COMSOL CONFERENCE 2016 BOSTON

A COMSOL Multiphysics® Analysis of Beam Tube Cooling in the High Flux Isotope Reactor of Oak Ridge National Laboratory

presented by:

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1:00-2:30pm, Thursday
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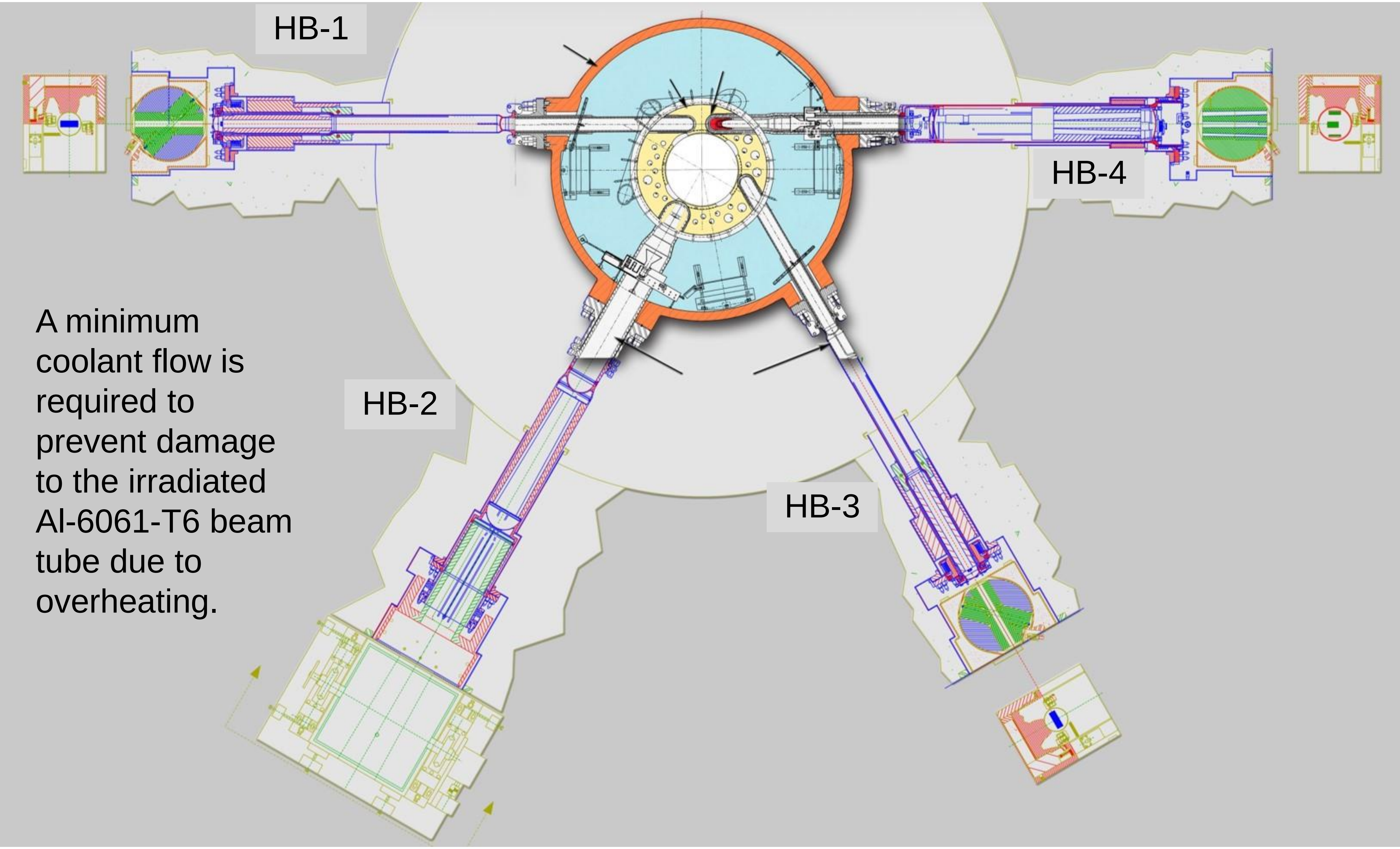
Oak Ridge National Laboratory | HIGH FLUX ISOTOPE REACTOR

The High Flux Isotope Reactor (HFIR) of ORNL is a Multi-Purpose User Facility

HFIR Beam Tubes Provide Pathway for Neutron Scattering Experiments



A minimum coolant flow is required to prevent damage to the irradiated Al-6061-T6 beam tube due to overheating.

Photo Images of HFIR HB-1 Mock-Up

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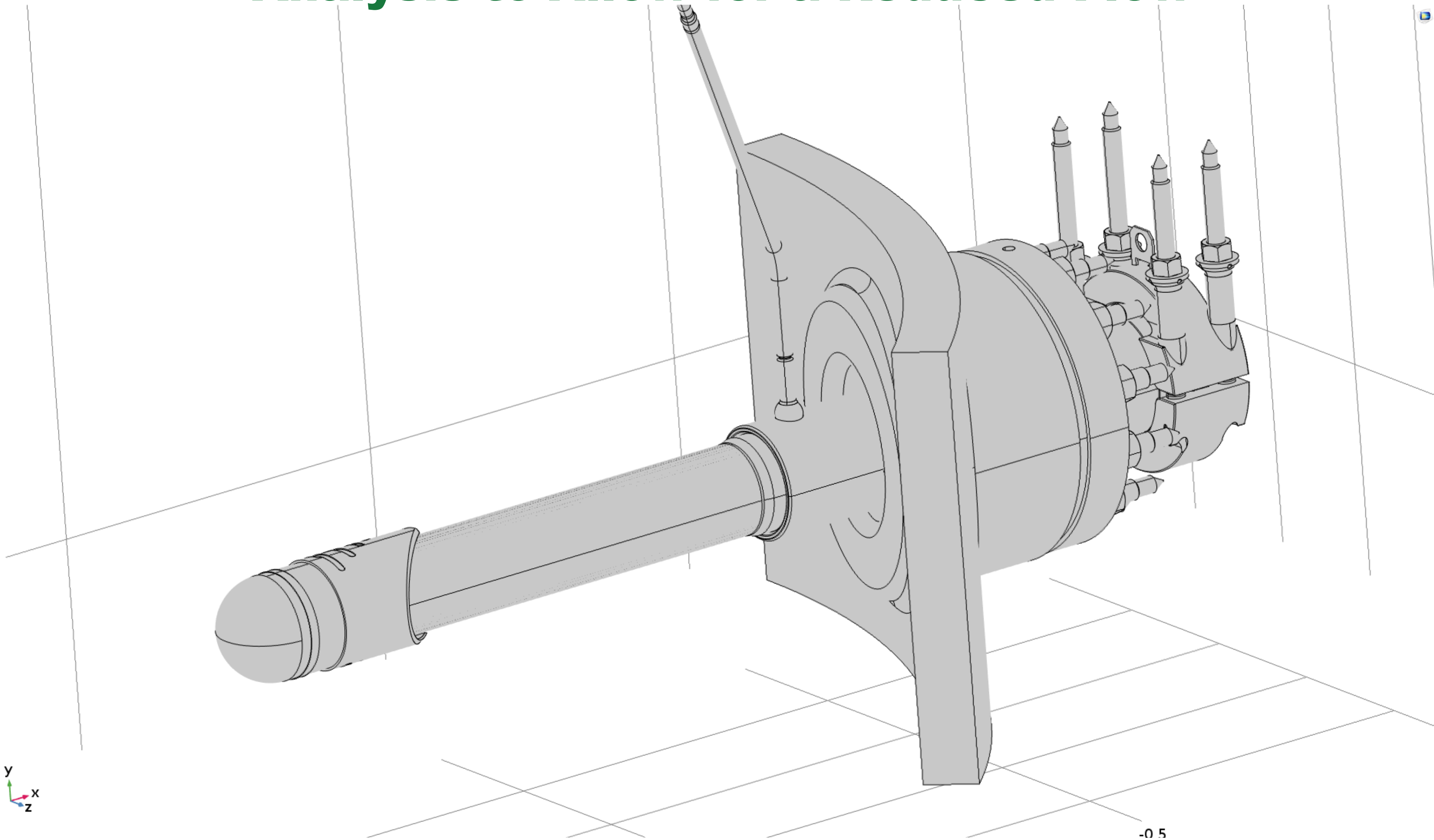
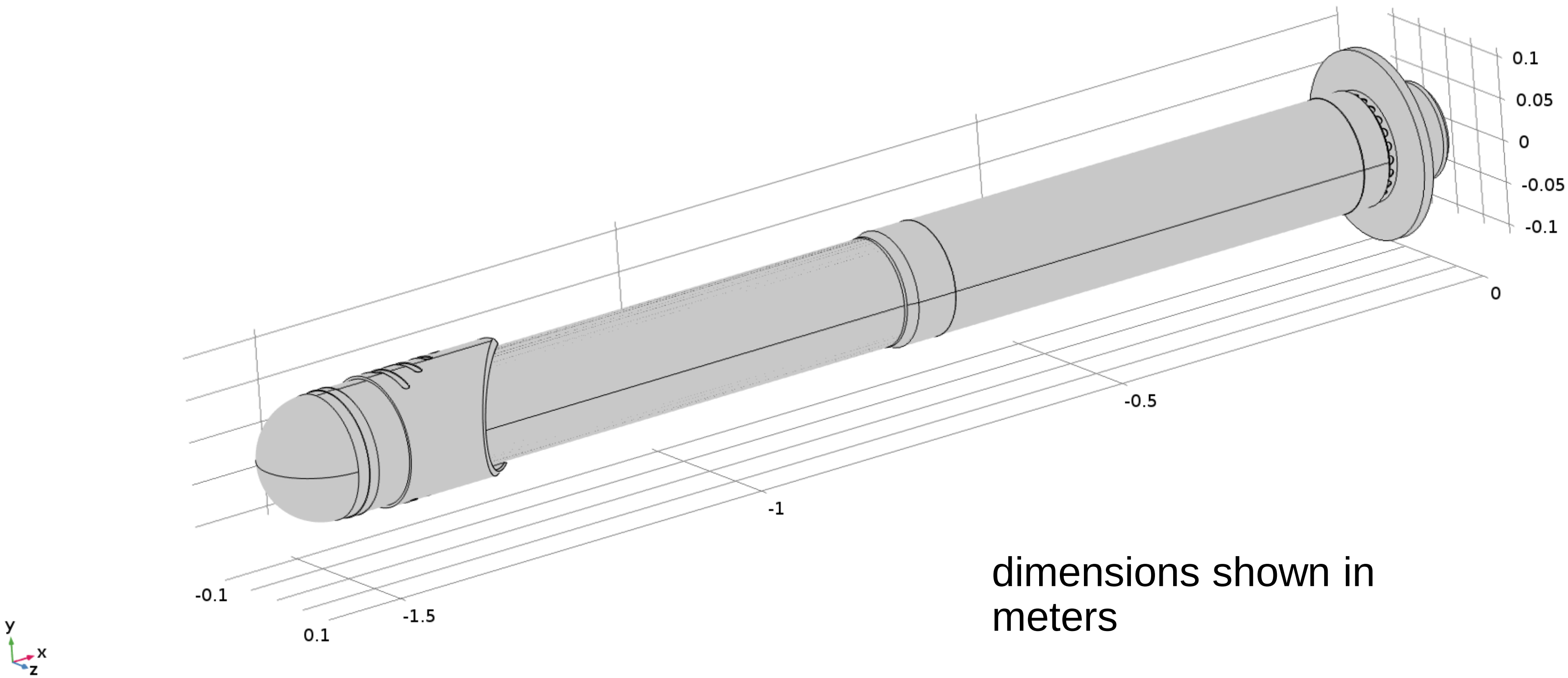
HB-1 is a Complex Design that Requires Detailed Analysis to Allow for a Reduced Flow



