THE OHIO STATE UNIVERSITY

Georgia Tech

Tritium Management in FHRs

Ongoing and Planned Activities in Integrated Research Project Led by Georgia Tech

Workshop on Tritium Control and Capture in Salt-Cooled Fission and Fusion Reactors: Experiments, Models and Benchmarking

Timothy Flaspoehler and Bojan Petrovic
Georgia Tech

Xiao Wu, Sheng Zhang, Richard Christensen, and Xiaodong Sun
The Ohio State University

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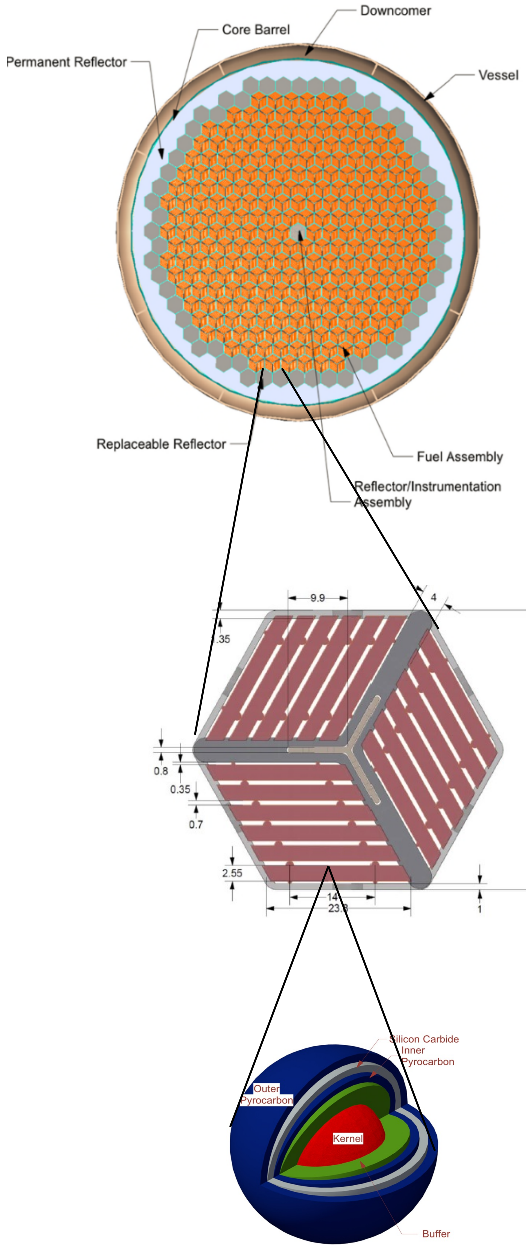
Outline

- Tritium Source Generation
  - Planned for Georgia Tech
- Design, Testing, Demonstration, and Modeling of Heat Exchangers for FHRs
  - Ongoing at Ohio State University
  - Heat Exchanger Design
  - Tritium Permeation Barrier Coating
- Tritium Control/Mitigation Strategy for FHRs
  - Redox Control Facility
  - Tritium Removal Facility
  - Planned Experiments

Tritium Source Generation

- INTRODUCTION
- Georgia Tech: Timothy Flaspoehler
  - Advisor (Bojan Petrovic)
- Use neutron transport to calculate accurate tritium source in FHR
  - Full-core
  - Time-dependent
- Funding doesn't start till 2nd fiscal year

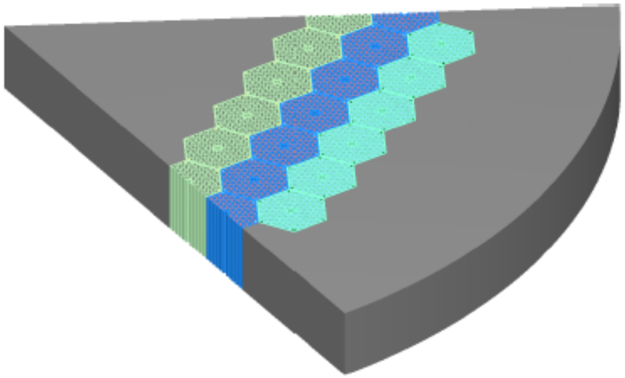
Pathway	MT #	Scale6.1
Ternary Fission	18 (x%yield)	YES
$^{6}\text{Li}\ (n, \alpha)\ ^{3}\text{H}$ or	107	NO
$^{6}\text{Li}\ (n, t)\ ^{4}\text{He}$	105	YES
$^{7}\text{Li}\ (n, n\alpha)\ ^{3}\text{H}$ or	22 / 105	NO / NO
$^{7}\text{Li}\ (n, nt)\ ^{4}\text{He}$ or	33	NO
$^{7}\text{Li}\ (n, Xt)$		*YES
$^{10}\text{B}\ (n, 2\alpha)\ ^{3}\text{H}$ or	108	NO
$^{10}\text{B}\ (n, t2\alpha)$	113	YES
$^{10}\text{B}\ (n, \alpha)\ ^{7}\text{Li}\ (n, n\alpha)\ ^{3}\text{H}$	107 & 22	YES & NO

