%2F99%5FSANDBOX%2FKAO%2F2023%2FCFD%5FSTS%5FMRA%2F0%5FSummary%2FPreliminary%20STS%20Upper%20Reflector%20Thermal%20Hydraulic%20Analysis%2FCFD%5FHeat%5FSources%5Fand%5FNeutronics%5FEnergy%5FDeposition&viewid=9be9bc88%2D5a13%2D48c7%2D9fff%2Dd22f94ffdeb5

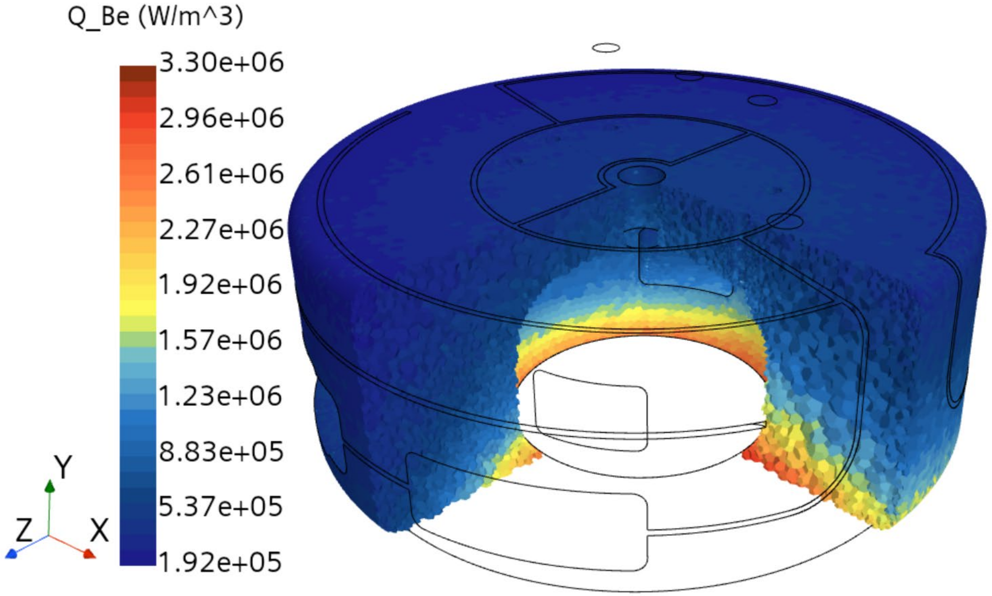
Q_Al





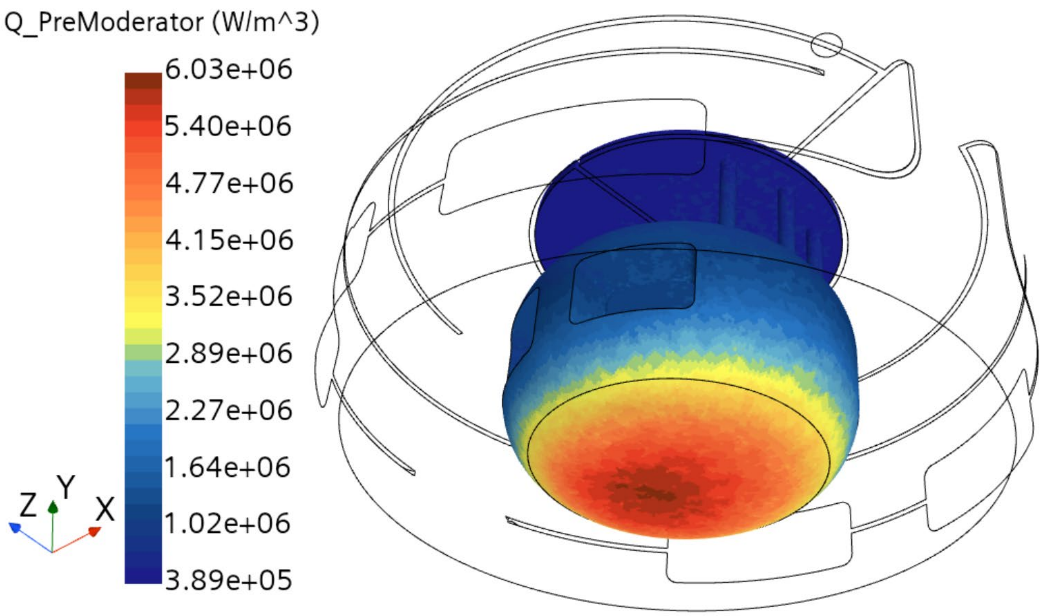
Q_Be

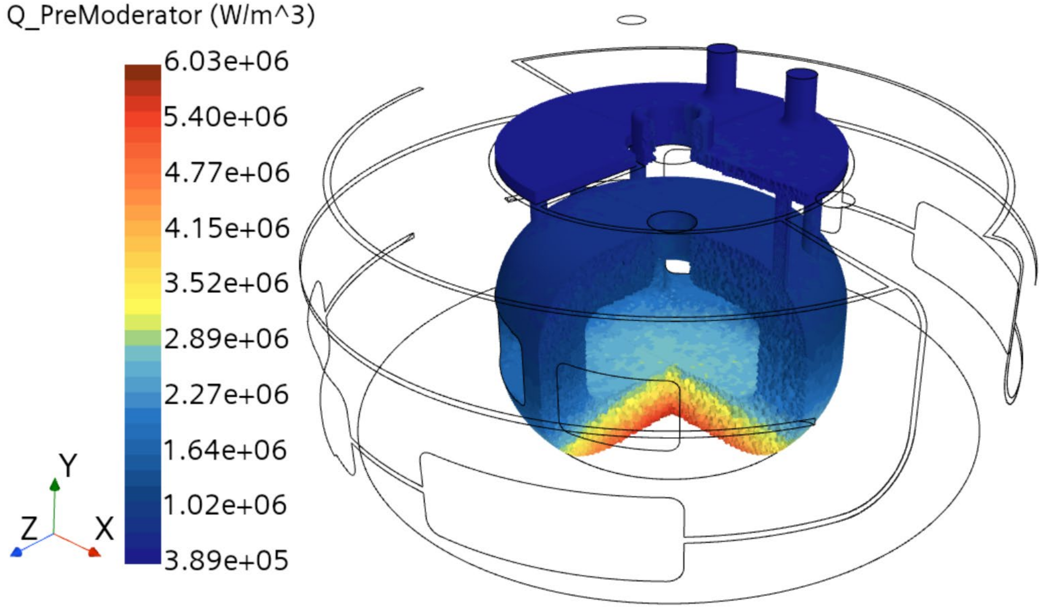




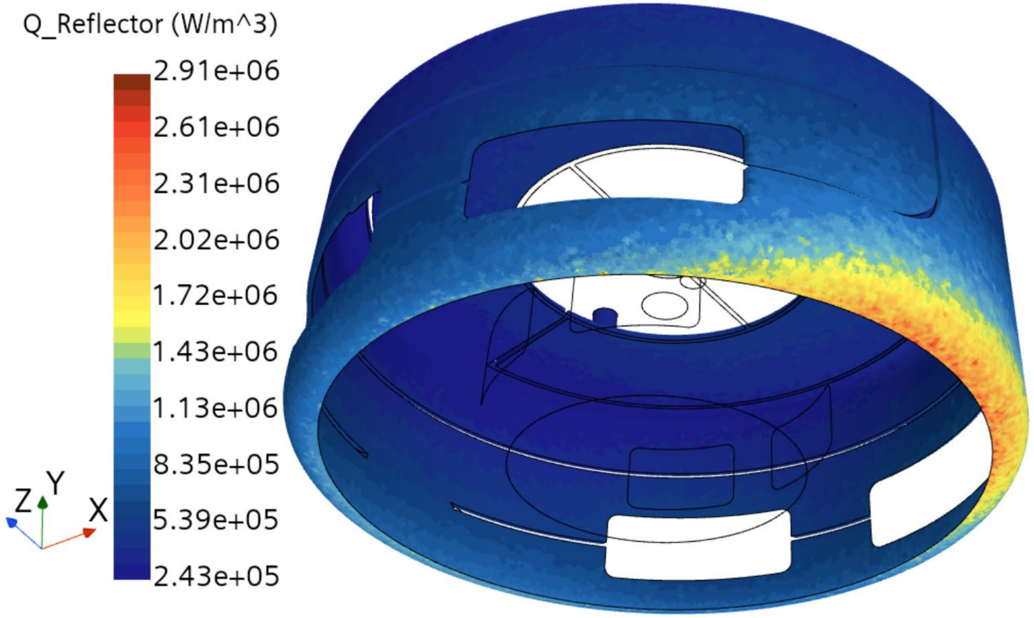
Steady State Heat Transfer Analysis for Upper MRA, Heat Source

