U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Molten Salt Reactor PROGRAM

Tritium Transport

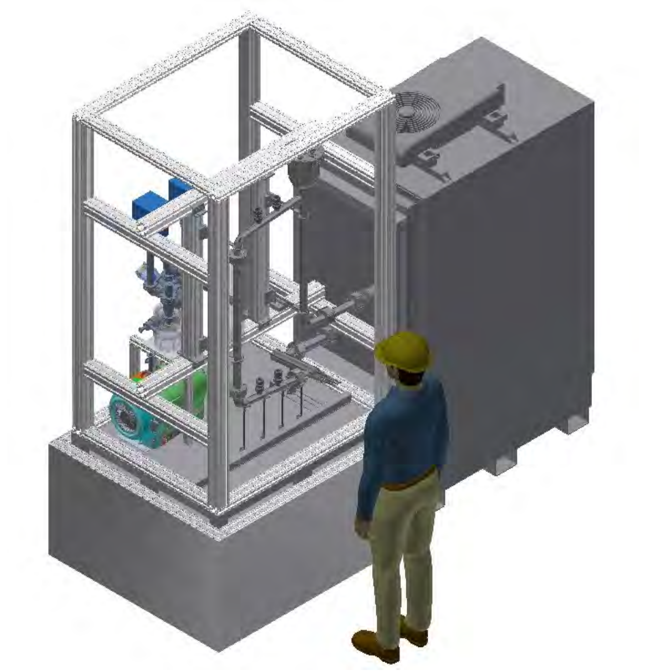
Thomas Fuerst, Ad Riet, Matt Eklund, Hanns Gietl, Chase Taylor, Shayne Loftus, Masashi Shimada, and Pattrick Calderoni

Idaho National Laboratory

Annual MSR Campaign Review Meeting 2-4 May 2023

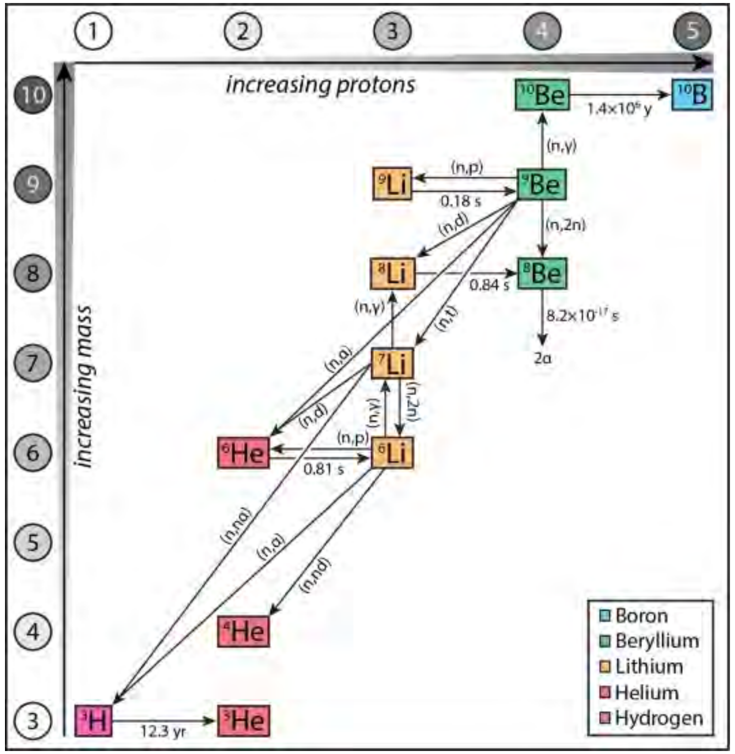
Outline

- **Tritium Transport Background**
  - Tritium Generation in MSRs
  - Transport Processes
  - Tritium Permeation
  - Tritium Transport Research Needs
- **M**olten **S**alt **T**ritium **T**ransport **E**xperiment
  - Overview
  - Research Goals
  - Components
  - Workplan



Tritium Generation in MSRs

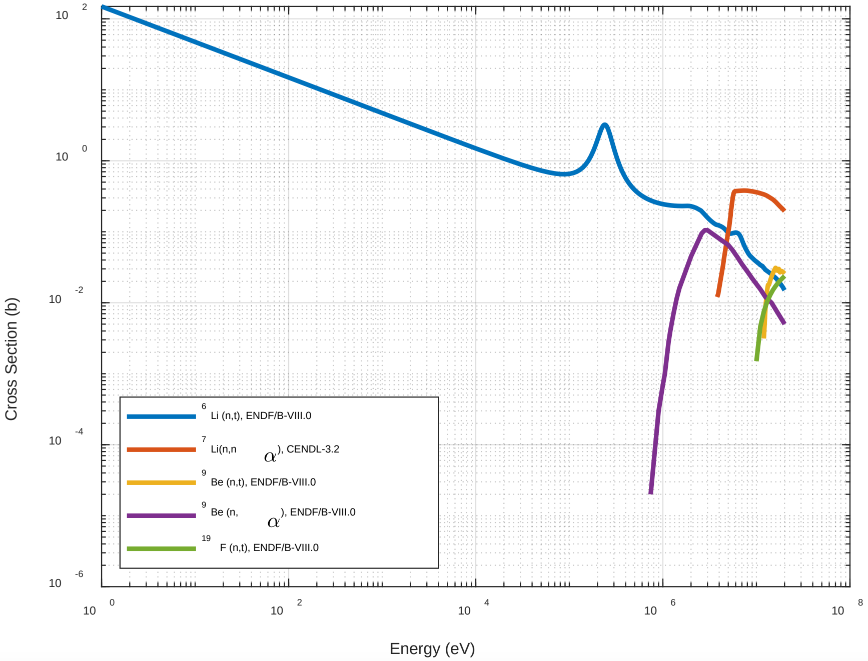
Tritium generated by neutron reactions with Li, Be, and F.



^{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 supply of tritium for peaceful purposes.

Tritium is a potential 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%).

