Concept Development and Engineering Considerations of a Steady-State Lithium-Coated Divertor

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Objectives

- Liquid lithium plasma-facing surface
  - Li actively supplied to capillary porous surface

- Actively-cooled
  - Maximize heat flux to coolant (vs. lost to Li evaporation)
  - But protected via Li evaporation in case of very high heat fluxes
  - Vapor and radiative shielding are neglected: conservative estimate.
  - (Calculations for NHTX showed 5-10x greater radiated power than evaporative cooling)

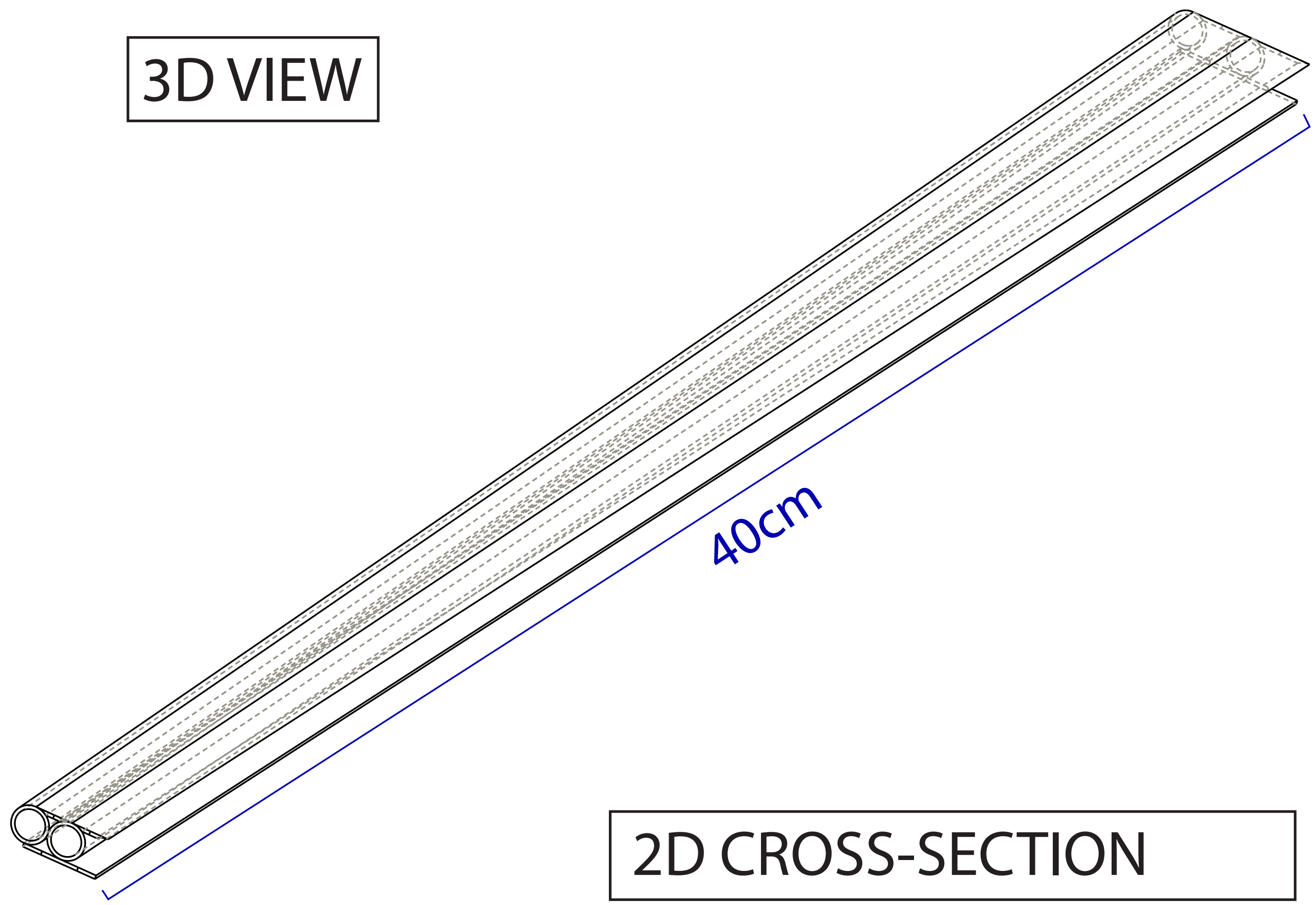
- Mechanical Engineering Considerations
  - Mechanical/thermal stress considerations
  - Minimize required pump power and design complexity

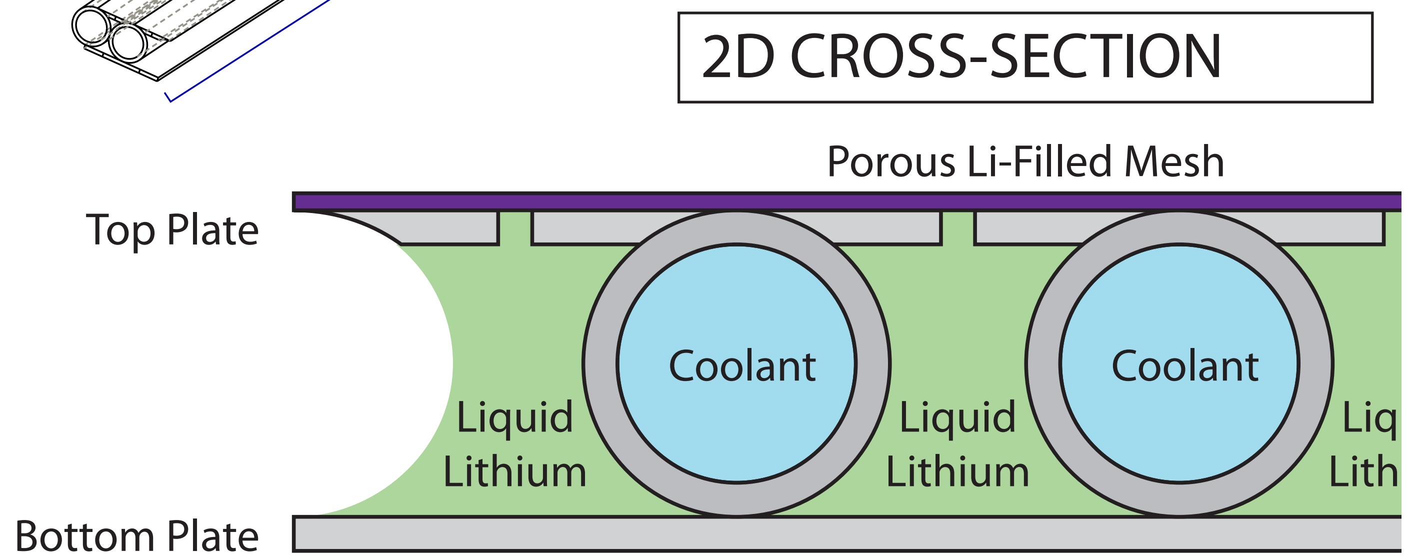
Geometry

- *'Soaker Hose'*
- Circular coolant pipes sandwiched between plates

- Space between pipes is channel for liquid lithium
  - Grows along divertor length

- Top-plate with grooves:
  - Mechanical structure and pipe placement
  - Surface to attach mesh
  - Holes for lithium flow to mesh

