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INL/MIS-24-77603

Molten Salt Reactor PROGRAM

Tritium Transport

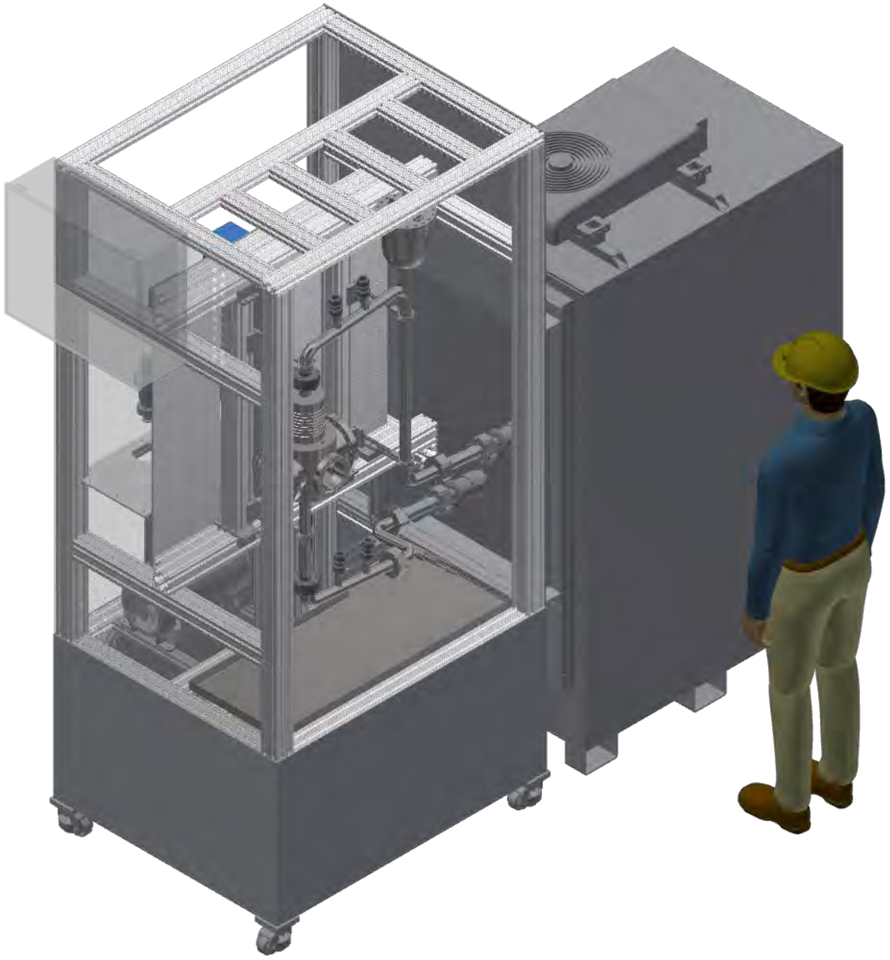
Thomas Fuerst

Idaho National Laboratory

Annual MSR Campaign Review Meeting: 16-17 April 2024

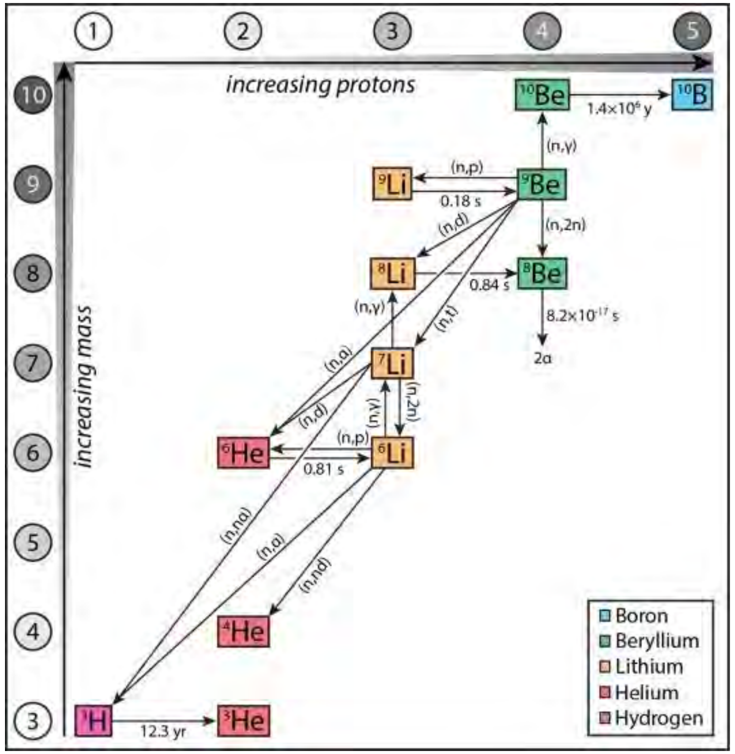
Outline

- **Tritium Transport Background**
  - Generation in MSRs
  - Transport in MSRs
- **M**olten **S**alt **T**ritium **T**ransport **E**xperiment
  - Overview
  - Component Update
  - Modeling Efforts
  - Status



Tritium Generation in MSRs

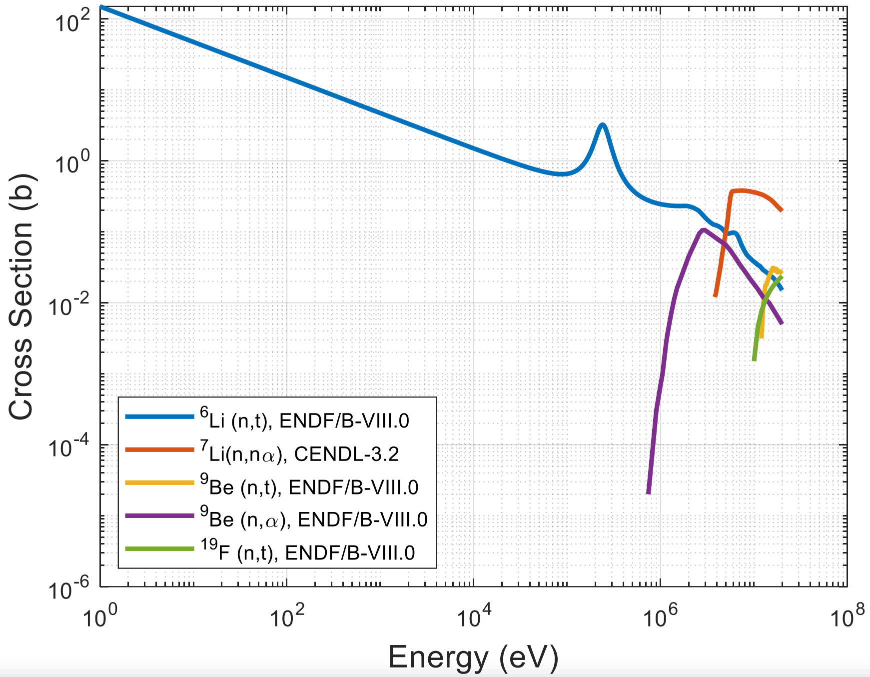
Tritium generated by neutron reactions with Li, Be, and F.



^{6}Li (7.5%) large thermal cross-section.

^{7}Li (92.5%) moderate cross-section in fast-spectrum.

^{9}Be and ^{19}F tritium in fast-spectrum.



Tritium generation rates in *fluoride* salt reactors are similar to CANDU reactors.

CANDUs produce world's commercial supply of tritium.

Tritium is a valuable byproduct of MSRs.

Reactor Type	Tritium Formation Rate 1000 MWe (Ci/day) [1]
MSR	2400*
CANDU	2700
HTGR	50
PWR	2

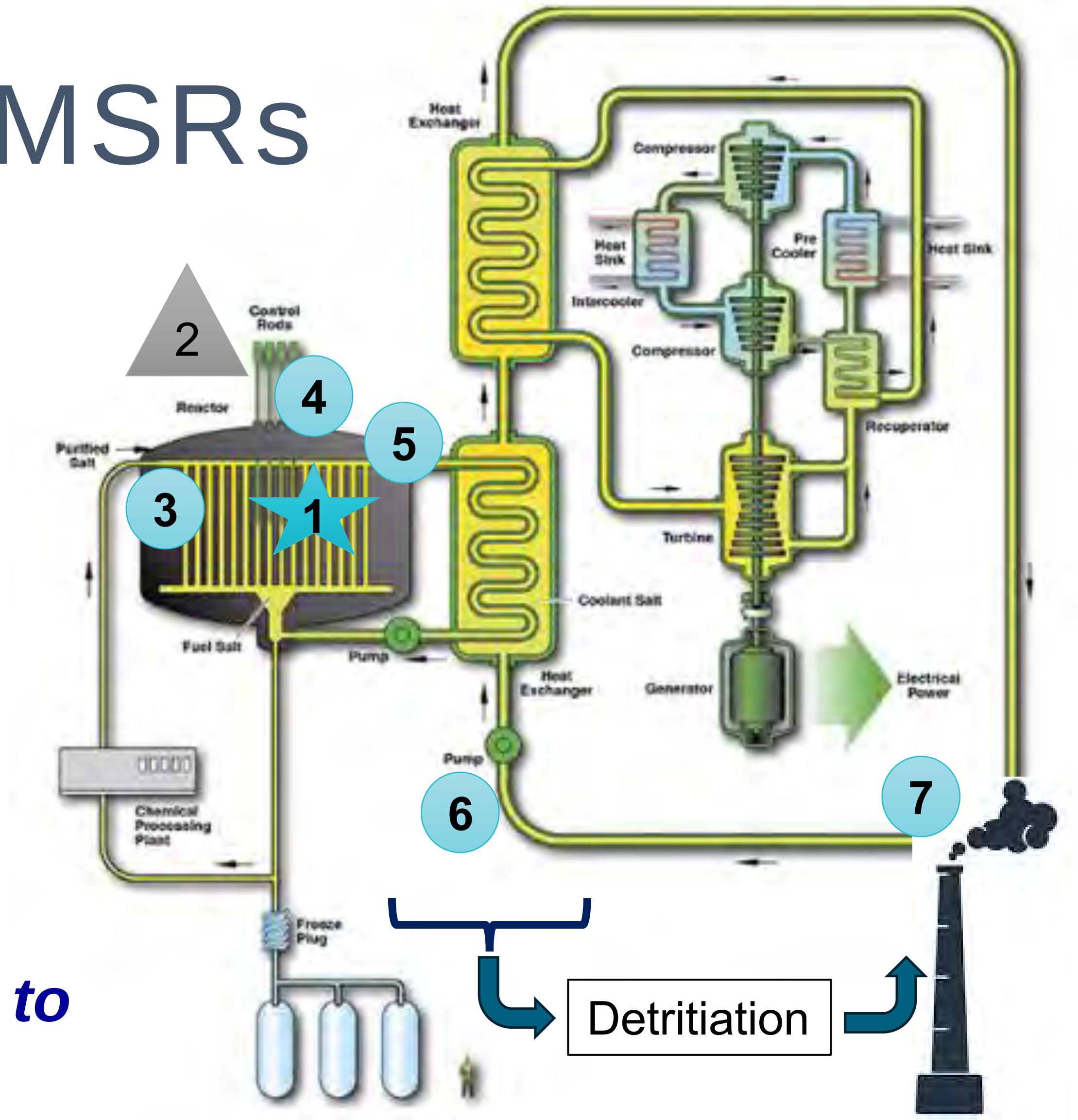
*MSBR enriched in ^{7}Li (99.992%).

