CFD Simulations and HHF Testing of Lithium-cooled Refractory Heatsinks

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Plasma Processes, Inc.

Princeton, NJ
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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

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**

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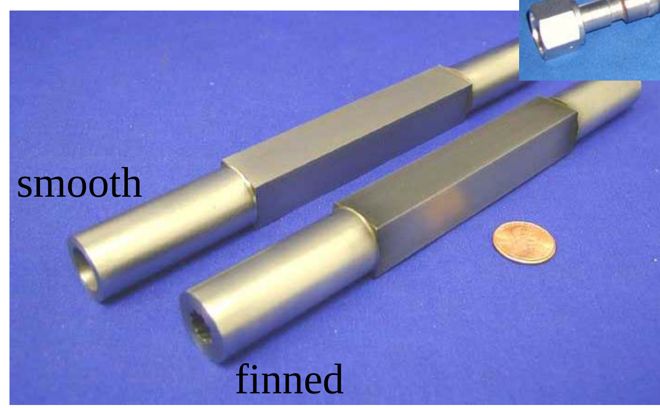
Only refractory heatsinks can operate at very high temperatures and are compatible with liquid lithium coolant.

- 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

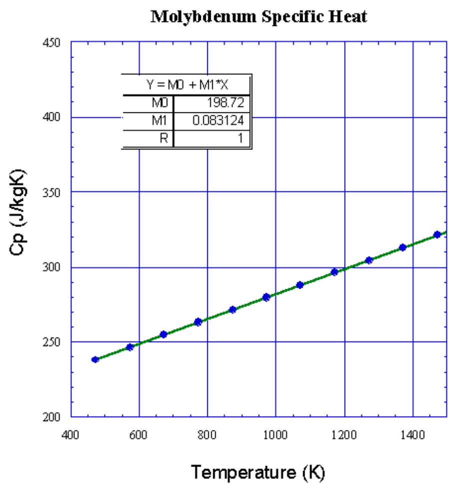
ID Number	Material	Bore Configuration	Bore Major ID	Bore Minor ID	Number of Fins
V2000-20	W-Ni-Fe	Smooth	~12.7mm	N/A	N/A
V2000-23B	W-Ni-Fe	Finned	9mm	7mm	8
V2000-3C	Molybdenum	Smooth	~12.7mm	N/A	N/A
V2000-24	Molybdenum	Finned	9mm	7mm	8
V2002-12D	Tungsten	Finned	9mm	6.7mm	8

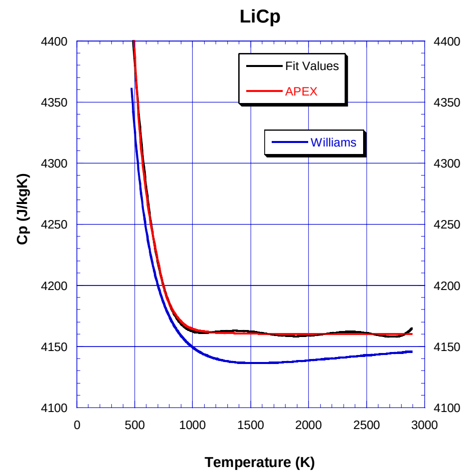
Computational Fluid Dynamics Finite Volume Modeling Process

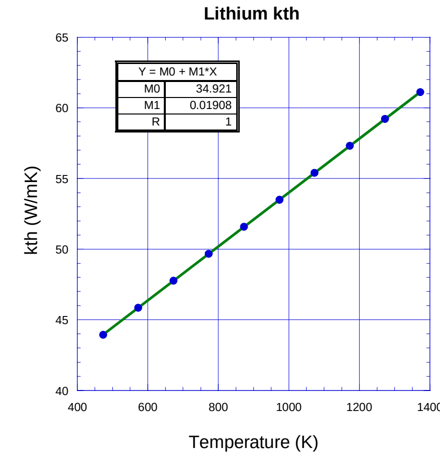
- Plan geometry with x,y,z symmetry
- Construct regions (manual CAD-type labor)
- Mesh regions into finite volumes (optimize)
- Add boundary conditions (walls, inlets, etc)
- Specify initial conditions & solution parameters
- Execute STORM solver (seek steady state)
  - Conservation of mass, momentum,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

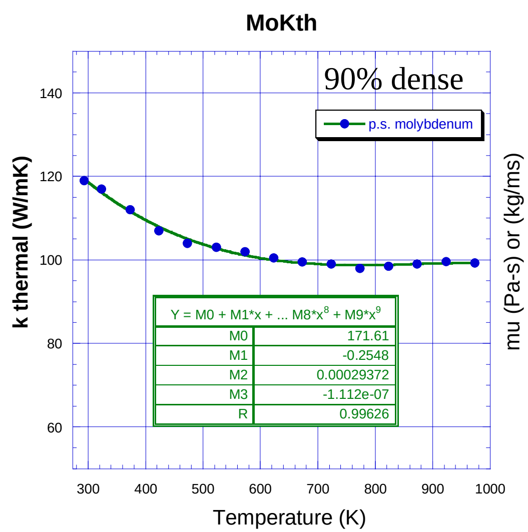
Analysis uses temperature dependent properties for heatsink and coolant (user coding)

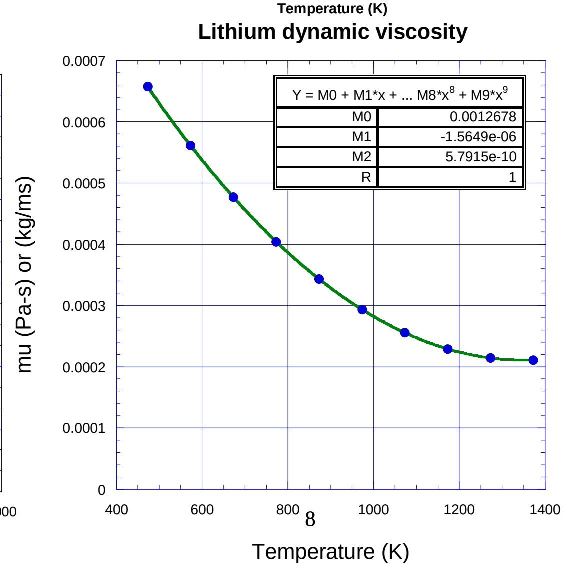
$$d\rho H/dt + d(\rho u_i H)/dx_i = d/dx_i[k/C_p\, dH/dx_i] + dp/dt + u_i dp/dx_i + \Phi + Q + S_H$$