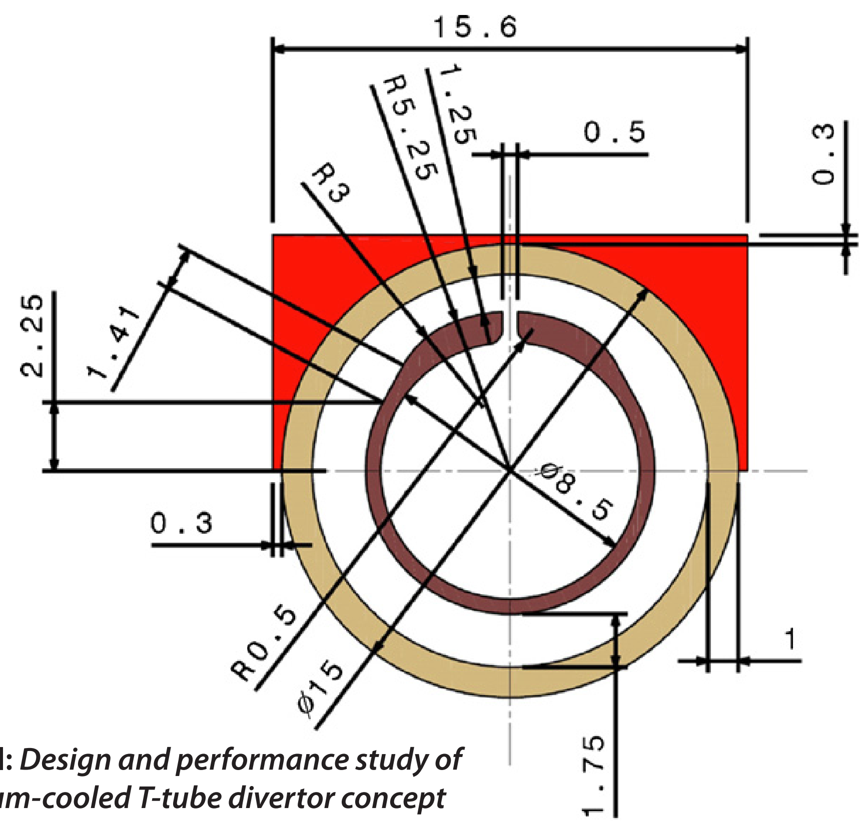




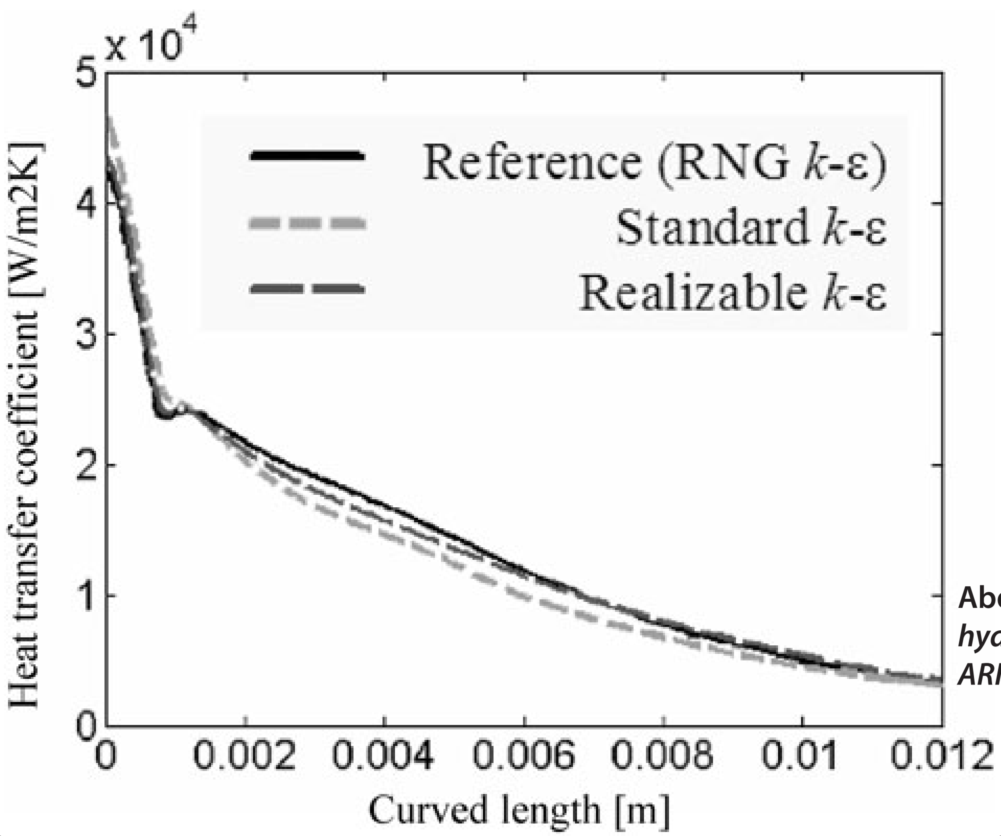
Geometry: ARIES T-Tube

- ARIES T-Tube design uses impinging jet for excellent cooling at top of pipe
  - Design method experimentally verified

- Originally designed for tungsten tubes and armor and 10MW/m[2] peak
  - How does T-Tube cooling compare w/ turbulent pipe flow for this application?
  - Implement published result for h on inside of pipe: valid for 13mm ID
  - Can play with outside geometry



Ihli et. al: ***Design and performance study of the helium-cooled T-tube divertor concept***