Sabharwall, P.; Schmutz, H.; Stoots, C.; Griffith, G. Tritium Production and Permeation in High-Temperature Reactor Systems;, 2013. https://doi.org/10.1115/HT2013-17036.

Andrews, Hunter B., et al. "Review of molten salt reactor off-gas management considerations." Nucl. Eng. Des. 385 (2021): 111529.

Tritium Transport in MSRs

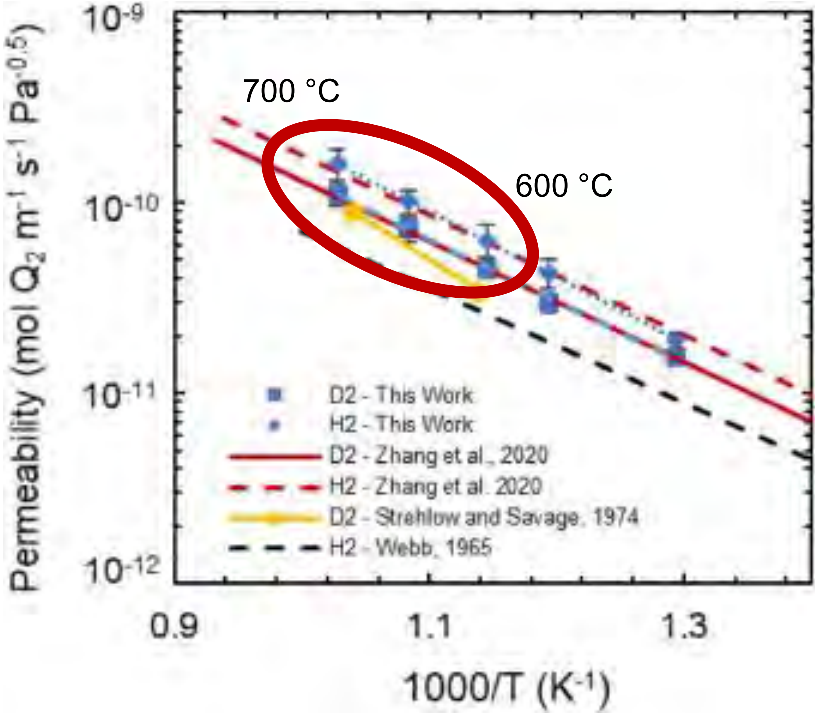
1. **Production (neutrons + Li, Be, F)**
2. ***Speciation (TF vs. T_2)***
3. ***Graphite***
4. **Evolution into off-gas system**
5. ***Diffusion through materials***
6. **Secondary system off-gas system**
7. **Onwards to detritiation/stack**

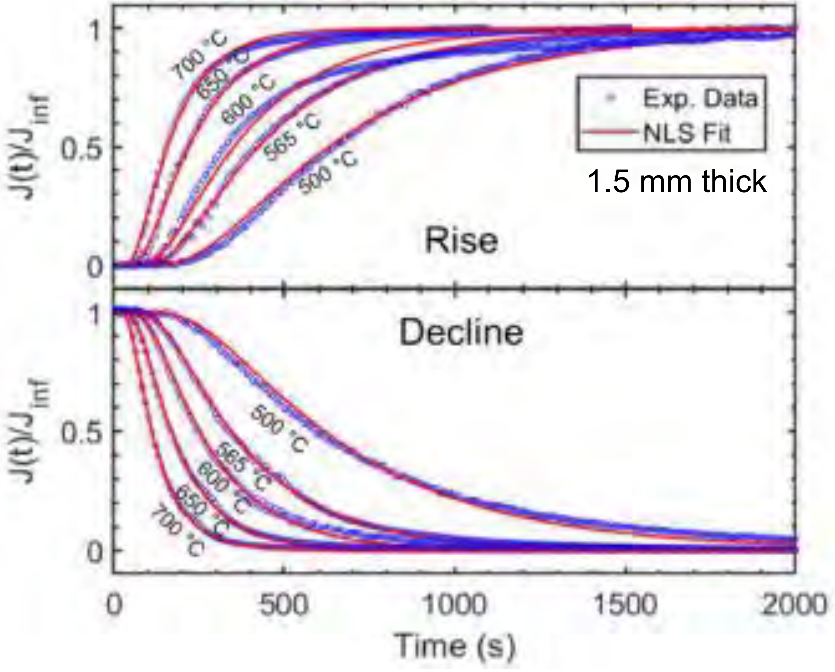


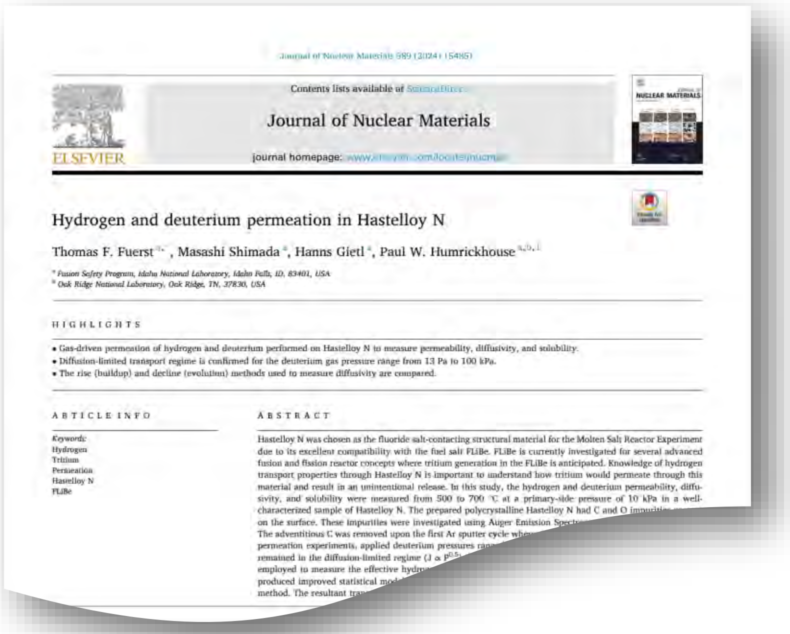
Can we predict tritium transport in order to develop required control technology?

Tritium: Diffusion through Metals

Example of hydrogen isotope permeation in Hastelloy N







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Hydrogen and deuterium permeation in Hastelloy N

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HIGHLIGHTS

- Gas-driven permeation of hydrogen and deuterium performed on Hastelloy N to measure permeability, diffusivity, and solubility.
- Diffusion-limited transport regime is confirmed for the deuterium gas pressure range from 13 Pa to 100 kPa.
- The rise (buildup) and decline (evolution) methods used to measure diffusivity are compared.

ARTICLE INFO

Keywords:
Hydrogen
Tritium
Permeation
Hastelloy N
FLiBe

ABSTRACT

Hastelloy N was chosen as the fluoride salt-contacting structural material for the Molten Salt Reactor Experiment due to its excellent compatibility with the fuel salt FLiBe. FLiBe is currently investigated for several advanced fusion and fission reactor concepts where tritium generation in the FLiBe is anticipated. Knowledge of hydrogen transport properties through Hastelloy N is important to understand how tritium would permeate through this material and result in an unintentional release. In this study, the hydrogen and deuterium permeability, diffusivity, and solubility were measured from 500 to 700 °C at a primary-side pressure of 10 kPa in a well-characterized sample of Hastelloy N. The prepared polycrystalline Hastelloy N had C and O impurities ... on the surface. These impurities were investigated using Auger Emission Spectr... The adventitious C was removed upon the first Ar sputter cycle wh... permeation experiments, applied deuterium pressures ra... remained in the diffusion-limited regime ($J \propto P^{0.5}$... employed to measure the effective hydr... produced improved statistical mod... method. The resultant tra...

Fuerst, Thomas F., et al. "Hydrogen and deuterium permeation in Hastelloy N." *Journal of Nuclear Materials* 589 (2024): 154851.. https://doi.org/10.1016/j.jnucmat.2023.154851

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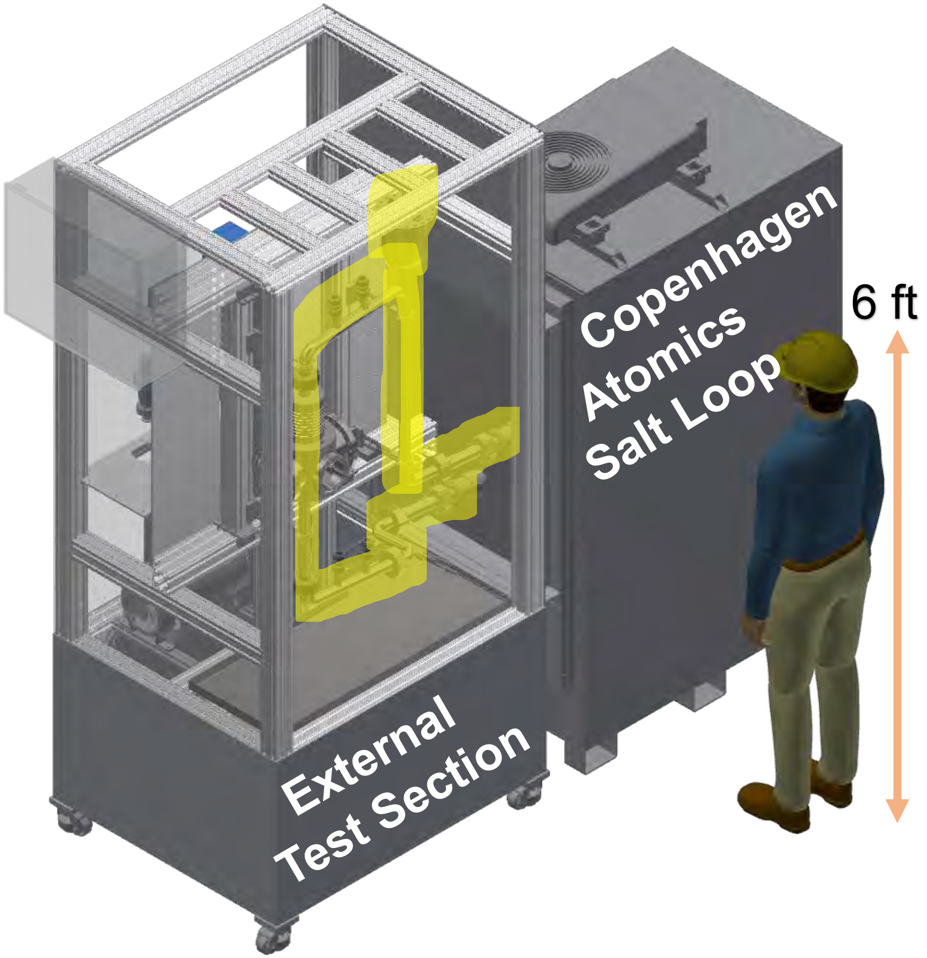
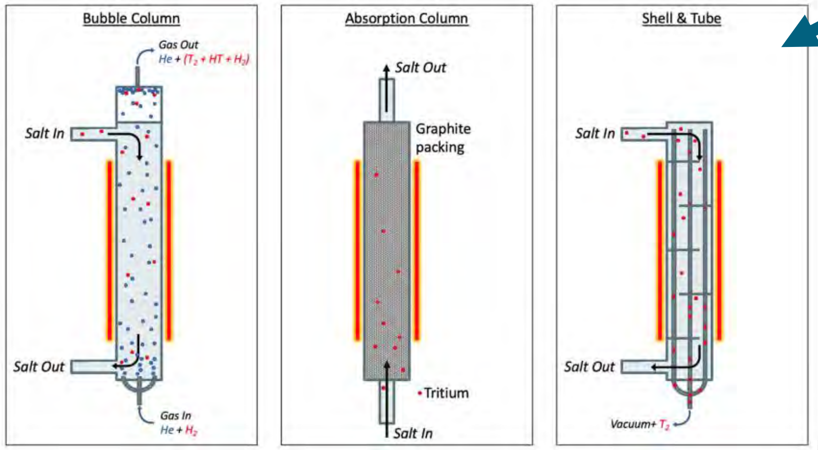
Molten Salt Tritium Transport Experiment

