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A MELCOR-TMAP Model of the Tritium Extraction eXperiment

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Changing the World's Energy Future

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Idaho National Laboratory

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CSARP 2023

June 7, 2023

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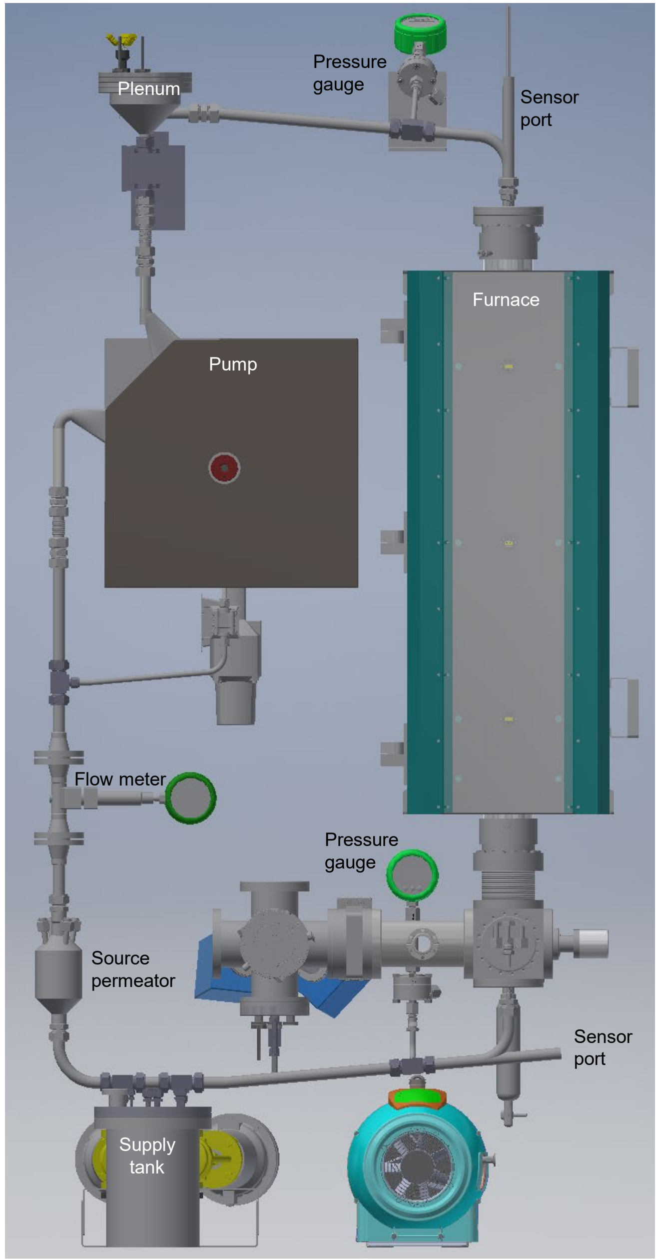
Background

- Vacuum permeators are one of the leading concepts for harvesting tritium from PbLi breeders.
- The Tritium Extraction eXperiment (TEX) will test the vacuum permeator concept for extracting tritium from PbLi.