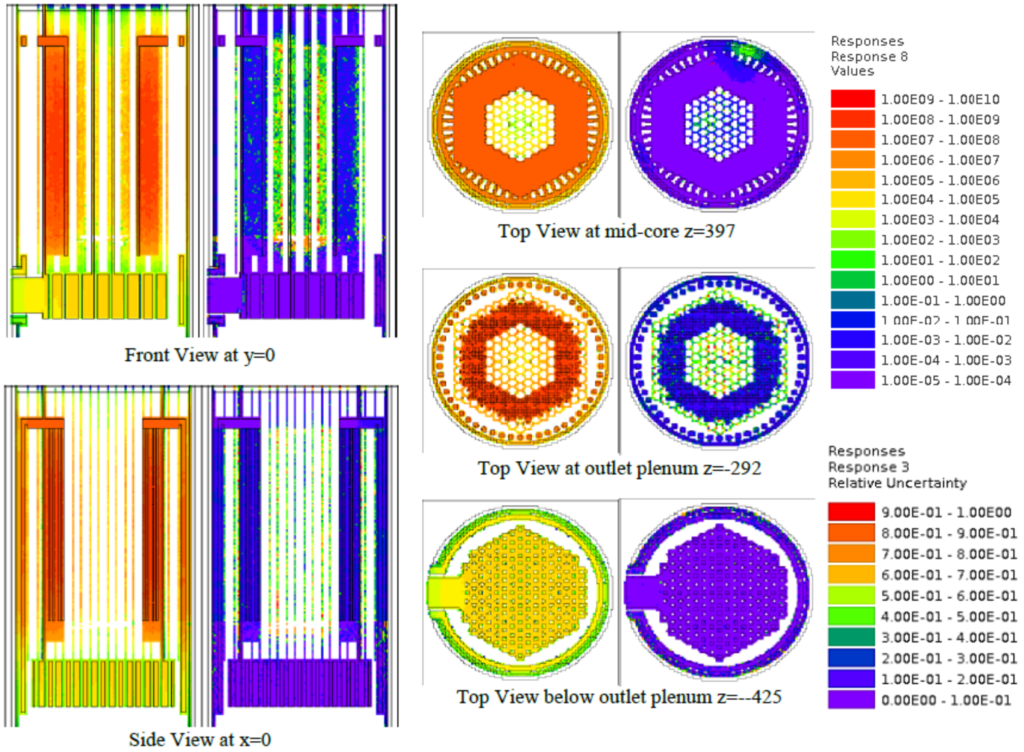


Tritium Source Generation

PREVIOUS WORK

- BACKGROUND: VHTR / NGNP goal to provide heat source for industrial applications
  - Also without NRC licensing secondary side
  - Tritium leakage to secondary must be below EPA limits
- RESULTS: Calculated different pathways in full-core model
  - Used MAVRIC shielding sequence
  - Globally converged MC tallies in reflector





Tritium production from ^{4}He impurities in coolant

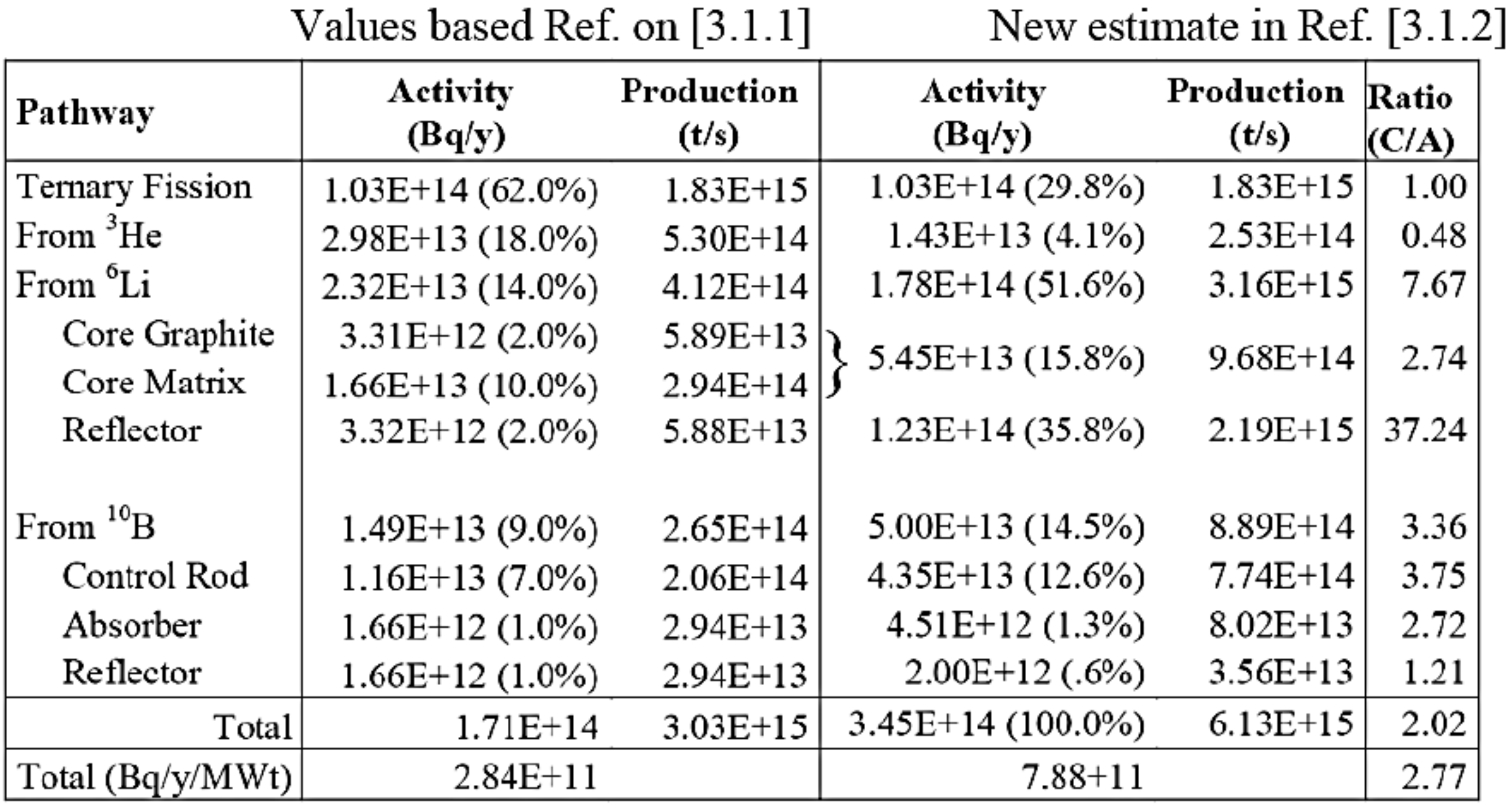
Georgia Tech

Tritium Source Generation

PREVIOUS WORK

- RESULTS: Possible underestimate of tritium source in VHTR from impurities in graphite reflector