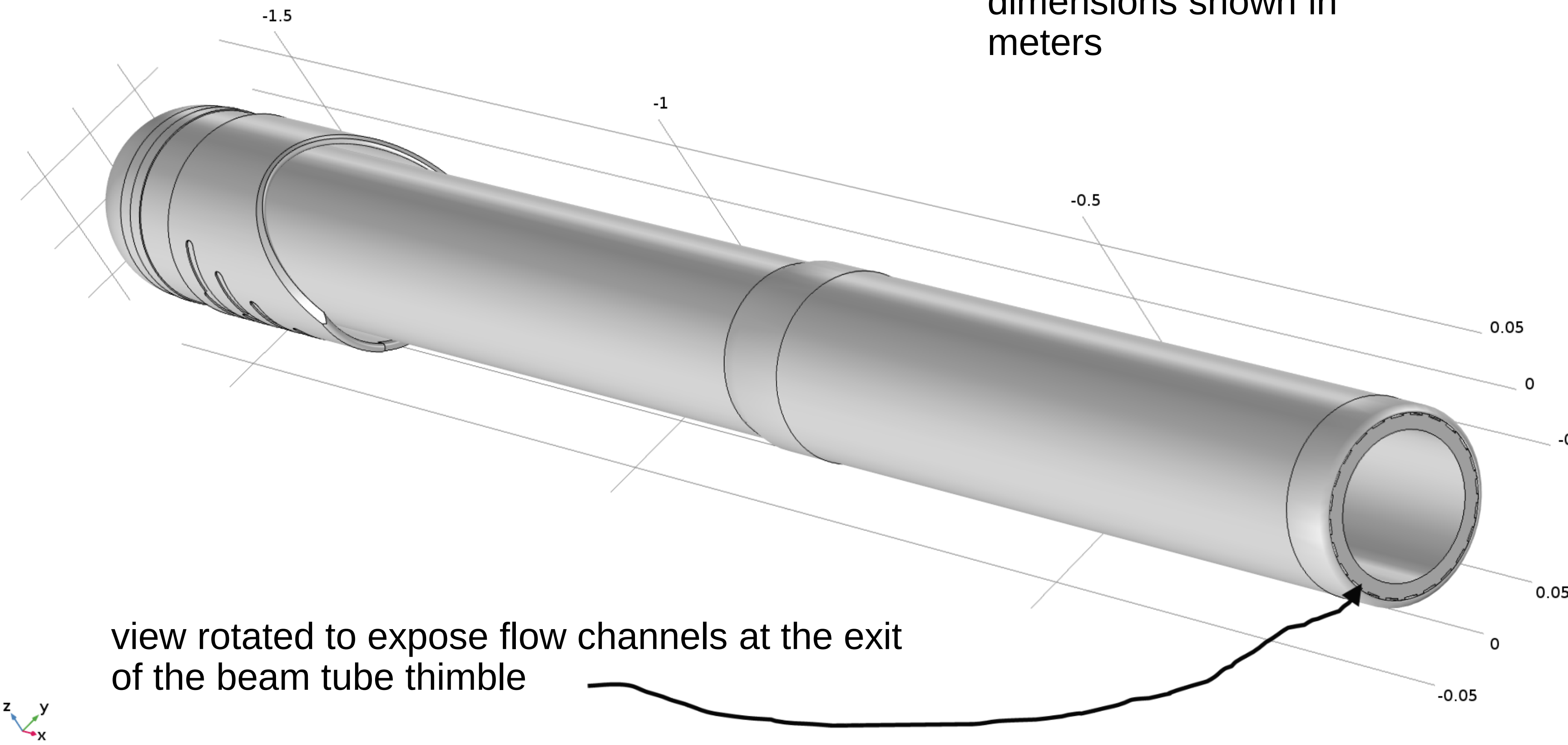
Remove Parts of HB-1 that are not Included in the Analysis



dimensions shown in meters

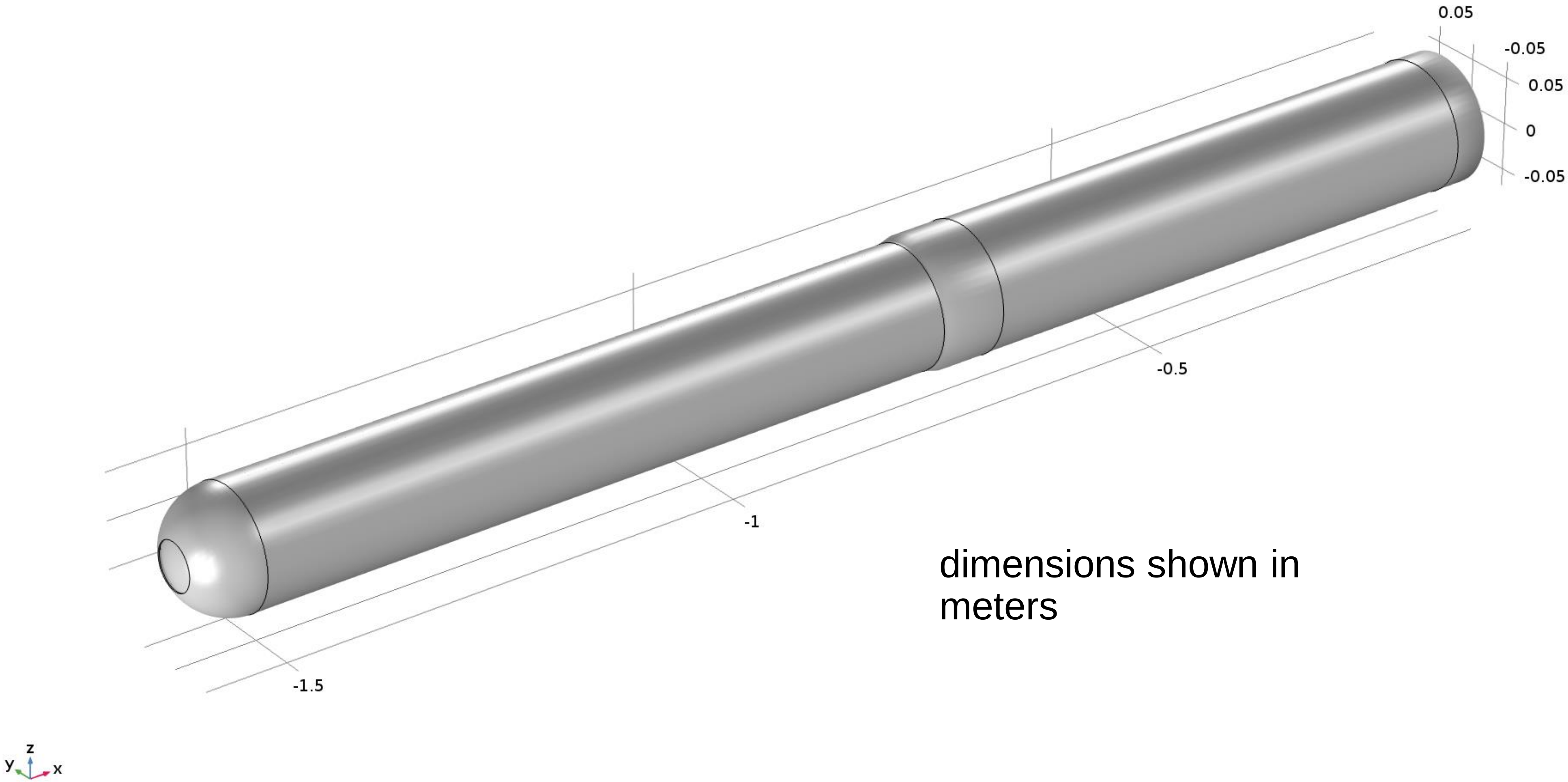
Cut off HB-1 Flange to Arrive at the "to be" Analyzed Geometry