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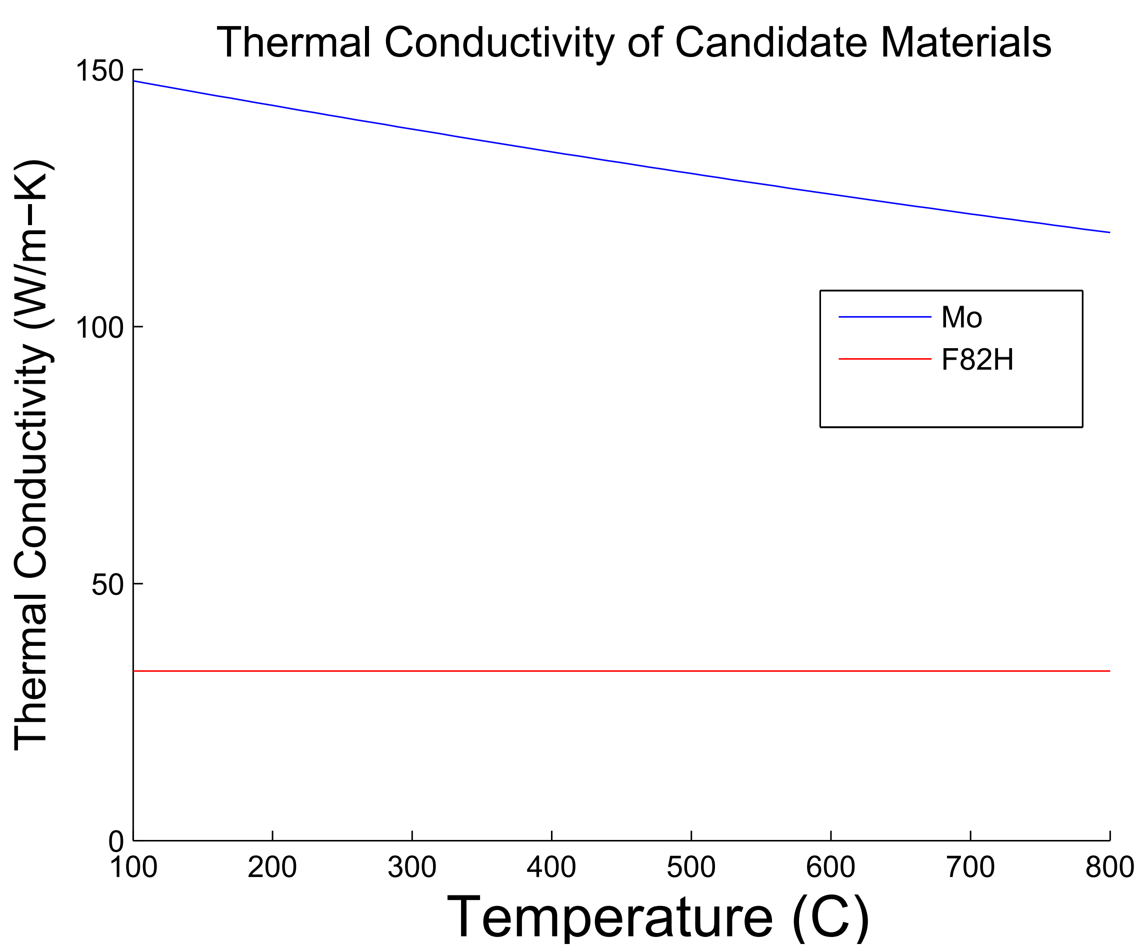
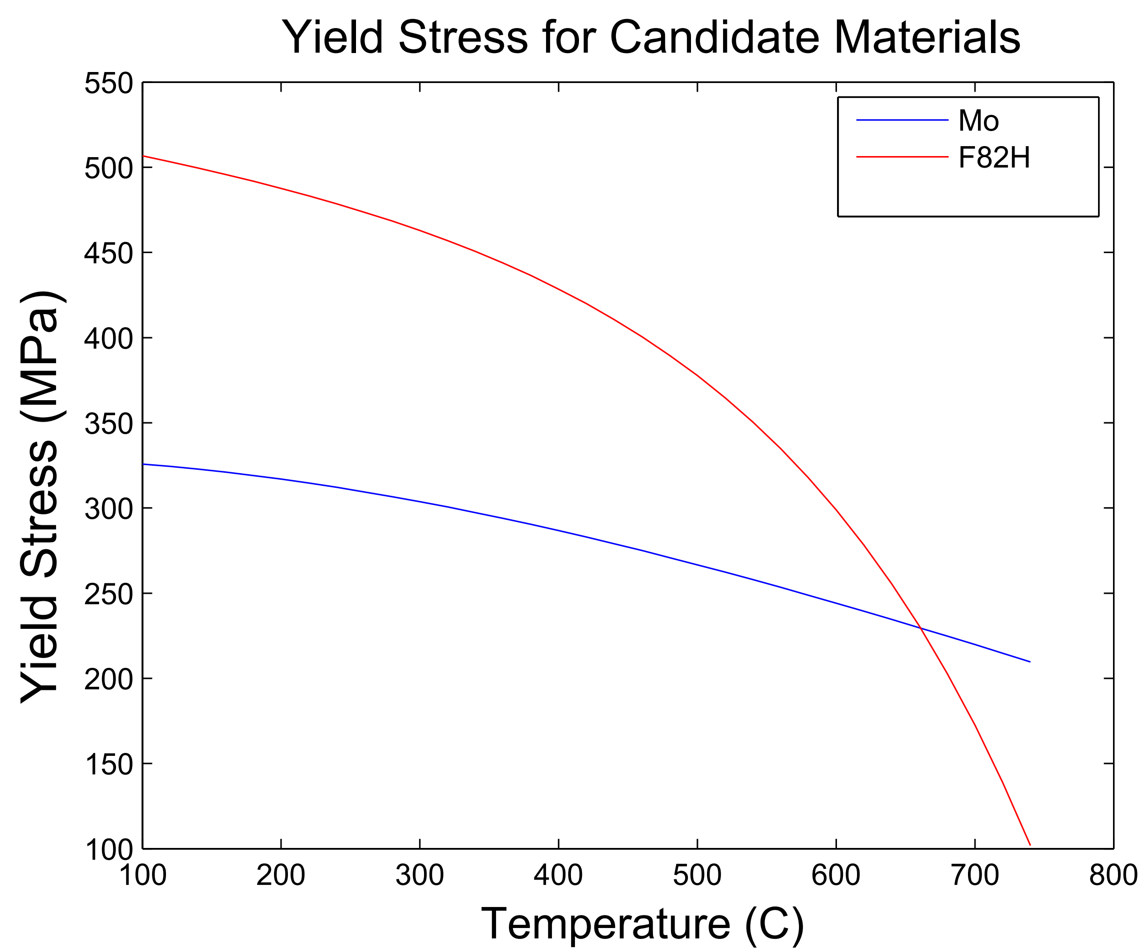
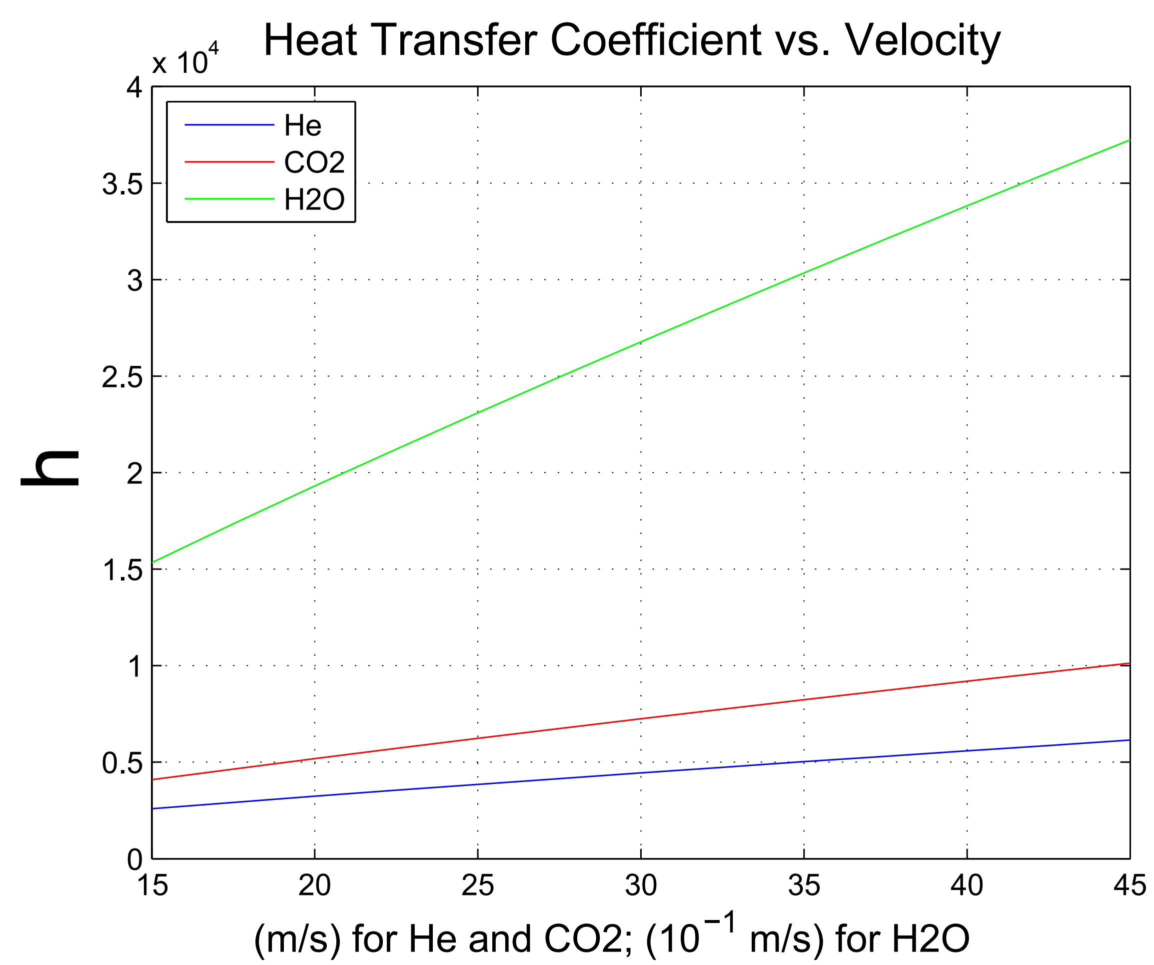
Candidate Materials

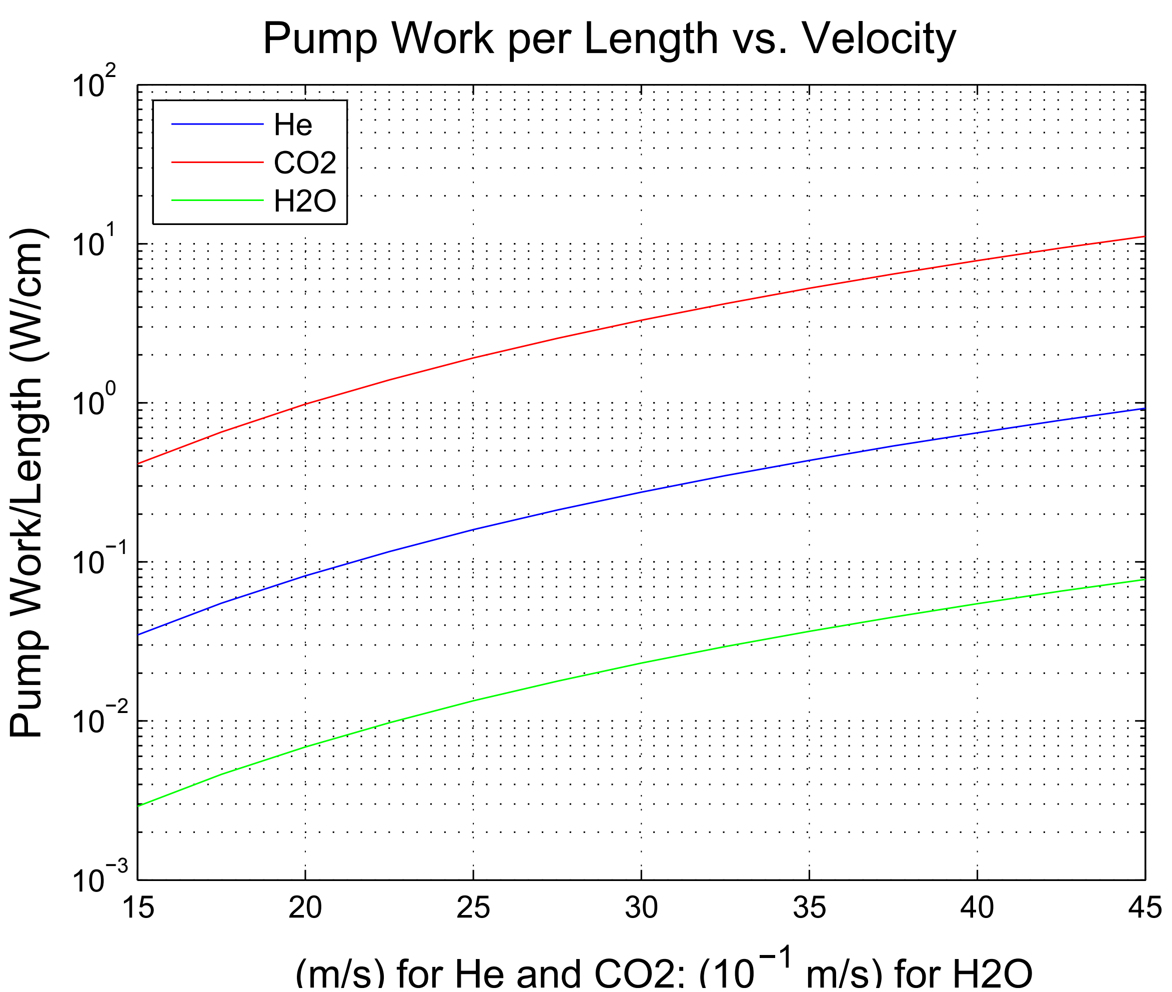




- **F82H or Moly**
  - **F82H:** Good for reactor situation with neutron fluence
    - But: low max. temp (~550C) and thermal conductivity *k*, potentially problematic magnetic properties for NSTX-U
  - **Moly:** Excellent *k*, operating temp range, magnetic properties, good proxy for tungsten

