INL/CON-23-73465-Revision-1

SOFE2023 Presentation: "Tritium Safety and Sensitivity Analysis of Tritium Extraction eXperiment (TEX) PbLi Loop Using MELCOR-TMAP"

Changing the World's Energy Future

Matthew D Eklund, Thomas F Fuerst, Adriaan Anthony Riet, Hanns Anton Gietl, Chase N Taylor

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OXFORD, UK

30TH IEEE SYMPOSIUM ON FUSION ENGINEERING

IEEE

UK Atomic Energy Authority

Tritium Safety and Sensitivity Analysis of Tritium Extraction eXperiment (TEX) PbLi Loop Using MELCOR-TMAP

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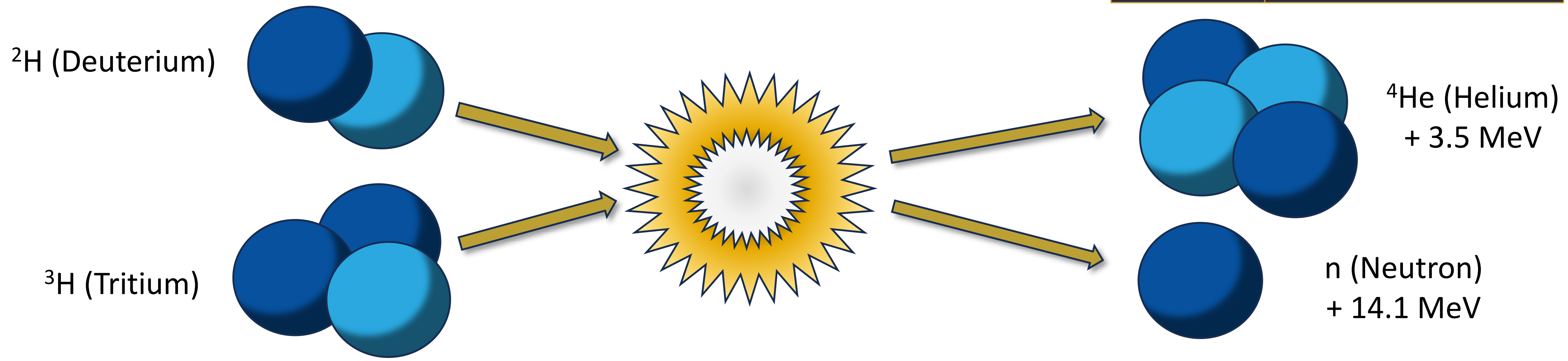
Outline

- Background
- Tritium Extraction eXperiment (TEX)
- MELCOR-TMAP
- TEX Model in MELCOR-TMAP
- MELCOR-TMAP Simulations
- Conclusions & Future Work

Background



- Tritium supply is a crucial consideration for the design of a self-sustaining fusion power plant
- Breeding & extraction of tritium from the coolant and/or breeder in the vacuum vessel is a main area of focus in fusion reactor science & engineering

Background

- Among liquid & solid breeder concepts, the lead-lithium eutectic alloy, Pb-15.72Li, or PbLi, is a leading candidate for liquid breeder blanket designs
- Efficient extraction systems for liquid breeders will limit permeation & release of radioactive tritium & provide tritium for continuous reactor operation

Background

Method	Description	Benefits	Issues
Gas-Liquid Contactor	Packed column, liquid-gas sparging system.	• Mature technology • Planned in ITER	• Large system • High energy consumption/low eff.
Vacuum Sieve Trays	Jet of droplets. T_2 evolves from droplet into vacuum.	• High efficiency • Simplicity	• Low flexibility with PbLi flowrate • High uncertainty, risk, and pressure drop
Regenerable Getters	Tritium gettering bed using high solubility materials.	• Compact • High efficiency	• Requires regeneration • High tritium inventory
Vacuum Permeator	Permeable membrane. Vacuum on secondary side.	• Continuous/simple • High efficiency	• Membrane stability • High capital costs – large surface area

Utili, Marco, et al. "Tritium Extraction From HCLL/WCLL/DCLL PbLi BBs of DEMO and HCLL TBS of ITER." IEEE Transactions on Plasma Science 47.2 (2019): 1464-1471.

Tritium Extraction eXperiment (TEX)

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- The Tritium Extraction eXperiment (TEX) in development at the Safety and Tritium Applied Research (STAR) Facility at Idaho National Laboratory (INL) includes a forced-convection PbLi loop designed to extract tritium using a vacuum permeator, one of several leading concepts for extracting tritium from PbLi breeders
- Goal for TEX is to test & measure the effectiveness of the vacuum permeator concepts for extracting tritium from PbLi. The versatile test stand is capable of testing multiple configurations and permeator materials.

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Tritium Extraction eXperiment (TEX)

