Fusion Energy System ARC System Modeling using SAM

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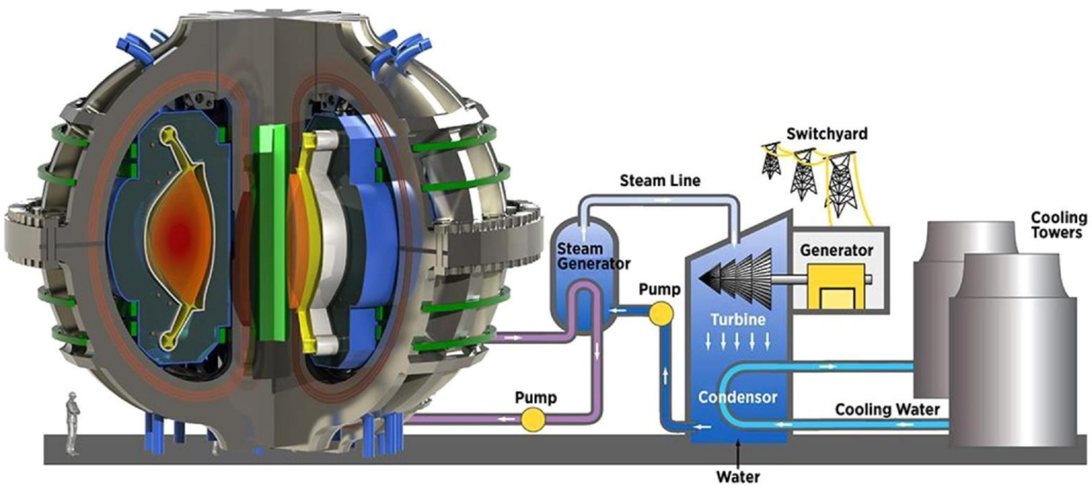
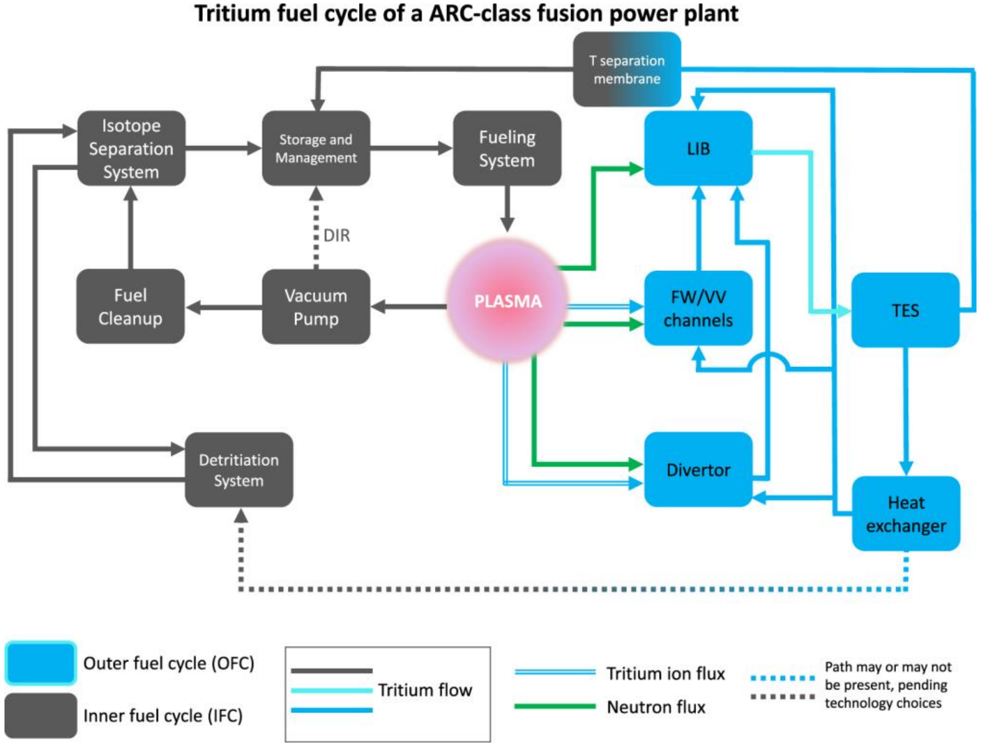
Motivation – Fusion Energy Systems

- For fusion pilot plant progress, development of enabling technology surrounding the blanket, inner and outer fuel cycles is a priority



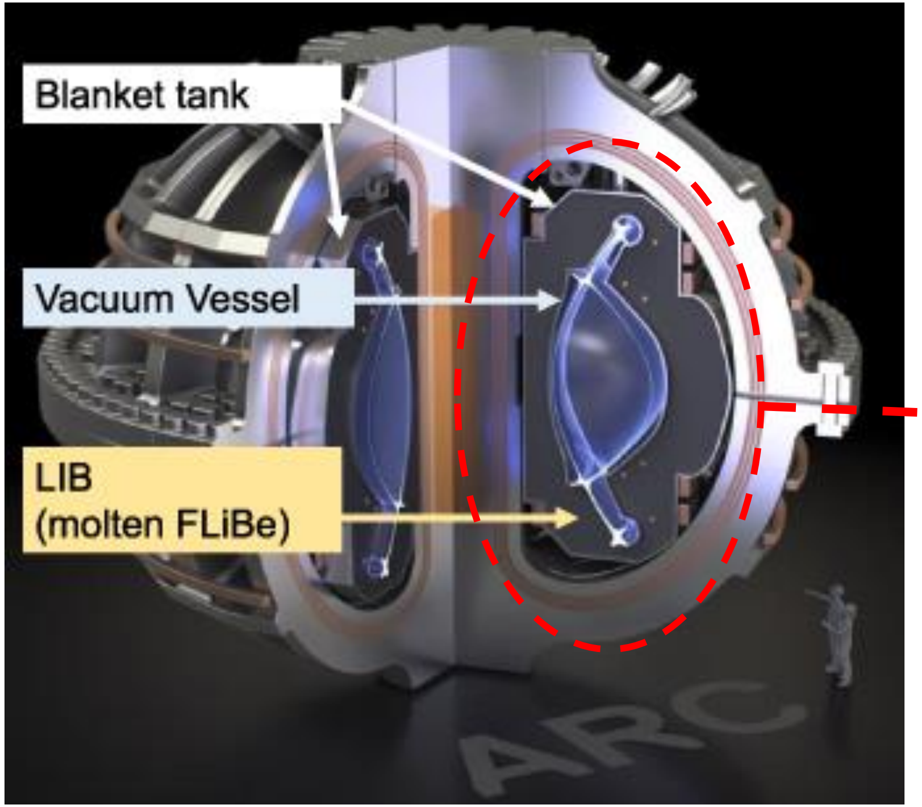
ARC-like system with a Rankine (Steam) power conversion system[1]



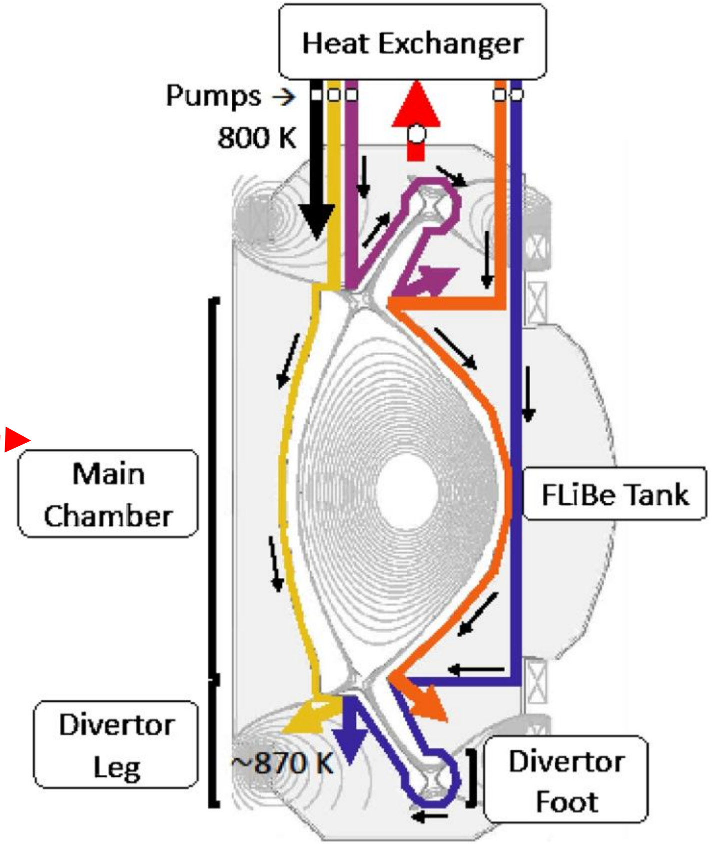
ARC Inner and Outer Fuel Cycle Schematic[2]

[1]S. Segantin, et al., 2020, Fusion Eng. Des., 10.1016/j.fusengdes.2020.111645
[2]S. Meschini et al Nucl. Fusion, 10.1088/1741-4326/acf3fc005

What are fusion breeder blankets (LIB)?



ARC with Blanket and Salt Identified[1]`



Cross-section of FLiBe Liquid Breeder Blanket Design for ARC type fusion energy system[2]

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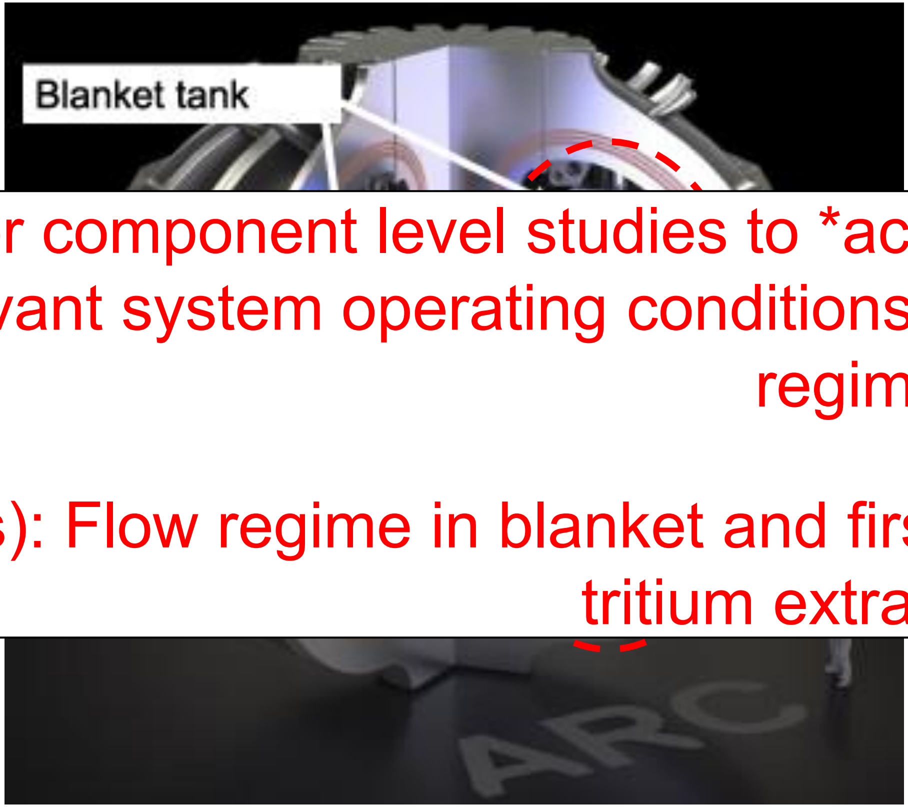

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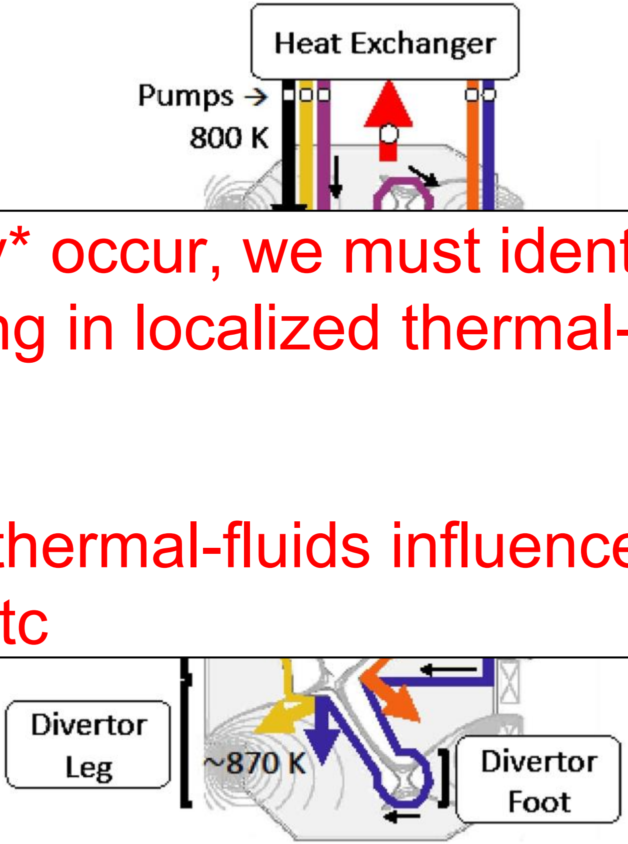


Cross-section of FLiBe Liquid Breeder Blanket Design for ARC type fusion energy system[2]

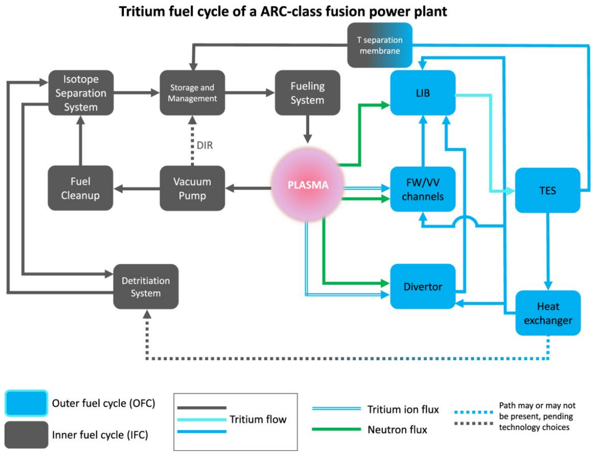
For component level studies to *accurately* occur, we must identify relevant system operating conditions resulting in localized thermal-fluid regimes.