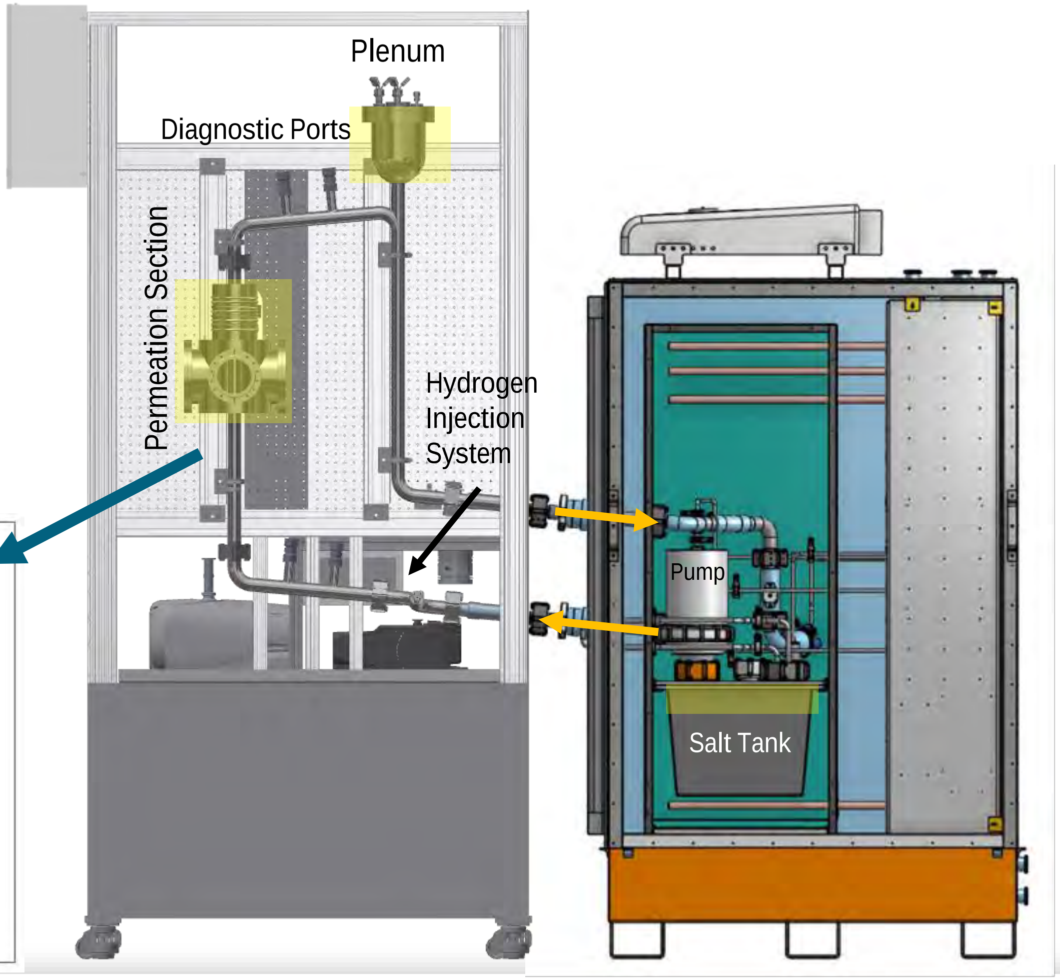
- ***MSTTE is a semi-integral tritium transport experiment for flowing fluoride salt systems.***
- **Location: S**afety and **T**ritium **A**pplied **R**esearch facility
- **Objectives:**
  (1) Safety code validation data.
  (2) Test stand for tritium control technology.
- ***Major Equipment:***
  - **Copenhagen Atomics Salt Loop**: salt tank, pump, flow meter, instrumentation and control
  - **External Test Section:** hydrogen injection, permeation, plenum, salt diagnostics, gas systems, controls, salt exchange tank, and *versatile*



MSTTE Transport Phenomena

- **Permeation through structural materials:** ***permeation test section: 316 SS***
  - 15,000 < $\mathbf{Re}_{FLiNaK}$ < 90,000
  - 7,000 < $\mathbf{Re}_{FLiBe}$ < 40,000
- **Evolution to off-gas: *plenum* and *salt tank.***
- **Versatile test section for future campaigns on transport or control technology.**
- **Examples:**
- Sparging
- Absorption
- Heat exchangers

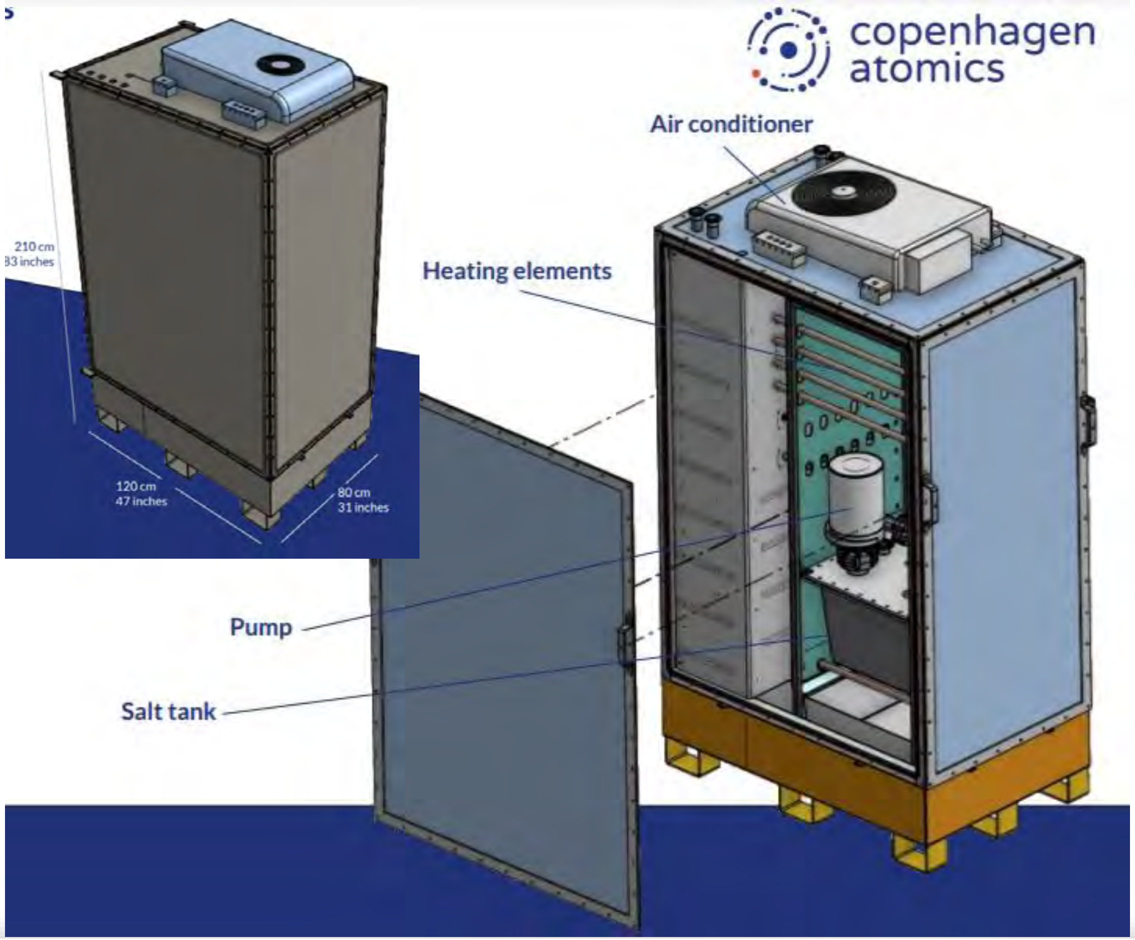




Copenhagen Atomics Salt Loop

- Pump, flow meter, & salt tank inside furnace.
- Flowing Ar cover gas for salt tank.
- All encased in inert atmosphere enclosure.
- Ships with purified FLiNaK in salt tank.
- Ports routed to external test section.