Table 3.1.1 Comparison of tritium generation rates in VHTR estimated in [3.1.1] and [3.1.2]



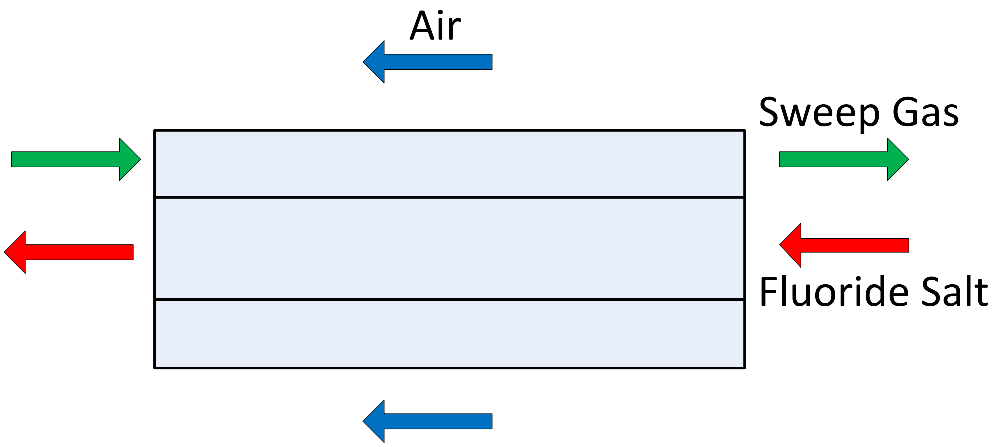
	Values based Ref. on [3.1.1]		New estimate in Ref. [3.1.2]		
Pathway	**Activity (Bq/y)**	**Production (t/s)**	**Activity (Bq/y)**	**Production (t/s)**	**Ratio (C/A)**
Ternary Fission	1.03E+14 (62.0%)	1.83E+15	1.03E+14 (29.8%)	1.83E+15	1.00
From ^{3}He	2.98E+13 (18.0%)	5.30E+14	1.43E+13 (4.1%)	2.53E+14	0.48
From ^{6}Li	2.32E+13 (14.0%)	4.12E+14	1.78E+14 (51.6%)	3.16E+15	7.67
Core Graphite	3.31E+12 (2.0%)	5.89E+13	5.45E+13 (15.8%)	9.68E+14	2.74
Core Matrix	1.66E+13 (10.0%)	2.94E+14			
Reflector	3.32E+12 (2.0%)	5.88E+13	1.23E+14 (35.8%)	2.19E+15	37.24
From ^{10}B	1.49E+13 (9.0%)	2.65E+14	5.00E+13 (14.5%)	8.89E+14	3.36
Control Rod	1.16E+13 (7.0%)	2.06E+14	4.35E+13 (12.6%)	7.74E+14	3.75
Absorber	1.66E+12 (1.0%)	2.94E+13	4.51E+12 (1.3%)	8.02E+13	2.72
Reflector	1.66E+12 (1.0%)	2.94E+13	2.00E+12 (.6%)	3.56E+13	1.21
Total	1.71E+14	3.03E+15	3.45E+14 (100.0%)	6.13E+15	2.02
Total (Bq/y/MWt)	2.84E+11		7.88+11		2.77

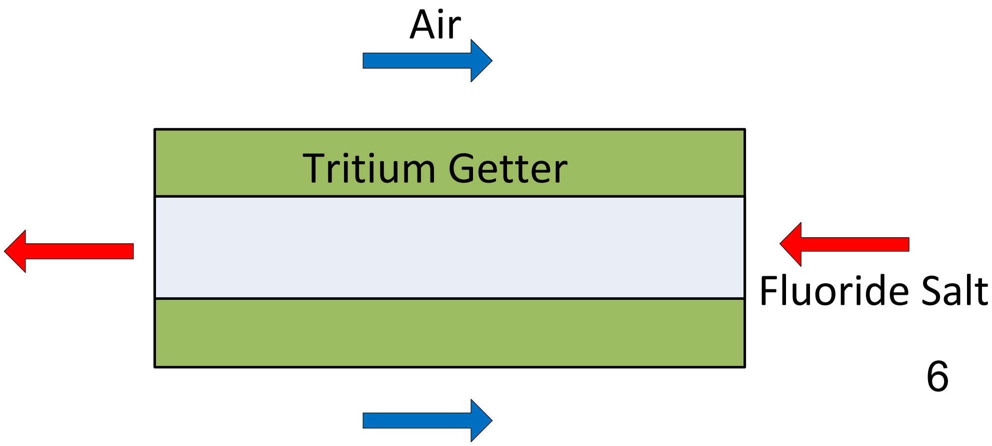
Design, Testing, Demonstration, and Modeling of HXs for FHRs

- Design of Heat Exchangers (IHX, SHX, DHX, and NDHX) for AHTR, considering Tritium Management and Heat Transfer Effectiveness
  - Goal: To reduce tritium diffusion into the secondary (cold) side while maintaining heat transfer rate
- Double-wall Heat Exchangers
  - Fluted tube heat exchanger
  - Printed circuit heat exchanger
- Tritium Permeation Barrier
  - Located between the outer tube and the inner tube walls
  - Fluoride salt (FLiNaK/FLiBe)
  - Sweep gas
  - Tritium getter

