INL/MIS-22-66363-Revision-0

# Heat Pipe Modeling Using Sockeye

March 2022

Joshua E Hansel

Changing the World's Energy Future

Idaho National Laboratory

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**March 2022**

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**Idaho Falls, Idaho 83415**

**http://www.inl.gov**

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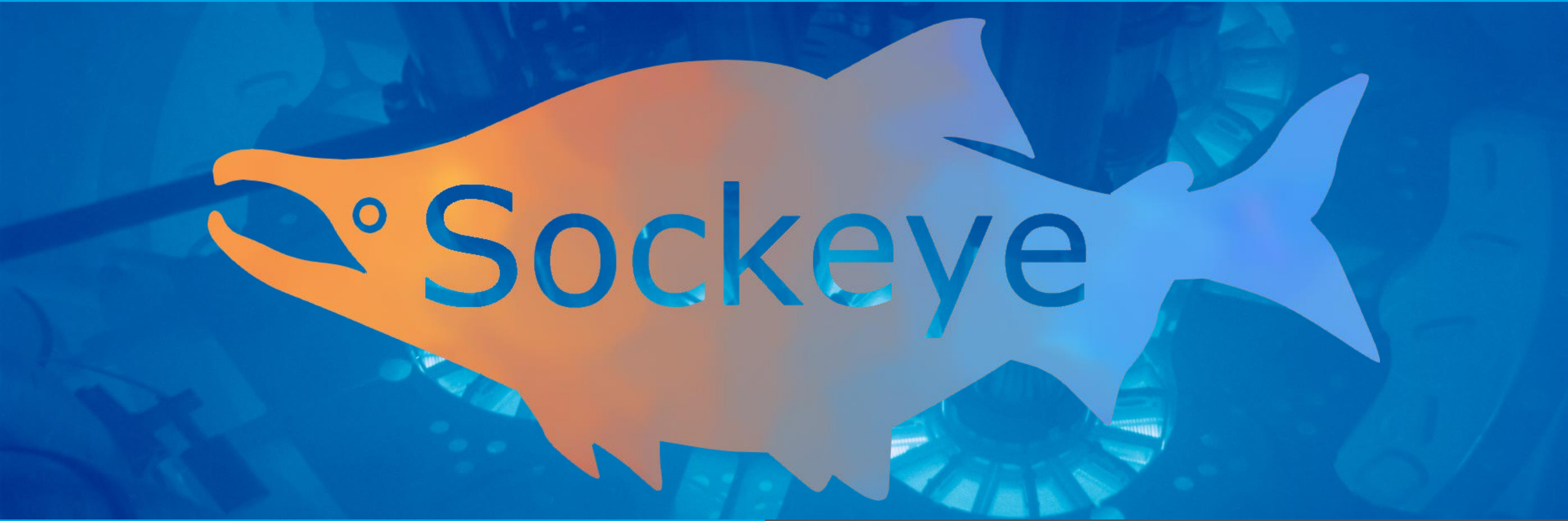


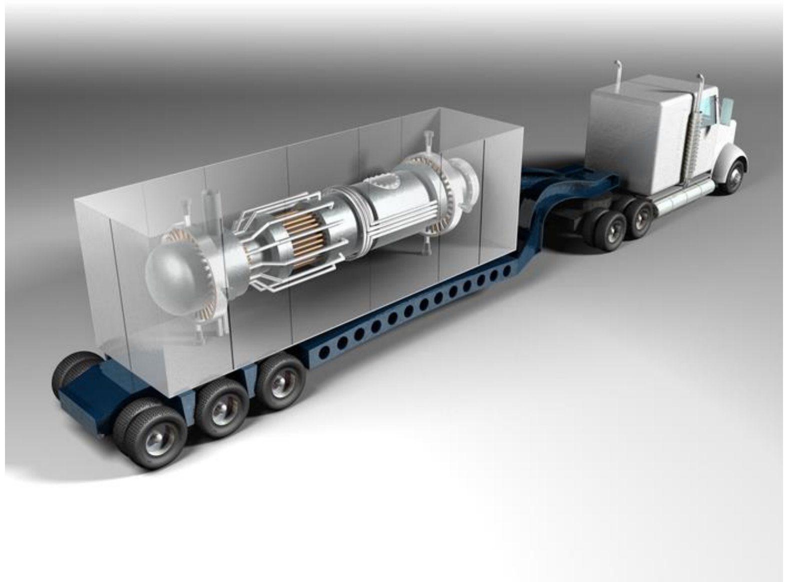

# Heat Pipe Modeling Using Sockeye


## Joshua Hansel

Computational Scientist (INL)

# Motivation

- Heat pipe modeling is a component of microreactor modeling
  - Many microreactor designs cooled by heat pipes
- Microreactors:
  - Relatively small power output, up to 20 MWth
  - Relatively small physical size
  - Portable - entire unit transportable via truck, shipping container, plane, or rail
    - Can be implemented in remote areas or areas of natural disaster for emergency power
    - Can be exchanged with ”fresh” microreactors quickly
  - Factory fabricated, eliminating some difficulties of large-scale construction projects
    - Reduced capital cost



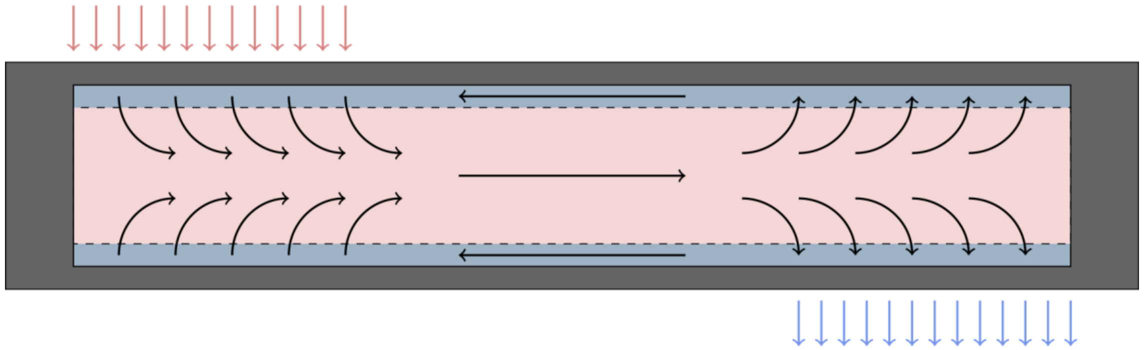
# What is a Heat Pipe?

- A heat pipe is a sealed tube with working fluid inside that transfers heat via an evaporation/condensation cycle and has a wicking structure inside
- Desirable properties:
  - Very efficient heat transfer
  - Near isothermal operation – little temperature drop over long distances
  - Passive, no moving parts
  - Compact cross section
- Used for a variety of applications:
  - Electronics cooling
  - HVAC
  - Space applications
  - Permafrost cooling

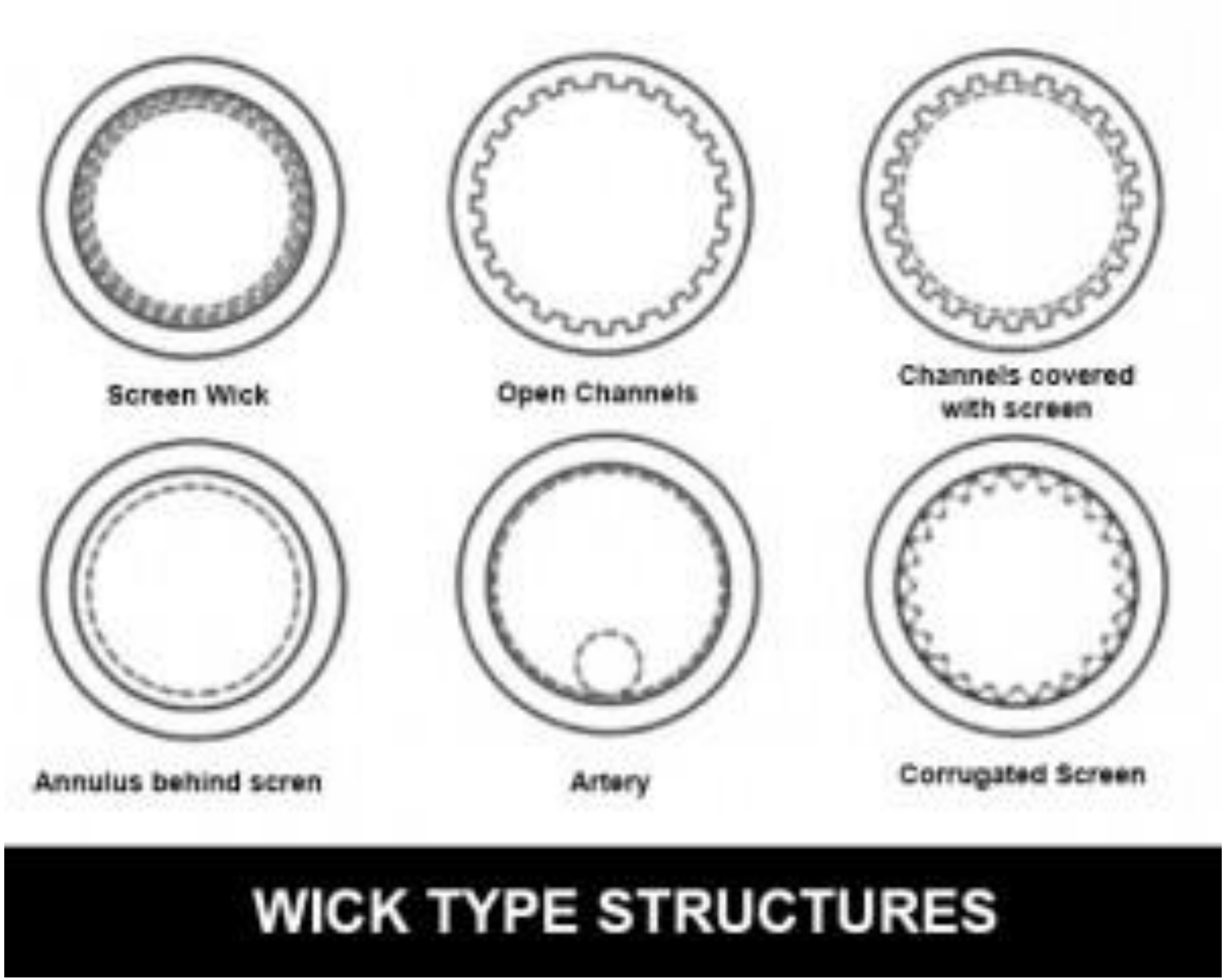
**Trans-Alaska Pipeline**

# The Basics of Heat Pipe Operation

- Heat pipes operate on an evaporation/condensation cycle:
  - Heat vaporizes working fluid in the “evaporator” end of the pipe
  - Vapor pressure gradient causes vapor to travel down length of heat pipe, passing through “adiabatic” section until it is cooled in the “condenser” section, condensing it and releasing its latent heat
  - Condensed fluid returns to the heated end:
    - Thermosyphons must use gravity to do this
    - Heat pipes use capillary forces to do this, sometimes counter to gravity
  - Cycle begins again



