Tritium migration predictions and pathways in the fusion core

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Quantities of Tritium in Fusion Devices

- Fusion reactors consume tritium at rate of 152 g/GW-d, and must breed it the same rate or higher
- This is about 10^3x the rate of production in a MSR, 10^6x of a LWR
- The plasma burns only a small fraction each pass, so fueling rate must be 20-200x larger
- Future reactors will produce tritium in a breeding blanket at the same rate it is consumed or higher to fuel other devices
- Safety concerns include:
  - Permeation of tritium through high temperature blanket and HX structures (pipes, vessel walls, etc.)
  - Large tritium inventories in components

Safety requires that tritium releases must be kept low

- DOE standard limits on routine airborne and liquid releases:
  - National Emission Standards for Hazardous Air Pollutants (40 CFR 61): 0.1 mSv/yr (10 mrem/yr)
  - National Primary Drinking Water Regulations (40 CFR 141.16): 0.04 mSv/yr (4 mrem/yr)
  - All sources (10 CFR 20.1301): 1 mSv/yr (100 mrem/yr)

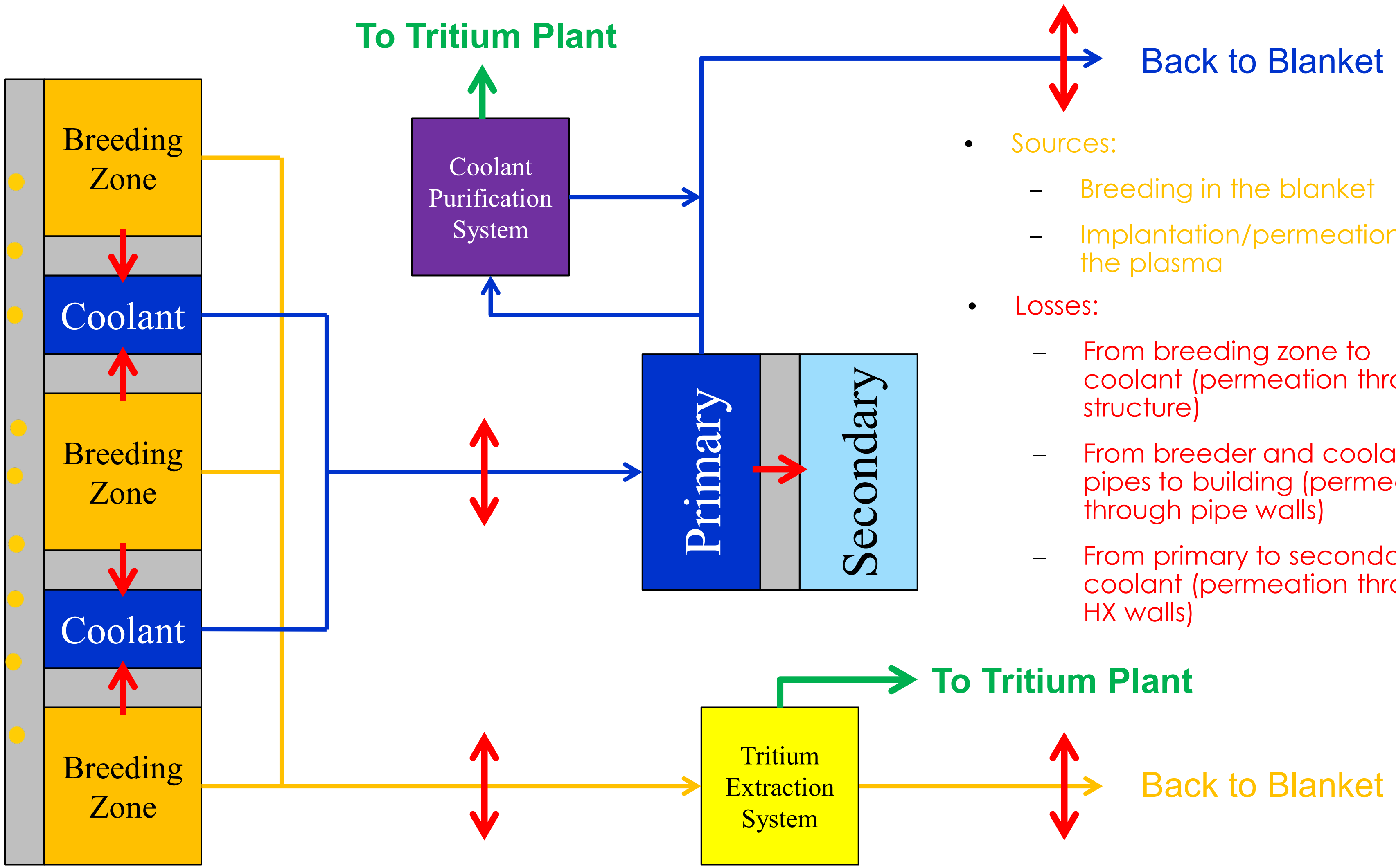
TABLE 1. Requirements for protection of the public from exposure to radiation[a]

	Fusion radiological release requirement	Regulatory limit (evaluation guideline)
Normal and anticipated operational occurrences	0.1 mSv/yr (10 mrem/yr)	1 mSv/yr (100 mrem/yr)
Off-normal conditions (per event)	10 mSv (1 rem) (No public evacuation)	250 mSv (25 rem)