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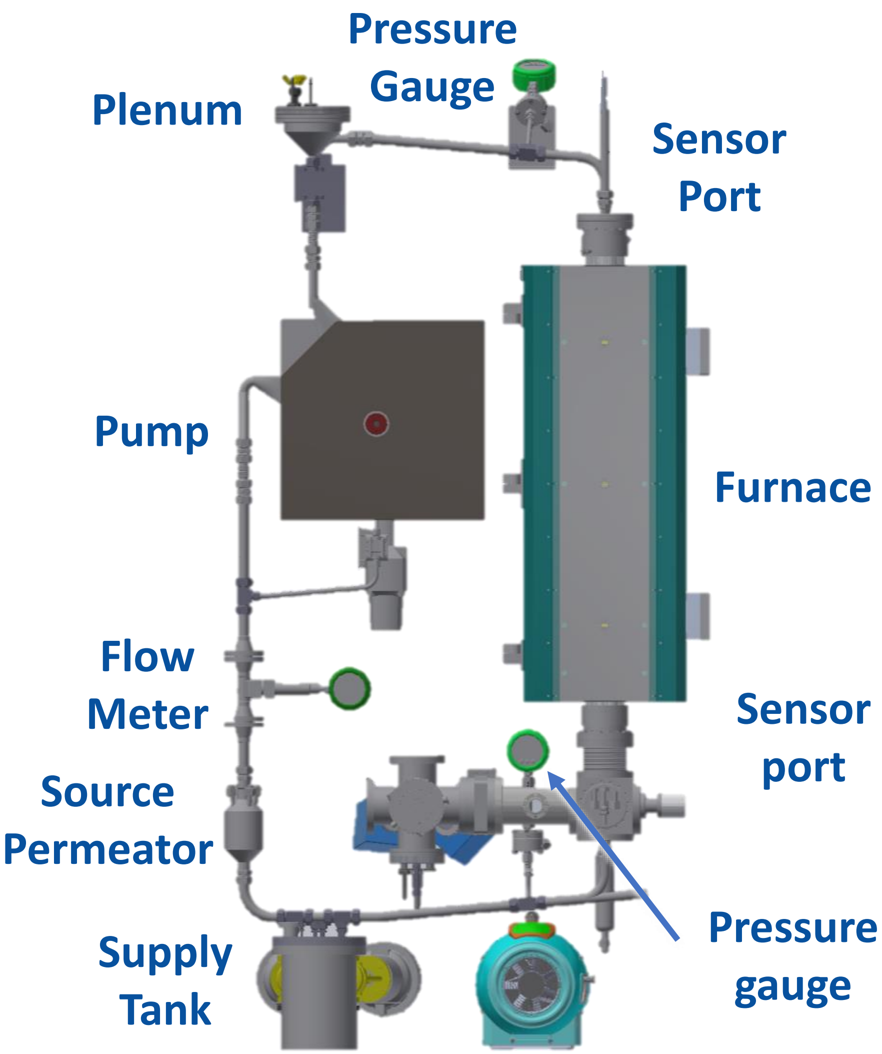
- Source permeator designed to inject hydrogen (deuterium, tritium) into the PbLi
- Furnace surrounds the test section to maintain the test section at a fixed temperature
- Vacuum is pumped outside the test section permeator tube. Hydrogen permeates through the permeator tube and the rate is measured with calibrated Quadrupole Mass Spectrometers



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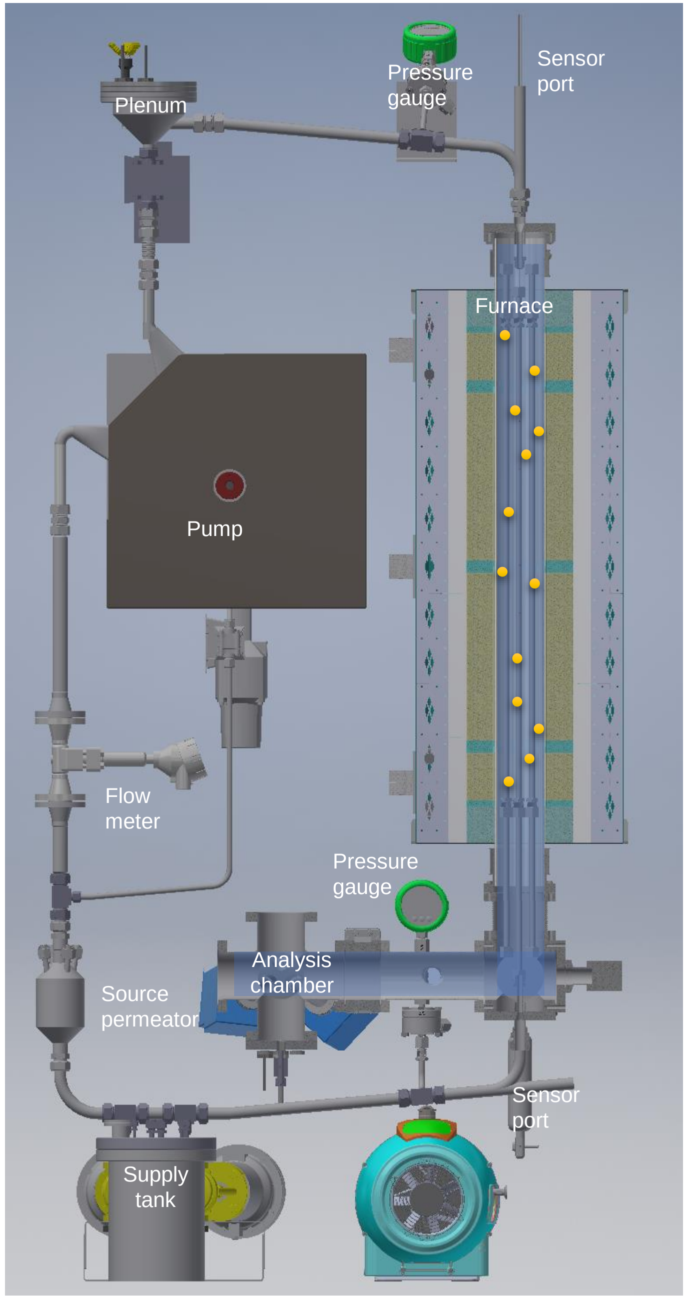
Tritium Extraction eXperiment (TEX)

- Unique features:
  - Interchangeable/expandable test section
  - Access for testing additional diagnostics
  - Ability to use tritium