dimensions shown in meters



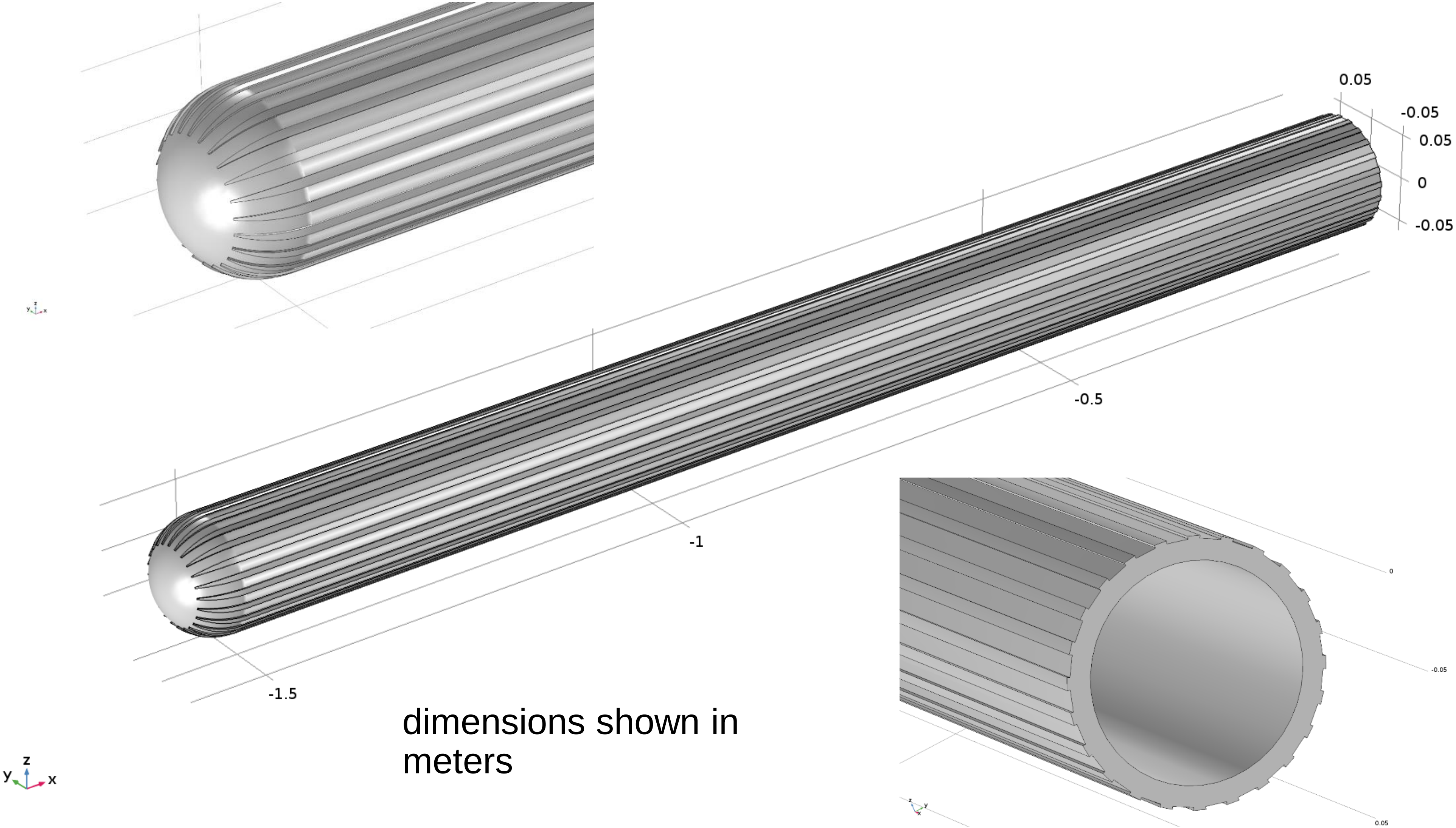
view rotated to expose flow channels at the exit of the beam tube thimble

Break Down HB-1 Geometry to be Analyzed: Remove Beryllium Liner



dimensions shown in meters

Break Down HB-1 Geometry to be Analyzed: Remove Sleeve



dimensions shown in meters

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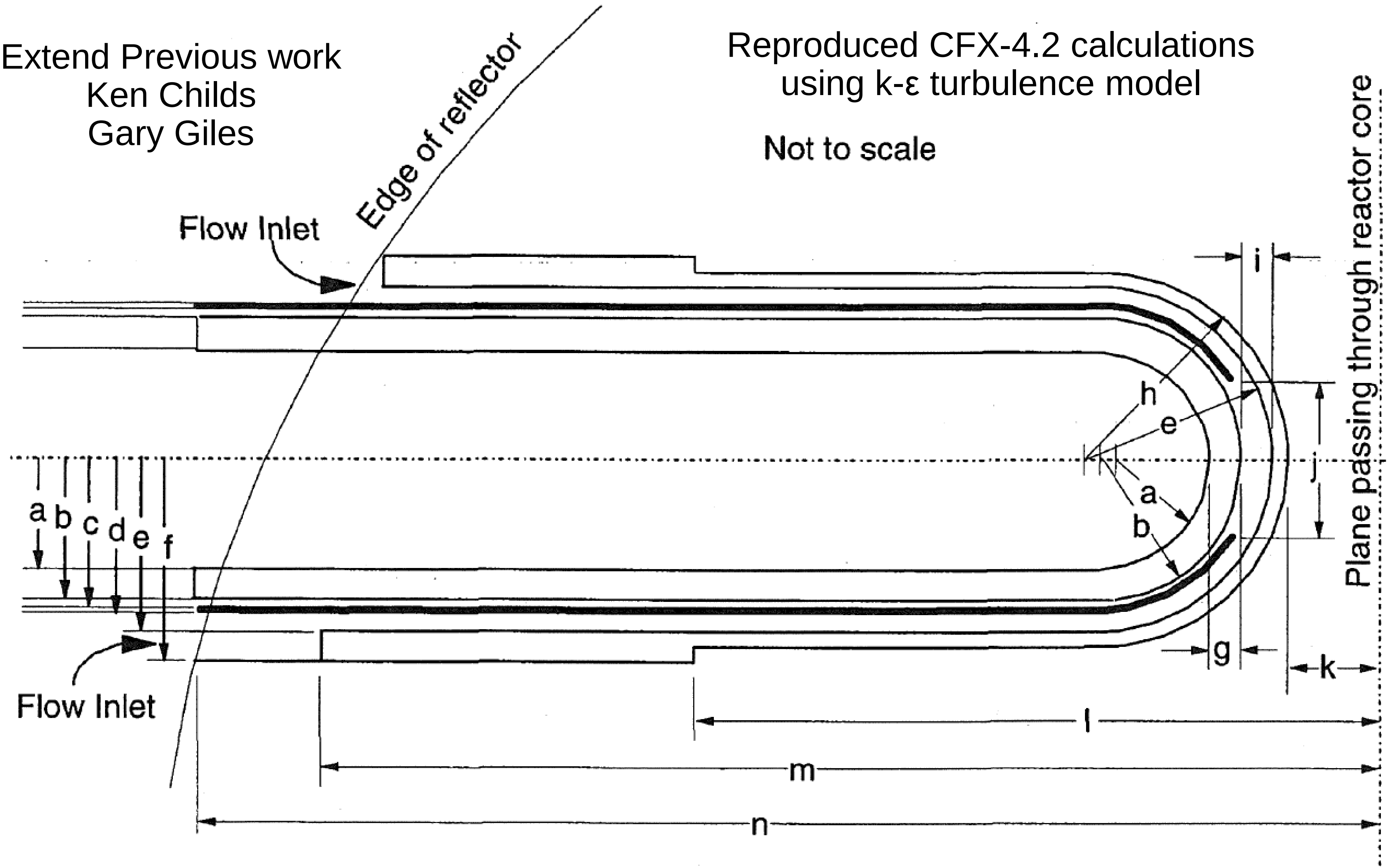
Take a Slice Down the Center to Create a 2D Axisymmetric Geometry for 1st Analysis

Extend Previous work
Ken Childs
Gary Giles

Reproduced CFX-4.2 calculations using k-ε turbulence model



Calculation Purpose and Requirements

1. Extend the range of this figure from 15-30 gpm to 3-35 gpm.

2. Assure that the maximum temperature of the pressure-boundary beam tube remains below a structurally-sound Al-6061-T6 threshold of 250 °F .