Heat Exchanger Design

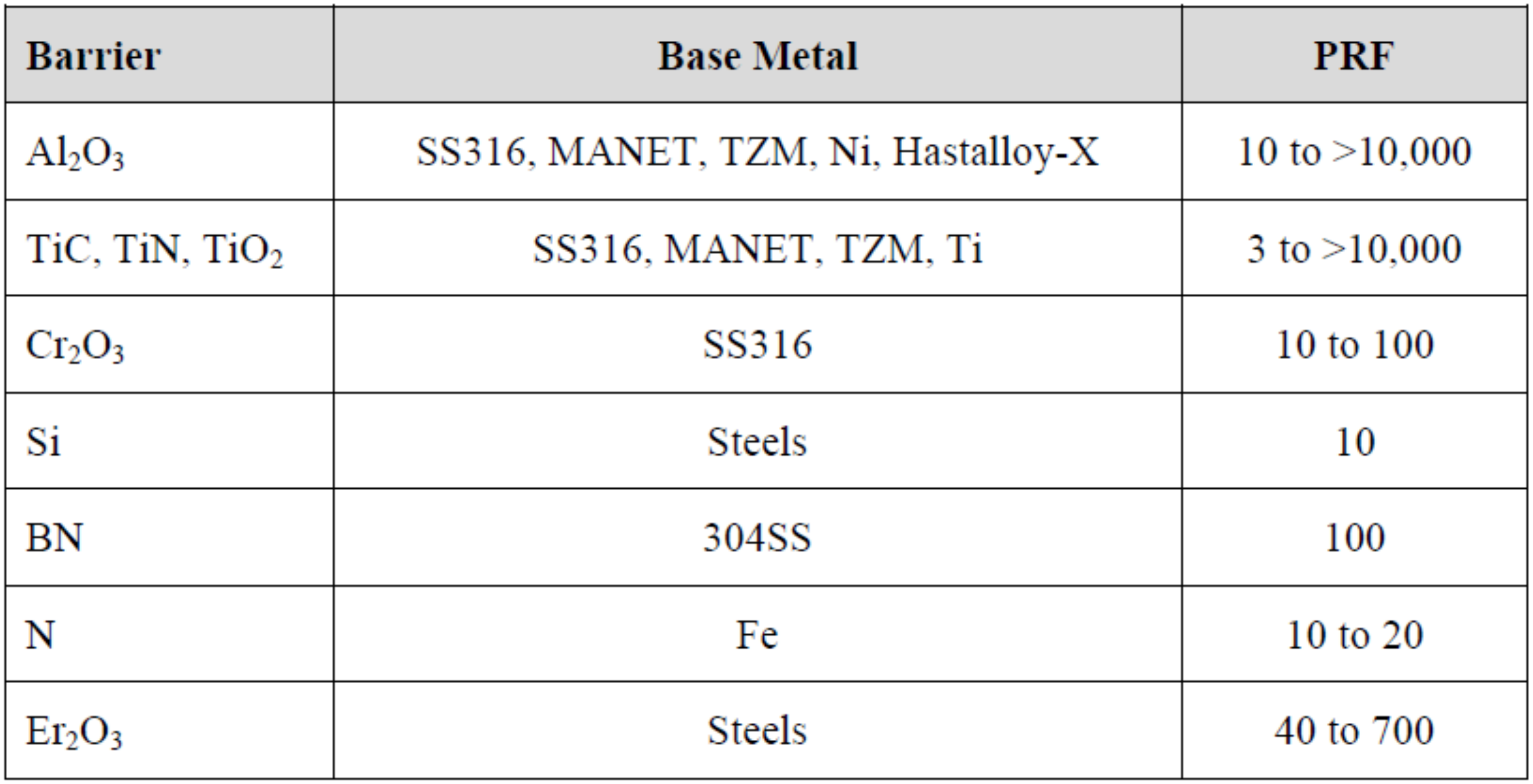
- Ongoing Activity for NDHX in DRACS: Two Preliminary Designs being Considered
  - Option 1: Double-wall NDHX with sweep gas in the annulus
    - Inner tube: Allow tritium permeation
    - Outer tube: Inhibit tritium permeation (with surface treatment if necessary)
    - Sweep gas: Pressurized helium
    - Tritium: Trapped in the gap and taken away by sweep gas
  - Option 2: Double-wall NDHX with tritium getter in the annulus
    - Gap/annulus filled with a tritium getter (yttrium) to sequester tritium





Tritium Permeation Barrier Coating

Surface Treatment: Tritium Permeation Barrier



Barrier	Base Metal	PRF
Al_2O_3	SS316, MANET, TZM, Ni, Hastalloy-X	10 to >10,000
TiC, TiN, TiO_2	SS316, MANET, TZM, Ti	3 to >10,000
Cr_2O_3	SS316	10 to 100
Si	Steels	10
BN	304SS	100
N	Fe	10 to 20
Er_2O_3	Steels	40 to 700

	Al_2O_3	Cr_2O_3-SiO_2	ZrO_2	MSZAC	W
Thickness [μm]	0.03-1.4	50	50	50-100	10
PRF	100-10^4	292	50	3-4	300
References	Levchuk (2004); Yang (2011); Forcey (1991); Forcey (1989)	Nakamichi (2007)	Nakamura (2010)	Nakamura (2010)	Moir (1984)