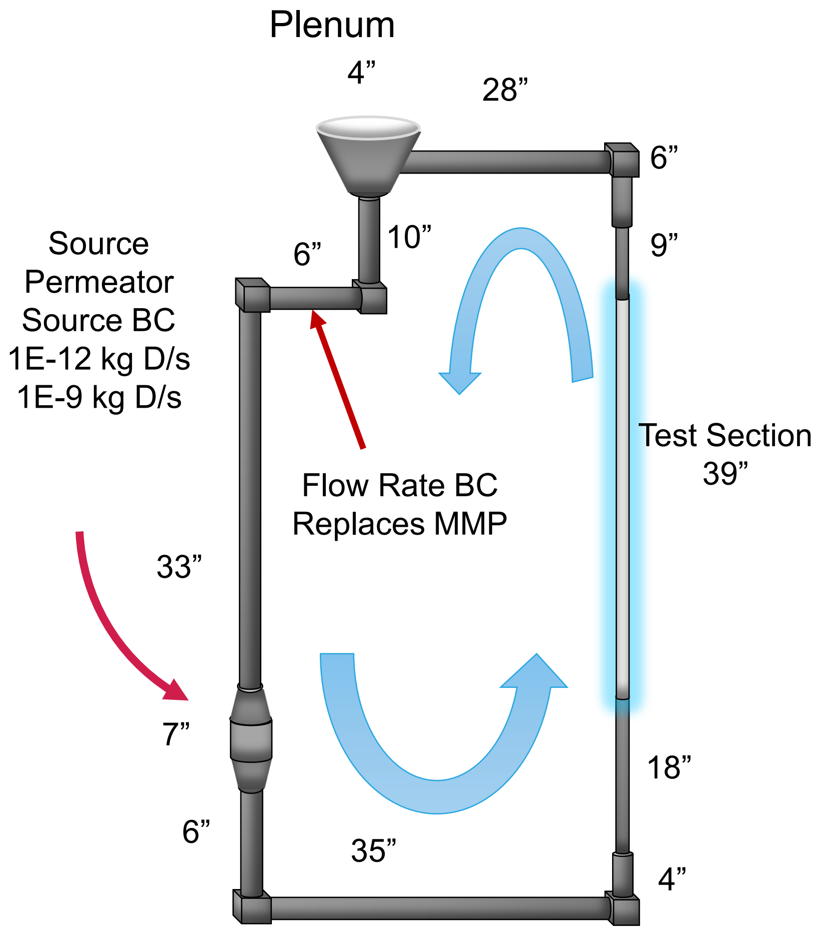
Goals:

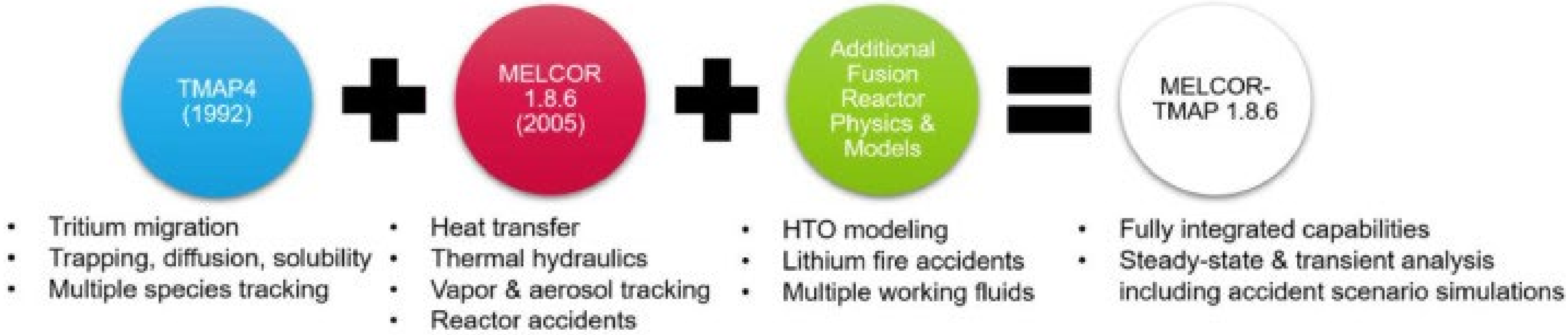
- Develop a versatile tritium extraction loop capable of testing multiple configurations and permeator materials with near prototypic conditions.
- FY23 Q2: Receive all components and complete system installation.
- FY23 Q3: Commission with He experiments.
- FY23 Q4: Melt PbLi