Candidate Coolants

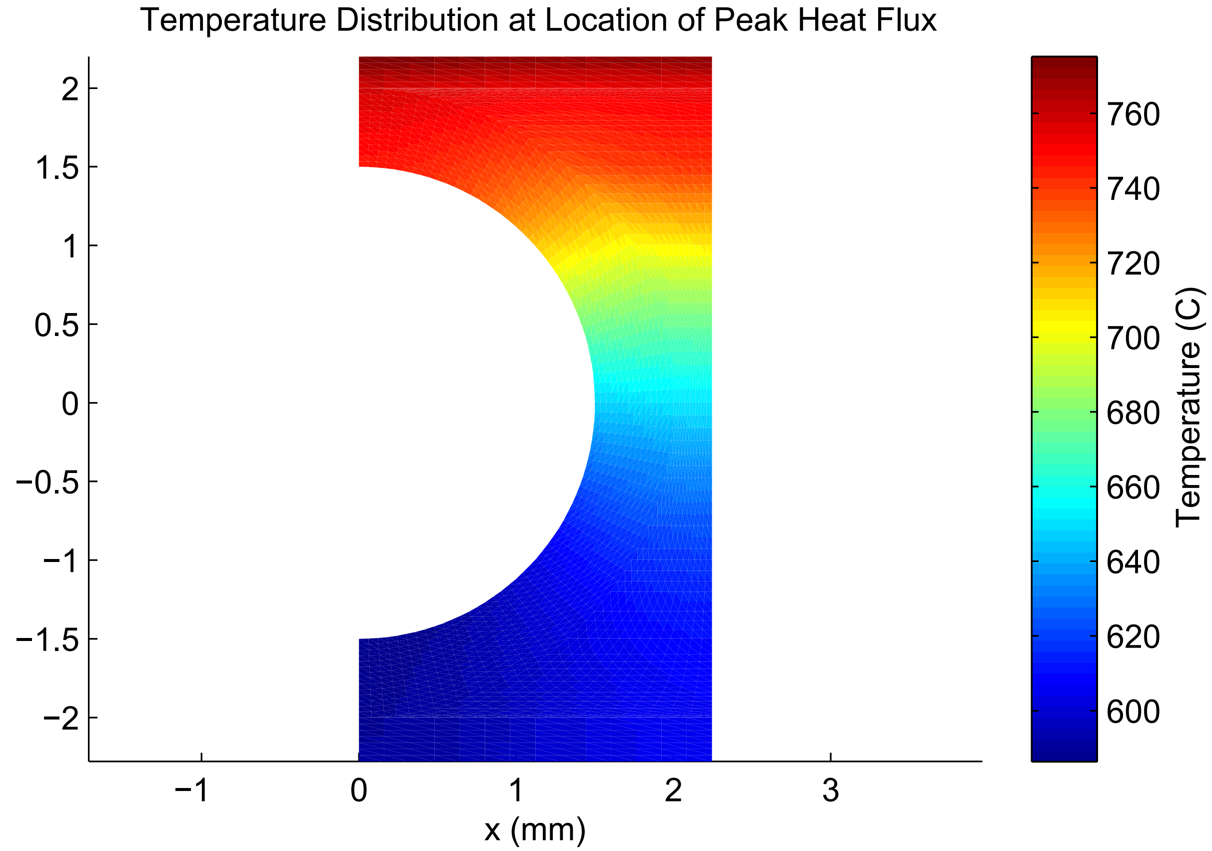


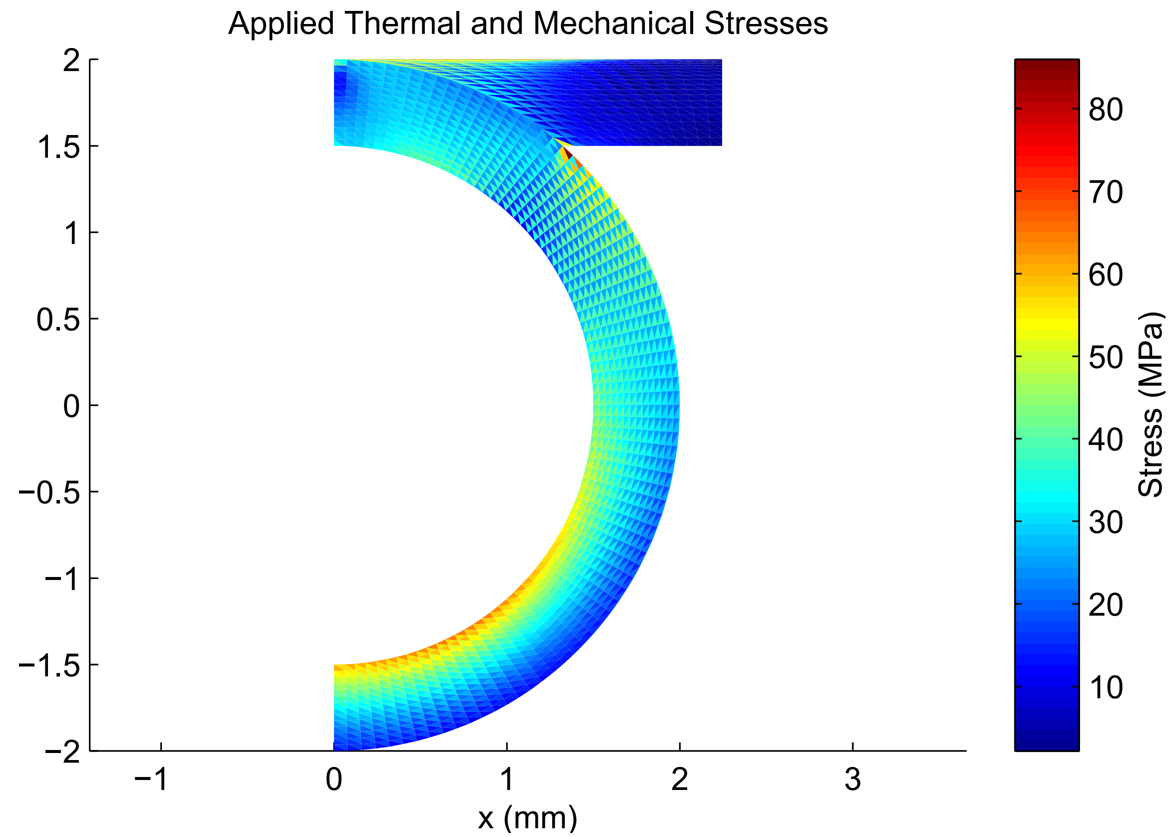


- **CO_2 or Helium** at 10MPa
  - Inlet temperature must be >181C to keep lithium liquid
  - Far above critical point
  - CO_2 is more effective coolant, but harder to pump
  - Cannot use water: reactivity with Li

