CFD Simulations and HHF Testing of Lithium-cooled Refractory Heatsinks

PFC Meeting, Spring 2005

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Plasma Processes, Inc.

Princeton, NJ
May 10, 2005

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Lithium-cooled refractories – P.S. fabrication
- LM Heat transfer in closed tubes and one-sided heating – understanding conductive fluids
- CFD modeling of smooth tubes and finned devices
- HHF testing setup using LIMITS and EBTS
- Conclusions

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Objectives of modeling and experiment

- Support PPI's phase-II SBIR project
- Compare smooth tubes to tubes with fin enhancements (turbulence & extended surface area)
- Effect of film boundary on convective heat transfer
- Evaluate flow parameters: ΔP, v_{in}, T_{in}, mixing
- Lithium reactions with plasma sprayed refractory walls
- Thermal cycling effects on actively cooled refractories

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SBIR/STTR partners make significant contributions to PFC research.

Plasma Processes, Inc.

- Constructed of plasma sprayed Molybdenum, Tungsten, and W-Ni-Fe Alloy
  - Refractory metals plasma sprayed over graphite mandrel
  - Graphite is then chemically etched away
- Advantages
  - Simplified machining for internal fins
- Disadvantages
  - Porous walls
  - Higher impurity content
  - Fin aspect ratio limitations

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Lithium coolant has some advantages.

advantages

- **Low pressure**
- **High temperature**
- **High conductivity**
- **Lithium is required for tritium breeding**

disadvantages

- **Pure lithium is molten between 454K and 1620K**
- **Lithium reacts with air, H20, Cu, etc…**

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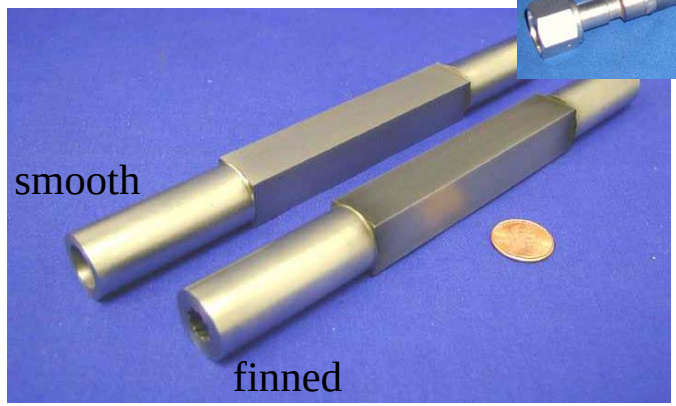
Only refractory heatsinks can operate at very high temperatures and are compatible with liquid lithium coolant.

- Mo, W and W-Ni-Fe plasma sprayed heatsinks (Plasma Processes, Inc. – phase-II SBIR)
- Smooth tubes and helical fins (pitch: 1 rev/7.4 cm)
- Applications: FW/blanket



Description of Spray Formed Refractory Metal Heat Sinks

ID Number	Material	Bore Configuration	Bore Major ID	Bore Minor ID	Number of Fins
V2000-20	W-Ni-Fe	Smooth	~12.7mm	N/A	N/A
V2000-23B	W-Ni-Fe	Finned	9mm	7mm	8
V2000-3C	Molybdenum	Smooth	~12.7mm	N/A	N/A
V2000-24	Molybdenum	Finned	9mm	7mm	8
V2002-12D	Tungsten	Finned	9mm	6.7mm	8

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Computational Fluid Dynamics
Finite Volume Modeling Process

- Plan geometry with x,y,z symmetry
- Construct regions (manual CAD-type labor)
- Mesh regions into finite volumes (optimize)
- Add boundary conditions (walls, inlets, etc)
- Specify initial conditions & solution parameters
- Execute STORM solver (seek steady state)
  - Conservation of mass, momentum, energy
- Graphically interpret results with FIELDVIEW

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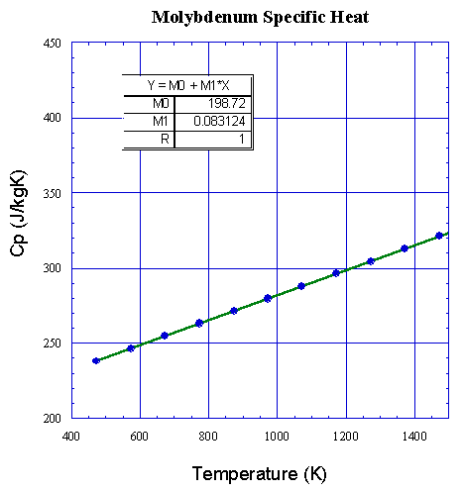
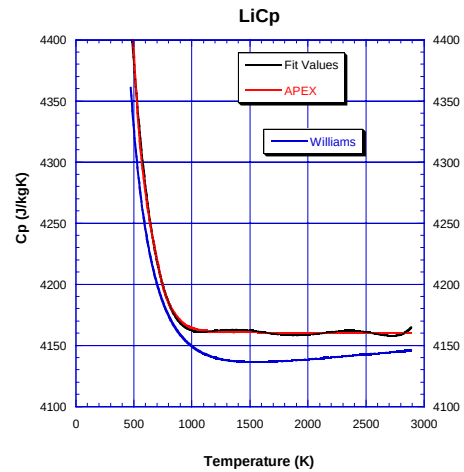
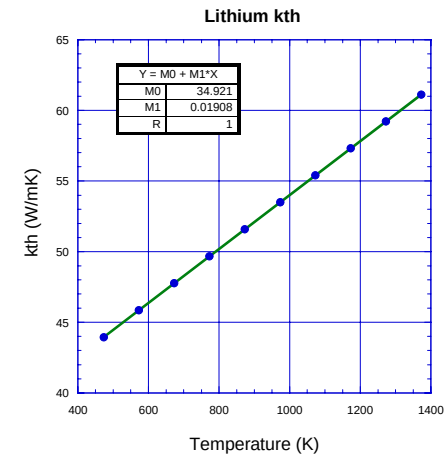
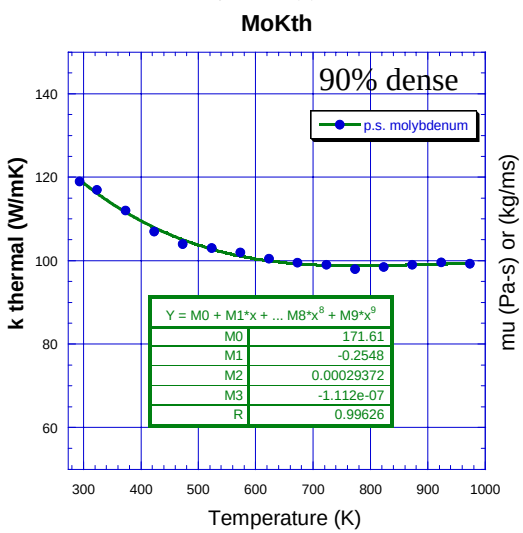
Analysis uses temperature dependent properties for heatsink and coolant (user coding)

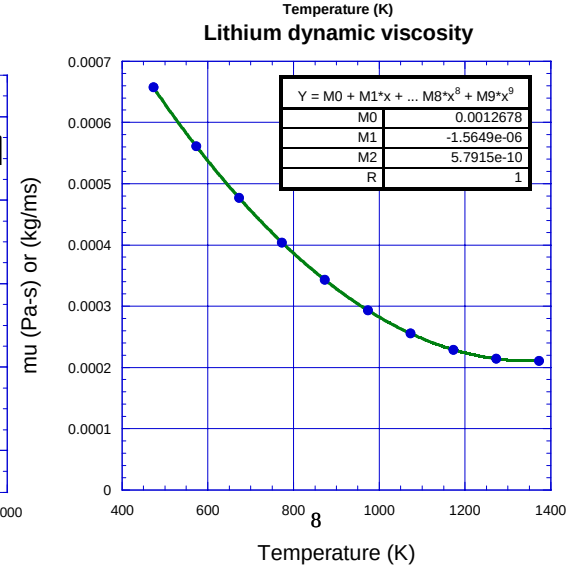
$$d\rho H/dt + d(\rho u_i H)/dx_i = d/dx_i[k/C_p dH/dx_i] + dp/dt + u_i dp/dx_i + \Phi + Q + S_{...}$$