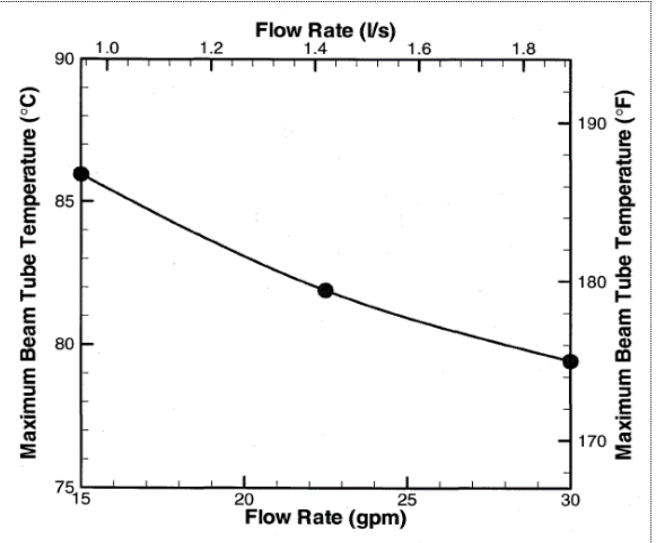
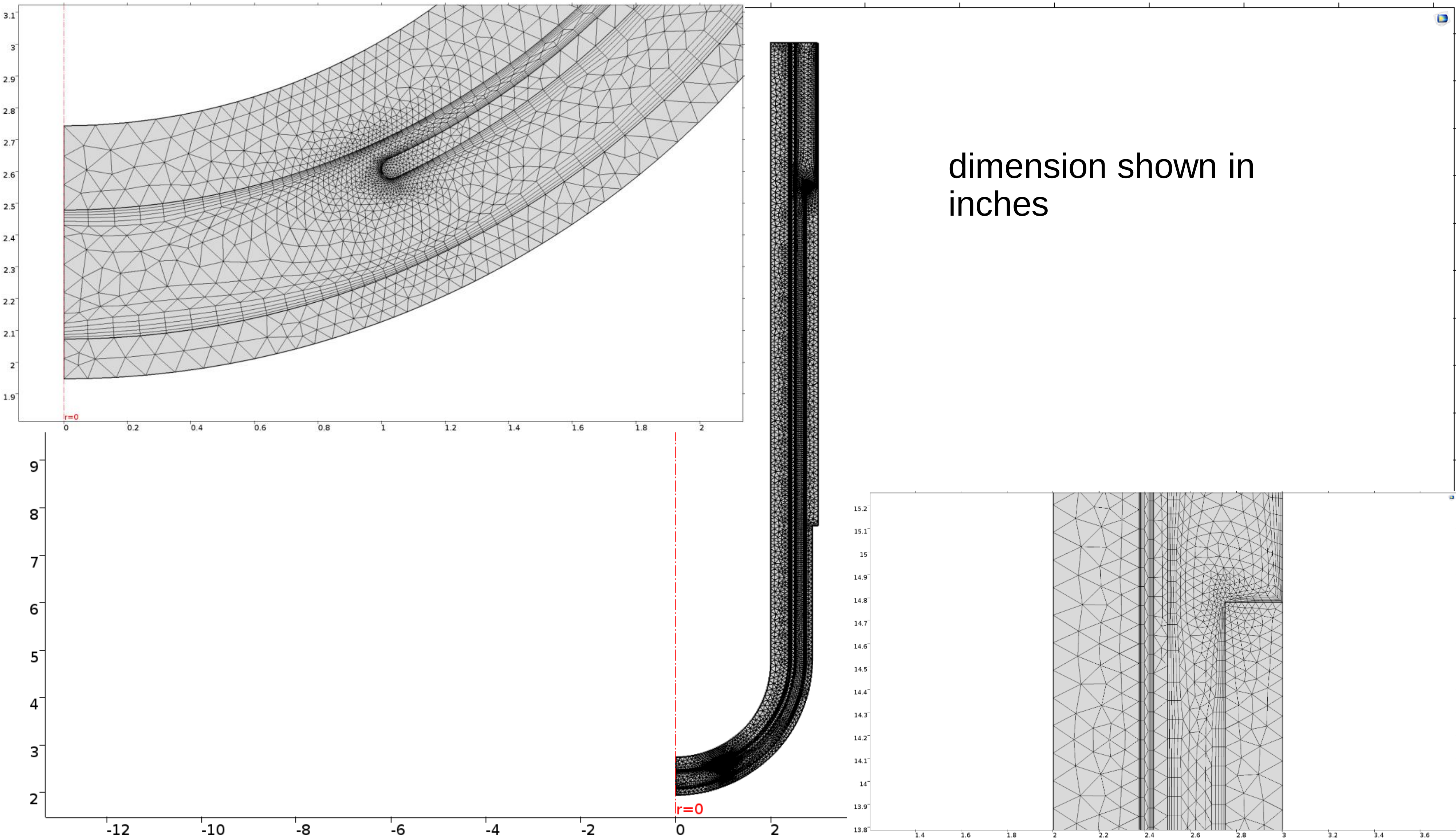


Figure 6. Maximum beam tube temperature versus flow rate.

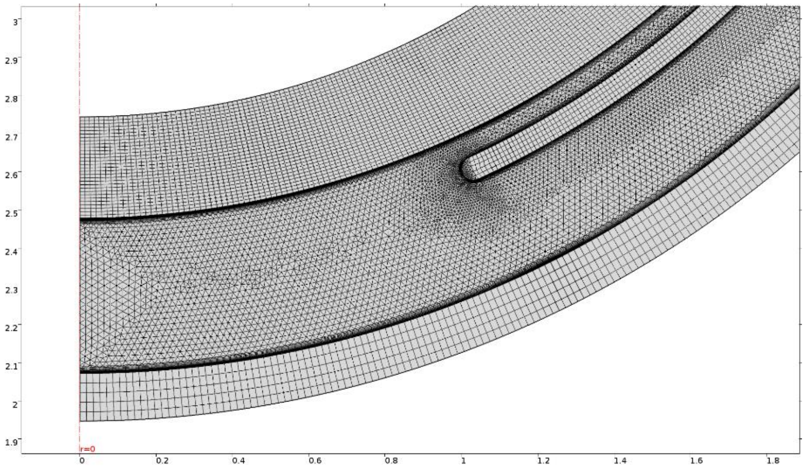
3. Improve on the calculation using new information and tools in geometry accuracy, material properties, thermal expansion, turbulence models, multi-physics replaced some assumptions.

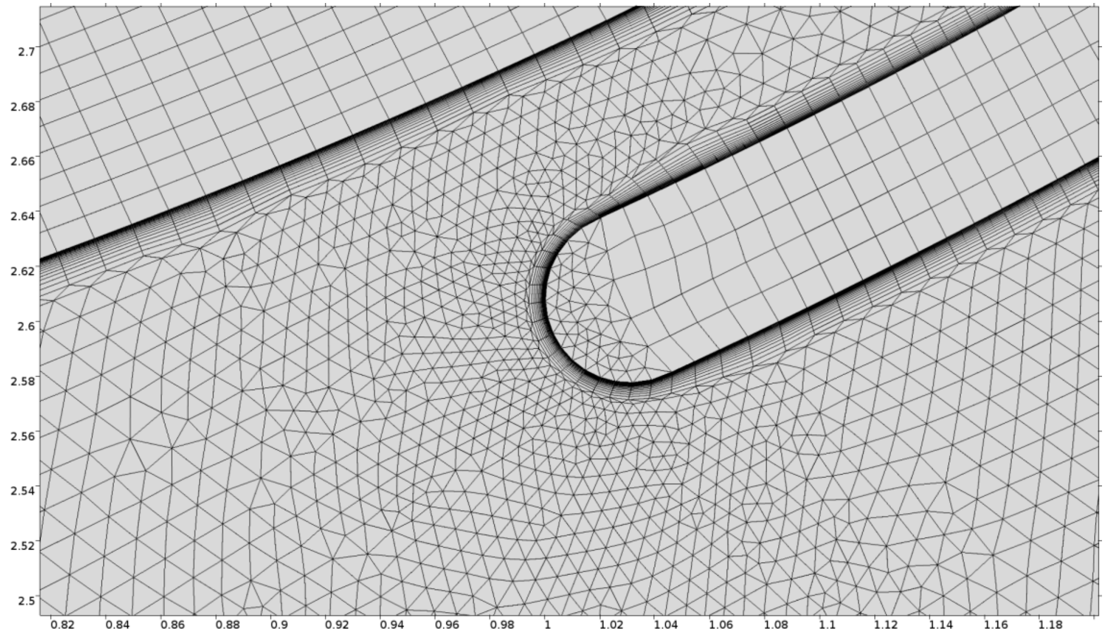
4. Comply with DOE, ORNL, and RRD requirements for nuclear-safety calculation rigor including software quality assurance (SQA), and formal calculation preparation.