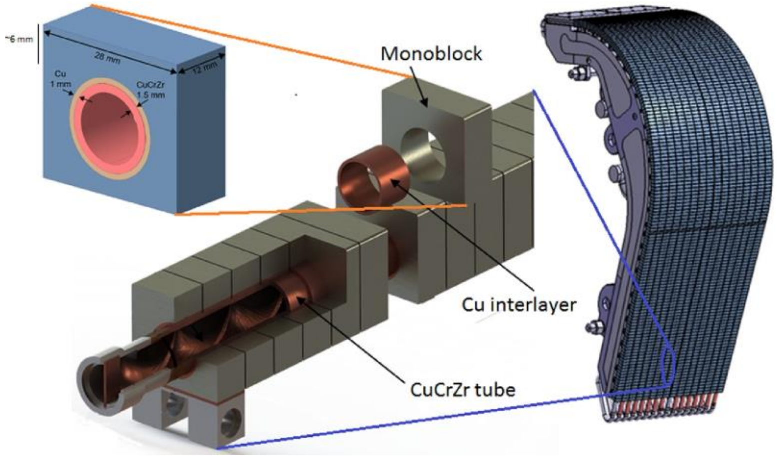
Ex(s): Flow regime in blanket and first wall, thermal-fluids influences of tritium extractors, etc

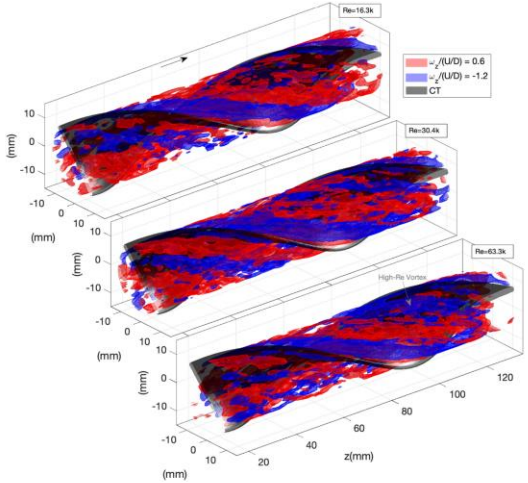
[1]S. Meschini et al Nucl. Fusion, 10.1088/1741-4326/acf3fc
[2]A.Q. Kuang et Al., Fus. Eng. Des. https://doi.org/10.1016/j.fusengdes.2018.09.007

What is a top-down to bottom-up design cycle?

System Level Design | Component Level Design | Separate Effect Studies







ARC Inner and Outer Fuel Cycle Schematic[1]

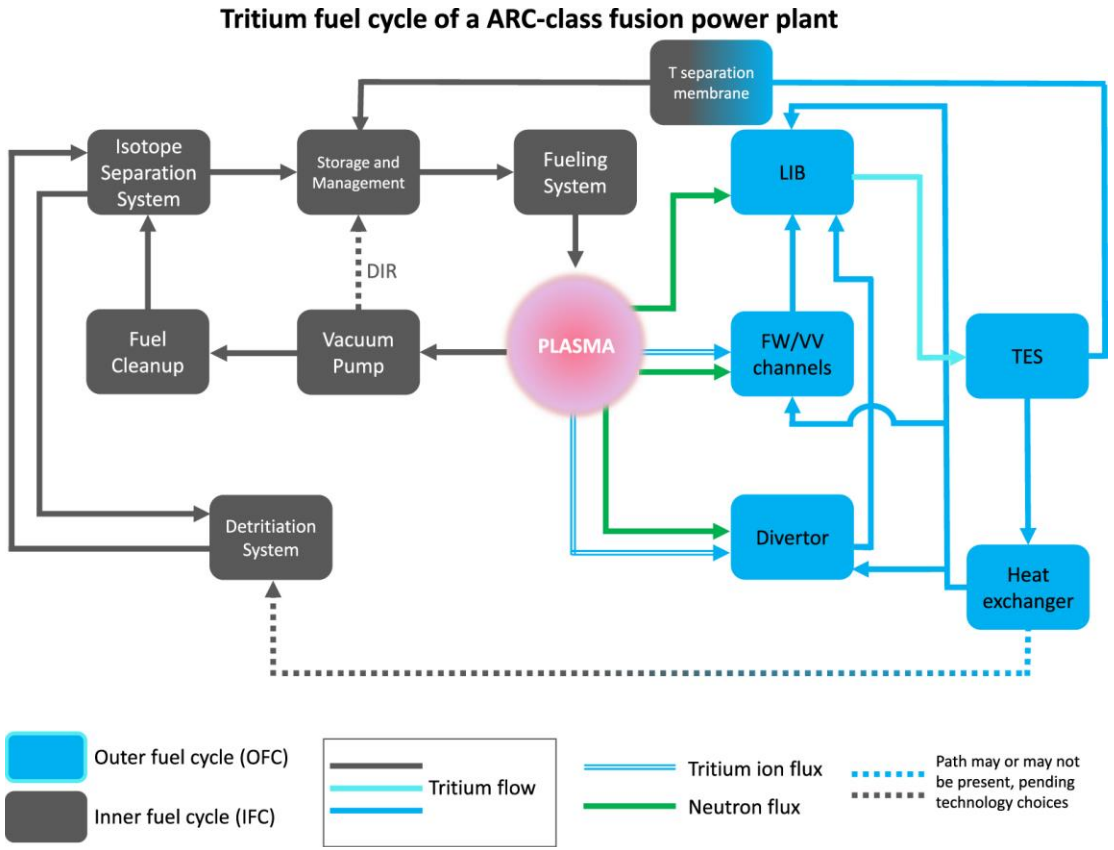
ARC Proposed Divertor Monoblock[2]

Twisted tape-insert flow experiment[3]

[1]S. Meschini et al Nucl. Fusion, 10.1088/1741-4326/acf3fc005
[2]A.Q. Kuang et Al., Fus. Eng. Des. https://doi.org/10.1016/j.fusengdes.2018.09.007
[3]C. S. Wiggins, …, L. B. Carasik*, 10.1007/s00348-024-03860-7,

Methodology – System Modeling of FES

- Few options exist for fusion system modeling to understand the behavior of inner and outer fuel cycles.
- These include such as System Analysis Module (SAM), MOOSE THM, ORNL's Modelica TRANSFORM library, RELAP5-3D, etc.



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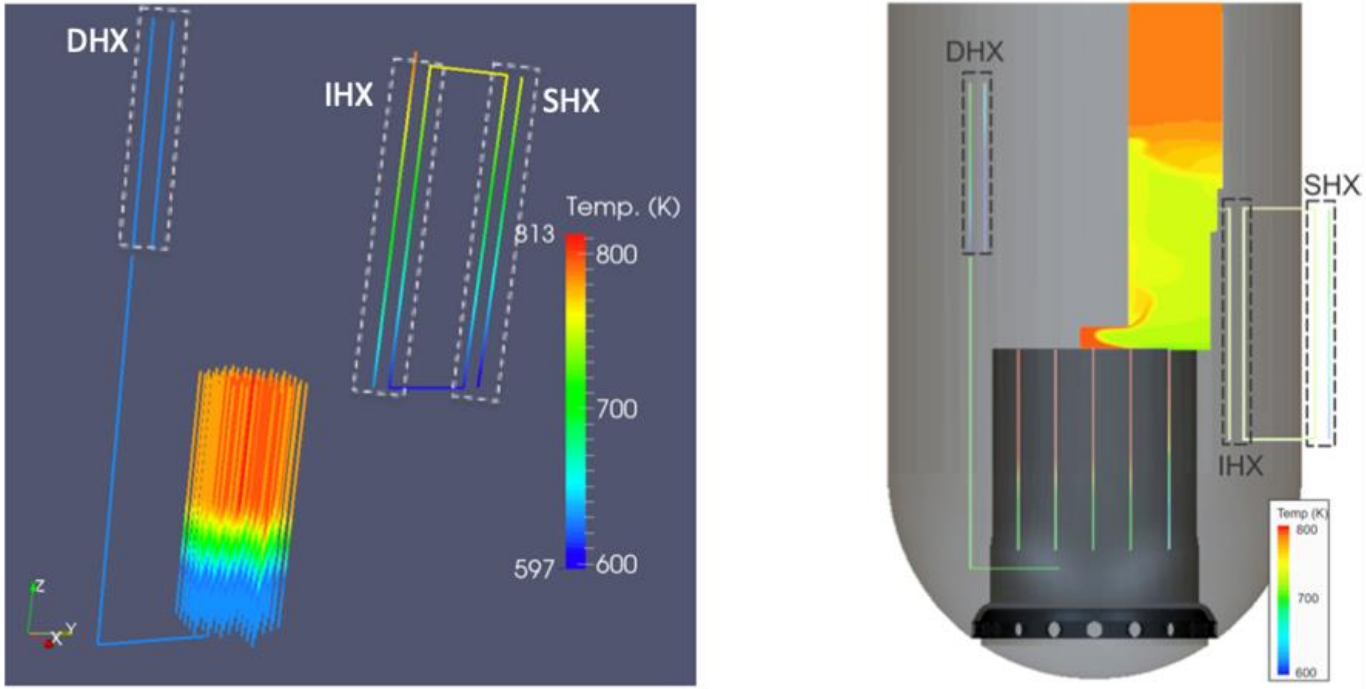
Methodology – System Modeling using SAM

- We use System Analysis Module (SAM)[1] developed in the **MOOSE[2]** framework created originally for advanced non-light water reactor design.
- This includes liquid metal (Sodium, Lead, Lead Bismuth) and high temperature & gas (Helium) systems.



(a) SAM model with 61 core channels

(b) Coupled SAM and CFD code simulation

Examples of System Modeling for Reactor Systems using SAM involving Sodium[1]

[1]R. Hu et al., 2021; https://doi.org/10.2172/1781819
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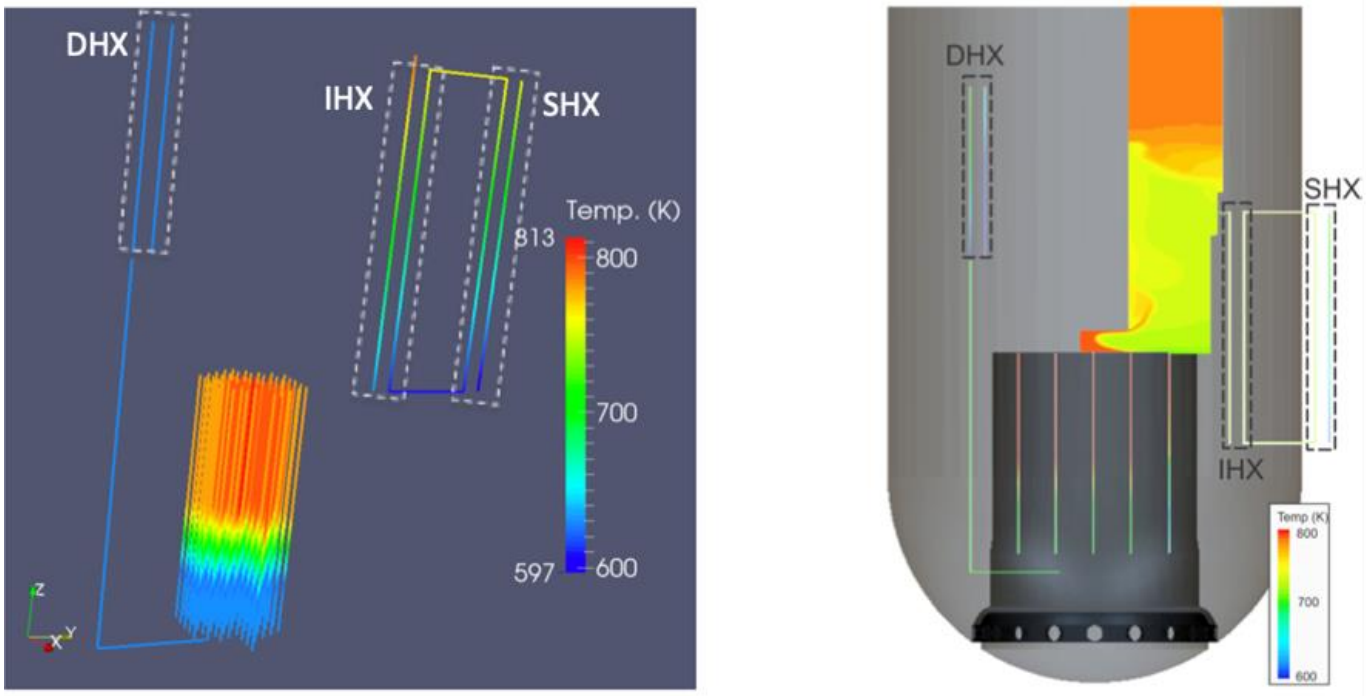