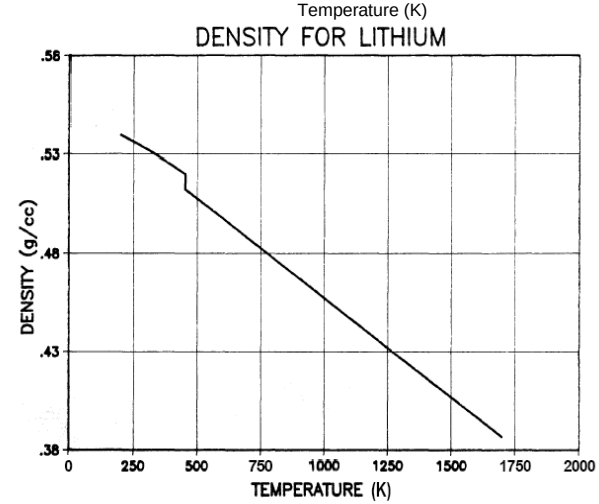




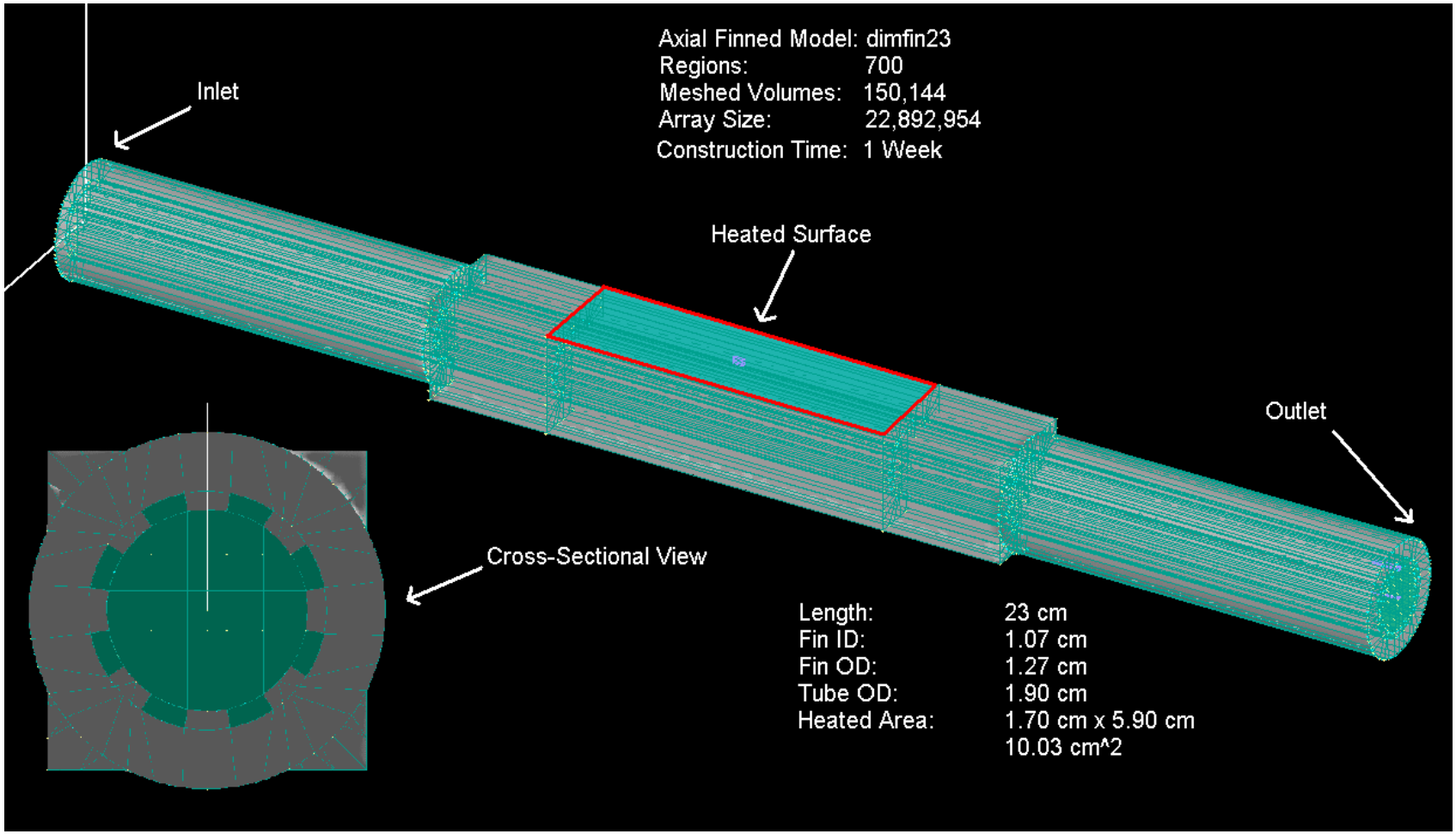








Axial Finned Model



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Conduction affects fin performance in this geometry.

- **Thermal conductivity of lithium and molybdenum is not significantly different.**
  - **Molybdenum: 106 [w/(m*K)]**
  - **Lithium: 43**

- **Boundary layer disruption does not significantly affect overall heat transfer for lithium cooling.**
- **Further modeling will be needed to determine if the conductive effects of thick walls help transfer heat to the bottom of the lithium column.**

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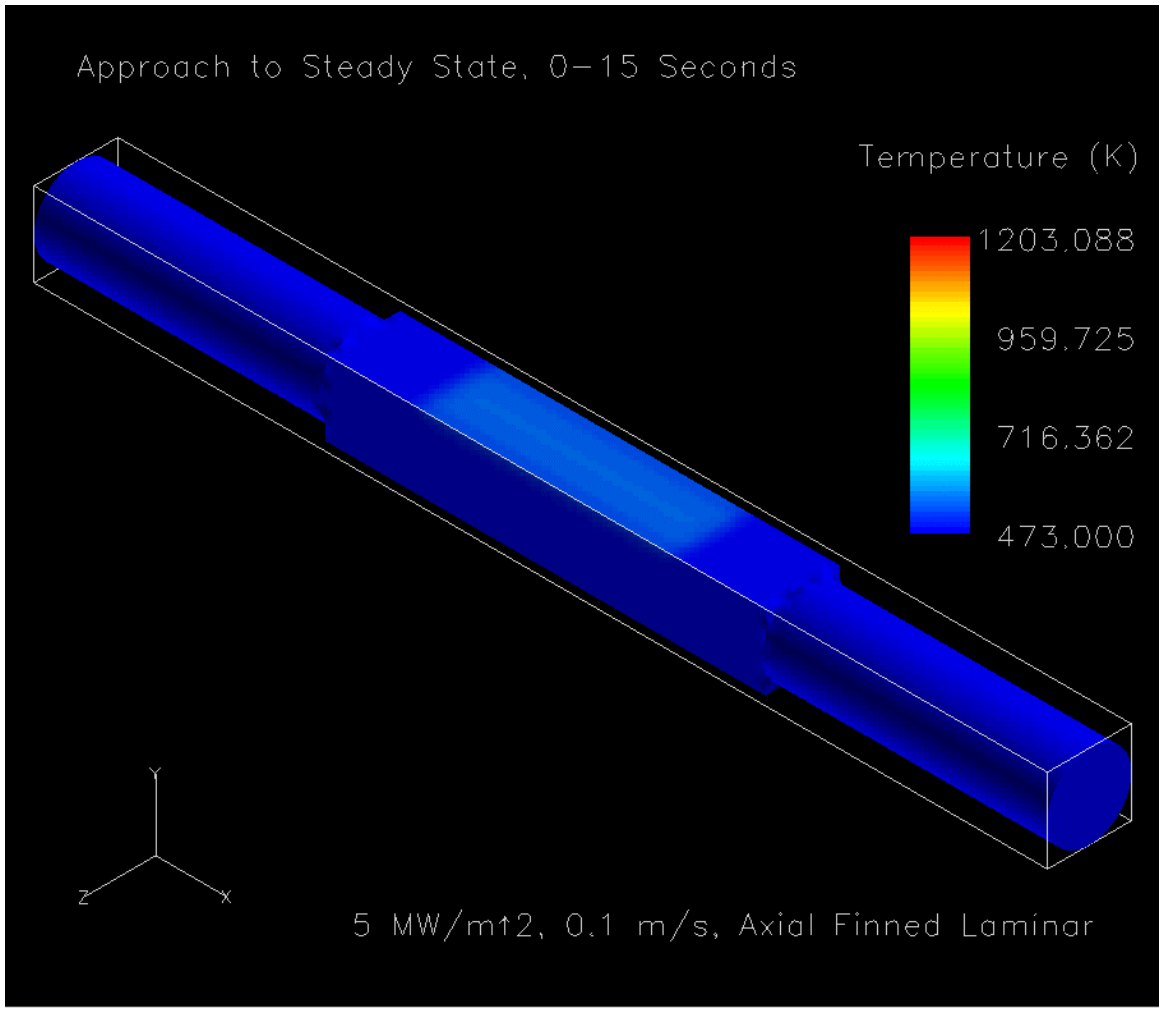
Approach to Steady State Conduction
3D View, 5 MW/m2, 0.1 m/s, Axial Finned Laminar



Temperature

1203 K

473 K

<--- Lithium Outlet

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Effect of Film not as important for LM as water.

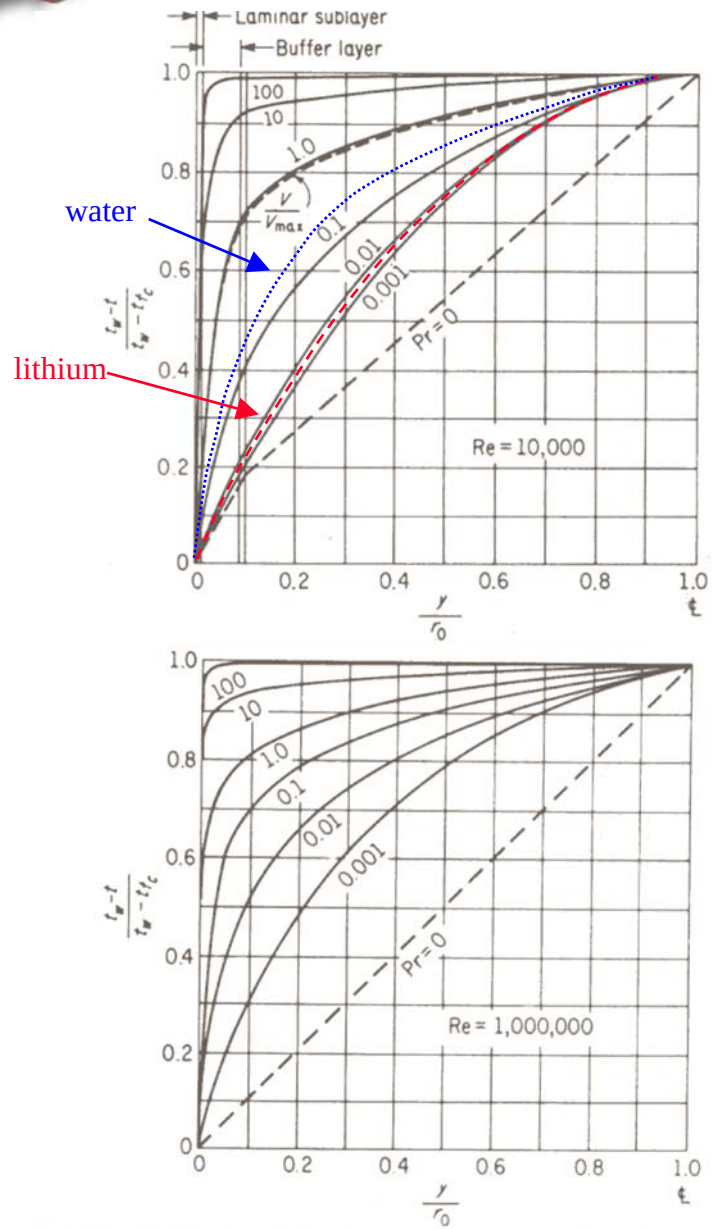

FIG. 9-3. Martinelli's solutions for the temperature gradients in pipe flow.