TEX MELCOR Model - Background

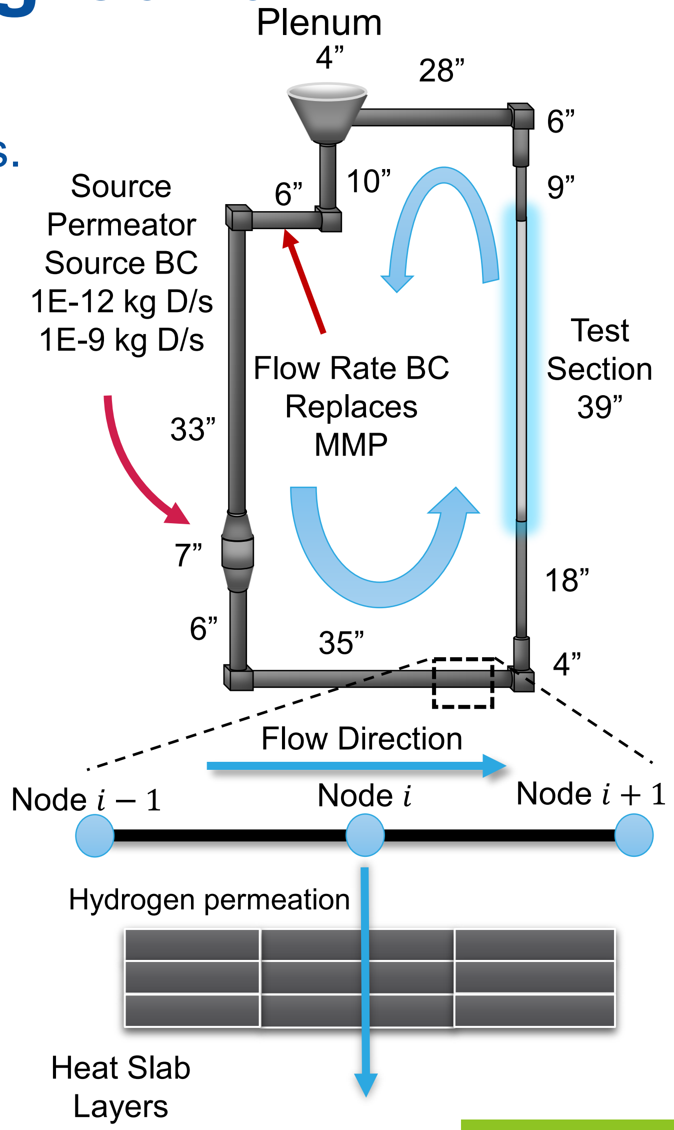
- MELCOR-Fusion is based on MELCOR 1.8.X with adaptations relevant to thermal hydraulics calculations in fusion designs
  - Does not simulate plasma or neutronics
  - Useful for accounting for steady-state and some accident profiles including
    - Loss of flow (coolant)
    - Loss of vacuum
    - Loss of coolant
- MELCOR-TMAP is a system-level engineering code based on MELCOR-Fusion 1.8.6 and TMAP for hydrogen species transport and safety analysis for fusion reactors and technologies.





TEX MELCOR Model - Background

- Control volumes used to represent pipes, plenum, source permeator, test section, vacuum, and surrounding volumes.
- Flow paths track transport of moving fluid (PbLi) and hydrogen species between control volumes.
- Heat structures used to simulate solid walls and interfaces through which hydrogen permeates.
- TEX experiment has been modeled in MELCOR-TMAP using several simplifications and assumptions:
  - Insertion of D/T at source permeator set as a source term boundary condition.
  - Moving magnet pump (MMP) replaced with a pipe & set as a flow rate boundary condition.
  - Volumes immediately outside of test section vacuum (furnace, etc.) are neglected.



Primary Tubing Specs (316 SS)
- OD: 1”
- ID: 0.87”
- Wall thickness: 0.065”

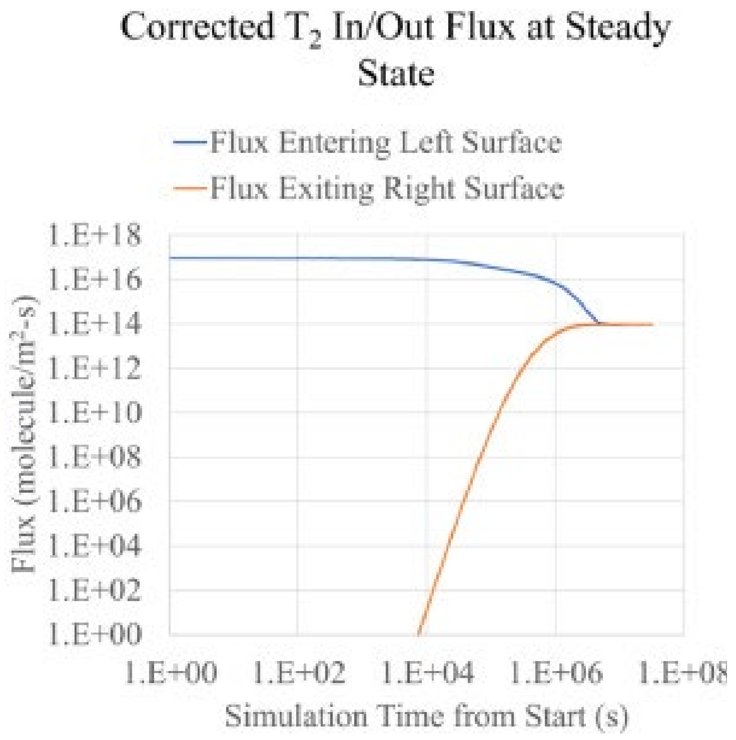
Secondary Tubing Specs (316 SS)
- OD: 0.5”
- ID: 0.37”
- Wall thickness: 0.065”