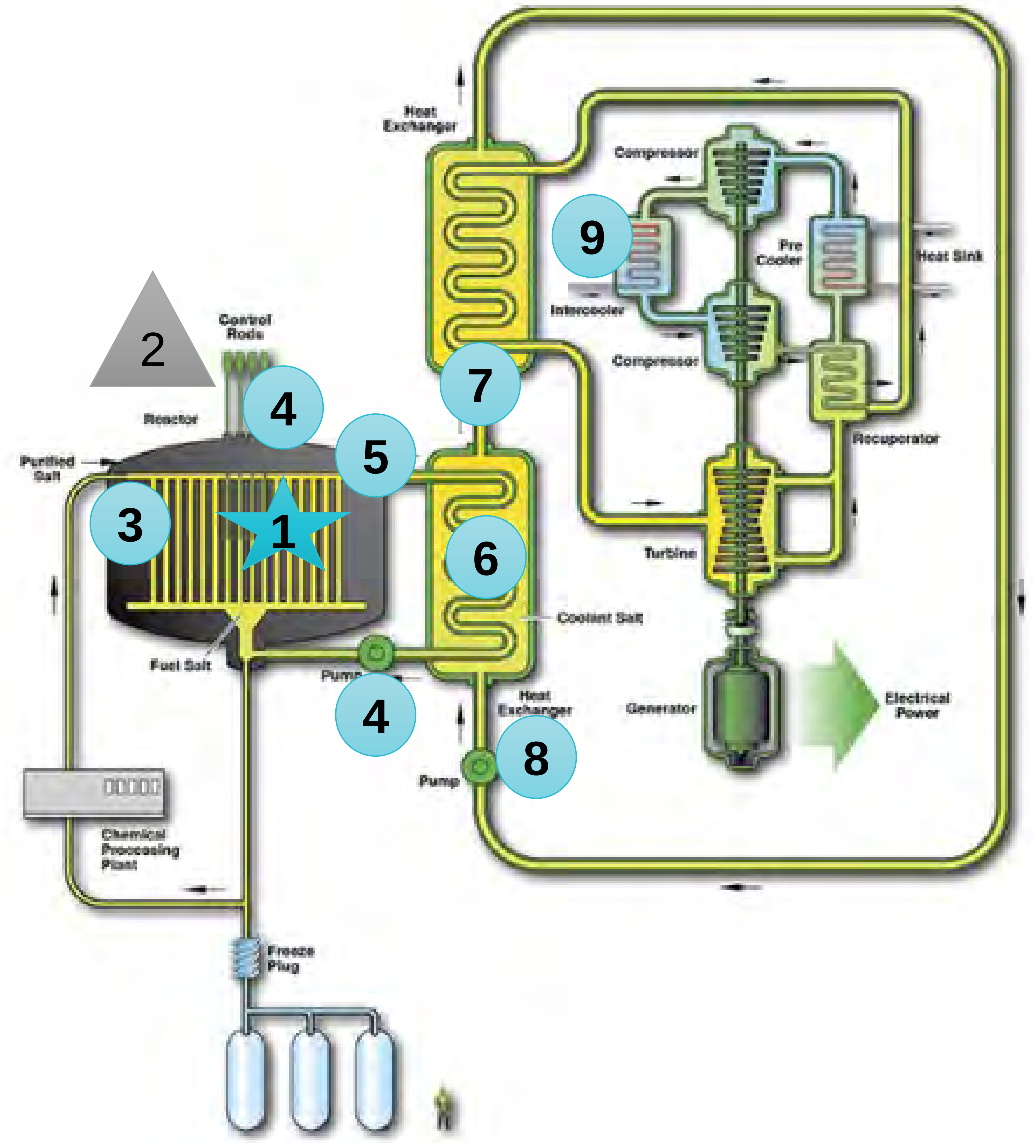
Sabharwall, P.; Schmutz, H.; Stoots, C.; Griffith, G. Tritium Production and Permeation in High-Temperature Reactor Systems;, 2013. https://doi.org/10.1115/HT2013-17036.

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

Transport Processes

1. Tritium production (neutrons + Li, Be, F)
2. *Speciation/corrosion (TF vs. T_2)*
3. *Graphite interaction*
4. Evolution into plenum/off-gas system
5. *Diffusion through primary system structural materials*
6. *Diffusion into secondary coolant*
7. *Diffusion through secondary system structural*
8. Release from secondary system plenum/off-gas system
9. Onwards into tertiary system

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



Idaho National Laboratory
U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Tritium Permeation Basics

Mass Transport Processes: J Flux (mol m^{-2} s^{-1})

1. Mass transfer in Salt: $J = \mathbf{K_{T,1}}(C_{B,1} - C_{B,2})$

   $\mathbf{K_T}(D_L, v, d_H, \mu, \rho)$: mass transfer coefficient (m s^{-1})

2. Dissociation on Surface: $J = \frac{\mathbf{k_d}}{\mathbf{K_H}} C_{B,2} - \mathbf{k_r} C_{S,1}^2$

   $\mathbf{k_d}$: dissociation coefficient (mol m^{-2} s^{-1} Pa^{-1})
   $\mathbf{k_r}$: recombination constant (m^4 mol^{-1} s^{-1})
   $\mathbf{K_H}$: T_2 solubility in salt (mol m^{-3} Pa^{-1})

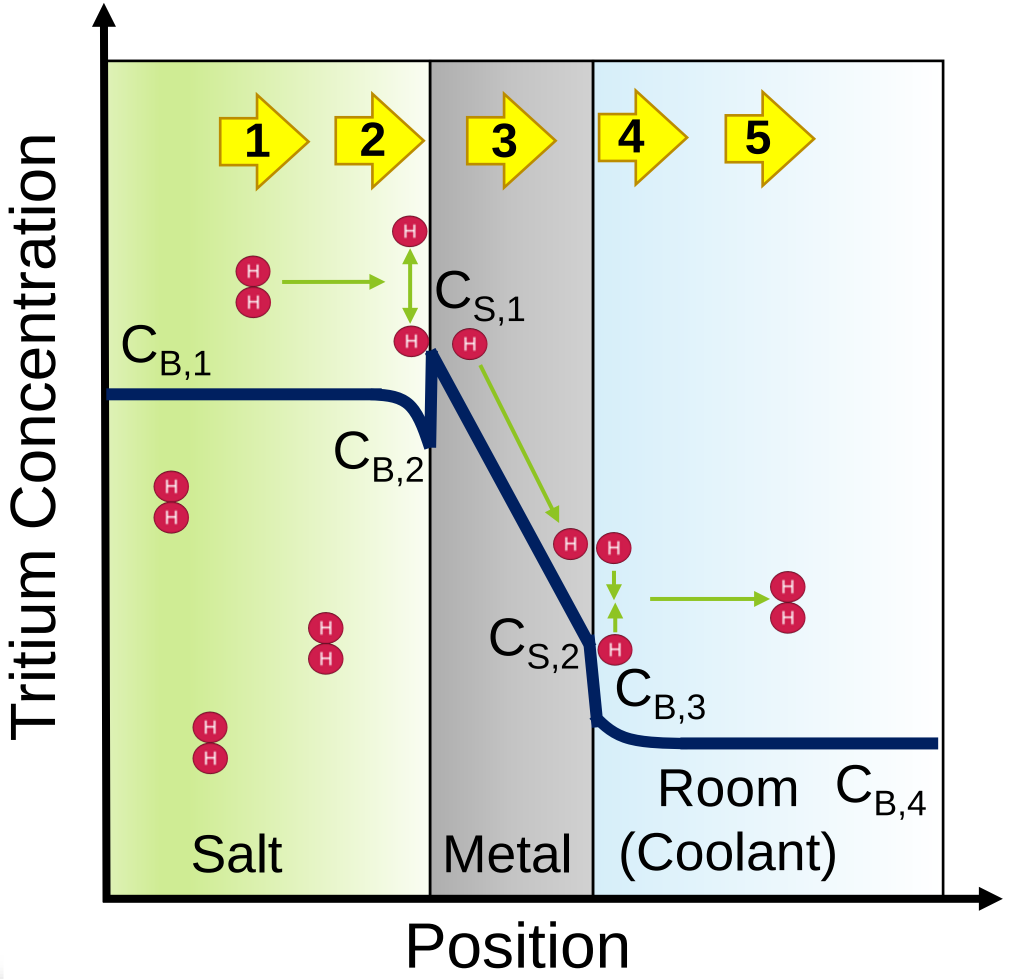
3. Diffusion through Metal: $J = -\mathbf{D_s} \frac{\partial C}{\partial x}$

   $\mathbf{D_s}$: diffusion coefficient (m^2 s^{-1})

4. Recombination on Surface: $J = \mathbf{k_r} C_{S,2}^2 - \mathbf{k_d} P_{S,2}$

5. Mass transfer in 2nd Fluid: $J = \mathbf{K_{T,2}}(C_{B,3} - C_{B,4})$

Red indicates parameters requiring experimental measurements



Tritium Transport Research Needs

Fundamental Measurements

- Salt Properties:
  - Thermophysical
  - Hydrogen: solubility, diffusivity, speciation
  - Data exists in literature with large uncertainty
- Material Properties:
  - Hydrogen diffusivity, solubility, surface reactions
  - Databases exist [1]
  - New materials require testing