Blanket Concepts

Parameter	TEX	DCLL	WCLL	HCLL
Flow rate (max)	0.5 L/s 4.7 kg/s	26000 kg/s	956 kg/s	890 kg/s
Permeator length	1-5 m			
Temperature	300-535ºC	535ºC	311.5ºC	300ºC
D concentration (mol/m^3)	≤ 2 x 10^{-2}	5.56 x 10^{-4}	1.41 x 10^{-2}	6.61 x 10^{-3}
Tritium capable	Yes	Yes	Yes	Yes

[1] M. Utili, et al., IEEE Trans. Plasma Sci. 47 (2019) 1464–1471
[2] B. Garcinuño, et al., Fusion Eng. Des. 137 (2018) 427–434



Tritium Extraction eXperiment (TEX)

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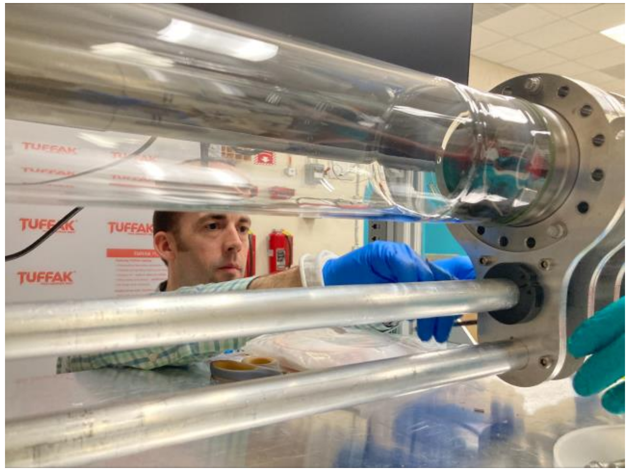
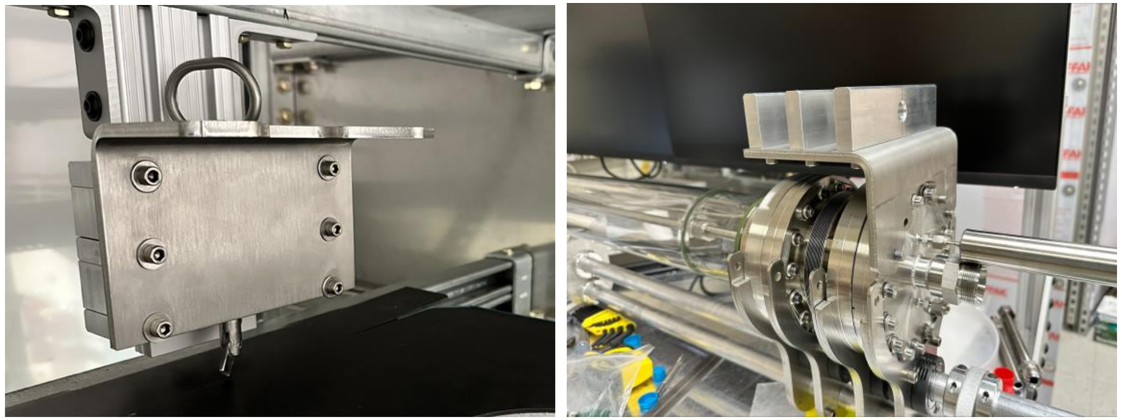
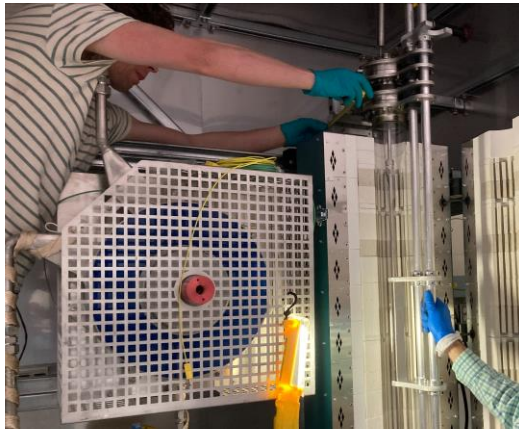
Installation complete of HEPA exhaust blower