- Dose conversion for stack releases depends on site characteristics, but for generic site considered for FNSF analysis, 0.1 mSv/yr (10 mrem/yr) -> 0.29 g T/yr
  - 0.29 g T/yr = 10^{-5} FNSF fusion/breeding rate

[1]DOE-STD-6002-96, "Safety of Magnetic Fusion Facilities: Requirements" https://www.standards.doe.gov/standards-documents/6000/6002-astd-1996
[2]P. W. Humrickhouse, *Fus. Eng. Des.* **135** (2018) 302-313; https://doi.org/10.1016/j.fusengdes.2017.04.099

Tritium flows and loss paths

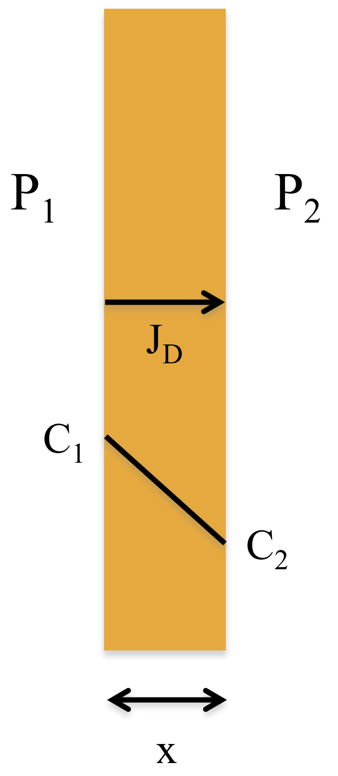


- Sources:
  - Breeding in the blanket
  - Implantation/permeation from the plasma
- Losses:
  - From breeding zone to coolant (permeation through structure)
  - From breeder and coolant pipes to building (permeation through pipe walls)
  - From primary to secondary coolant (permeation through HX walls)

Safety analyses seek to quantify the rate of tritium loss through all systems, in both normal and off-normal operating scenarios

The Tritium Migration and Permeation (TMAP) code was originally developed at INL for this purpose

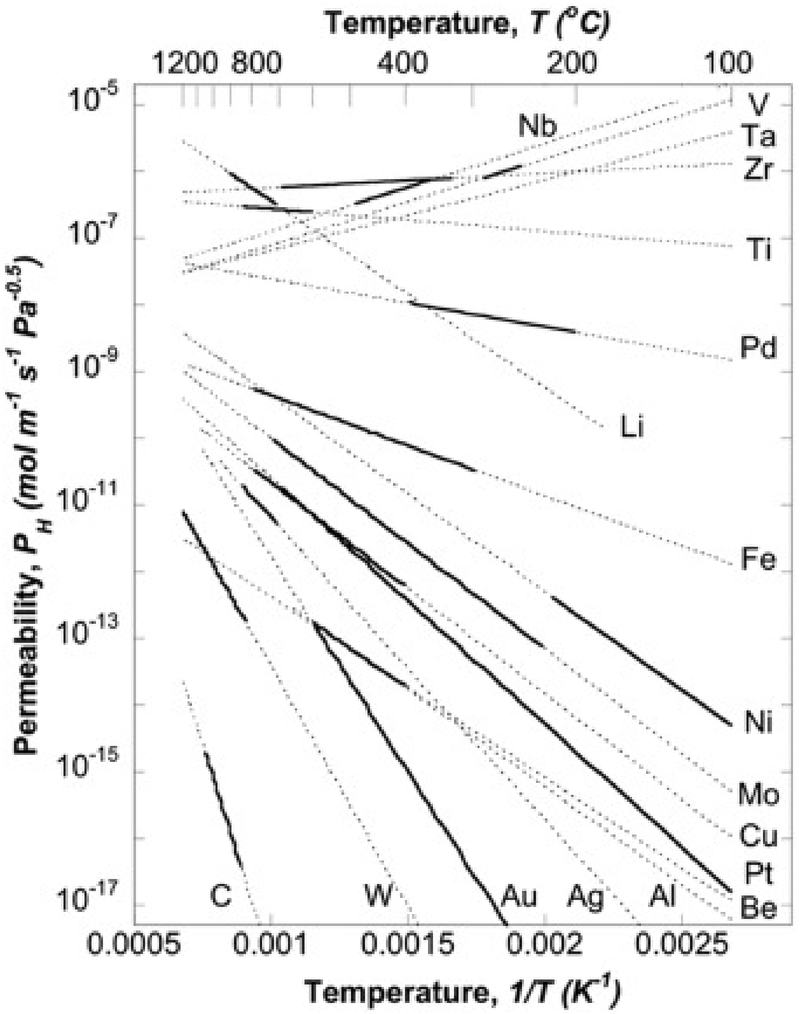
Diffusion/Permeation



- The fundamental driver of tritium migration is its ability to diffuse through metals, with permeation flux $J = -D(\partial C/\partial x)$
- At moderate to high pressures, the partial pressure and solid concentration at gas/solid interfaces are related by Sieverts' Law: $C_i = K_S\sqrt{P_i}$
- The resultant "permeation" flux is given by