Semi-Integral and Integral Experiments

- Mass transfer
  - Fluid phase boundaries
  - Evolution from free surfaces
- Coupled phenomena
  - Corrosion and interfaces
- Generation
- Speciation / Redox Control
  - TF vs. T_2

Development of control technology [1,2]

- Sparging to off-gas
  - Addition of H_2
- Novel HX designs
- Online tritium specific extraction systems
  - Membranes, vacuum disengage, absorbers
- Permeation barriers

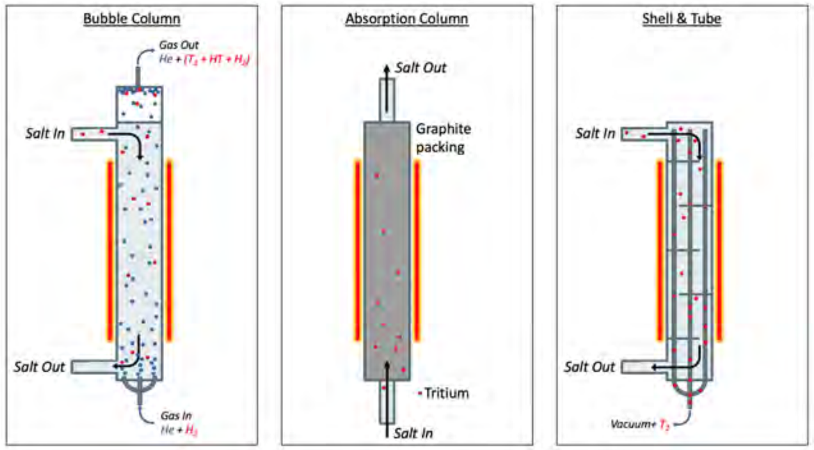
[1] PW Humrickhouse and TF Fuerst. INL/EXT-20-59927 United States, 2020
[2] C Forsberg et al. *Nuclear Technology* 206.11 (2020): 1778-1801.

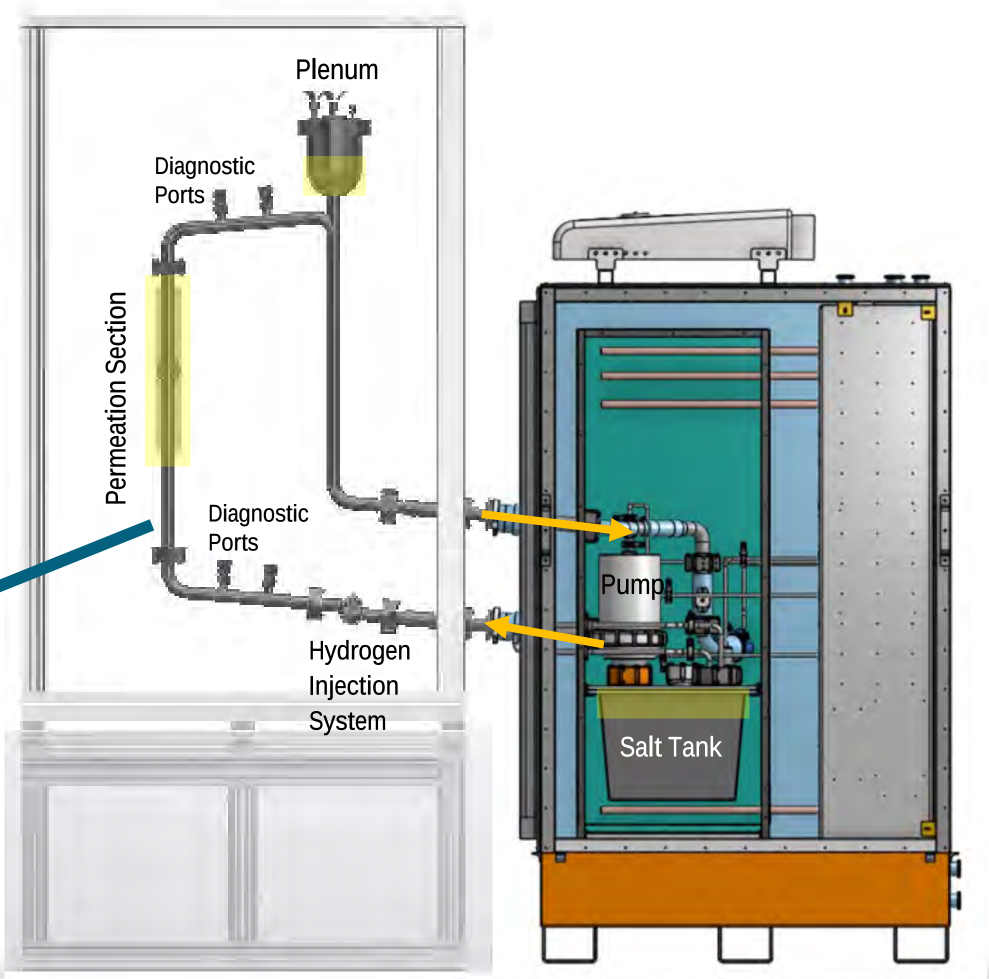
Molten Salt Tritium Transport Experiment

- ***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
  - **External Test Section:** hydrogen injection, permeation, & plenum
- ***Phased approach***
  - **Phase I:** FLiNaK and D_2
  - **Phase II:** FLiBe and D_2
  - **Phase III:** FLiBe and T_2

MSTTE Transport Phenomena

- **Permeation through structural materials:** ***permeation test section***
  - 2000 < **Re**$_{Flinak}$ < 80,000 **&** 1000 < **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