Low Tritium Permeability Metal

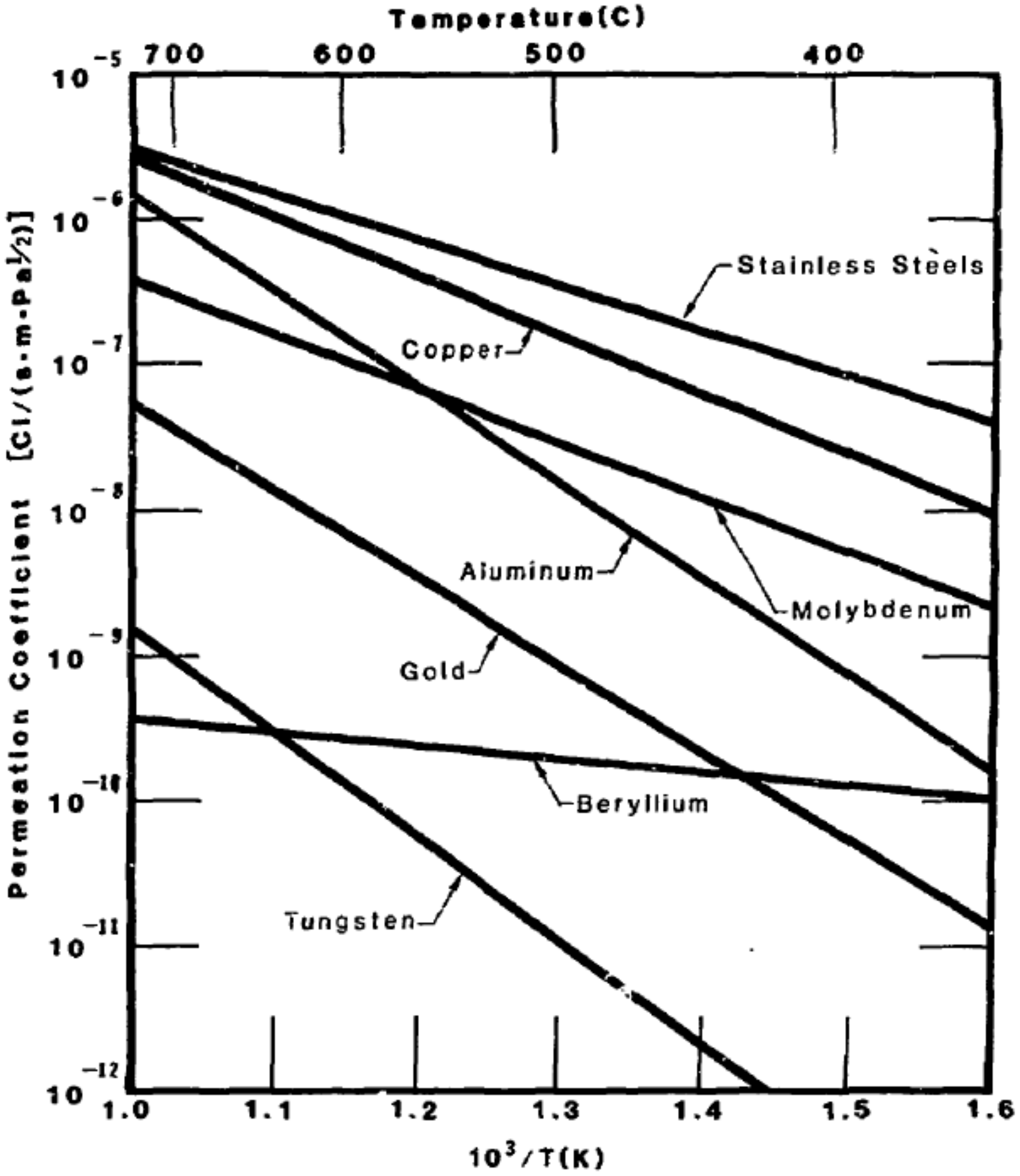


Figure 8.10-18

Permeation coefficient of tritium through metals.

Tritium Permeation Barrier Coating (Cont'd)