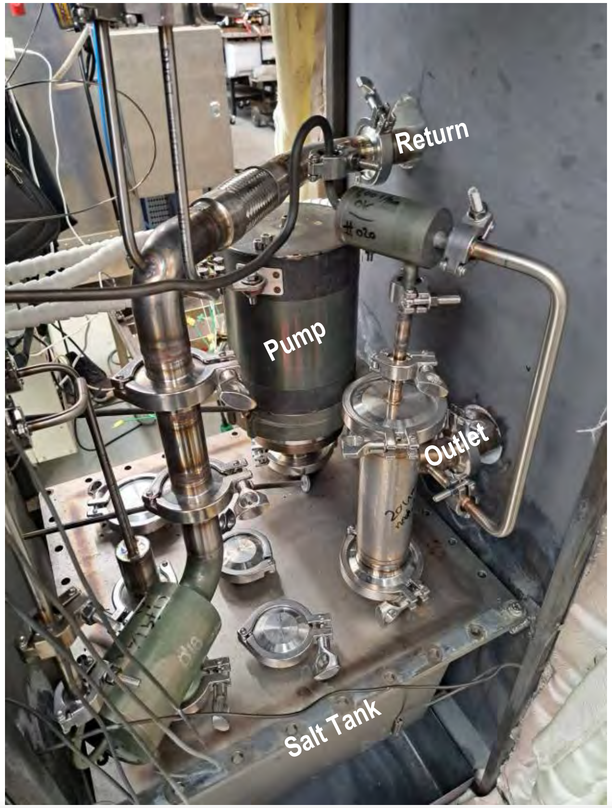
GENERIC LOOP TECHNICAL SPECIFICATIONS	
Max input power	22kW (32Amp – 3phase - 400Volt)
Max temperature	700°C.
Max flow speed	300 liters per minute
Min flow speed	50 liters per minute
Max salt load	100 liters
Cover gas	Argon (Pressure gas cylinders not included)
Typical initialization and heat-up time	12 hours
Total loop weight	1000 kg (including salt)



https://www.copenhagenatomics.com/pdf/Loop_v5.2_Datasheet.pdf

Copenhagen Atomics Loop Status

Inside Enclosure Furnace



Prototypic test section

Delivered March 5, 2024

Unpackaged and Positioned

Courtesy of Aslak Stubsgaard, Copenhagen Atomics

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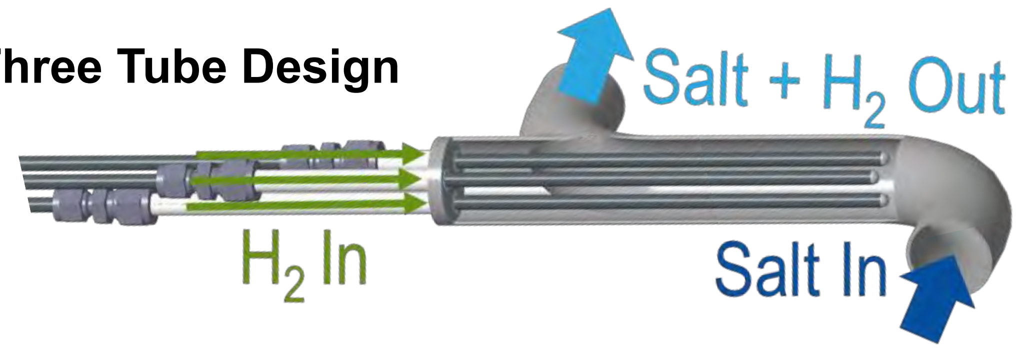
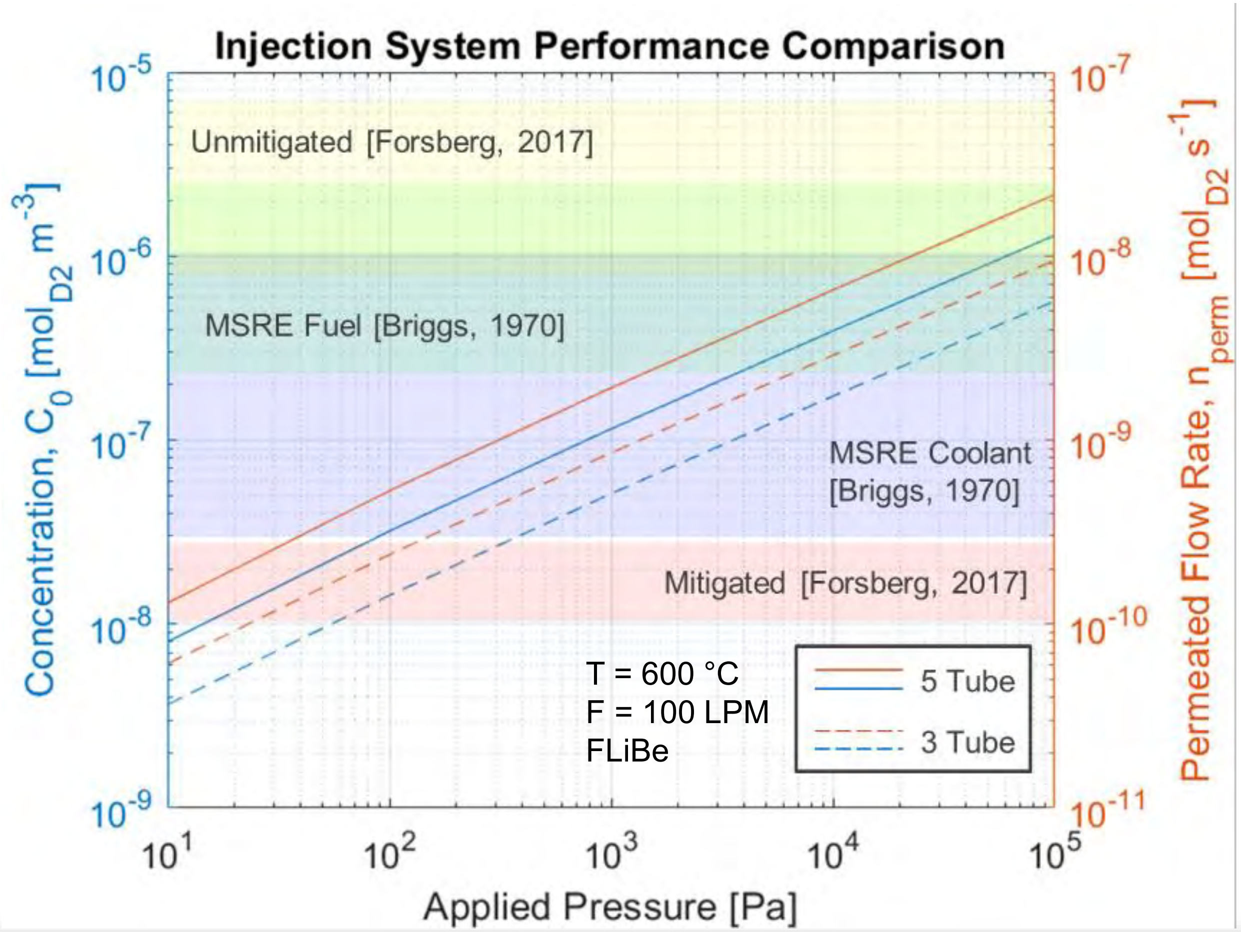
Hydrogen Injection System

Three Tube Design

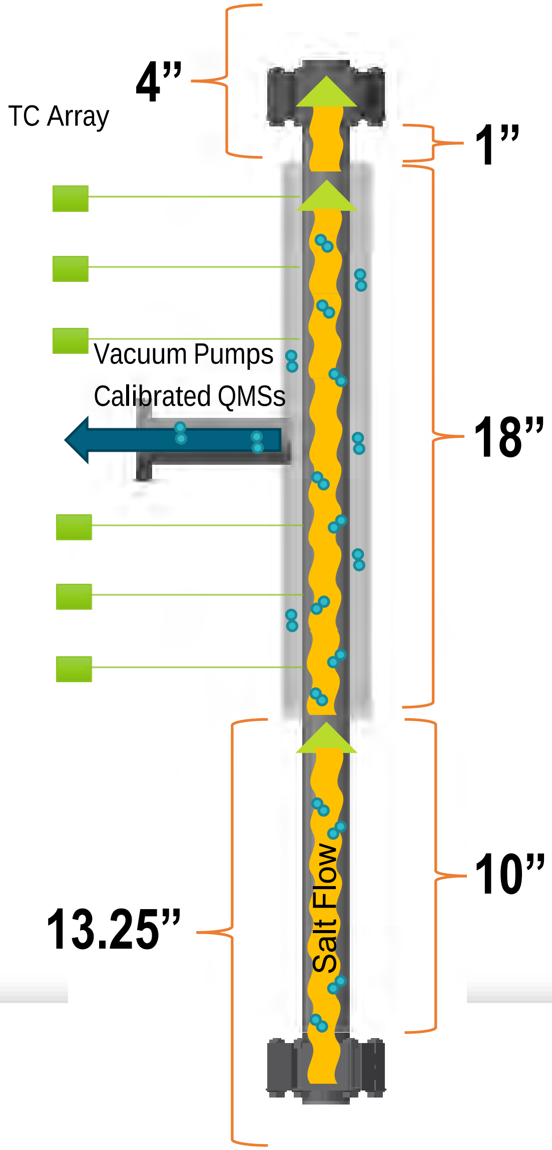


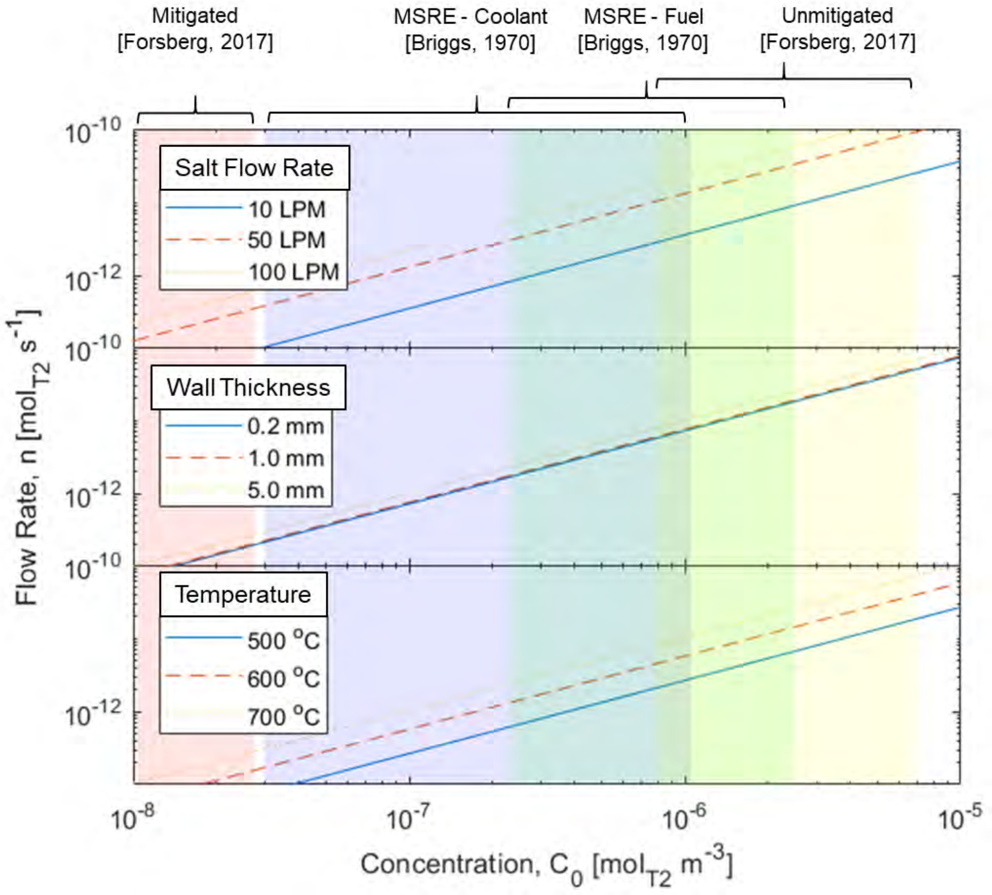
Five Tube Design



Permeation Test Section

- ***Goal: Measure hydrogen permeation through structural materials in flowing salt.***
- *Design Considerations:*
    - Permeation rates measurable with QMS?
    - Fully-developed flow in permeation section?