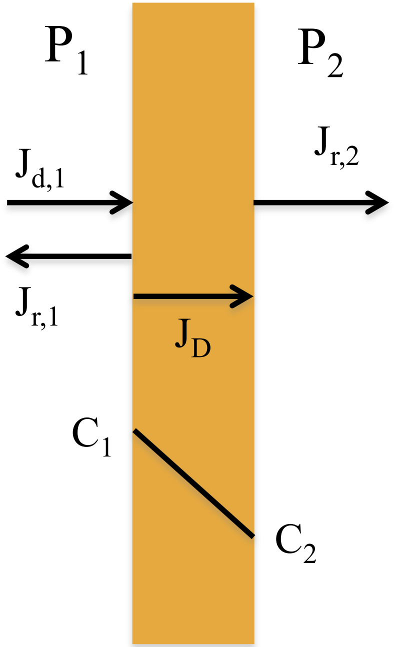
$$J = \frac{DK_S(C_1 - C_2)}{x}$$

- The constant of proportionality $\Phi = DK_S$ is the permeability



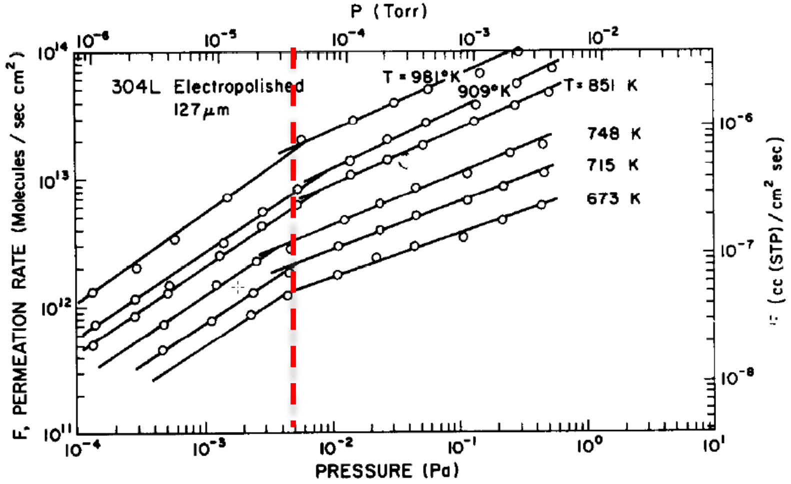
M. Shimada in *Comprehensive Nuclear Materials*
https://doi.org/10.1016/B978-0-12-803581-8.11754-0

Surface Phenomena

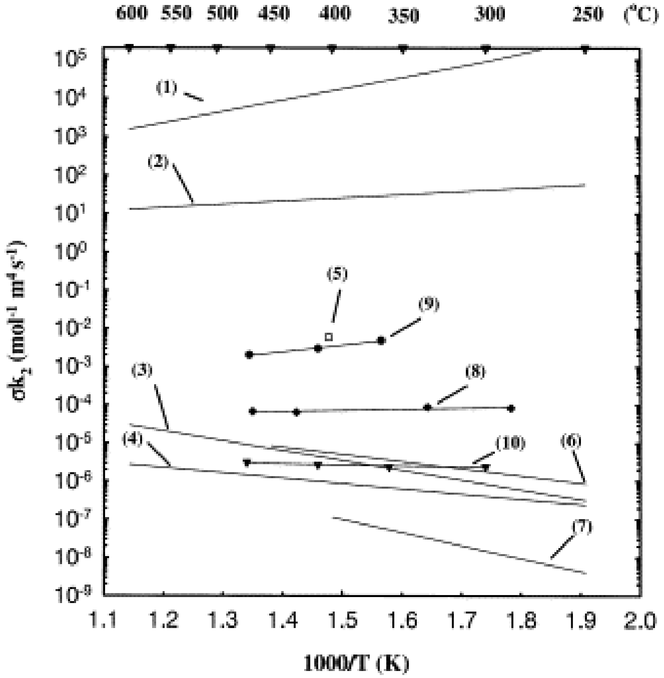


- A more general model is obtained by considering directional, competing *dissociation* and *recombination* fluxes: $J_1 = K_{d,1}P_1 - K_r C_1^2$
- In the limit in which they are equal ($W \gg 1$), Sieverts' Law is recovered (with $K_S = \sqrt{K_d/K_r}$)
- At low driving pressure ($W \ll 1$), surface effects are rate-limiting and $J = K_d P_1/2$
- $W = \frac{2K_d x\sqrt{P}}{DK_S}$ is a dimensionless permeation number*

Perkins and Noda *J. Nucl. Mater.* **71** (1978) 349-364. https://doi.org/10.1016/0022-3115(78)90435-X

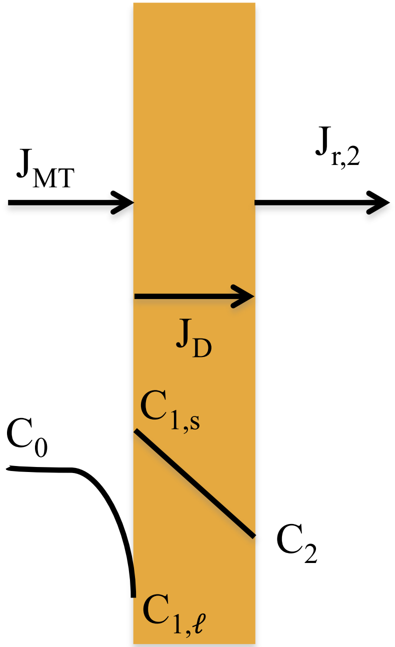


Serra & Perujo, *J. Nucl. Mater.* **240** (1997) 215-220. https://doi.org/10.1016/S0022-3115(96)00679-4



*I. Ali-Kahn et al., *J. Nucl. Mater.* **76/77** (1978) 337-343. https://doi.org/10.1016/0022-3115(78)90167-8