- **Our helical fin R_e ranges from 821 to 82150 (0.1 to 10 m/s)**
- **Pr = .0047 @ 200 C**
- **Convection contribution is same order of magnitude as conduction: Bi~Nu<10, Pr<.01**
- **For water, convection is more than 2 orders higher, Bi>10, Nu~1000s, Pr~.34 (x100)**

$R_e = D_e V \rho / \mu$

$Pr = C_p \mu / k$

$Bi = h L_c / k_s$

$Nu = h L_c / k_f$

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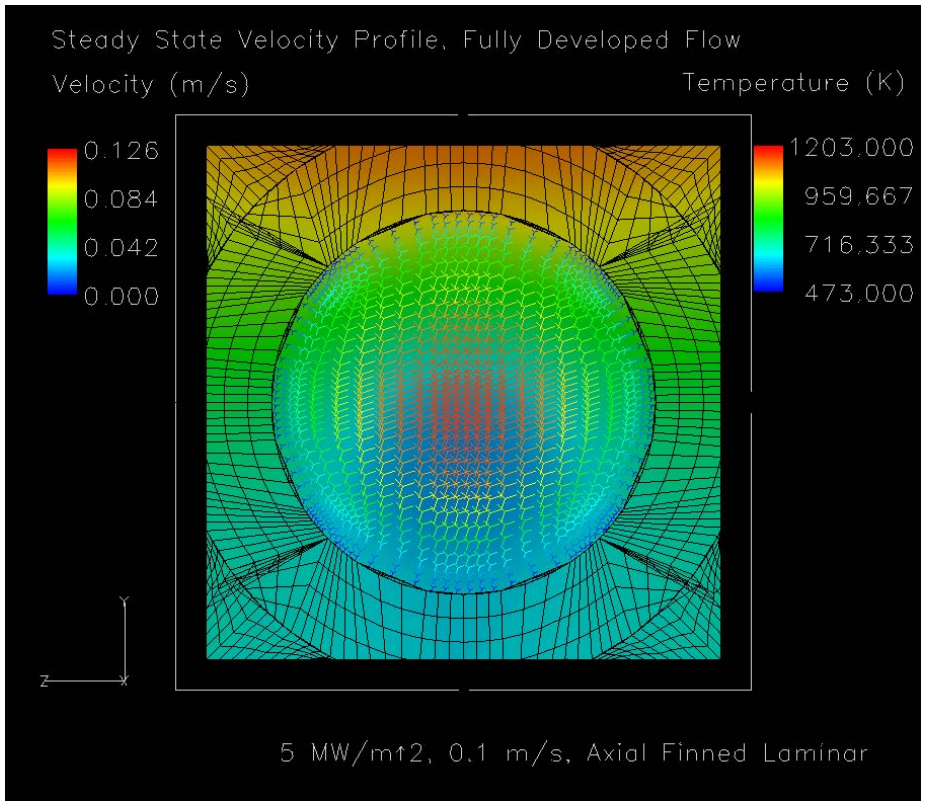
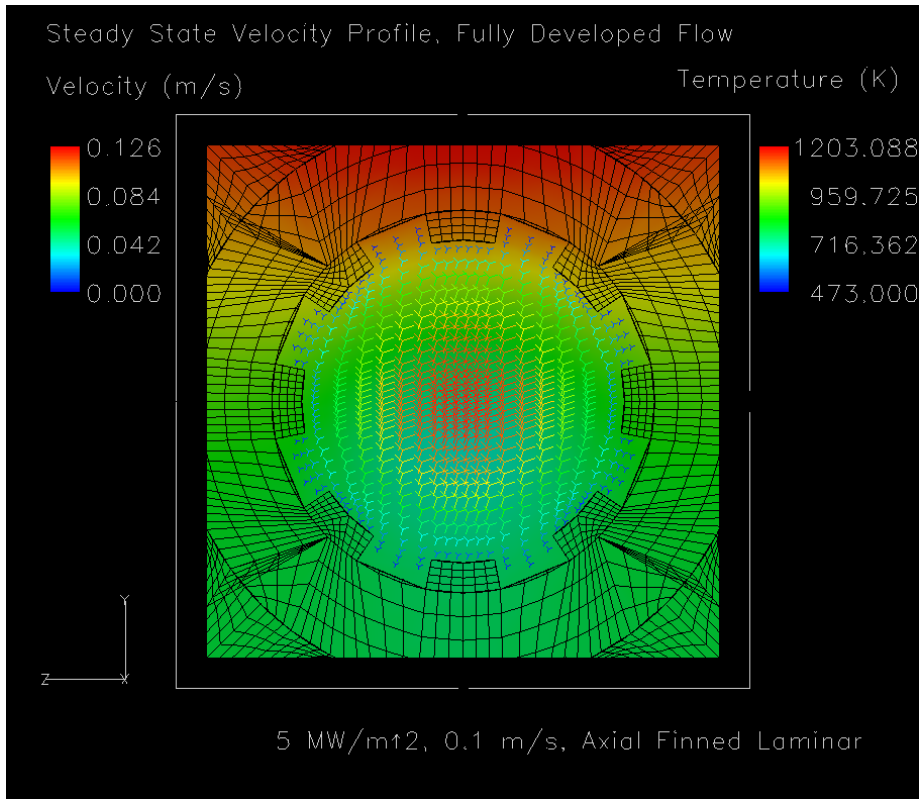
Axial fins of this geometry decrease heat transfer!





- **With constant inlet velocity, less lithium flows through finned model due to the volume of the fins.**

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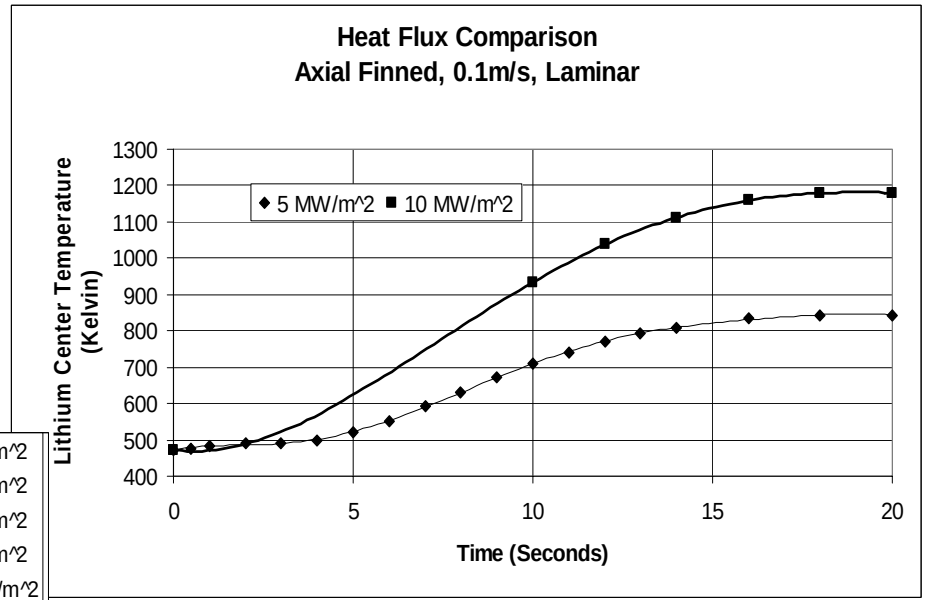
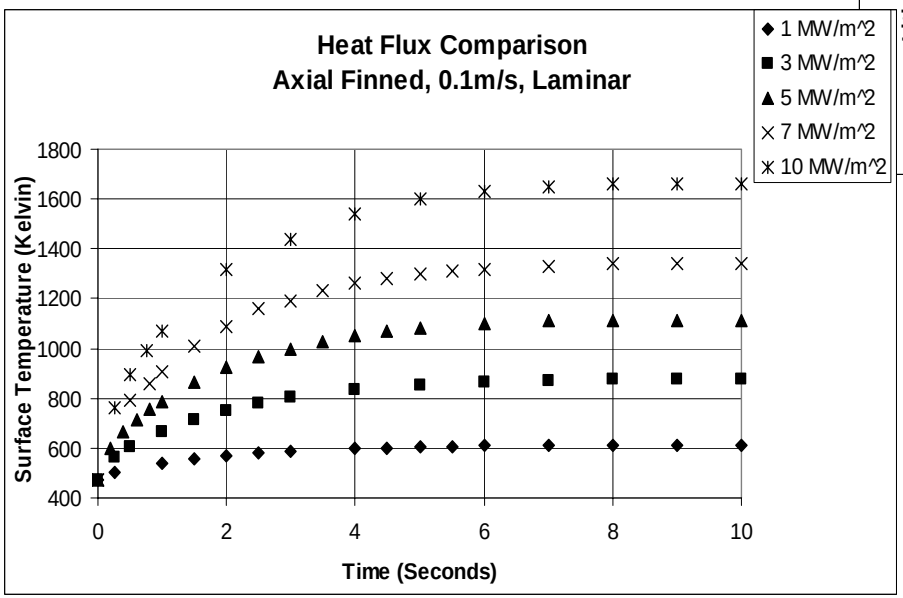
Laminar conditions are easy to model.