Test Section (Vanadium)
- OD: 0.5”
- ID: 0.46”
- Wall thickness: 0.02”

Tritium Migration Model

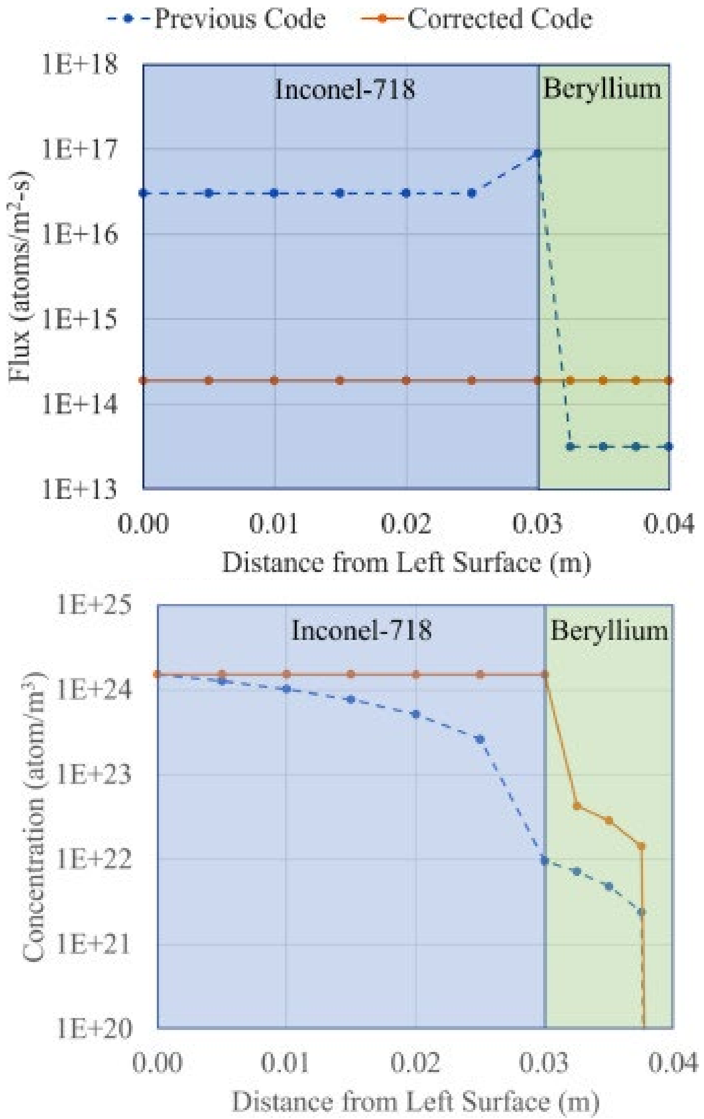
- Based on a finite difference species balance
- Allows for transport across multiple interfaces with source terms
- Trapping physics also incorporated
- Assumes 1-D cartesian diffusion