FEM Model

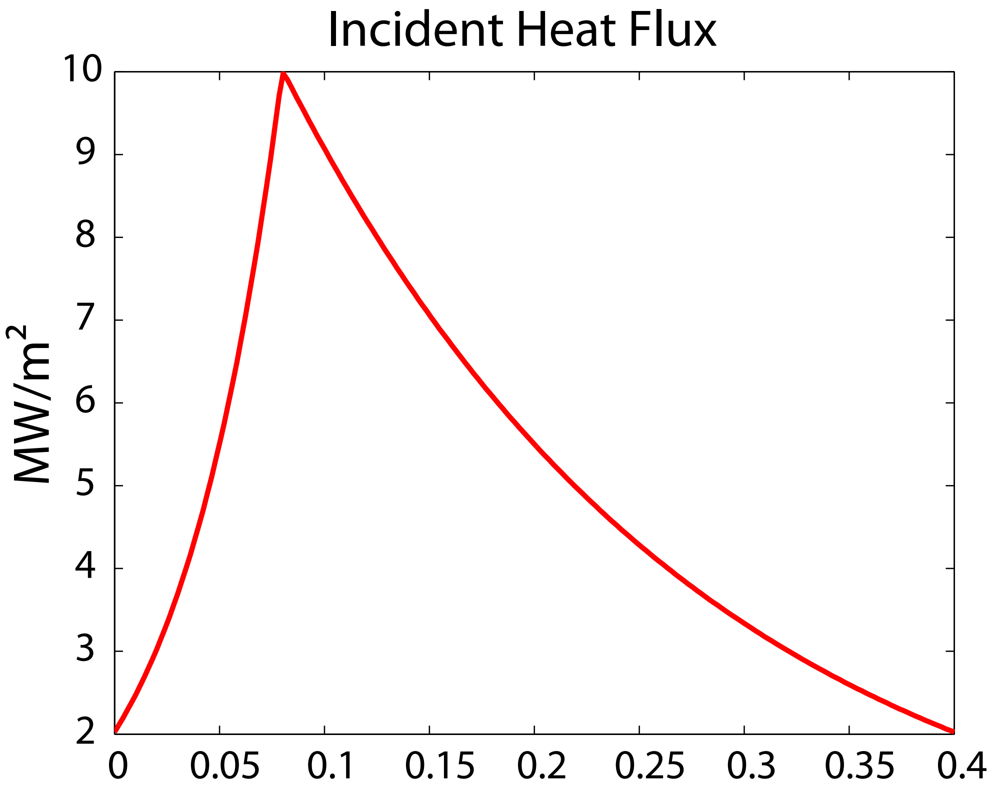
- **Pseudo-3d FEM model in MATLAB w/ Evaporation:**
  - Implement established correlations for coolant properties
  - 2d heat transfer, mechanical, and thermal stress FEM analysis
  - Iterate to solve for: Nusselt number (depends on inner pipe temp.)
    - and Li evaporation (depends on divertor temp.)
  - Track evolution of coolant properties along pipe
  - Using assembly of 2d slices: assumes axial conduction is small





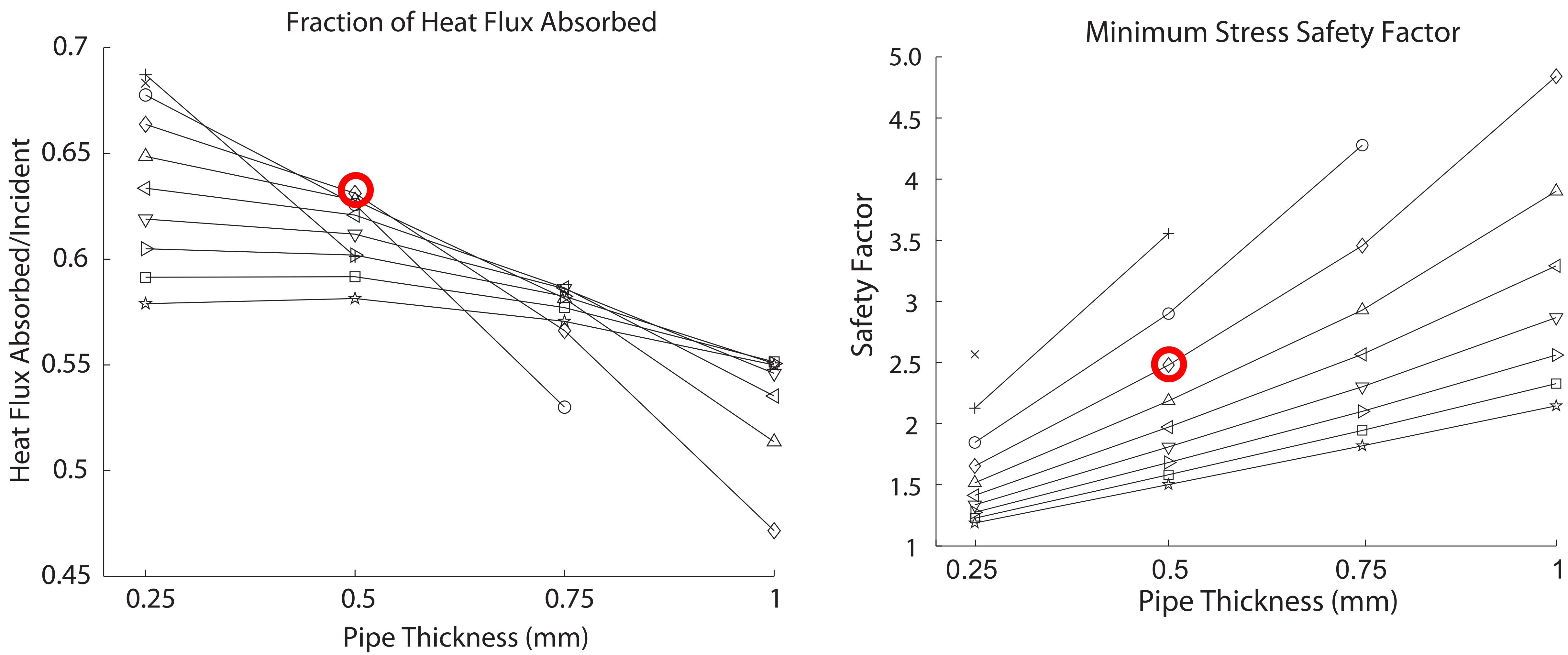
Preliminary Scans

- Scan parameter space:
  - Vary pipe diameter, pipe thickness, coolant pressure, coolant speed
- Important Metrics:
  - Total heat flux absorbed into coolant/Total heat incident heat-flux
  - Total lithium evaporation rate
  - Safety factor: (Thermal + Mechanical Stress)/Yield Stress
  - Max surface temperature

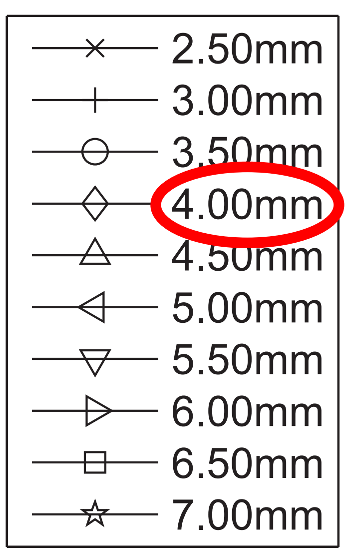


- Incident Heat Flux:
  - Peaks at 10MW/m2
  - Total On Divertor = 10MW

Parameter Scan Results: CO_2 at 30m/s, Mo pipe



Pipe OD



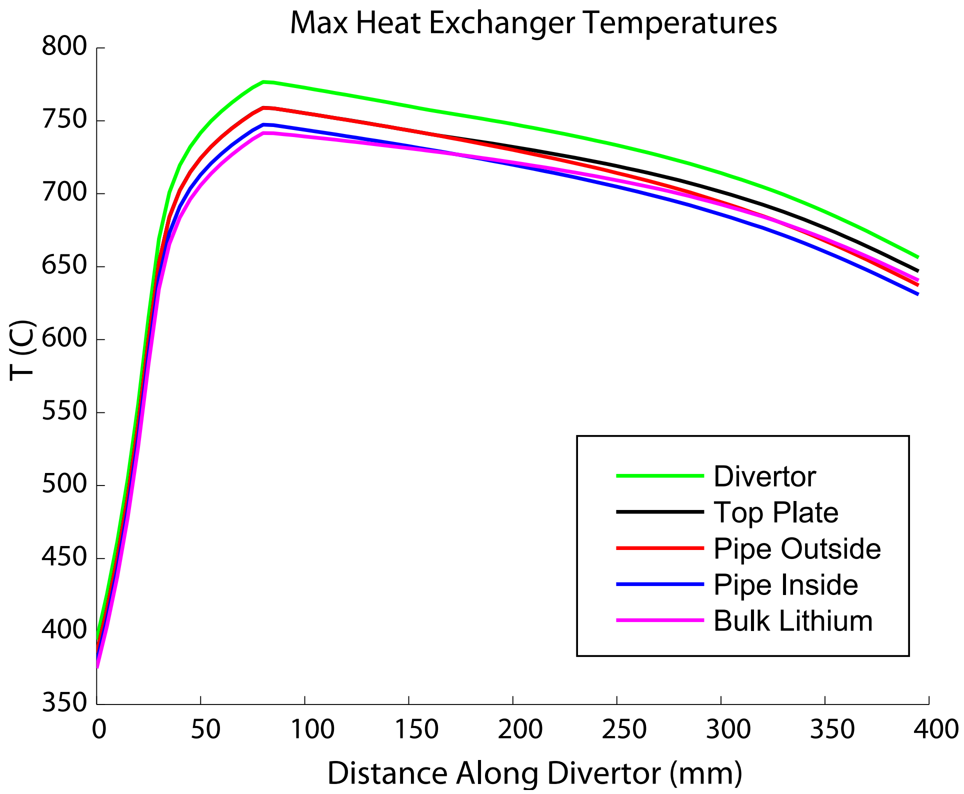
- **Selection Procedure:**
  - Minimize heat flux evaporated
  - S.F. > 2
  - Follow same procedure for other coolants, materials