Installation of mockup tube into test section housing



Test section support track



Installation of test section into loop

Current view of TEX

Steady-State Tritium Transport Model

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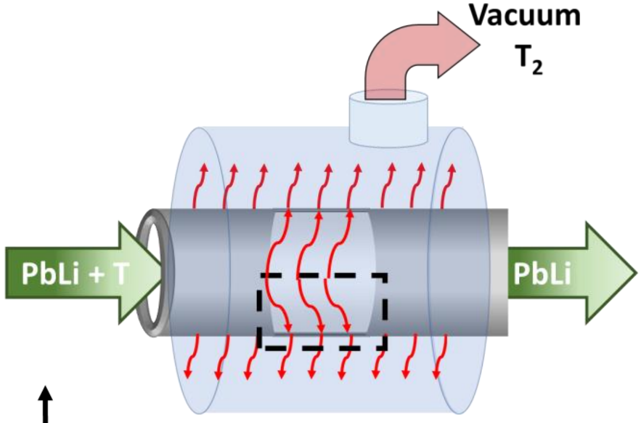
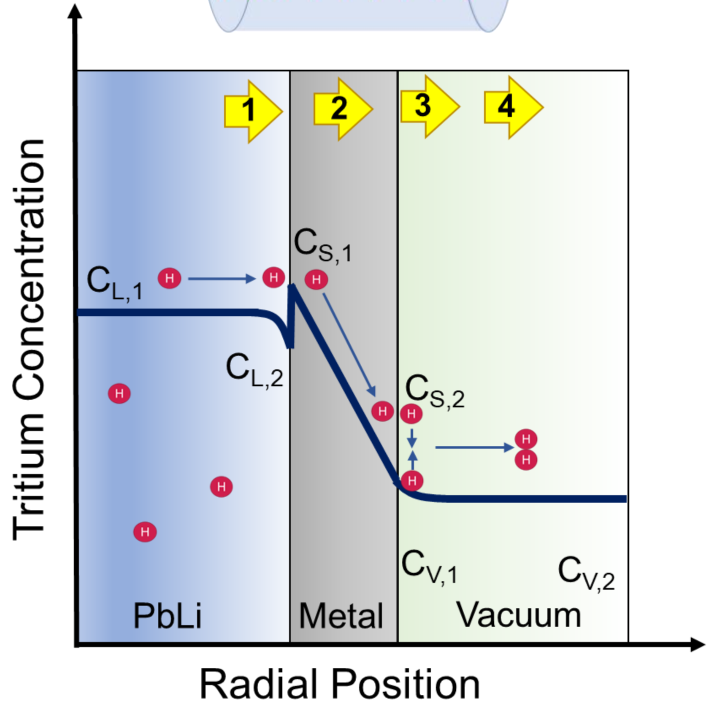
- PbLi flows inside tube, vacuum on shell side
- T diffuses through wall and collected by vacuum
- Steady-state 1D radial T flux (J):

1. Mass transfer in PbLi: $J = \mathbf{k_{T,1}}(C_{L,1} - C_{L,2})$
2. Diffusion through metal: $J = -\mathbf{D_S}\frac{\partial C_S}{dr}$
3. Recombination: $J = \mathbf{k_r}C_{S,2}^2 - \mathbf{k_d}P_{V,1}$
4. ~~Mass transfer vacuum: $J = \mathbf{k_{T,2}}(C_{V,1} - C_{V,2})$~~

- Models are only as accurate as the input parameters… which can encompass significant uncertainty.





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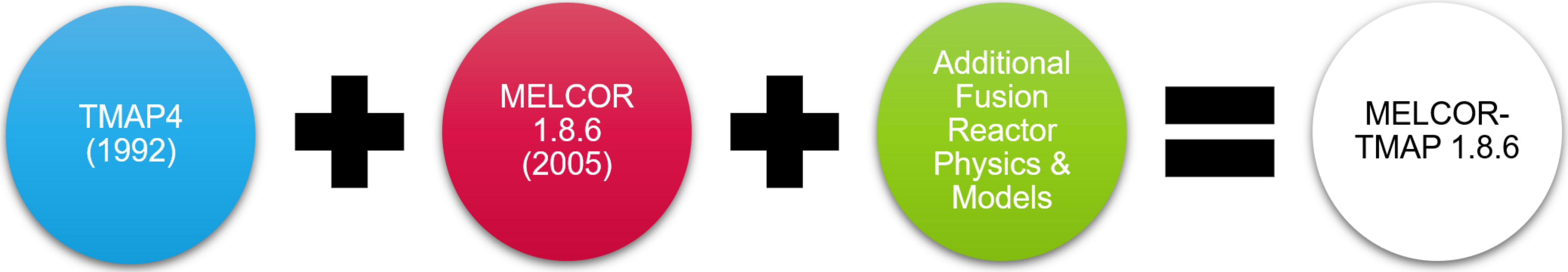
MELCOR-TMAP

- Part of the safety analysis for TEX includes modeling & simulation of the experiment loop using MELCOR-TMAP, owned & developed by the Fusion Safety Program at INL
- MELCOR-TMAP (latest version 1.8.6) is a system-level engineering code based on MELCOR and TMAP4 for hydrogen species transport & safety analysis for fusion reactors & related technologies



- Tritium migration
- Trapping, diffusion, solubility
- Multiple species tracking

- Heat transfer
- Thermal hydraulics
- Vapor & aerosol tracking
- Reactor accidents

- HTO modeling
- Lithium fire accidents
- Multiple working fluids

- Fully integrated capabilities
- Steady-state & transient analysis including accident scenario simulations

MELCOR-TMAP

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● = developed by Sandia National Laboratory (SNL)

● = developed by Idaho National Laboratory (INL)

TMAP/MOD1 (1988)
Initial release of the Tritium Migration and Permeation (TMAP) code

TMAP4 (1992)
Improved version went through extensive verification & validation (V&V) efforts; has a wide distribution & user base

MELCOR 1.8.2 (1993)
An improvement on previous versions of MELCOR based on Fortran 77 for analysis of light water reactors (LWRs) & related technologies

MELCOR for ITER (1994)
Enhanced version of MELCOR 1.8.2 with modeling capabilities to address modeling & safety issues for ITER. Continues to be used for ITER analysis & safety documentation: “Rapport Préliminaire de Sûreté” (Preliminary Report on Safety – RPrS), non-specific site safety reports (NSSR-1 & NSSR-2), & Generic Site Safety Report (GSSR)

MELCOR 1.8.6 (2005)
Models for spent fuel pools (SFPs), hydrogen chemistry, flashing, etc. were included in this new release of MELCOR

MELCOR-TMAP
Includes improvements and modifications made in previous versions of MELCOR for fusion added to 1.8.6

Current version of code in use at INL for analysis of fusion reactors & systems involving tritium transport

MELCOR 2.2 (2017)
Improved code architecture based on Fortran 90 including dynamic memory allocation, point kinetics models, turbulent deposition models, etc.