$$
\begin{aligned}
&-C^{n}_{s_{i+1}}\left\{\left(\frac{D_{i+1}+\ D_i}{\Delta x_{i+1}+\Delta x_i}\right)\times\left[1+\frac{(Q^{*}_{i+1}+Q^{*}_{i})}{R(T_{i+1}+T_i)^2}(T_{i+1}-T_i)\right]\right\} \\
&+C^{n}_{s_i}\left\{\frac{\Delta x_i}{\Delta t}+\left(\frac{D_{i+1}+\ D_i}{\Delta x_{i+1}+\Delta x_i}\right)\times\left[1-\frac{(Q^{*}_{i+1}+Q^{*}_{i})}{R(T_{i+1}+T_i)^2}(T_{i+1}-T_i)\right]+\right. \\
&\left.\left(\frac{D_i+\ D_{i-1}}{\Delta x_i+\Delta x_{i-1}}\right)\times\left[1+\frac{(Q^{*}_{i}+Q^{*}_{i-1})}{R(T_i+T_{i-1})^2}(T_i-T_{i-1})\right]+\sum_{j=1}^{N_t}\left(\frac{\alpha_{t_{s,i}}C^{e^n}_{j,t_i}\Delta x_i}{N(1+\ \alpha_{r_i}\Delta t)}\right)\right\} \\
&-C^{n}_{s_{i-1}}\left\{\left(\frac{D_i+\ D_{i-1}}{\Delta x_i+\Delta x_{i-1}}\right)\times\left[1-\frac{(Q^{*}_{i}+Q^{*}_{i-1})}{R(T_i+T_{i-1})^2}(T_i-T_{i-1})\right]\right\}=\frac{C^{o}_{s_i}\ \Delta x_i}{\Delta t}+\ S_{s_i} \\
&+\sum_{j=1}^{N_t}\left(\frac{\alpha_{r_i}C^{t^o}_{s_{i,j}}\Delta x_i}{1+\ \alpha_{r_i}\Delta t}\right)
\end{aligned}
\qquad (1)
$$



Verification of flux

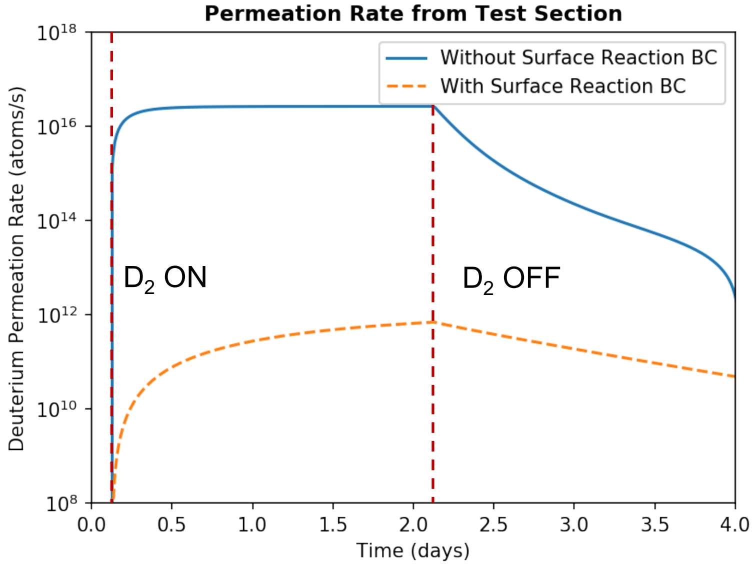
- Simulation of a beryllium-coated inconel interface
- Flux balance is conserved across interface
- Total flux and concentration gradient consistent with steady-state analytical model is observed