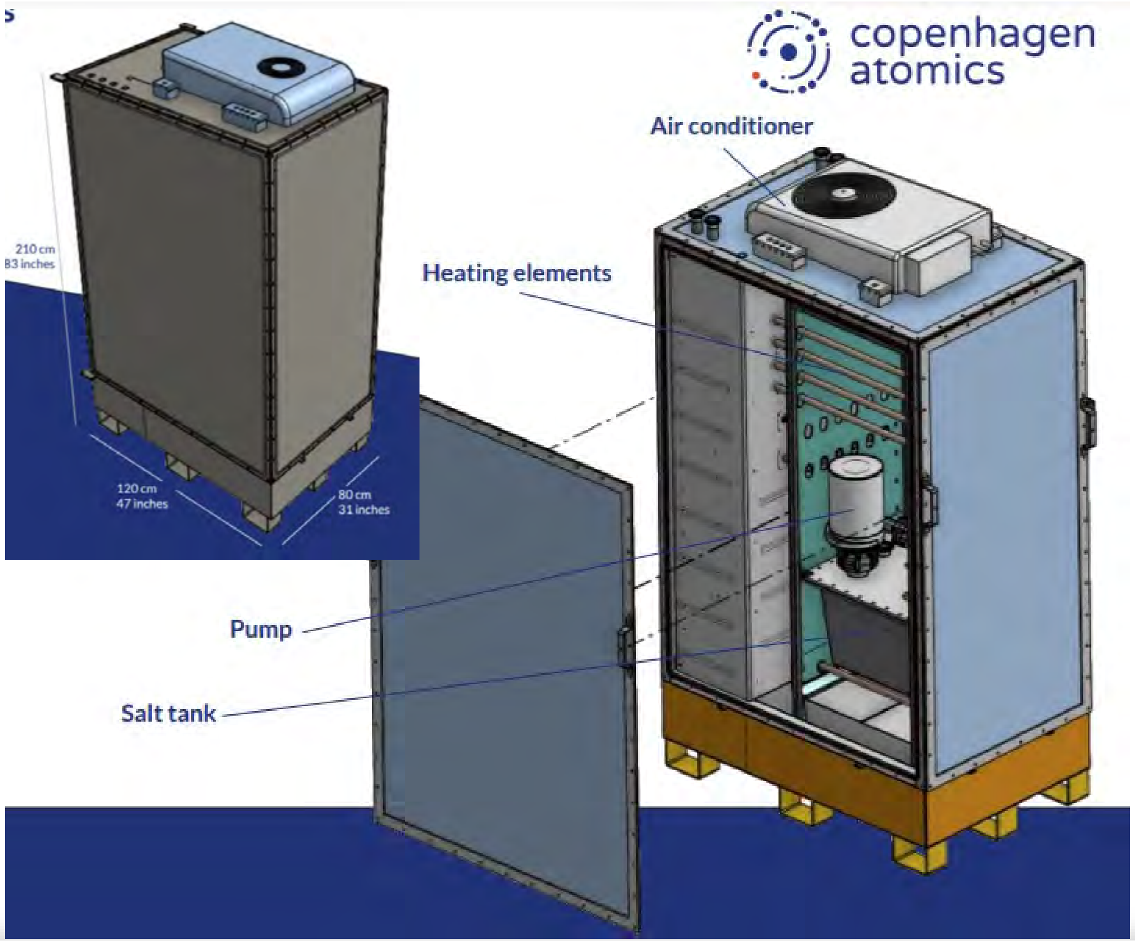




Copenhagen Atomics Salt Loop

- **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)

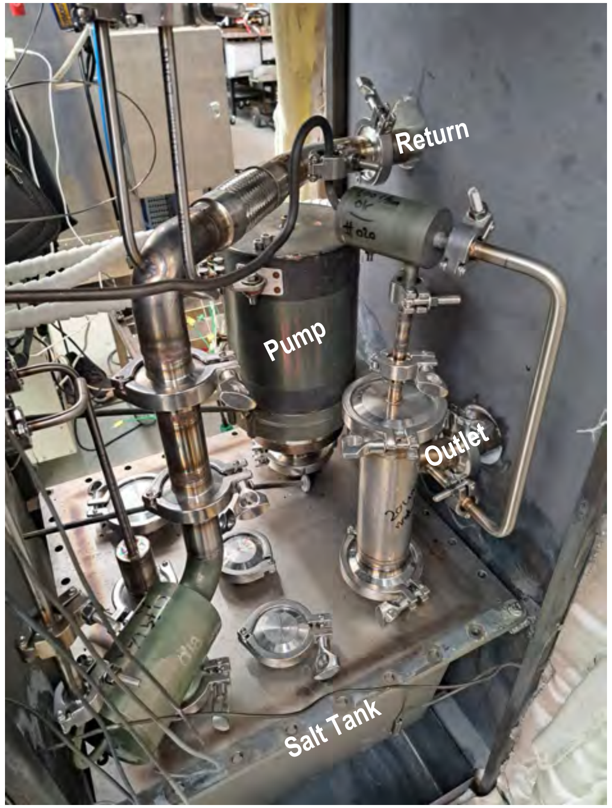


https://www.copenhagenatomics.com/pdf/Loop_v5.2_Datasheet.pdf

Copenhagen Atomics Loop Status

- **Loop assembled at Copenhagen Atomics**
- **Water testing underway with prototypic external section.**
- **Salt commissioning next step.**
- **NRTL field evaluation phase-I complete.**
- **Delivery Date: July 3, 2023**