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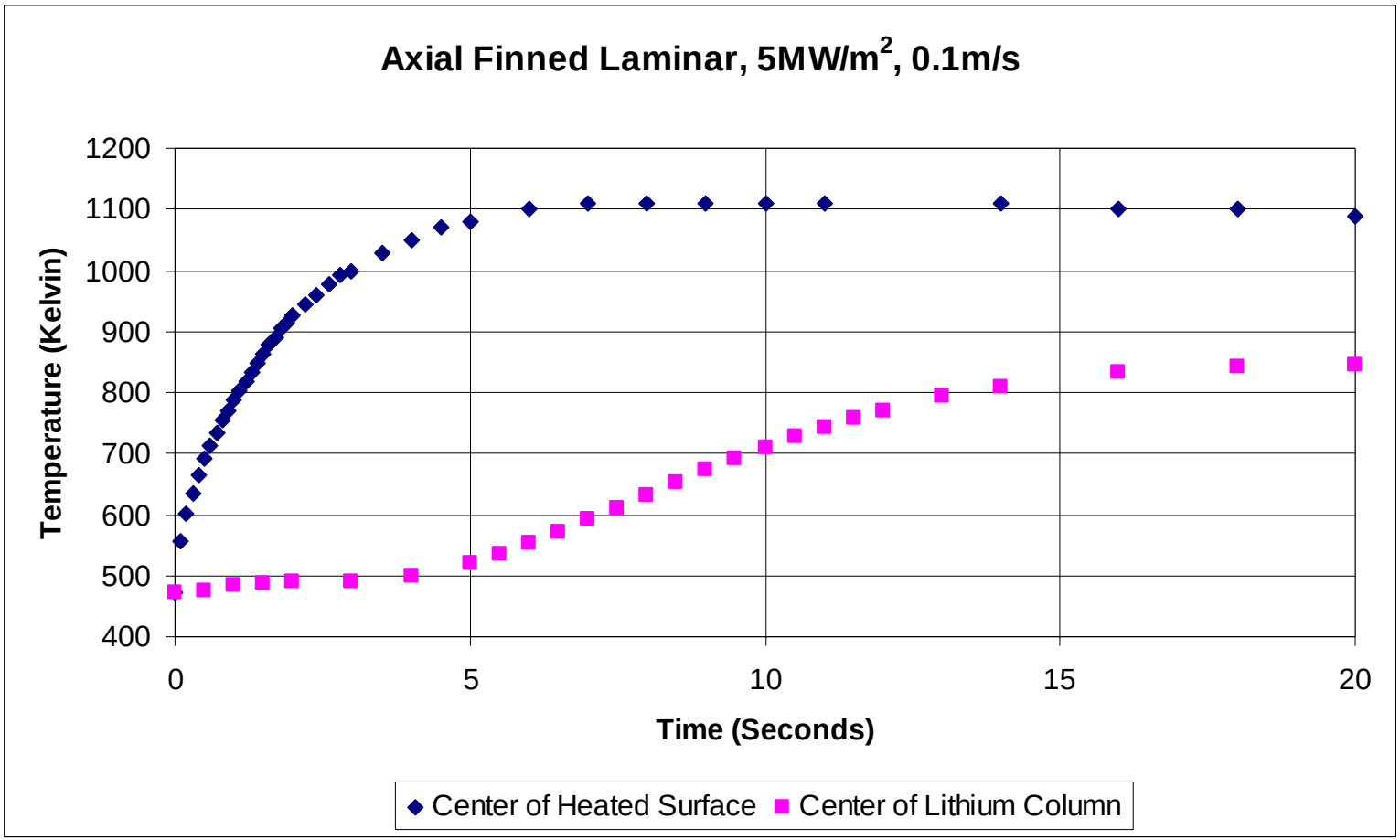
Transient is controlled by conduction in the wall.



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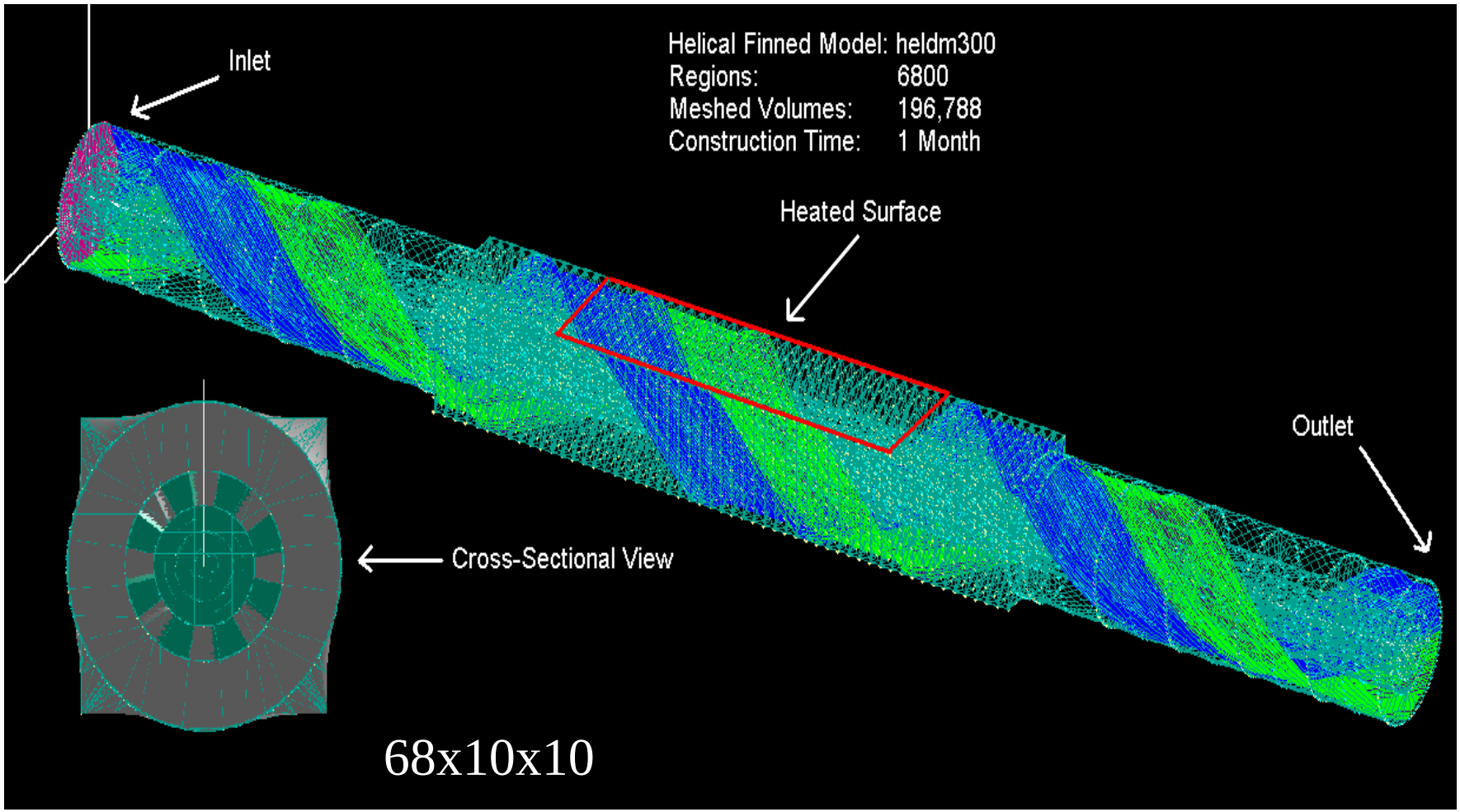
Helical Finned Model



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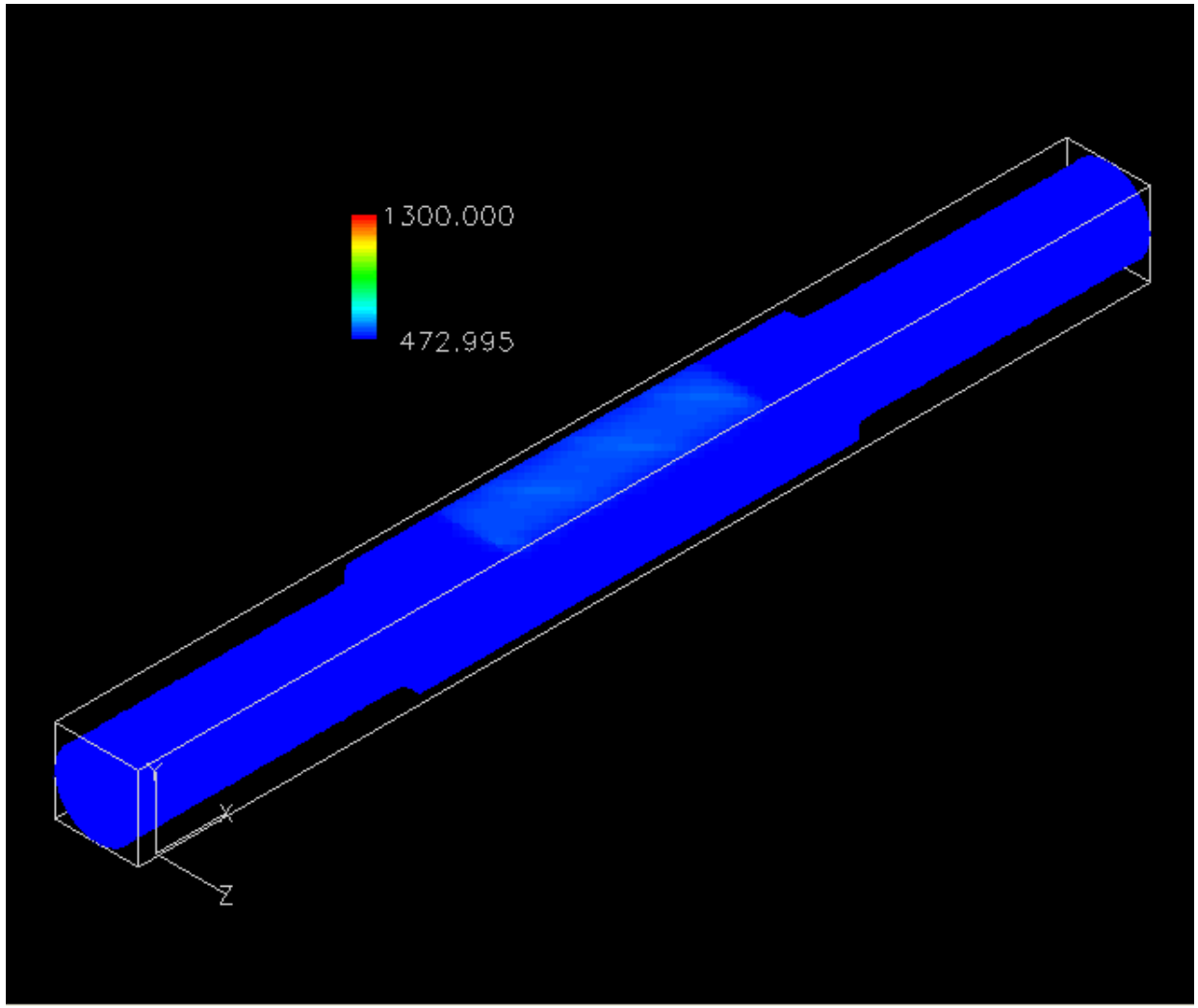
5 MW/m^2 heating to s.s. with 0.1 m/s flow.