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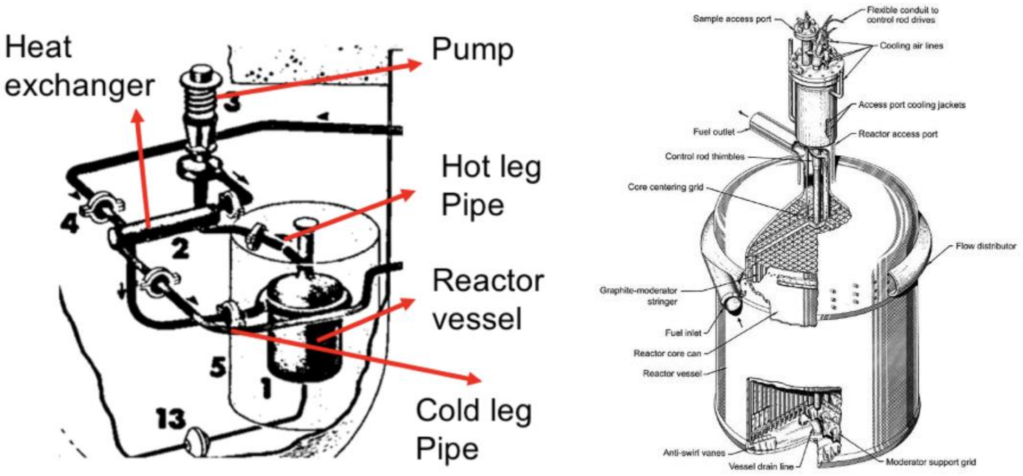
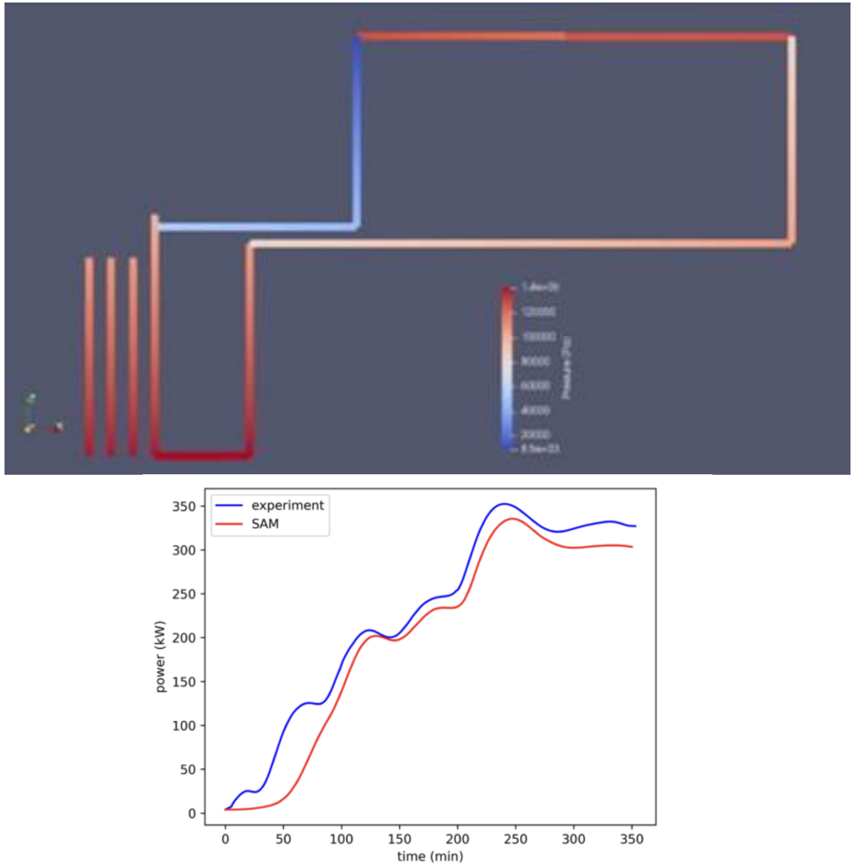
Methodology – System Modeling using SAM

- SAM was later extended for molten salt (FLiBe) based nuclear energy systems including the Fluoride salt cooled High temperature Reactor (FHR)



Molten Salt Reactor Experiment Systems[1,2]



Molten Salt Reactor Experiment Modeling using SAM[1,2]

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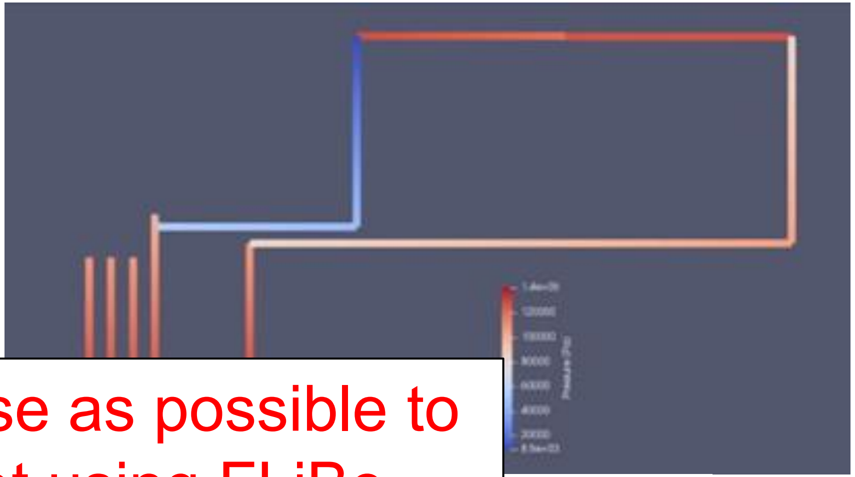
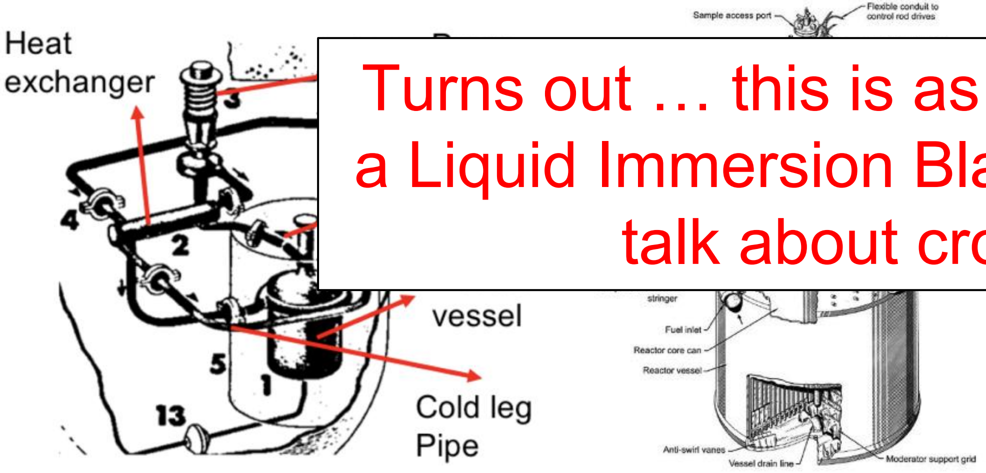
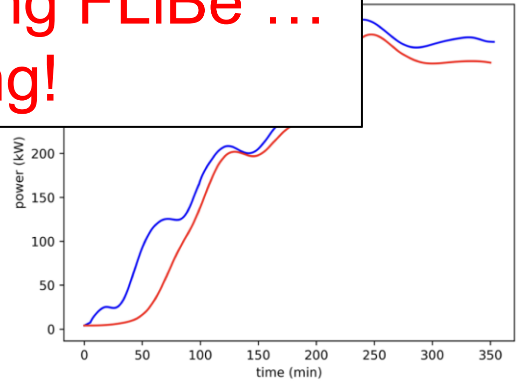




Molten Salt Reactor Experiment Systems[1,2]

Turns out … this is as close as possible to a Liquid Immersion Blanket using FLiBe … talk about cross-cutting!



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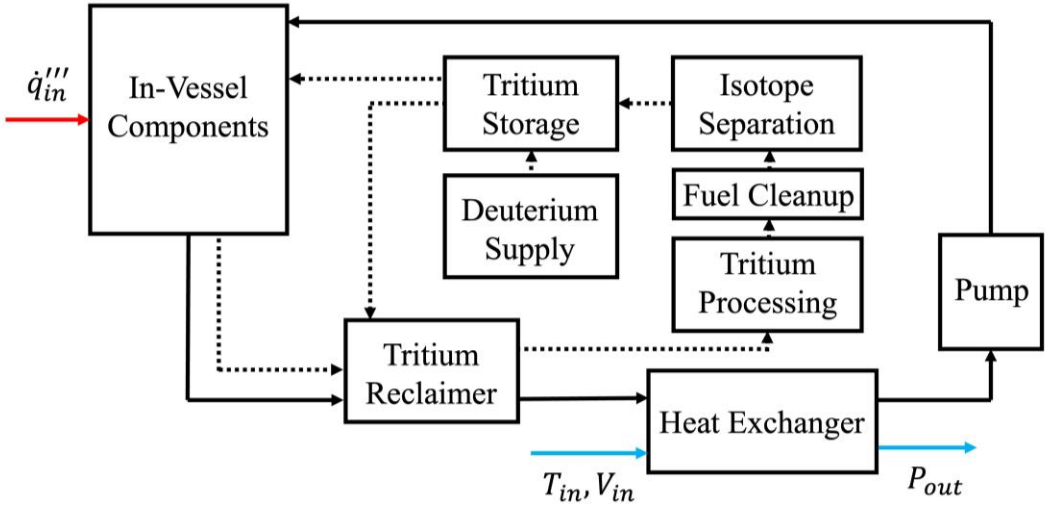
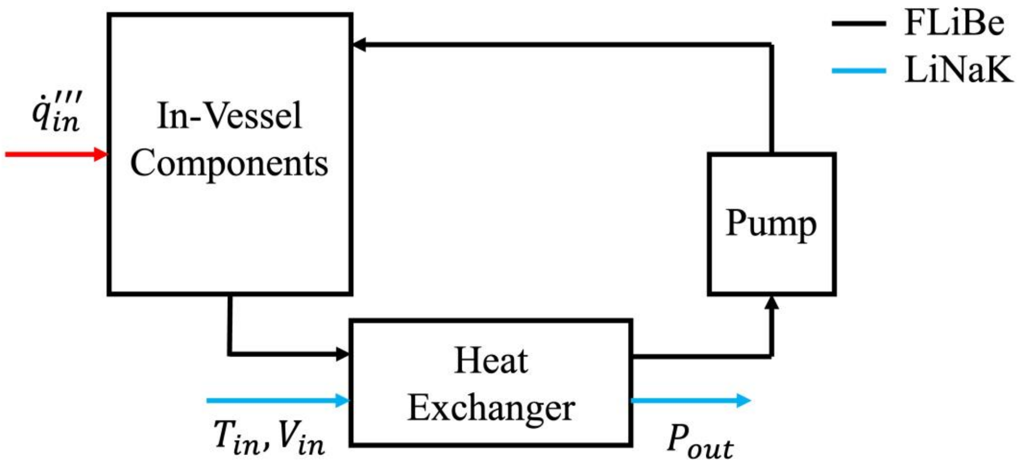
Methodology – Computational Domain of LIB Outer Fuel Cycle System



Simplified Schematic for a LIB Inner (Fuel) and Outer (Heat Transport) Fuel Cycle Systems[1,2]



Simplified Outer Fuel Cycle System used in this Study[1,2]

- For coolants, FLiBe salt was used in the heat transport loop while LiNaK (carbonate) salt[3] was modeled using the equations of state implemented in SAM.
- The structural materials are modeled as V alloy[4] or Inconel 718[4] for the thermal physical properties.

[1]T. Franklin, et al., 2025. 10.1080/15361055.2025.2503679
[2]T. Franklin et al., 2025. In Draft
[3]A. Cabral et al. 2022. Int. J. Energy Res. 46 3554–3571
[4]B. Bocci et al., 2020. Fusion Eng. Des. 154 111539

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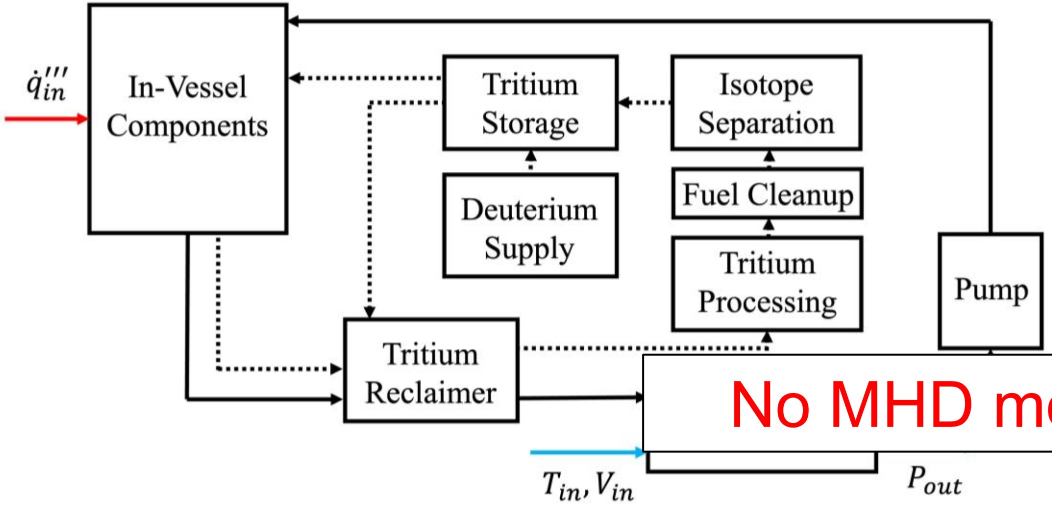

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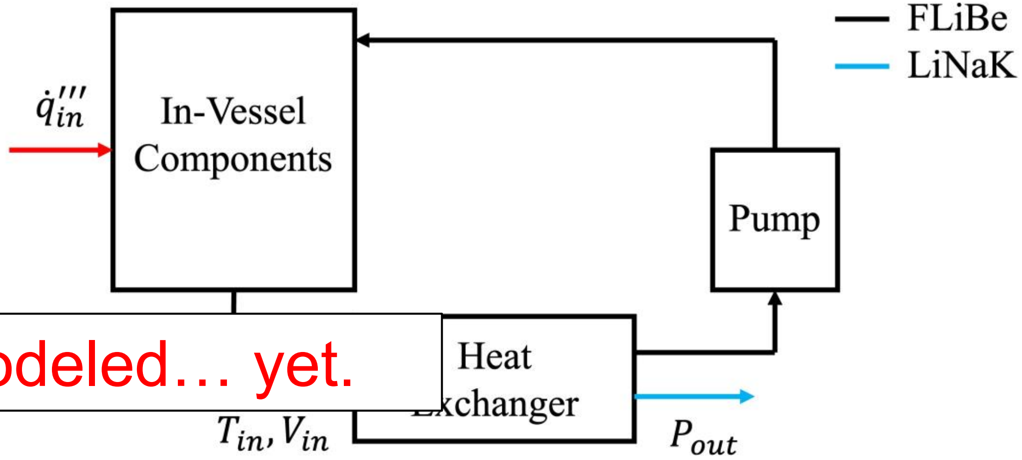

Simplified Outer Fuel Cycle System used in this Study[1,2]

No MHD modeled… yet.