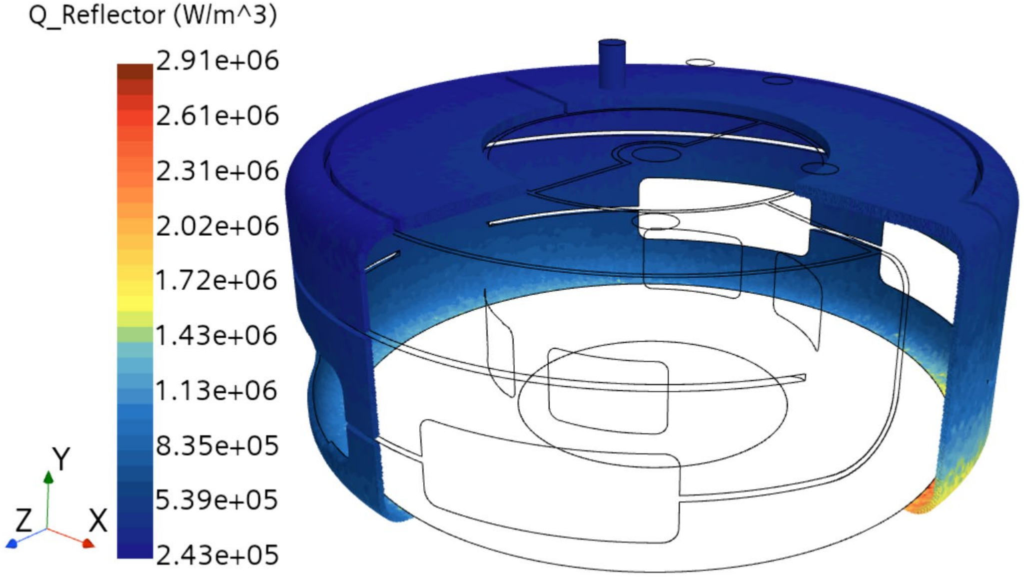
Q_PreModerator





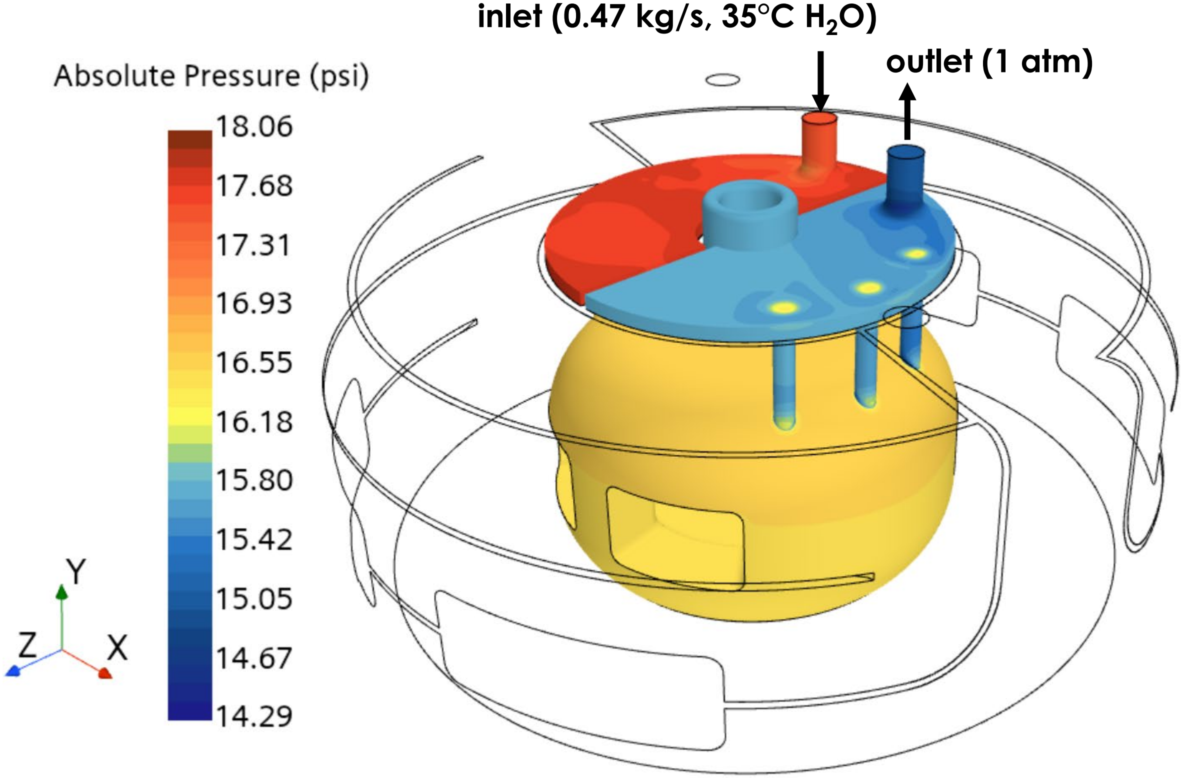
Q_Reflector

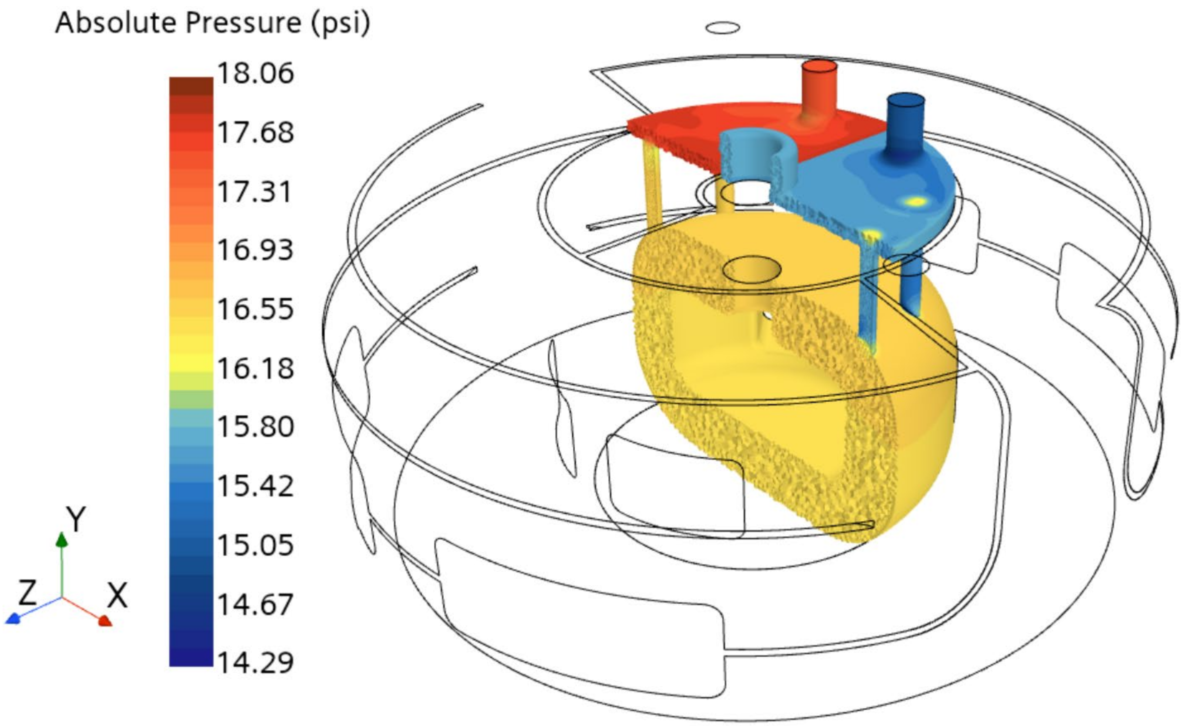




Steady State Heat Transfer Analysis for Upper PreModerator, Pressure

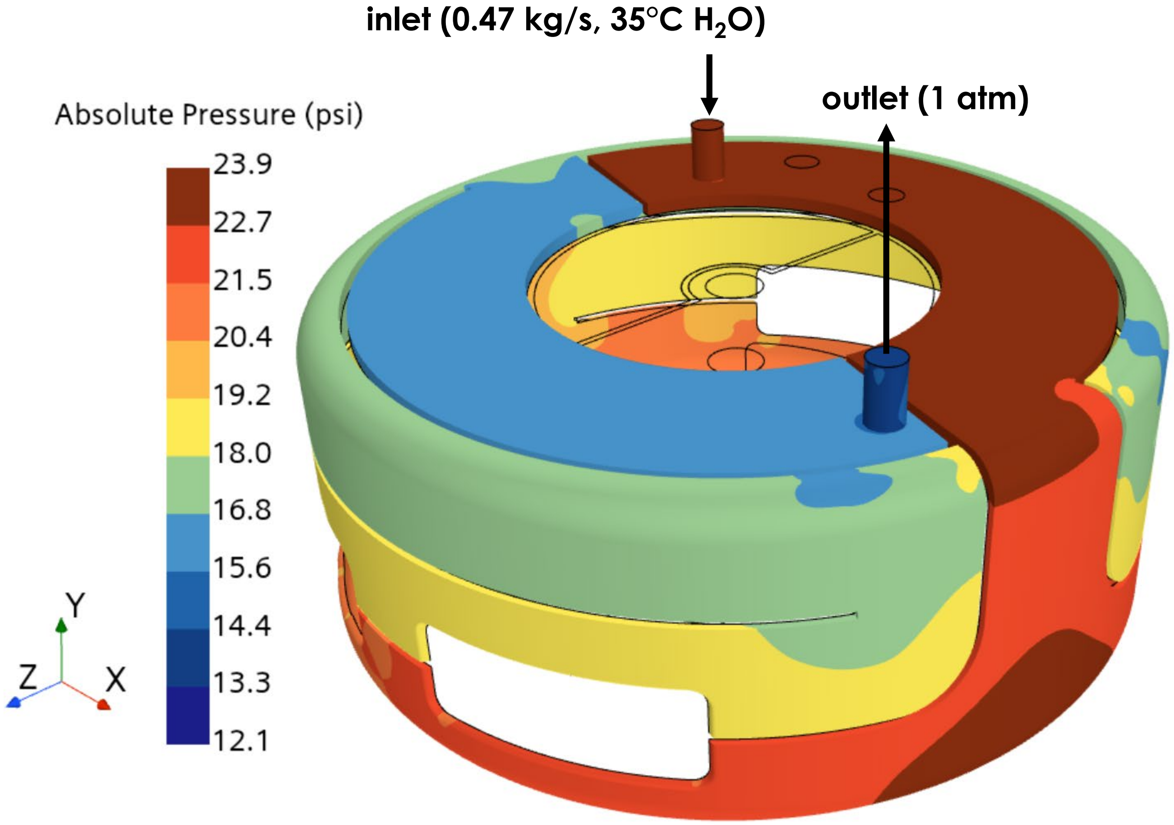
$$\Delta P_{inlet-outlet} = 0.17 \text{ bar } (= 17.4 \text{ kPa} = 2.53\ psi = 0.17\ atm)$$

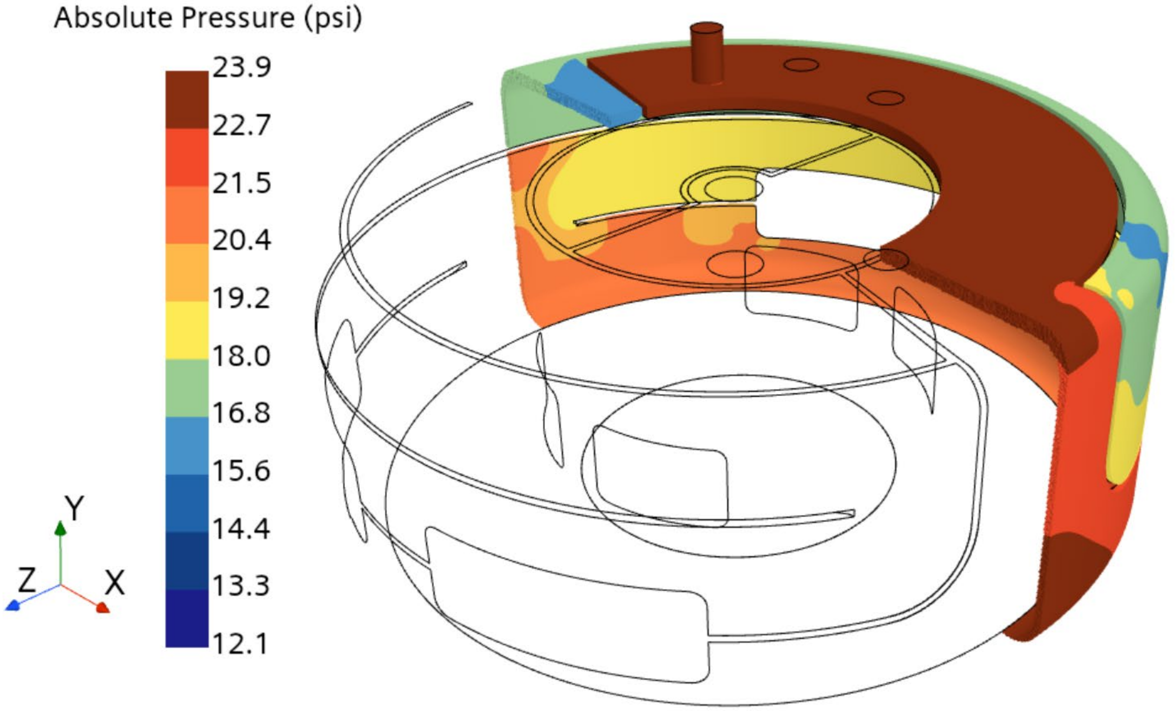




Steady State Heat Transfer Analysis for Upper Reflector, Pressure

$$\Delta P_{inlet-outlet} = 0.56 \text{ bar } (= 56.5 \text{ kPa} = 8.2\ psi = 0.56\ atm)$$

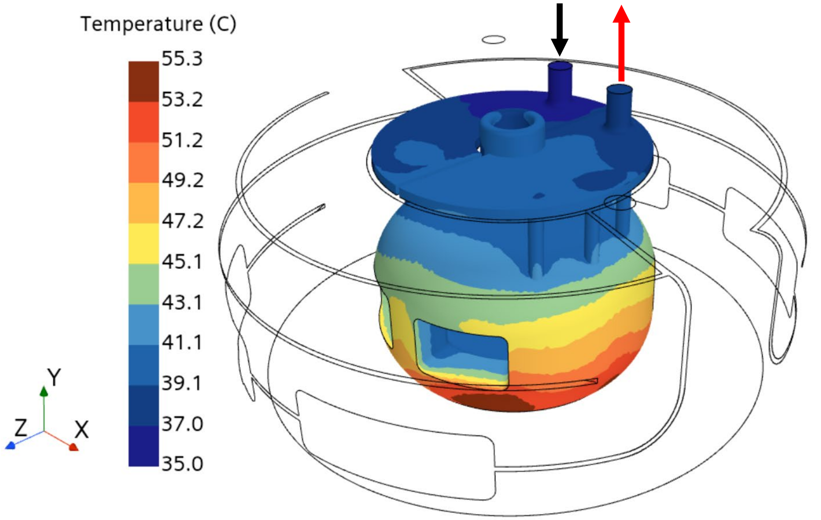


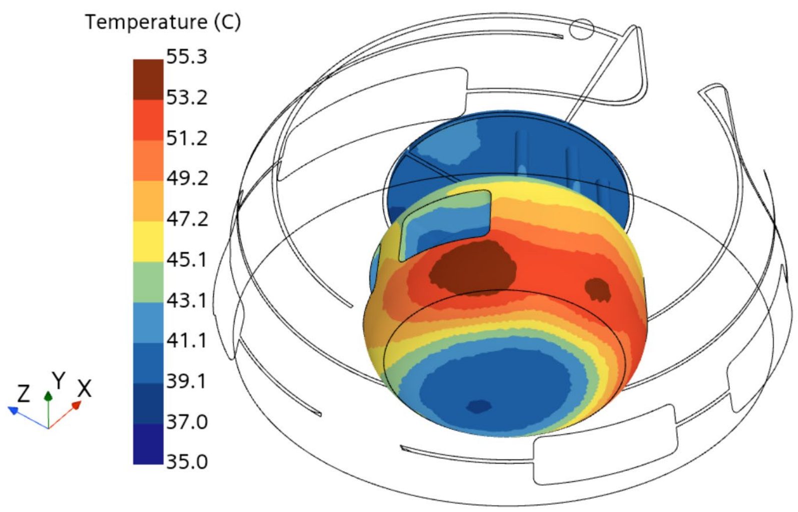


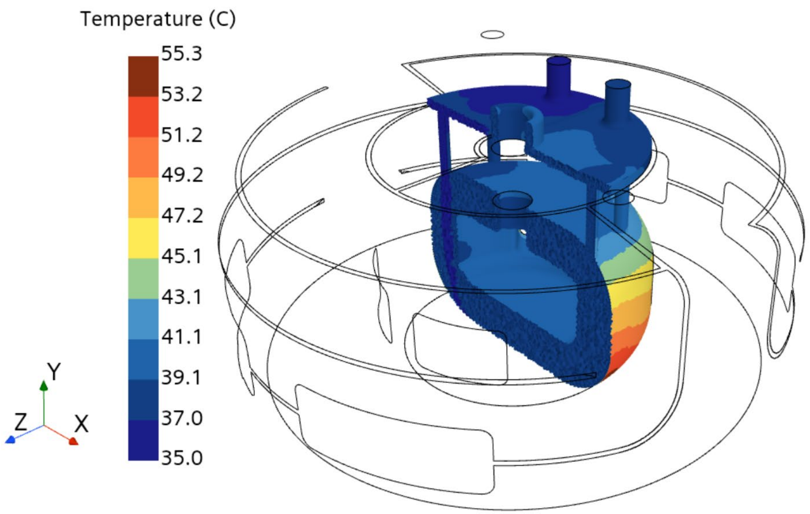
Steady State Heat Transfer Analysis for Upper PreModerator (H_2O), Temperature