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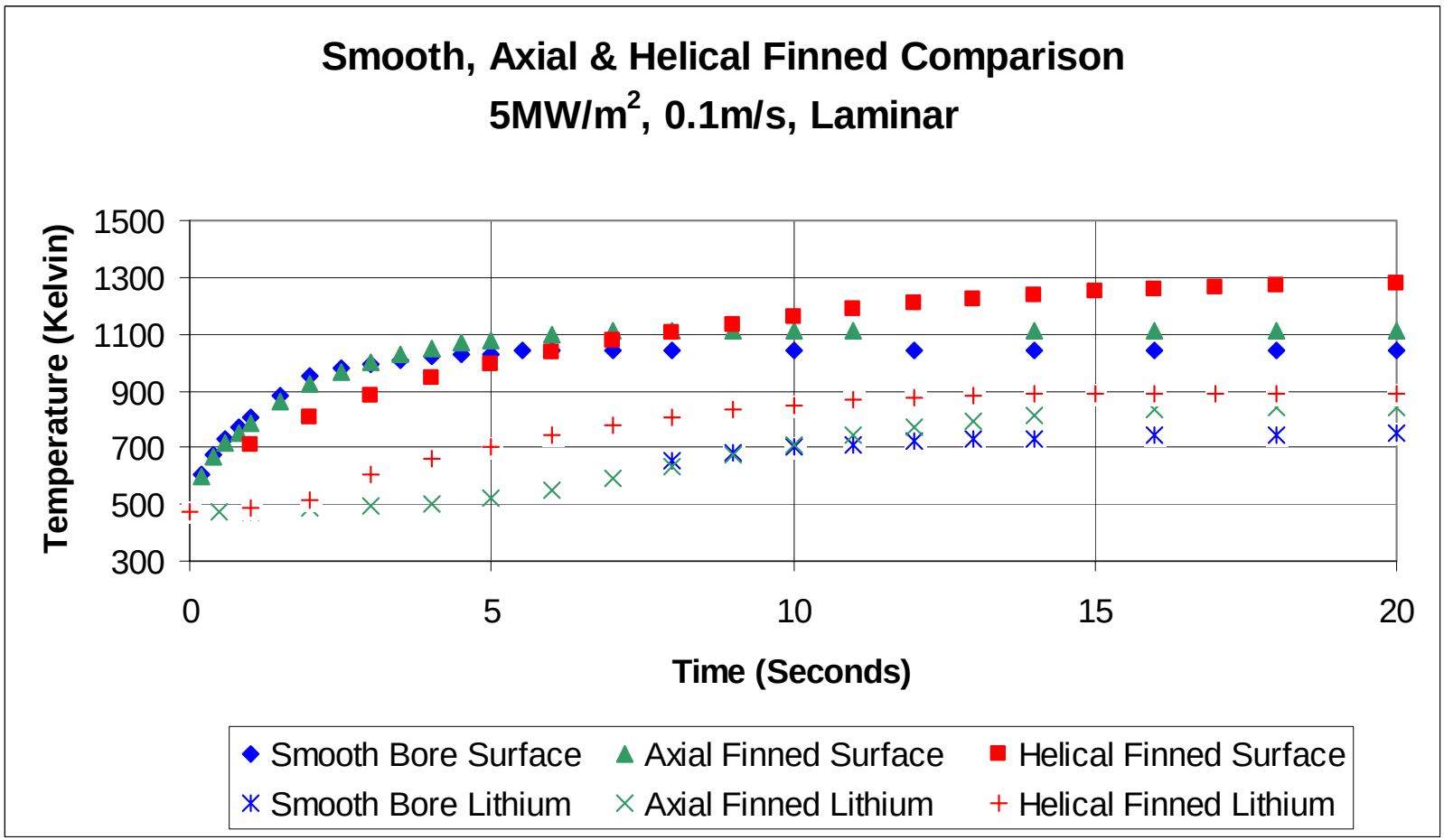
Finned refractories have negative impact on heat transfer compared to smooth tubes.



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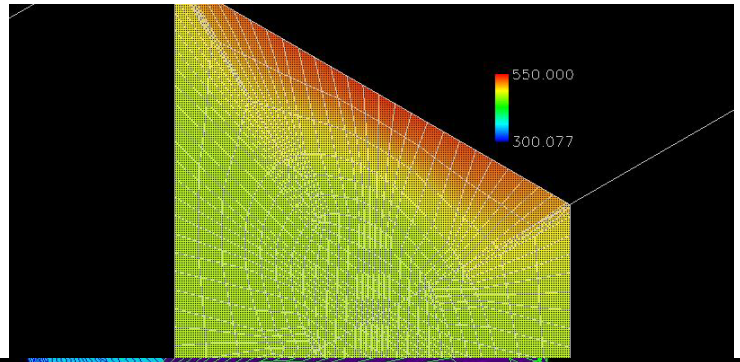
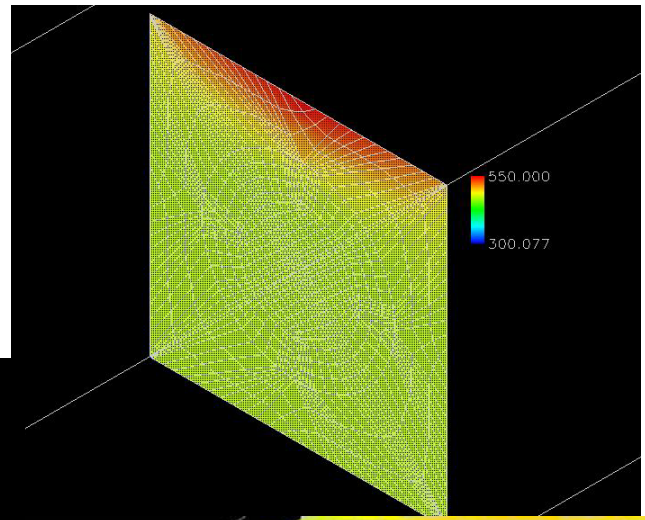
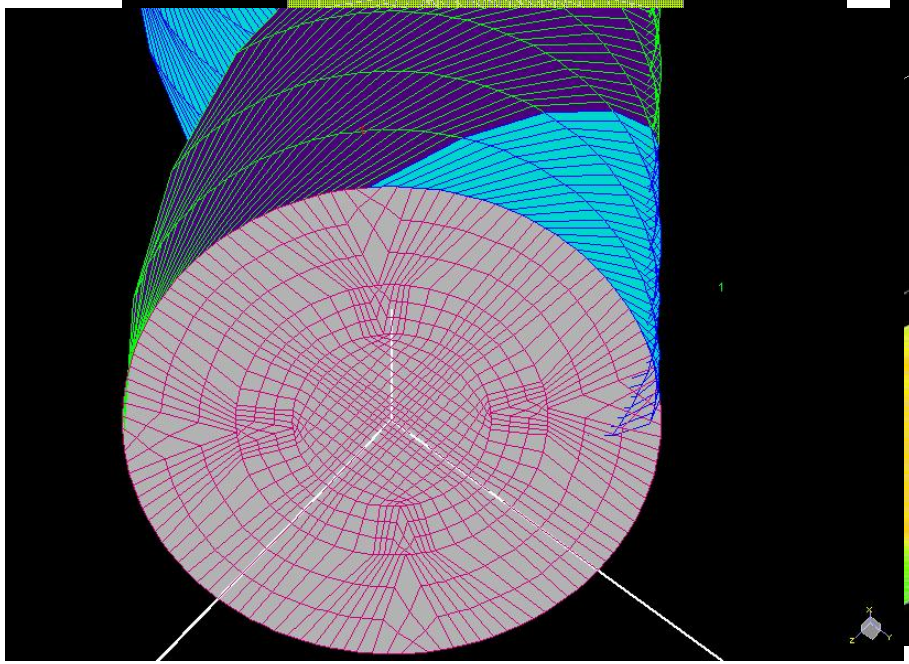
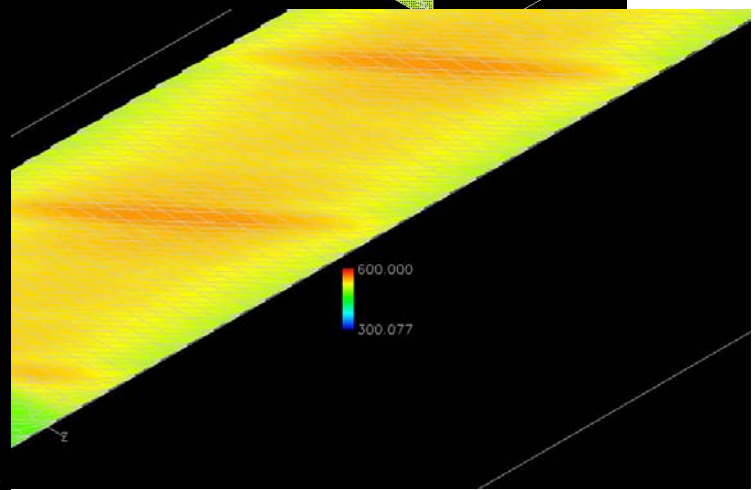
Code has heatflux problem on elements with coplanar sides. Only affects surface elements in helical model at j,k boundary.