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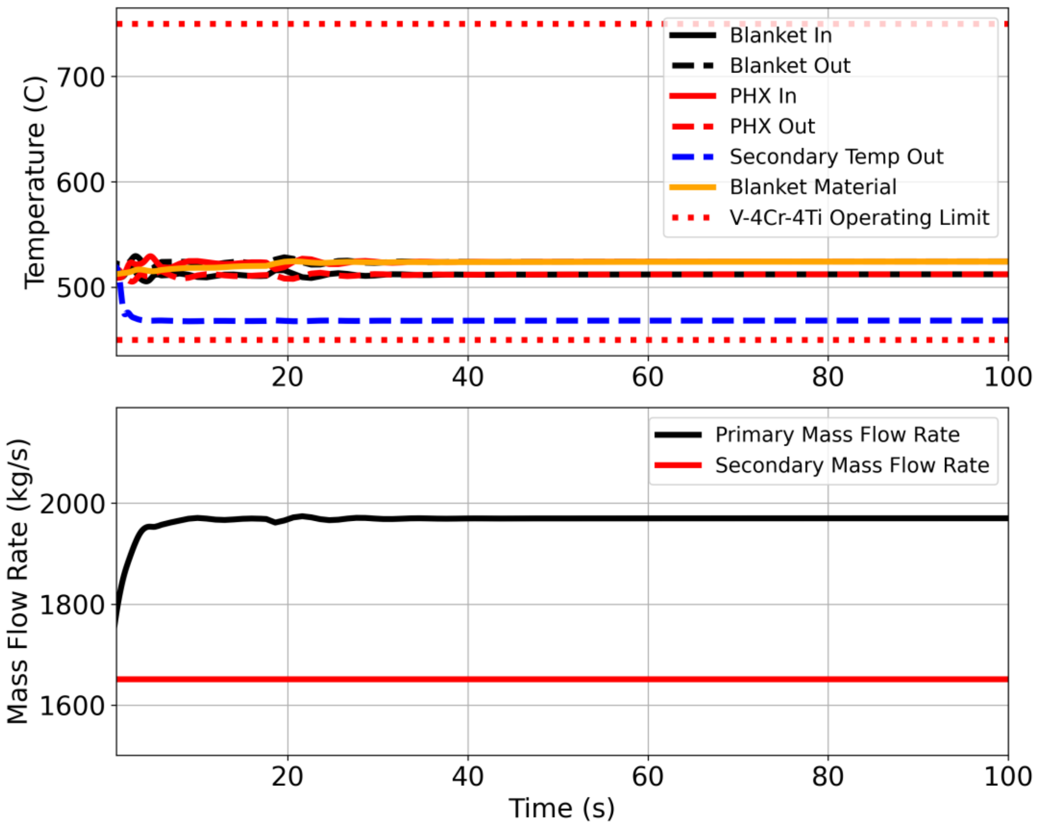
Results – Overview of Study

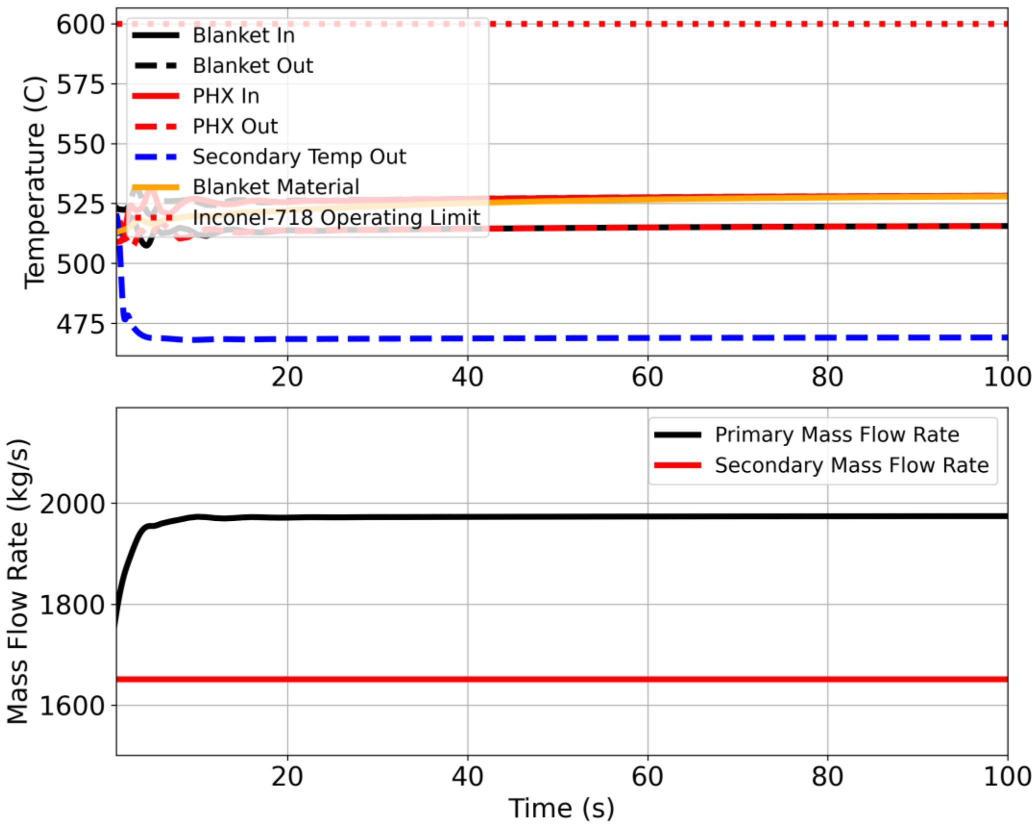
- (Latent Heating) How much ”latent” heating is needed to keep the molten salt at sufficiently high temperatures to avoid freezing?
- (Start-Up) Start-up for the outer fuel cycle loop from a ”standby” condition.
- (Shutdown) A nominal shutdown scenario for the outer fuel cycle loop to a ”standby” condition.
- (Unprotected Pump Trip) An initial severe transient where primary pump(s) trips or fails without signals to stop fusion core operations in the outer fuel cycle to understand component level temperature response (i.e. forced to natural circulation).

[1]T. Franklin, et al., 2025. 10.1080/15361055.2025.2503679
[2]T. Franklin et al., 2025. In Draft

Results – Latent Heating Transient



22% Power Addition with V-4Cr-4Ti[1,2]



22% Power Addition with Inconel-718[1,2]

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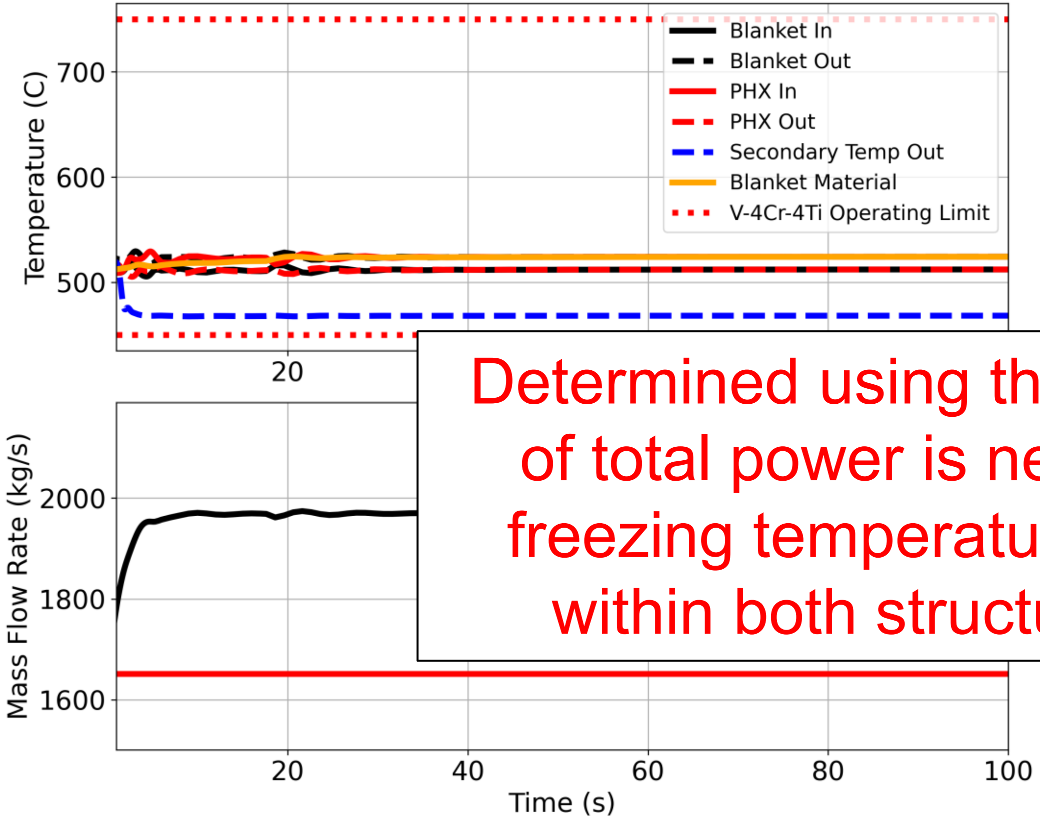

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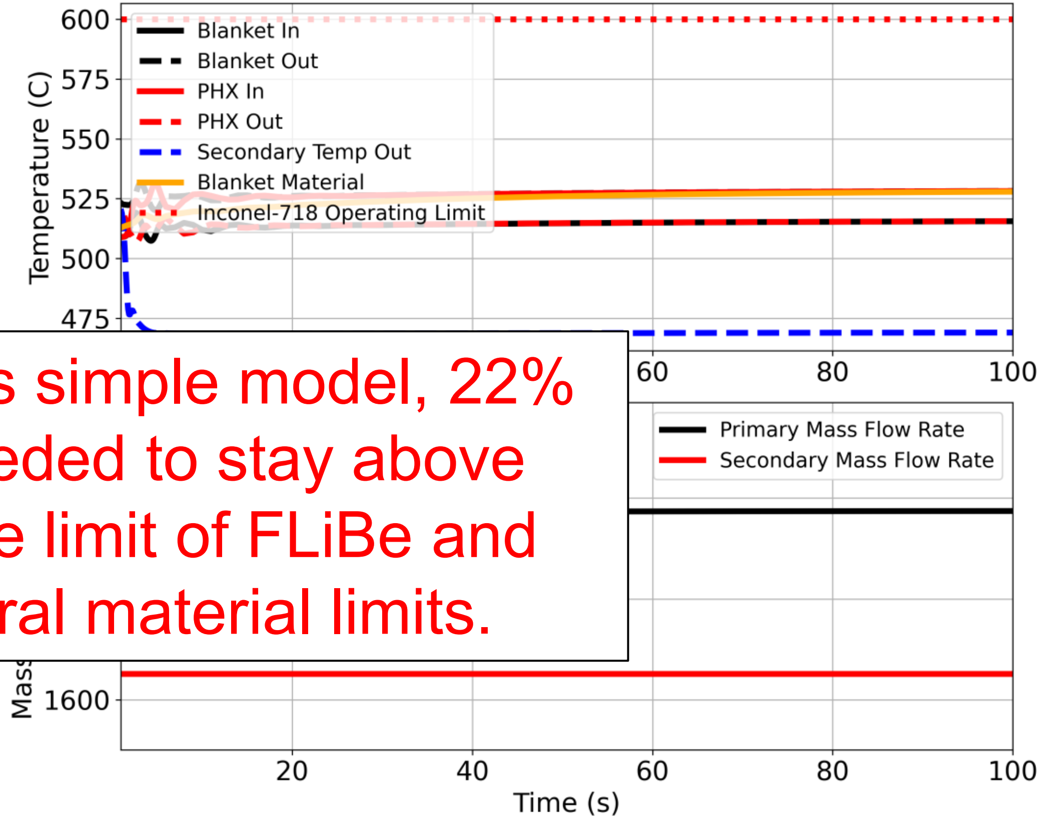
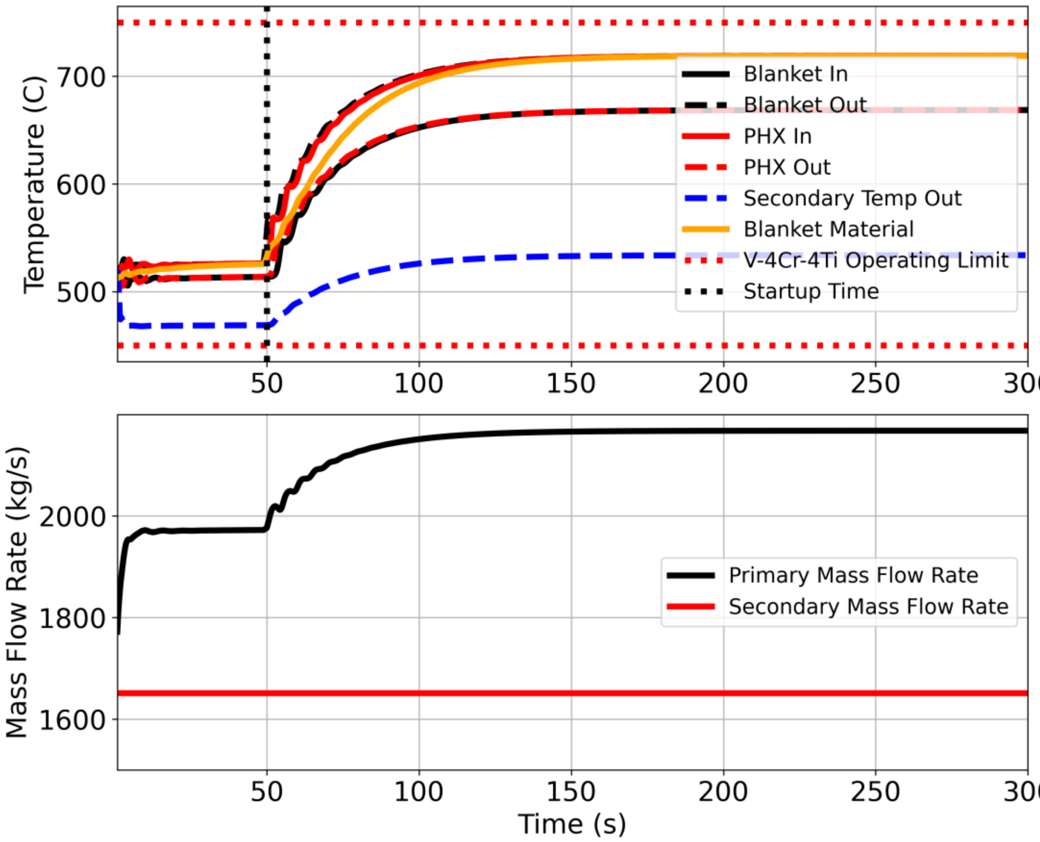