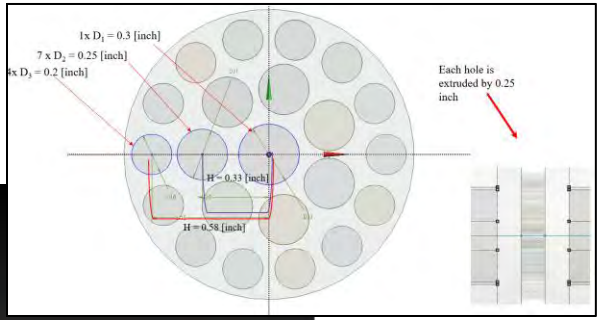


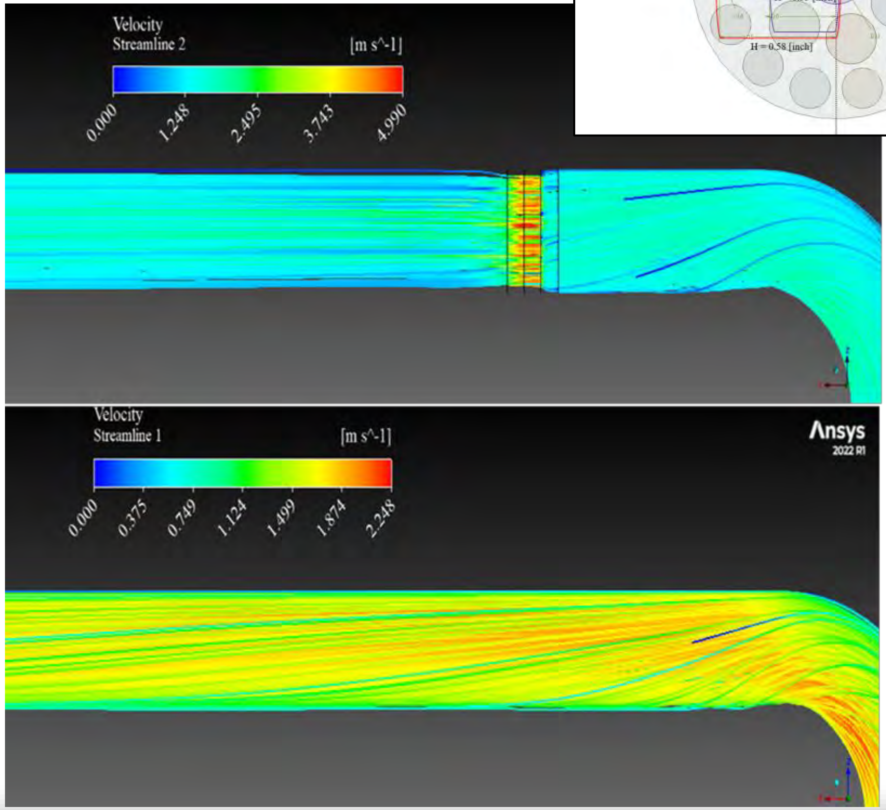
Permeation Test Section

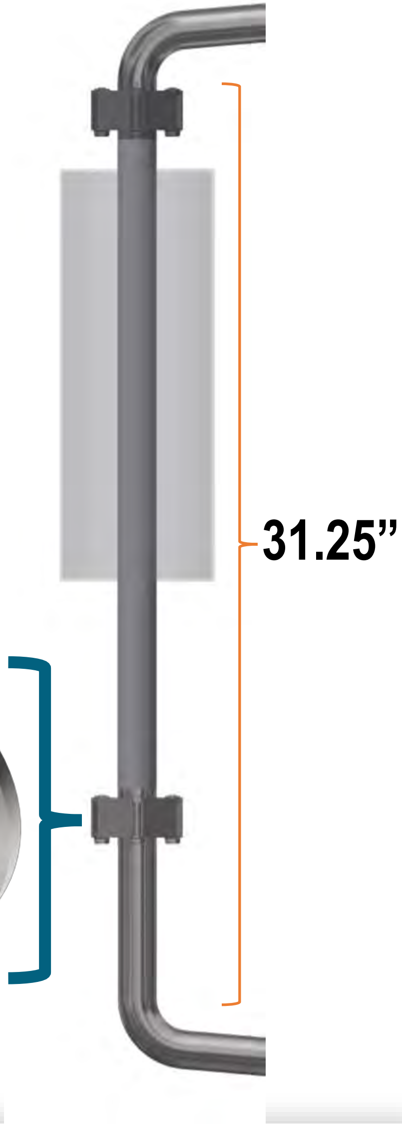
Challenge: Balance minimizing length scale to fully-developed flow and minimizing pressure drop.

Solutions:

- ☒ Reducers: High pressure drop (0.5 in tube required).
- ☑ Flow Conditioners: Stabilize swirling with minimal pressure drop, high component risk