# Types of Wick Structures

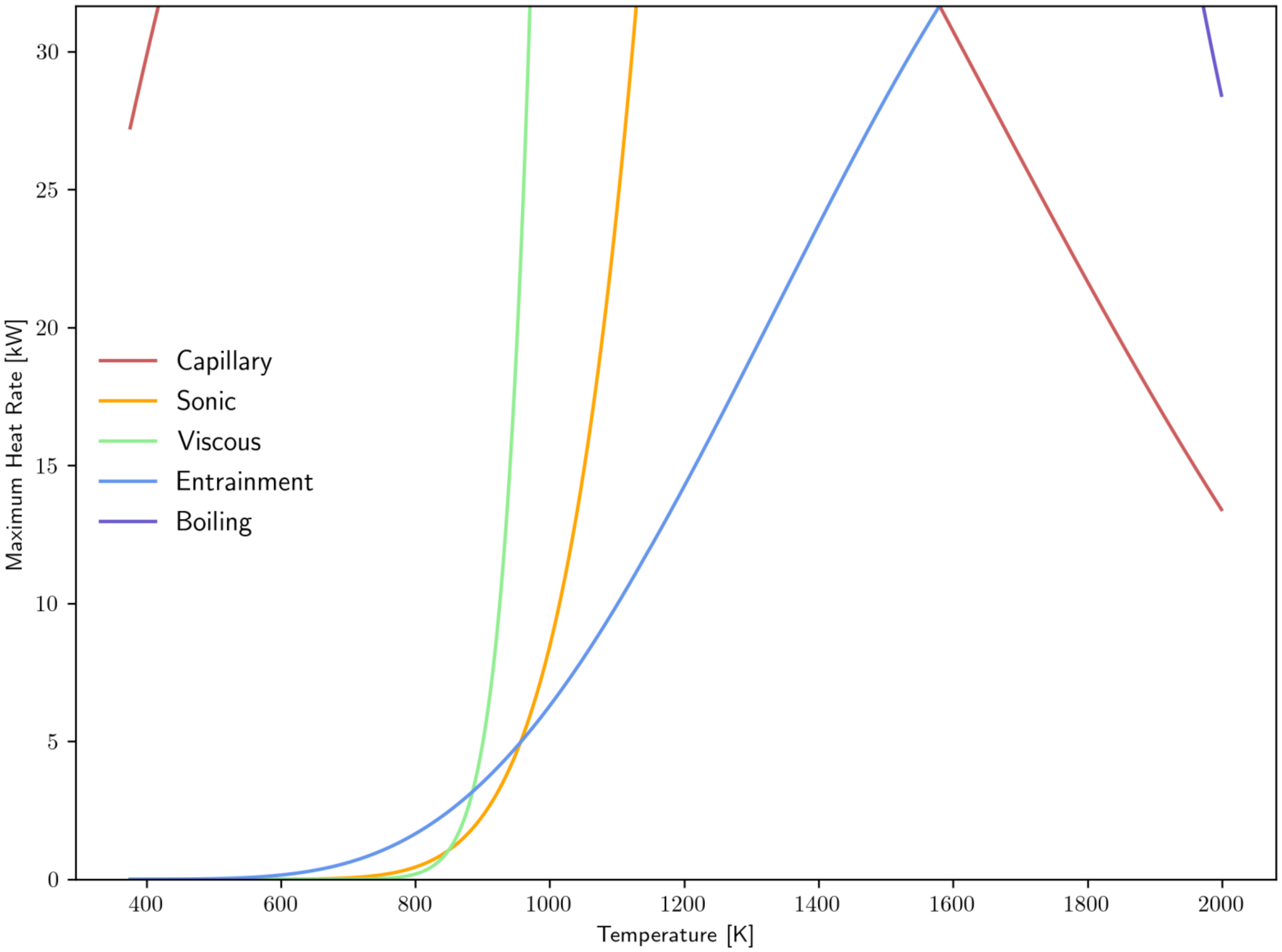


# Heat Pipe Limits

- While reliable, they must be used within some limits
  - Various fluid mechanics limit heat throughput
- **Capillary limit**: The capillary pressure may be insufficient to sustain the pressure drops around the heat pipe circuit.
- **Viscous limit**: Viscous drag in vapor may prevent movement to condenser end.
- **Sonic limit**: Vapor can be “choked” at evaporator exit, leading to a sonic bottleneck.
- **Entrainment limit**: Liquid can be sheared off wick surface into vapor core.
- **Boiling limit**: Excessive boiling at wall and in wick can impede capillary action, preventing liquid from returning to evaporator.

# Heat Pipe Limits

- Designers often consult analytic expressions of various heat pipe limits
- Typically give maximum heat rate through heat pipe vs. some reference temperatures
- Operating space is area under all curves



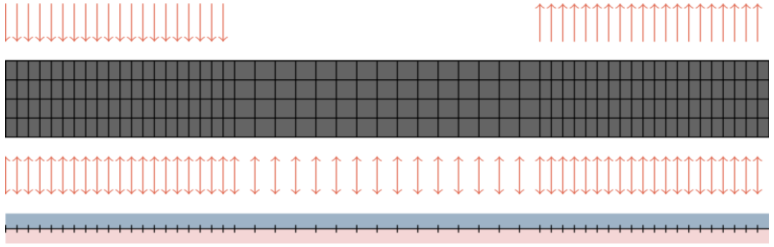
# Sockeye Introduction

- Objective of Sockeye:
  *Provide an engineering scale tool for the evaluation of heat pipes in microreactors.*
- *Engineering scale*: Need to minimize computational expense → minimize dimensionality to reduce degrees of freedom
  - Primary model is 1D, but there is also 2D heat conduction.
- "*Heat pipes in microreactors*": Focus on types of heat pipes that have been identified as likely candidates in microreactor designs:
  - High-temperature heat pipes
    - Implies working fluid options
    - Implies operational limits of greatest concern
  - Annular wicks, like mesh screen (for now, no grooved or artery wicks)

# Simulation Capabilities

## Flow Model

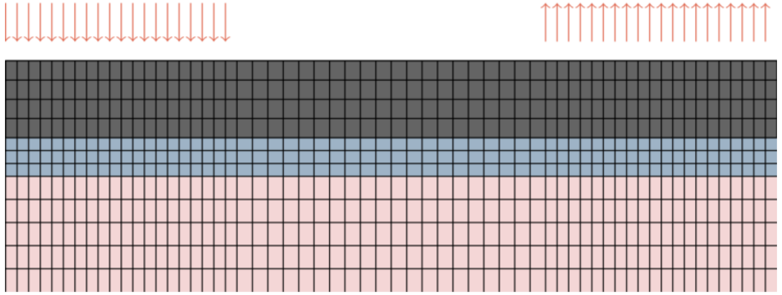
### 1D Flow + 2D Heat Conduction



- Heat applied to outer surface of cladding.
- Cladding exchanges heat with working fluid.

## Conduction Model

### 2D Effective Heat Conduction



- Heat applied to outer surface of cladding.
- Liquid approximated as at rest.
- Vapor core approximated using high effective thermal conductivity.

# Flow Model

- 1D, two-phase, compressible flow model
- Assumes heat pipe to have annular wick
- Solves 7 PDEs:
  - Conservation of mass (each phase)
  - Conservation of momentum (each phase)
  - Conservation of energy (each phase)
  - Volume fraction propagation (liquid phase)
- Closures:
  - Working fluid equation of state
  - Capillary pressure
  - Interfacial area density
  - Interfacial heat transfer coefficients
  - Wall heat transfer coefficients
  - Friction factors and correction factors

$$\frac{\partial \alpha_\ell A}{\partial t} + u_{\text{int}} \frac{\partial \alpha_\ell}{\partial x} A = \mu \left( p_\ell + \Delta p^{\text{cap}}_{\ell \to v} - p_v \right) A - \frac{\Gamma^{\text{int}}_{\ell \to v} a_{\text{int}} A}{\rho_{\text{int}}} - \frac{\Gamma^{\text{wall}}_{\ell \to v}}{\rho_{\text{int}}} P_{\text{wall}} ,$$

$$\frac{\partial \alpha_\ell \rho_\ell A}{\partial t} + \frac{\partial \alpha_\ell \rho_\ell u_\ell A}{\partial x} = -\Gamma^{\text{int}}_{\ell \to v} a_{\text{int}} A - \Gamma^{\text{wall}}_{\ell \to v} P_{\text{wall}} ,$$

$$\begin{aligned}\frac{\partial \alpha_\ell \rho_\ell u_\ell A}{\partial t} + \frac{\partial \alpha_\ell \left( \rho_\ell u_\ell^2 + p_\ell \right) A}{\partial x} = & p_{\text{int}} \frac{\partial \alpha_\ell}{\partial x} A - F_\ell A + \alpha_\ell \rho_\ell g_x A \\ & - \Gamma^{\text{int}}_{\ell \to v} u_{\text{int}} a_{\text{int}} A - \Gamma^{\text{wall}}_{\ell \to v} u_{\text{int}} P_{\text{wall}} ,\end{aligned}$$

$$\begin{aligned}\frac{\partial \alpha_\ell \rho_\ell E_\ell A}{\partial t} + \frac{\partial \alpha_\ell u_\ell \left( \rho_\ell E_\ell + p_\ell \right) A}{\partial x} = & \, p_{\text{int}} u_{\text{int}} \frac{\partial \alpha_\ell}{\partial x} A + \frac{\partial}{\partial x} \left( \alpha_\ell k_\ell \frac{\partial T_\ell}{\partial x} A \right) \\ & - \bar{p}_{\text{int}} \mu \left( p_\ell + \Delta p^{\text{cap}}_{\ell \to v} - p_v \right) A + \alpha_\ell \rho_\ell g_x u_\ell A \\ & + q^{\text{conv}}_{\text{wall} \to \ell} P_{\text{wall}} + q_{\text{int} \to \ell} a_{\text{int}} A - \Gamma^{\text{int}}_{\ell \to v} E^{\text{int}}_\ell a_{\text{int}} A - \Gamma^{\text{wall}}_{\ell \to v} H_\ell P_{\text{wall}} .\end{aligned}$$

$$\frac{\partial \alpha_v \rho_v A}{\partial t} + \frac{\partial \alpha_v \rho_v u_v A}{\partial x} = \Gamma^{\text{int}}_{\ell \to v} a_{\text{int}} A + \Gamma^{\text{wall}}_{\ell \to v} P_{\text{wall}} ,$$

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$$\begin{aligned}\frac{\partial \alpha_v \rho_v E_v A}{\partial t} + \frac{\partial \alpha_v u_v \left( \rho_v E_v + p_v \right) A}{\partial x} = & \, p_{\text{int}} u_{\text{int}} \frac{\partial \alpha_v}{\partial x} A \\ & + \bar{p}_{\text{int}} \mu \left( p_\ell + \Delta p^{\text{cap}}_{\ell \to v} - p_v \right) A + \alpha_v \rho_v g_x u_v A \\ & + q_{\text{wall} \to v} P_{\text{wall}} + q^{\text{boil}}_{\text{wall} \to \ell} P_{\text{wall}} + q_{\text{int} \to v} a_{\text{int}} A + \Gamma^{\text{int}}_{\ell \to v} E^{\text{int}}_v a_{\text{int}} A + \Gamma^{\text{wall}}_{\ell \to v} H_\ell P_{\text{wall}} .\end{aligned}$$

# Capillary Pressure Model

- Capillary pressure $p_{cap}$ depends on a few factors:
  - Surface tension $\sigma$ at the given temperature
  - Contact angle $\theta$ at the given temperature
  - Wick pore radius $R_{pore}$
  - Saturation of the wick (dependence given by “J function” $J(\alpha_v)$)

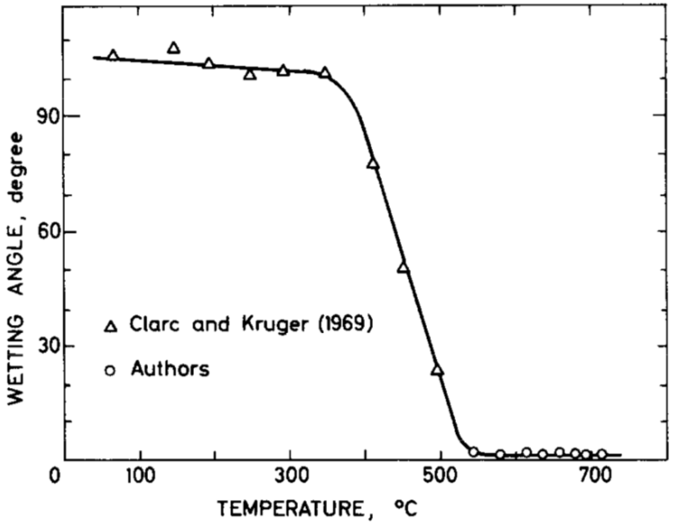
$$p_{cap} = \frac{2\sigma \cos\theta \, J}{R_{pore}}$$

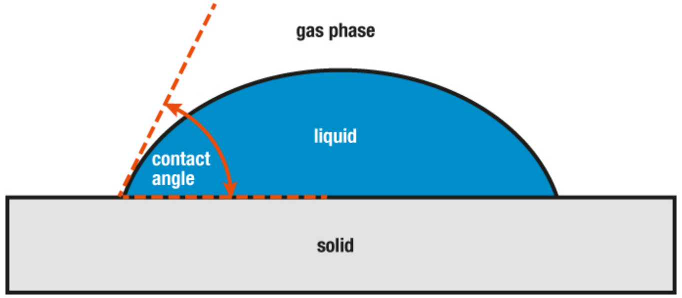
- Phases expand/contract toward equilibrium condition:

$$p_v - p_\ell = p_{cap}$$

- Captured via pressure relaxation term:

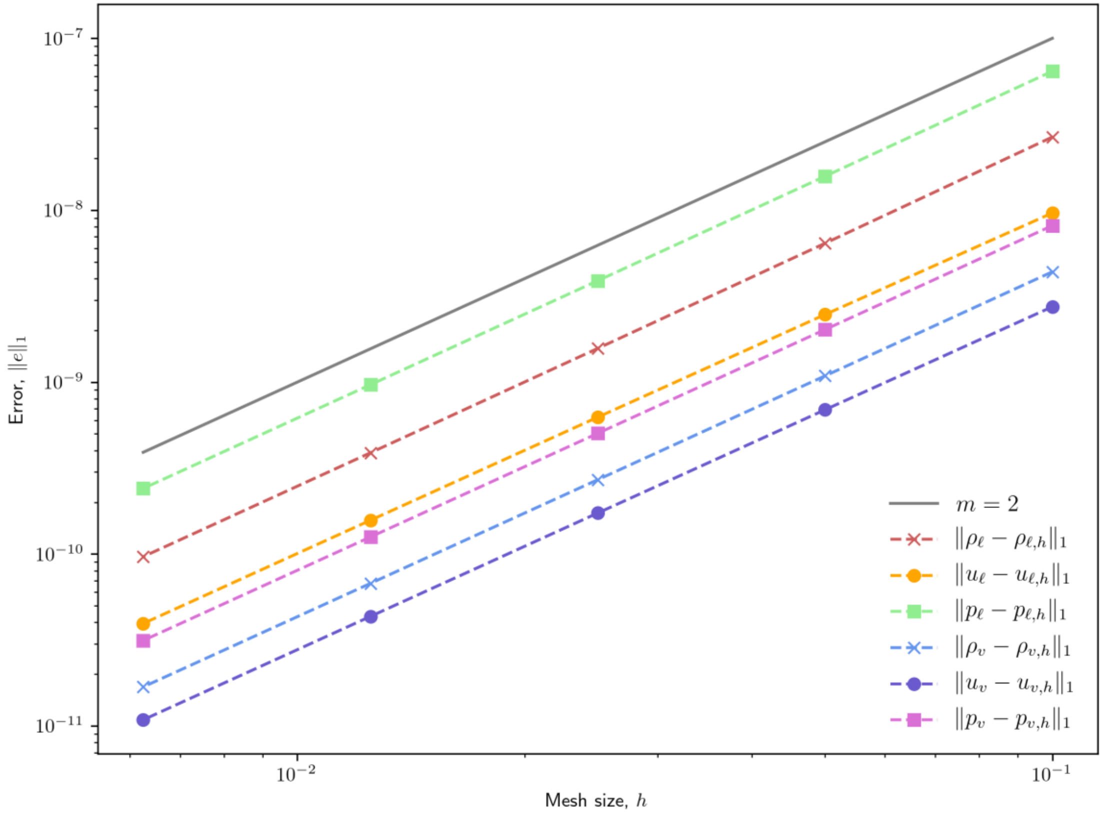
$$\frac{\partial \alpha_\ell}{\partial t} = \Theta\left(p_\ell - p_v + p_{cap}\right) + \cdots$$



# Spatial Convergence Verification of Flow Model

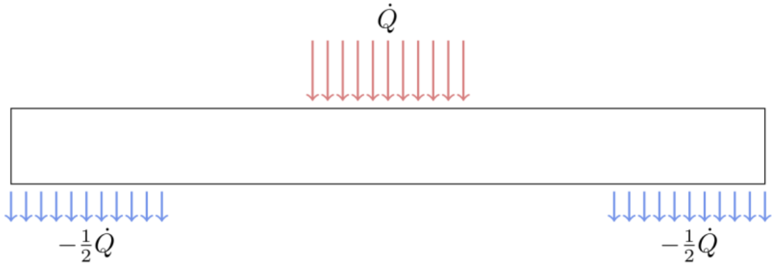
- Used Method of Manufactured Solutions (MMS) to verify theoretical spatial convergence rates.
  - Should recover 2nd-order accuracy when using slope reconstruction.
  - Simplifications:
    - Used uniform phase distribution and dropped relaxation terms.
    - Manufactured solutions for density, pressure, and velocity.
    - Used ideal gas EOS.

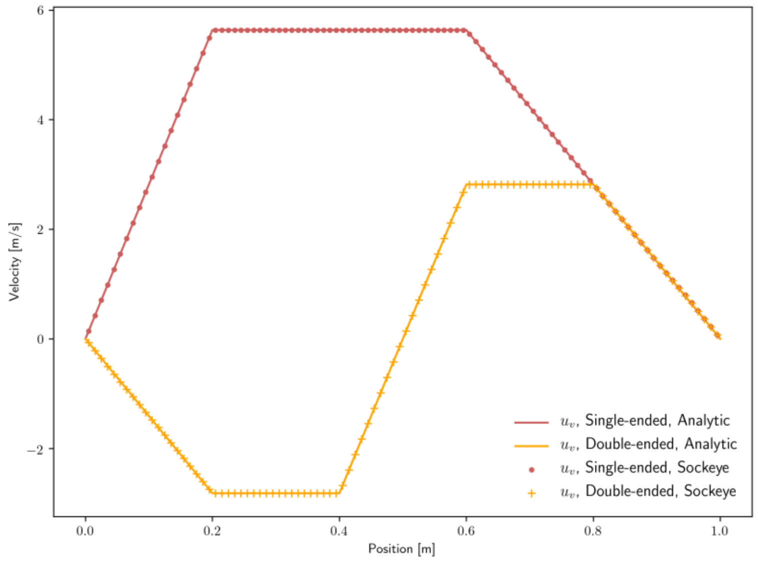


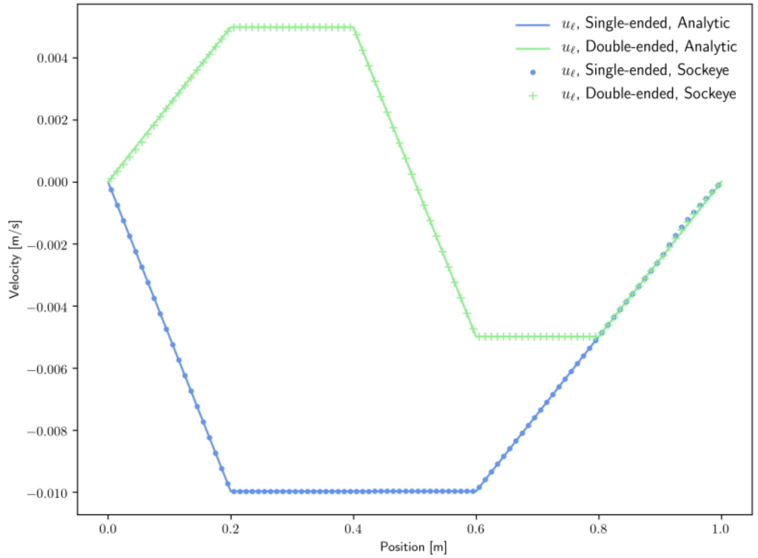
# Steady-State Solutions

- Obtained steady-state solution for two different configurations:
  - Single-ended:

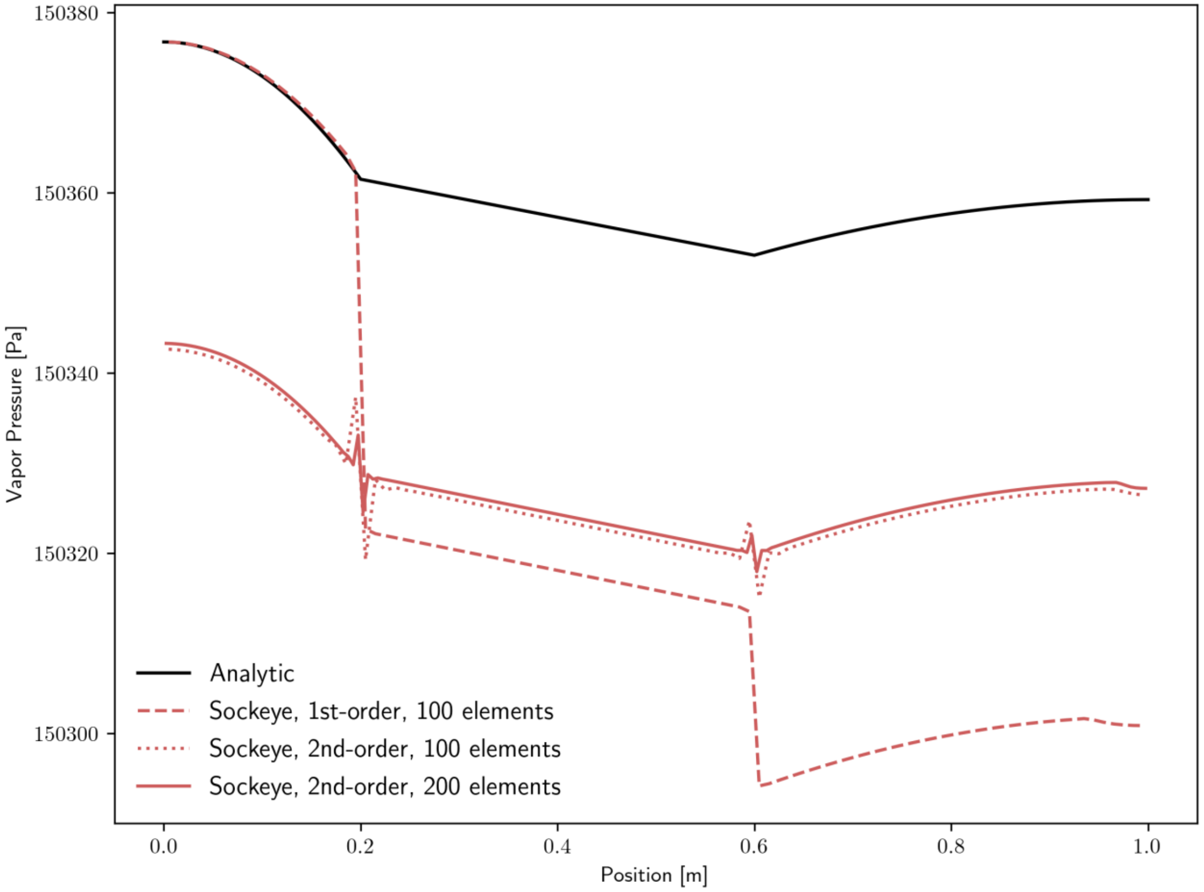

  - Double-ended:

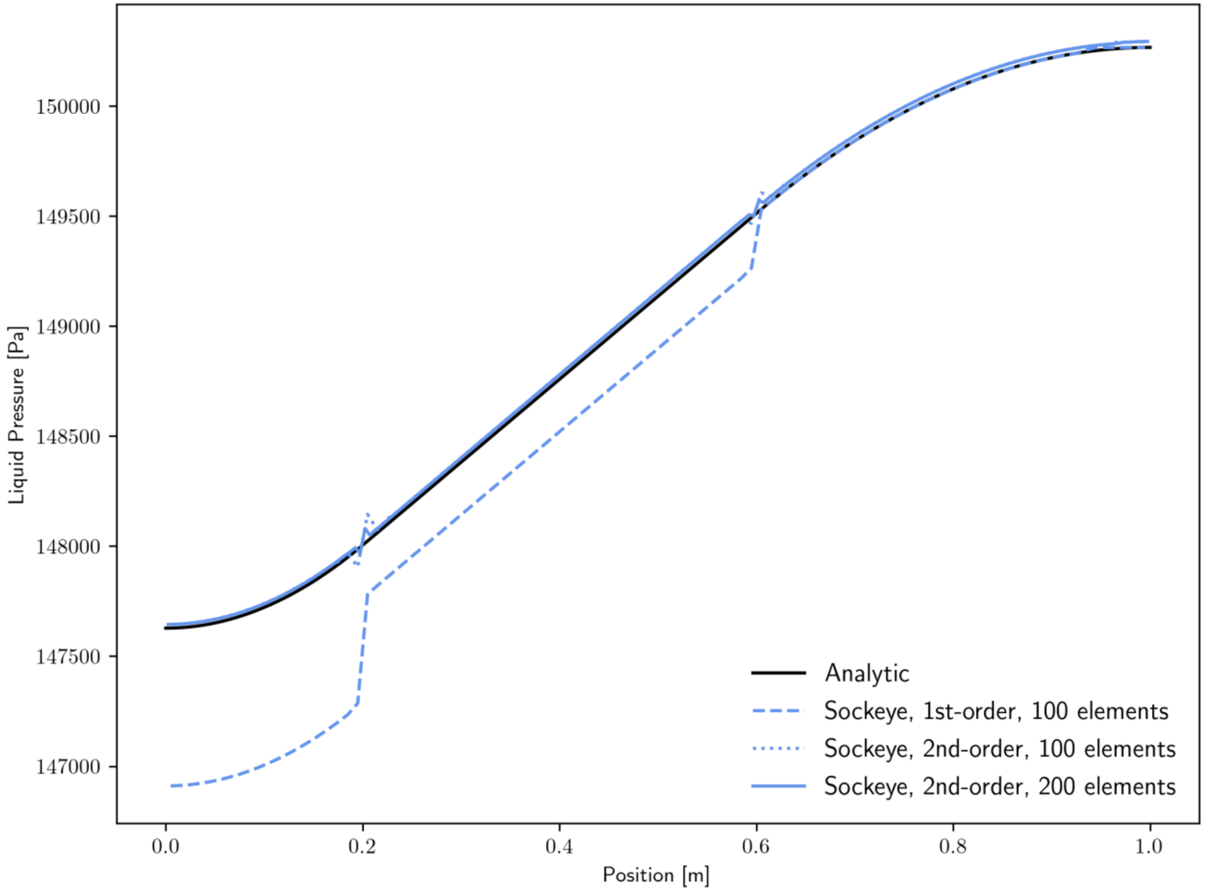


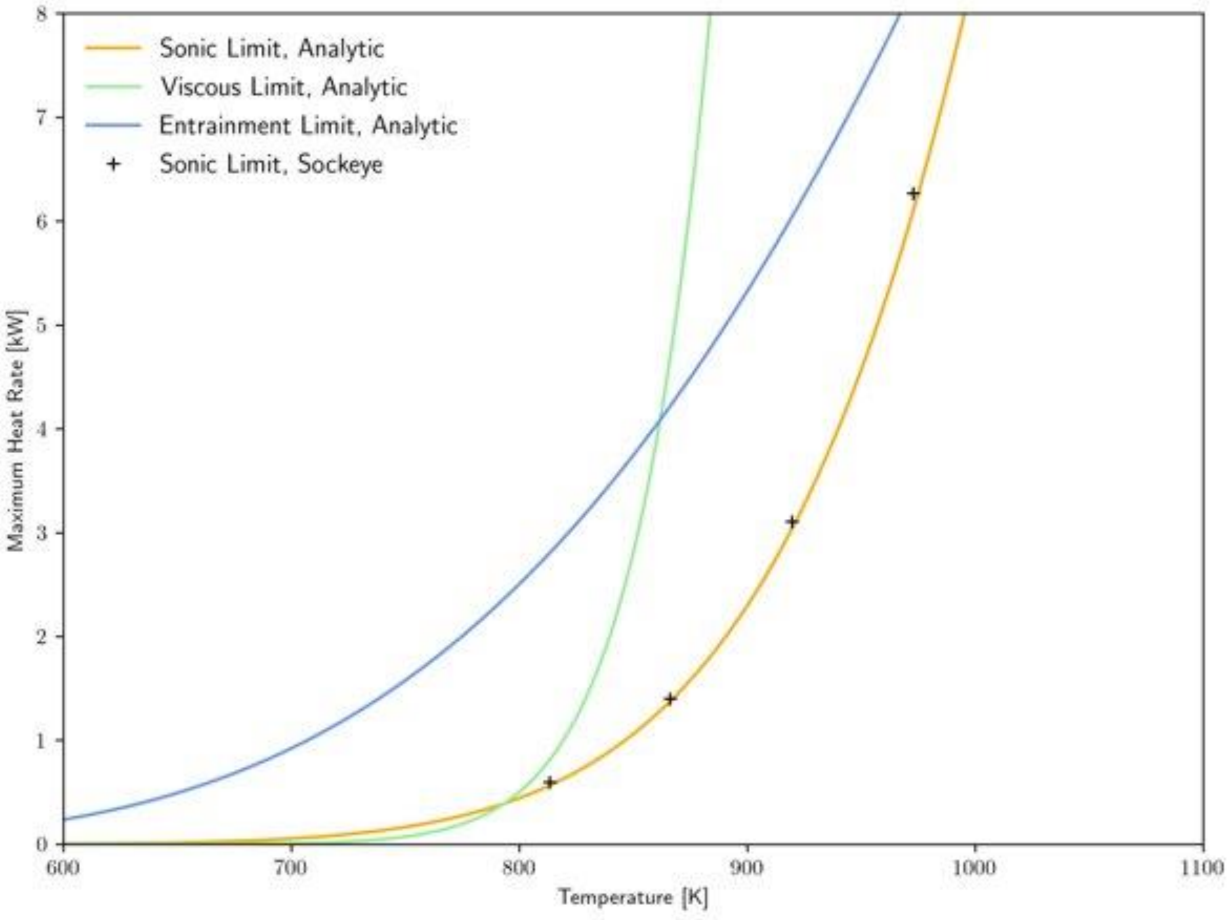
# Steady-State Pressure Solutions



# Sonic Limit Assessment

- Performed several runs at various operating temperatures to compare predicted sonic limit against analytic sonic limit curve.
- For a given operating temperature (dictated by condenser boundary conditions), slowly increased power until a sonic condition appeared.
- Plotted evaporator end cap temperature vs. the power at which the sonic point occurred:

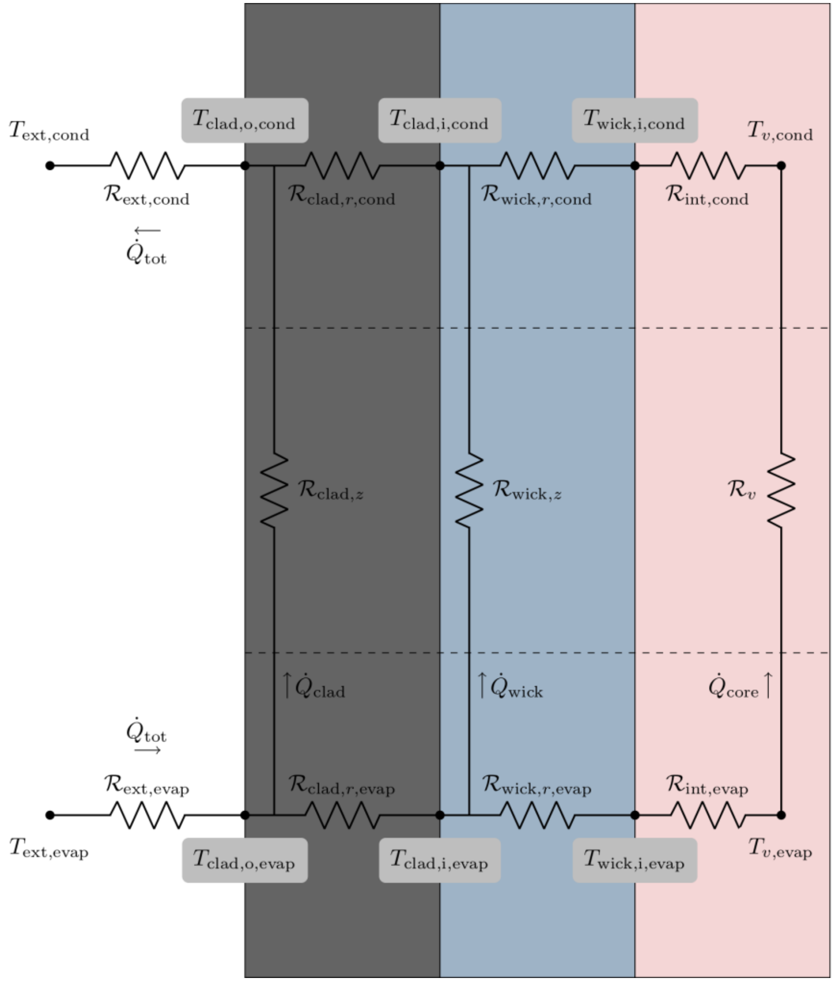


# Conduction Model

- All radial regions of heat pipe (cladding, liquid/wick, and core) modeled with 2D heat conduction:

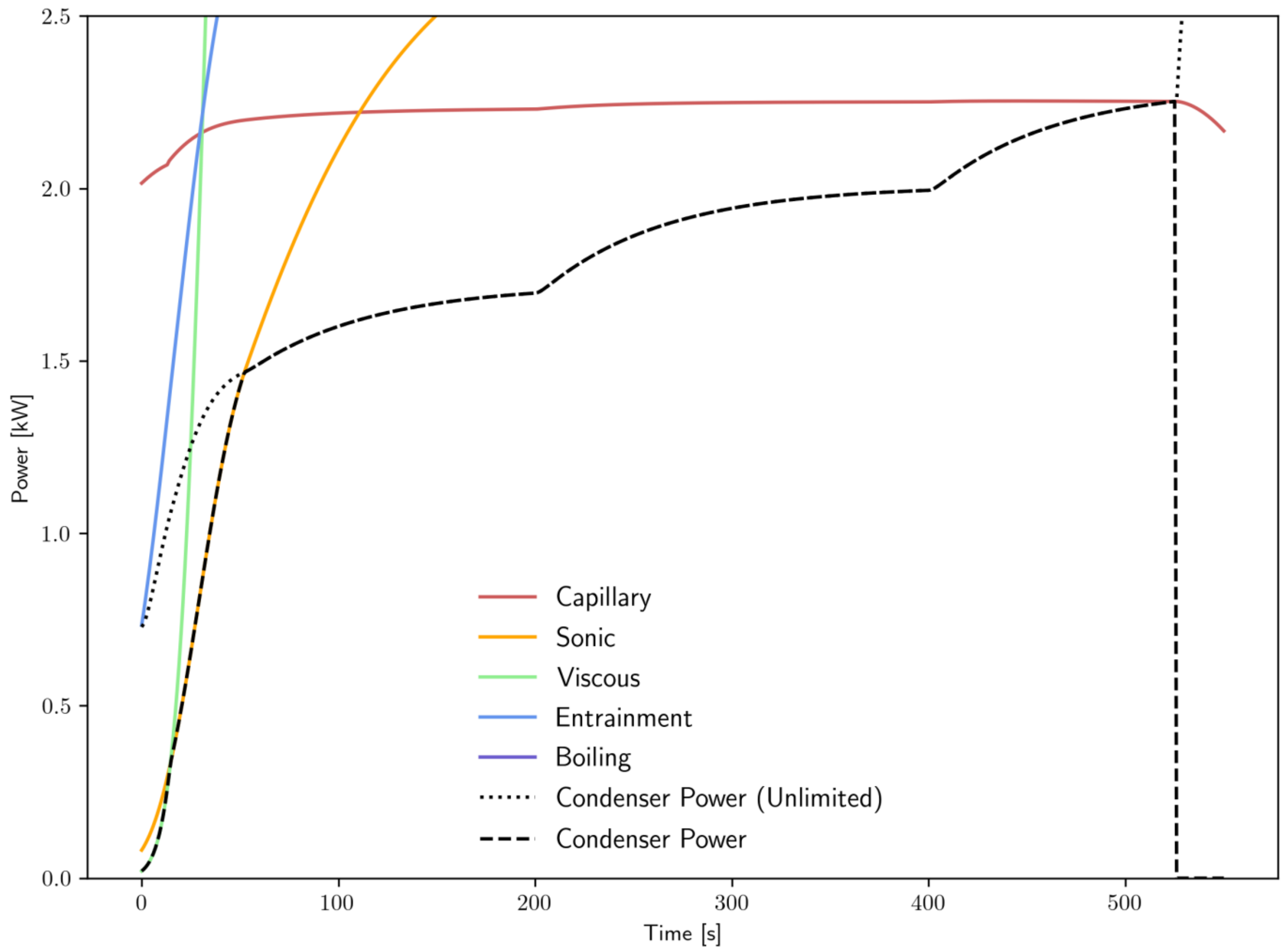
$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = 0$$

- Effective thermal conductivity for the liquid/wick region is used based on porosity-weighted average of constituent thermal conductivities.
- Core region gets a very high effective thermal conductivity that is controlled to obey analytic limits.
- Approach can be compared to thermal resistance analysis.