- Tritium Permeation Reduction Factor (PRF) of candidate coatings

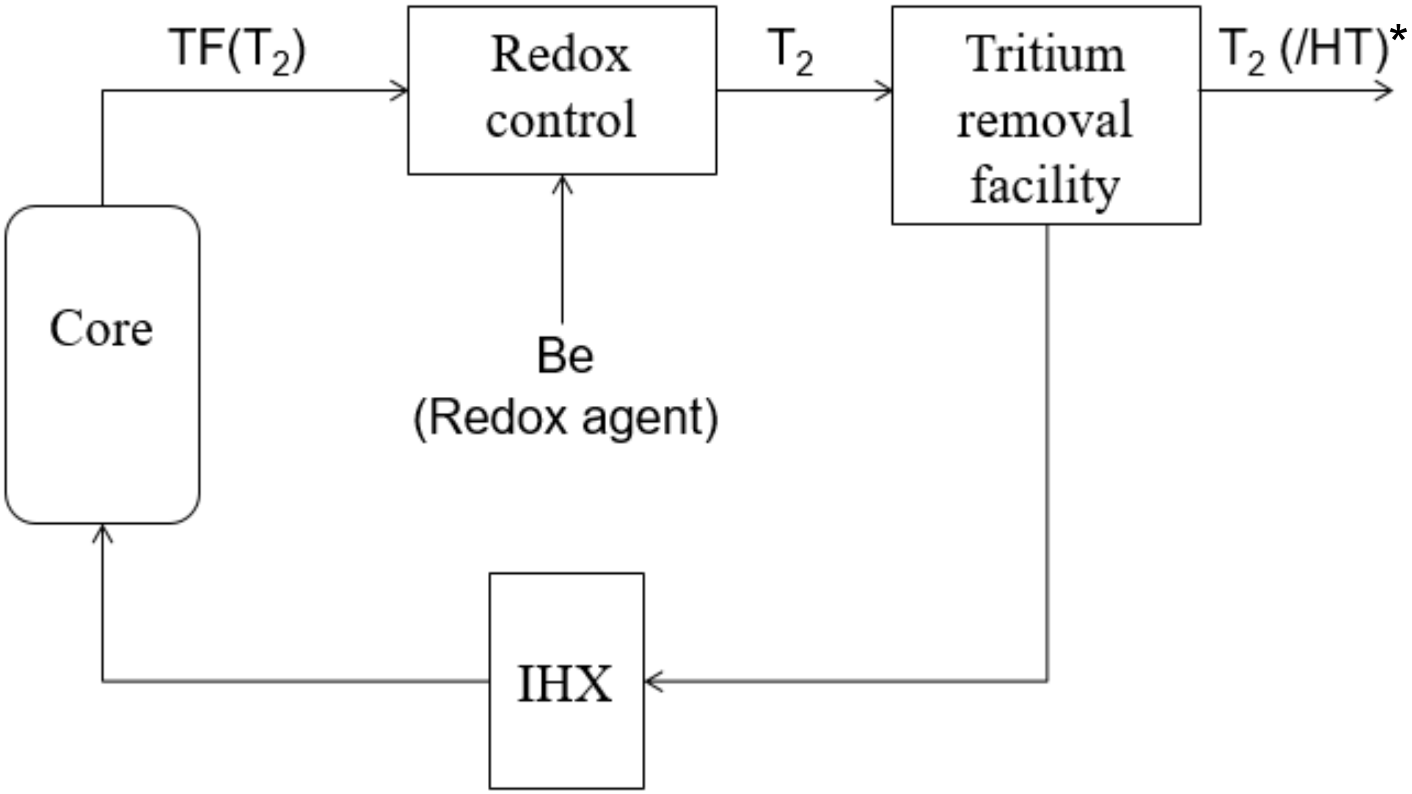
$$\mathrm{PRF}=\frac{\text{Permeation flux without coating}}{\text{Permeation flux with coating}}$$

- Al_2O_3 Coating Methods
  - Hot-dip aluminazation
  - Chemical vapor deposition (CVD)
  - Sol-gel
- Potential Issues with Al_2O_3 Coating
  - Integrity is crucial to the surface coating
  - Cracks can lead to significant decrease in the PRF

Tritium Control/Mitigation Strategy for FHRs

- Generation
  - Major form of tritium in the core: TF (corrosive)
- Redox Control
  - Beryllium metal is used to convert TF to T_2: $Be + 2TF \rightarrow T_2 + BeF_2$
- Tritium Removal Facility
  - Goal: Removal rate similar to the production rate
  - Cross-flow plate-type T_2 removal facility
- Tritium Permeation Barrier
  - FLiNaK/FLiBe could be used as the barrier in intermediate heat exchanger (IHX)
  - Tritium permeation barrier used as the outer wall coating in necessary areas

Schematic of Tritium Mitigation/ Control System for FHRs



Core

$TF(T_2)$

Redox control

Be
(Redox agent)