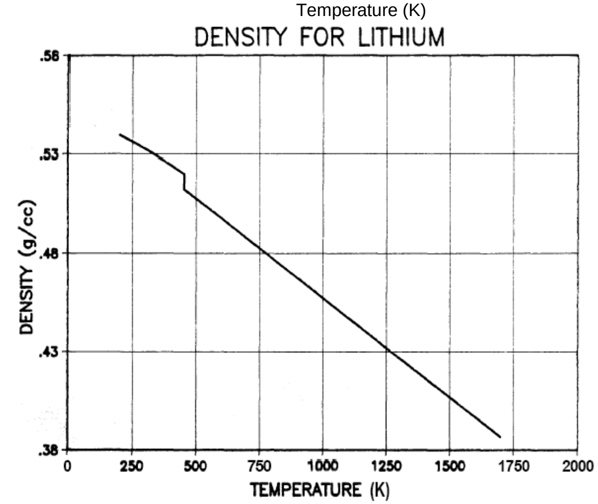












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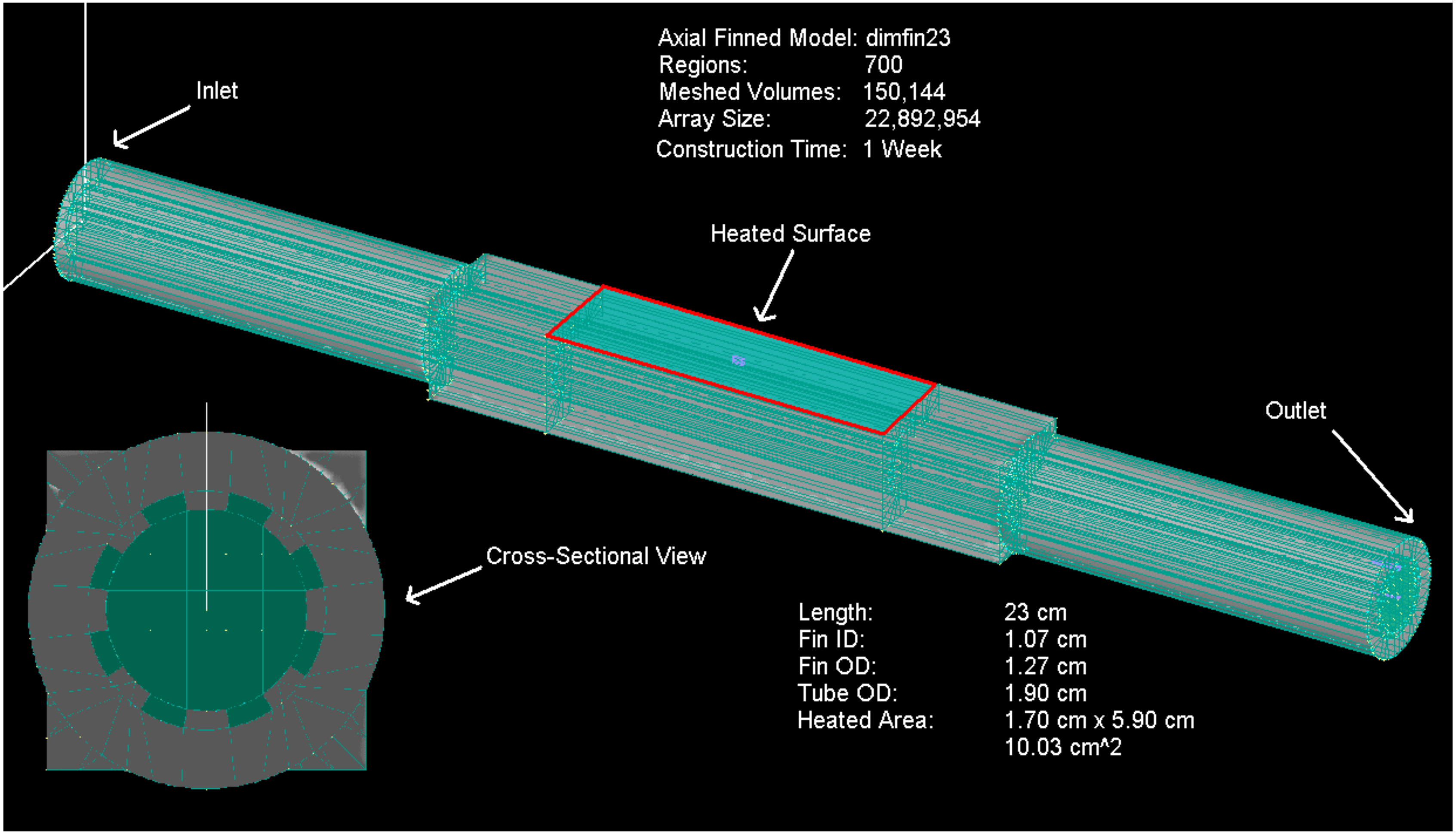
Axial Finned Model



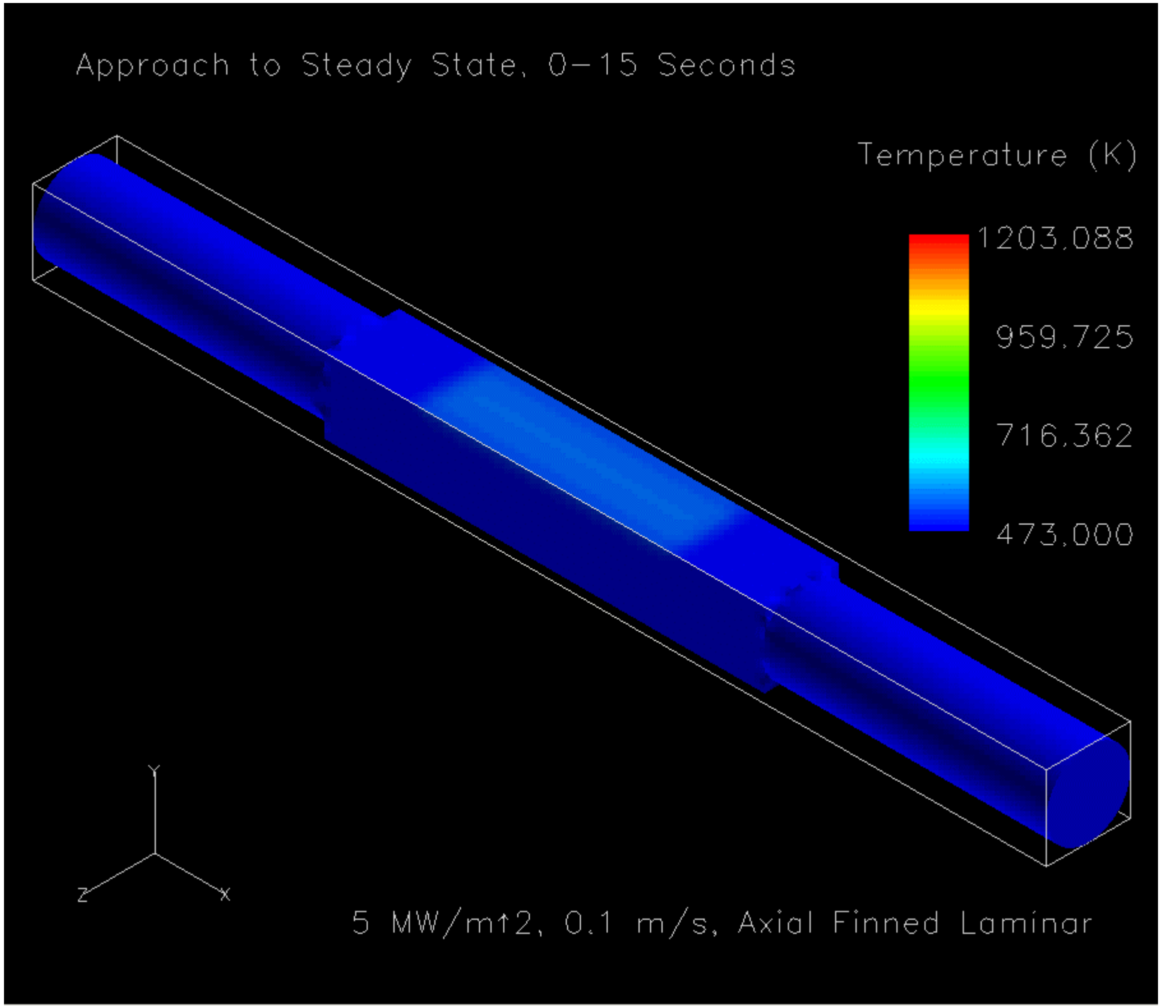
Conduction affects fin performance in this geometry.

- 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.

Approach to Steady State Conduction

3D View, 5 MW/m2, 0.1 m/s, Axial Finned Laminar



Temperature

1203 K

473 K

<--- Lithium Outlet

Effect of Film not as important for LM as water.

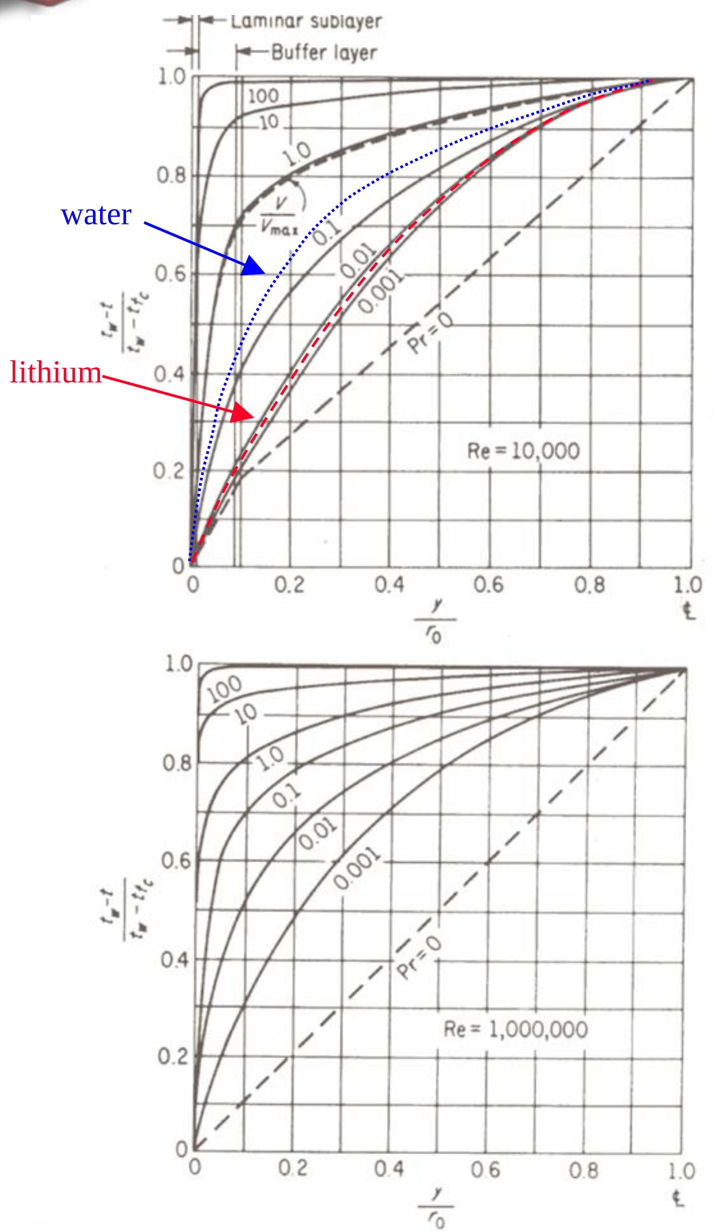


FIG. 9-3. Martinelli's solutions for the temperature gradients in pipe flow.