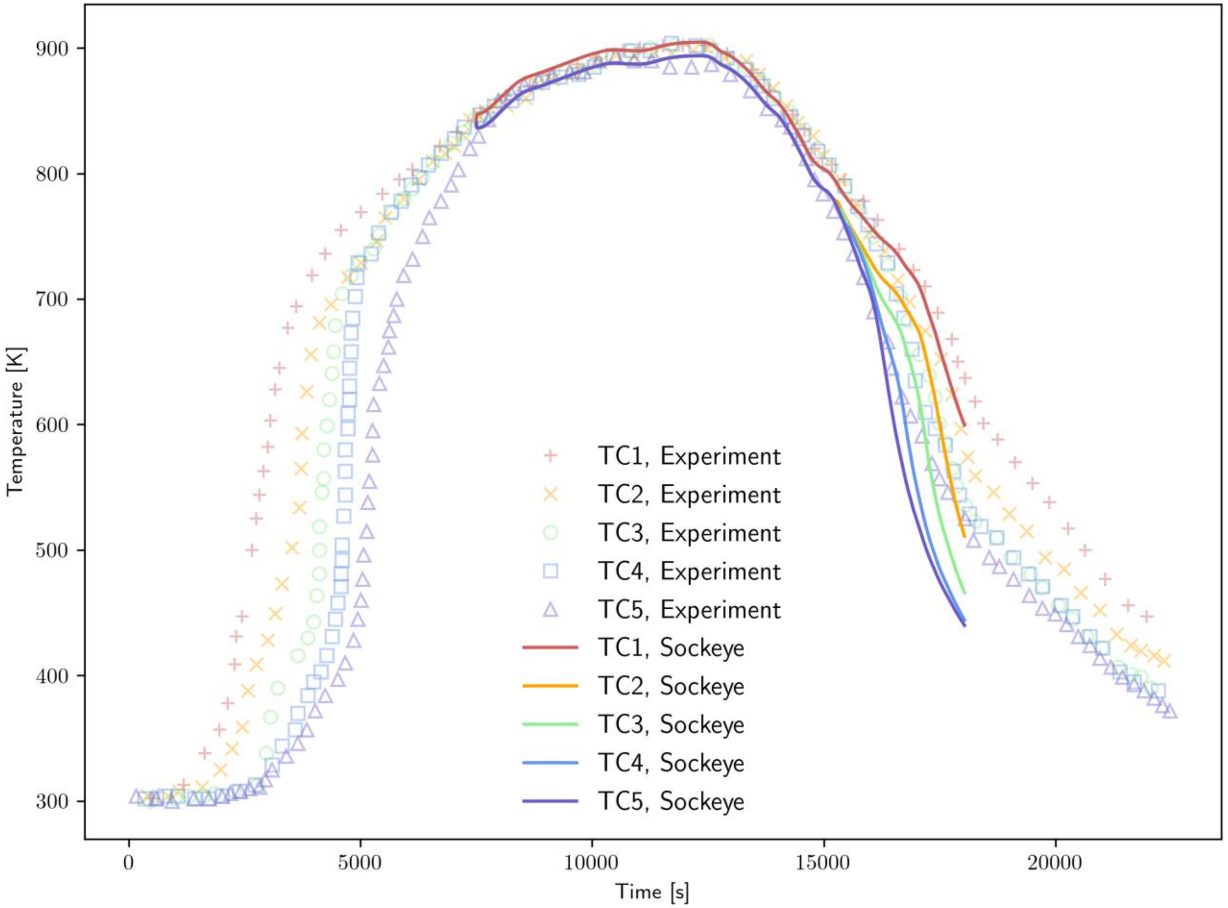
# Conduction Model Example

- Cascading failure example:
  - For 200 s, heat at rate Q.
  - At 200 s, increase heat rate by Q/6 due to failure of adjacent heat pipe.
  - At 400 s, increase heat rate by another Q/6 due to failure of another adjacent heat pipe.
- Results:
  - In beginning of transient, heat rate is limited by viscous and sonic limits until it heats up enough.
  - Heat pipe handles one adjacent failure, but not two - the capillary limit is reached.
  - Unlike viscous and sonic limits, capillary limit leads to dryout, making heat pipe ineffective for heat removal.