T_2

Tritium removal facility

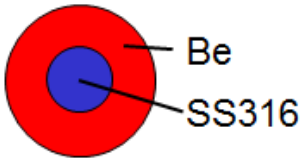
T_2 (/HT)*

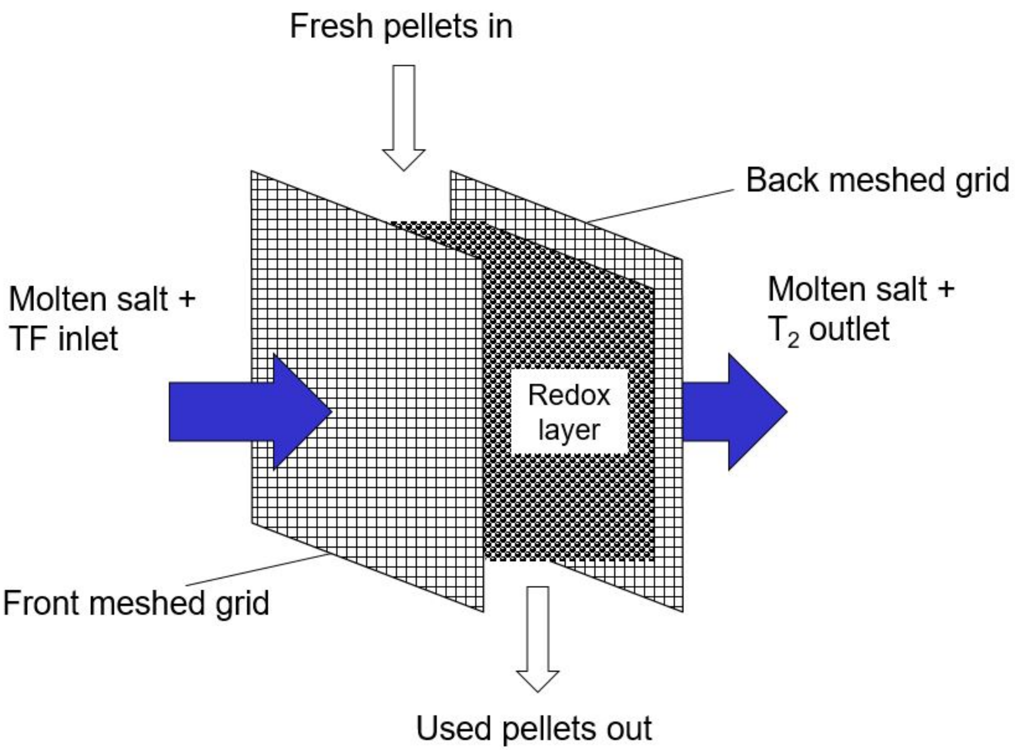
IHX

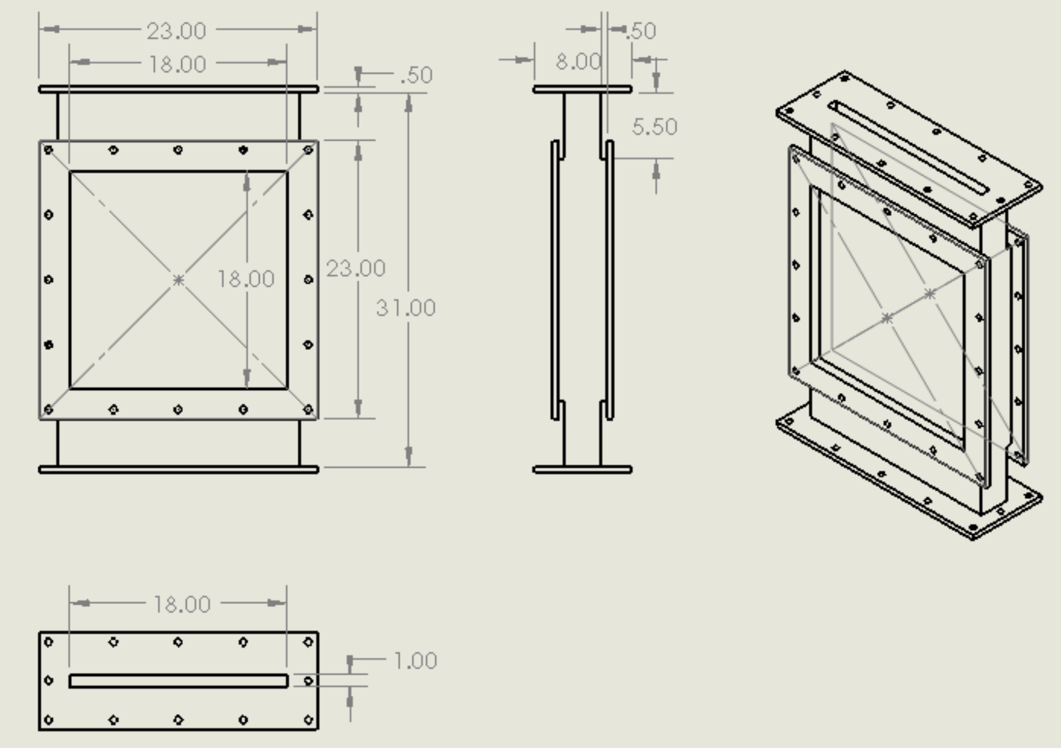
* :1. HT exists if H_2 is used in the purging gas
2. Studies have shown that by adding H_2 in the purging gas, T_2 removal efficiency can be improved

Redox Control Facility

- Easy Replenishment of Redox Pellets
- Modular Design
  - Located prior to the tritium removal module
- Pellet with SS316 Core
  - Beryllium pellets with a spherical SS316 core
  - To avoid used (smaller) pellets from being carried away by the salt with meshed grids