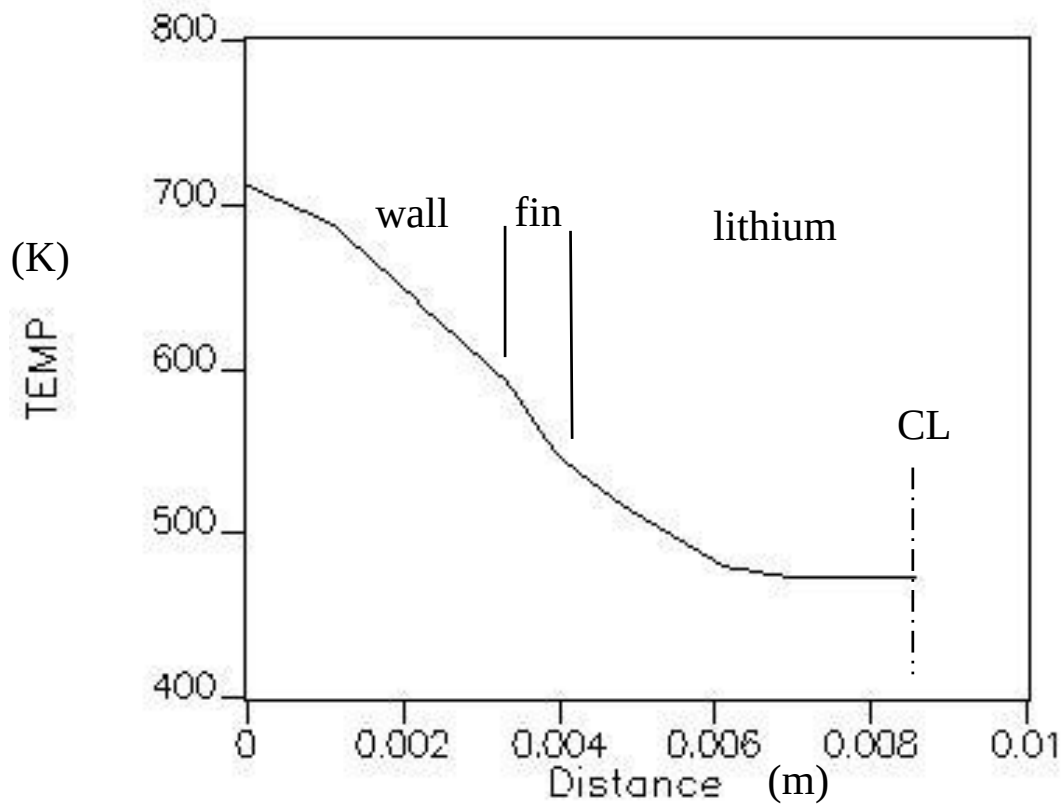






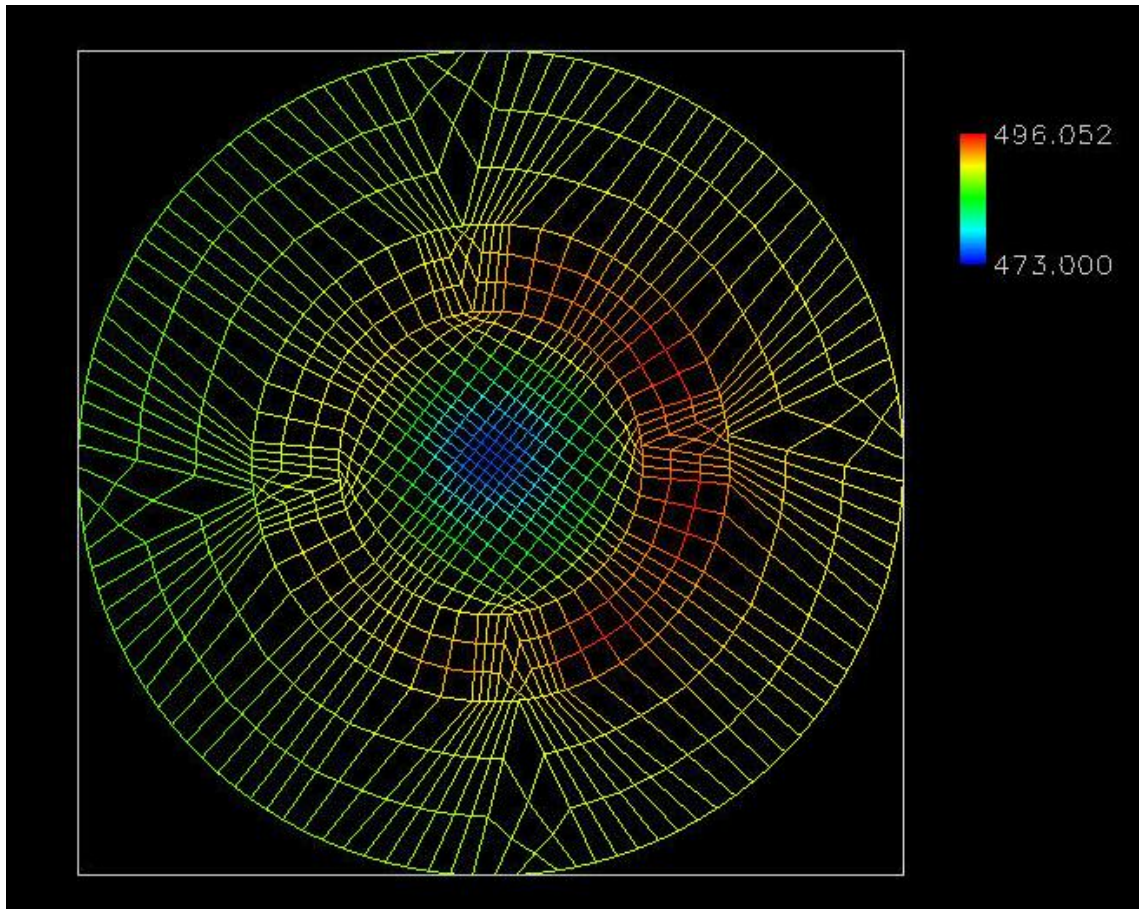


Temperature gradient is only in outer 2 mm of lithium at 4 m/s.



Lithium temperature is highest in low velocity grooves, with little mixing even at the exit.

exit temperatures 4 m/s



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Axial velocity in grooves ~1 m/s.

core velocity 4 m/s

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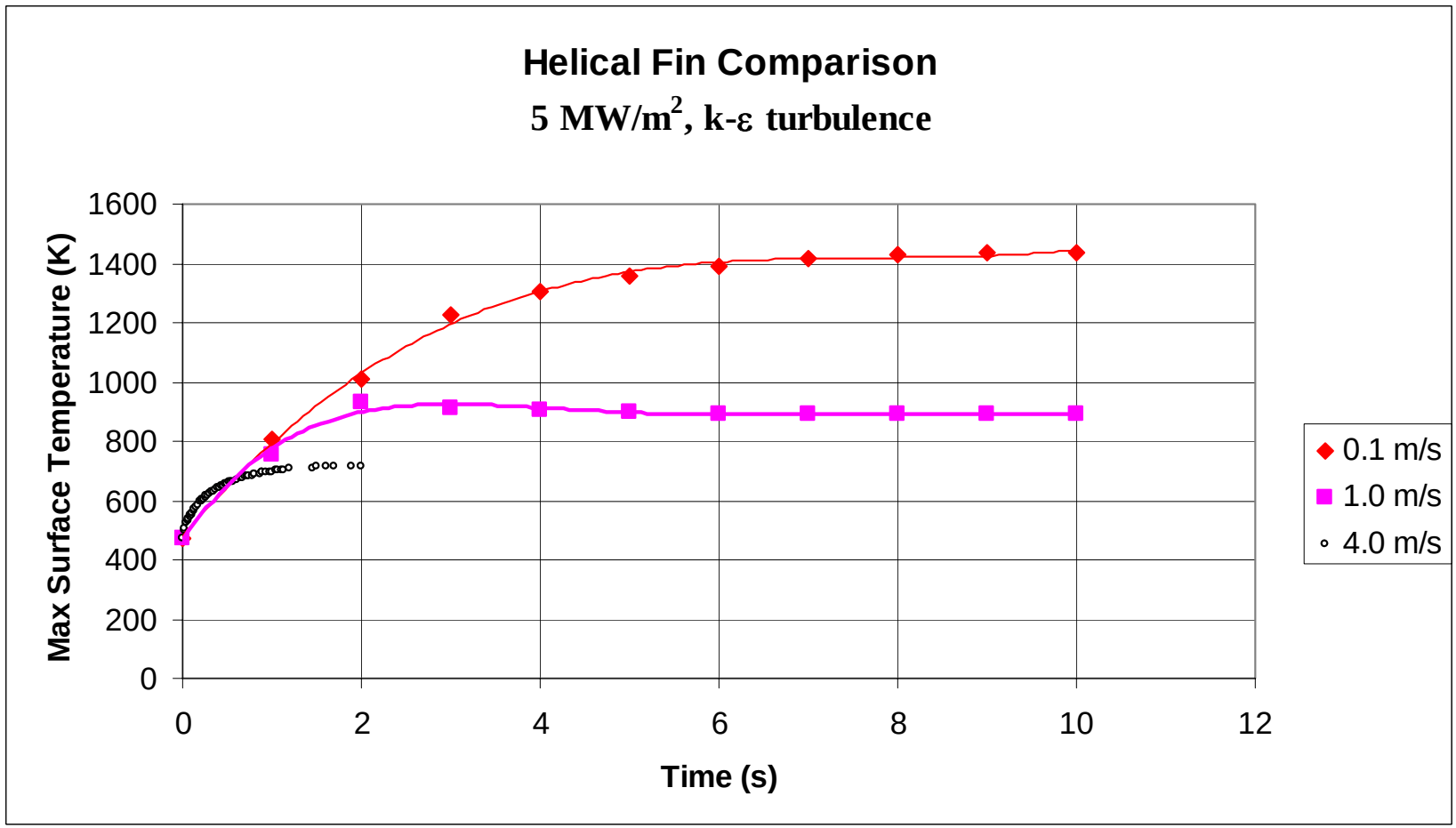
Highly turbulent flows are difficult to initiate.