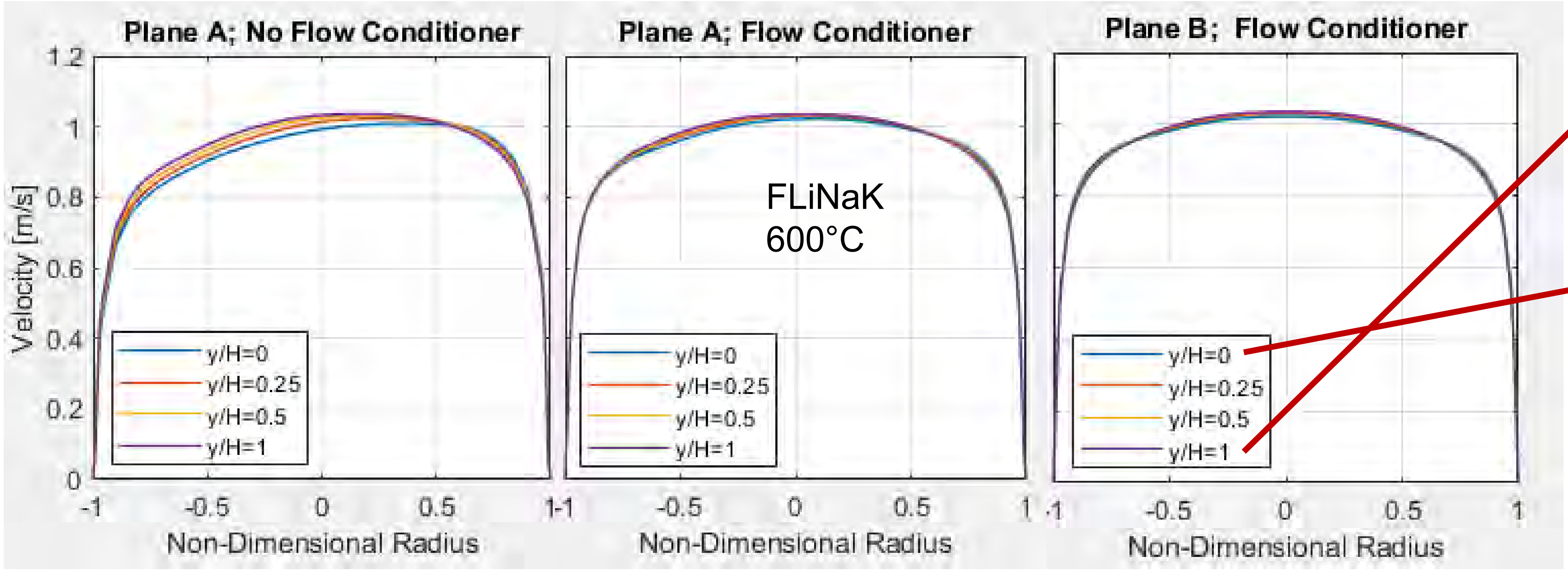


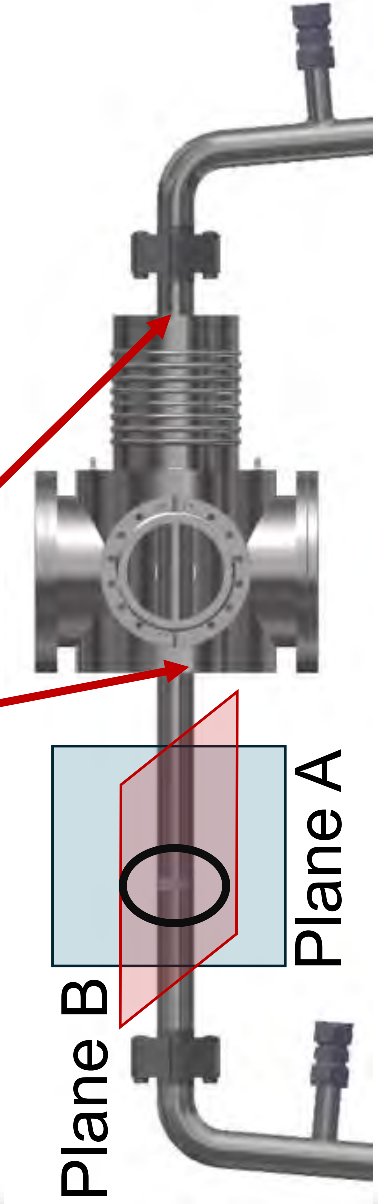




CFD Courtesy of A Bowers and S Sharma at UML

Test Section CFD – 50 LPM





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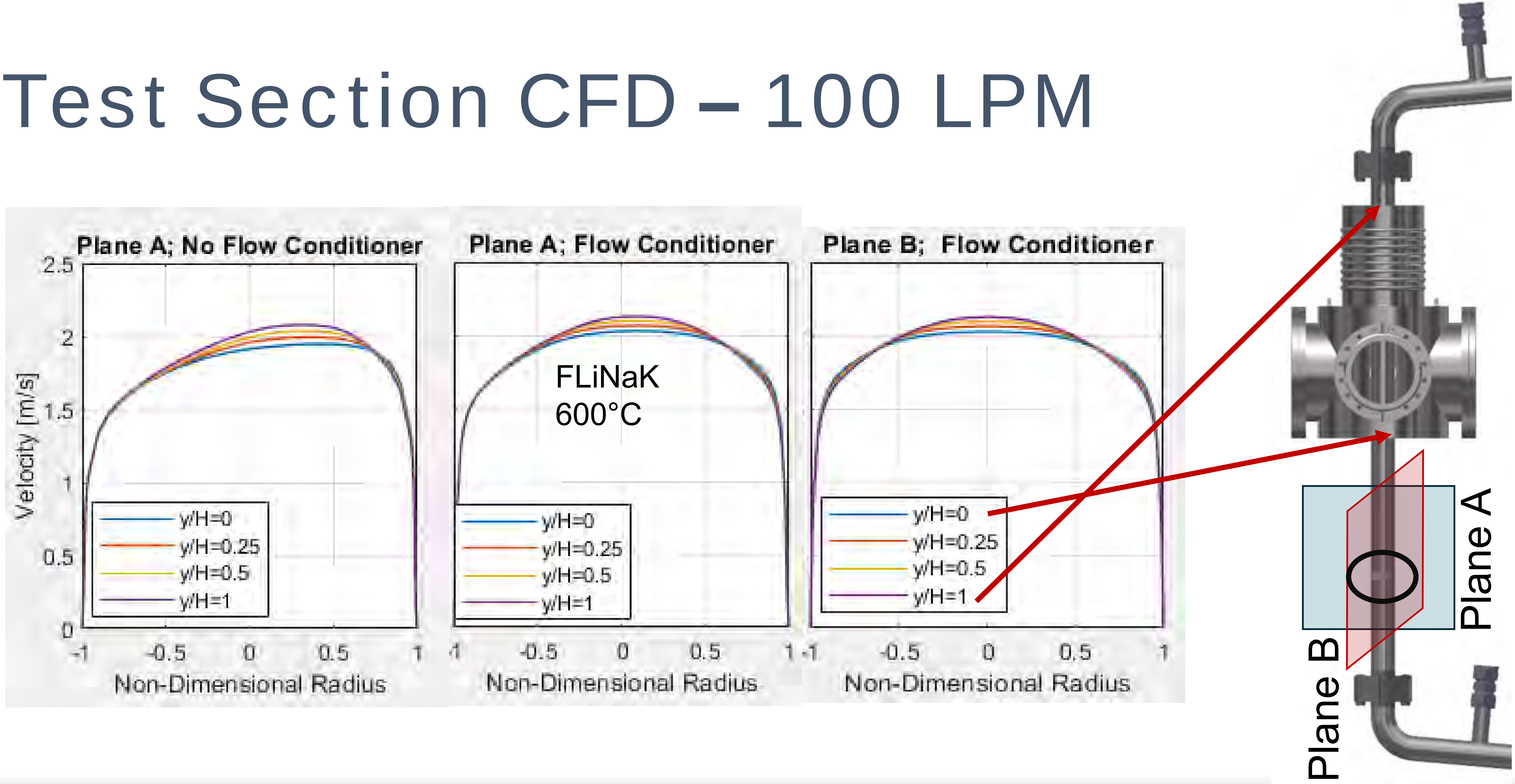
Test Section CFD – 100 LPM



CFD Courtesy of A Bowers and S Sharma at UML

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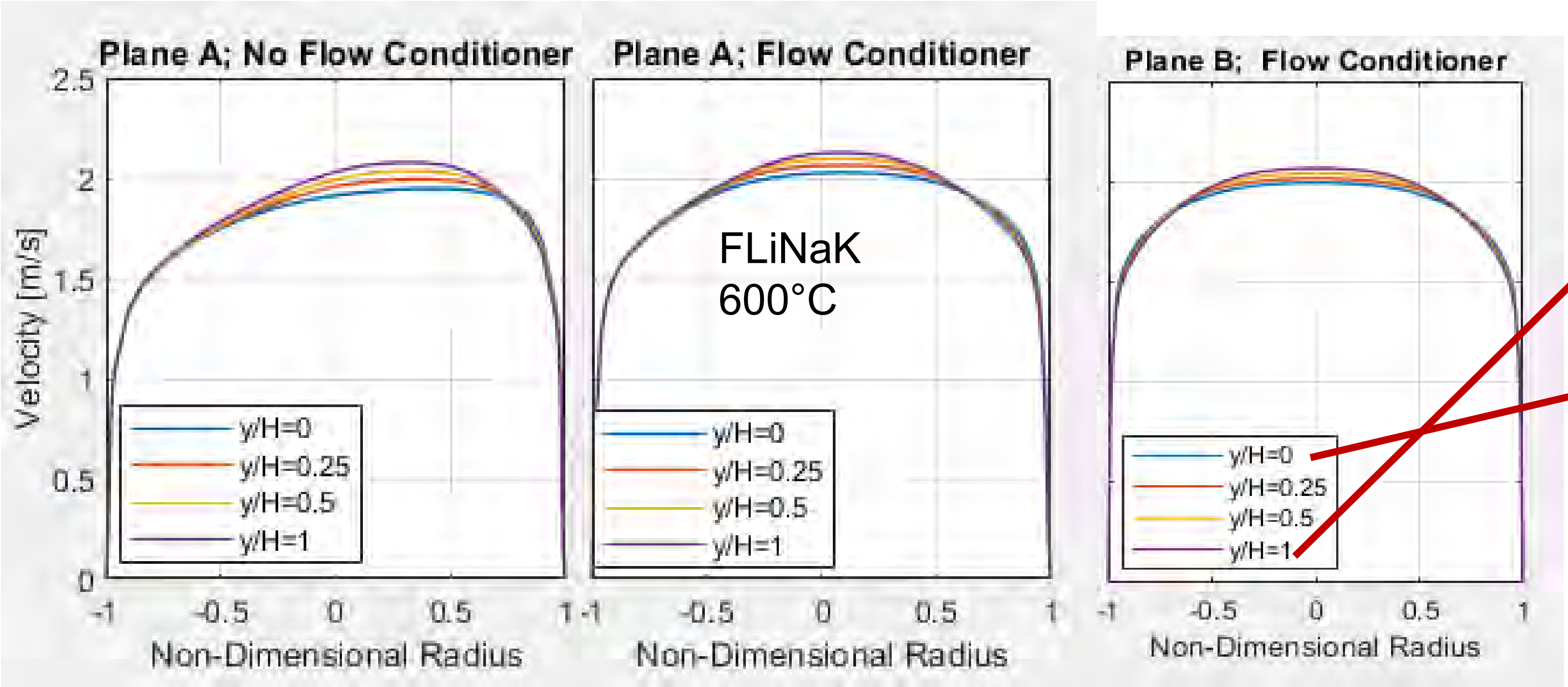
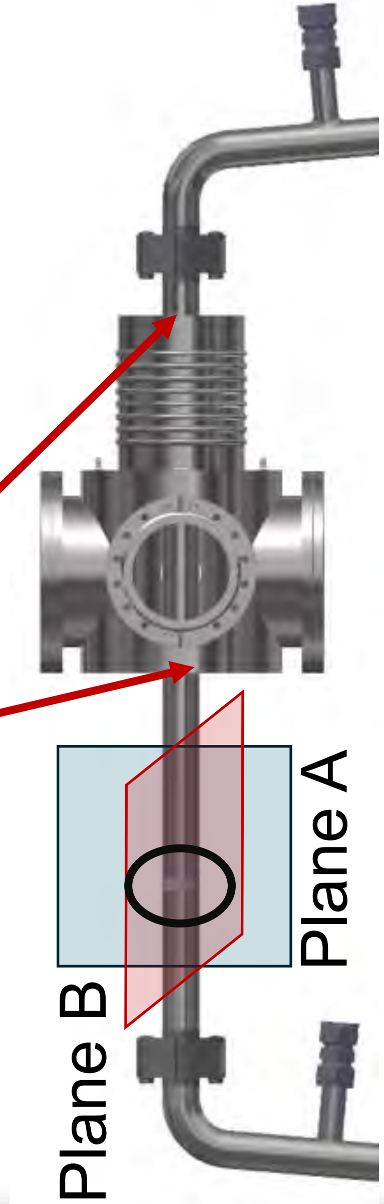
Test Section CFD – 200 LPM





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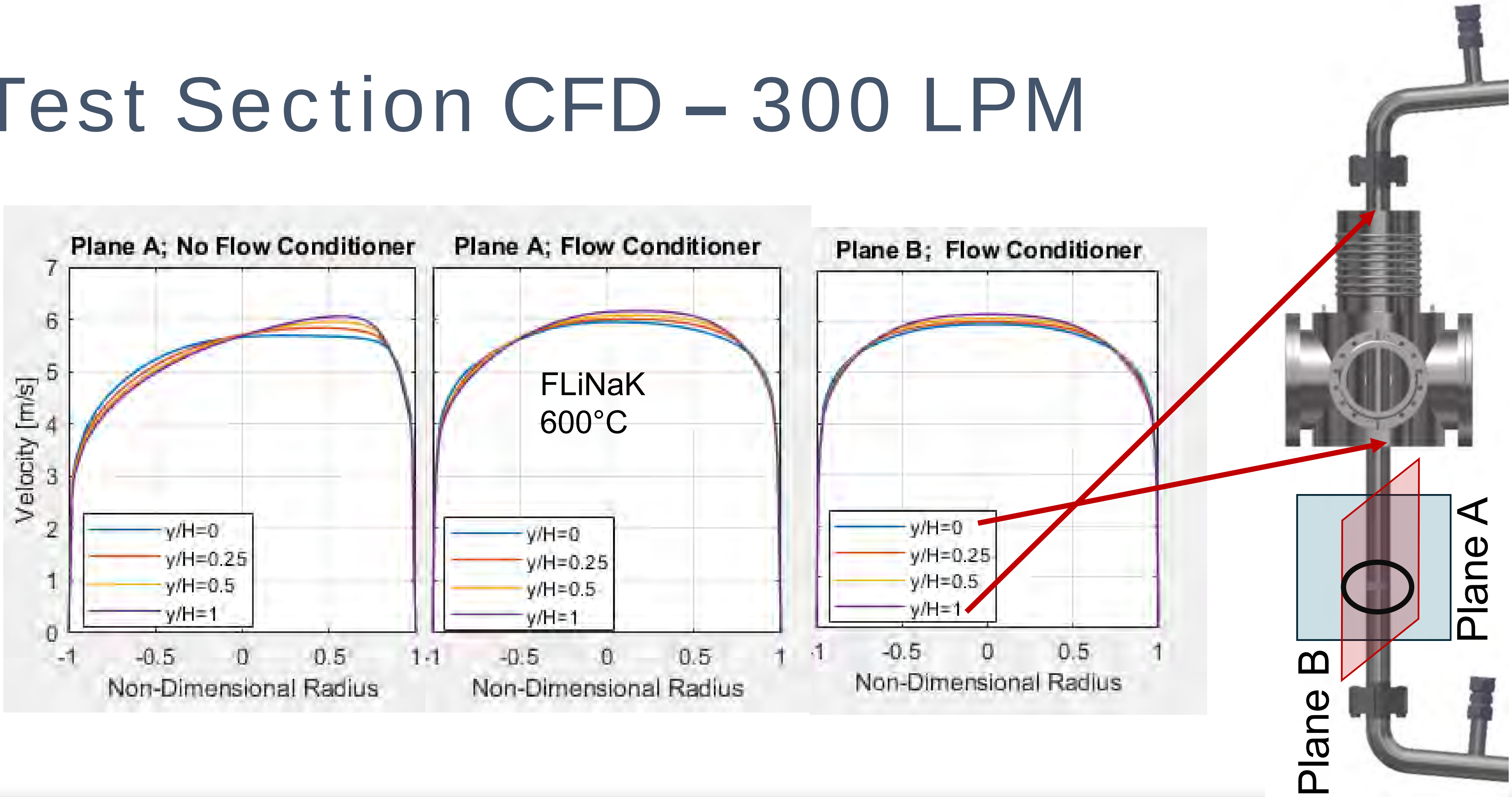
Test Section CFD – 300 LPM