Mass transport in liquids



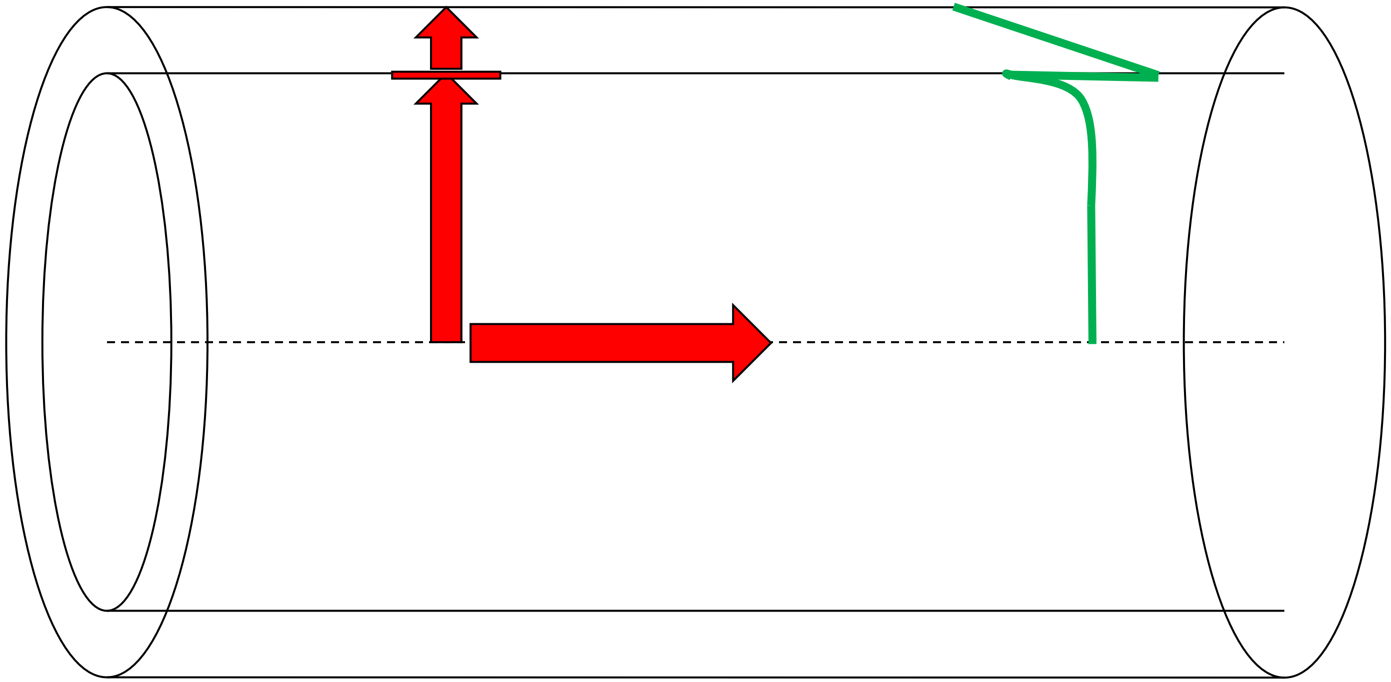
- Especially in liquids, convective mass transport processes may be important or rate-limiting

$$J_{MT} = K_T\left(C_0 - C_{1,\ell}\right)$$

- Mass transport coefficients may be obtained from turbulent diffusion models (e.g. in CFD/MHD analyses)
- Or from suitable empirical correlations for the Sherwood number, $Sh = xK_T/D$
  - Analogue of the Nusselt number
- E.g., $Sh = \beta Re^a Sc^b$ where Sc is the Schmidt number (Prandtl number analogue): $Sc = \mu/\rho D$

Combined transport phenomena: permeation from a pipe

- Transport processes:
  - Axial convection
  - Radial mass transport
  - Interface condition (solubility ratio or Sieverts' law)
  - Diffusion through (high permeability) tube wall



Rate-limiting phenomena

- All transport phenomena can be modeled using computer codes, but some systems have a clear rate-limiting effect
- Can be understood through dimensionless numbers like the permeation number:

$$W = \frac{2K_d x\sqrt{P}}{DK_S} \approx \frac{\text{Diffusion resistance}}{\text{Surface resistance}}$$

- Others[1,2] can be formulated:

$$\zeta = \frac{DK_{S,s}}{K_T K_{S,\ell} x} \approx \frac{\text{Mass transport resistance}}{\text{Diffusion resistance}}$$

$$\frac{K_d RT}{K_T} \approx \frac{\text{Mass transport resistance}}{\text{Surface resistance}}$$

- These are ratios of transport resistances, analogous to the Biot number in heat transfer

[1]P. W. Humrickhouse, *Fus. Sci. Technol.* **68:2** (2015) 295-302; https://doi.org/10.13182/FST14-941
[2]P. W. Humrickhouse, INL/EXT-20-59927, https://www.osti.gov/biblio/1777267