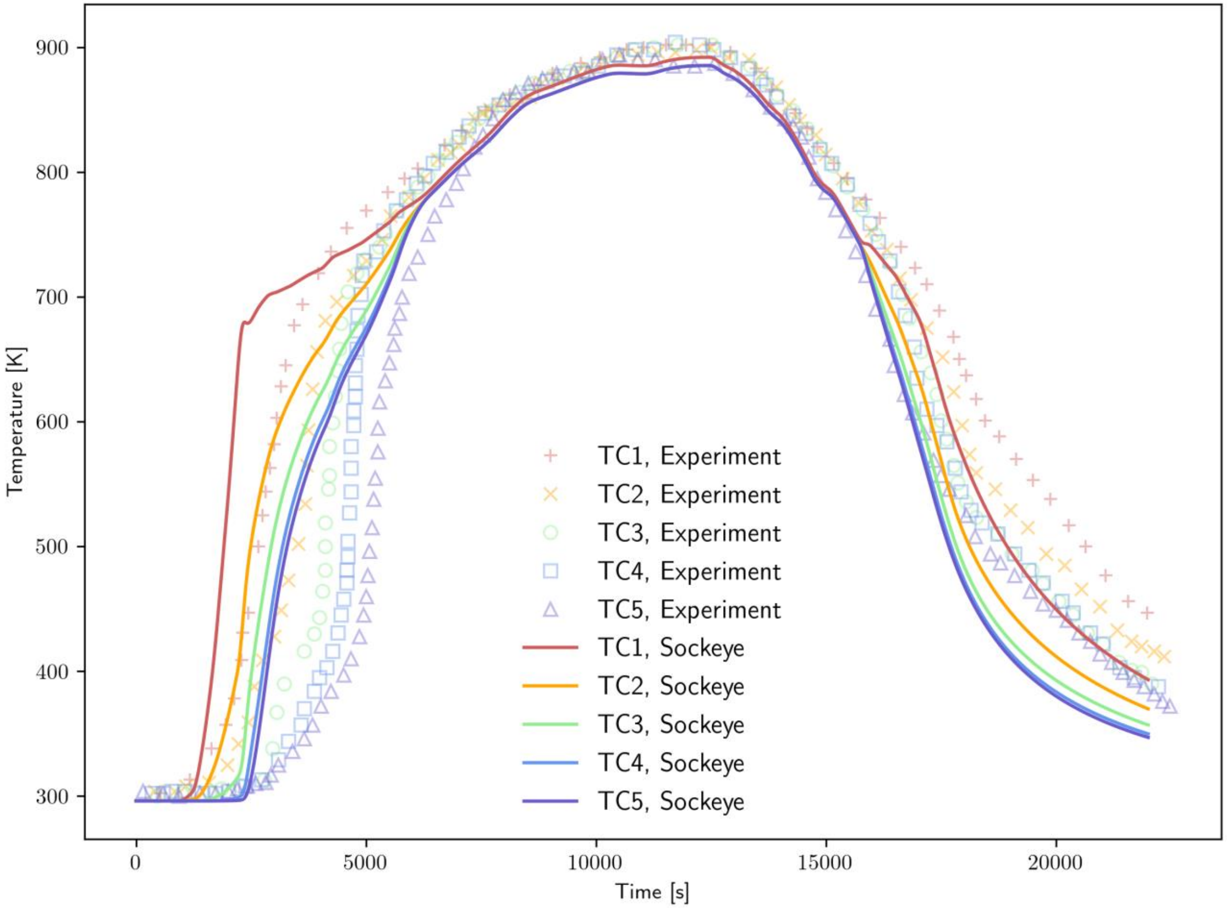


# SAFE-30 Simulation Results

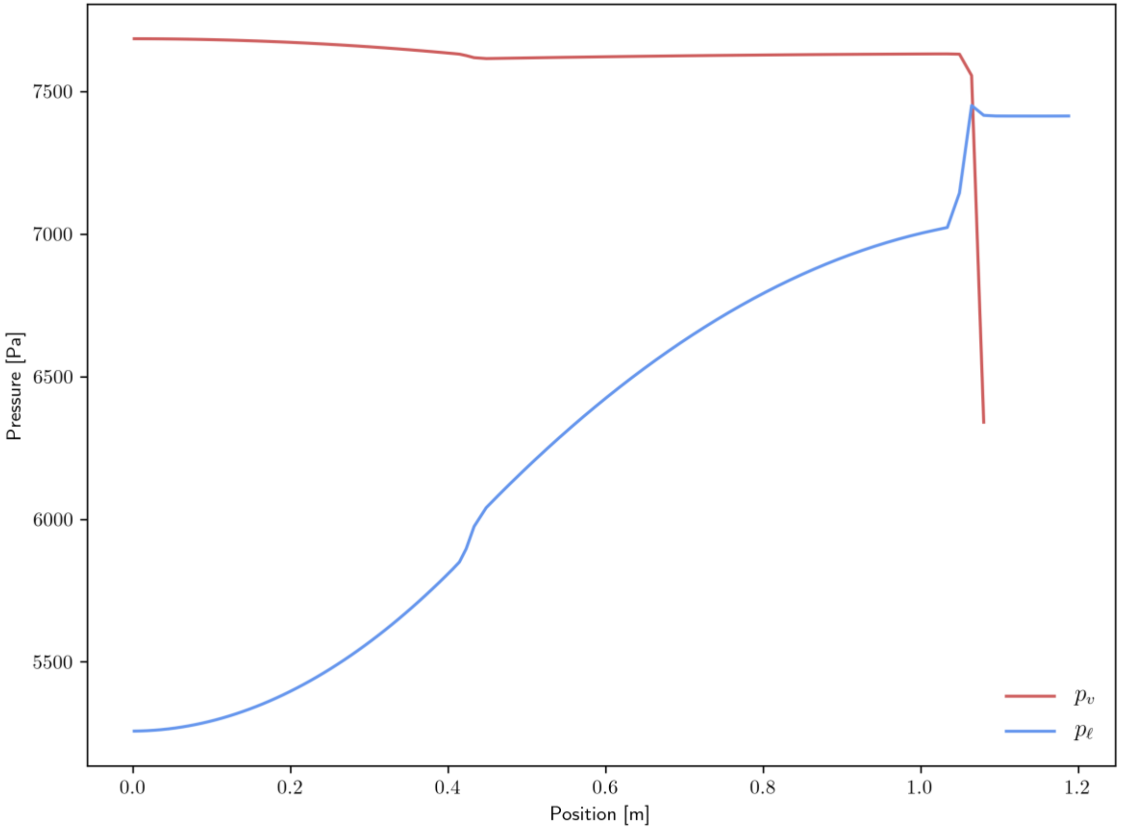
## Flow Model

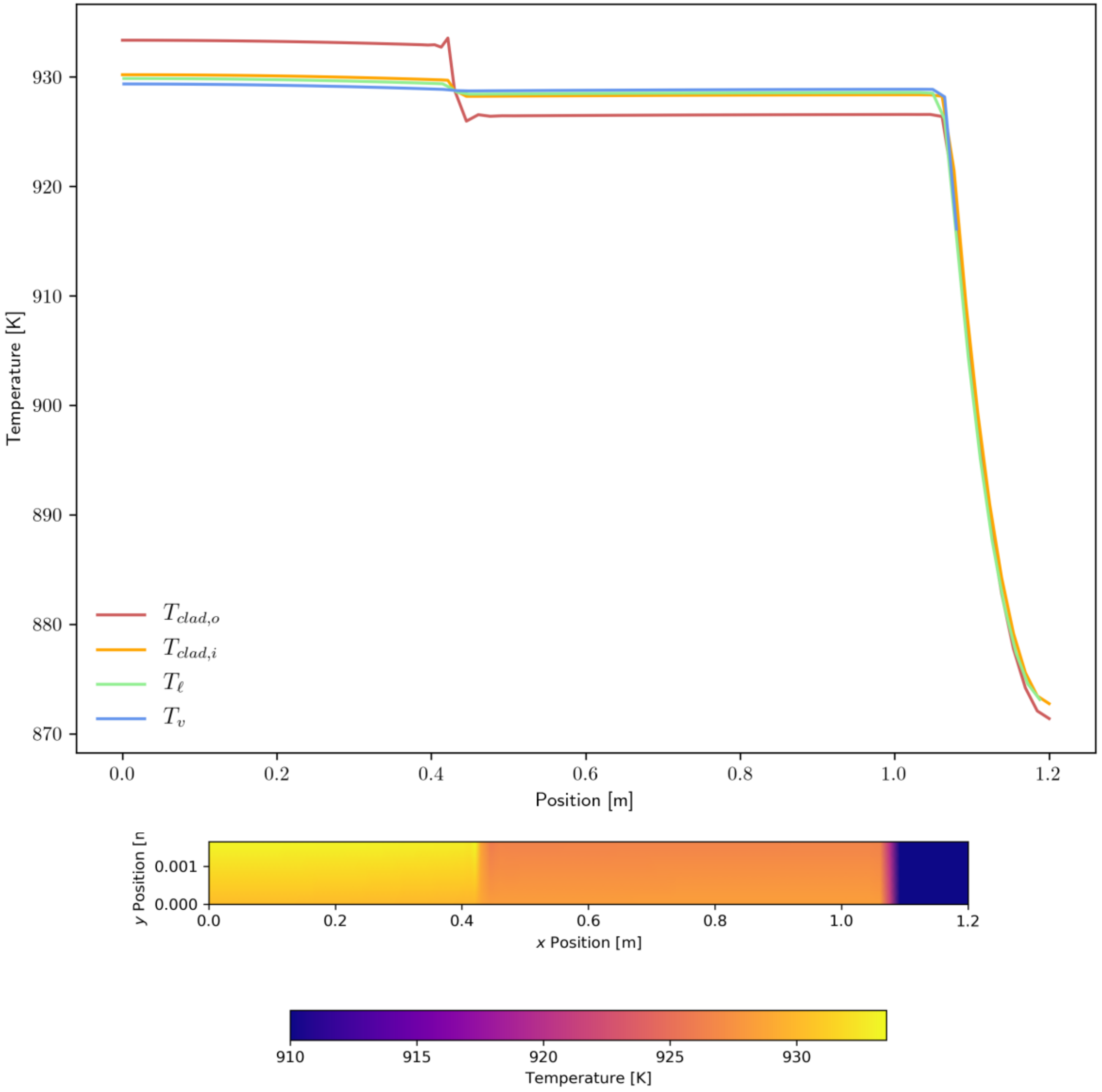



## Conduction Model



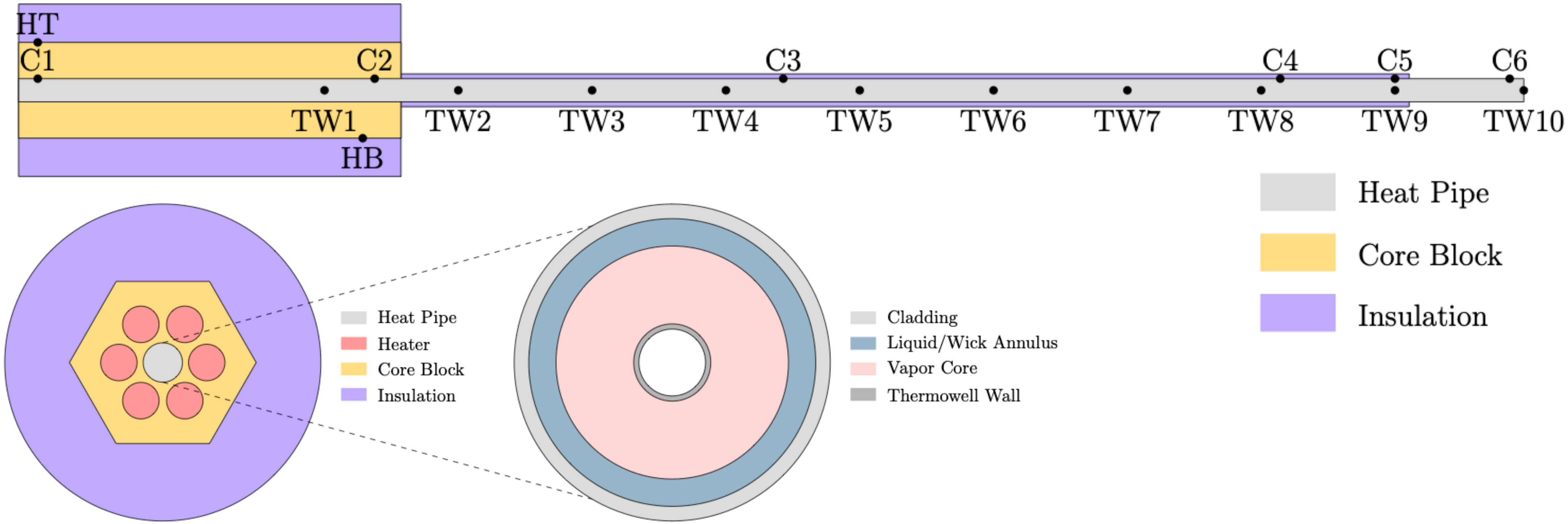
# SAFE-30 Simulation Results



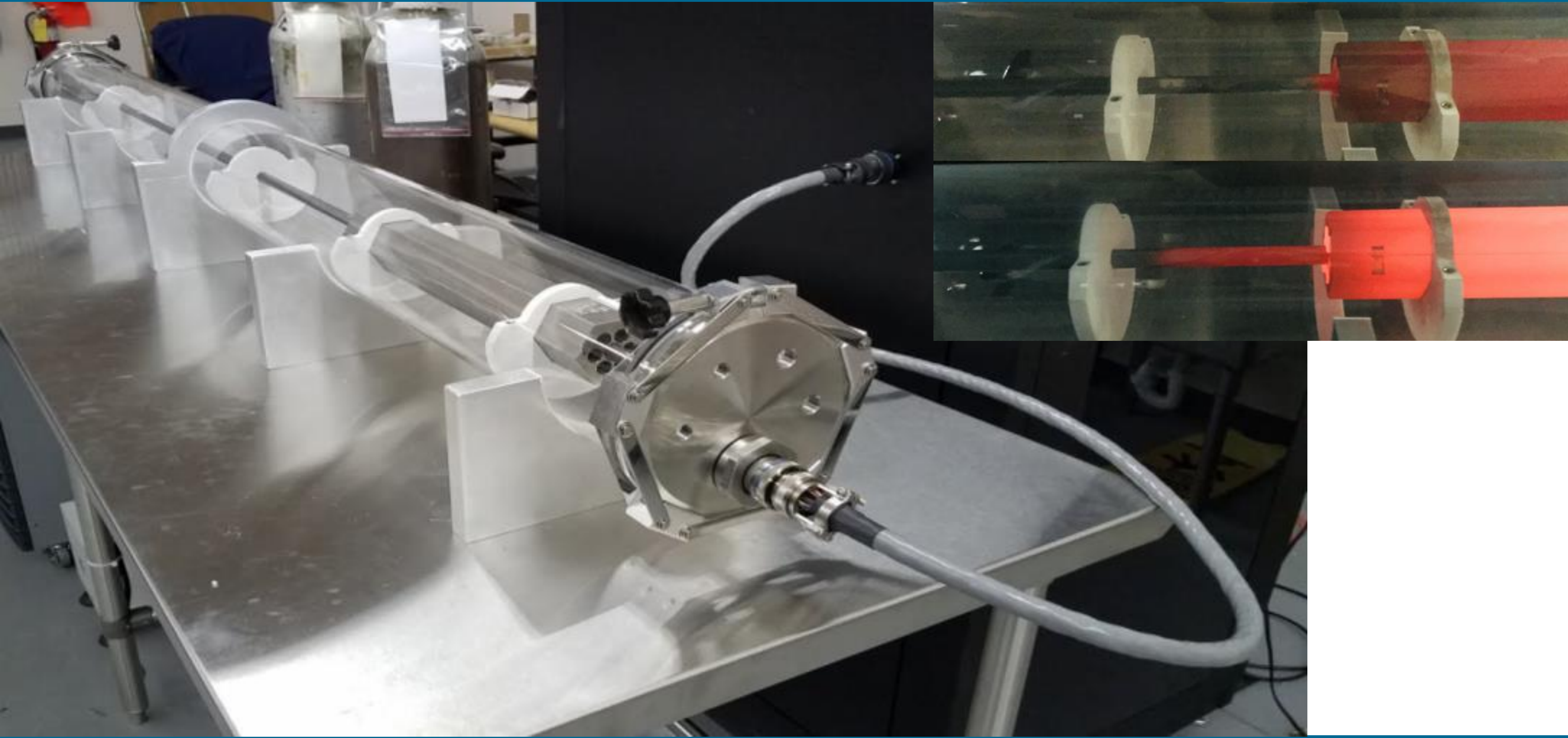



# SPHERE Test Facility

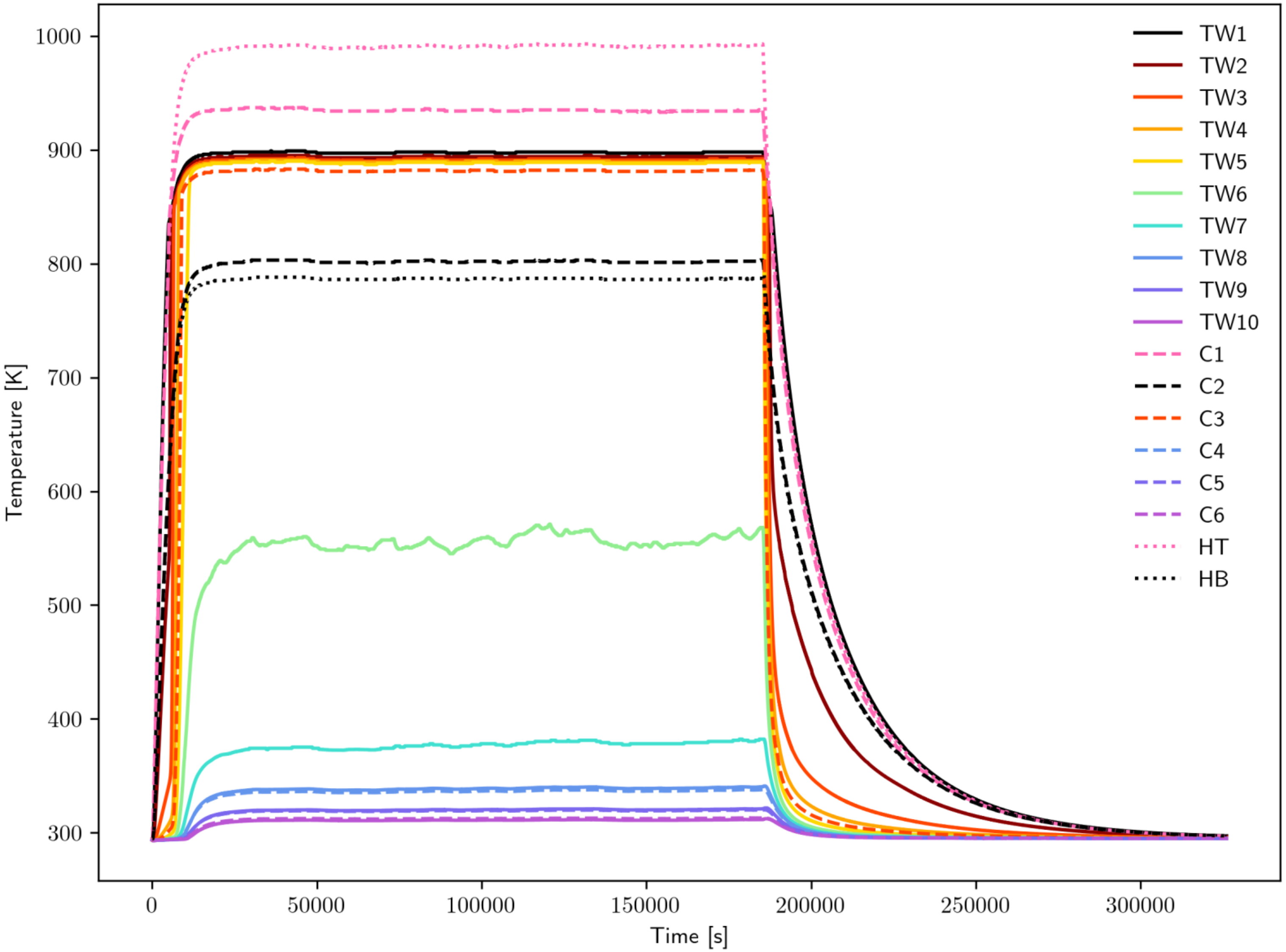
- Single Primary Heat Extraction and Removal Emulator (SPHERE)
- Single sodium heat pipe coupled to hexagonal heating block
- Enclosed in vacuum chamber
- Heated by 6 cartridge heaters