- 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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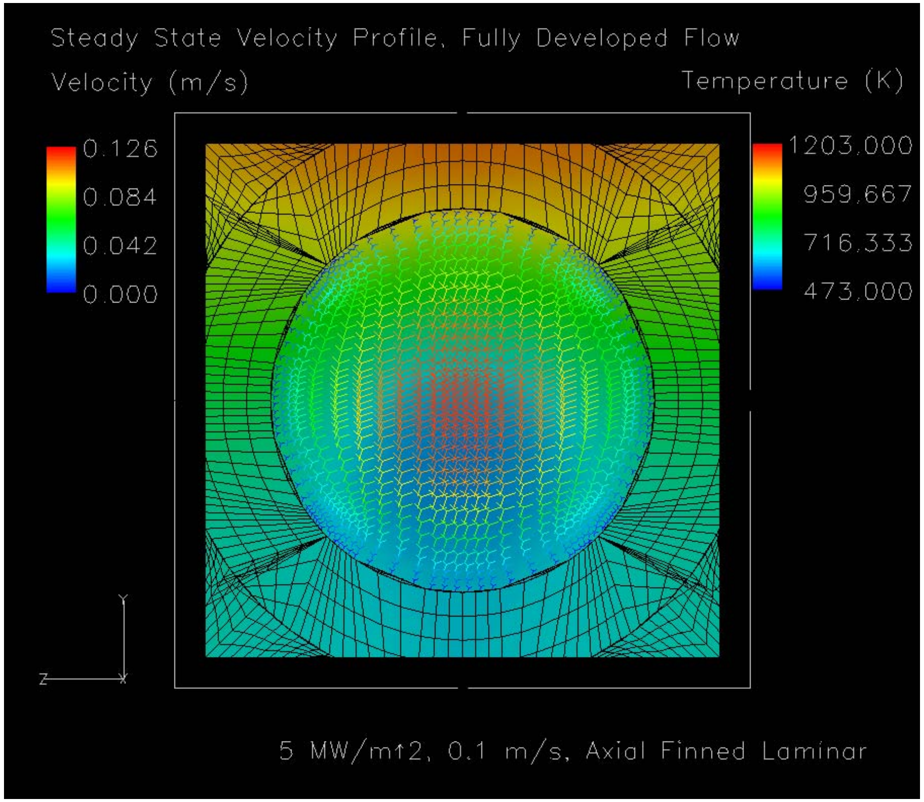
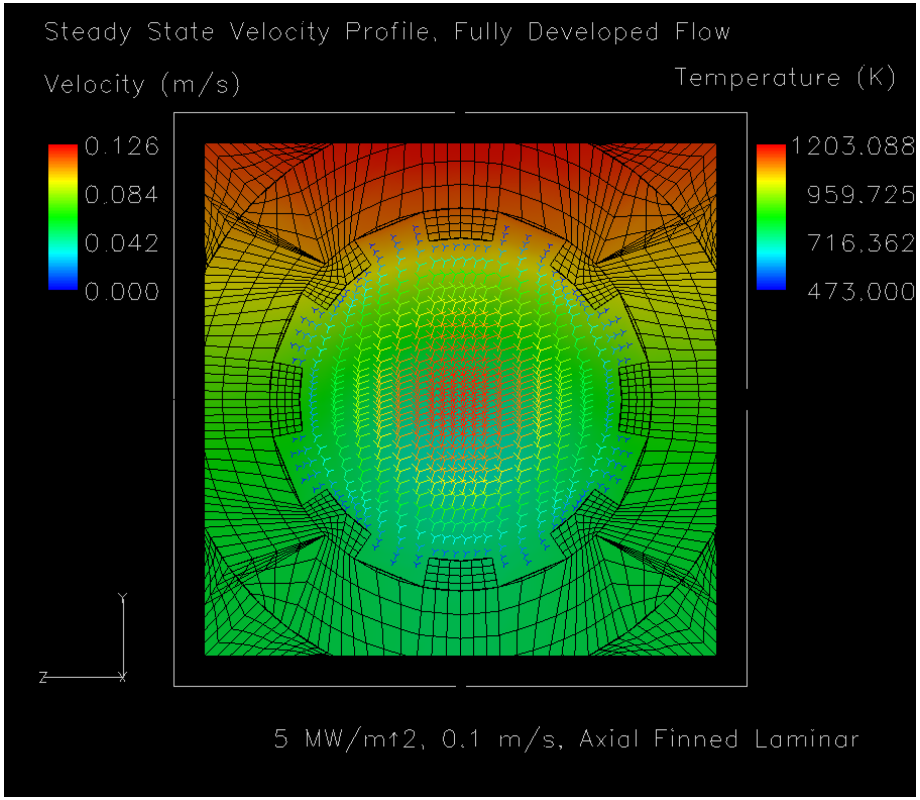
Axial fins of this geometry decrease heat transfer!





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

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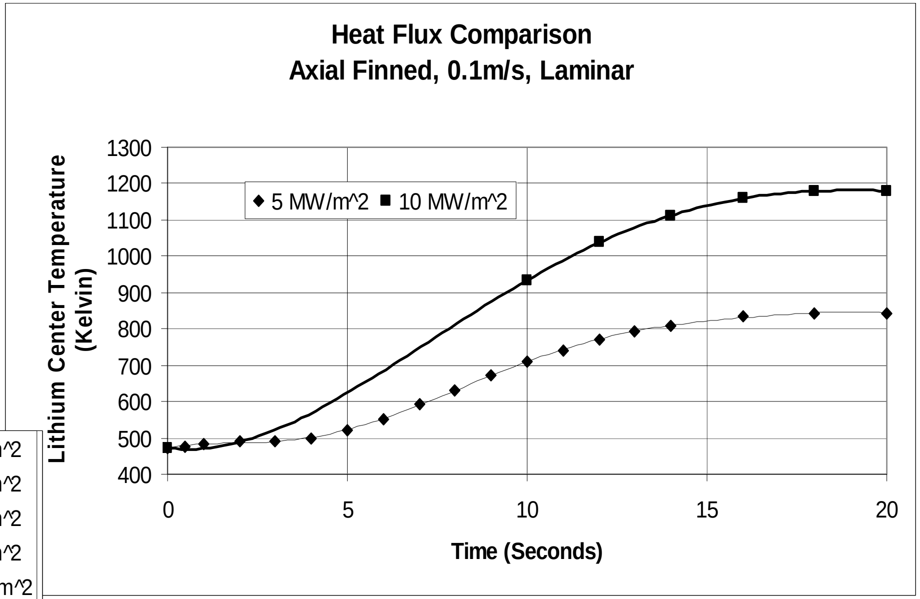
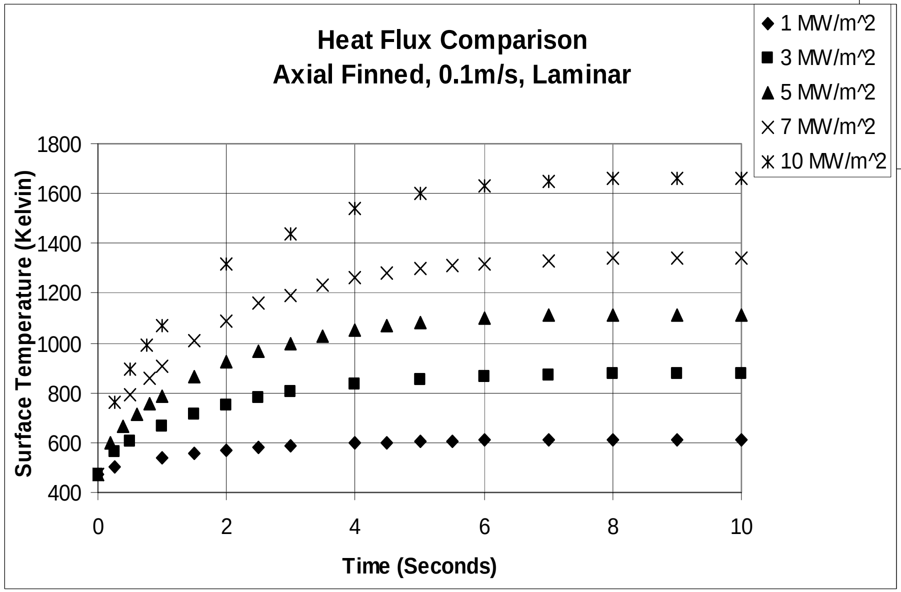
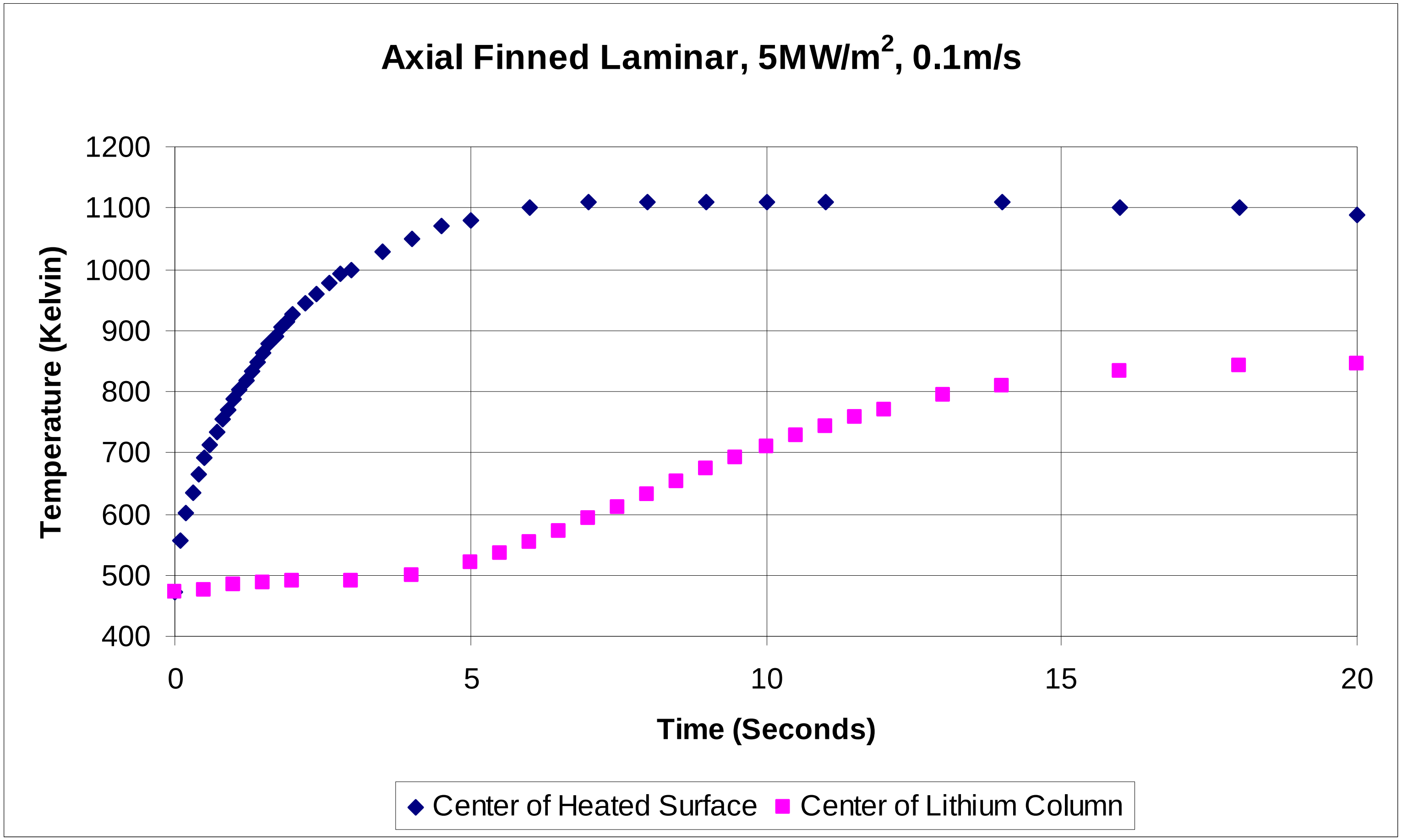
Laminar conditions are easy to model.