22% Power Addition with Inconel-718[1,2]

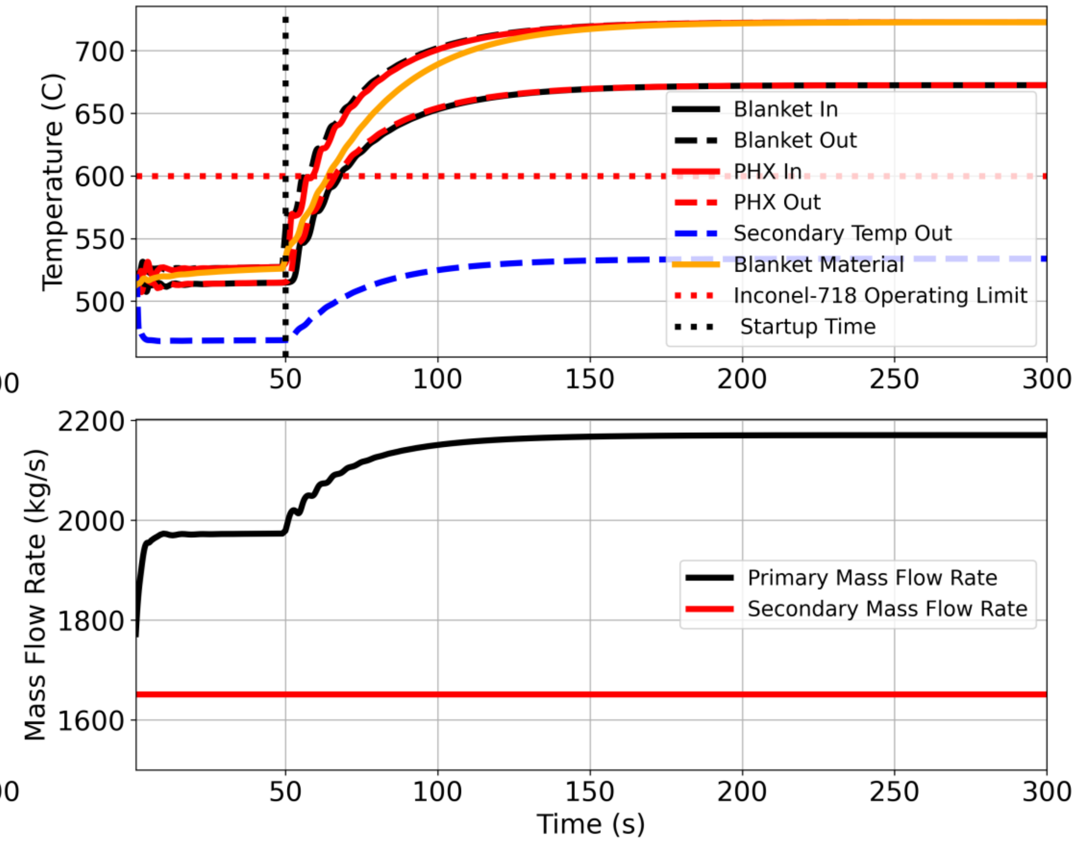
Determined using this simple model, 22% of total power is needed to stay above freezing temperature limit of FLiBe and within both structural material limits.

[1]T. Franklin, et al., 2025. 10.1080/15361055.2025.2503679, [2]S. Zinkle et al., 2009. Materials Today 12(11) 12-19

Results – Start-up Transient



Start-up to Full Power with V-4Cr-4Ti[1,2]



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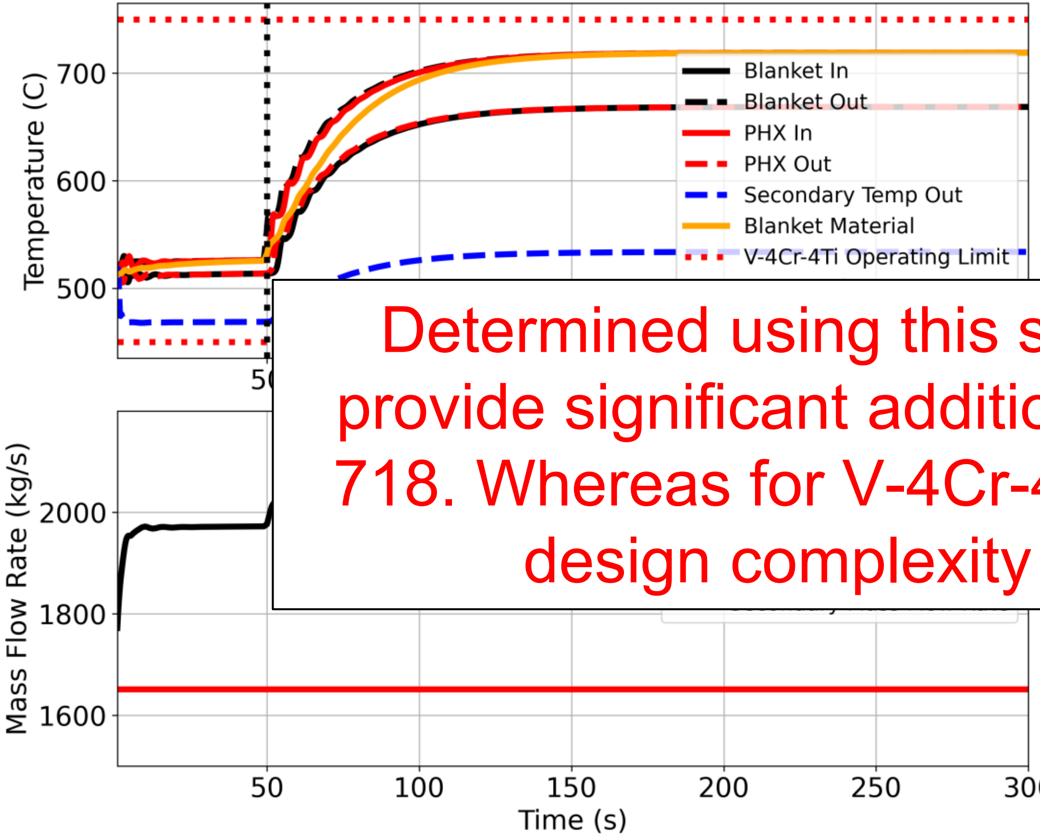

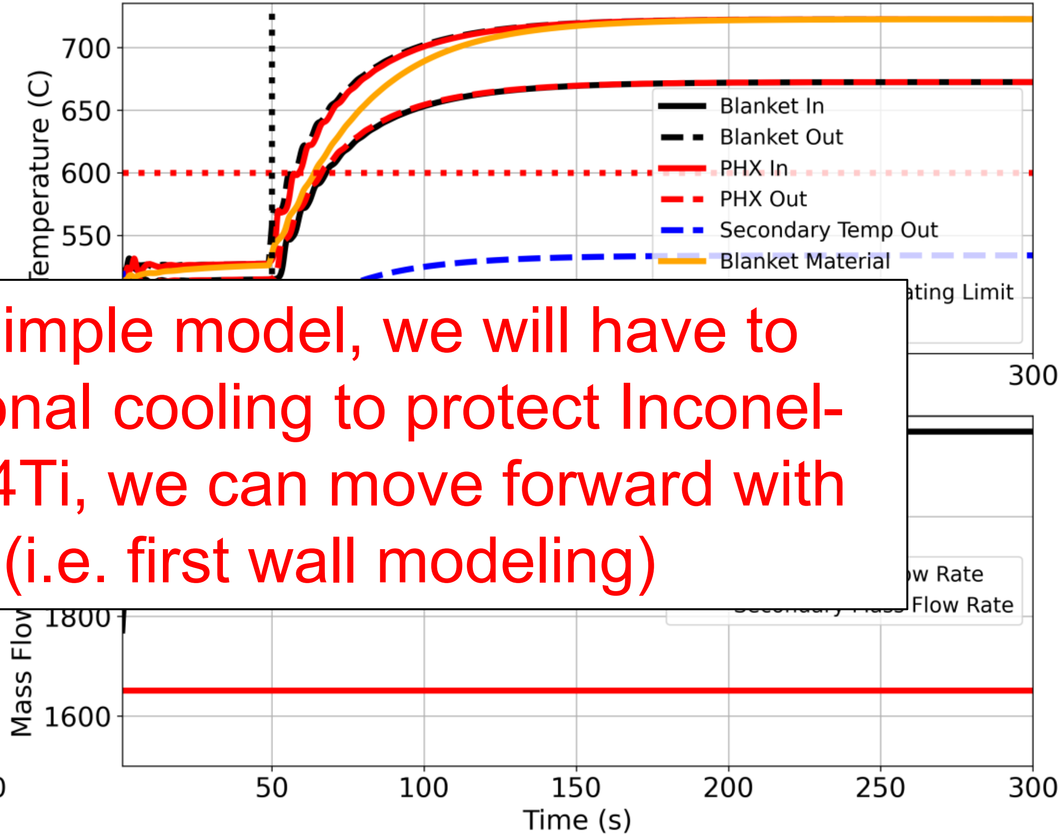

Determined using this simple model, we will have to provide significant additional cooling to protect Inconel-718. Whereas for V-4Cr-4Ti, we can move forward with design complexity (i.e. first wall modeling)

Start-up to Full Power with V-4Cr-4Ti[1,2]

Start-up to Full Power with Inconel-718[1,2]

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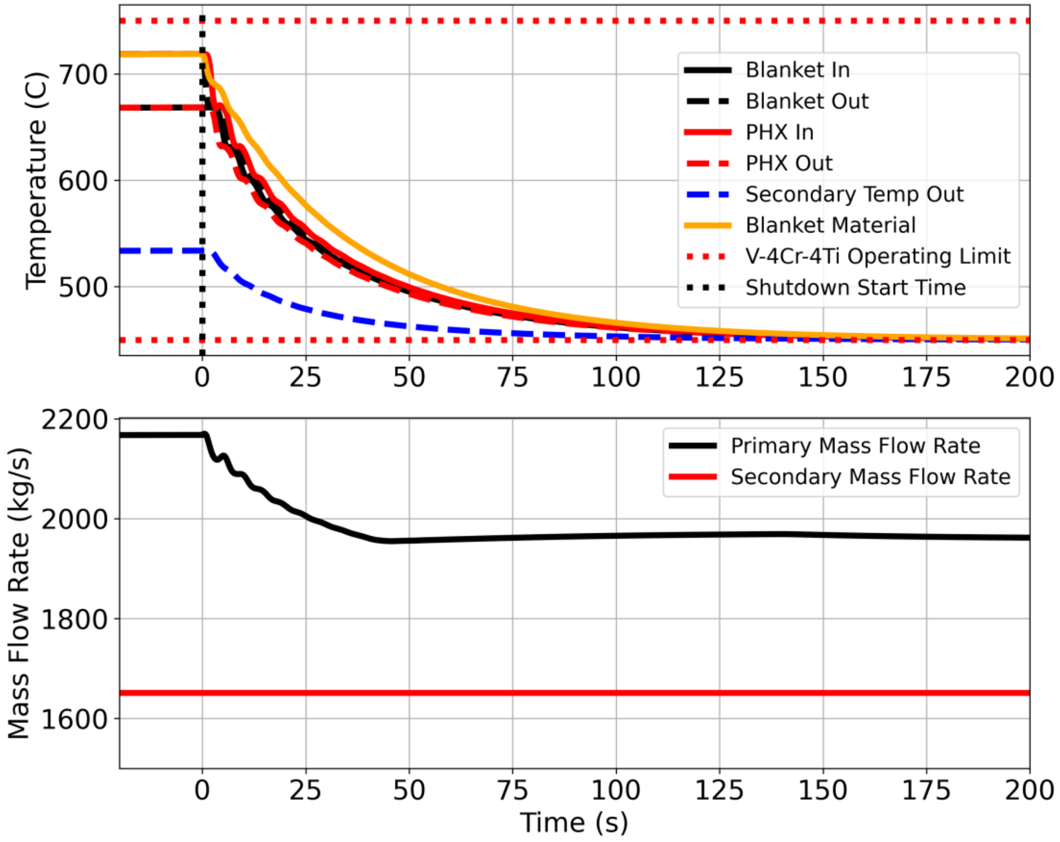
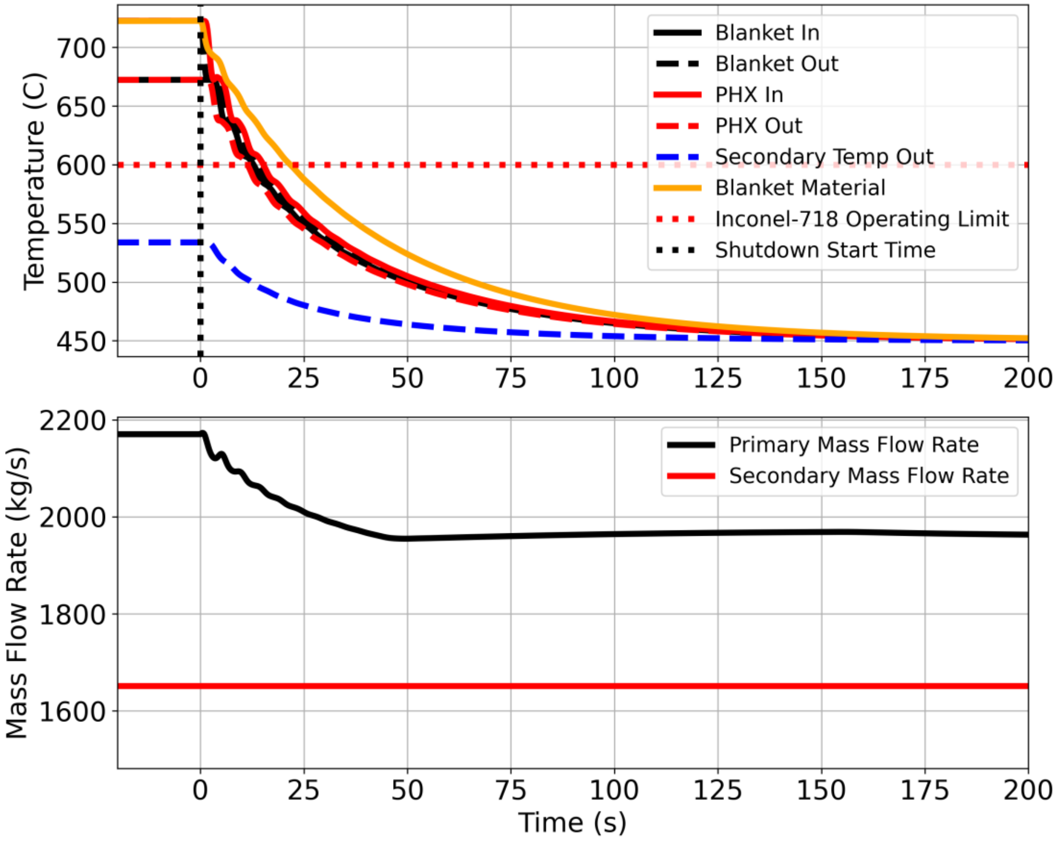
VCU