Inside Enclosure Furnace

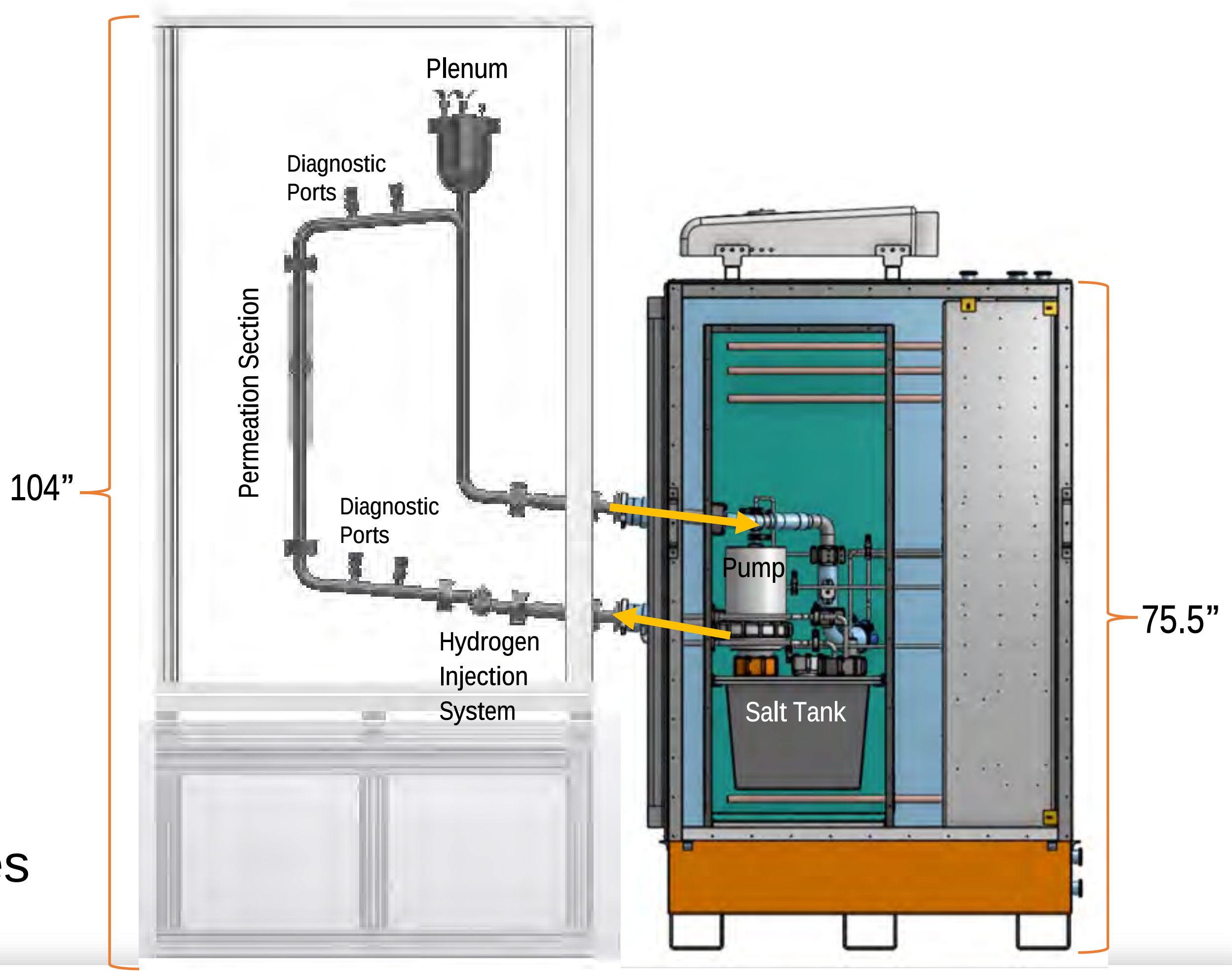


Prototypic test section

Courtesy of Aslak Stubsgaard, Copenhagen Atomics

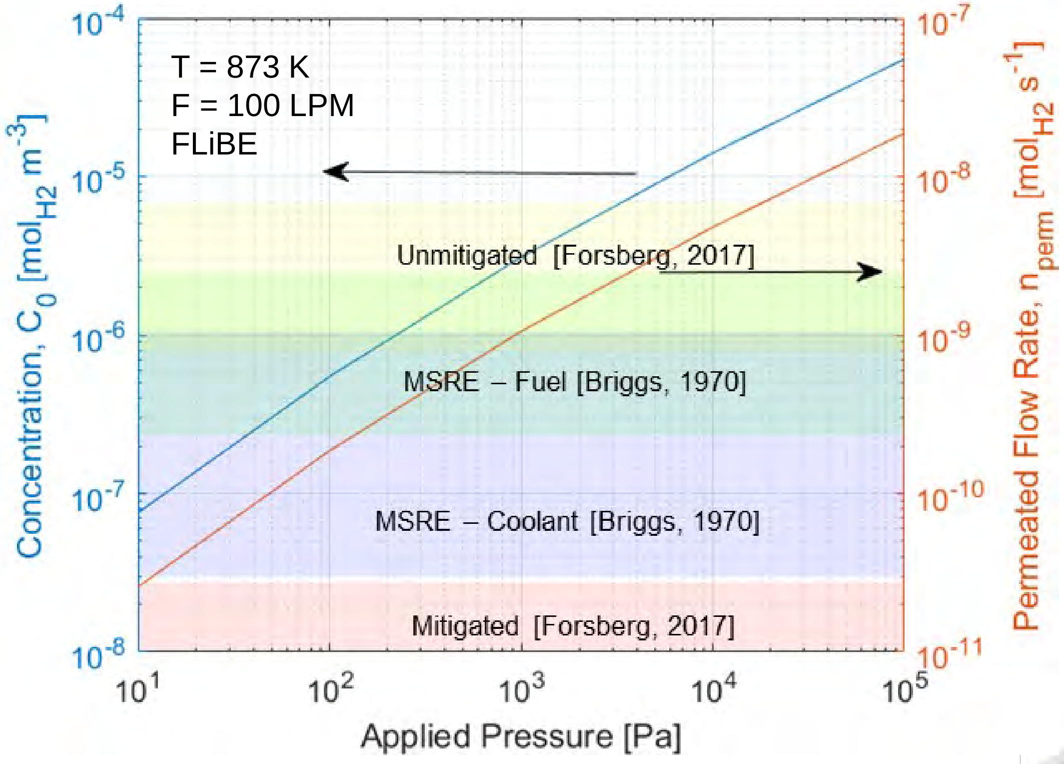
External Test Section

- **Major Components**
  - Hydrogen Injection System
  - Permeation Section
  - Plenum
  - Diagnostic Ports
- **Specifications:**
  - Structural Material:
    - 316 Stainless Steel
    - 1.5" Outer Diameter
    - 0.065" Wall Thickness
  - Sealing: Copenhagen Atomics custom flanges



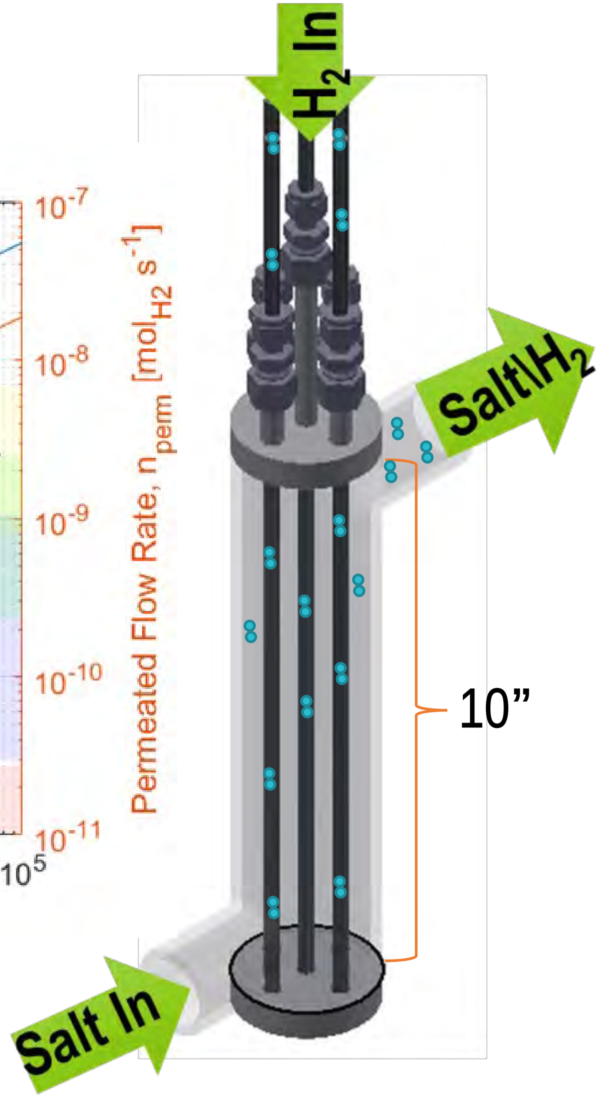
Hydrogen Injection System

- **Injection through method of permeation. “Source Permeator”**
- Five 10-in long 1/4” OD closed-end tubes internally pressurized with H_2.
- Designed as unbaffled in-line square pitch shell-and-tube HX.
- Tubes are exchangeable.
- **Design achieves prototypic concentrations for MSR system.**
- Modeled once-through permeation rate through system numerically.
  - Mass transfer taken from heat transfer
  - Donohue, 1949
- Assumptions:
  - Zero initial concentration
  - Steady-state permeation