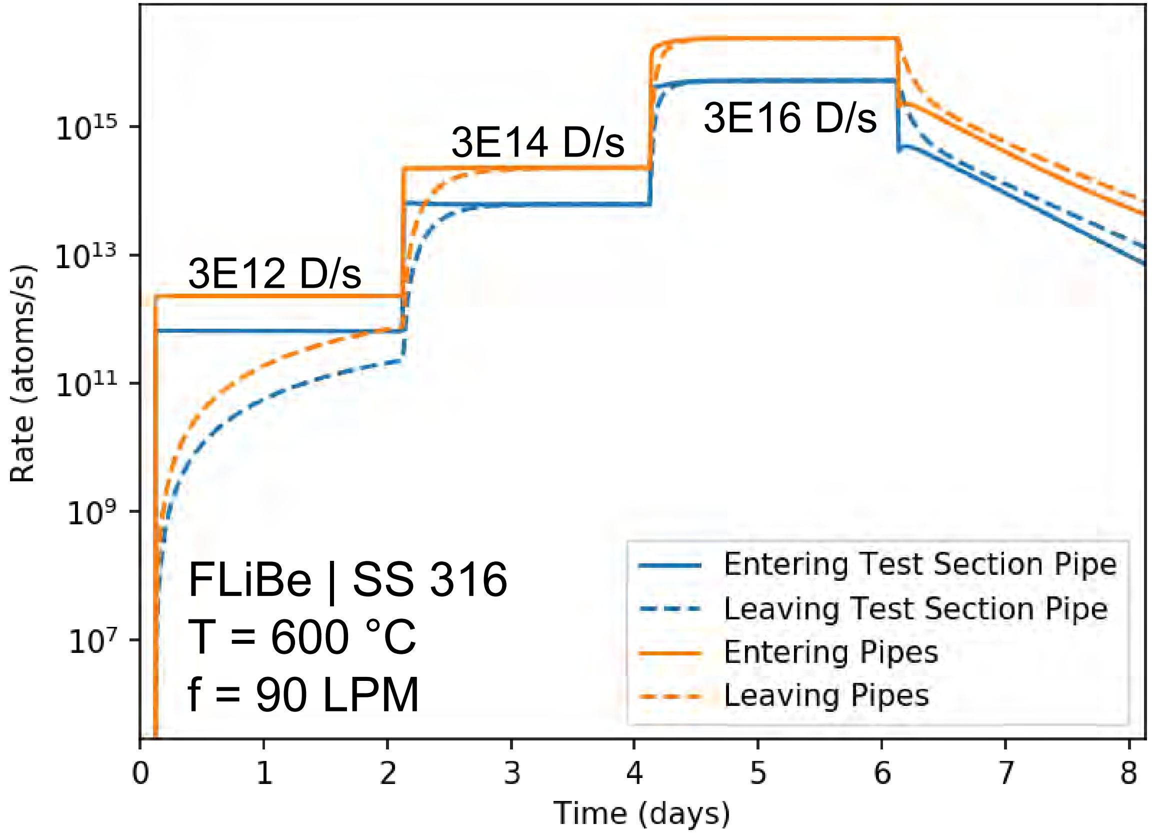


CFD Courtesy of A Bowers and S Sharma at UML

Experimental Campaigns

- **Variables:**
  - **Flow Rate:** Salt Mass Transfer Coefficients
  - **Source Term:** Permeation Mass Transport
  - **Temperature:** Arrhenius Dependence
- **Example Procedure:**
  1. Loop heat up
  2. Pump priming
  3. Start hydrogen injection
  4. Stop hydrogen injection
  5. Stop pump
  6. Cool down

Deuterium Permeation Rate through Test Section & Pipes

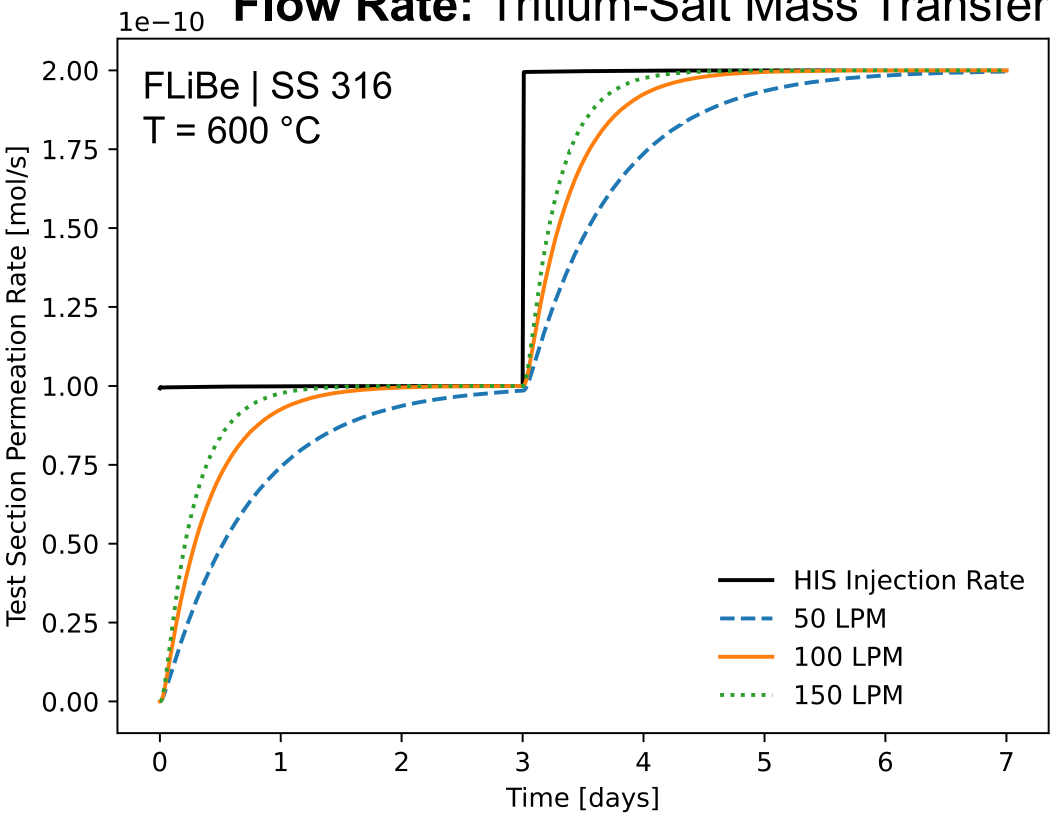


Modeled with Melcor-TMAP [1]

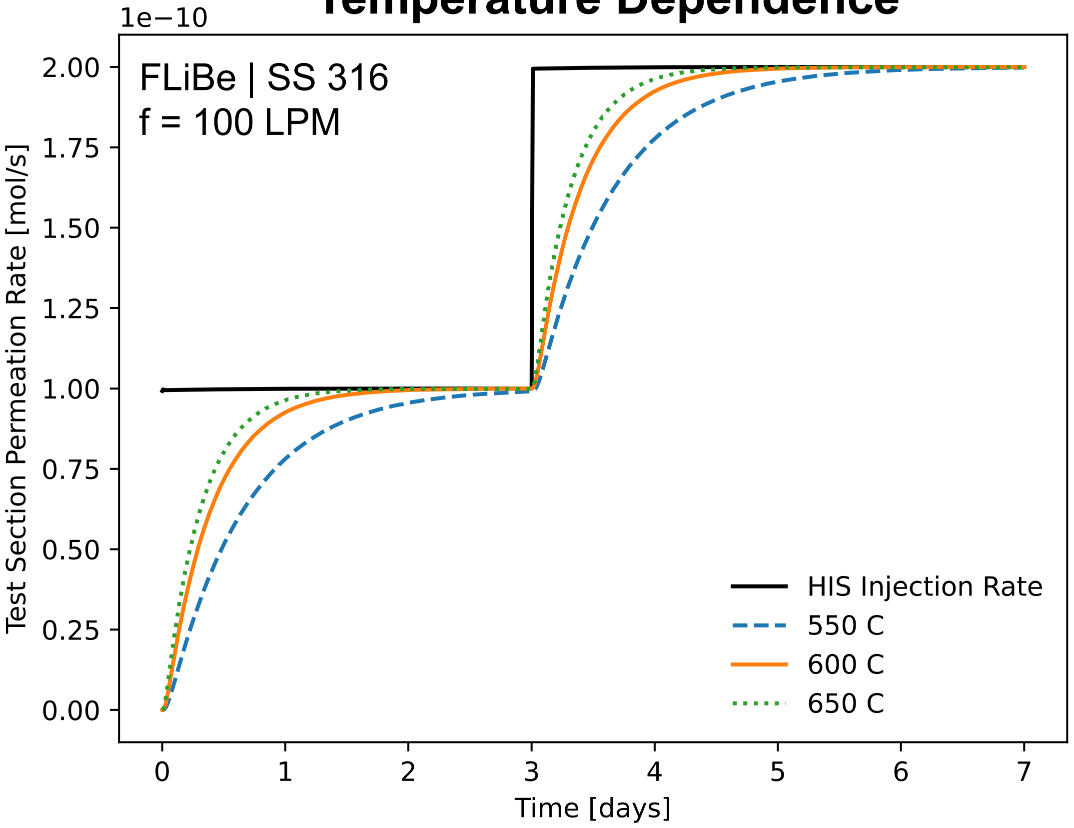
[1] MD Eklund and AA Riet. Fusion Engineering and Design 194 (2023): 113743.