Transient is controlled by conduction in the wall.



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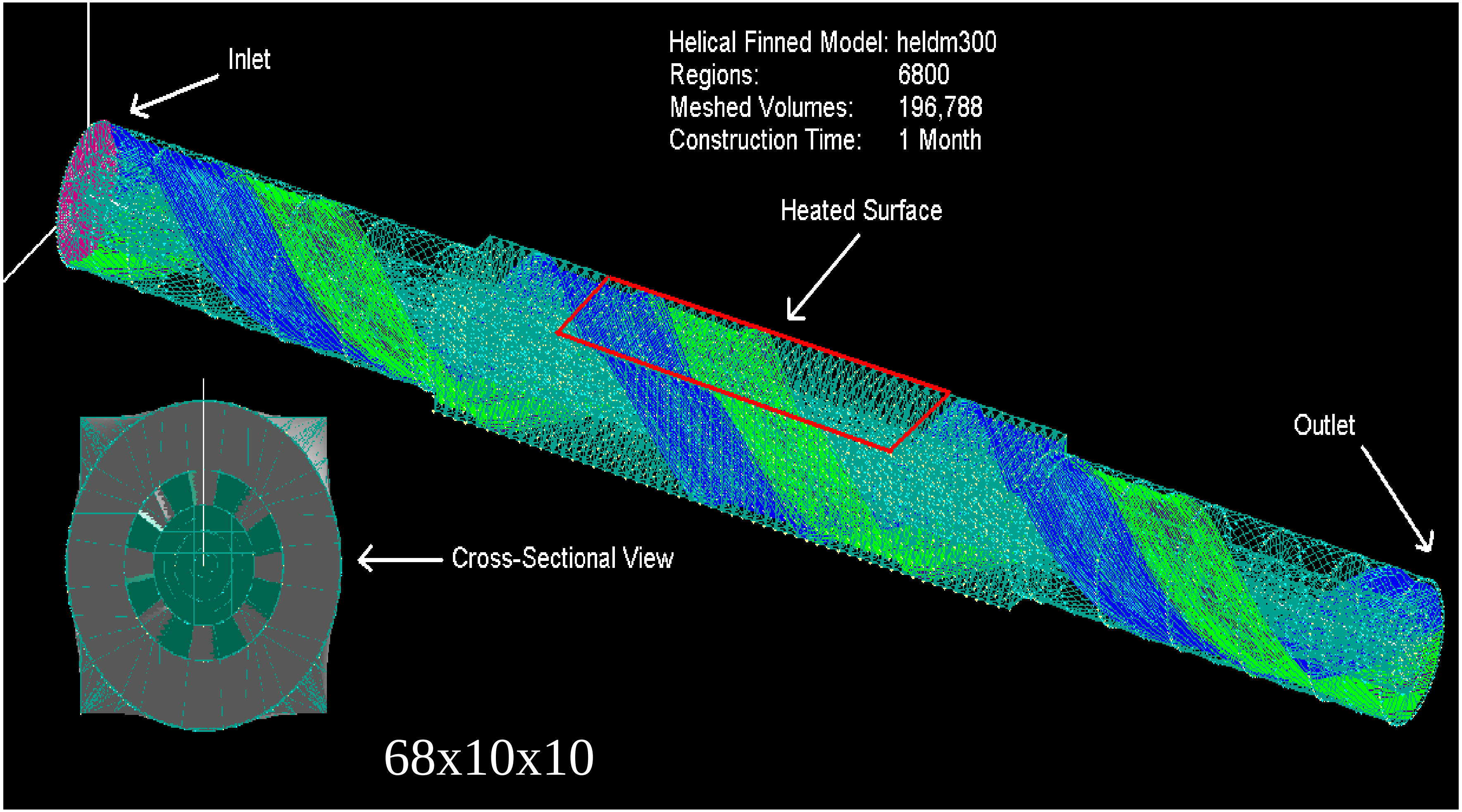
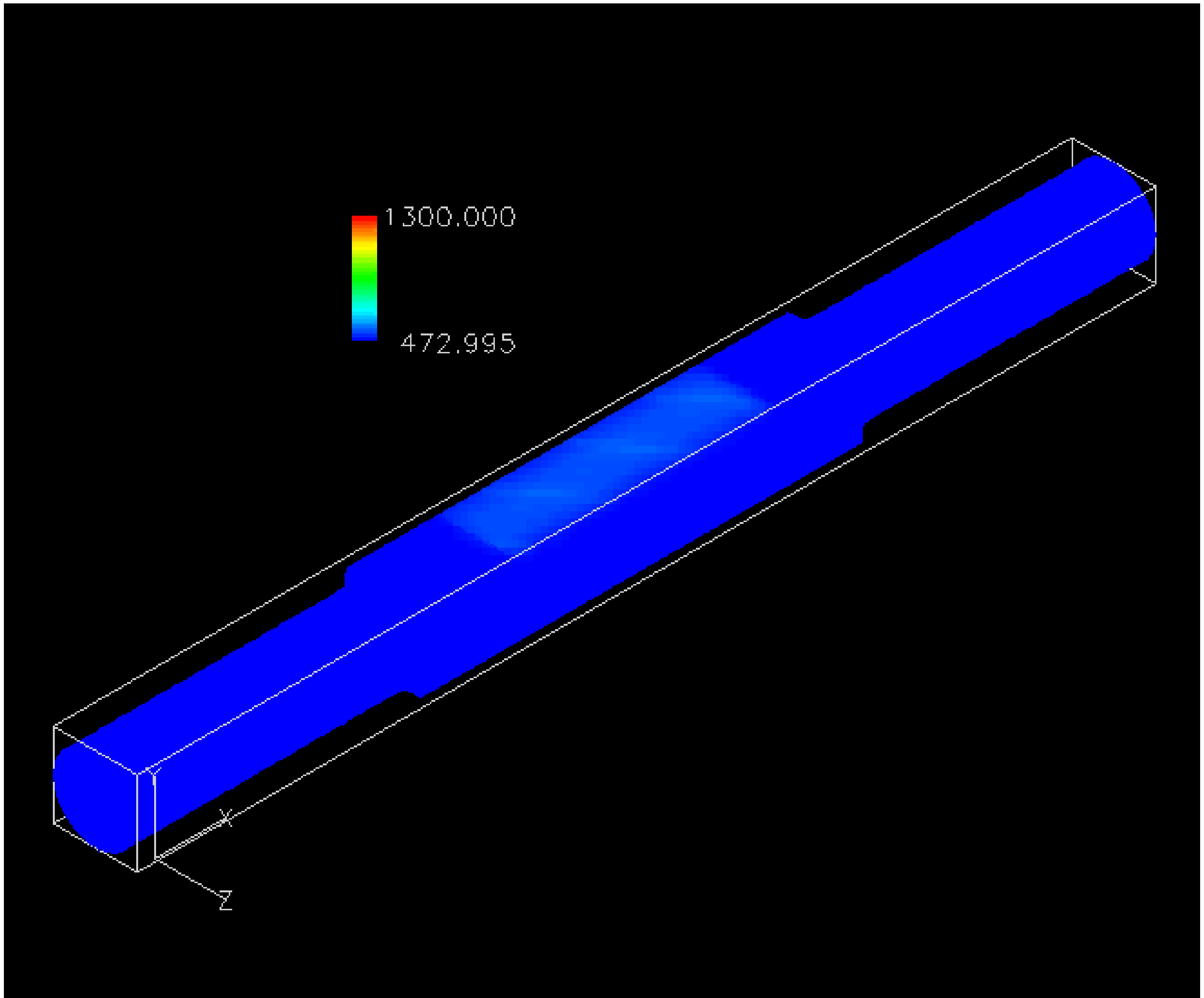
Helical Finned Model