Peak Temperature of Upper PreModerator: 55.3°C

inlet (0.47 kg/s, 35°C H_2O) T_{out}= 38.30°C



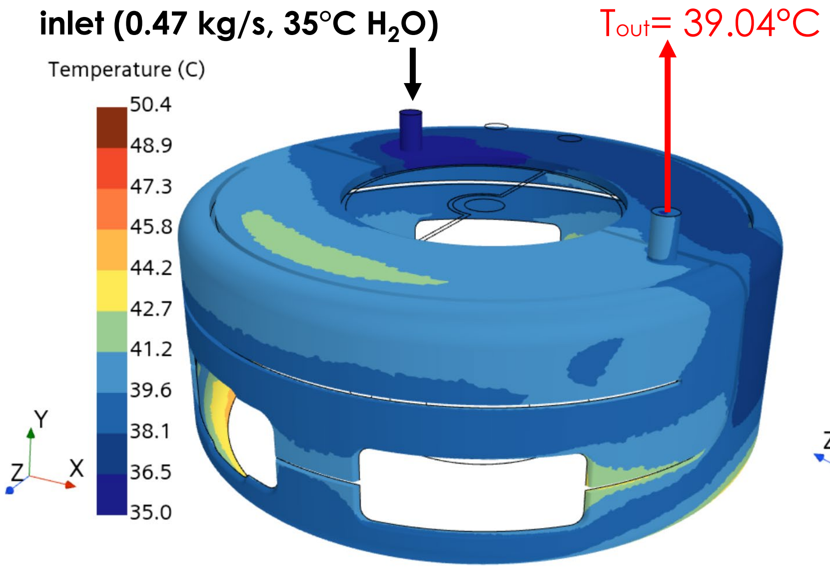


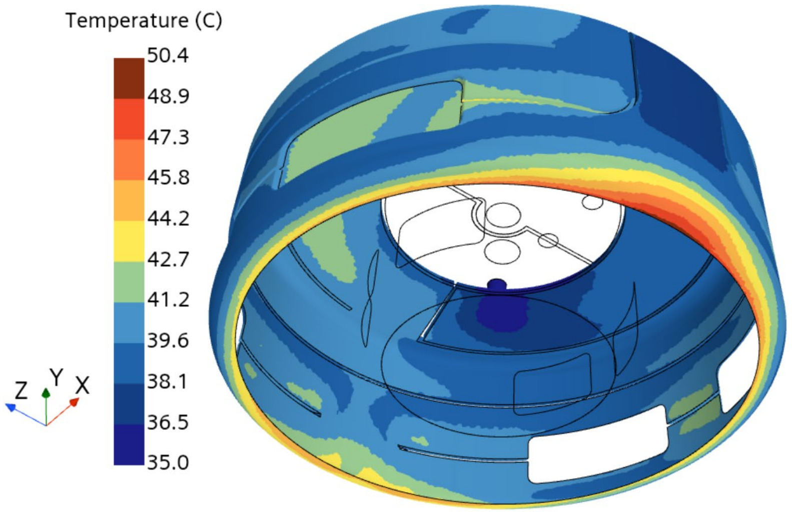


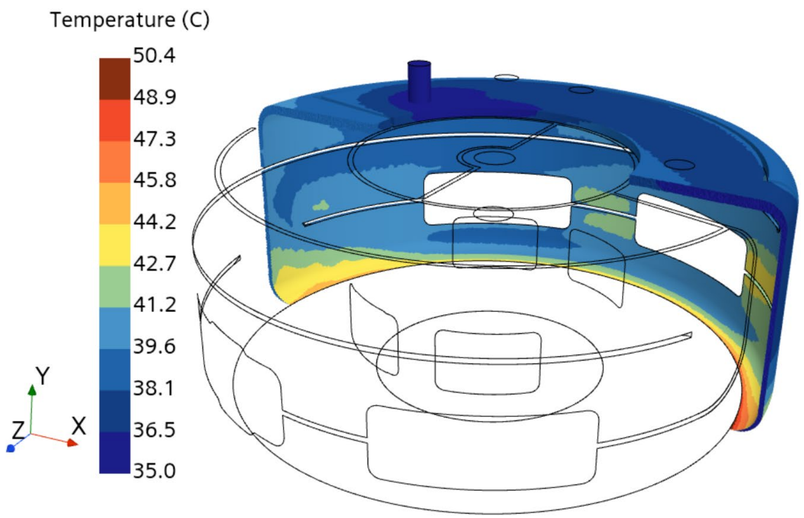
Oak Ridge National Laboratory

Steady State Heat Transfer Analysis for Upper Reflector(H_2O), Temperature

Peak Temperature of Upper Reflector: 50.4°C

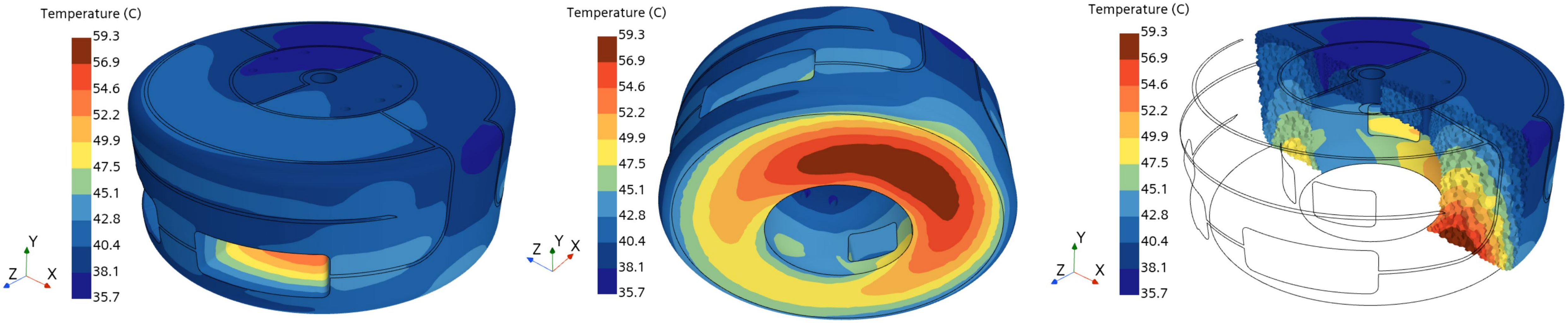






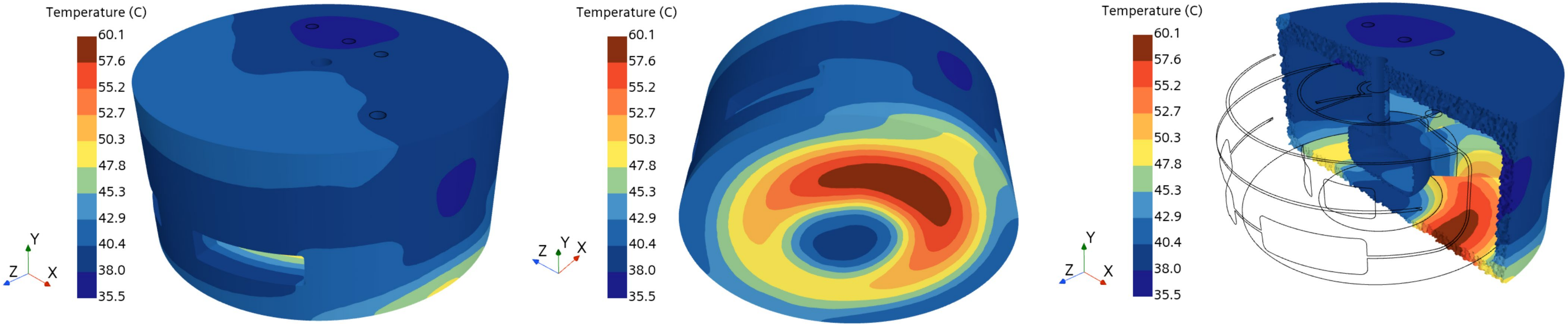
Steady State Heat Transfer Analysis for Upper Be, Temperature

Peak Temperature of Upper Be: 59.3°C

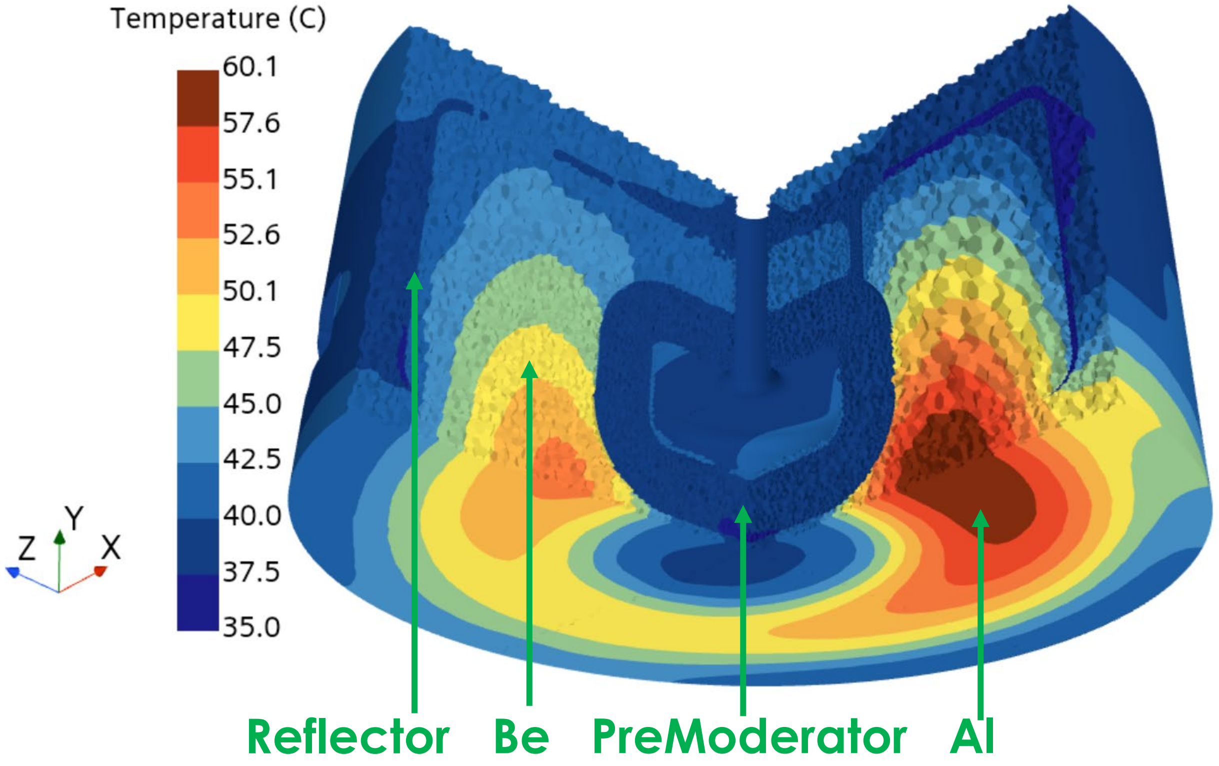


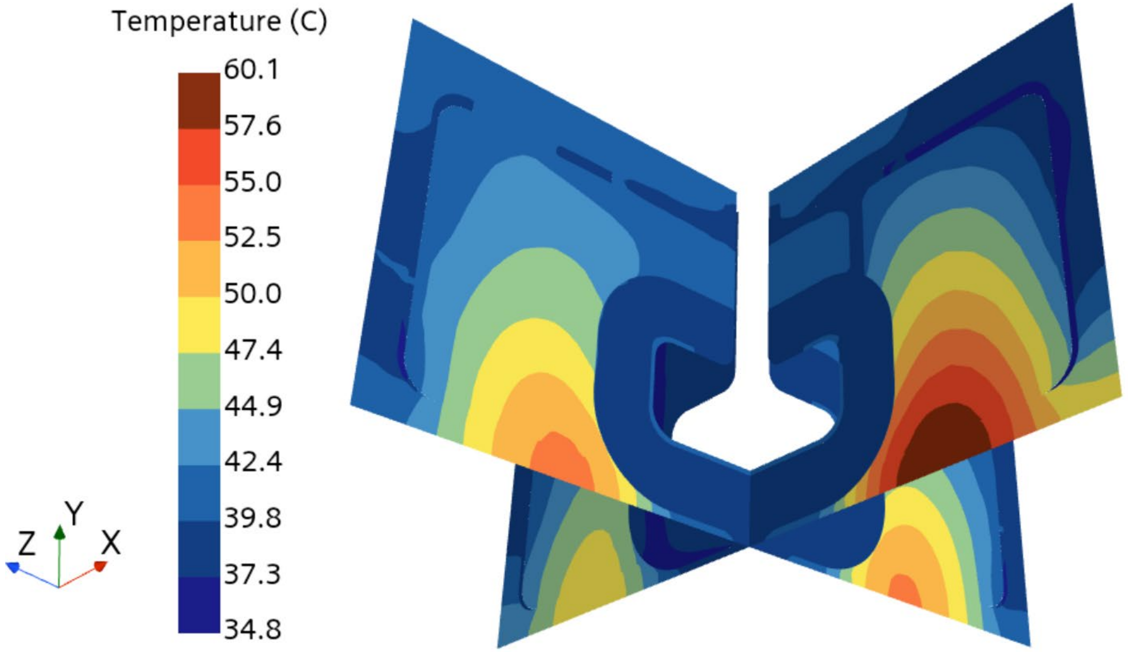
Steady State Heat Transfer Analysis for Upper Al, Temperature