Results – Shutdown Transient



Full Power to Shutdown with V-4Cr-4Ti[1,2]



Full Power to Shutdown with Inconel-718[1,2]

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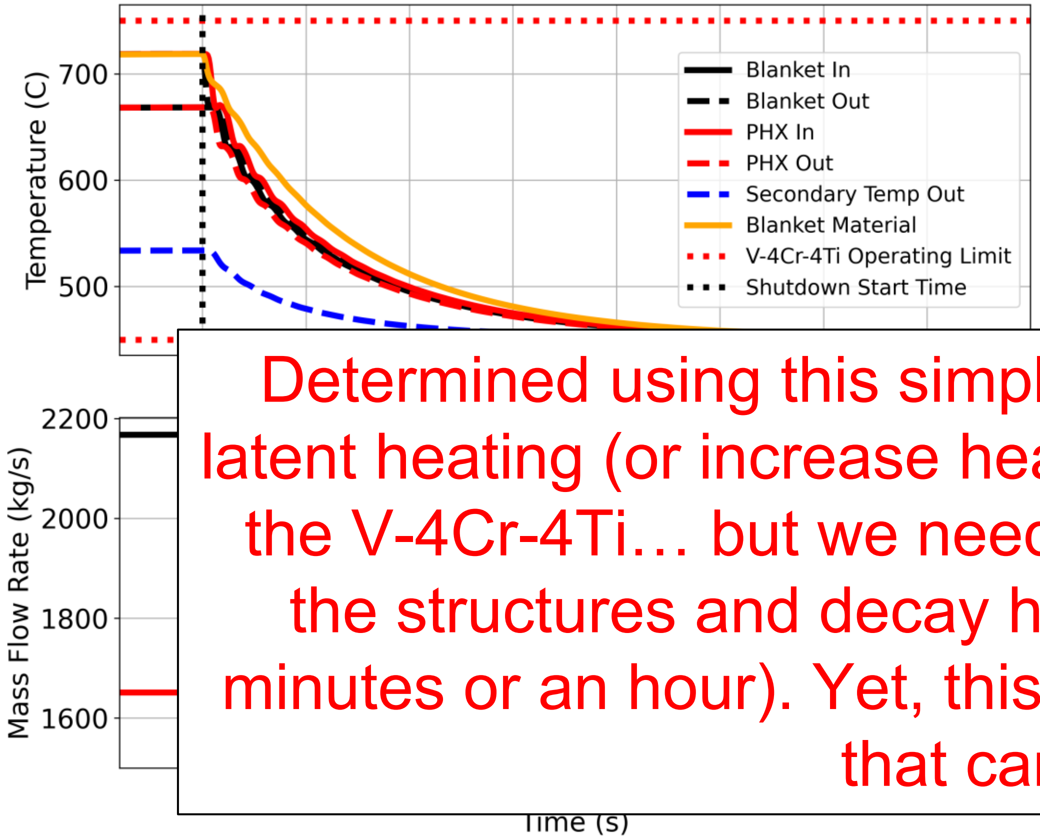

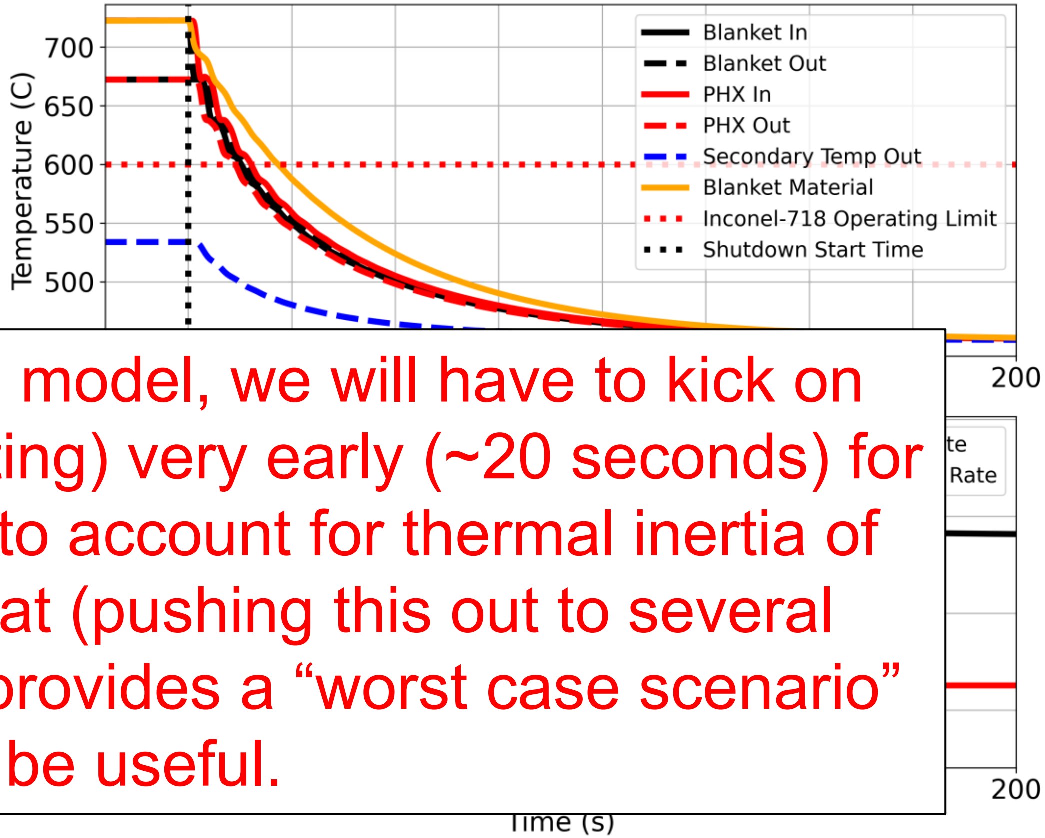

Determined using this simple model, we will have to kick on latent heating (or increase heating) very early (~20 seconds) for the V-4Cr-4Ti… but we need to account for thermal inertia of the structures and decay heat (pushing this out to several minutes or an hour). Yet, this provides a “worst case scenario” that can be useful.

Full Power to Shutdown with V-4Cr-4Ti[1,2]

Full Power to Shutdown with Inconel-718[1,2]

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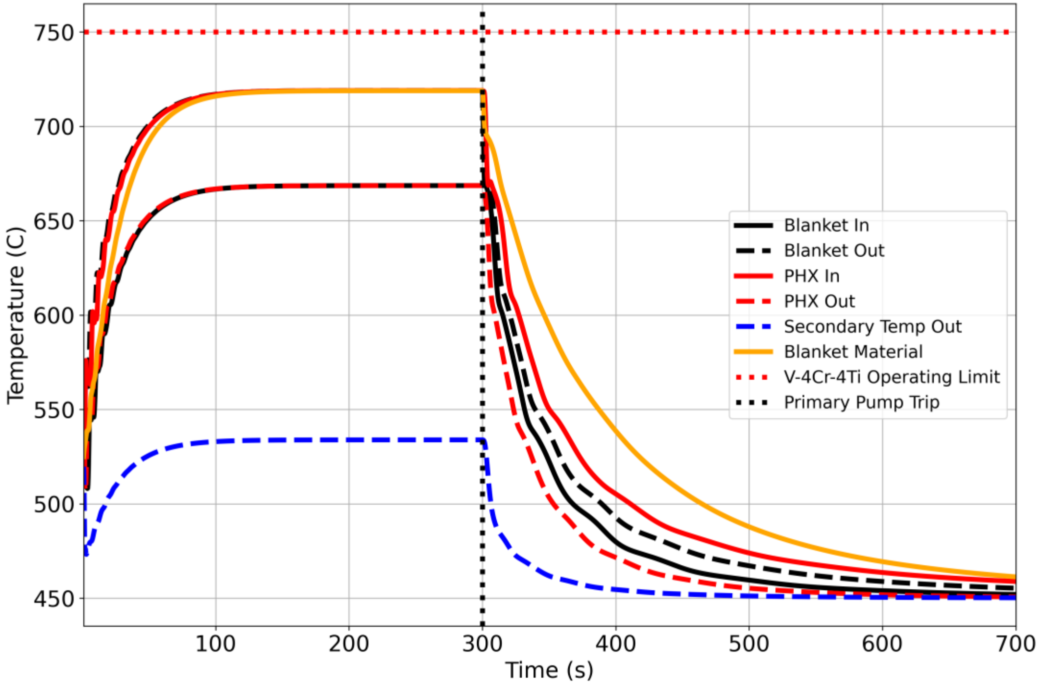
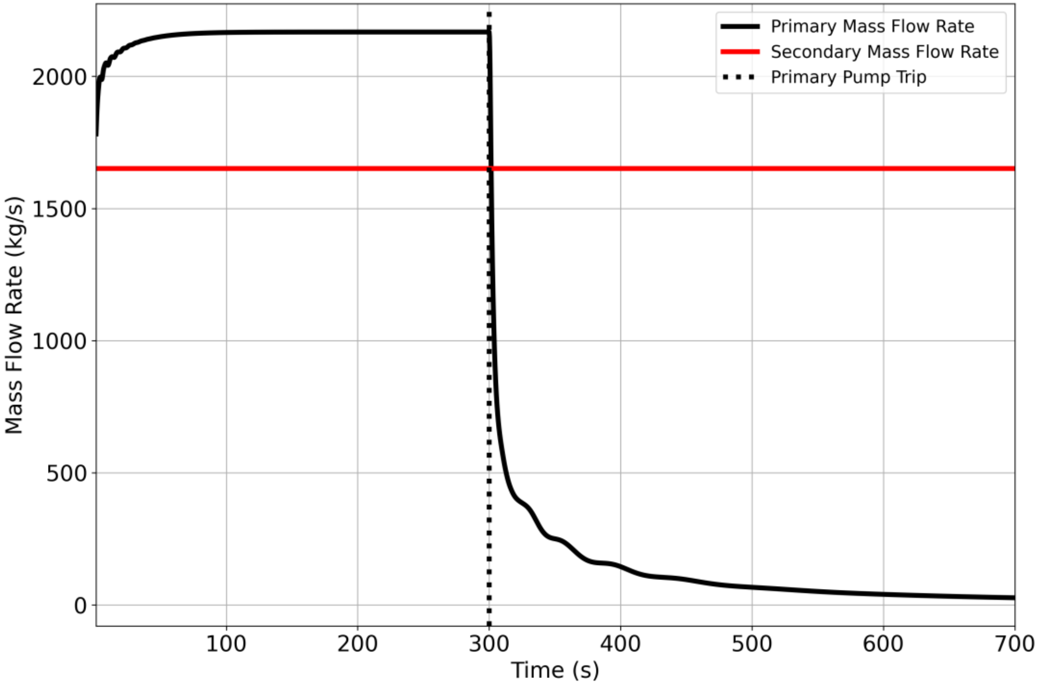
VCU