Future Versions of MELCOR-TMAP
Significant software development will be required for integrating MELCOR-TMAP capabilities to the newest version of MELCOR 2.2 in collaboration between INL & SNL

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TEX Model in MELCOR-TMAP

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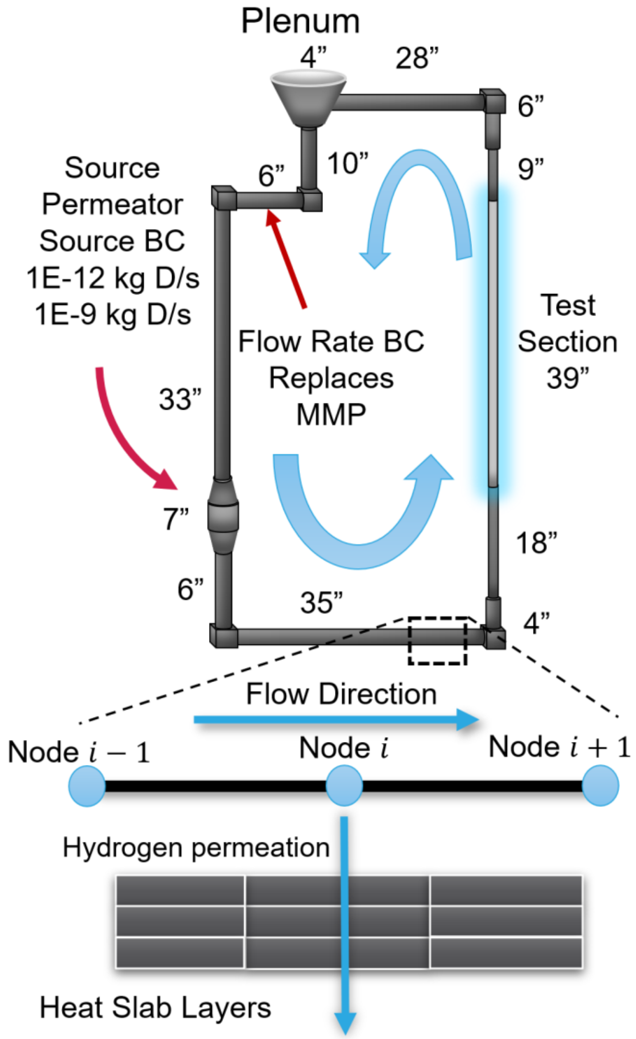
- Control volumes (CVH) used to represent pipes, plenum, source permeator, test section, vacuum, and surrounding volumes
- Flow paths (FL) track advection of moving fluid (PbLi) and hydrogen species between control volumes
- Heat structures (HS) used to simulate solid walls and interfaces through which hydrogen permeates



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”

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TEX Model in MELCOR-TMAP

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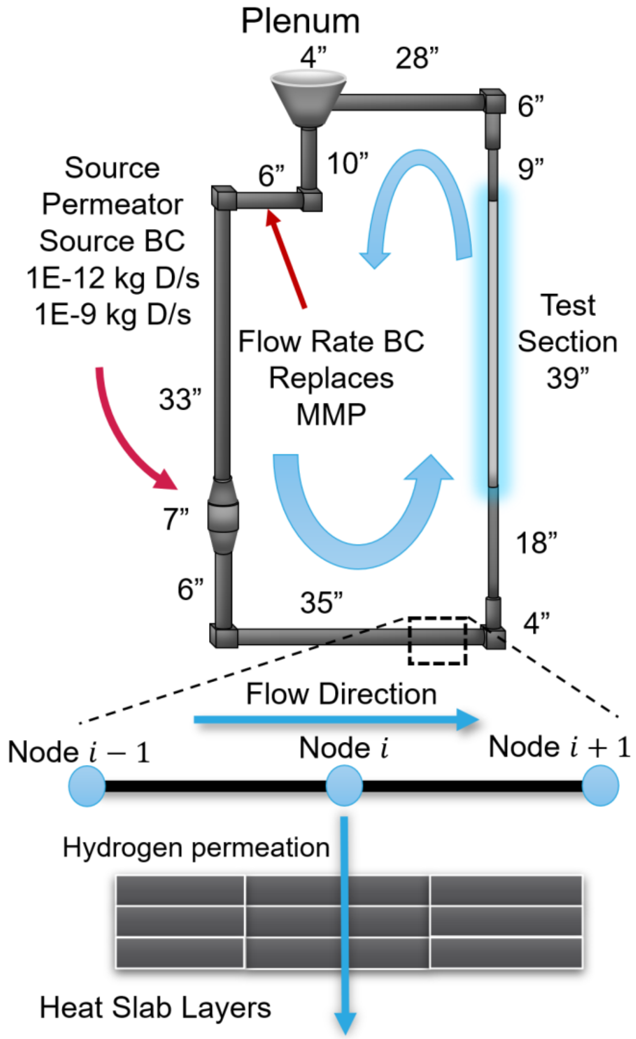
- TEX experiment has been modeled in MELCOR-TMAP using several simplifications and assumptions:
  - Insertion of deuterium at source permeator set as a source term boundary condition (BC)
  - Moving magnet pump (MMP) replaced with a pipe & set as a flow rate BC
  - Volumes immediately outside of test section vacuum (furnace, etc.) are neglected and replaced by BCs and initial conditions (ICs) as appropriate