“Normal” Mesh Auto-Generated. Examine Mesh Convergence to assure adequate Discretization

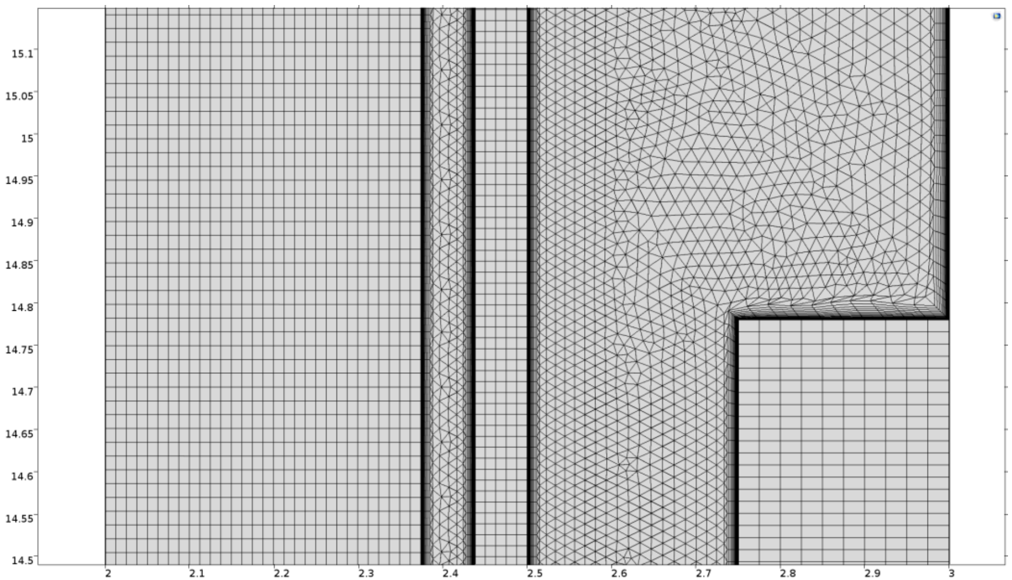


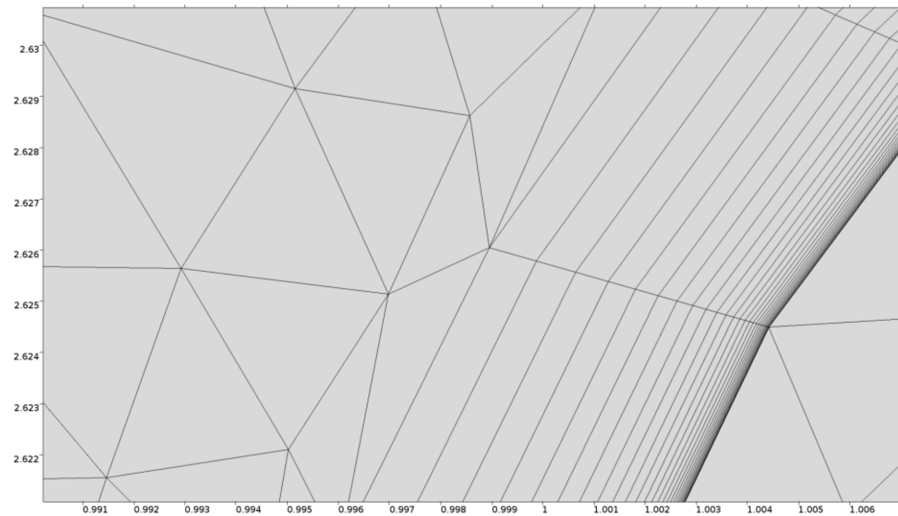
“Refined” Mesh User-Generated. Extremely Fine Boundary Layer Wall Mesh





dimension shown in inches





This Problem Requires Coupled Physics to Obtain Accurate Results

- Conjugate Heat Transfer – Navier Stokes + Energy Equation
  (u_r,u_z) – velocity, p – pressure, T – temperature
- Turbulence Model (k-ε), or (k,ω), or SST --- requires SST for best results
- Solid Mechanics ($u2_r$,$u2_z$) displacement
- Material Coordinates of Deformed Geometry (R, Z)
- Wall distance from SST turbulence model (G)
- Operational constraints define two free input parameters: (1) power level, and (2) beam tube inlet flow rate.
- Boundary Conditions: inlet flow, inlet temperature, exit pressure, exit heat flow, insulated boundaries, temperature boundaries, axisymmetric boundary, wall boundaries, fixed displacement constraints, prescribed mesh displacement from thermal expansion into fluid mesh, and zero mesh displacement at appropriate boundaries due to symmetry and fixed displacement fluid boundaries.
- Source term: all materials have a heat source applied obtained from external program (MCNP)
- Multiphysics coupling from (1) thermal expansion of the solid, and (2) temperature dependence of all material properties.

Due to the Complexity of the Physics, a Unique Solution Procedure has been Devised as a 4-step Process

1. Solve traditional Conjugate Heat Transfer: segregated by groups of variables (G) , (u_r,u_z,p) , (T) , (k,ω) . Coarse mesh solution supplied as initial condition.

2. Solve for structural mechanics and deformed mesh from thermal expansion: segregated by groups of variables ($u2_r$,$u2_z$) , (R,Z). Step 1 solution supplied as input to Step 2.

3. Repeat Step 1 with Step 2 solution supplied as input to Step 3. The fluid geometry is now altered from the deformation of the solid boundary by thermal expansion.

4. Solve for all variables coupled with Step 3 solution supplied as input to Step 4. Variables are segregated into group as before: (G) , (u_r,u_z,p) , (T) , (k,ω) , ($u2_r$,$u2_z$) , (R,Z) .

Additional Notes on the Solution Process

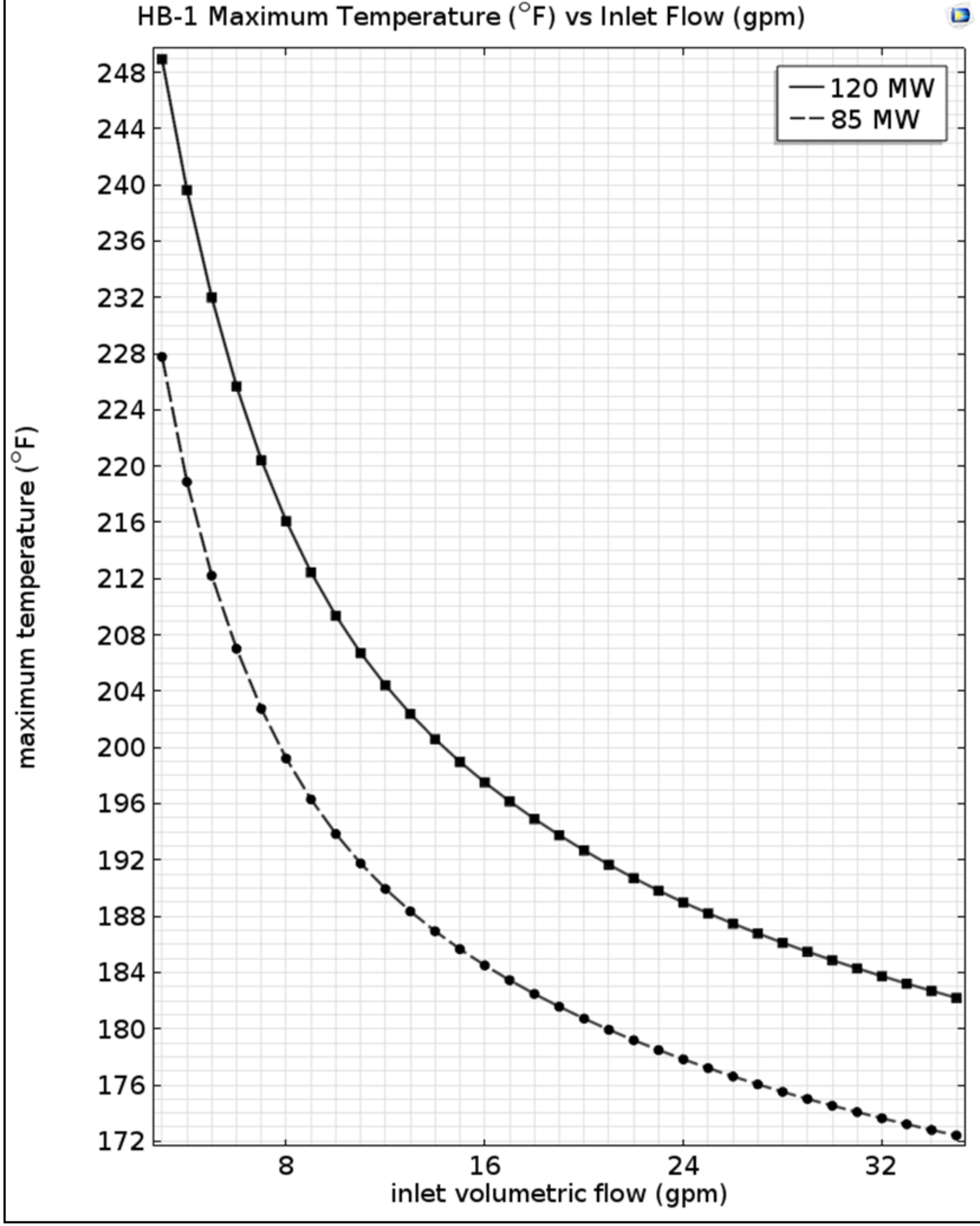
- Several mesh densities were examined for this 2D axi-symmetric model up to ≈ 6.2x10^6 dof. A user-generated mesh density of ≈ 2.5x10^6 dof was settled on as the appropriated mesh-converged level of refinement for the SST turbulence model.
- A parametric sweep over the entire solution sequence was implemented on the inlet flow rate over the range of 35 to 3 gpm in increments of -1 gpm.
- Two power levels were examined: 85 MW (normal operation) and 120 MW (extreme steady-state power considered for safety analysis).
- The following table was generated at a nominal flow rate = 22.5 gpm, by varying turbulence model type and mesh density