Trapping

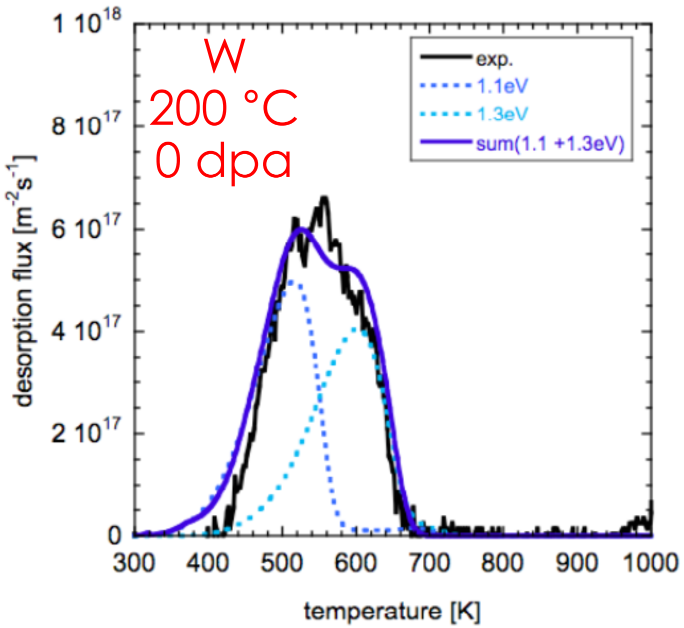
- Tritium is subject to ***trapping*** at defect sites in structural materials
- The density of trap sites increases with radiation damage; irradiation increases the density of higher energy traps

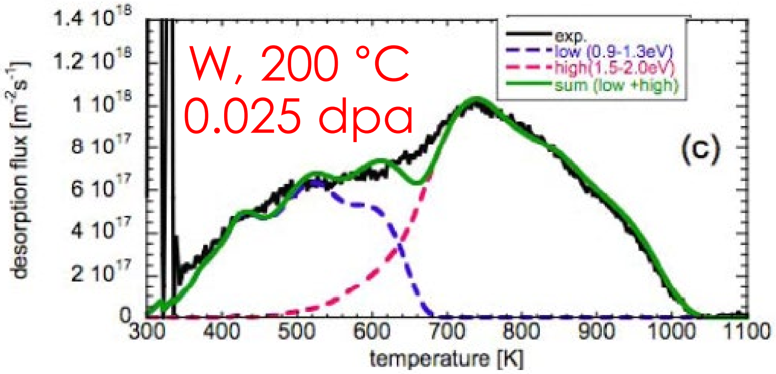
$$\frac{\partial C_t}{\partial t} = \alpha_t f_t C_m - \alpha_r C_t$$

C_t – Trapped concentration (m^{-3})
α_t – Trapping rate coefficient (s^{-1})
f_t – Probability of landing in a trap site (-)
C_m – Mobile concentration (m^{-3})
α_r – Release rate coefficient (s^{-1})

$$\alpha_t = \frac{D}{\lambda^2}\,;\; f_t = \frac{c_t^o - C_t}{N}\,;\; \alpha_r = \nu_o \exp\left(-\frac{E_t}{kT}\right)$$

D – Tritium diffusion coefficient (m^2-s^{-1})
λ – jump distance or lattice constant (m)
c_t^o – Trap site concentration (m^{-3})
N – Bulk material atom density (m^{-3})
ν_o – Debye frequency (s^{-1})
E_t – Trap energy (eV)