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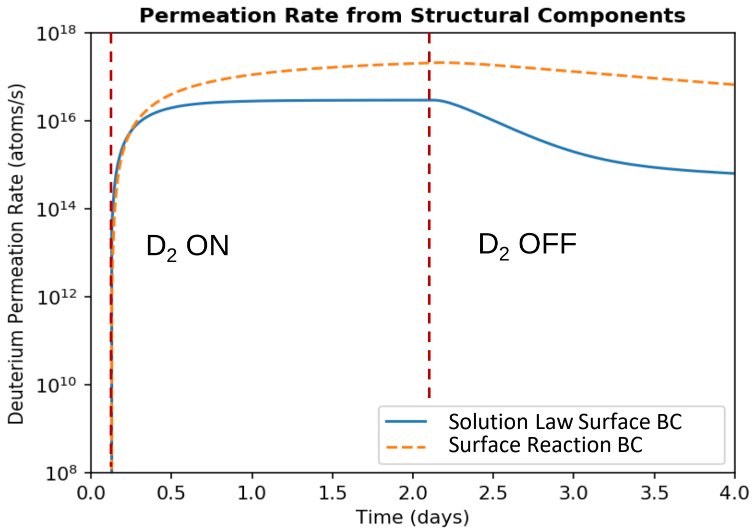
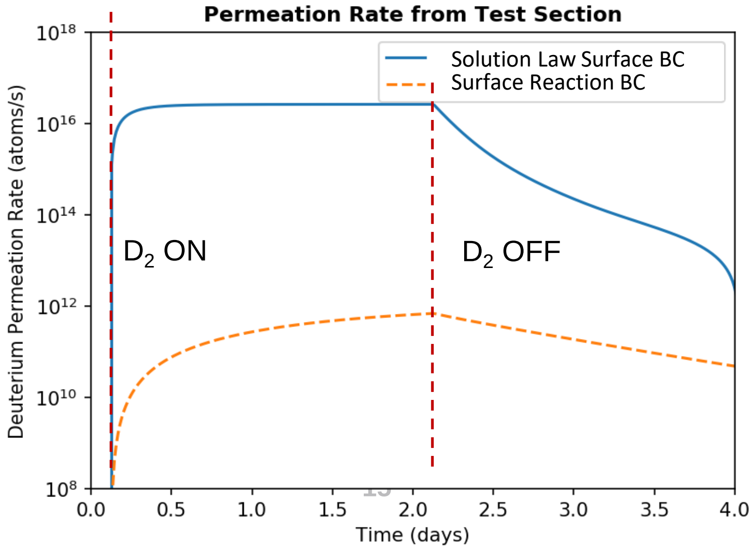
MELCOR-TMAP Simulations

- Deuterium source:
  - Source boundary condition: 3e+17 atom/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., Sieverts' 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 (i.e., solubility and recombination)



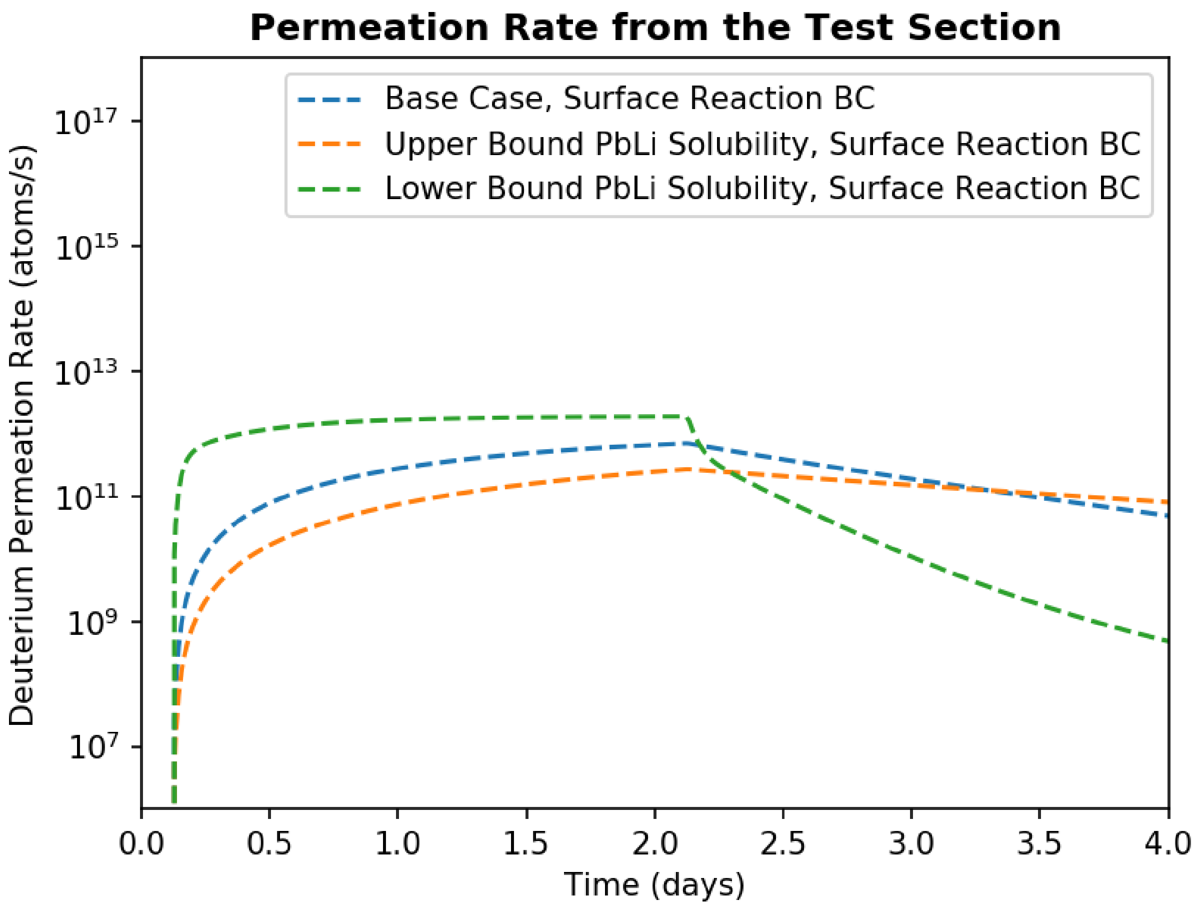


Sensitivity Simulations

- Sensitivity of permeation rates from test section to multiple parameters was performed in MELCOR-TMAP:
  - PbLi solubility
  - Recombination of permeator material
  - Deuterium source rate