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



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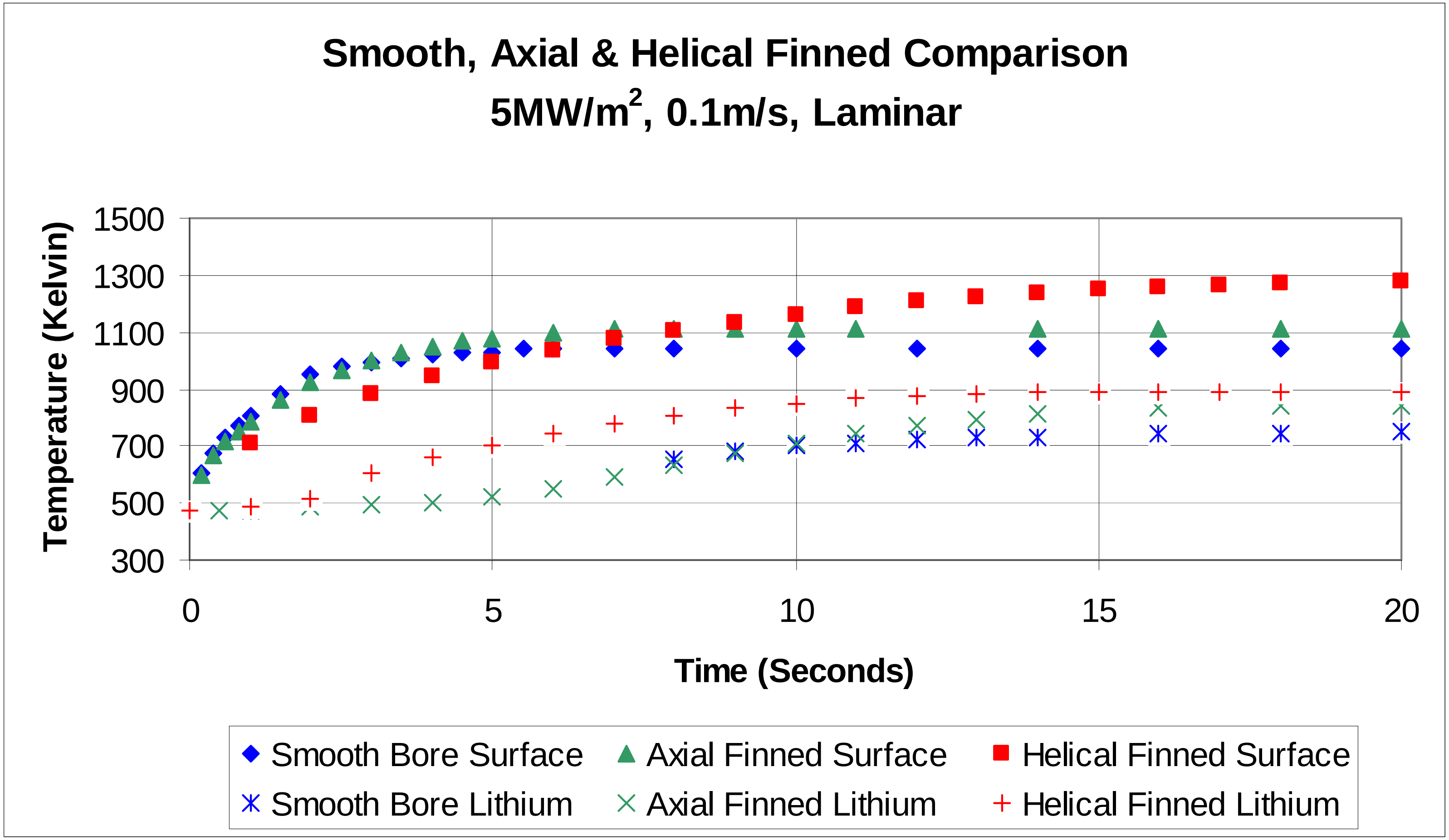
Finned refractories have negative impact on heat transfer compared to smooth tubes.



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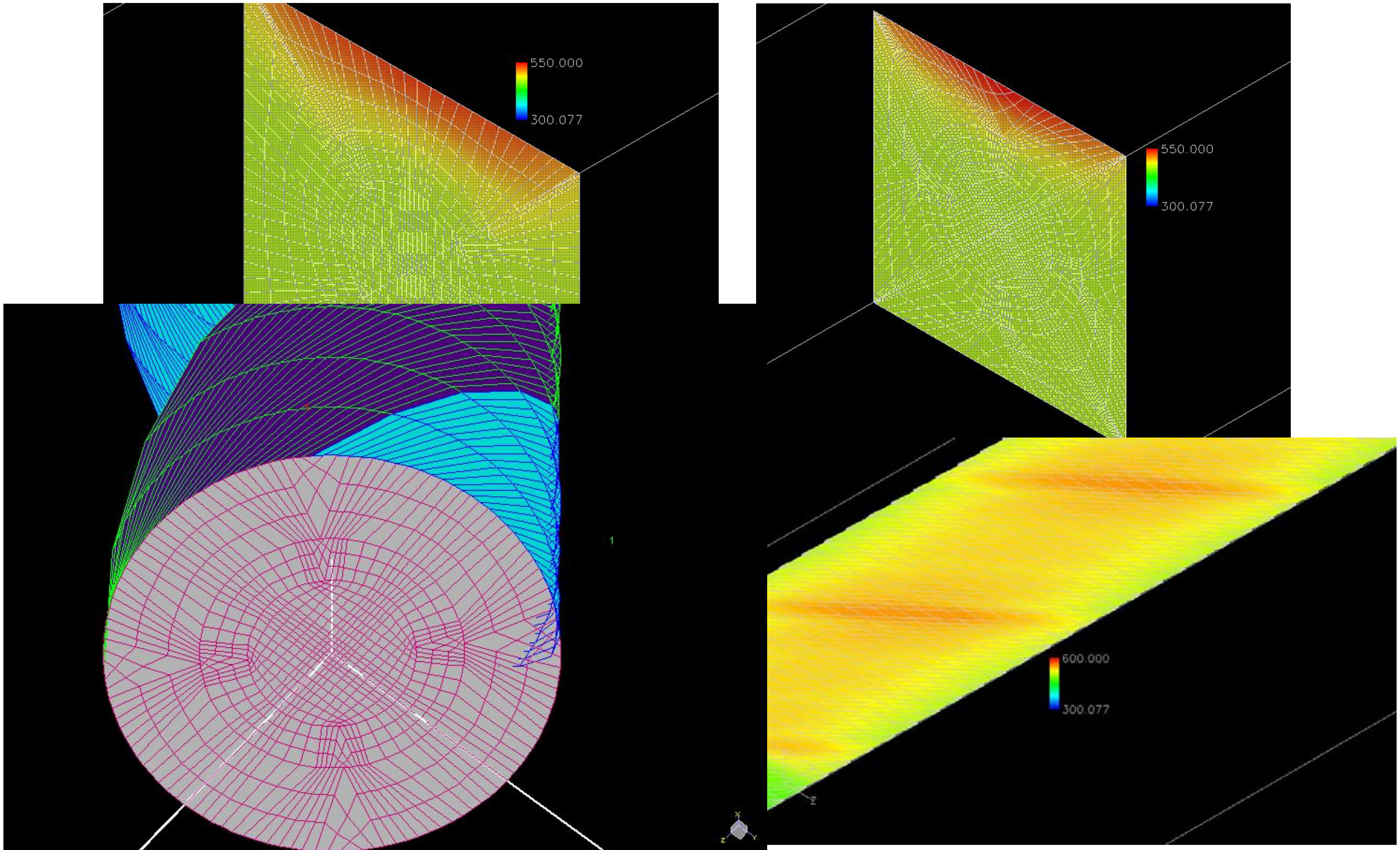
Code has heatflux problem on elements with coplanar sides. Only affects surface elements in helical model at j,k boundary.