Mesh Case	Turbulence Model	Mesh Density (dof)	T_{max} of Beam Tube (°F)	Comments – 179.4 °F by comparison to previous calculation
1	k-ε	101066	184.090	physics-controlled mesh (normal)
2	k-ε	229699	184.741	physics-controlled mesh (fine)
3	k-ε	543234	184.897	physics-controlled mesh (finer)
4	k-ε	558466	184.923	physics-controlled mesh (extra fine)
5	k-ε	618617	184.837	physics-controlled mesh (extremely fine)
8	k-ε	1674947	183.943	user-controlled mesh, boundary layer set for y^+ ~ 11.06
9	k-ω	1674947	187.229	user-controlled mesh, boundary layer set for y^+ ~ 11.06
10	SST	2484914	190.256	user-controlled mesh, boundary layer set for l_c^* ~ 0.5

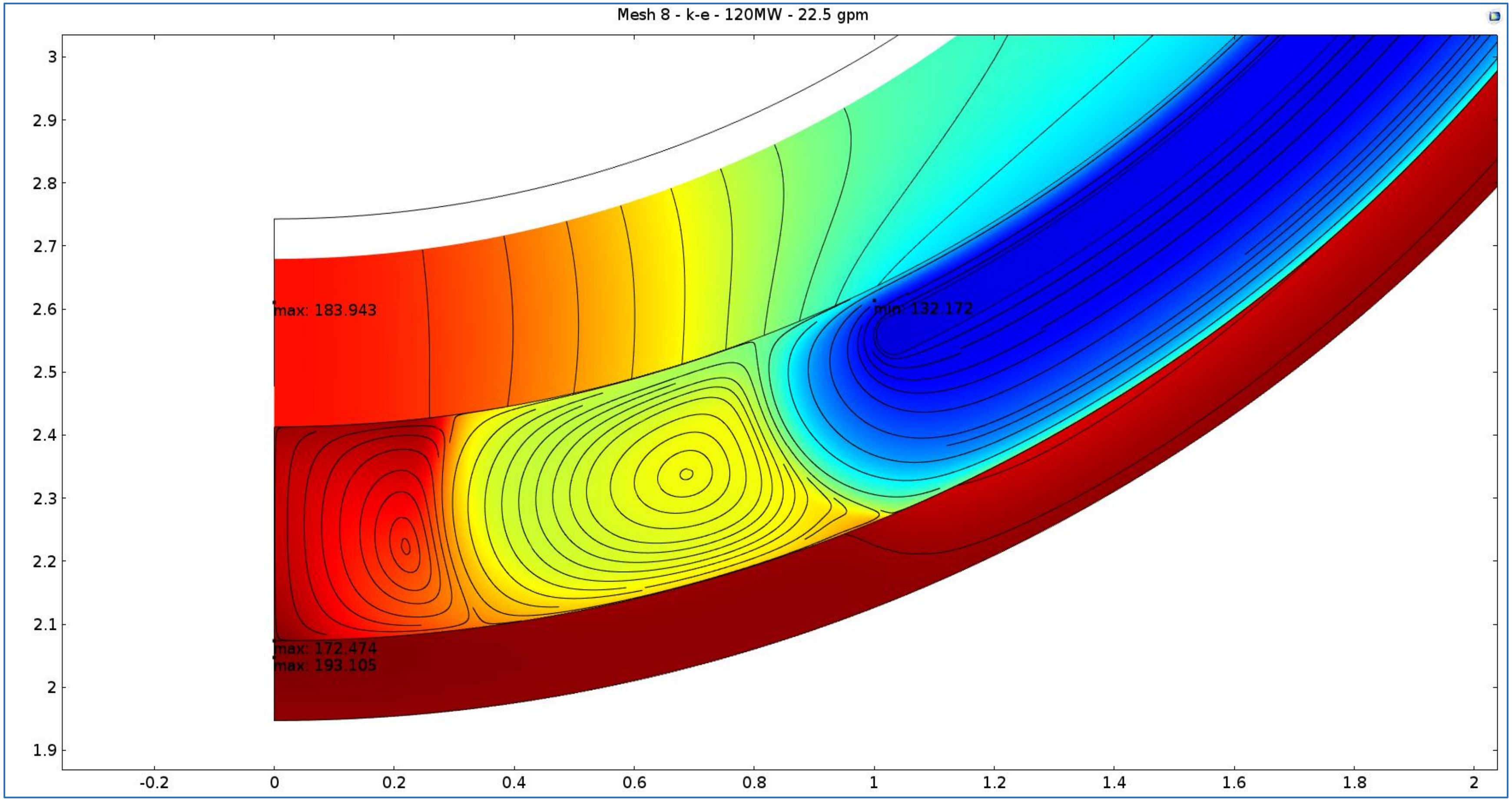
Final Results

Maximum Beam Tube Temperature (°F) as a Function of HB-1 Inlet Flow (gpm) for Conservative Power Level (120 MW solid line and square symbols) and Best-Estimate Power Level (85 MW dashed line and circle symbols). Note that the region less than 11 gpm is for information purposes only and is *NOT* recommended for normal operation.

Why 11 gpm limit ?