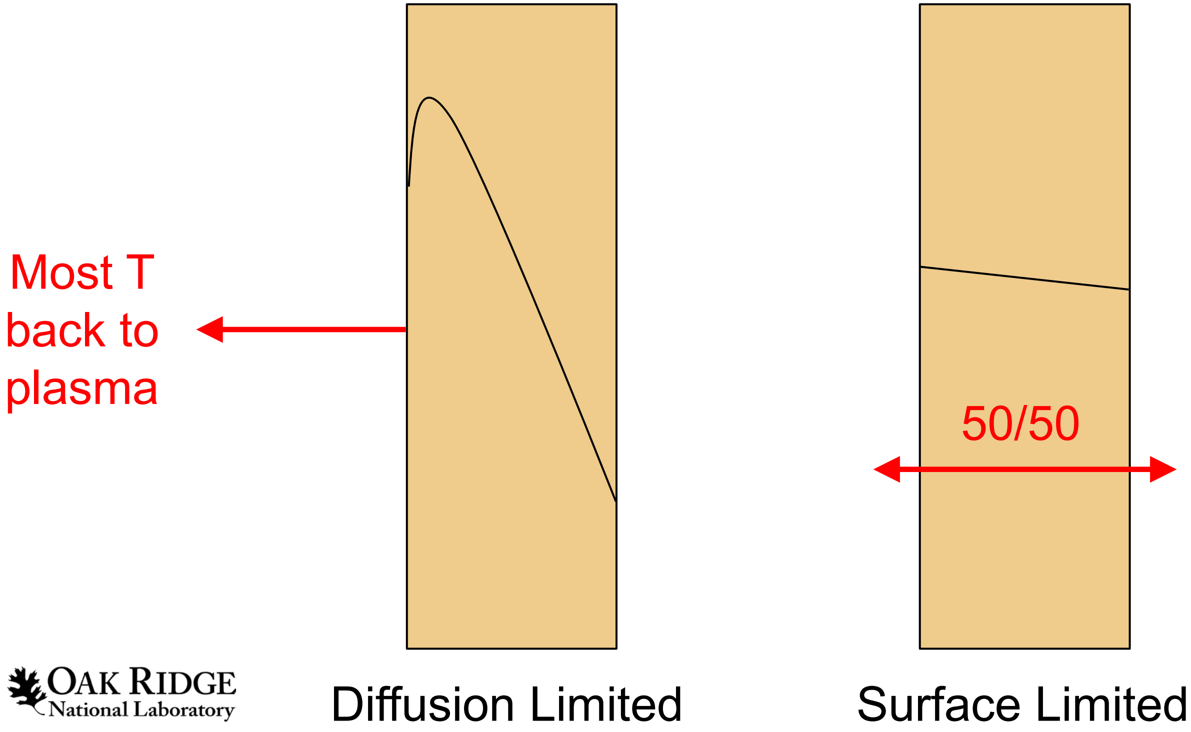




M. Shimada, *Phys. Scr. T.* **T145** (2011) 014051.
https://doi.org/10.1088/0031-8949/2011/T145/014051

Tritium transport through the first wall

- Tritium incident on the FW/divertor with flux ϕ will be implanted some depth x_0 into the material
- It may then:
  - Diffuse (a very short distance) back to the FW surface
  - Diffuse (a much longer distance) through the FW to He coolant



- In surface-limited case, up to 50% of implanted tritium permeates through FW into coolant

$$\frac{x_0\sqrt{\phi K_r}}{D} \ll 1$$

B. L. Doyle *J. Nucl. Mat.* **111-112** (1982) 628-635.
https://doi.org/10.1016/0022-3115(82)90277-X

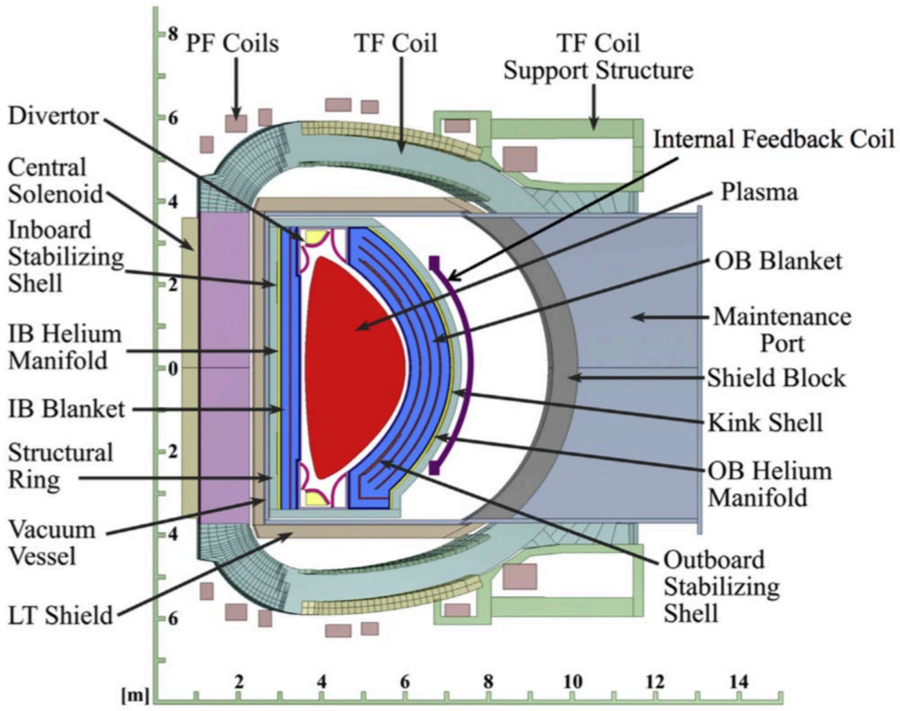
Estimates of FW plasma-driven permeation

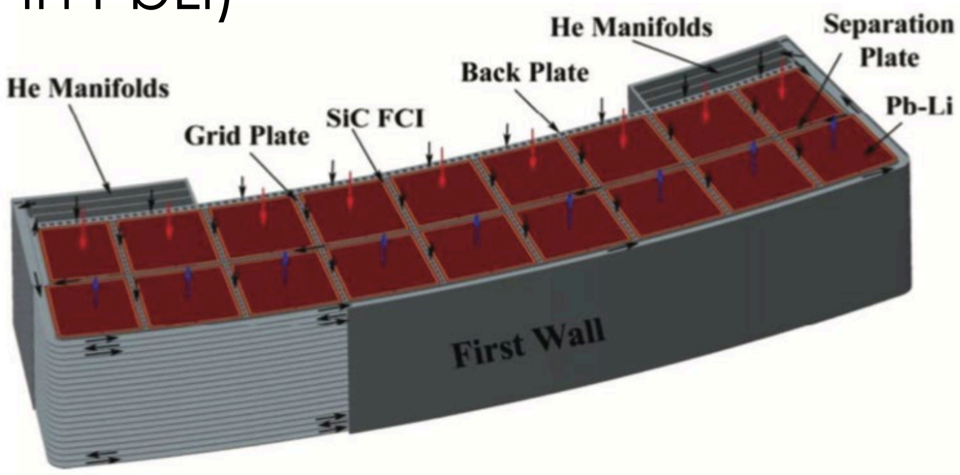
Reference	Design	Permeation rate	Notes
Wienhold, *J. Nucl. Mater.* **93-94** (1980) 866-870. https://doi.org/10.1016/0022-3115(80)90220-2	INTOR	4.5 g/day	Wall temp 600 °C
Baskes, *J. Nucl. Mater.* **111-112** (1982) 663-666. https://doi.org/10.1016/0022-3115(82)90286-0	INTOR	0.005 – 8.8 g/day	Wall temps from 200 – 500 °C
Brice, *J. Nucl. Mater.* **120** (1984) 230-244. https://doi.org/10.1016/0022-3115(84)90061-8	INTOR	0.011 – 0.039 g/day	Wall temp 100 °C at back; dT from 0 – 300 °C
Pisarev, Sov. Atom. Energy 62:2 (1987) 87-93. https://doi.org/10.1007/BF01123660	INTOR	10^{-6} – 2 g/day	Diffusion & recombination coefficient uncertainties
Ogorodnikova, *Fusion Eng. Des.* **49-50** (2000) 921-926. https://doi.org/10.1016/S0920-3796(00)00339-2	EU DEMO	$2x10^{-5}$ – 81 g/day	Strongly influenced by surface condition
Huang, *Fusion Eng. Des.* **152** (2020) 111430. https://doi.org/10.1016/j.fusengdes.2019.111430	CFETR	0.35 – 3.15 g/day	Fusion power 0.2 – 1.5 GW
Arredondo, Nucl. Mater. Energy 28 (2021) 101039. https://doi.org/10.1016/j.nme.2021.101039	EU DEMO	0 – 0.16 – 6.6 g/day	W armor thickness and many other parameters varied