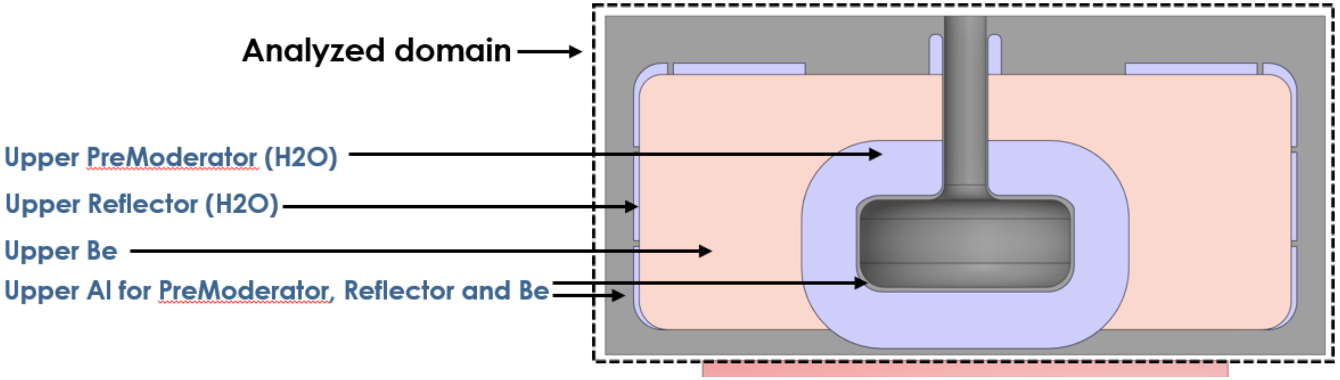
Peak Temperature of Upper Al: 60.1°C



Steady State Heat Transfer Analysis for Upper MRA (without H2 Moderator), Temperature

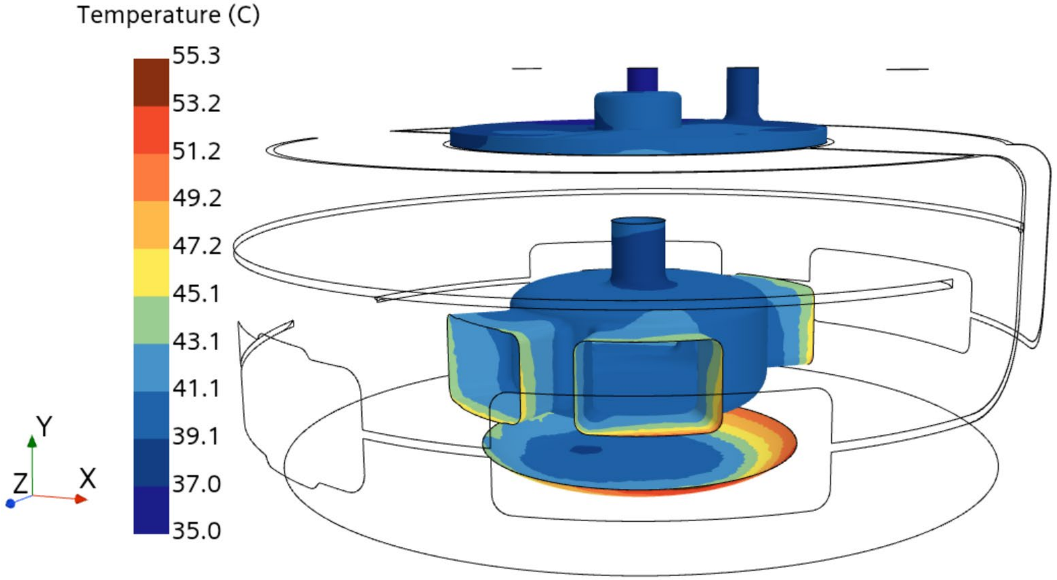




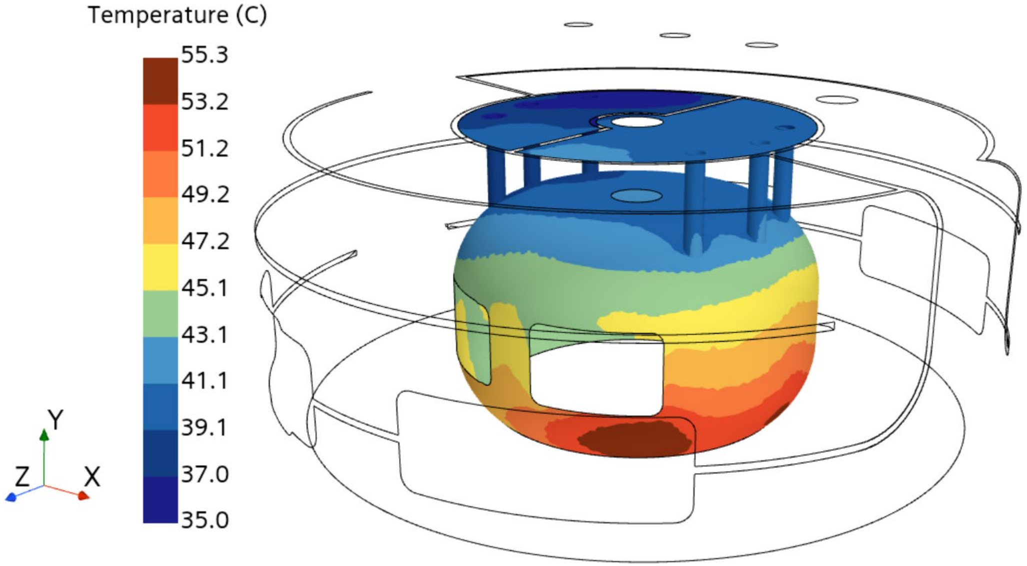


Steady State Heat Transfer Analysis for Upper MRA (without H2 Moderator), Interface Temperature