Sensitivity to PbLi Solubility

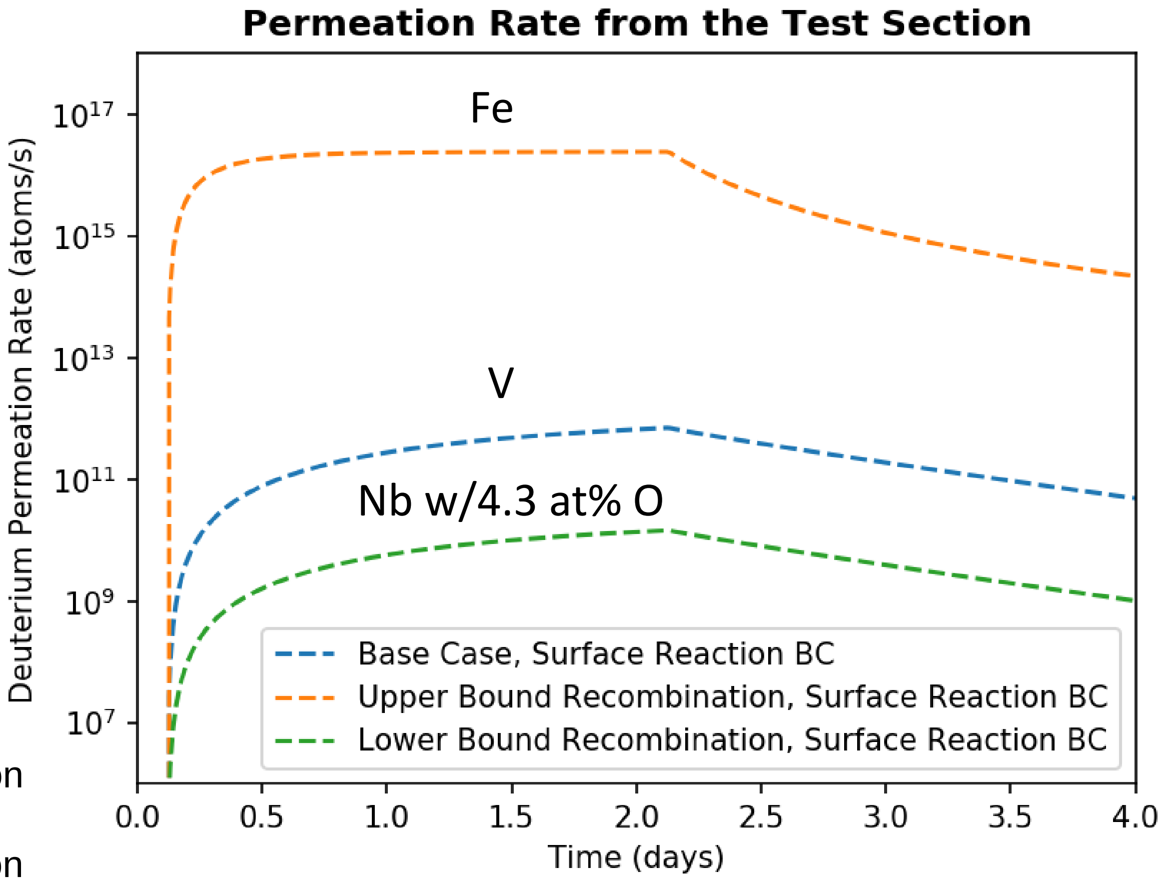
- PbLi solubility modified:
  - Upper bound[1]
    = 3.6e+22 atoms/($m^3 \cdot Pa^{1/2}$)
  - Nominal case[2]
    = 1.4e+23*exp(-0.13/kT) atoms/($m^3 \cdot Pa^{1/2}$)
  - Lower bound[3]
    = 7.7e+20*exp(-0.01/kT) atoms/($m^3 \cdot Pa^{1/2}$)
- Results show solubility affects rate of change in permeation rate, but doesn't greatly affect the SS permeation value



[1]H. Katsuta et al. 1985. "Hydrogen Solubility in Liquid Li17-Pb93." J. Nucl. Mater. 133-134: 167-170.
[2]A. Aiello, Ciampichetti A., and Benamati G. 2006. "Determination of hydrogen solubility in lead lithium using sole device." Fusion Eng. Des. 81, no. 1: 639-644
[3]F. Reiter. 1991. "Solubility and diffusivity of hydrogen isotopes in liquid Pb-17Li." Fusion Eng. Des. 14: 207-211.