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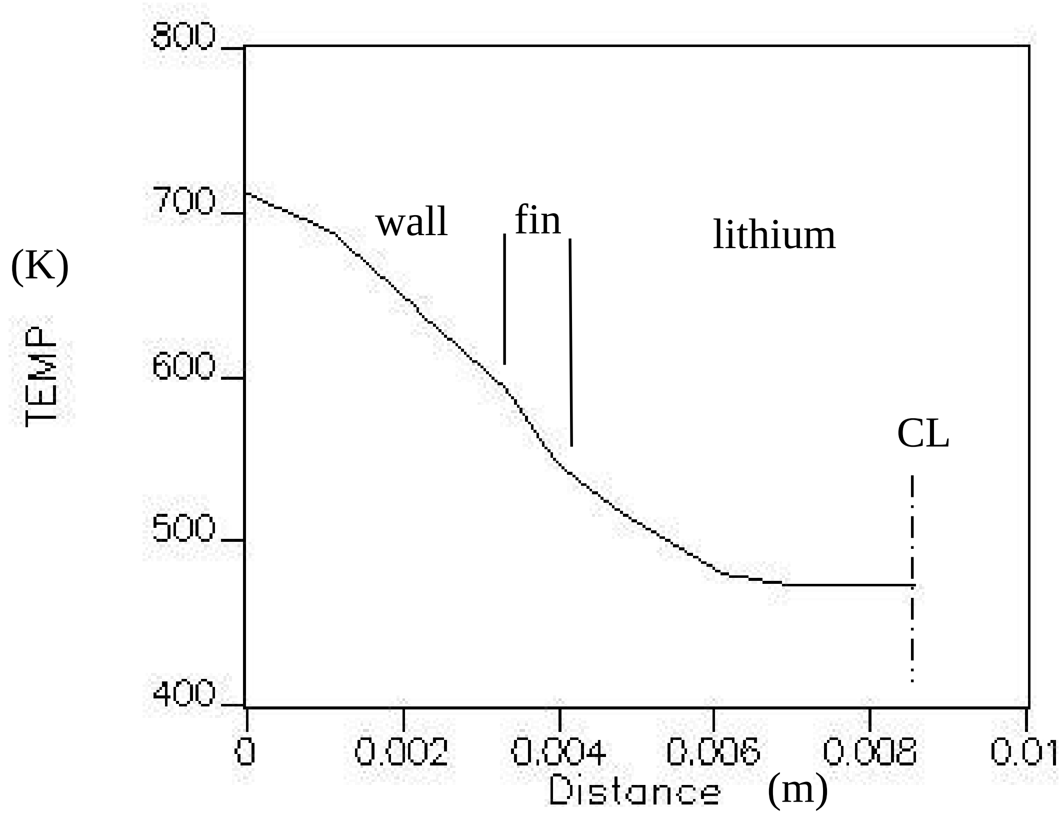
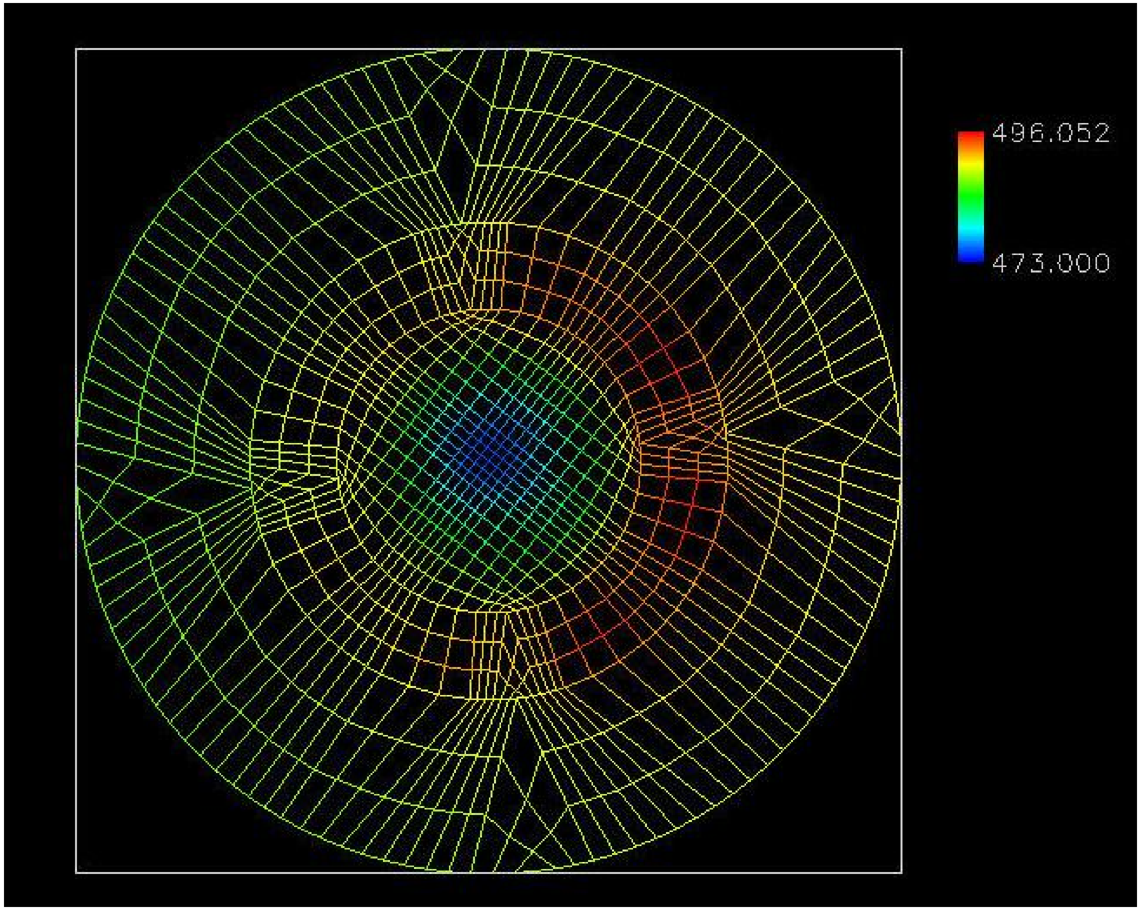
Temperature gradient is only in outer 2 mm of lithium at 4 m/s.



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

exit
temperatures
4 m/s



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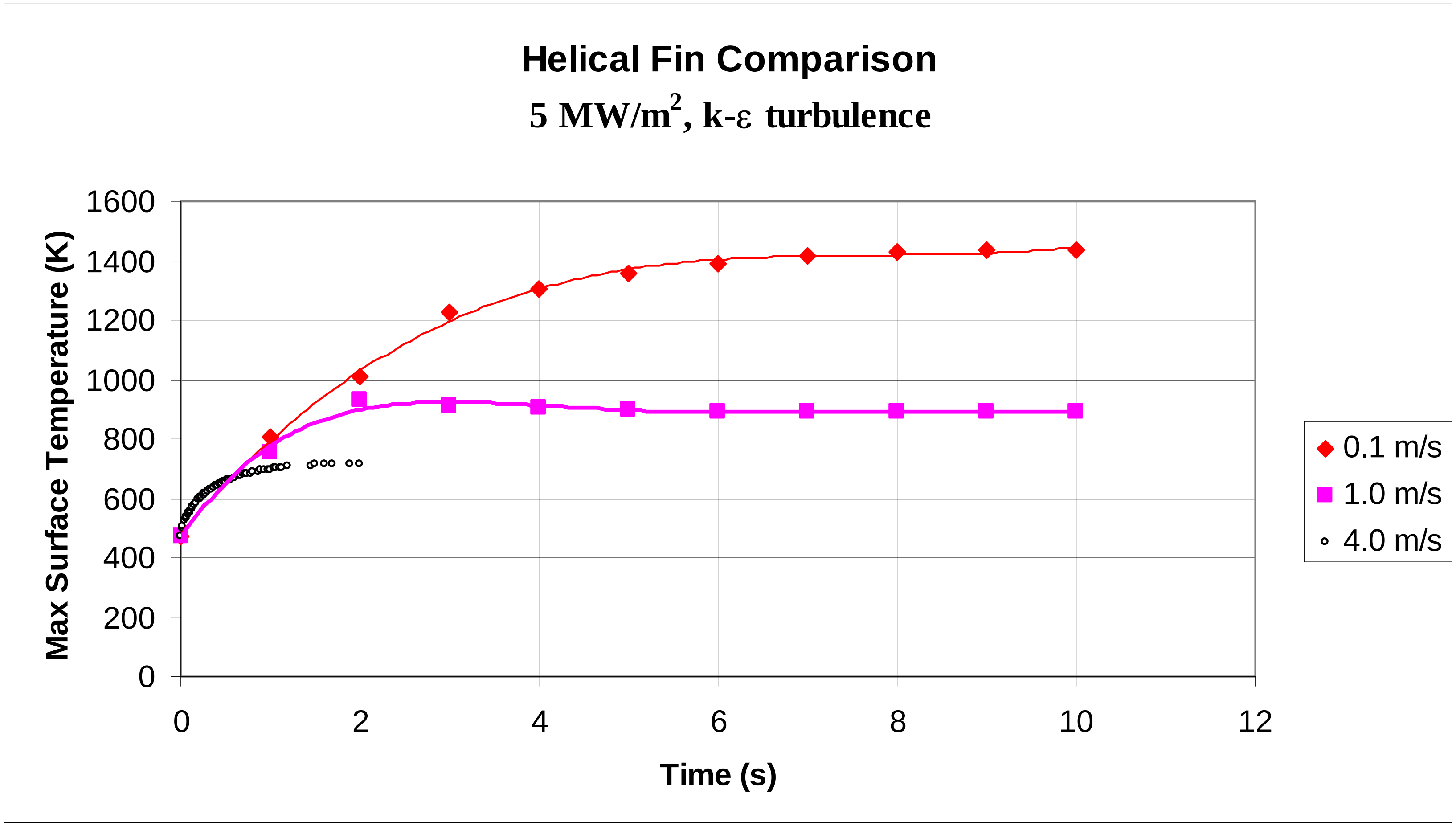
Axial velocity in grooves ~1 m/s.