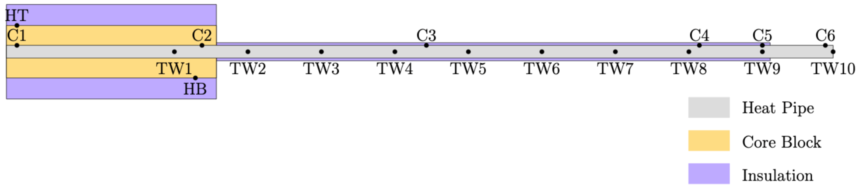


# SPHERE Test Facility



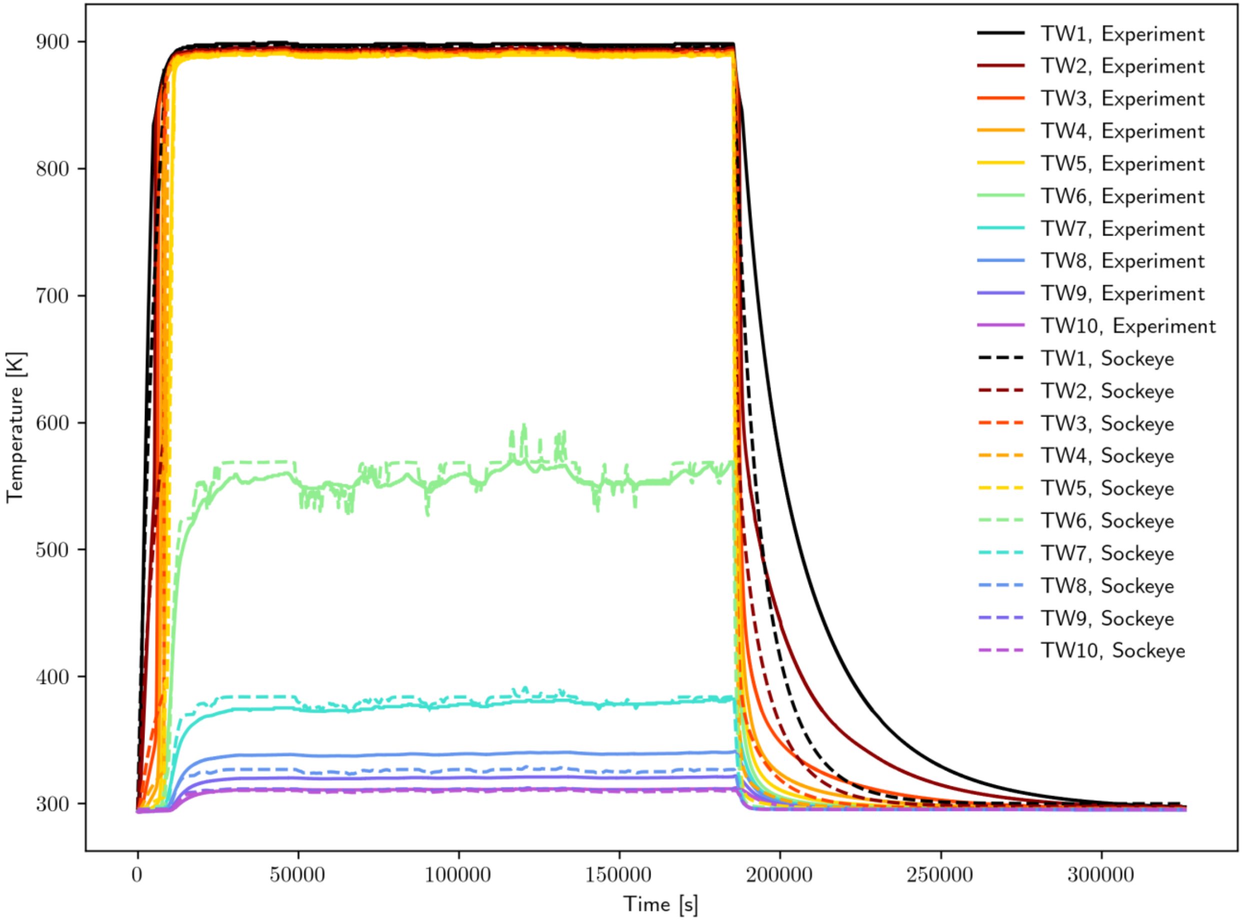
# SPHERE Experimental Results



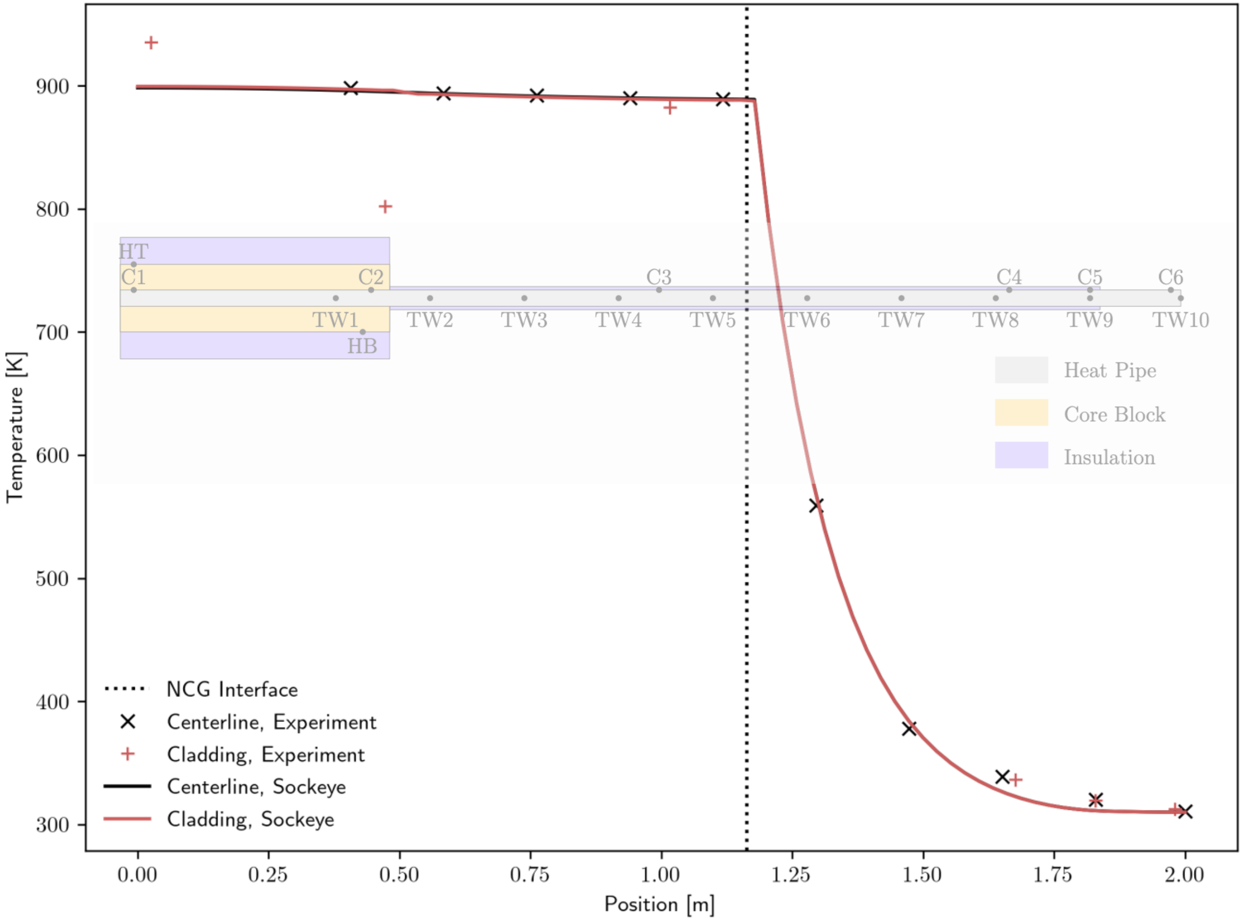



# SPHERE Simulation Results

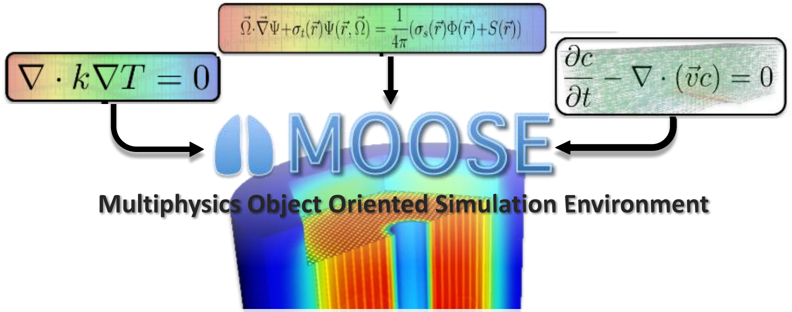
## Centerline Transient

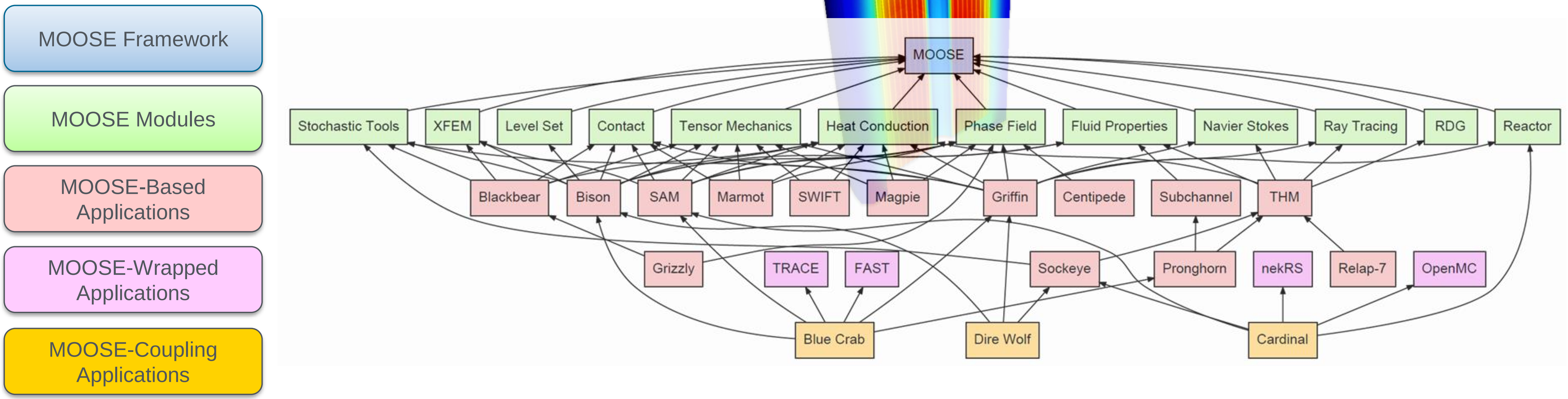



## Steady Centerline and Cladding



# MOOSE Framework Ecosystem for Non-LWR Analysis




HTGR

FHR

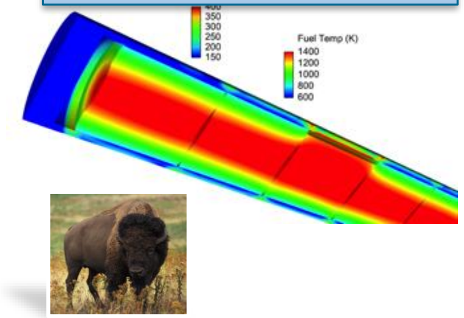
MSR

Microreactor

LMFR

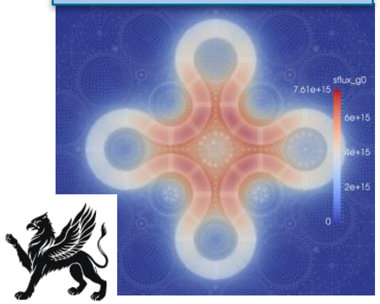
# Some MOOSE-Based Applications

**Bison**
Nuclear Fuel Performance

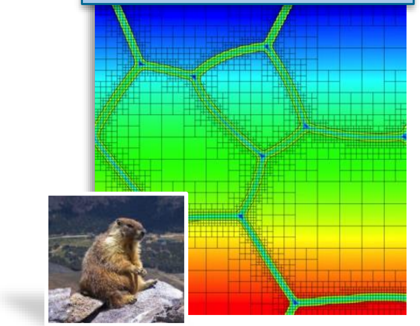



**Grizzly**
Structural Mechanics for Component Aging

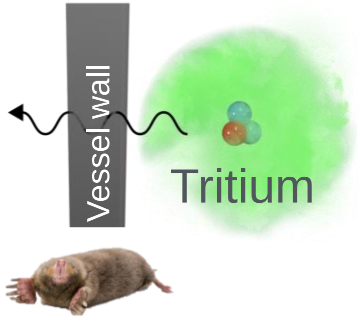
**Griffin**
Radiation Transport



**Marmot**
Mesoscale Materials

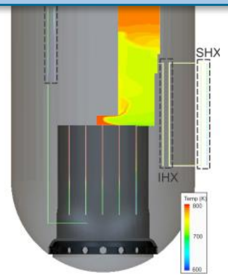


**Mole**
Species Transport

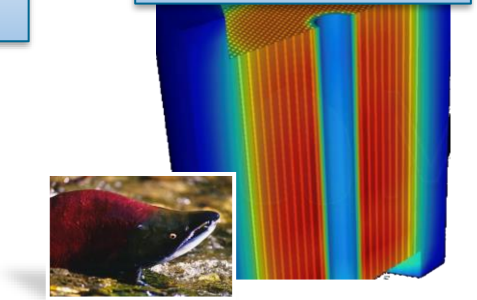



**Pronghorn**
Medium-fidelity CFD

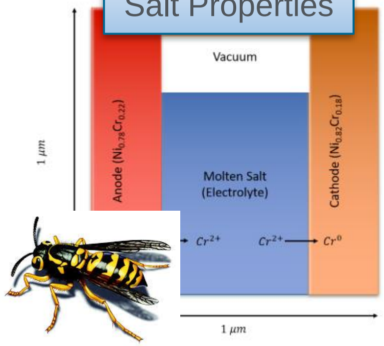
**SAM**
Multiscale Multiphysics Systems Analysis