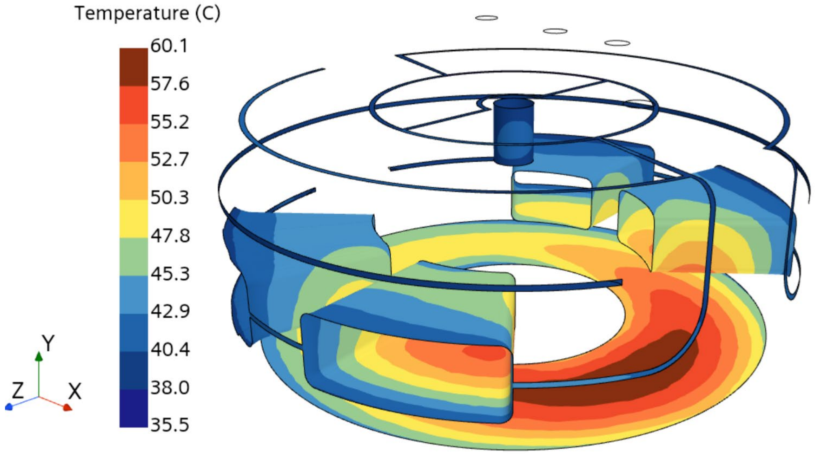
Pre-Moderator/Al



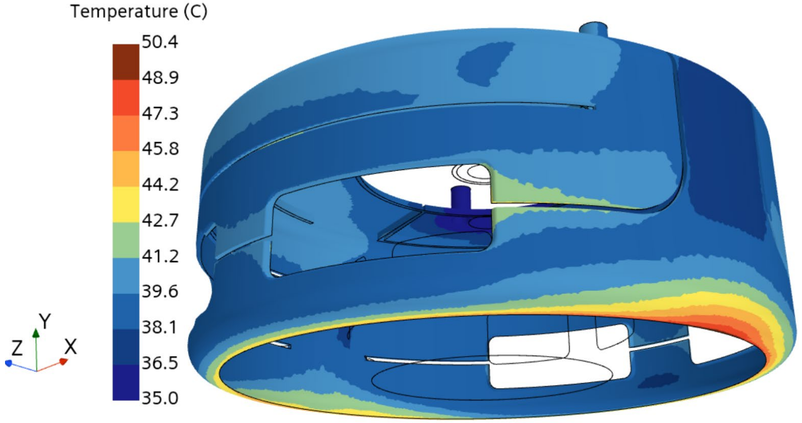
Pre-Moderator/Be



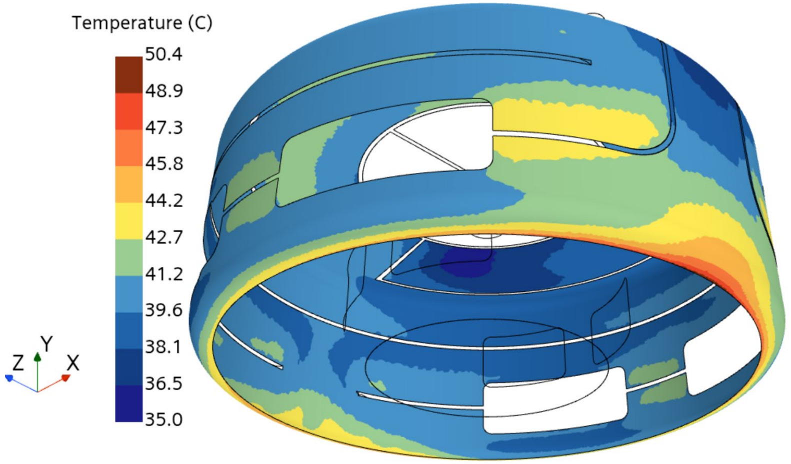
Al/Be



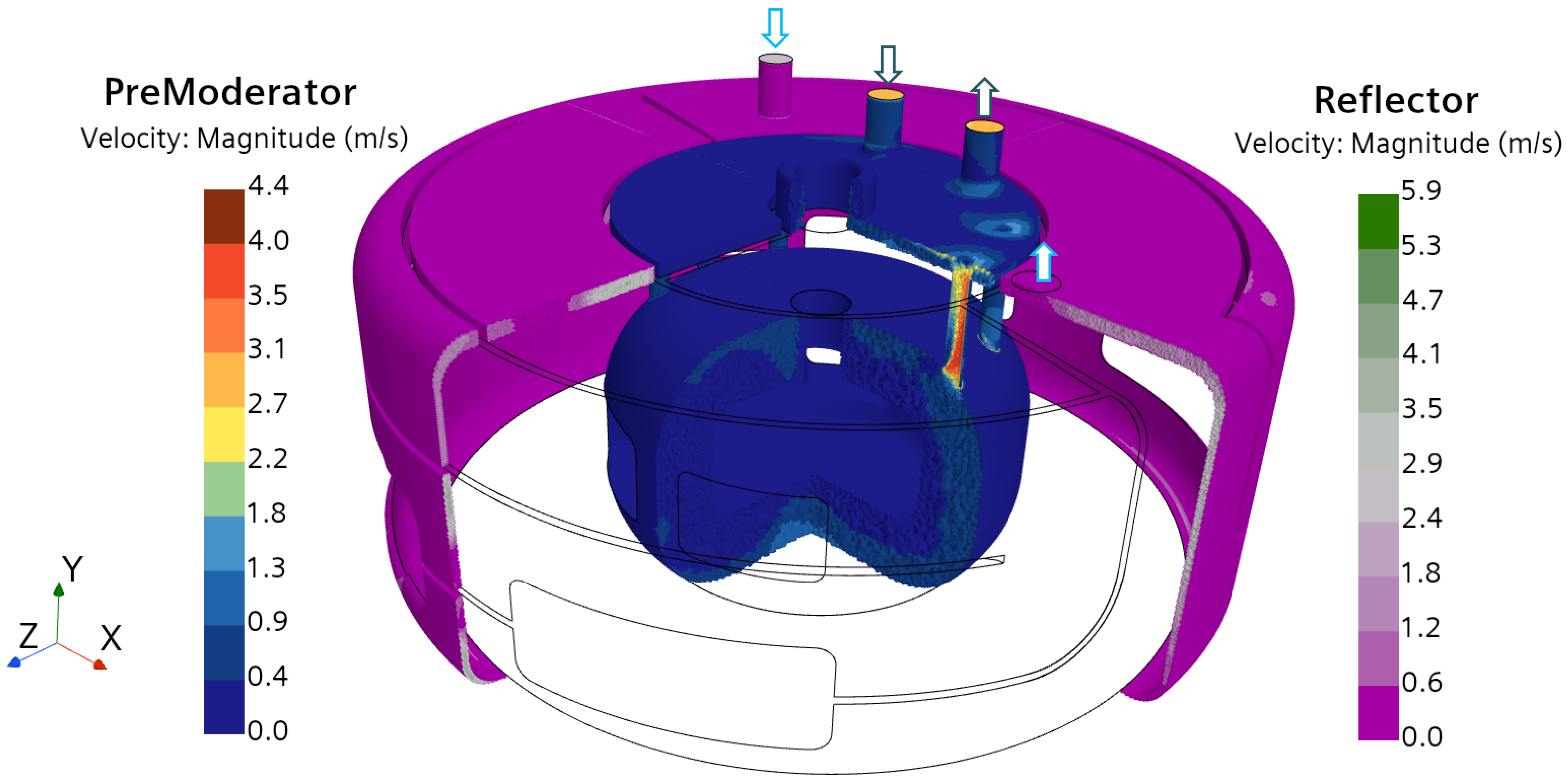
Reflector/Al



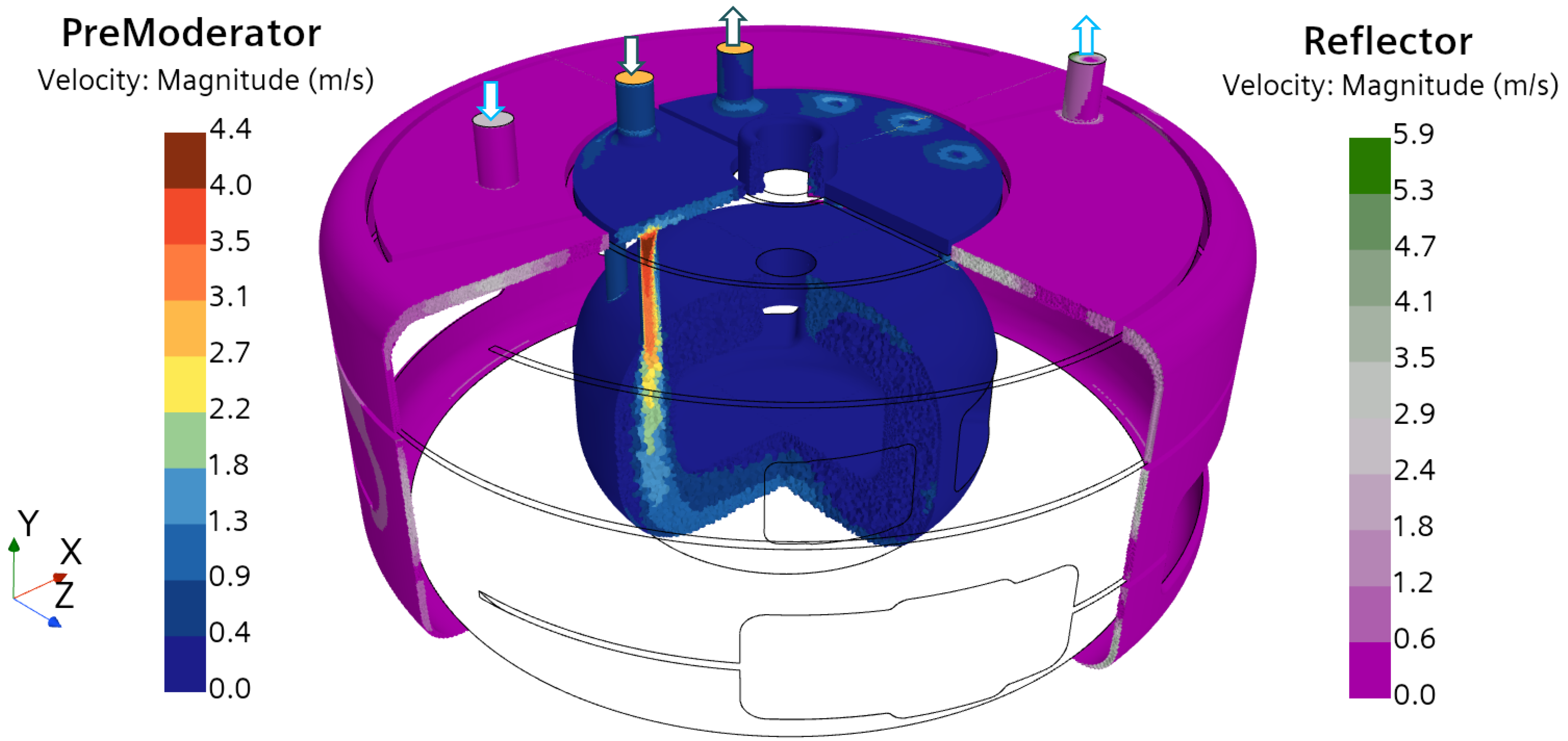
Reflector/Be



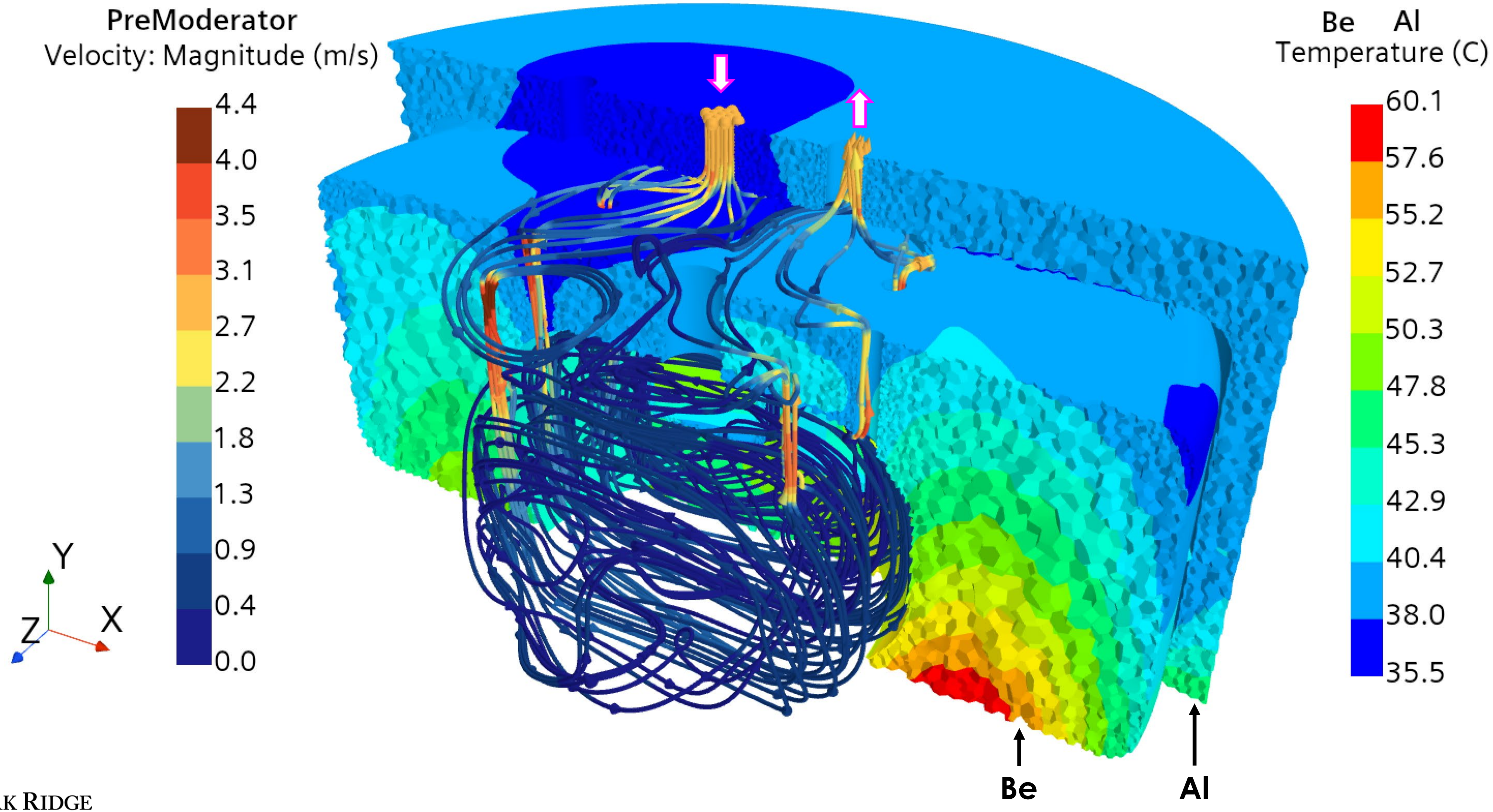
Steady State Heat Transfer Analysis for Upper MRA, Velocity



Steady State Heat Transfer Analysis for Upper MRA, Velocity



Steady State Heat Transfer Analysis for Upper MRA, Velocity & Temperature



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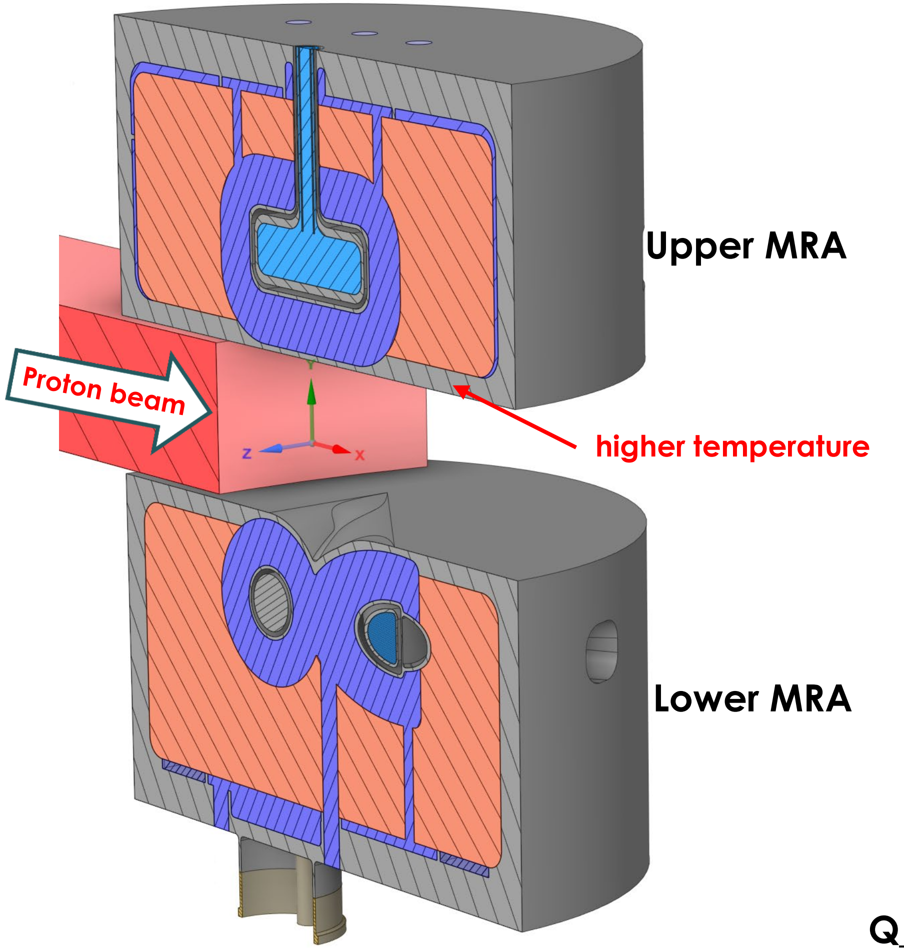
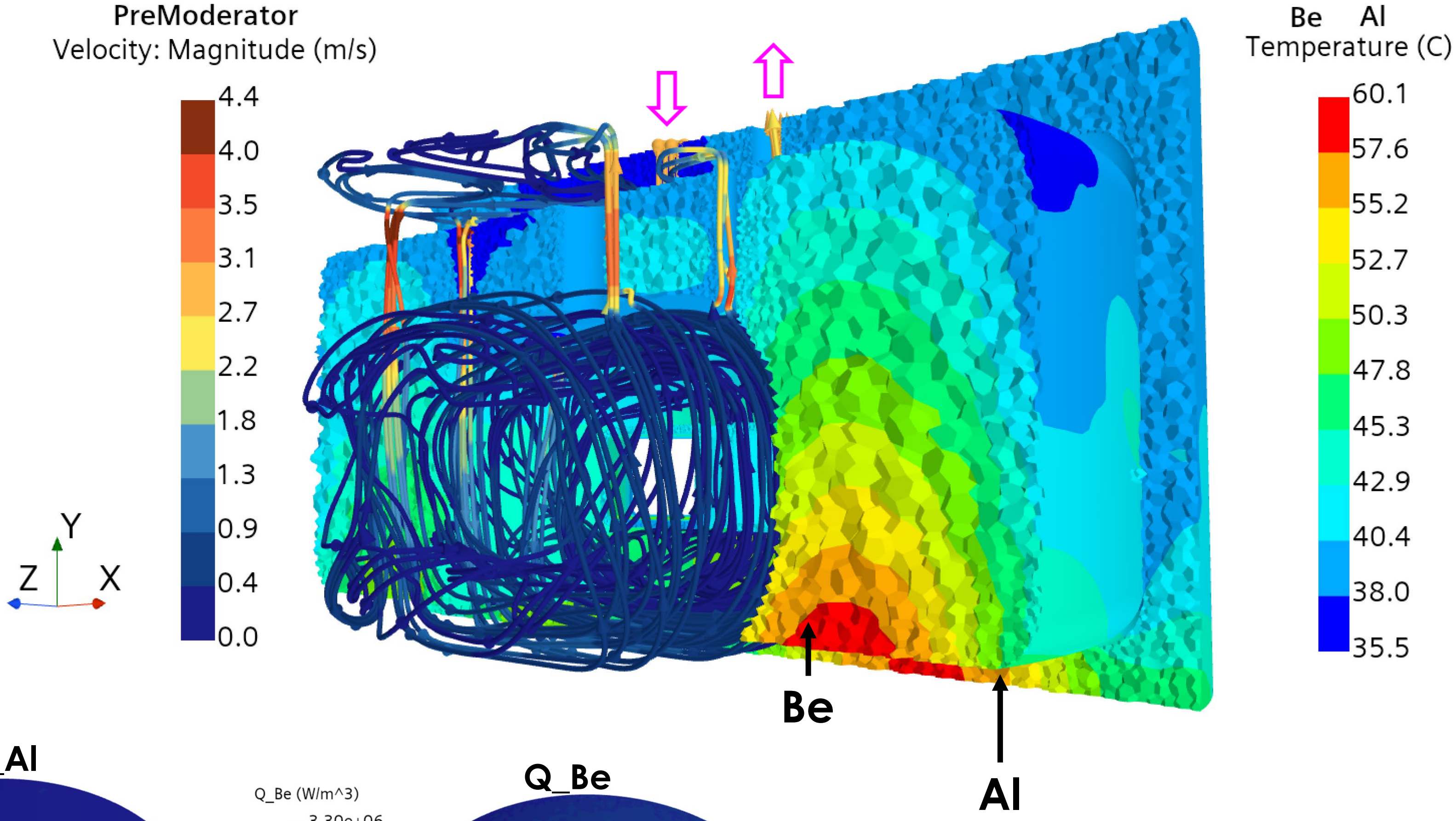
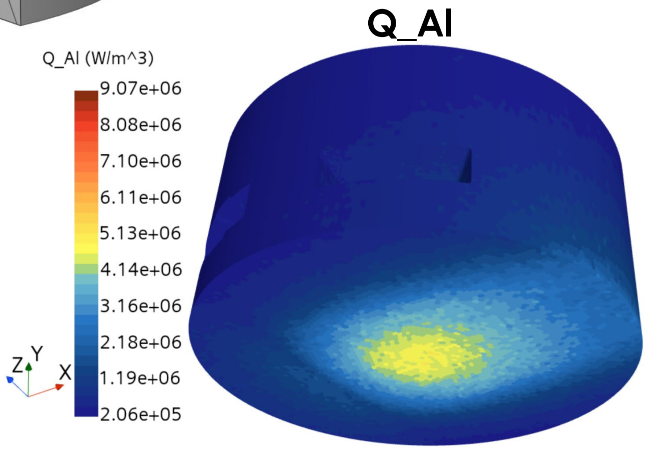
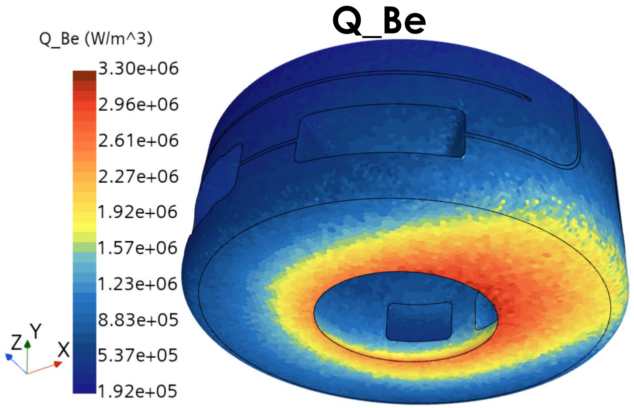
Steady State Heat Transfer Analysis for Upper MRA, Velocity & Temperature