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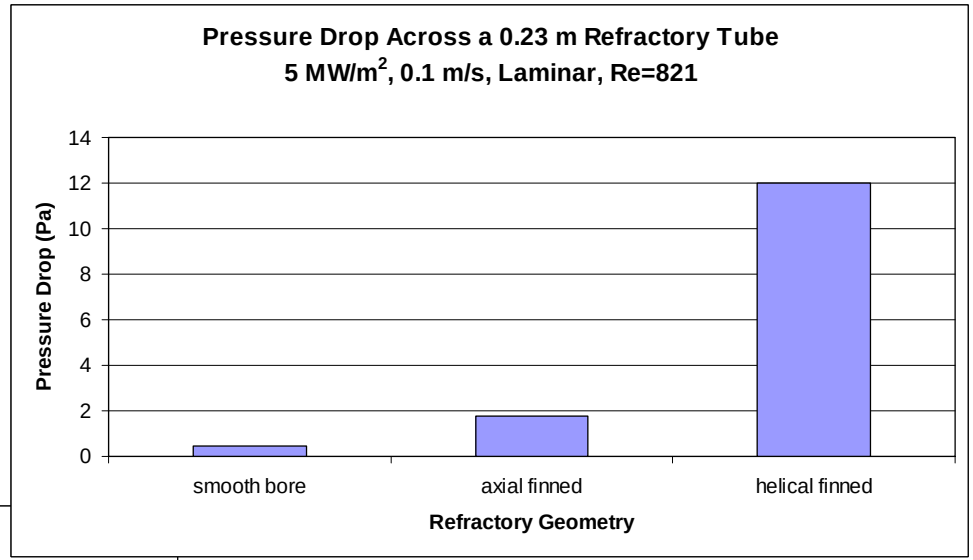
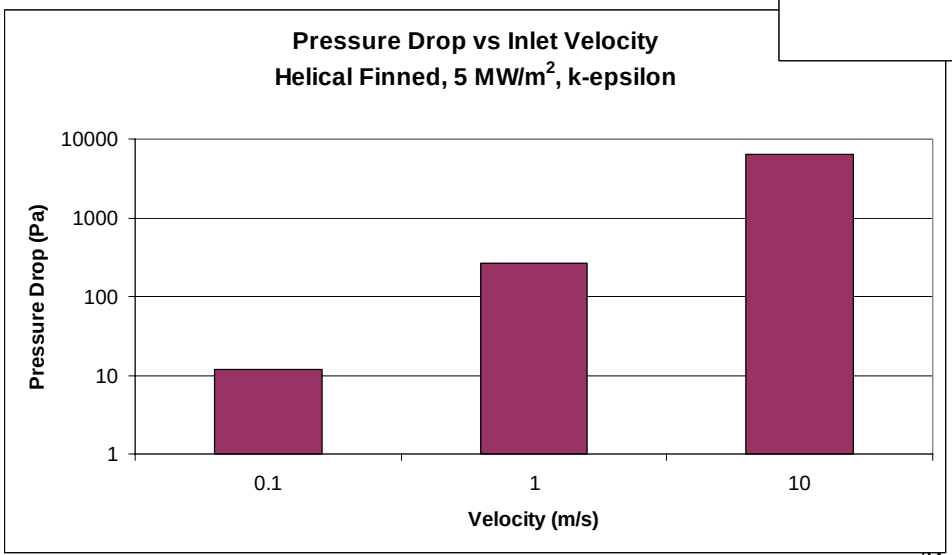
Fins significantly increase pressure drop.

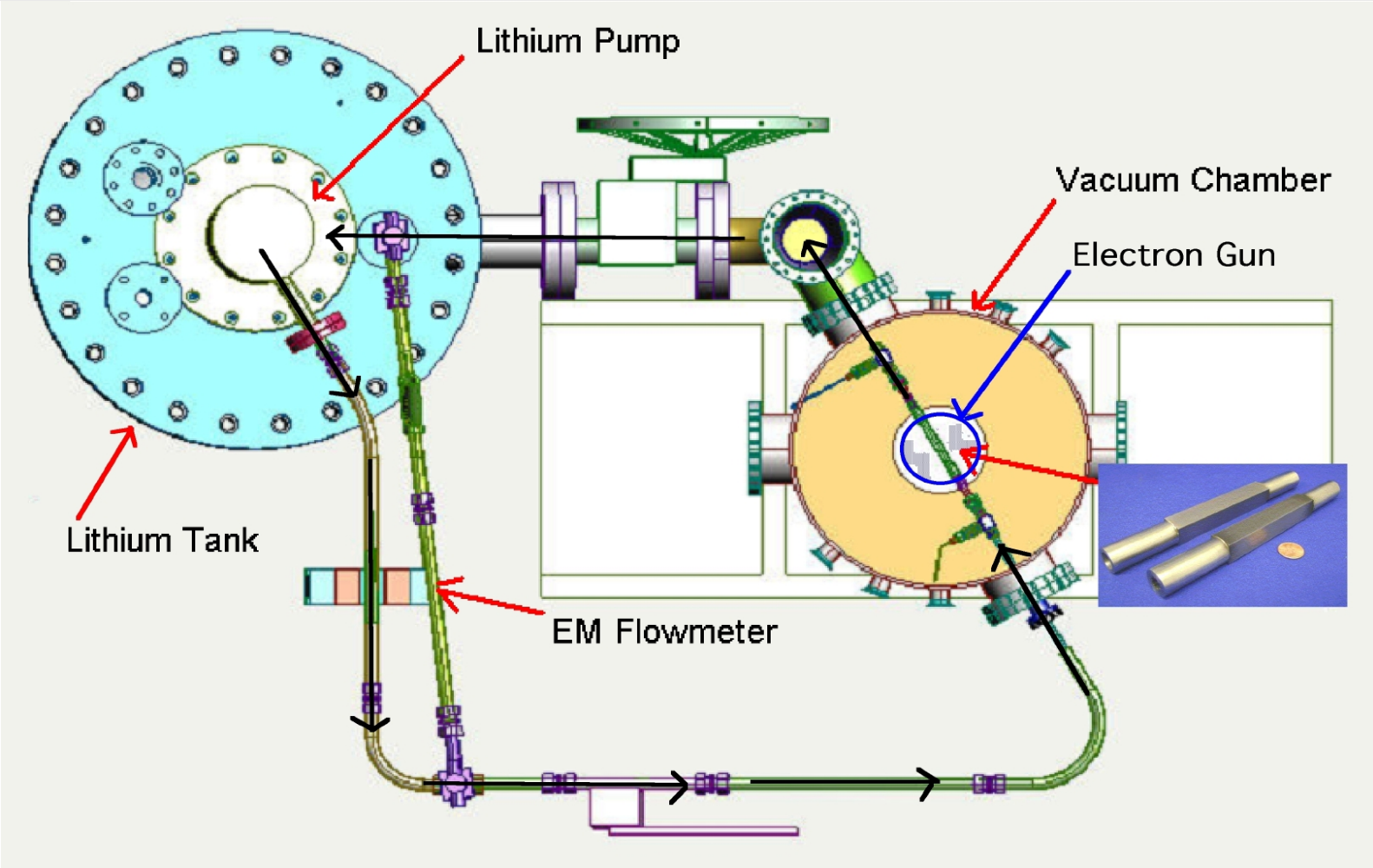
Fins are not always good!





Pumping power requirements increase with very little gain in heat transfer.

Experimental Setup (Top View): LIquid Metal Integration Test System (LIMITS)



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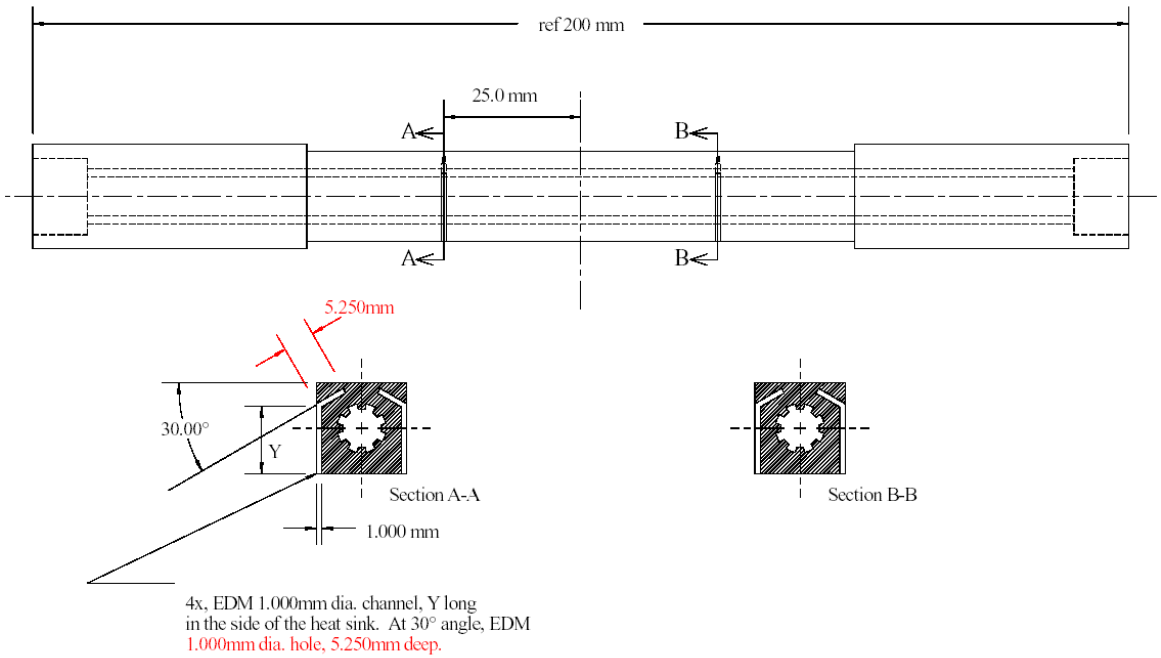
Refractories are instrumented with 4 type-K thermocouples.