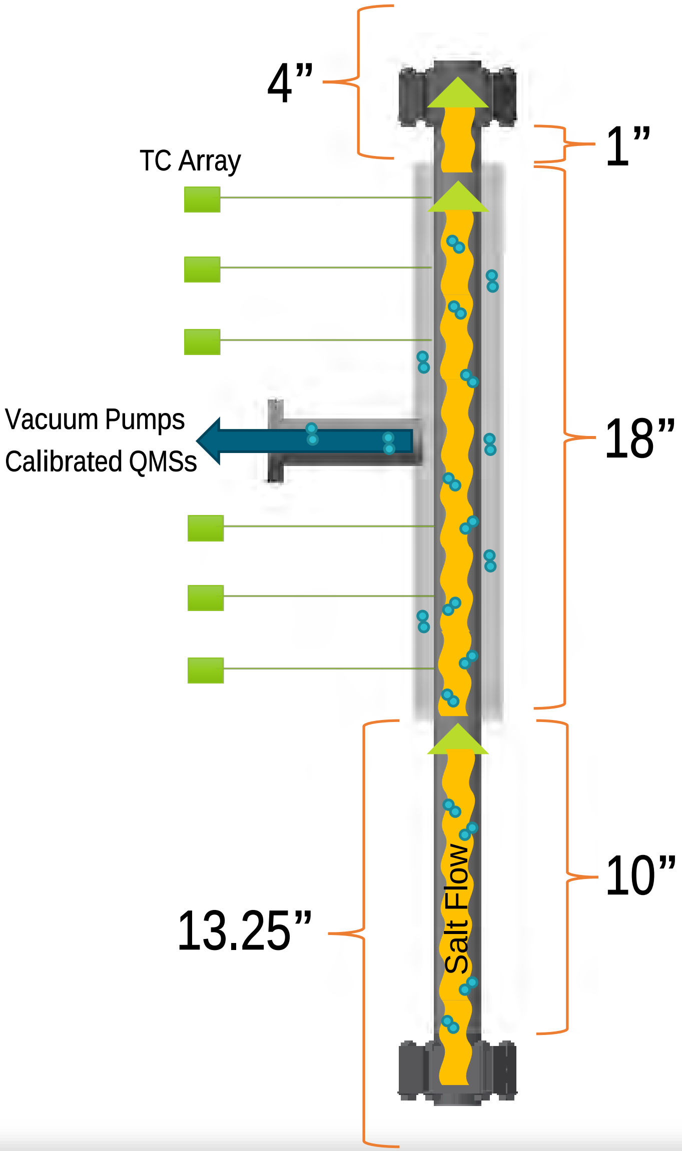
$$Sh = 0.128 D_e' Re^{0.6} Sc^{0.33}$$

D. Donohue *Ind. Eng. Chem.* 1949, 41, 11, 2499–2511



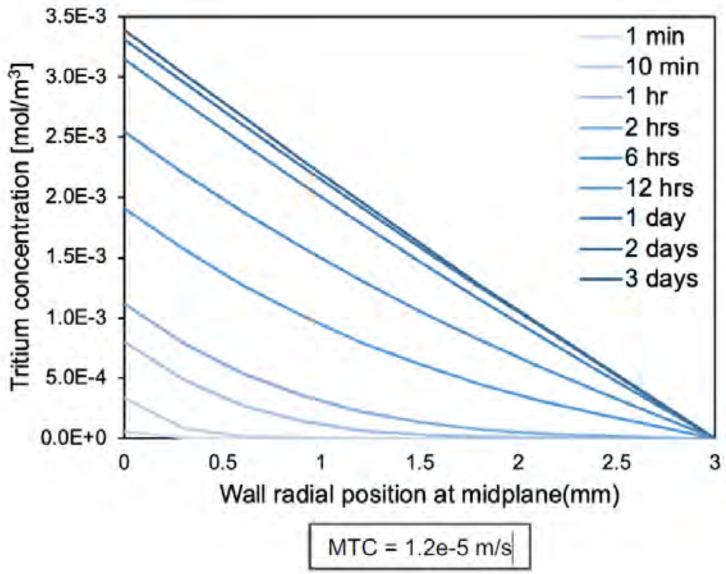
Permeation Section

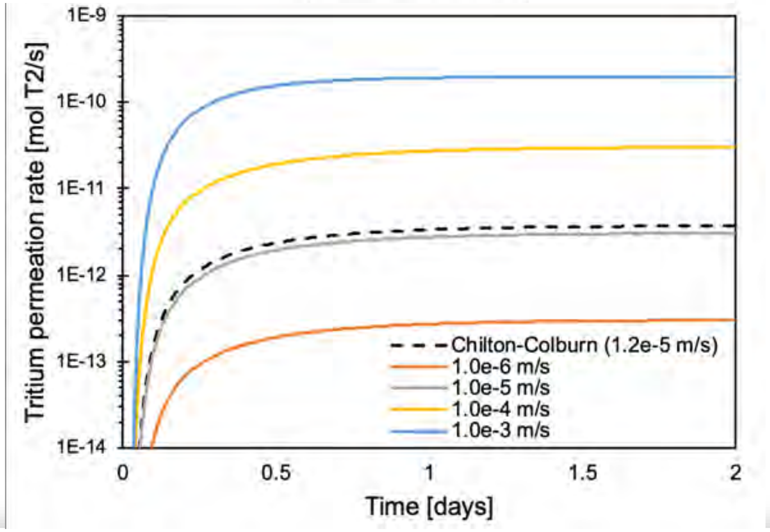
- **Goal:** Measure hydrogen permeation through structural materials in flowing salt.
- Mass Balances:
  - Salt with dissolved H_2 flows through tube.
  - Vacuum boundary around 18 in length.
  - H_2 permeates through metal into vacuum pumping system. Rates monitored with QMS.
- Design Considerations
  - Fully-developed flow in permeation section.
  - Permeation rates measurable with QMS.



Test Section SAM Model

- **System Analysis Module (SAM) is a systems code for advanced non-LWR safety analysis developed by ANL as a NEAMS tool. Tritium transport capabilities incorporated for MSR/FHR analysis.**
- **MSTTE test section modeled under transient conditions.**
  - Analysis based on 0.61m length and 3 mm wall thickness
  - *Note new design is 0.46 m length and 1.65 mm wall thickness.*
  - Flibe flow rate = 100 LPM, T= 700 ◦C, $C_T = 10^{-5}$ mol T_2 m^{-3}
  - Probe concentration evolution in test section.
  - Steady-state achieved after ~2 days (dependent on mass transfer)
  - Investigated mass transfer: T mass transfer in FLiBe rate-limiting.
  - Defines tritium permeation rate and transient profile.
- **Complete system model planned *this summer*.**



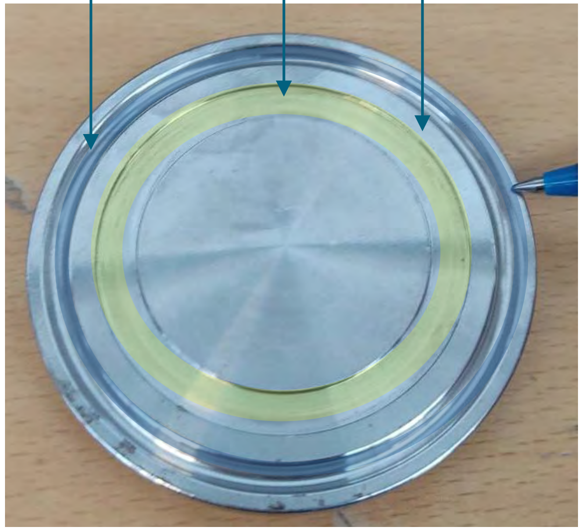


Courtesy of T. Mui and R. Hu at ANL

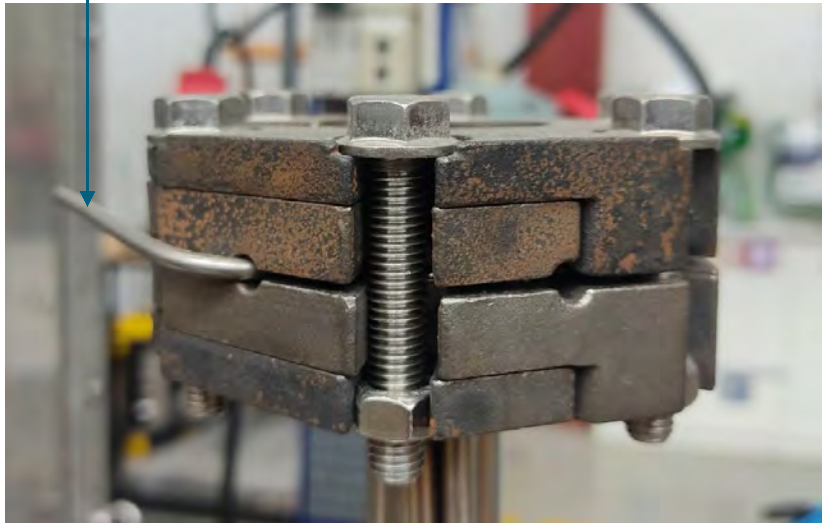
Copenhagen Atomics Flanges

- **Flanges required to mount external test section to pump loop and to mount permeation test section.**
- **High risk component to contaminant salt with air and avenue for salt leakage.**
- **Double seal method with localized inert Ar atmosphere developed.**