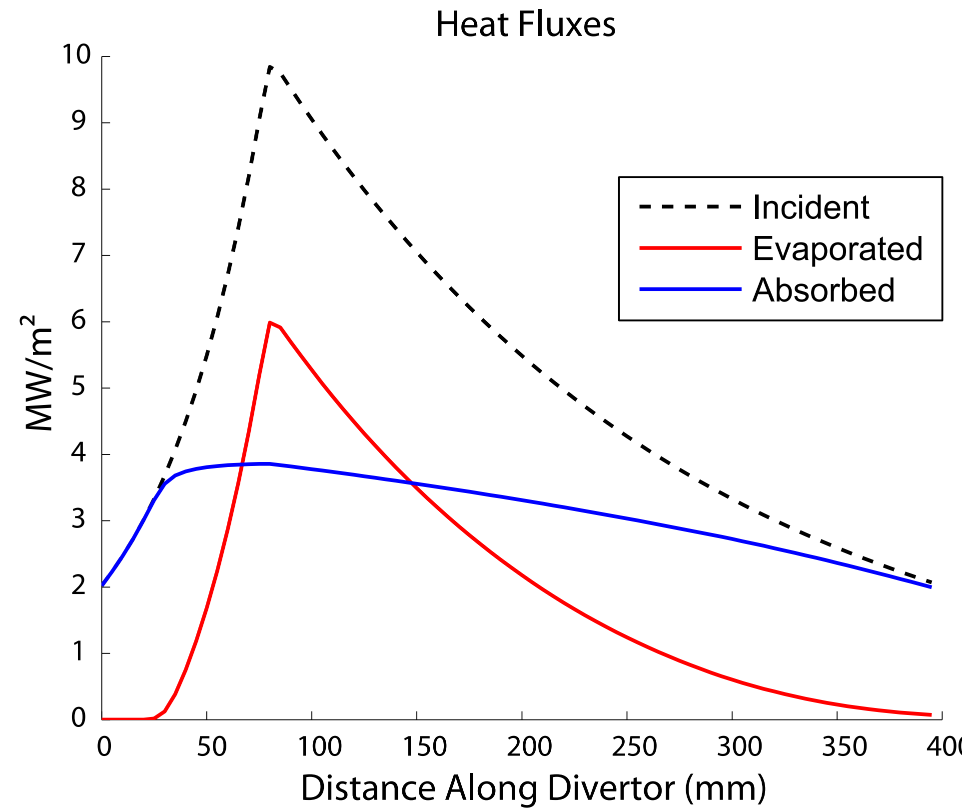
Chosen Solutions - Detailed Comparison

Parameter	T-Tube He	He	CO2
Outer Diameter (mm)	14.00	5.0	4.0
Wall Thickness (mm)	1.0	0.5	0.5
Armor Thickness (mm)	2.0	0.5	0.5
Coolant Velocity (m/s)	–	45	30
HF Absorbed/Incident	0.91	0.57	0.63
Total power evaporated (MW)	0.84	4.4	3.8
Total lithium evaporation rate (g/s)	40	205	178
Max lithium velocity in channel (mm/s)	33.3	175	191
Max divertor temperature (C)	786	779	777
Number of pipes	275	823	1030
Total pump work (MW)	0.19	0.035	0.13
Minimum safety factor	1.6	2.0	2.4
Coolant temperature gain (C)	42	225	203
Total mass flow (kg/s)	44	2.4	14