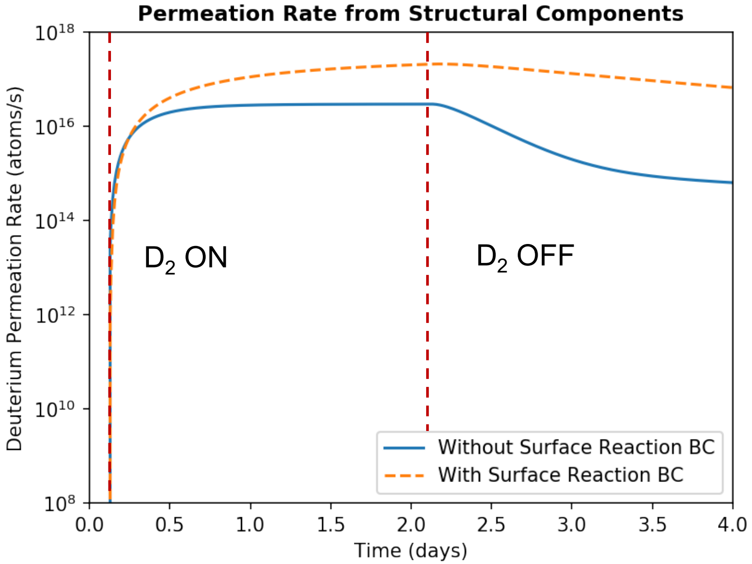


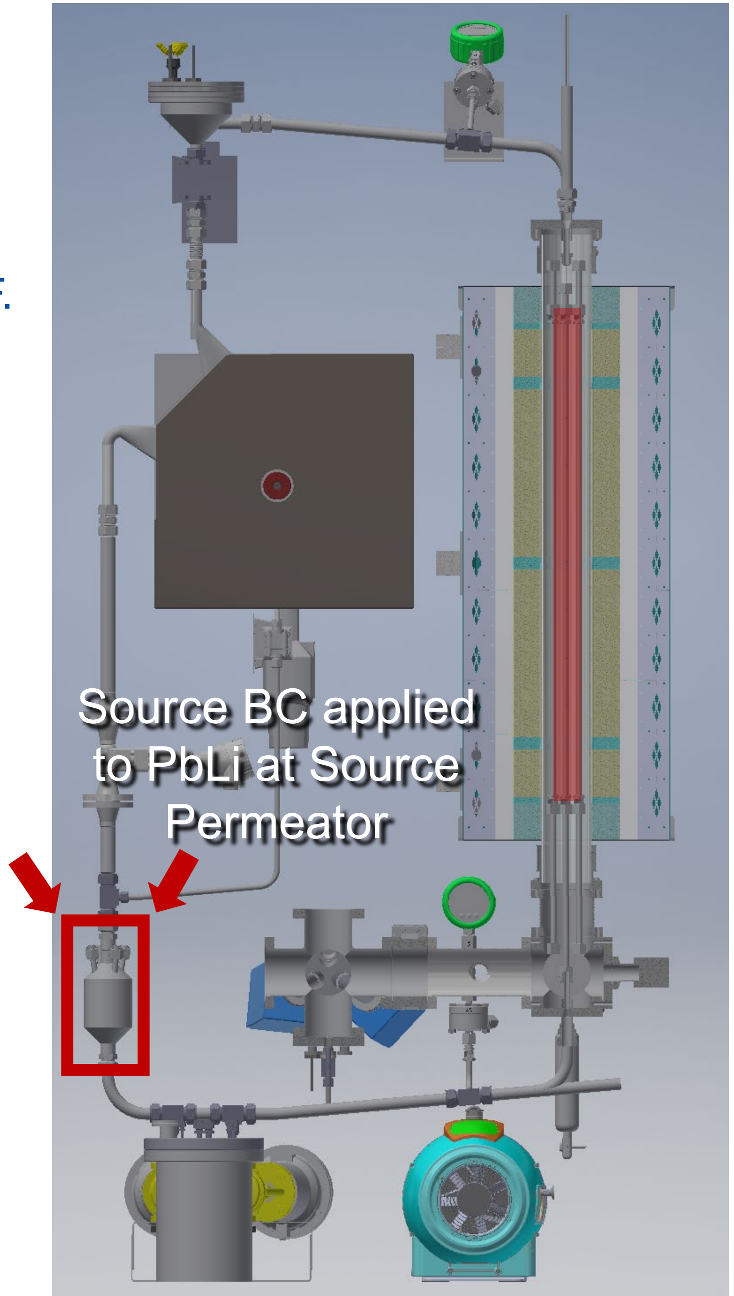
MELCOR-TMAP: The integration of MELCOR for fusion and TMAP4 for fusion reactor systems safety analysis and tritium inventory tracking, Fusion Engineering and Design, 2023

MELCOR-TMAP TEX Model

- Deuterium source:
  - Source boundary condition: 1e-9 kg/s source term. 48 hours ON and 48 hours OFF.
- Permeation rates and transient behavior depend on boundary conditions applied (solution law vs. surface reaction rates).
- Surface-reaction BC accounts for:
  - Recombination of deuterium on the outside of test section and piping.
  - Solution law BC at the PbLi-tube interface (i.e., Sievert's law).
  - Dissociation from atmosphere back into the tubing + PbLi (unlikely).
- Simulation results demonstrate permeation rate from test section impacted heavily by surface reaction rate BC; confirms the outer test section material must be carefully chosen for suitable material properties (e.g., solubility and recombination).