Materials List

Part #	Material	Bore	Y
V2000-23B	tungsten heavy alloy	helical fin	12.250mm
V2000-24	molybdenum	helical fin	12.250mm
V2002-12C	tungsten	helical fin	12.250mm
V2002-12D	tungsten	helical fin	12.250mm
V2000-3B	molybdenum	smooth	12.750mm
V2000-3C	molybdenum	smooth	12.750mm
V2000-20	tungsten heavy alloy	smooth	12.750mm

Tolerances:
X +/- 1mm
X.X +/- 0.5mm
X.XX +/-0.25mm
X.XXX +/- 0.125mm

Plasma Processes, Inc.
Huntsville, Alabama

TC holes for refractory metal mockups (Revision A)

Prepared by: Scott O'Dell

Date: 8/14/02 | Scale: None | Sheet: 1 of 1

Drawing Number: PP1049 (Revision A)

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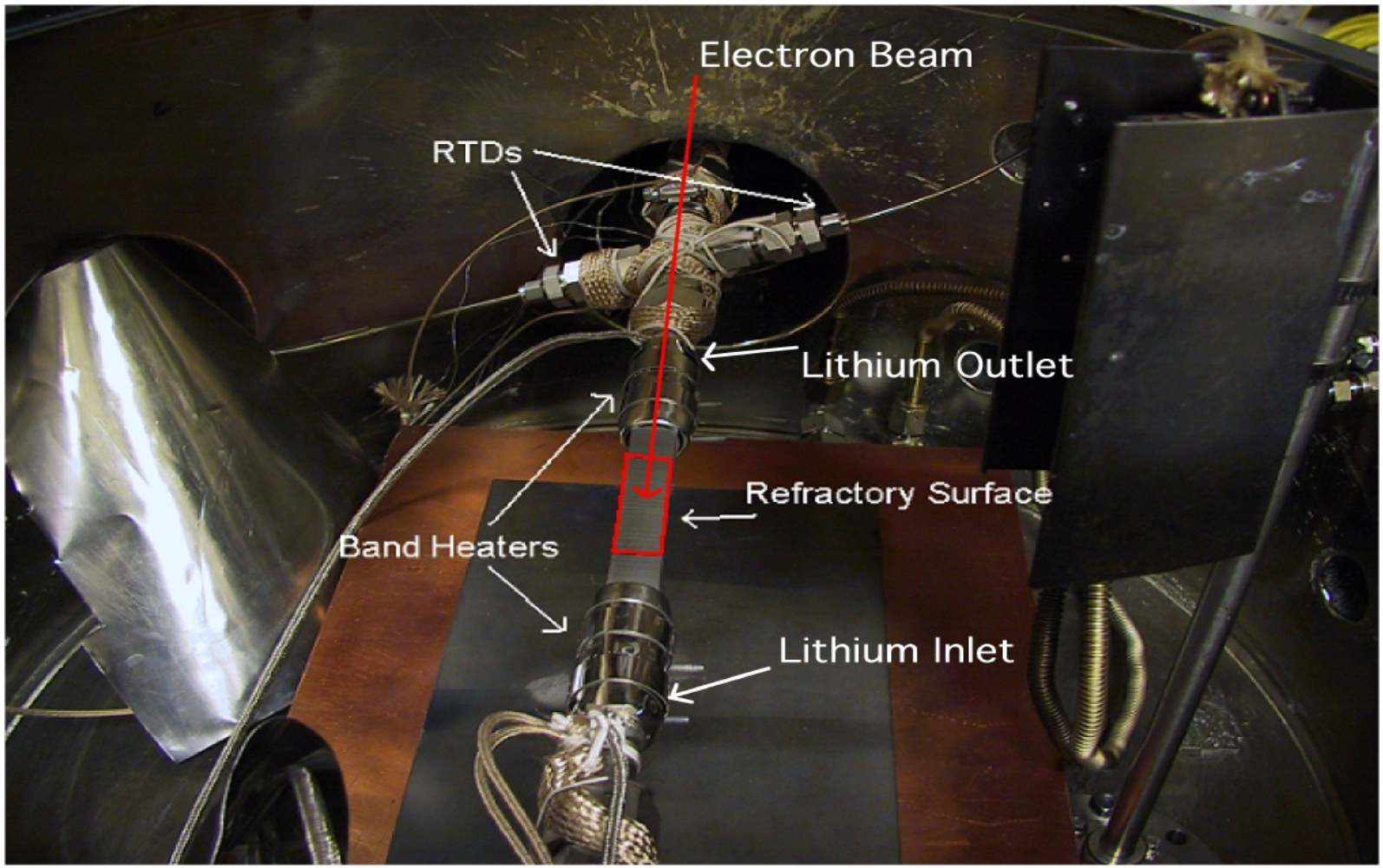
Coolant Channel Mounted in LIMITS Vacuum Chamber



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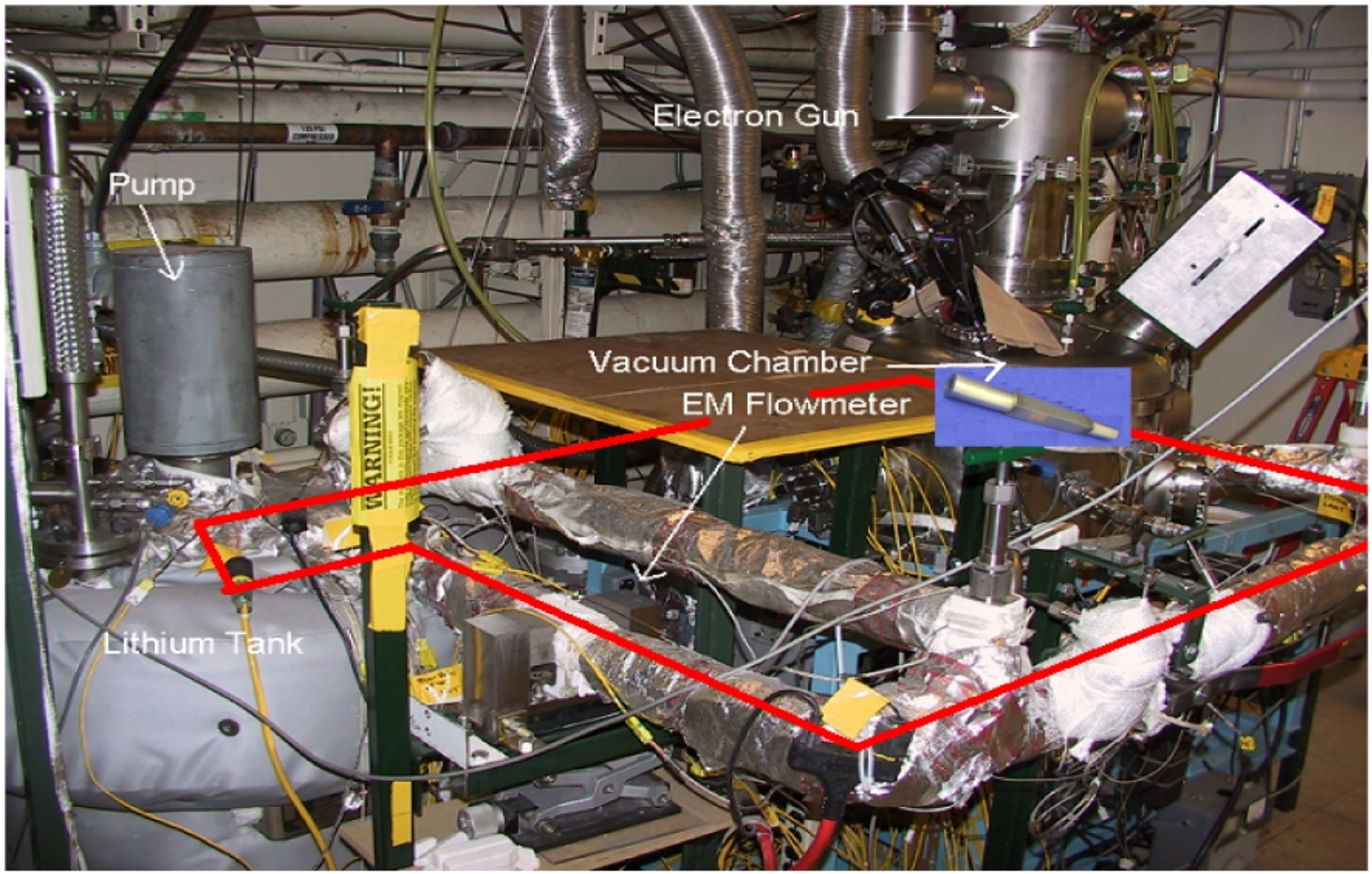
LIMITS at SNL's
Plasma Materials Test Facility

Test support: J. McDonald, T. Lutz, K. Troncosa, F. Bauer



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Conclusions

- Enhancing convection through the fin-effect is not beneficial for liquid metals compared to water in this example.
- Better heat transfer at higher velocities is too costly in pressure drop.
- High temperature, low pressure lithium applications using refractories require thin-walled, smooth tubing (or thin face plates on the heat flux side).
- Cracking in thin-walled refractories will be a problem.
- LIMITS will provide experimental data to benchmark CFD calculations
- Fins in refractory metals is a good demonstration of plasma spray fabrication; however, it may be more useful for helium than LM.
- Closer coordination between PFC institutions and SBIR/STTR companies can identify design issues early in a project. PFCs require a comprehensive treatment of materials, fabrication, heat transfer and PMI issues.

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