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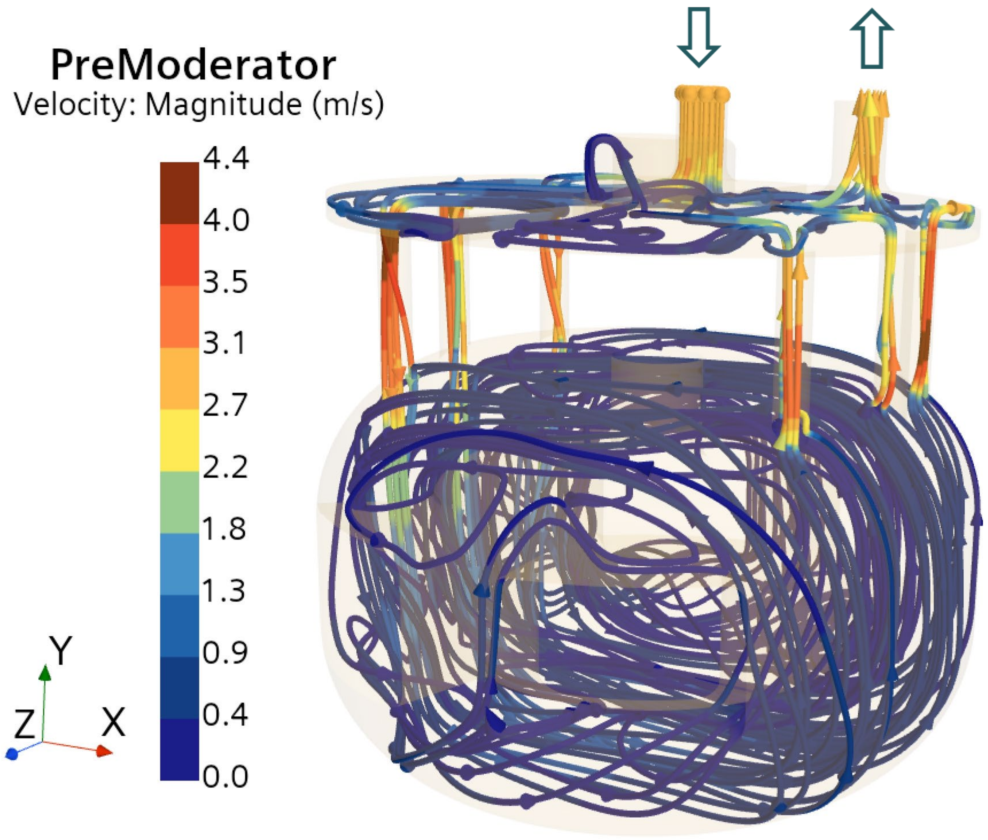
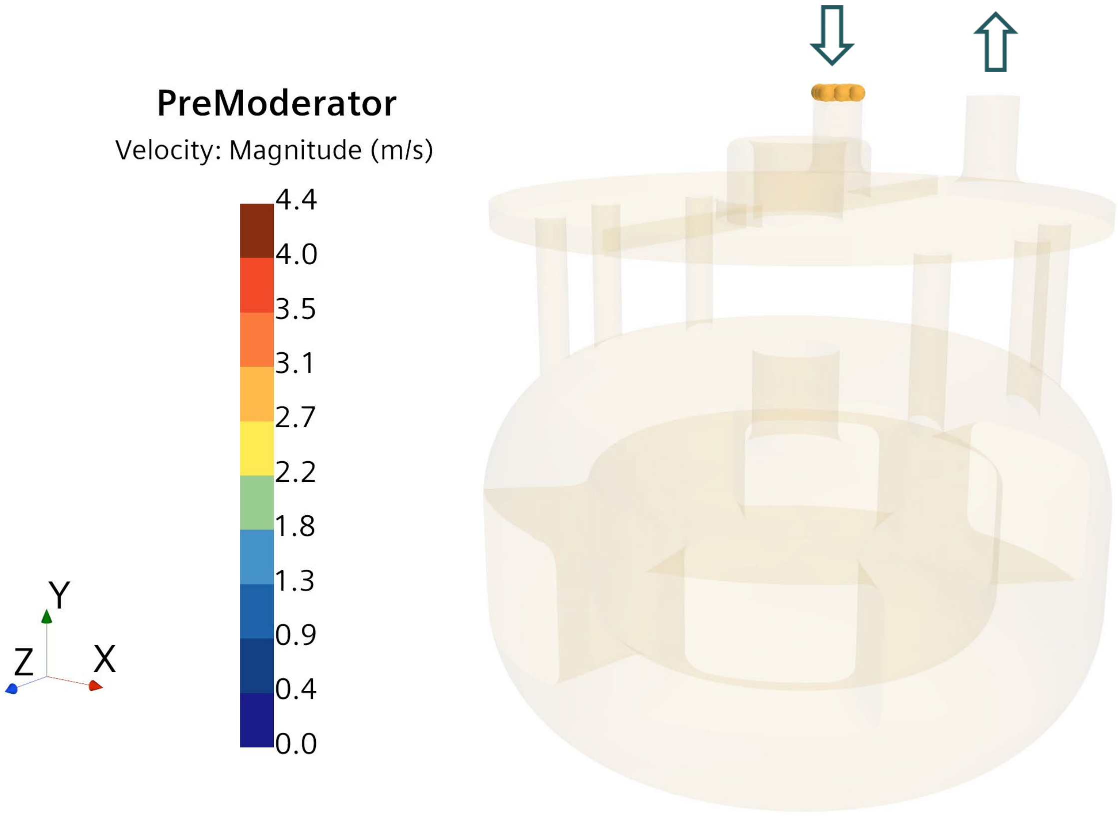
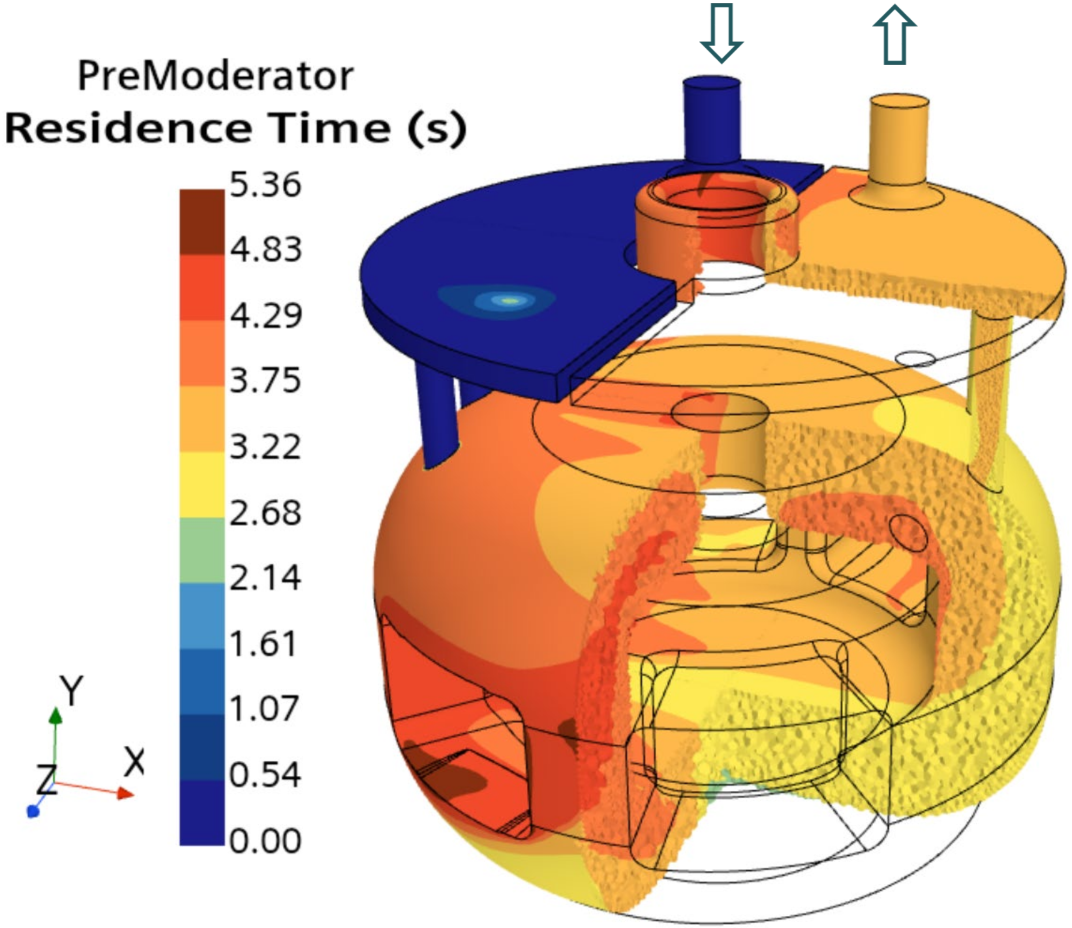
Steady State Heat Transfer Analysis for Upper PreModerator, Streamlines