Example Flange Interface



Example Flange Assembly



Courtesy of Aslak Stubsgaard, Copenhagen Atomics

Corrosion and Wall Thickness

Wall Thickness: 0.065 in = 1.65 mm

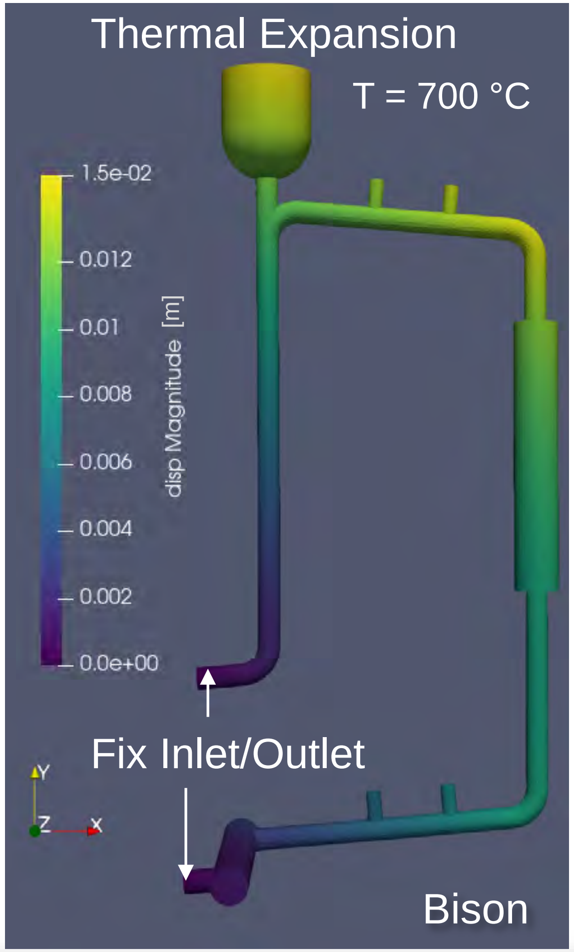
- Required for short radius bends
- Dimension of CA flange ports

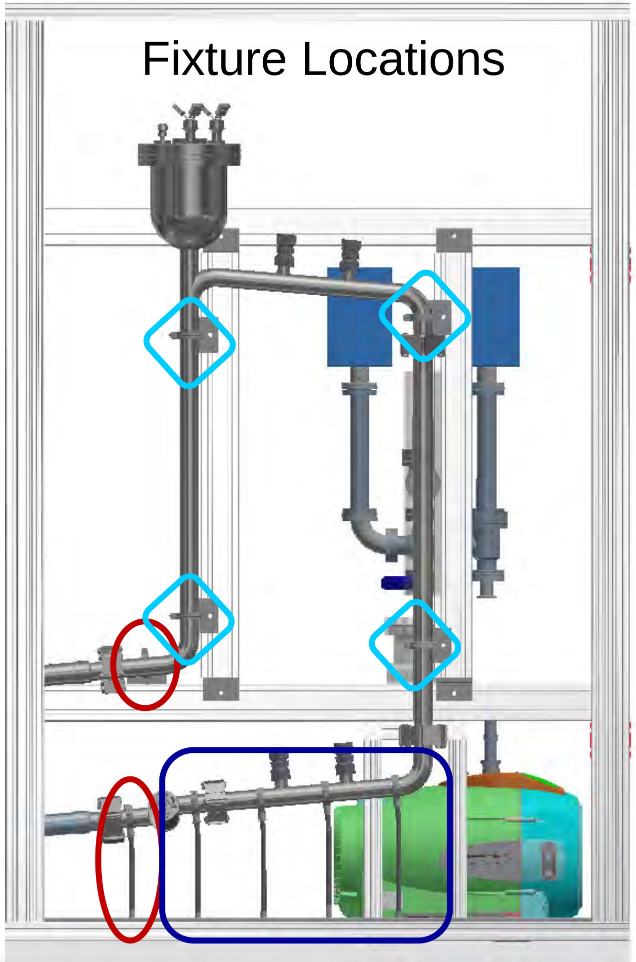
Minimum thickness (t_m) is 0.40 mm per B31.3

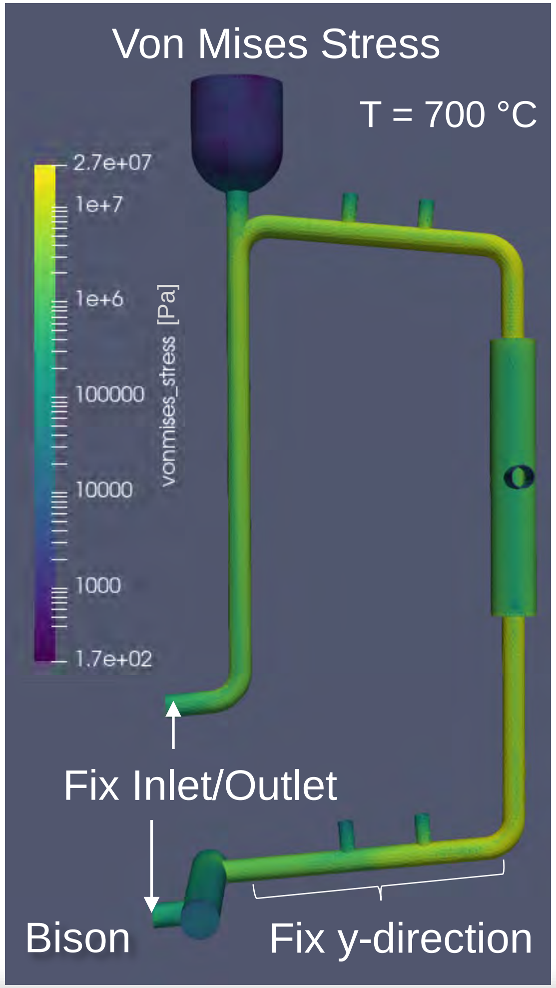
- Corrosion Thickness: c = 0.05 mm (10,000 h at 43.8 μm/y)
- Design pressure thickness: t = 0.35 mm (0.3 MPa)

Alloy	Salt	Condition	Temp. (°C)	Duration (h)	Corrosion Rate (μm/yr)	Reference
316	FLiBe	Static	700	3000	17.1 (316 in 316) 31.2 (316 in Graphite)	Zheng, 2015 10.1016/j.jnucmat.2015.03.004
316	FLiBe	Static	700	3000	16 (prediction)	Zheng, 2016 10.1016/j.jnucmat.2016.10.023
316H	FLiNaK	Flowing	650	1000	5 μm / 1000 h (hot leg) 43.8 μm/y	Raiman, 2022 10.1016/j.jnucmat.2022.153551
316L	FLiNaK	Static	600	300	996.3 (austenite) 3650.4 (ferrite)	Maric, 2018 10.1016/j.corsci.2018.07.006
316	FLiBe	Flowing	650 max	25,103	15 (as received salt) <2 (with Be addition)	Keiser, 1979 10.1016/0022-3115(79)90505-1