Results – Protected Primary Pump Trip



Temperature Evolution for a V-4Ci-4Ti Loop



Mass Flow Evolution for a V-4Ci-4Ti Loop

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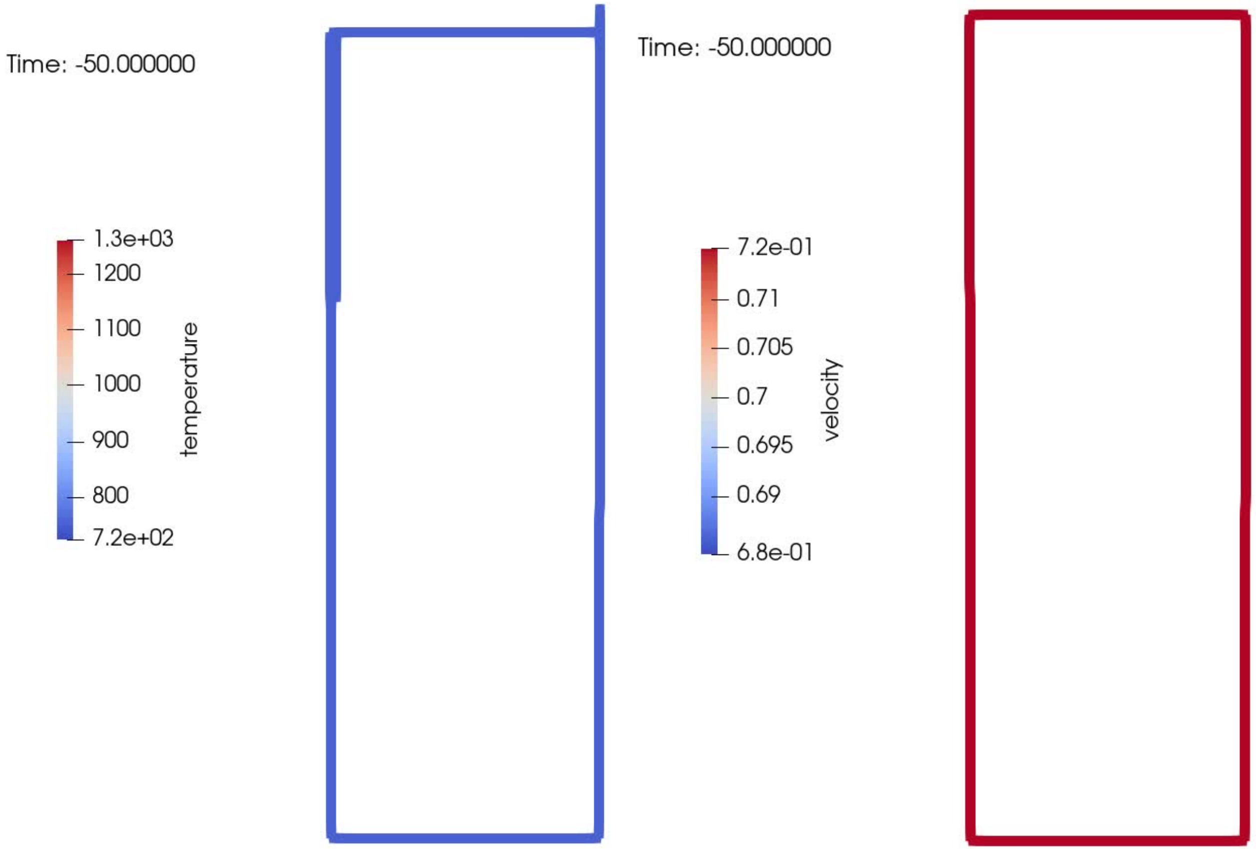
Results – Unprotected Primary Pump Trip

$$P_{head} = \begin{cases} 10^4 & \text{if } t \leq 300 \\ 0 & \text{if } t \geq 301 \end{cases}$$

Primary pump trip with fusion core continuing to run.



Velocity and Temperature Visualization at t=300s

[1]T. Franklin et al., 2025. In Draft, [2]S. Zinkle et al., 2009. Materials Today 12(11) 12-19

VCU

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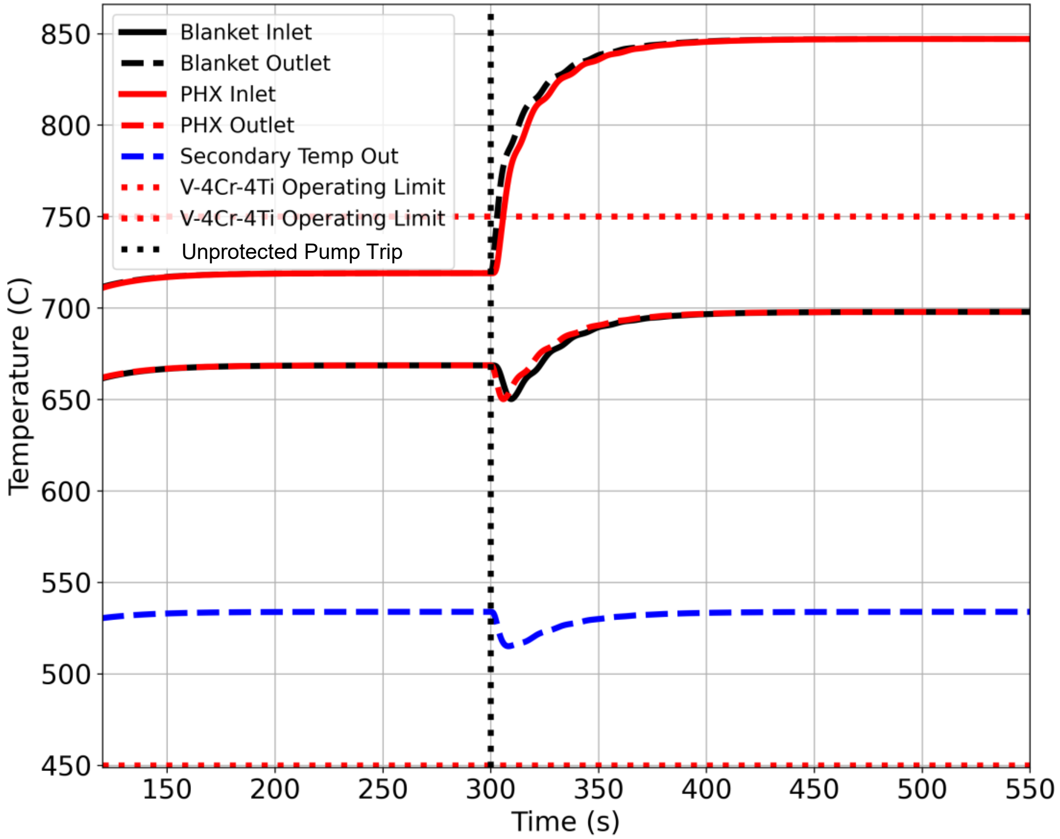

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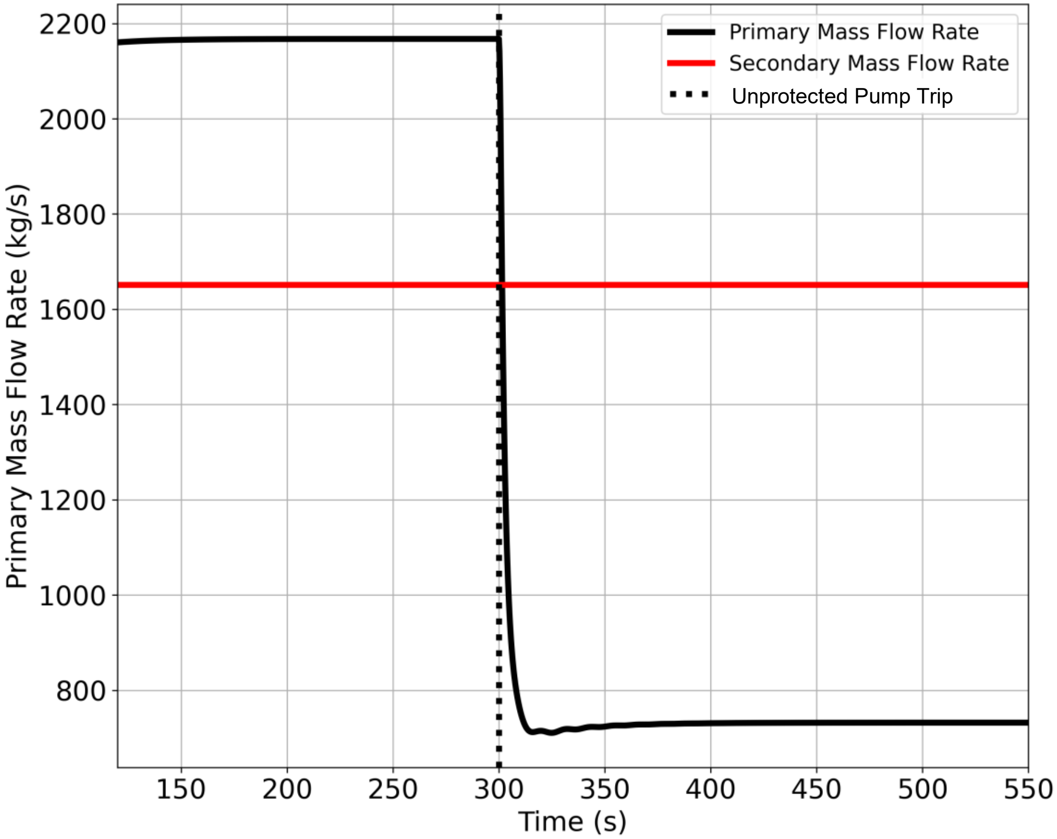

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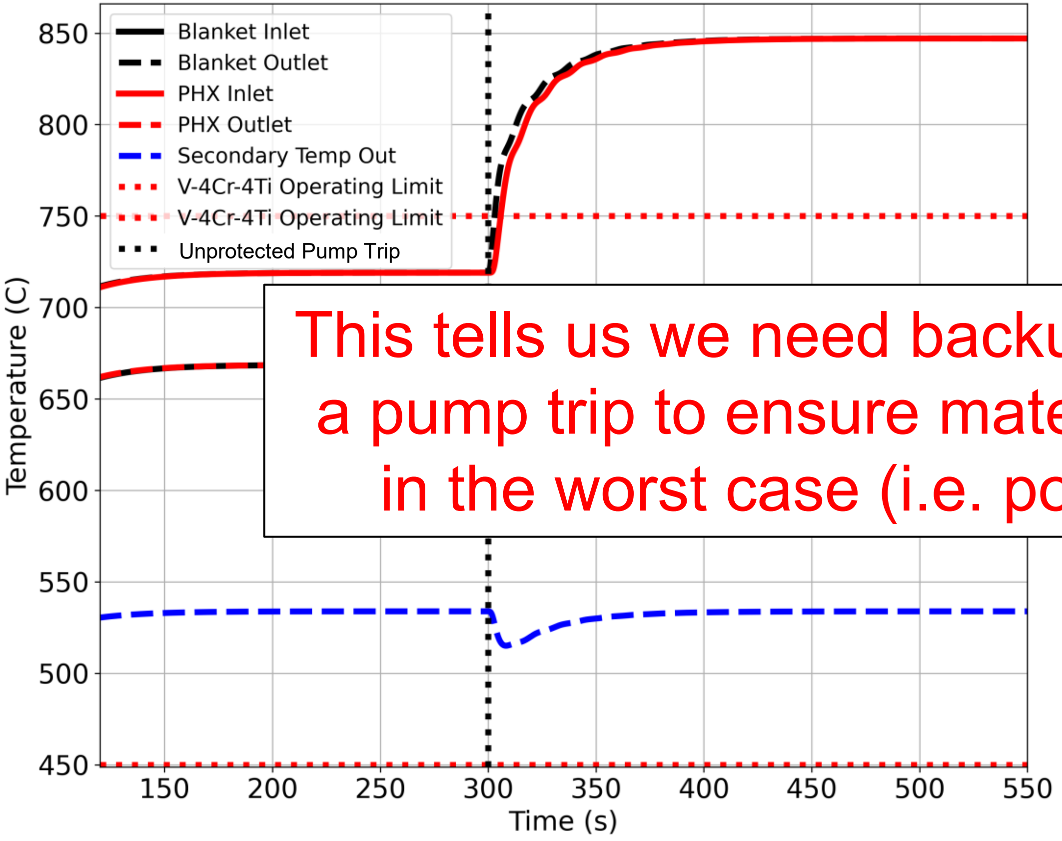

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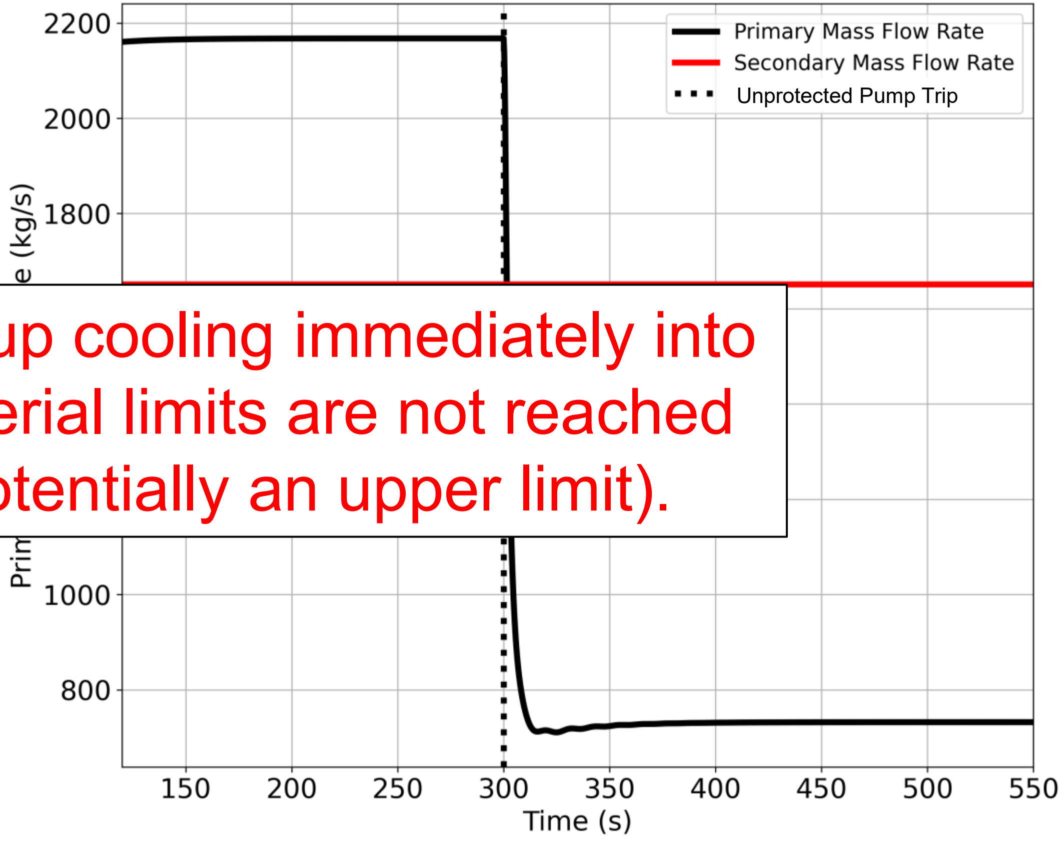


Mass Flow Evolution for a V-4Ci-4Ti Loop

This tells us we need backup cooling immediately into a pump trip to ensure material limits are not reached in the worst case (i.e. potentially an upper limit).