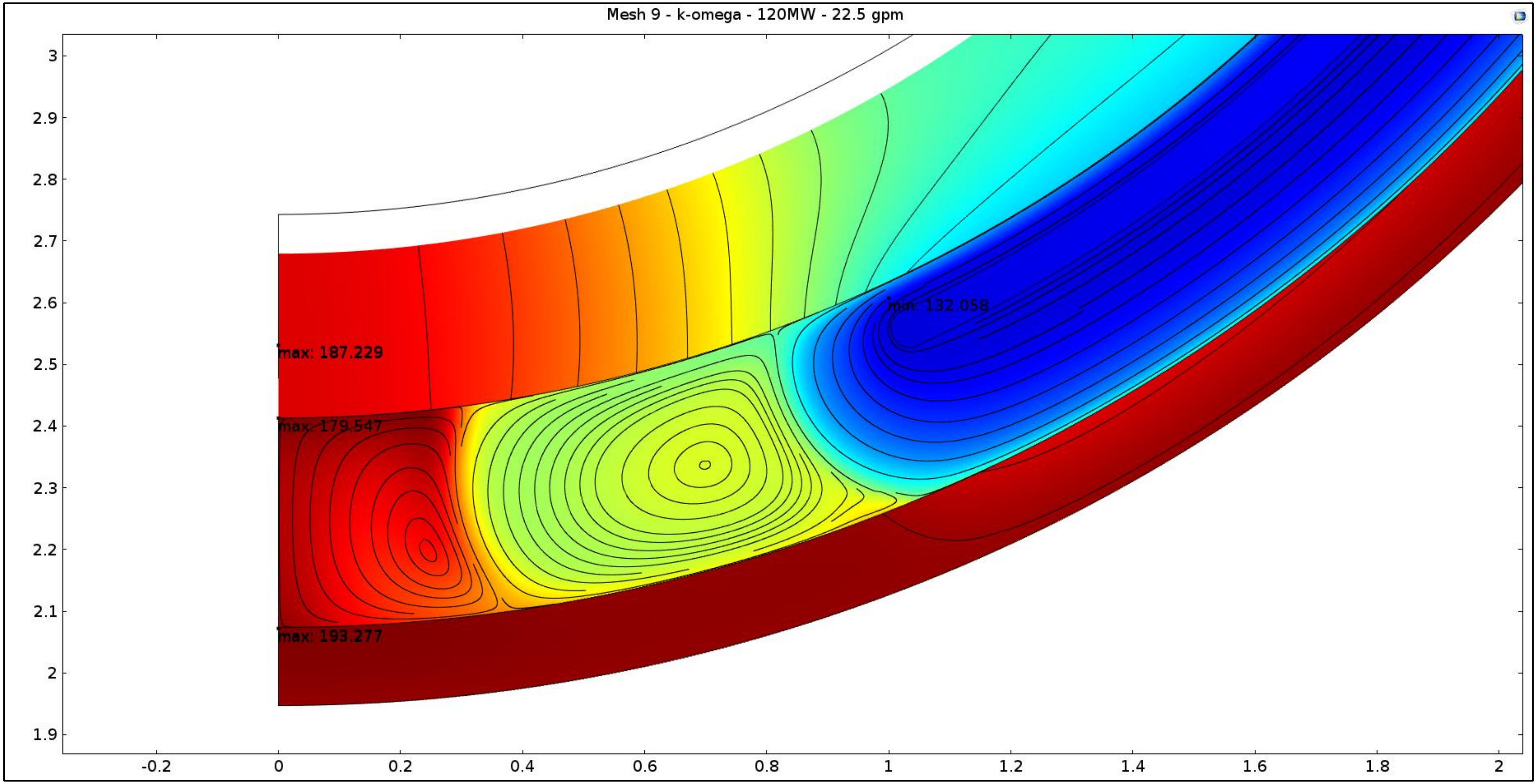


Nominal Flow (22.5 gpm) Results: k-ε



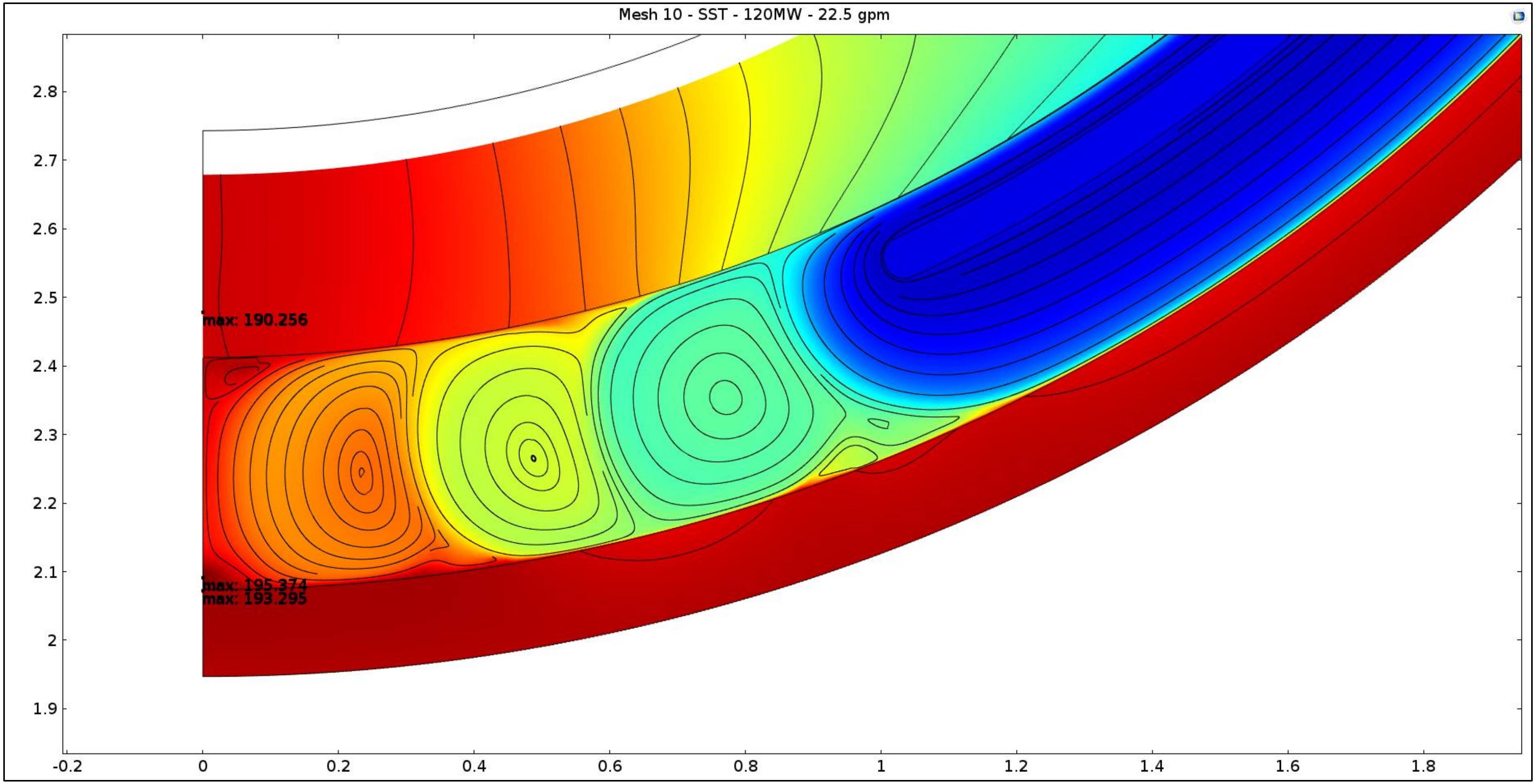
Solution View at Beam Tube Nose Detailing Temperature Contours and Velocity Streamlines for the Nominal Flow and Power Levels Using k-ε Turbulence Model.

Nominal Flow (22.5 gpm) Results: k-ω



Solution View at Beam Tube Nose Detailing Temperature Contours and Velocity Streamlines for the Nominal Flow and Power Levels Using k-ω Turbulence Model.

Nominal Flow (22.5 gpm) Results: SST



Solution View at Beam Tube Nose Detailing Temperature Contours and Velocity Streamlines for the Nominal Flow and Power Levels Using SST Turbulence Model.