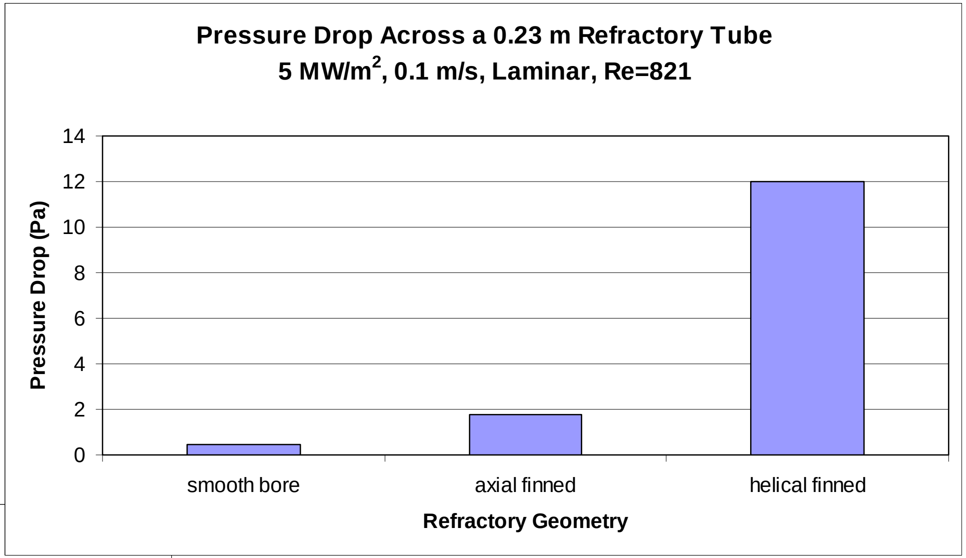
core velocity 4 m/s

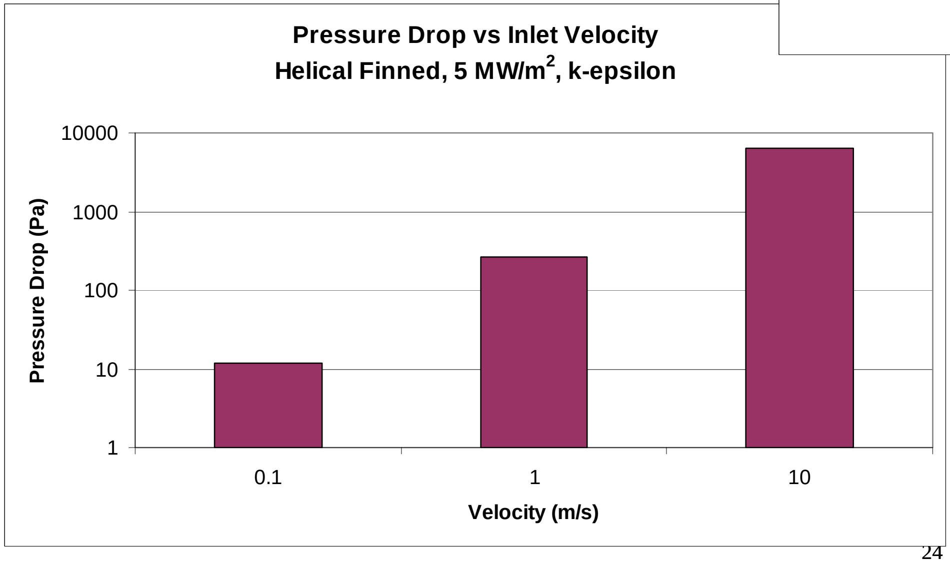
Highly turbulent flows are difficult to initiate.



Fins significantly increase pressure drop.

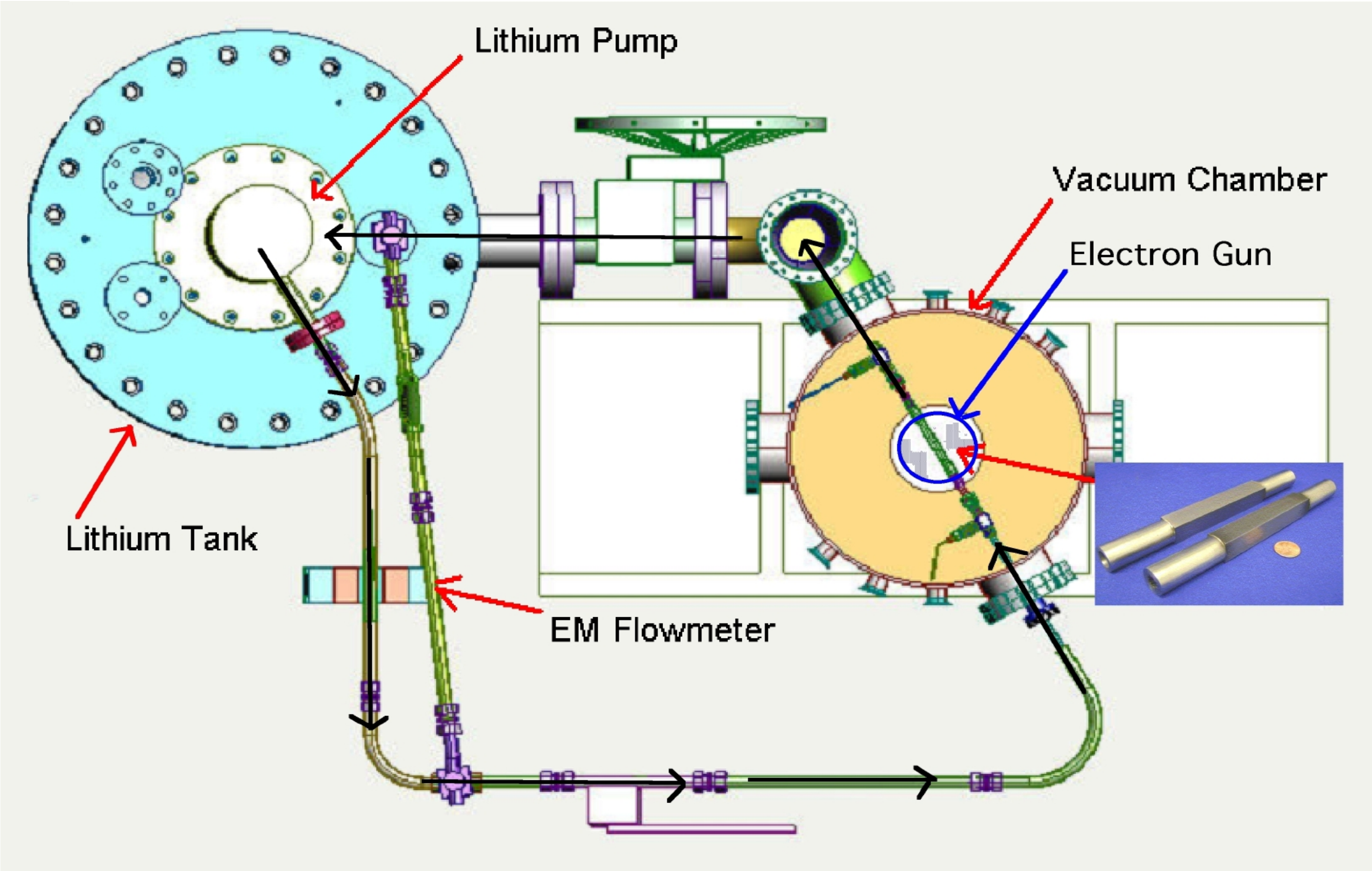
Fins are not always good!