[1]T. Franklin et al., 2025. In Draft, [2]S. Zinkle et al., 2009. Materials Today 12(11) 12-19

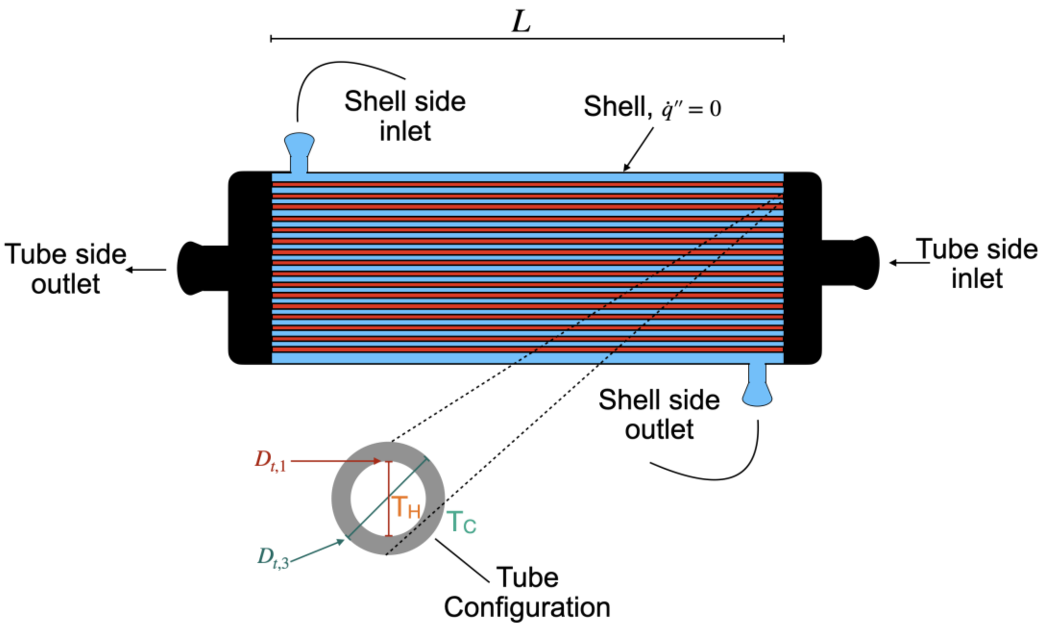
Conclusions and Future Work

- This study provides an initial preconceptual design using SAM for a liquid immersion blanket outer fuel cycle system to determine future component level conditions, flow regimes, and heat transfer modes.

- Future work will involve refinement of the simplified model, unprotected and protected transients to provide information for follow-on component studies including 1st wall, blanket, and primary heat exchanger design.

The Future? Component "Design" Work!

HX Type	Counter-flow Shell & Tube	
Number of Heat Exchangers	4	
Tube Arrangement (Pitch Angle)	Triangular (30°)	
Tube Pitch to Diameter Ratio	1.25	
Baffles	None	
Tube Material	V_4Cr_4Ti Alloy	
Stream	Tube	Shell
Molten Salt:	FLiBe	LiNaK
Inlet Temperature (°C)	720	443
Outlet Temperature (°C)	670	535
Mass Flow Rate (kg/s)	2124	1650



Machine Learning based Multi-Objective Optimization for a ARC Heat Exchanger

[1]A. Coxe and L. B. Carasik, In-Prep

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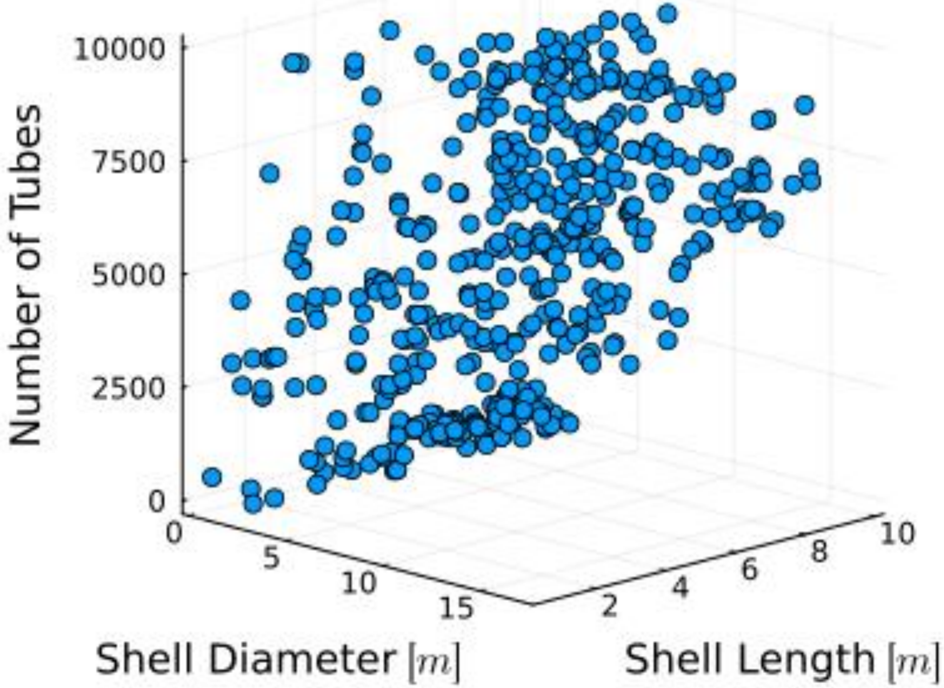

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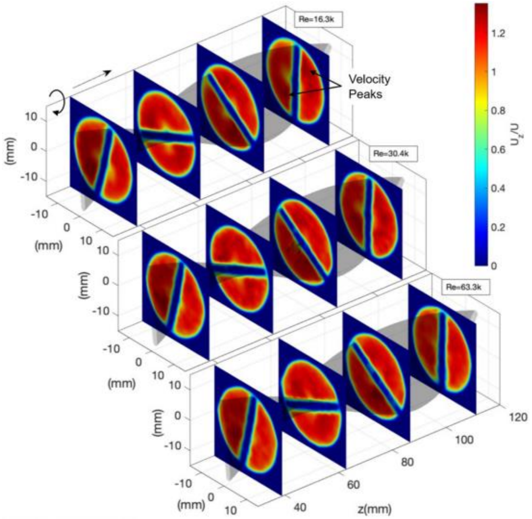
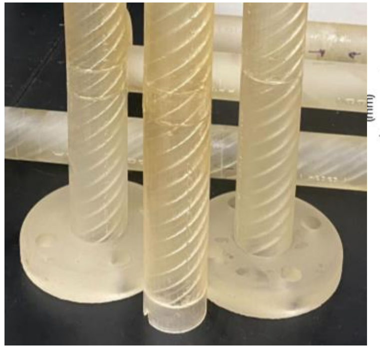
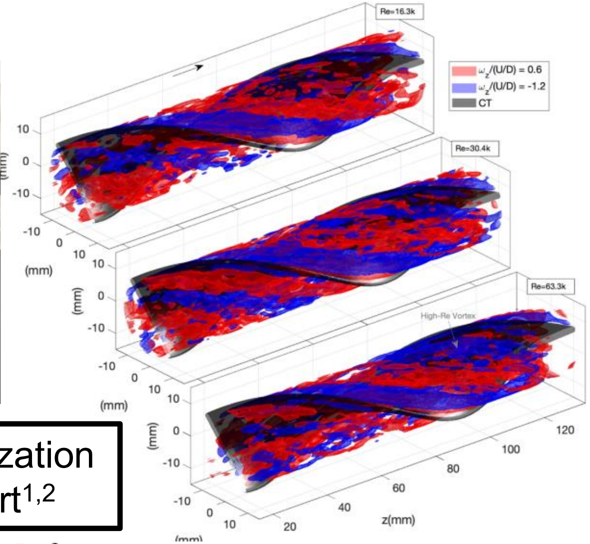
[1]A. Coxe and L. B. Carasik, In-Prep

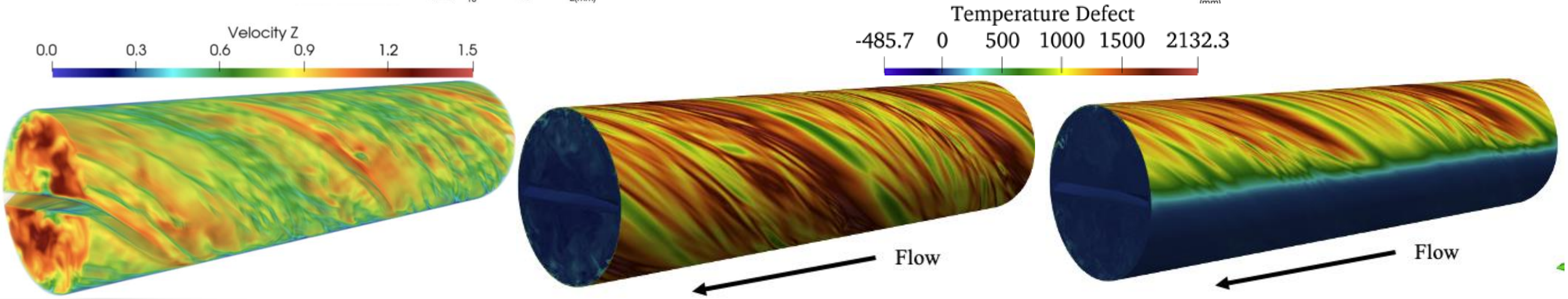
The Future? Component Level Investigations!







Experimental Flow Visualization from Twisted Tape-Insert[1,2]



CFD Visualization of Twisted Tape-Insert[3,4]

[1]C.S. Wiggins, …, L. B. Carasik*, 10.1016/j.nucengdes.2022.112125,[2]C. S. Wiggins, …, L. B. Carasik*, 10.1007/s00348-024-03860-7,
[3]Sierra Tutwiler, …, Lane B. Carasik*, 10.1080/15361055.2025.2463818, [4]Sierra Tutwiler, .., Lane B. Carasik*, DOI: 10.1080/15361055.2025.2470044

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The FAST Research Group

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Fluids in Advanced Systems and Technology (FAST) Research Group:

- Advanced thermal hydraulics (fusion, fission, and solar)
- Advanced instrumentation
- Isotope production

Postdocs

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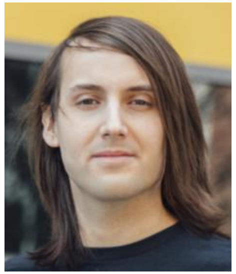

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Ryan McGuire+

Trevor Franklin*,+

Jerel Houston^

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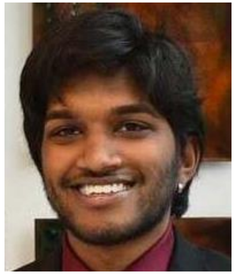
Jesse East>



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Ethan Villarreal

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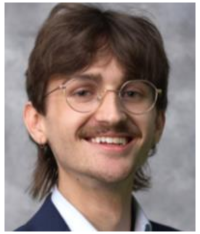
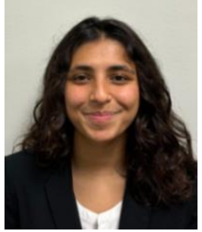


Gavin Standish



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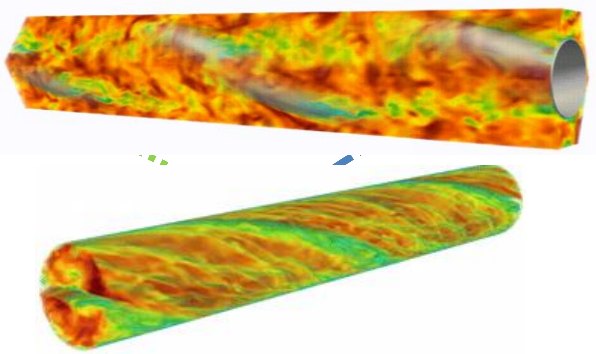
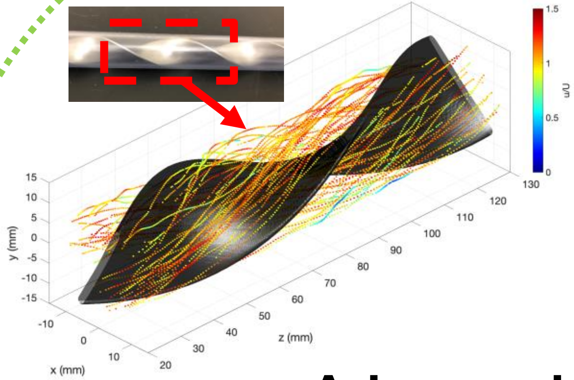
Advanced thermal hydraulics

(fusion, fission, and solar)

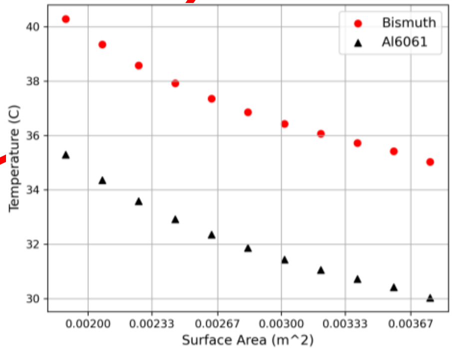




Advanced instrumentation

PEPT
Fiber Optics

FAST Research Group



Isotope Production

Target Design

Thank you!

VCU College of Engineering
Mechanical and Nuclear Engineering

Fusion Energy System ARC System Modeling using SAM

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