- In the FNSF study, plasma-driven permeation increased FW inventories by ~20%, but did not significantly influence circulating tritium

Tritium transport analysis of the FNSF

- The Fusion Nuclear Science Facility (FNSF) is a 518 MW US design featuring a DCLL blanket
- Tritium permeation and the influence of design features was systematically analyzed
- The base design had tritium permeation losses of **6.18 g/yr**, larger than **0.29 g/yr** target
  - Partly a result of conservative parameter choices (e.g. lowest measured T solubility in PbLi)
    - More optimistic choices (within measured ranges) give as low as 0.05 g/yr
  - Driven primarily by PbLi pipe losses
- Quantitative effect of design features systematically evaluated…





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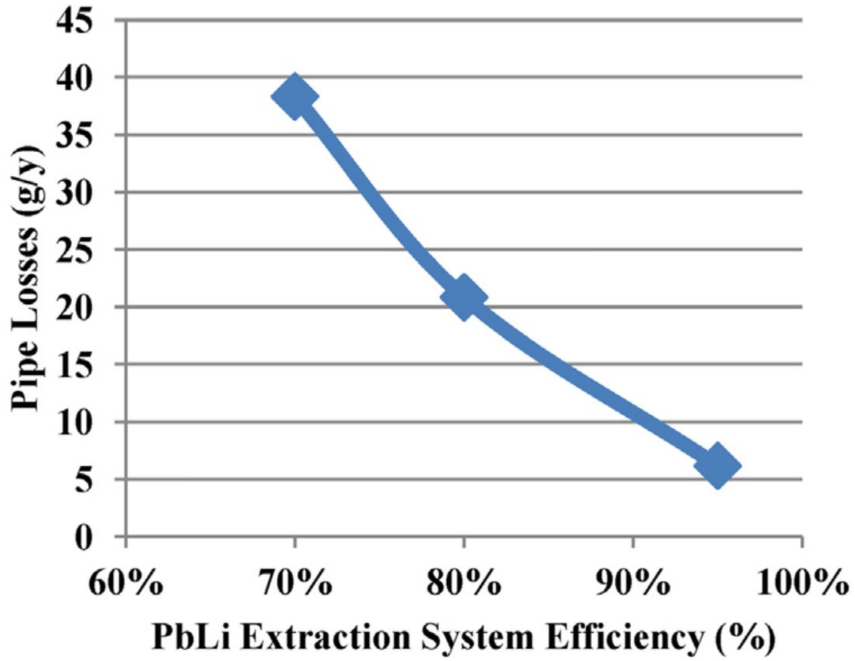
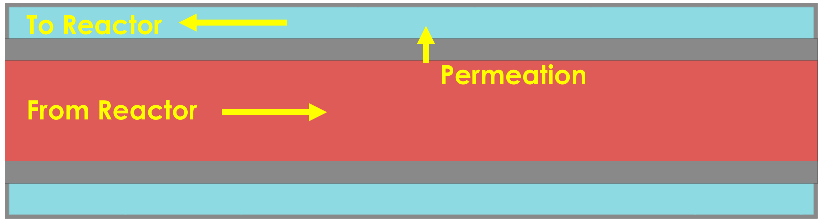
P. W. Humrickhouse, *Fus. Eng. Des.* **135** (2018) 302-313; https://doi.org/10.1016/j.fusengdes.2017.04.099

Tritium transport analysis of the FNSF (cont'd)

- Significant design features and impacts:
  - DCLL Blanket
    - High flow rates reduce residence times
    - SiC flow channel inserts act as a permeation barrier
  - High efficiency (95%) vacuum permeator for T extraction from PbLi
    - A relatively compact design based on tantalum permeator tubes (764 ,15m long) provided, but needs engineering demonstration
    - Permeation increases significantly as efficiency is reduced
  - Concentric hot/cold leg piping
    - Single most effective mitigation!
    - Permeation increases to 115 g/yr without it