Sensitivity to Permeator Recombination

- Permeator recombination modified:
  - Upper bound[1]: Fe recombination
  = 5.9e-27*exp(-0.20/kT) m^4·molecule/(s·$atom^2$)
  - Nominal case[2]: V recombination
  = 7.6e-25*exp(-1.32/kT) m^4·molecule/(s·$atom^2$)
  - Lower bound[3]: Nb with 4.3 at% O
  = 2.6e-30*exp(-0.81/kT) m^4·molecule/(s·$atom^2$)
- Results demonstrate permeation rate is highly sensitive to recombination of permeator material, ranging in ~6 orders of magnitude from lower to upper bounds



[1]F. Waelbroeck, I. Ali-Khan, K.J. Dietz, P. Wienhold. 1979. "Hydrogen solubilisation into and permeation through wall materials." J. Nucl. Mat. 85-86 Part 1: 345-349.
[2]T. Fuerst, P.W. Humrickhouse, C.N. Taylor, M. Shimada. 2021. "Surface effects on deuterium permeation through vanadium membranes." J. Membrane Sci. 620:118949
[3]R. Hayakawa, A. Busnyuk, Y. Hatano, A. Livshits, K. Watanabe. 2003. "Relation between Recombination Rate Constant of Deuterium at Niobium Surface and Oxygen Concentration in Bulk." Physica Scripta 113.

Sensitivity to Source Rate

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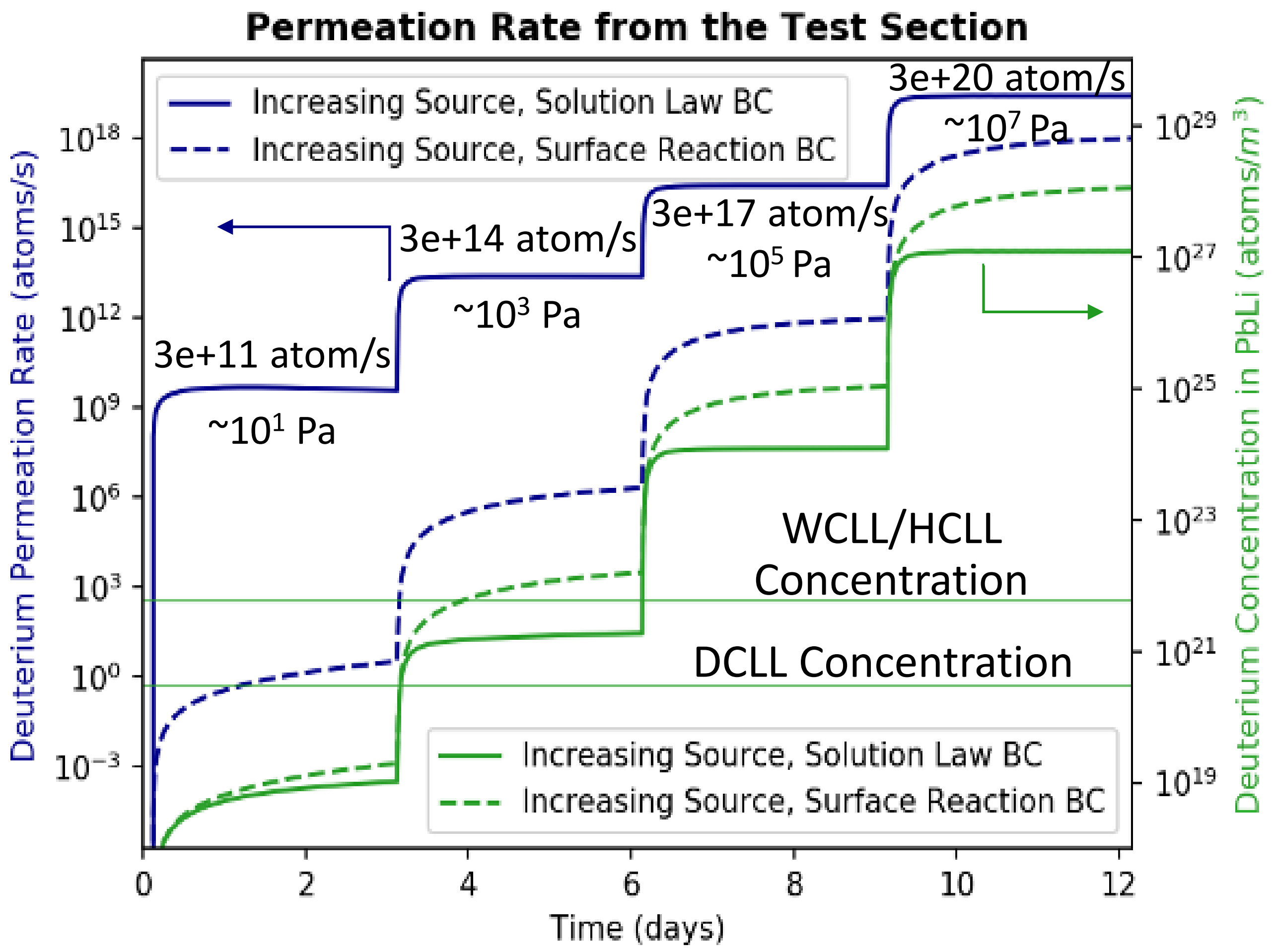
- Source rate was ramped up between 3e+11 to 3e+20 atom/s for 3 days at a time
- Simulations show permeation rate from test section are highly sensitive to source rates
  - Surface reaction rates matter less (converge) as the deuterium concentration in PbLi increases (departing from surface-limited regime)



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Summary of Sensitivity Simulations

- Simulations show permeation rate from test section are less sensitive to range of PbLi solubilities & highly sensitive to permeator recombination and source rates

Conclusions

- TEX is designed to test the effectiveness and various component designs for a vacuum permeator extraction system
- Modeling of TEX using MELCOR-TMAP provides insights into dependence of hydrogen permeation based on material properties & other operation parameters
- Continued testing & modeling of system parameters will provide further understanding of extraction efficiency & safety of TEX for operation using tritium

Future Work

- 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 Colorado School of Mines
- Include MELCOR-TMAP model for transfer of hydrogen from PbLi in the plenum to the vapor phase

Questions?