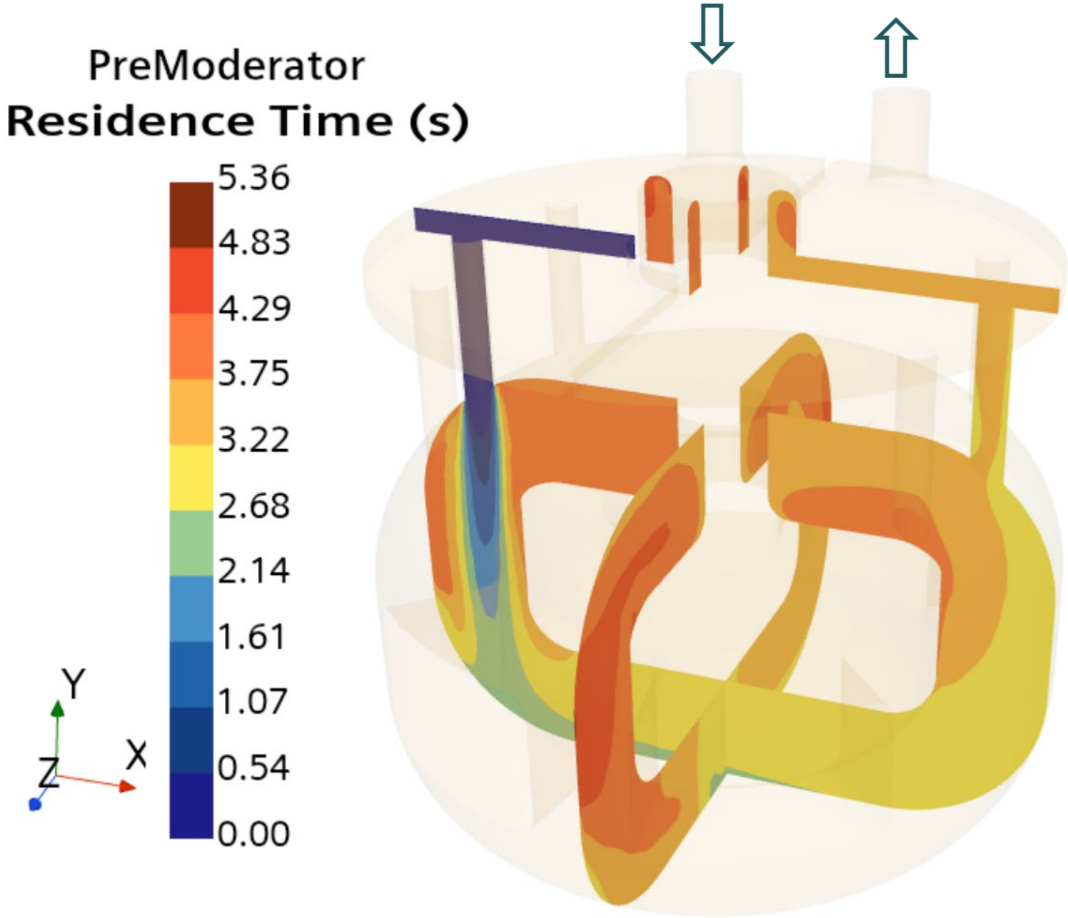


Animation



Steady State Heat Transfer Analysis for Upper PreModerator, Residence Time





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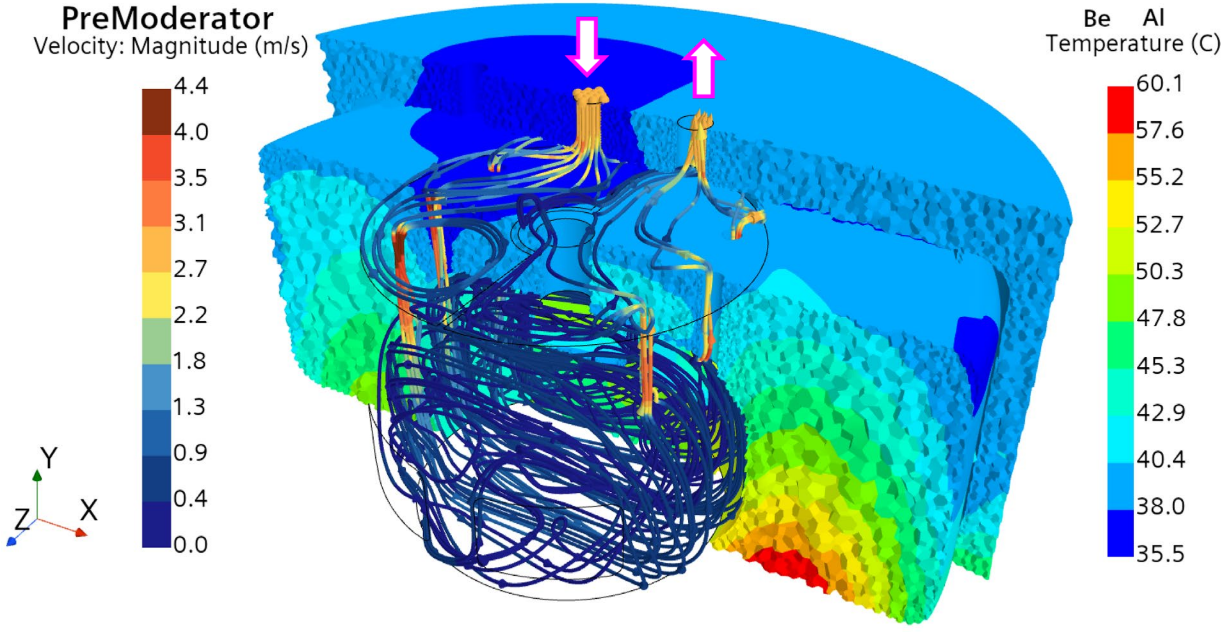
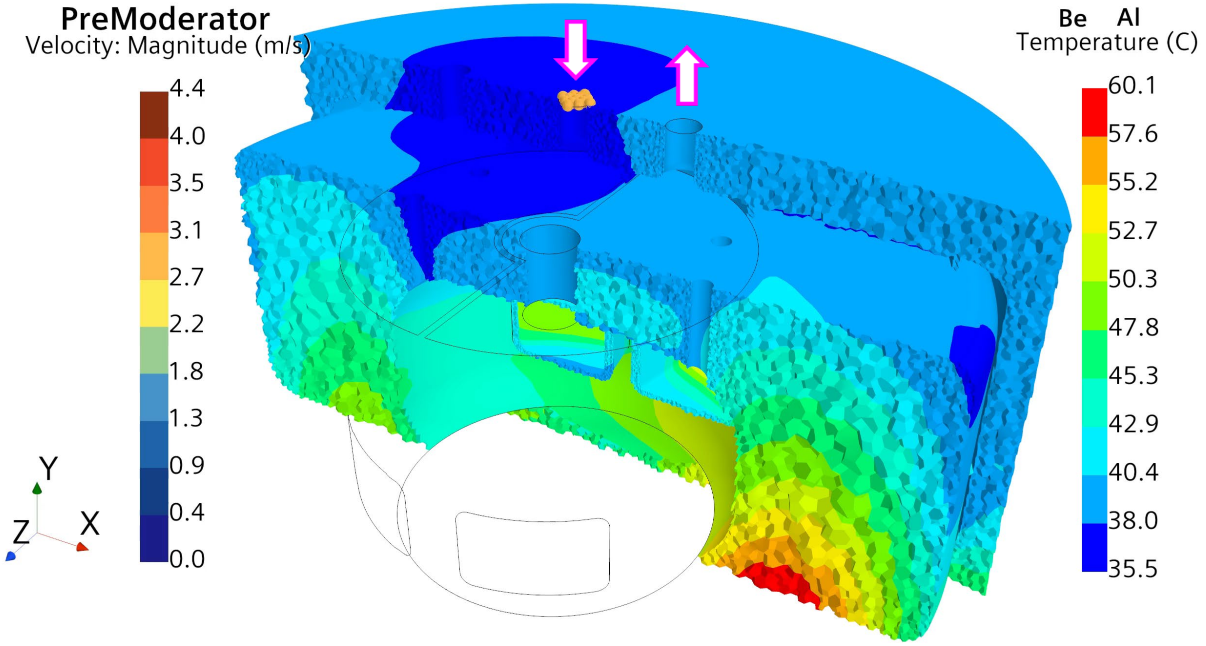
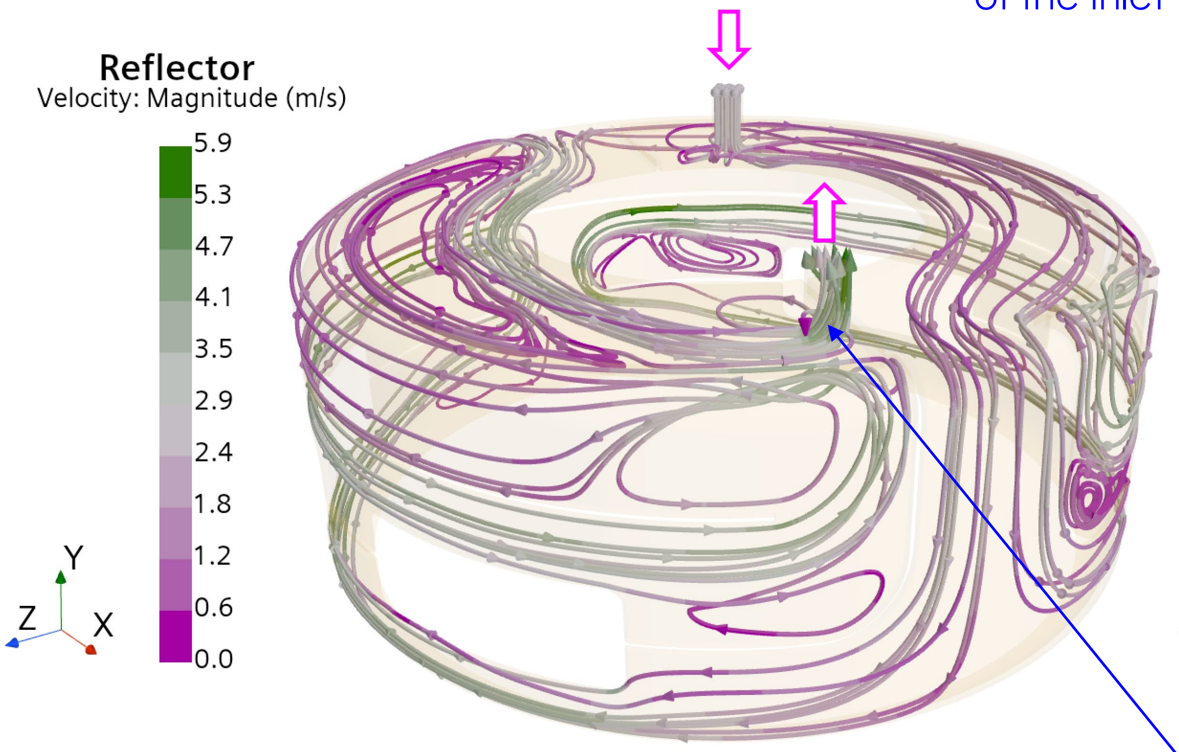
Steady State Heat Transfer Analysis for Upper PreModerator, Streamlines