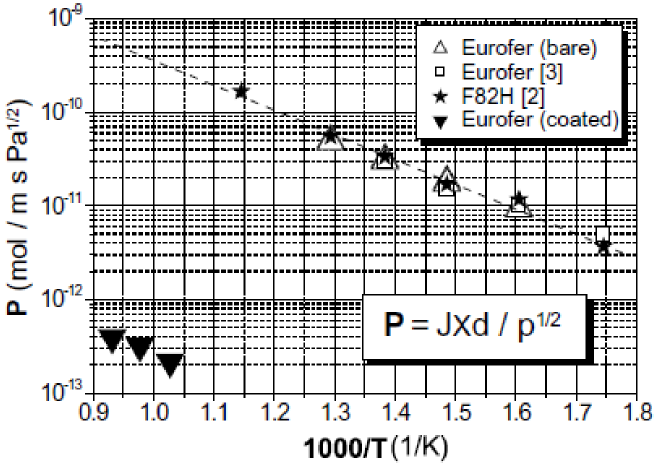


P. W. Humrickhouse, *Fus. Eng. Des.* **135** (2018) 302-313; https://doi.org/10.1016/j.fusengdes.2017.04.099

Permeation barrier coatings

- The FNSF design did not take credit for any permeation barriers
- Ceramic (e.g. Al_2O_3, Er_2O_3) coatings have shown significant promise in laboratory settings, but significantly degraded performance in reactor environments
- The reasons are not completely understood, but may result from a combination of:
  - Degradation of the coating (e.g. cracks)[1]
  - Radiation-enhanced diffusion[2]
  - Radiation damage to microstructure[3]
- Remains an ongoing area of research

D. Levchuck, *J. Nucl. Mater.* **328** (2004) 103.
https://doi.org/10.1016/j.jnucmat.2004.03.008



Irradiation testing of tritium/hydrogen barriers

Test	Barrier system[a]	Effective PRF
LIBRETTO-2	Alum/316L	<80
LIBRETTO-3	316L/TiC	3
	Al_2O_3/316L	3
	316L/alum/Al_2O_3	15
TREXMAN	Cr_2O_3/SS316	10
	SS316/Cr_2O_3	100
Loop-1	Alum/SS316/alum	150
WC-1	Alum/SS316/alum	150

G. W. Hollenberg, *Fus. Eng. Des.* **28** (1995) 190.
https://doi.org/10.1016/0920-3796(95)90039-X

[1]R. Causey, in *Comprehensive Nuclear Materials*, 2012.
[2]W. Luscher, J. Nucl. Mater. **437** (2013) 373.
[3]X.-D. Pan, Nucl. Fusion 61 (2021) 036004.

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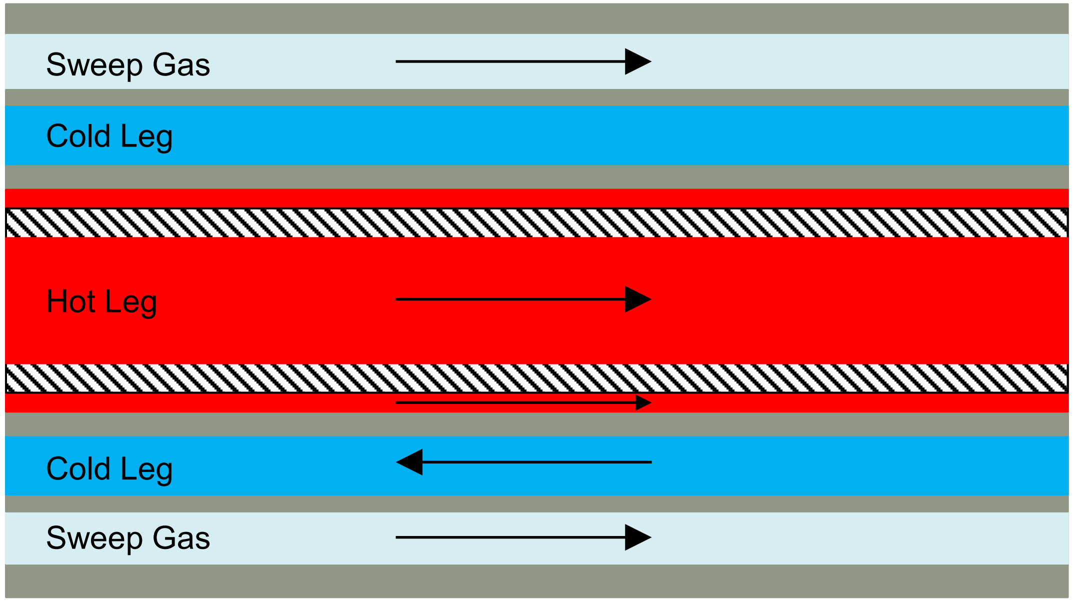
Guard pipes

- Permeation barriers may be effective in less demanding environments that target permeation loss paths, e.g. on the outside of ex-vessel piping
- Other engineered barriers may be effective here as well
- In the FNSF design, guard pipes swept with low pressure He significantly reduced permeation with no significant heat loss

He purge velocity (m/s)	Outer pipe temp (C)	Inner pipe temp (C)	Heat loss (W)	Tritium loss (g/y)
N/A	-	417	-	4.21
0.1	94	416	65	0.014
1.0	353	414	2,083	1.19
10.0	350	414	21,350	0.58



Summary

- Tritium is highly mobile in high-temperature systems and this migration poses a significant safety & environmental issue for future fusion reactors
- Solution, diffusion, surface effects, mass transport, and trapping all play a role in tritium transport predictions
  - Parameter uncertainties are a significant hindrance to predictive models
  - Integral test data needed for validation
- Inner (plasma/exhaust) and outer (blanket) tritium loops couple at plasma facing surfaces
  - Implantation models predict widely variable permeation rates through the FW; this topic is worthy of additional experimental scrutiny
- Permeation barriers are needed to help limit tritium permeation