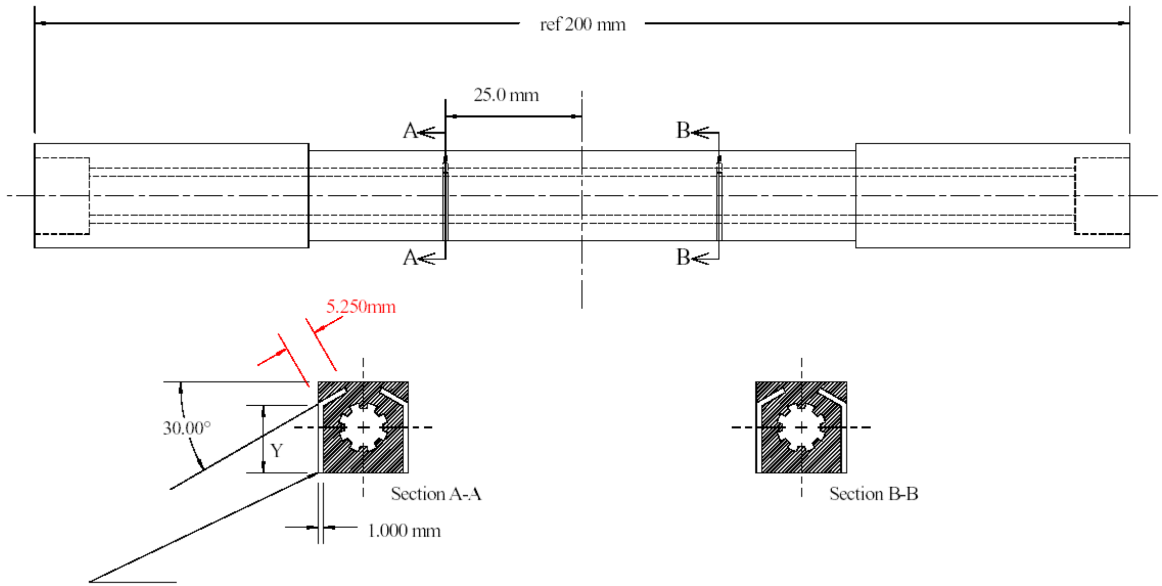


Pumping power requirements increase with very little gain in heat transfer.

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



Refractories are instrumented with 4 type-K thermocouples.



4x, EDM 1.000mm dia. channel, Y long
in the side of the heat sink. At 30° angle, EDM
1.000mm dia. hole, 5.250mm deep.

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

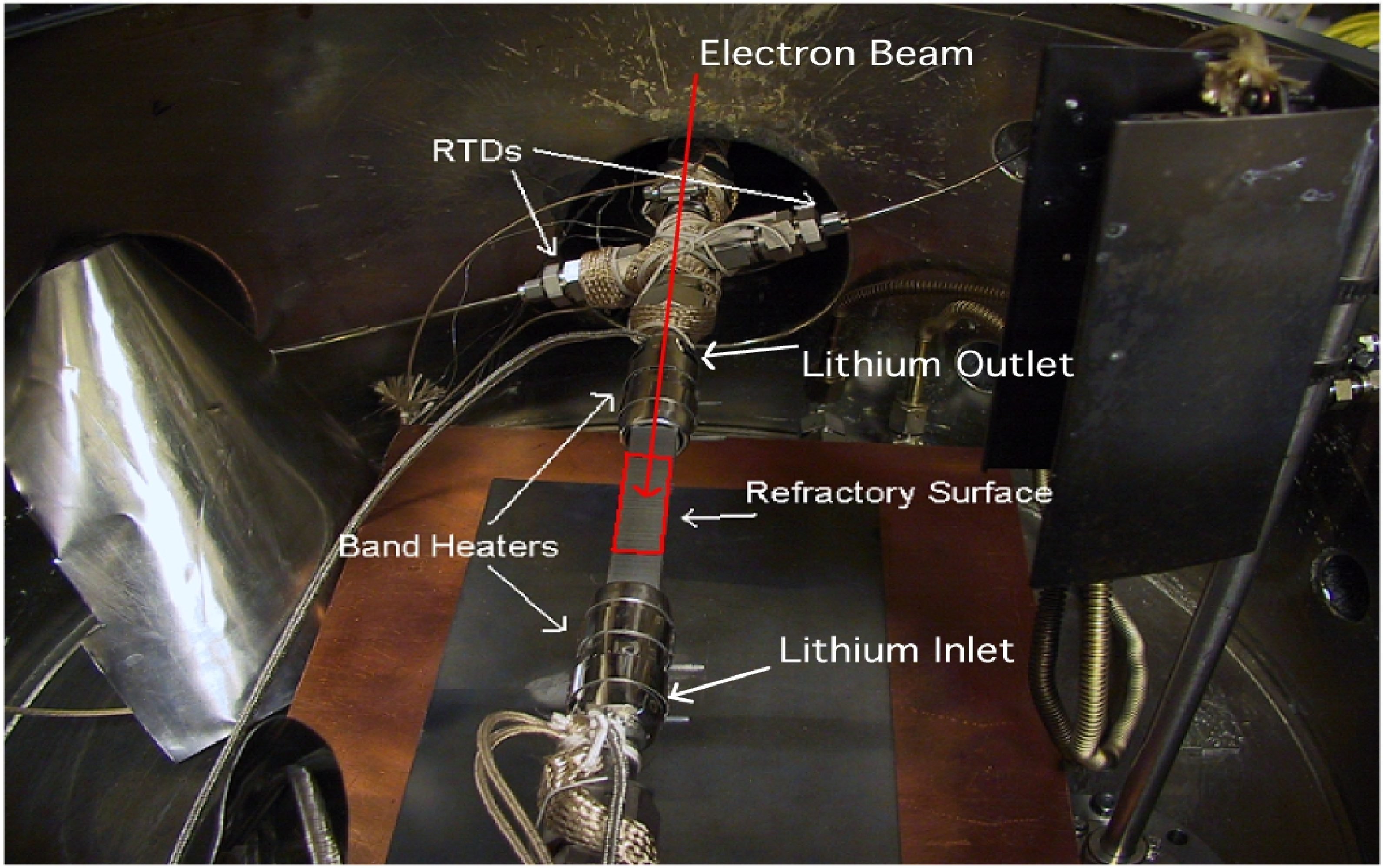
Date: 8/14/02

Scale: None

Sheet: 1 of 1

Drawing Number: PP1049 (Revision A)

Coolant Channel Mounted in LIMITS Vacuum Chamber



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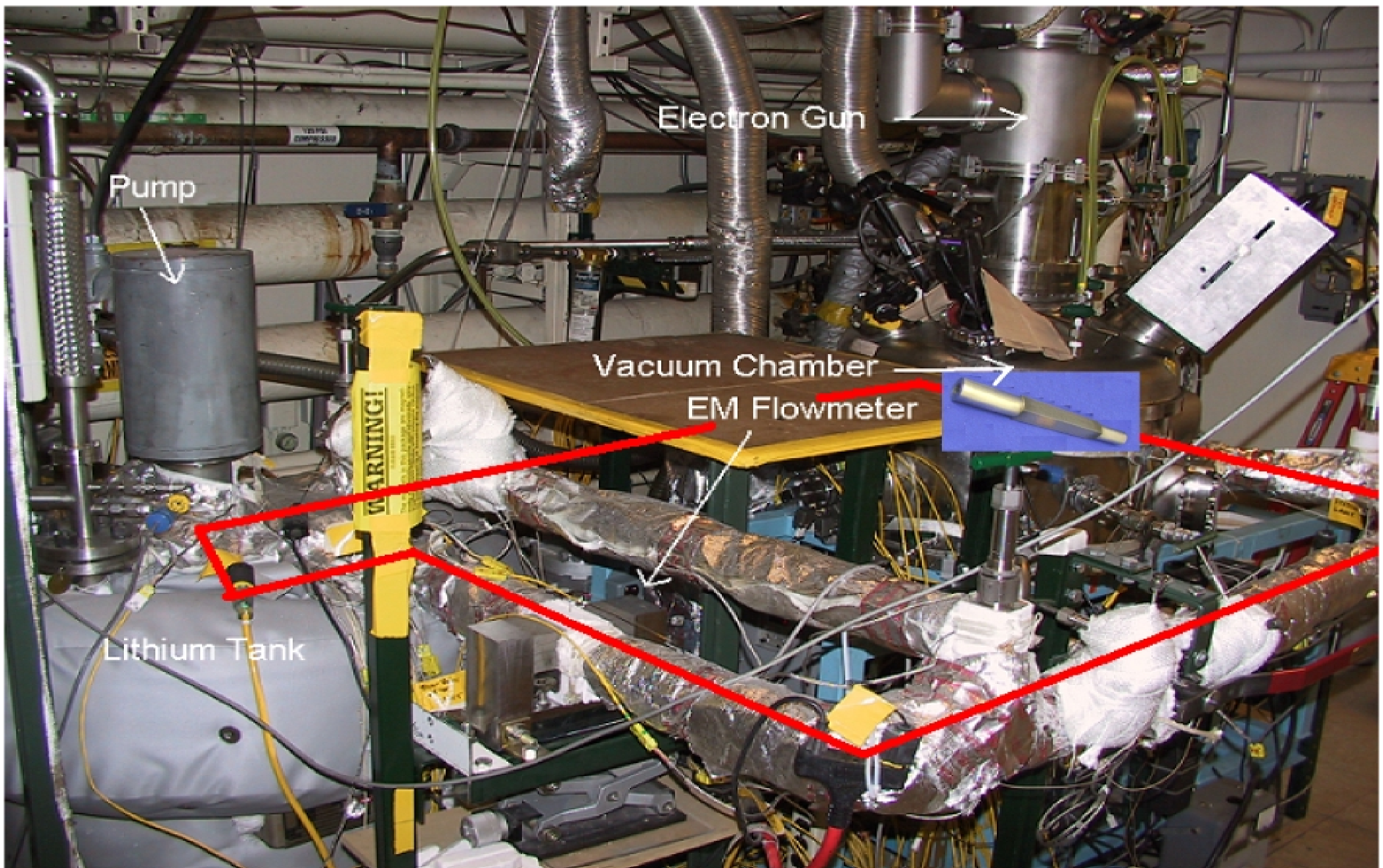
LIMITS at SNL's
Plasma Materials Test Facility

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.