Animation

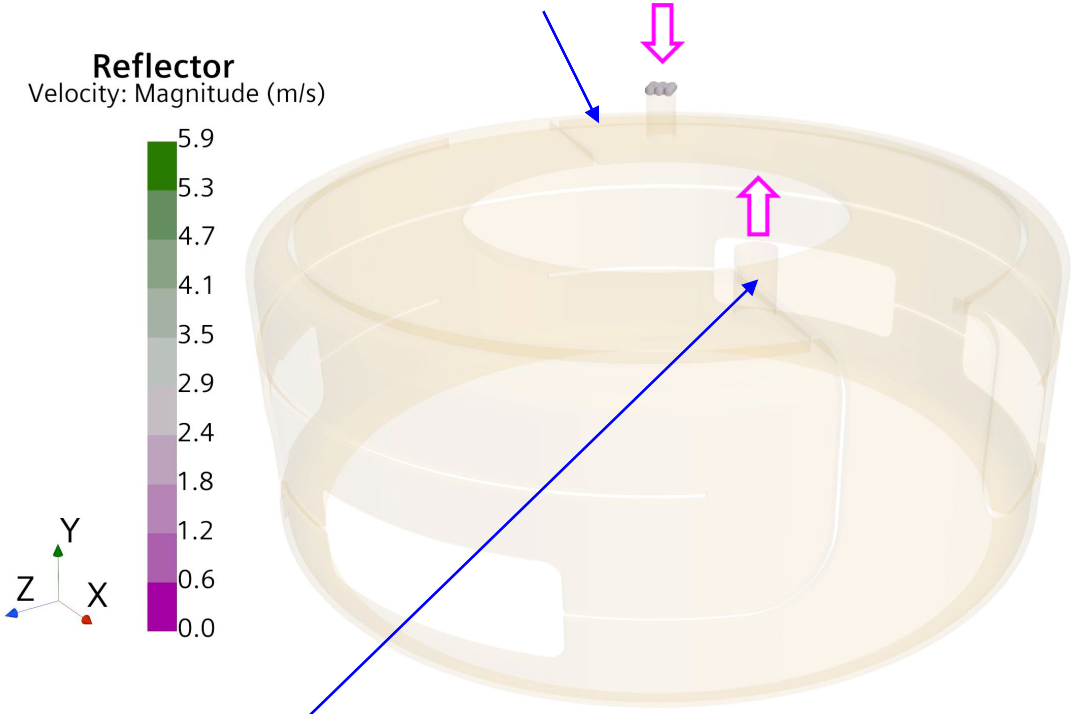


Steady State Heat Transfer Analysis for Upper Reflector, Streamlines



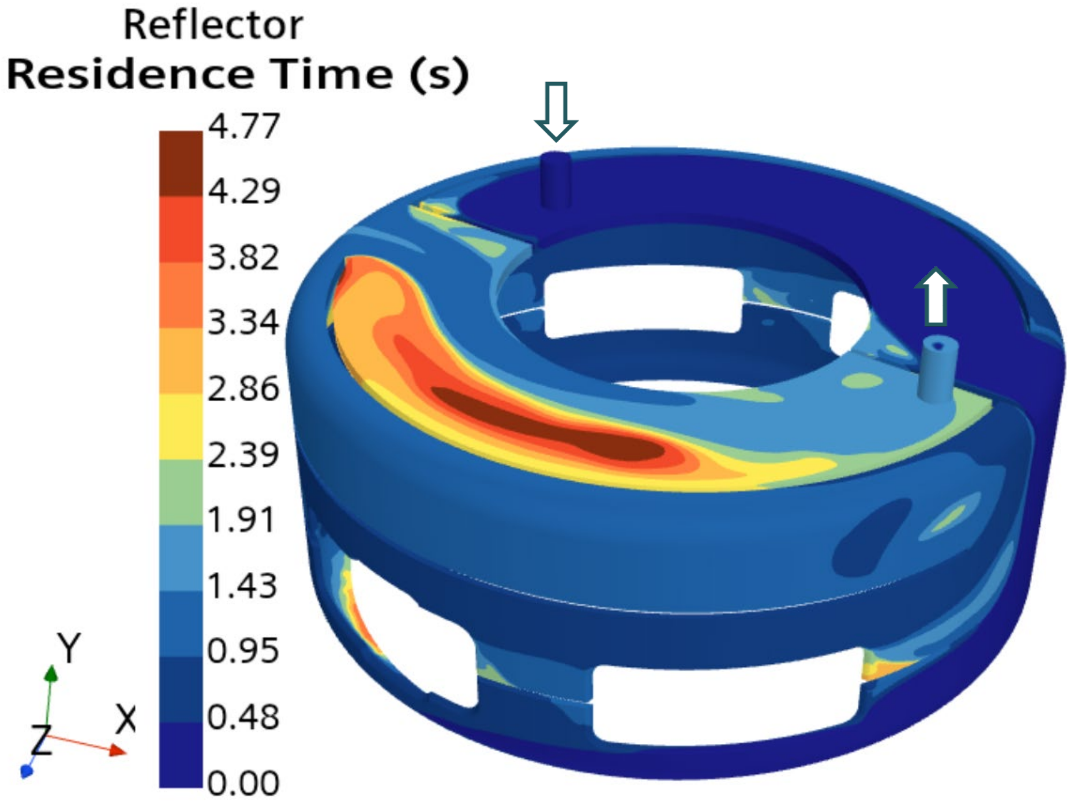
Animation

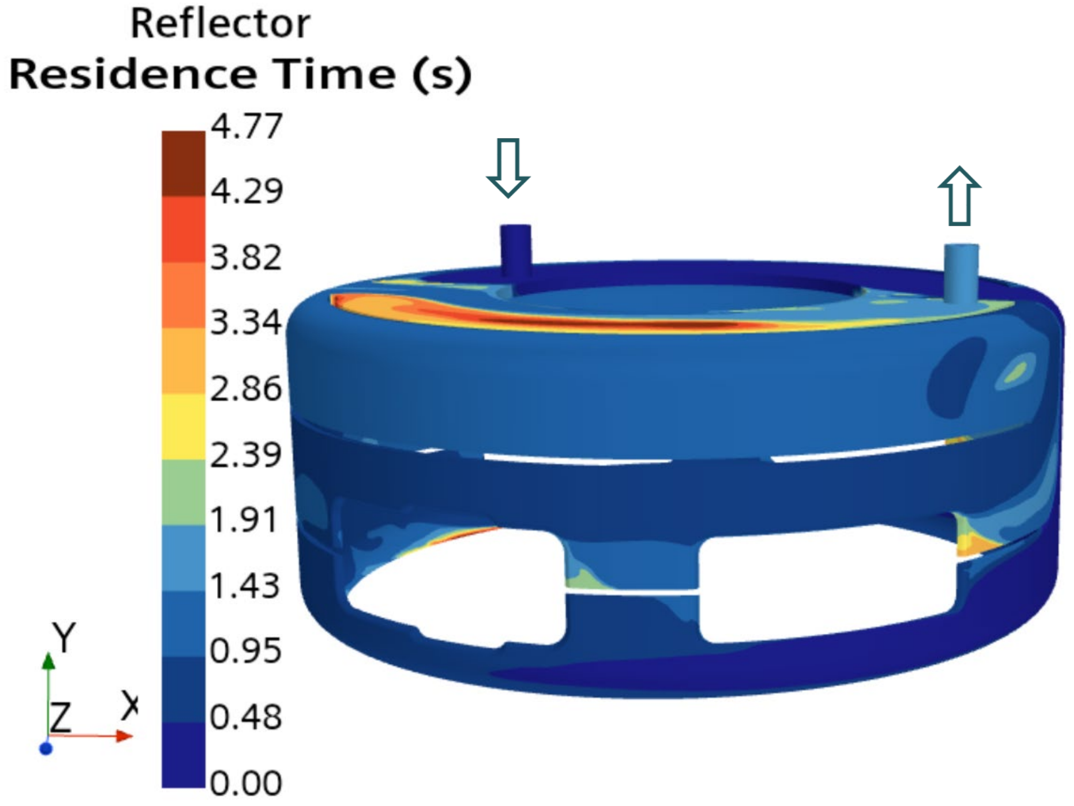
Inlet tube is away from the edge wall (to have room for cooling lines in the backbone) and there is not much vortex generated in **this region**. ➔location of the inlet tube has less impact on the pressure drop.



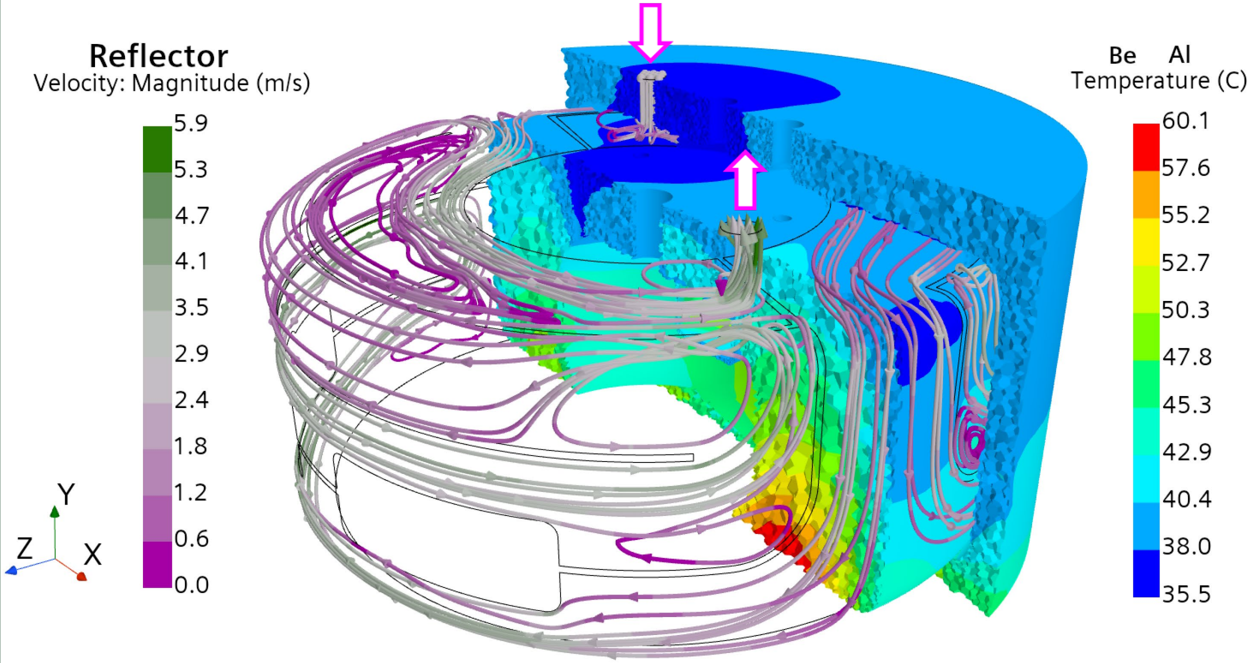
Outlet tube is close to the edge wall and the strength of the vortex at the outlet is reduced. ➔ Pressure drop reduces. Another factor that contributes the pressure drop reduction is the increase of the water layer thickness from 3 mm to 6 mm (see lower MRA presentation for more information.)

Steady State Heat Transfer Analysis for Upper Reflector, Residence Time

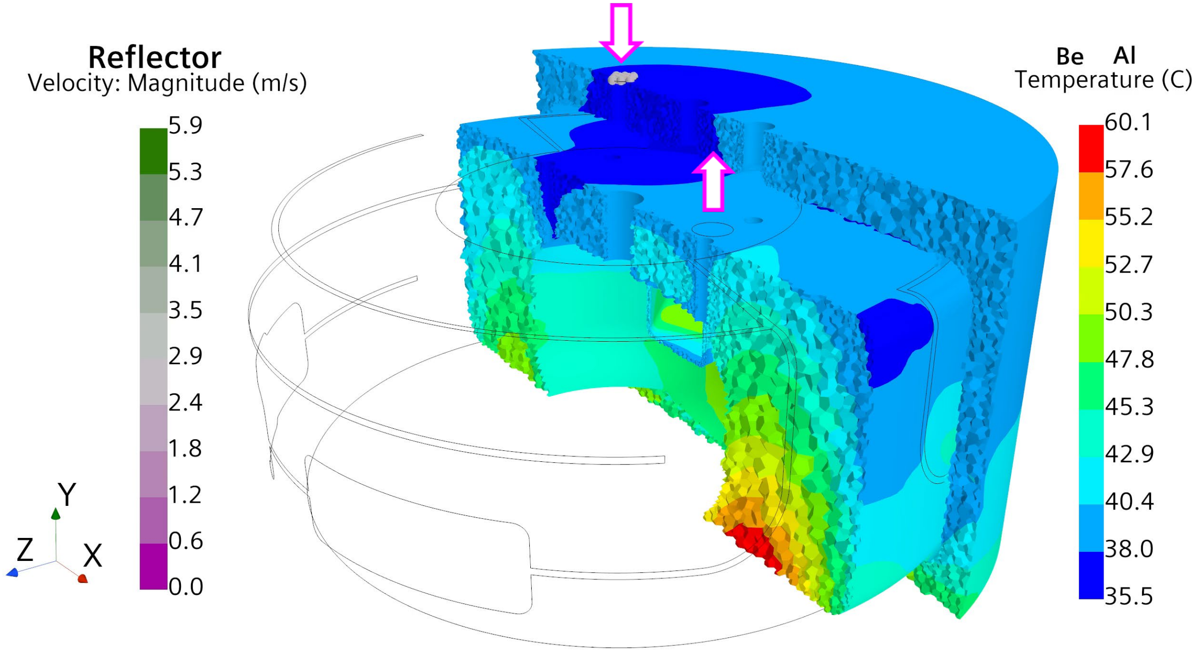




Steady State Heat Transfer Analysis for Upper Reflector, Streamlines



Animation



Comparison between Requirements and CFD Results

Upper MRA (without Moderator)

	Requirement	CFD Result	
Maximum Aluminum Temperature (°C)	< 100	60.1	
Maximum Beryllium Temperature (°C)	< 100	59.3	
		PreModerator	**Reflector**
Pressure Drop (psi)	< 15	2.53	8.2
Maximum Water Temperature (°C)	< 100	55.3	50.4

- All requirements are met with at least a factor of 1.83 margin
  - High confidence that margin to requirements is significantly higher than uncertainties

Summary

- The locations of the inlet and outlet for the reflector were adjusted several times to reduce the pressure drop from 22 psi to 8 psi. The main idea is to reduce the vortex near the outlet since the pressure within the vortex region is very low and thus the pressure would be increased.
- All requirements are met with high margins
- Items to be included in final analysis
  - Update inlet/outlet geometry based on final backbone design
    - Preliminary backbone inlet/outlets are moved slightly from locations used in this analysis
  - Update inlet temperature to match final process systems inlet temperature – current estimate is 32.3 C
  - Include weld backer geometry for the reflector vessel welds