External Test Section Mounting

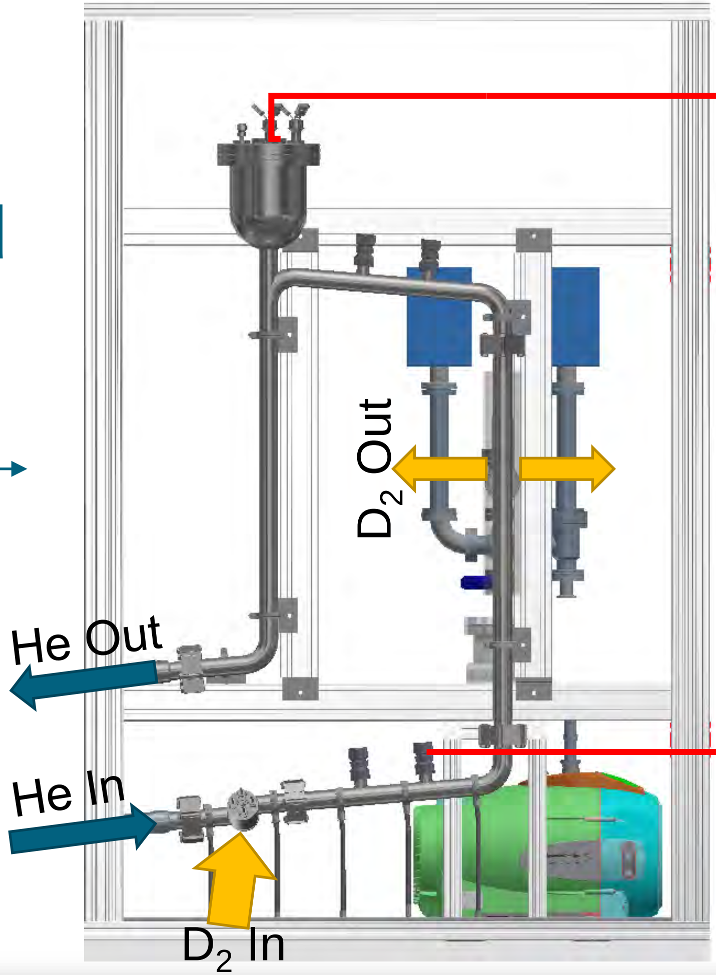






Commissioning Tests

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



Gas Chromatograph Equipped: 2 PDHID for trace H_2 in He

Work plan

Phase I: D_2 & FLiNaK
- FY23-24*
- System shakedown
  - Ensure proper functionality of loop components
  - Test exchange and operating procedures
- Initial dataset for code validation: transport through structural and HX materials
- Design salt exchange and purification system
- Design alternate test sections

Phase II: D_2 & FLiBe
- FY25*
- Implement salt exchange and salt purification system
- Replicate structural and HX material experiments with FLiBe
- Extraction/control campaigns: sparging, absorption, permeation extraction
- Design, procure, and prepare facility for tritium operation

Phase III: T_2 & FLiBe
- FY25/26* - Onward
- Tritium validation testing
- Permeation campaigns for structural and HX materials
- Extraction/control campaigns: sparging, absorption, permeation extraction

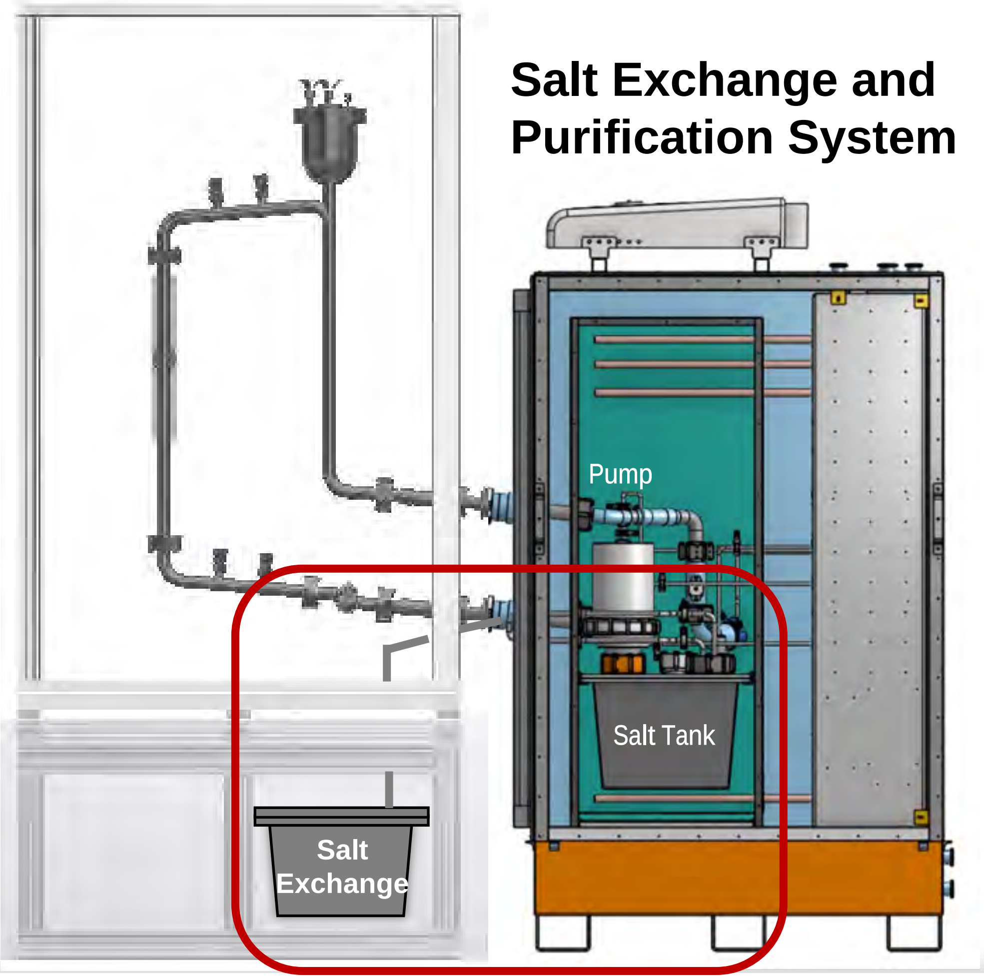
*Timelines are subject to change based on program needs

Future Work Implementation

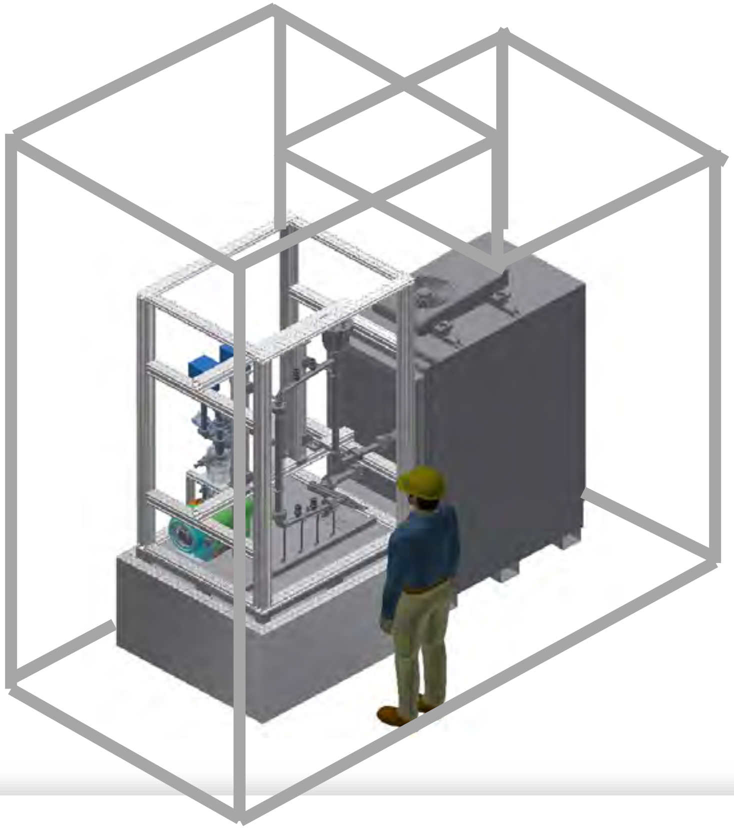
Safety and Tritium Applied Research facility

- Tritium handling < 1.5 g
- Be handling

Salt Exchange and Purification System



Secondary Enclosure for Be and Tritium Work



Summary

- **Tritium is a unique radionuclide relevant to fluoride-salt molten salt reactors due to its generation and ability to uptake and permeate through materials.**
- **Molten Salt Tritium Transport Experiment is a unique and versatile capability designed to provide tritium transport data and test control technology related to Molten Salt Reactors.**
- **MSTTE Status: design is complete and is currently under construction.**
- **Commissioning to start this FY.**

Thank you

thomas.fuerst@inl.gov