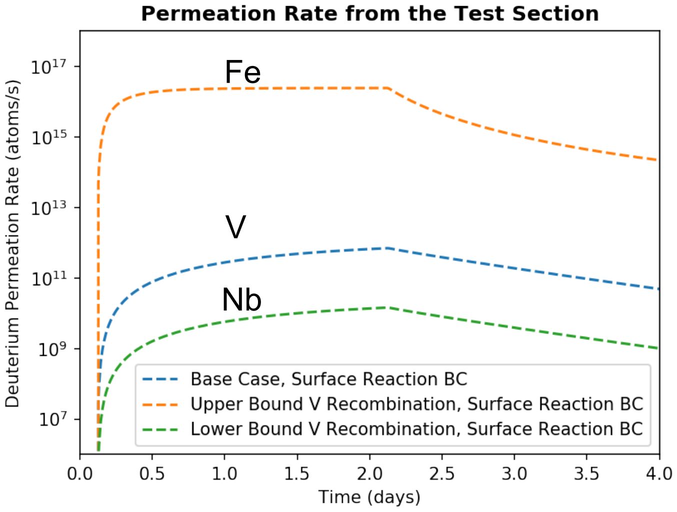


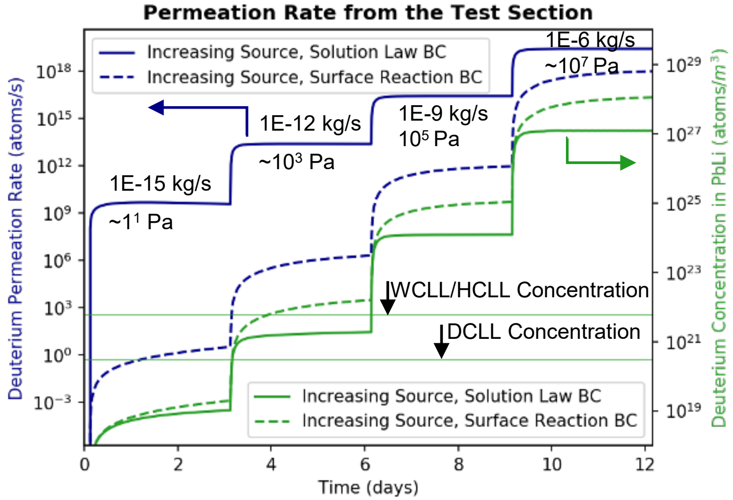




TEX MELCOR Model – Sensitivity Analysis

- Sensitivity of permeation rates from test section to multiple parameters was performed in MELCOR-TMAP:
  - PbLi flow rates (0.1 L/s to 0.5 L/s)
  - PbLi solubility
  - Vanadium solubility & recombination
  - Deuterium source rate (1e-15 to 1e-6 kg/s)
- Simulations show permeation rate from test section are insensitive to flow rates & highly sensitive to vanadium recombination and source rates.
  - Surface reaction rates matter less (converge) as the deuterium concentration in PbLi increases (departing from surface limited regime).
- Future plan is to incorporate Pd coating & interdiffusion barriers into MELCOR-TMAP model:
  - Pd coating intended to enhance recombination coefficient at permeator surface to greatly increase H permeation rates.
  - Focus of ARPA-E GAMOW project with CSM.
- Future plan to model plenum region pool-atm transfer.





Construction status

- Control system hardware:
  - Construction underway.
- Vortex PbLi flow meter:
  - Welded and installed
- Test section
  - New borosilicate test section has been fabricated.
  - Awaiting installation.
- PbLi pump and tube furnace
  - Power supplies installed. Wiring underway.

PbLi pump and tube furnace controllers.

Gas distribution and control system

Questions?