Experimental Campaigns

Flow Rate: Tritium-Salt Mass Transfer



Temperature Dependence

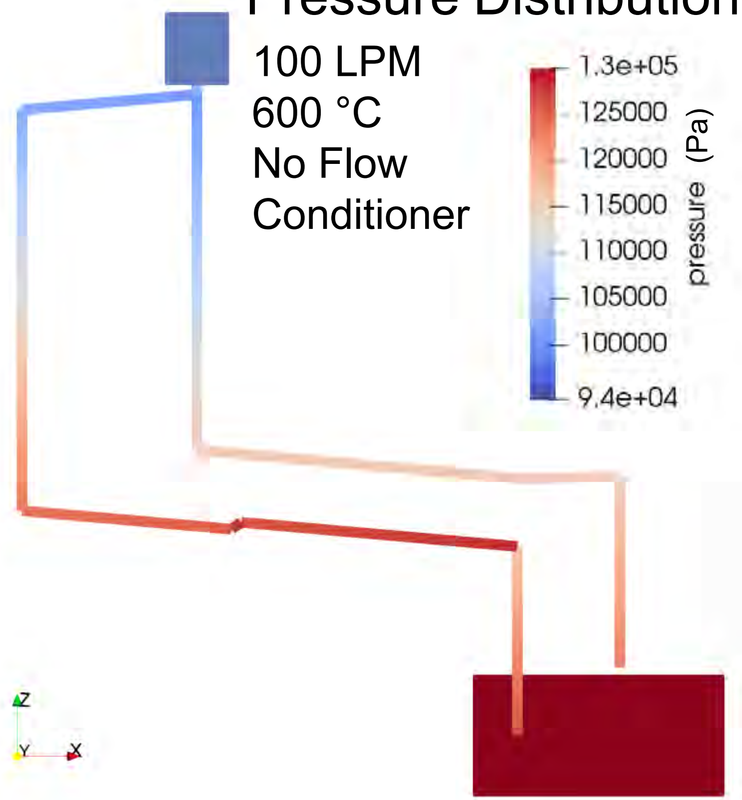


Modeled with: System Analysis Module (SAM)

Courtesy of T. Mui and R. Hu at ANL

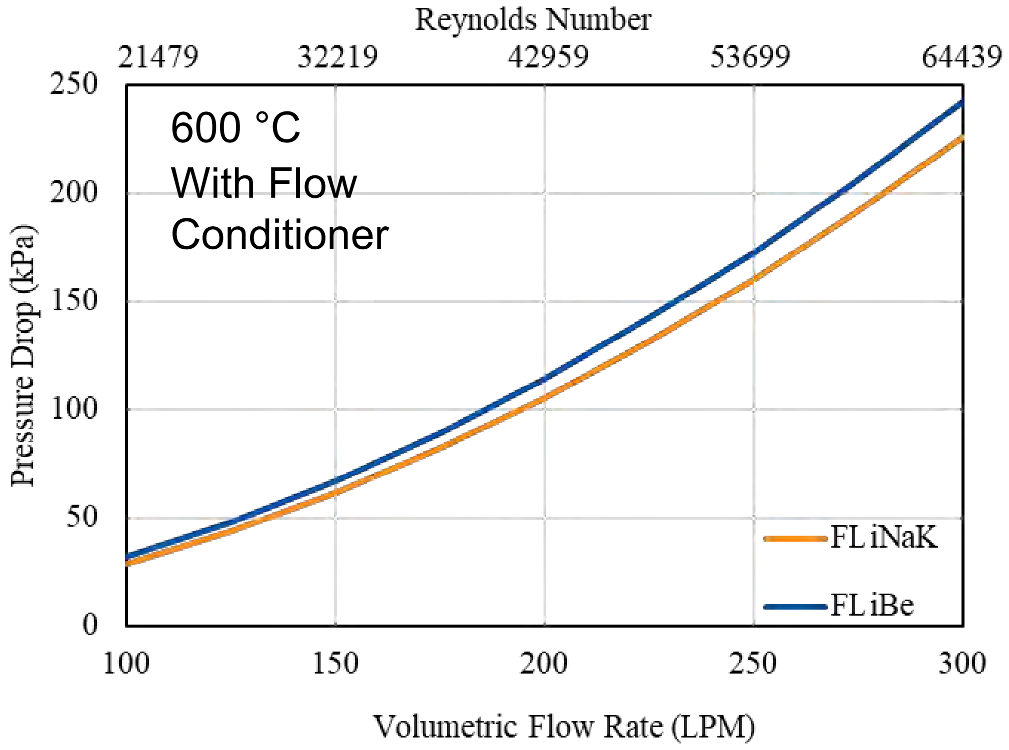
Loop Pressure Drop

Pressure Distribution



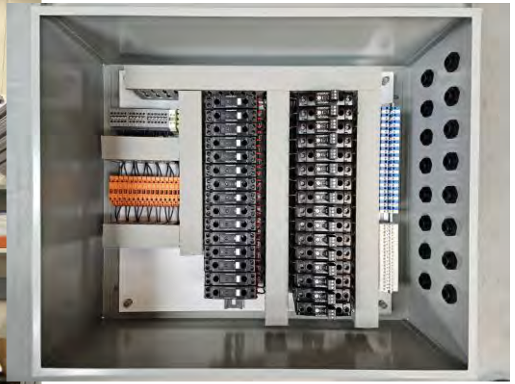
Modeled with: System Analysis Module (SAM)

Total Pressure Drop Across External Test Section



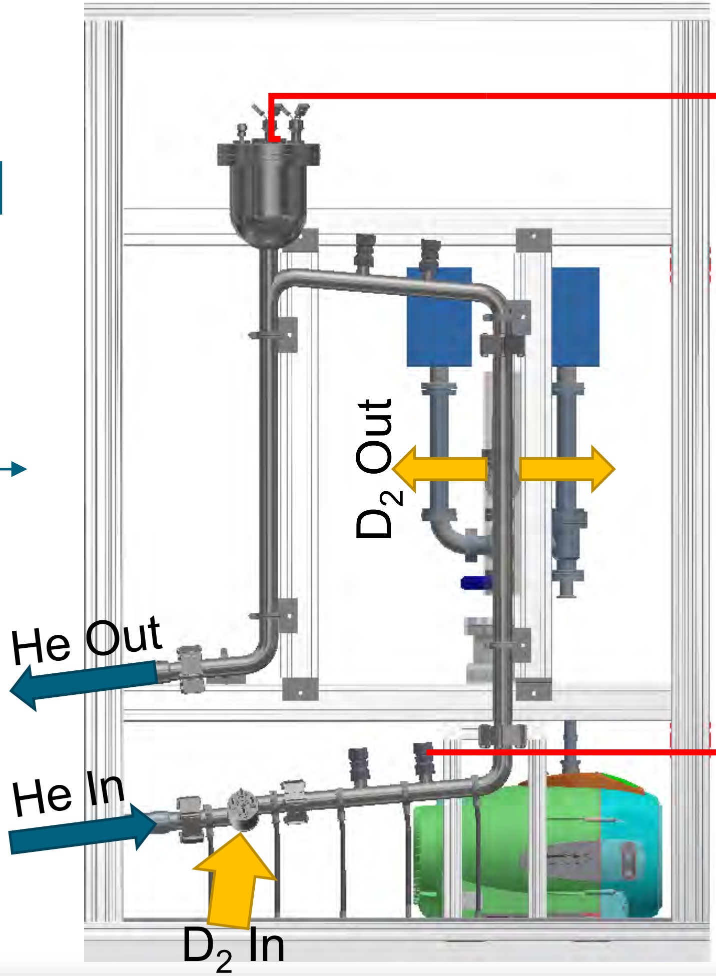
External Test Section Status

- ☑ **Design complete**
- ☑ **Frame constructed**
- ☑ **Major components delivered**
- ☐ **Fabrication/assembly**
  - ☑ Gas distribution system
  - ☑ Vacuum system
  - ☑ Control system
  - ☐ Custom tube segments → Ordered
  - ☐ Move to STAR
- ☐ **Commission**

Commission Test Section

1. **Helium leak check: assembly.**
2. **Thermal test: heating system and support structures.**
3. **Helium/D_2 permeation tests: hydrogen systems operate properly and analysis codes.**
4. **Mate to Copenhagen Atomics loop: leak check full assembly.**
5. **Begin salt campaigns!**



Gas Chromatograph Equipped: 2 PDHID for trace H_2 in He

Commission Salt Loop

- ☑ **Procured**
- ☑ **Delivered**
- ❑ **Facilities**
  - ❑ Electrical upgrade → Equipment onsite
  - ❑ Gas connections → Equipment onsite
  - ❑ Network connections
- ❑ **Test system with external loop**
  - ❑ Heat up and cool down
  - ❑ Pumping systems
  - ❑ Emergency shutdown

External Loop Installed

Summary

- **Molten Salt Tritium Transport Experiment is versatile capability designed to provide tritium transport data and test control technology related to Molten Salt Reactors.**
- **FY23 Report Details Experiment** →
- **Commissioning to start this FY**
- **Sensors and Diagnostics**
- **Modeling and Simulation**

Connect with me!

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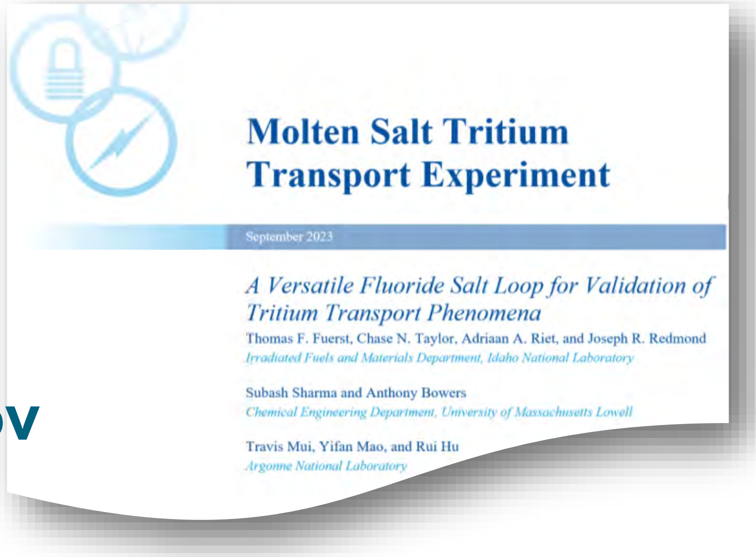

Molten Salt Tritium Transport Experiment

September 2023

A Versatile Fluoride Salt Loop for Validation of Tritium Transport Phenomena

Thomas F. Fuerst, Chase N. Taylor, Adriaan A. Riet, and Joseph R. Redmond
Irradiated Fuels and Materials Department, Idaho National Laboratory

Subash Sharma and Anthony Bowers
Chemical Engineering Department, University of Massachusetts Lowell

Travis Mui, Yifan Mao, and Rui Hu
Argonne National Laboratory

Contributions/Collaborations

Safety and Tritium Applied Research Facility

- ***Joseph Redmond (MSU)***
- Chase Taylor
- Hanns Gietl
- Masashi Shimada
- Shayne Loftus
- Bob Pawelko
- Taylor Hill
- Casey White
- Travis Neuman
- Rowdie Shepherd

Modeling and Simulation

- Ad Riet
- Matt Eklund
- Travis Mui
- Rui Hu
- ***Yifan Mao***
- Anthony Bowers
- Prof. Subash Sharma

Thank you

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