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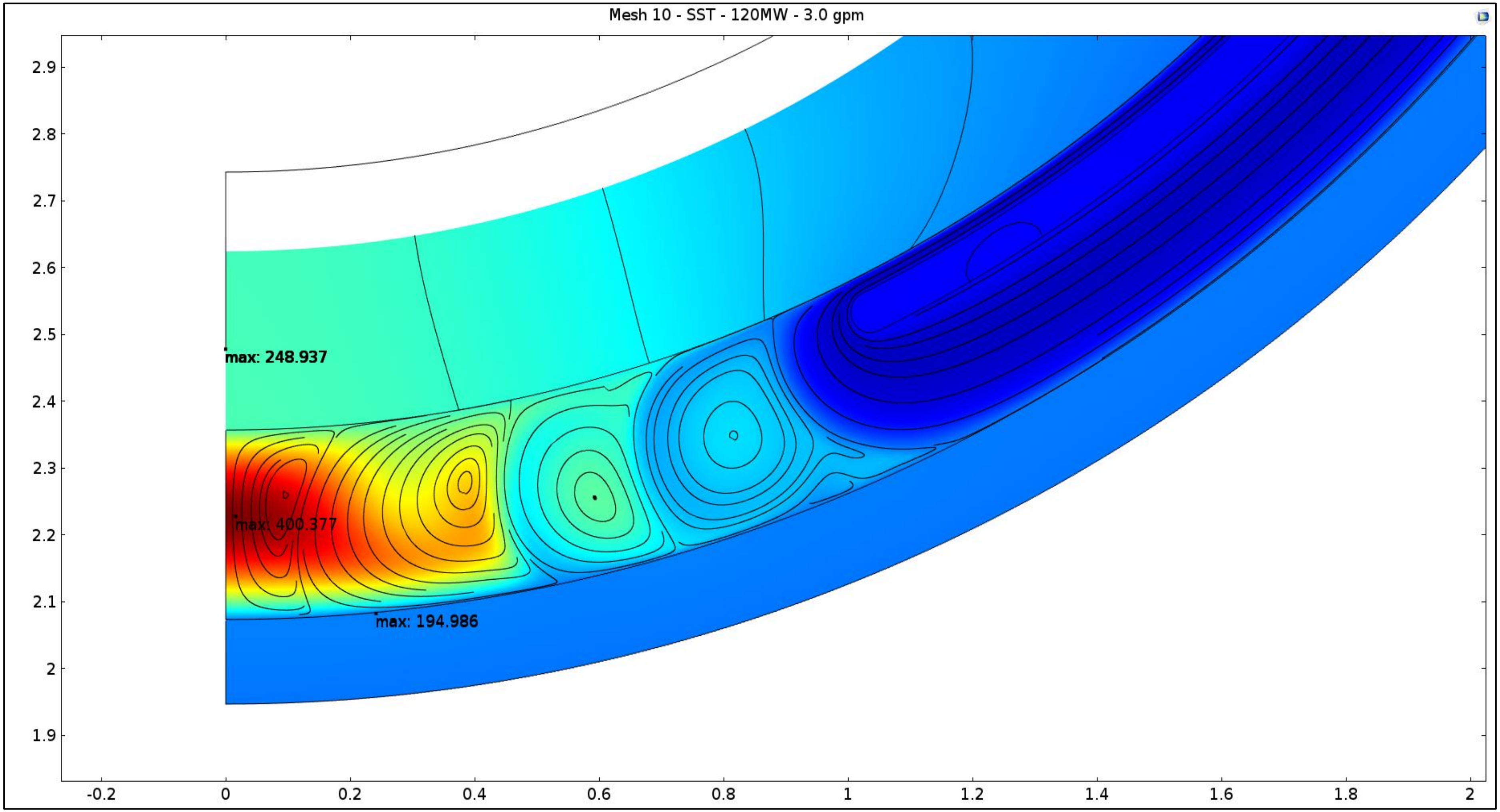
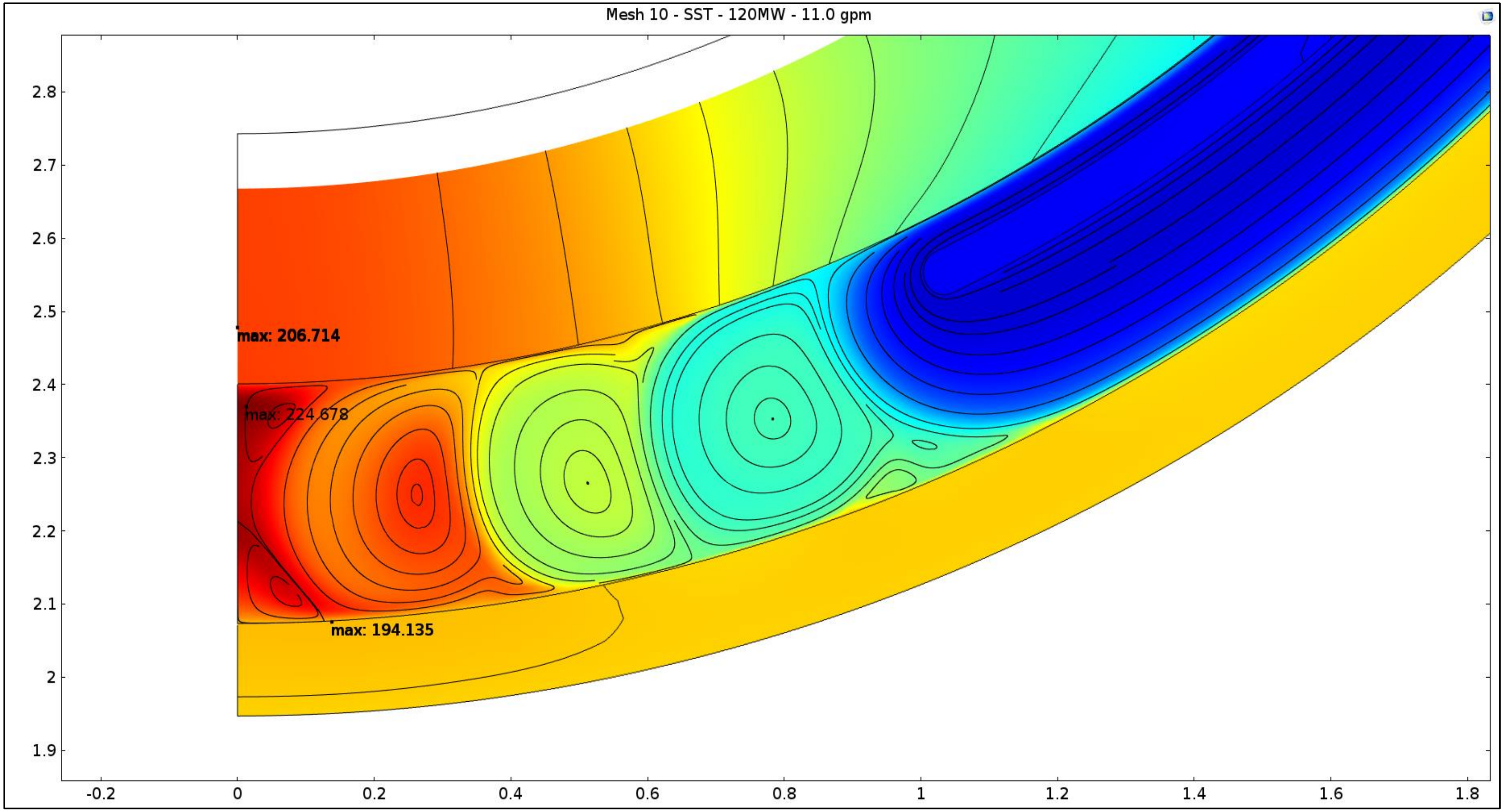
Reduced Flow (3.0 gpm) Results: SST



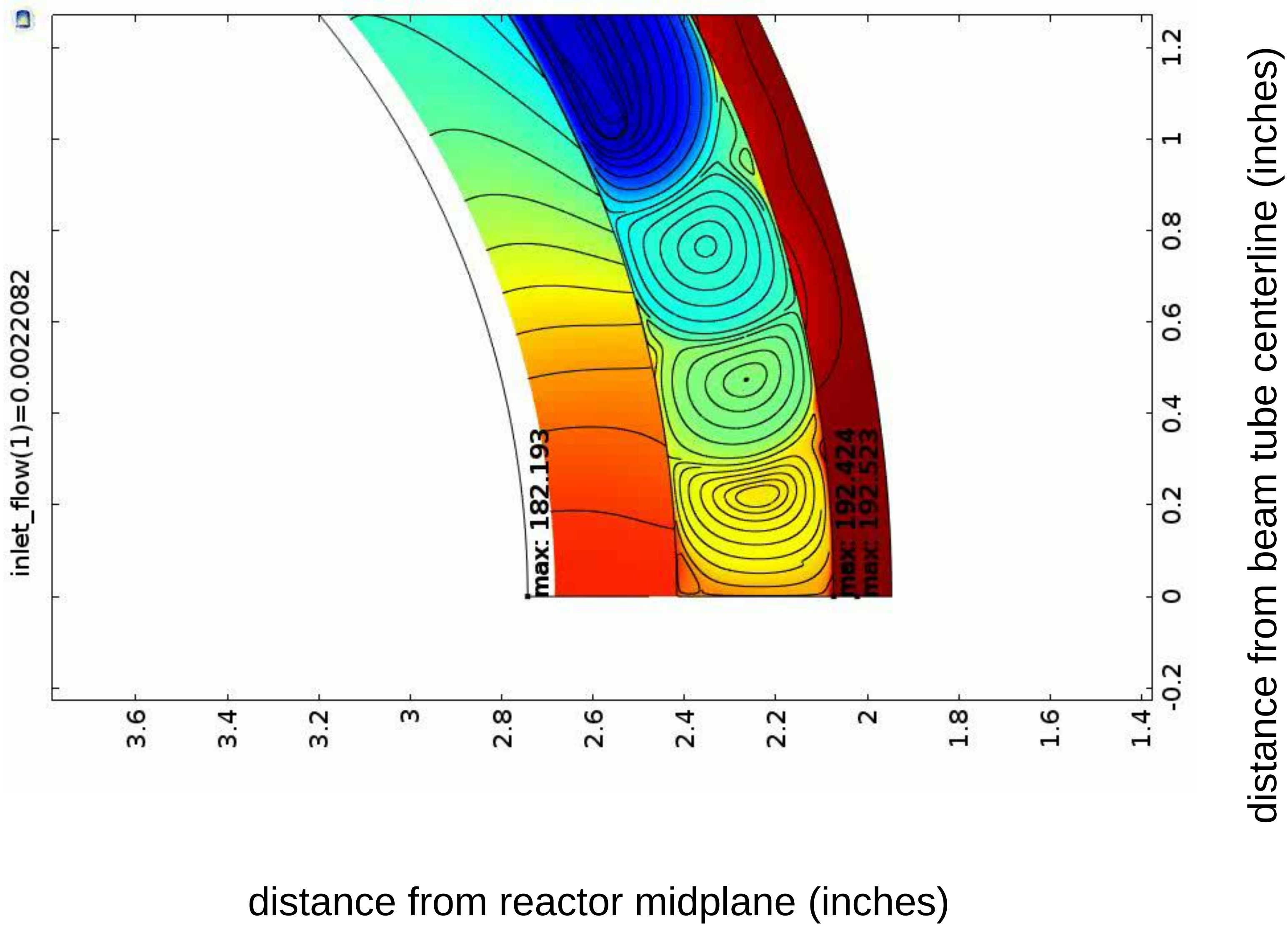
Solution View at Beam Tube Nose Detailing Temperature Contours and Velocity Streamlines for the 3.0 gpm Flow Rate and 120 MW Power Using SST Turbulence Model.

Reduced Flow (11 gpm) Results: SST



Solution View at Beam Tube Nose Detailing Temperature Contours and Velocity Streamlines for the 11.0 gpm Flow Rate and 120 MW Power Using SST Turbulence Model.

Sweep Flow (35-3gpm) Results: SST



Solution Video at Beam Tube Nose Detailing Temperature Contours and Velocity Streamlines for a Range of Flow Rates from 35-3 gpm and 120 MW Power Using SST Turbulence Model.

Conclusions and Recommendations

- Repeated the previous work with k-ε model and obtained similar results.
- Expanded the calculation to include a wider range of flow rates.
- New calculation includes corrected geometry, variable properties, mesh-convergence, thermal expansion, turbulence model investigation, and fluid-structure interaction due to thermal expansion.
- Successfully reduced the low flow rate from 15 to 11 gpm.
- Recommendations for additional analysis include: (1) more accurate heat generation data, (2) expand to 3D analysis, (3) obtain field measurements of flow, temperature, and pressure to the extent possible to validate the model.

Acknowledgements/Copyright

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