**Sockeye**
Heat pipe Simulation

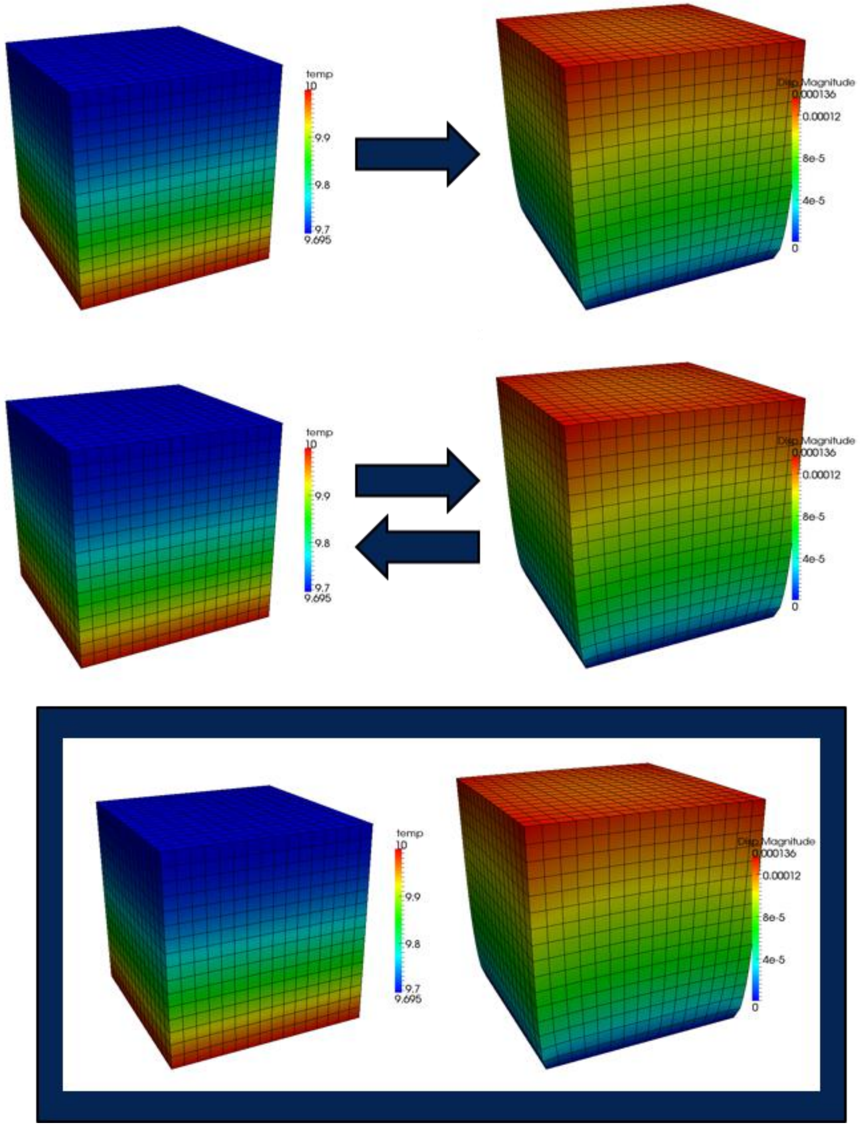


**Yellowjacket**
Salt Properties



# Multiphysics Coupling Approaches

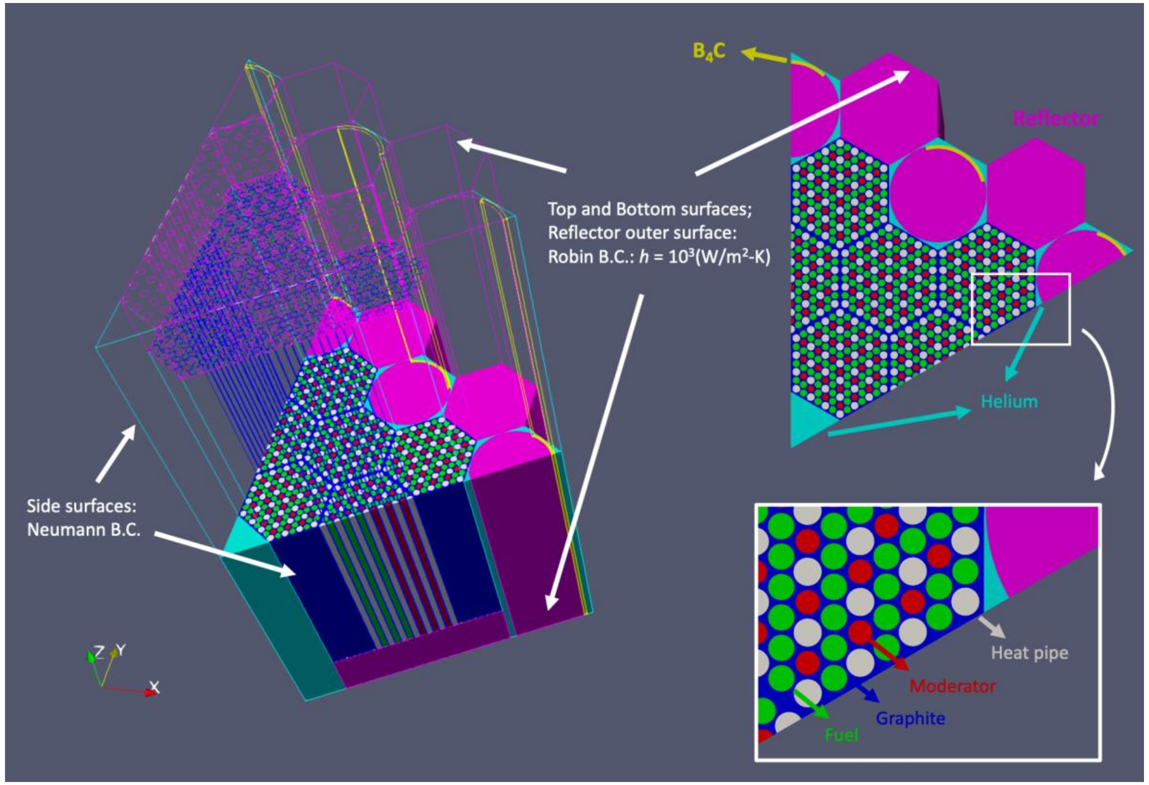
- **Loosely-Coupled**
  - Each physics solved with a separate linear/nonlinear solve.
  - Data exchange once per timestep (typically)
- **Tightly-Coupled / Picard**
  - Each physics solved with a separate linear/nonlinear solve.
  - Data is exchanged and physics re-solved until “convergence”
- **Fully-Coupled**
  - All physics solved for in one linear/nonlinear solve

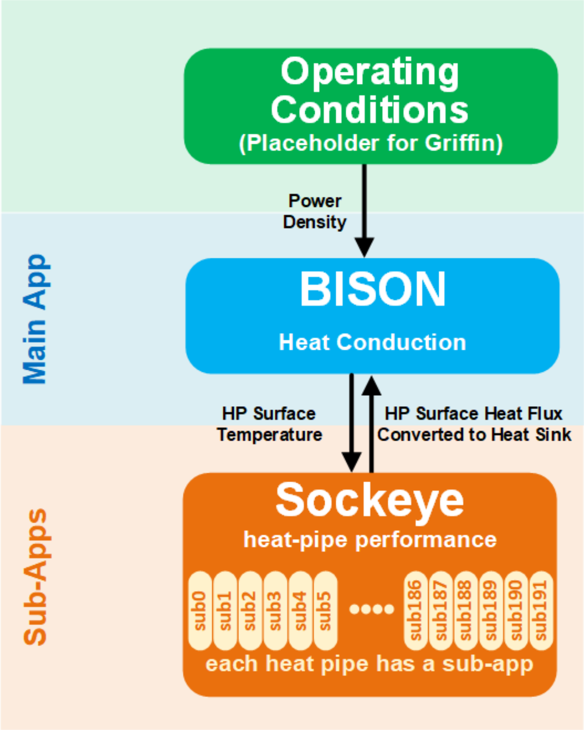


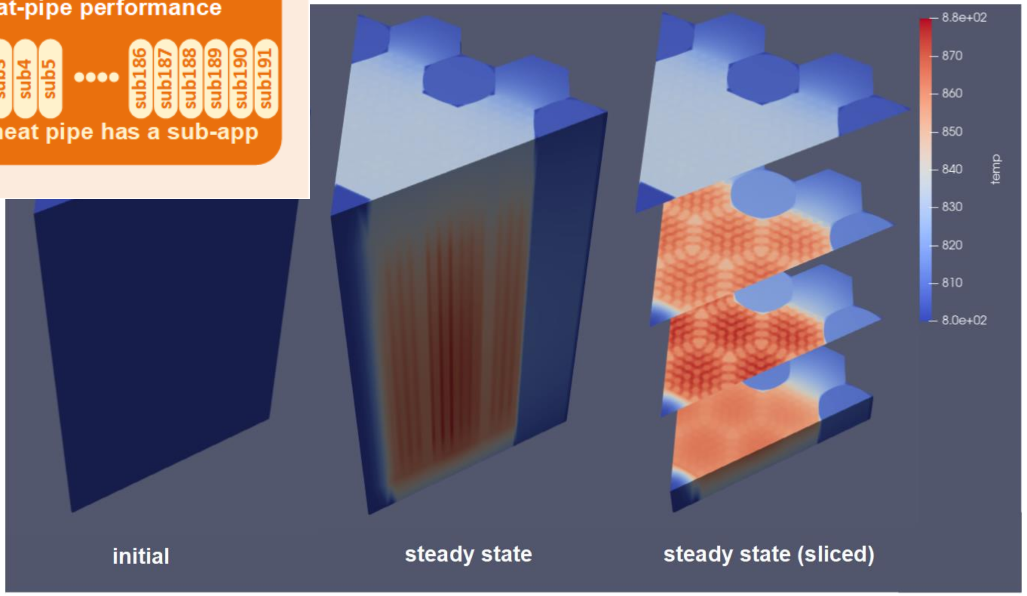
# Potential Multiphysics Couplings

- Primary side heat transfer:
  - Interface conditions between heat pipe and surrounding monolith
- Secondary side heat transfer:
  - Interface conditions between heat pipe and heat exchanger
- Thermomechanics:
  - Thermal expansion of heat pipe cladding
- Chemical reactions:
  - Accumulation of undesirable non-condensable gases
  - Wick and wall surface corrosion and contamination
- Neutronics:
  - Temperature feedback into heat pipe neutronic cross sections
  - Direct heating of heat pipe by neutron interactions

# Some Microreactor Modeling



# Conclusions

- Heat pipe simulation is challenging!
  - Huge temperature range, e.g., 300 K – 1200 K
    - Thermodynamic properties of working fluid must be accurate throughout range
    - Thermal properties (density, heat capacity, thermal conductivity, radiative properties) must be accurate throughout range
    - Significant thermal expansion of both container and working fluid
    - Capillary pressure varies due to varying contact angle
  - Startup at low or vacuum pressure:
    - Flow solver difficulties near zero pressure
  - Two-phase flow
  - Not only evaporation/condensation, but also melting/solidification
  - Capillary pressure modeling
  - Compressibility needed to model vapor phase (and thermal expansion of liquid phase)
  - Subsonic and supersonic flow – transition to supersonic flow gives convergence difficulties

# Future Work

- Improvements to Flow Model:
  - Support non-condensable gases
  - Improve robustness with phase disappearance
  - Improve robustness of supersonic transition
  - Improve robustness of startup
  - Support for thermosyphons and hybrid heat pipes
- Improvements to Conduction Model:
  - Reformulate to track melting and account for latent heat of fusion
  - Condenser pool modeling
  - Improvements to underlying analytic limits
- Validation

# Questions