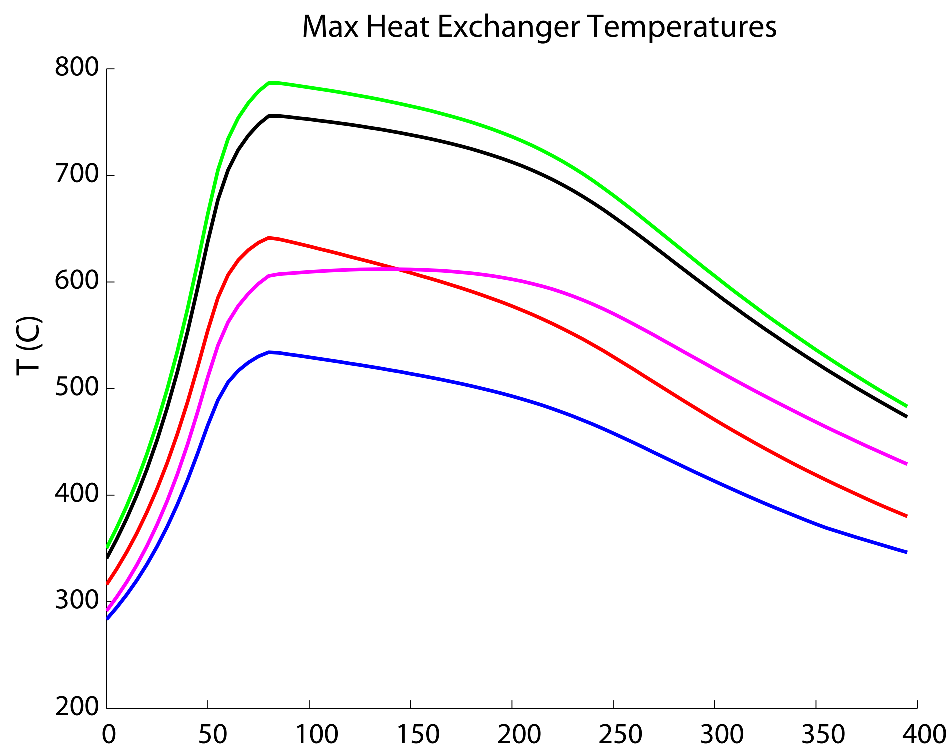
Variation Along Divertor Length

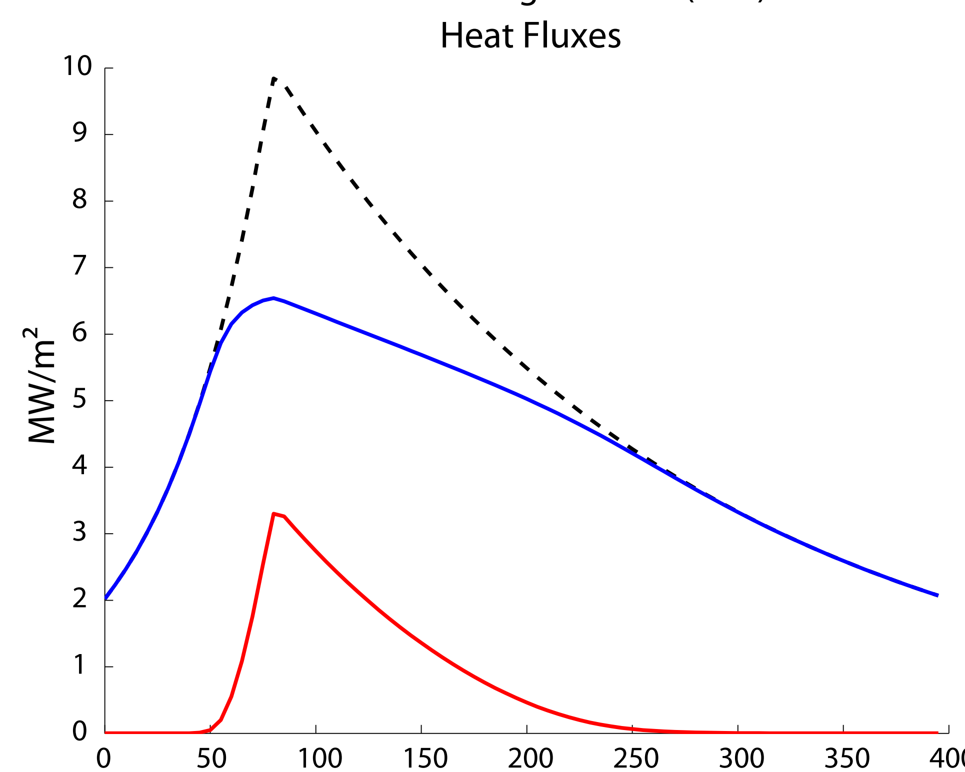
Helium Pipe





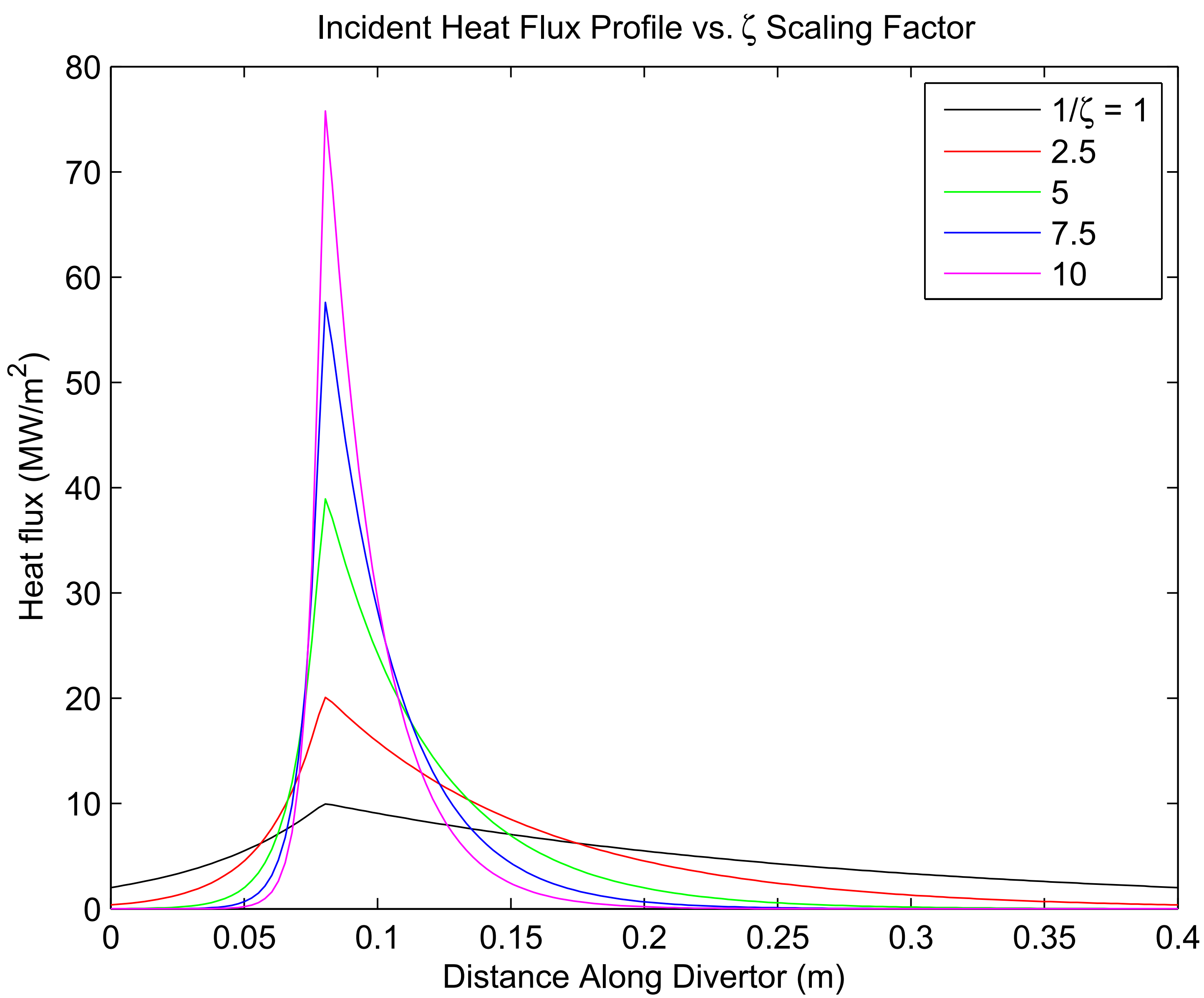
Helium T-Tube



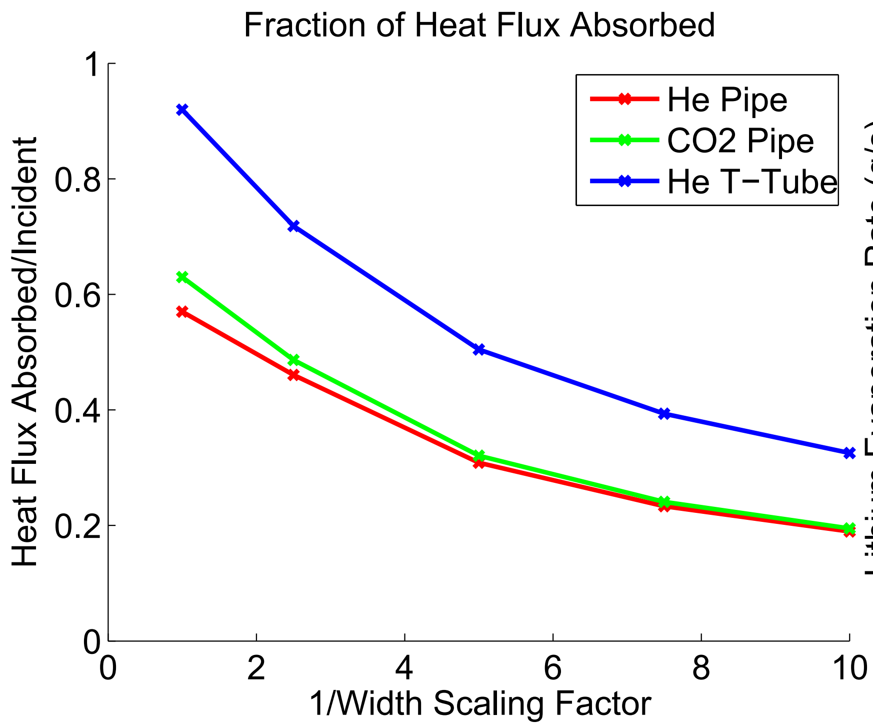


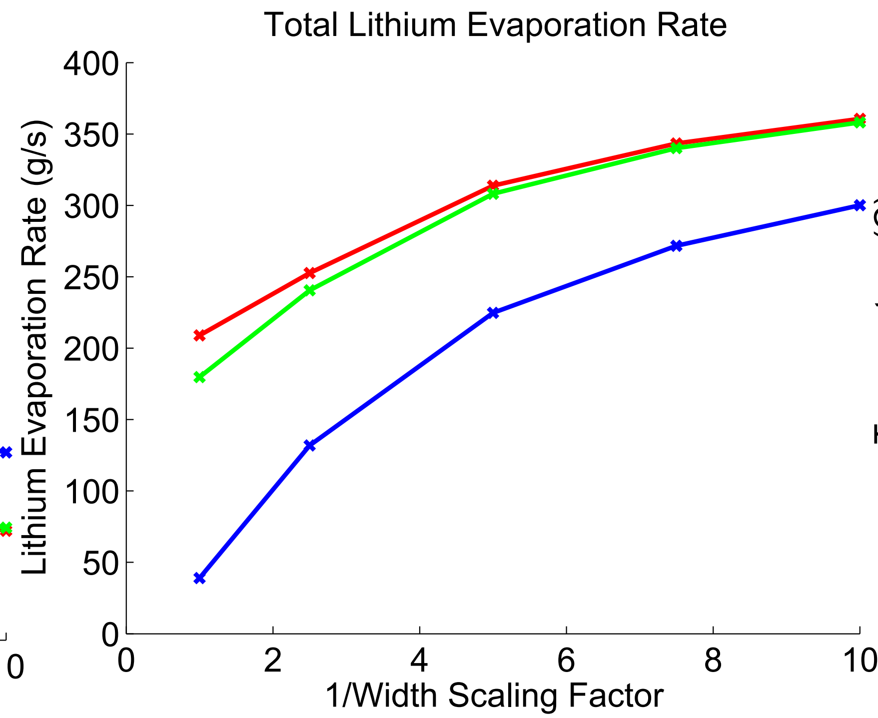
Effect of Heat Flux Profile

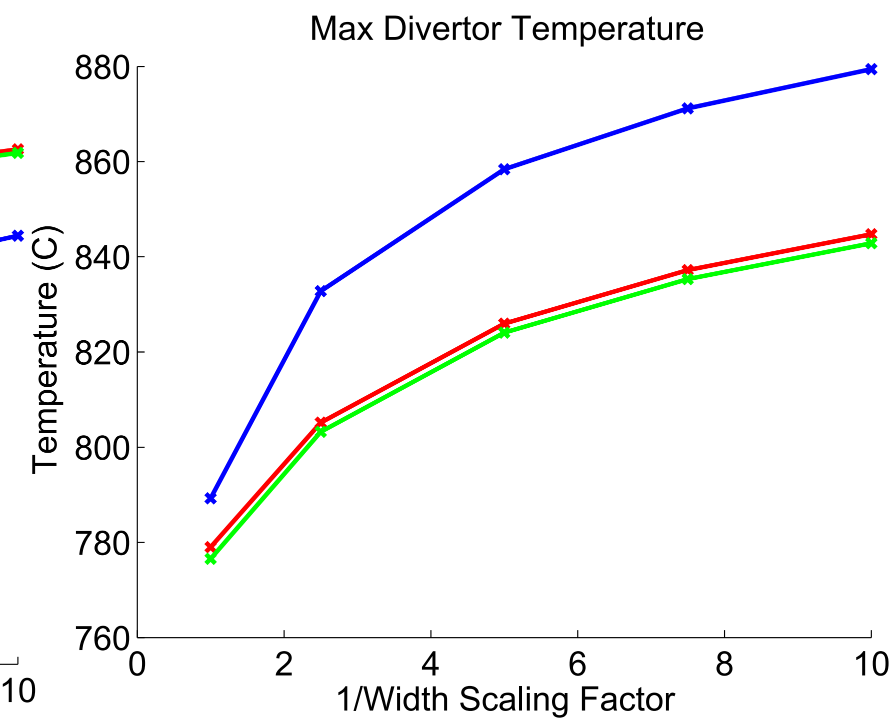
- **Test robustness to very high heat fluxes:**
  - Use same total heat flux, reduce e-folding distance
  - Not accounting for vapor cloud or radiation: conservative estimate

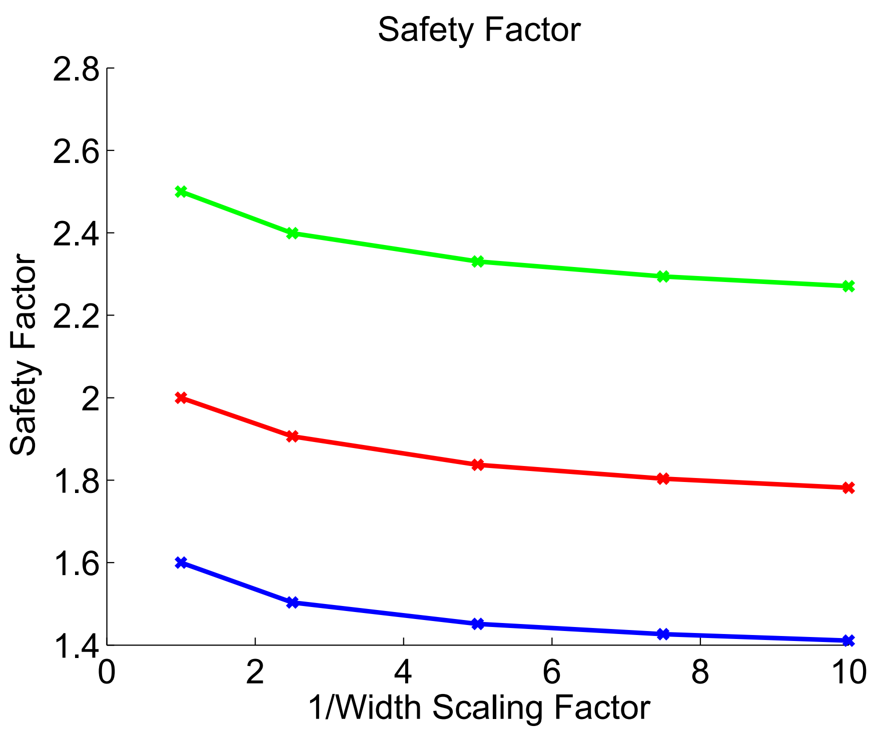


Effect of Heat Flux Profile Results



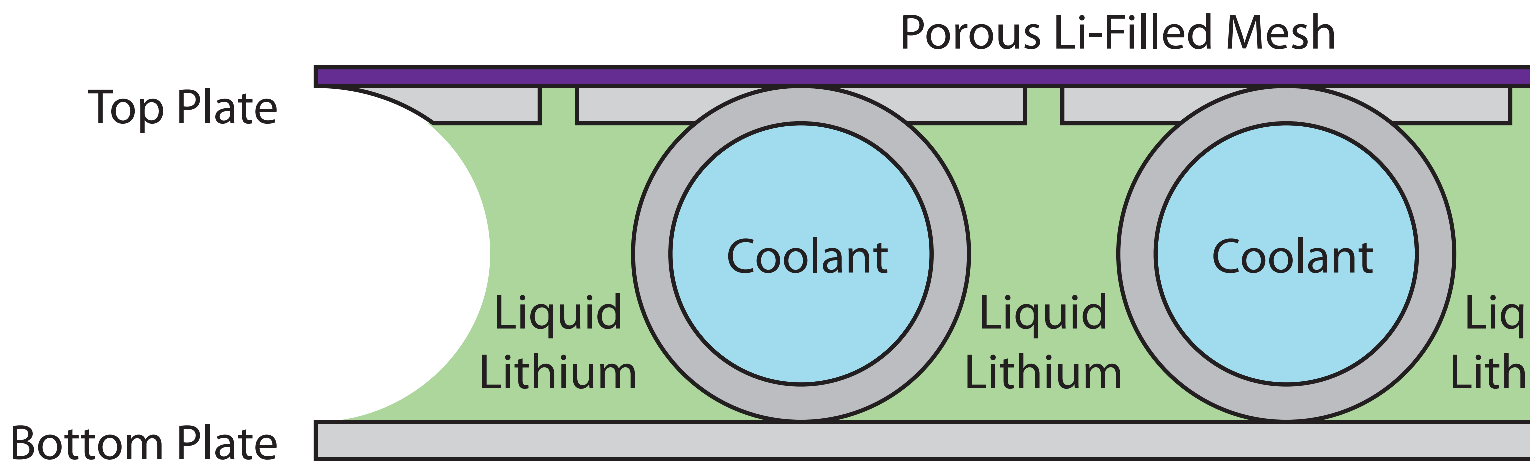






- **Solutions are robust:**
  - Safety factors are O.K.
  - Temperatures are O.K.

Conclusions



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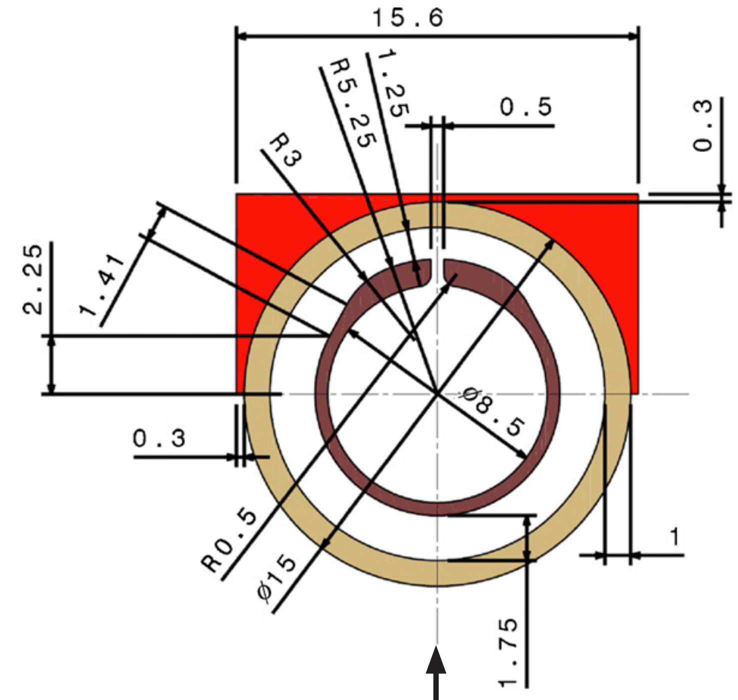

'Soaker Hose'-Style Liquid Lithium Divertor
'Coolant': Simple Turbulent Pipe Flow or ARIES T-Tube

- Actively-cooled liquid-Li divertor feasible for NSTX-U type heat flux
- 9% heat flux to evaporation with complex solution (T-Tubes)
- 37% heat flux to evaporation w/ simple solution (CO_2 pipe flow)
- Li evaporation effectively clamps system temperatures
- Protects divertor from very high heat fluxes: safety factor/temps O.K.

Remaining Work

- **Remaining Work:**
  - Fluid + MHD flow of lithium in channels, capillary mesh
    - Figure out right size, location of holes in top plate
  - Time-dependent 3d simulation, including axial conduction
  - Try T-tubes with smaller ID: Need turbulent CFD
  - P_{rad} vs. P_{evap} by lithium: better estimate of evaporation rate
  - Manifold and endplate designs, mounting
  - Disruption forces