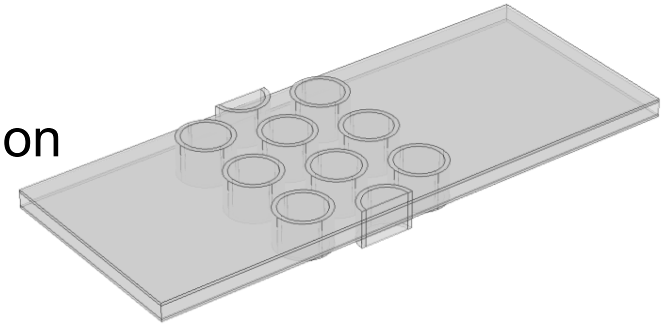




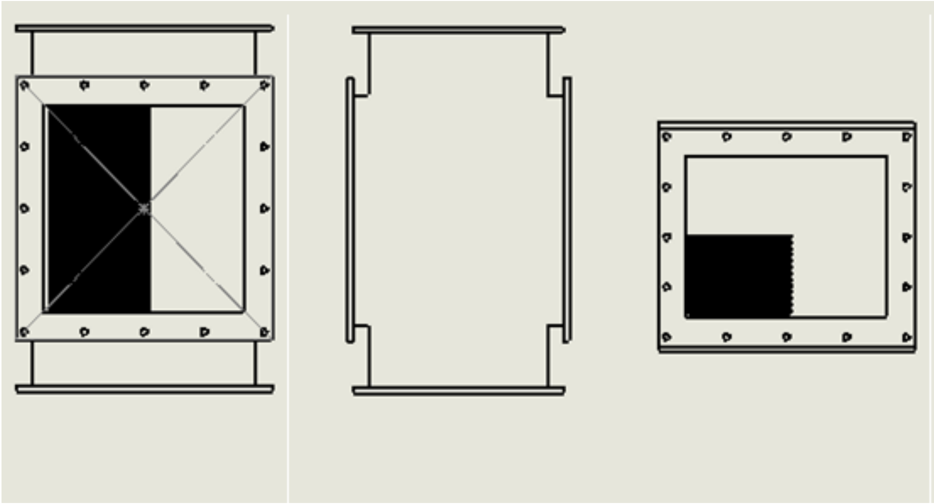


Tritium Removal Facility

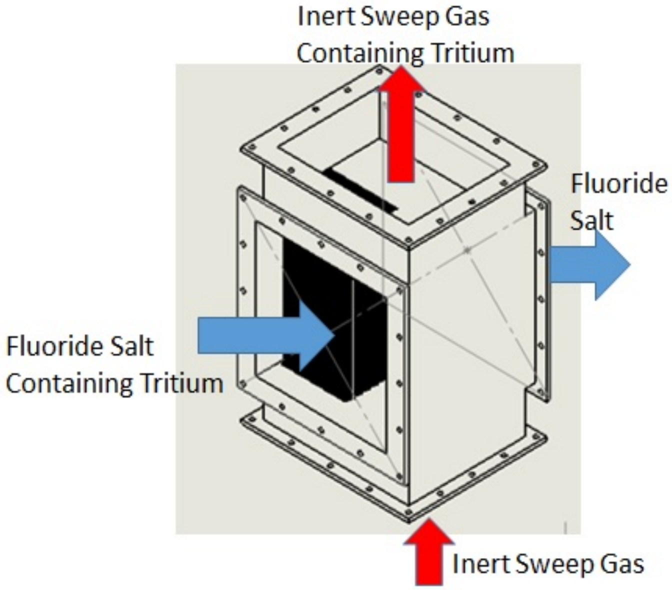
- Cross-flow Configuration
  - Purging gas flows in the tube bank
  - Molten salt flows in the perpendicular direction to the tube bank
  - Increase the salt flow turbulence level
- Modular Design
  - Located after the redox control facility
  - Flexibility for applications of different tritium removal rates



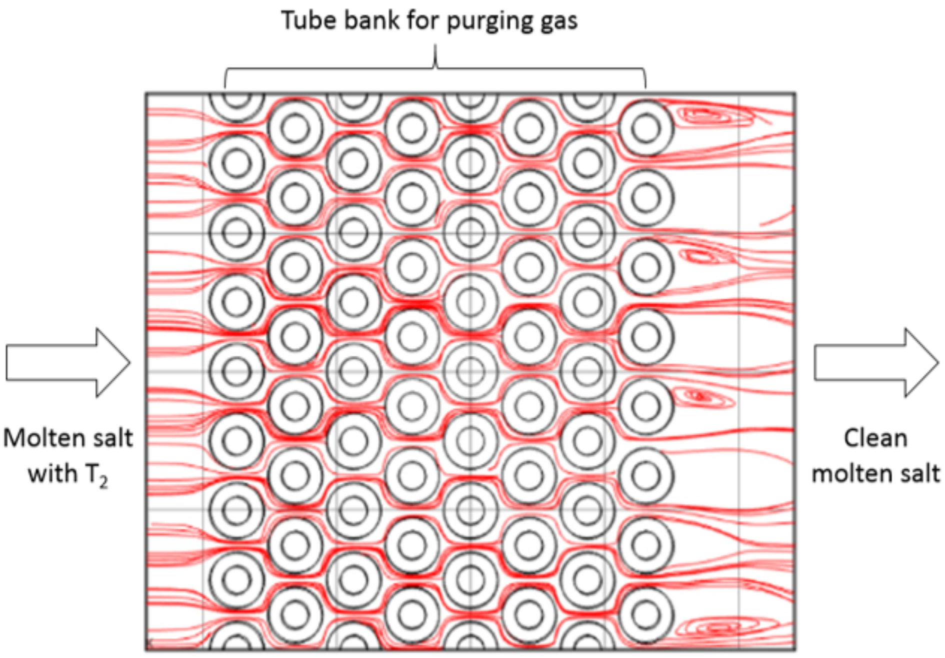
Cut view of a unit cell of the facility

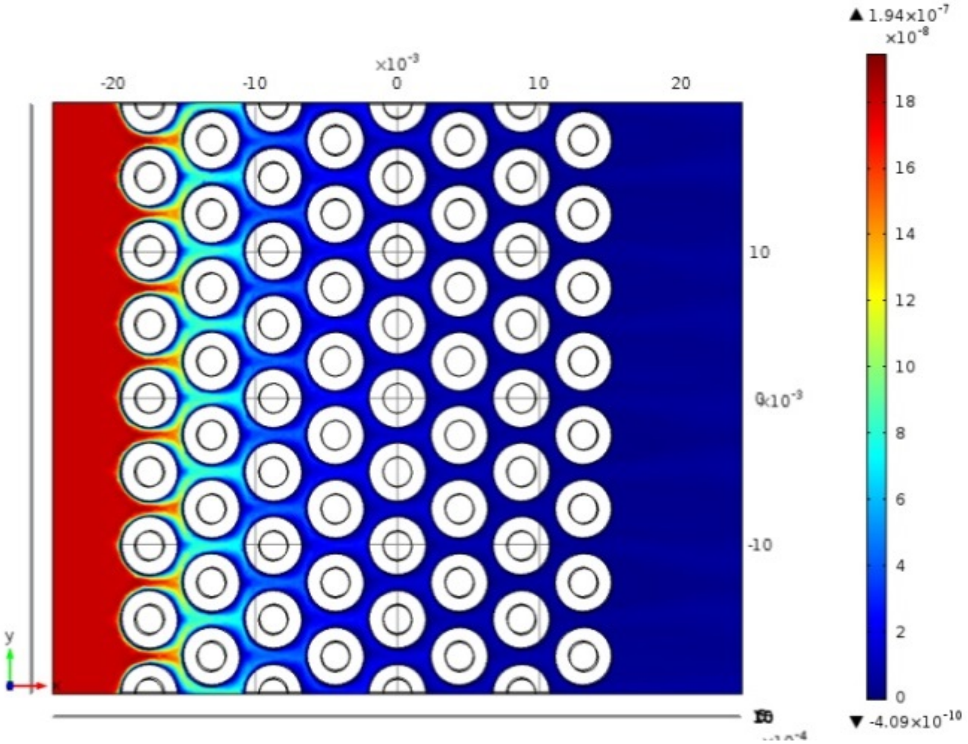


Front view Side view Top view



Computational Simulation Using COMSOL

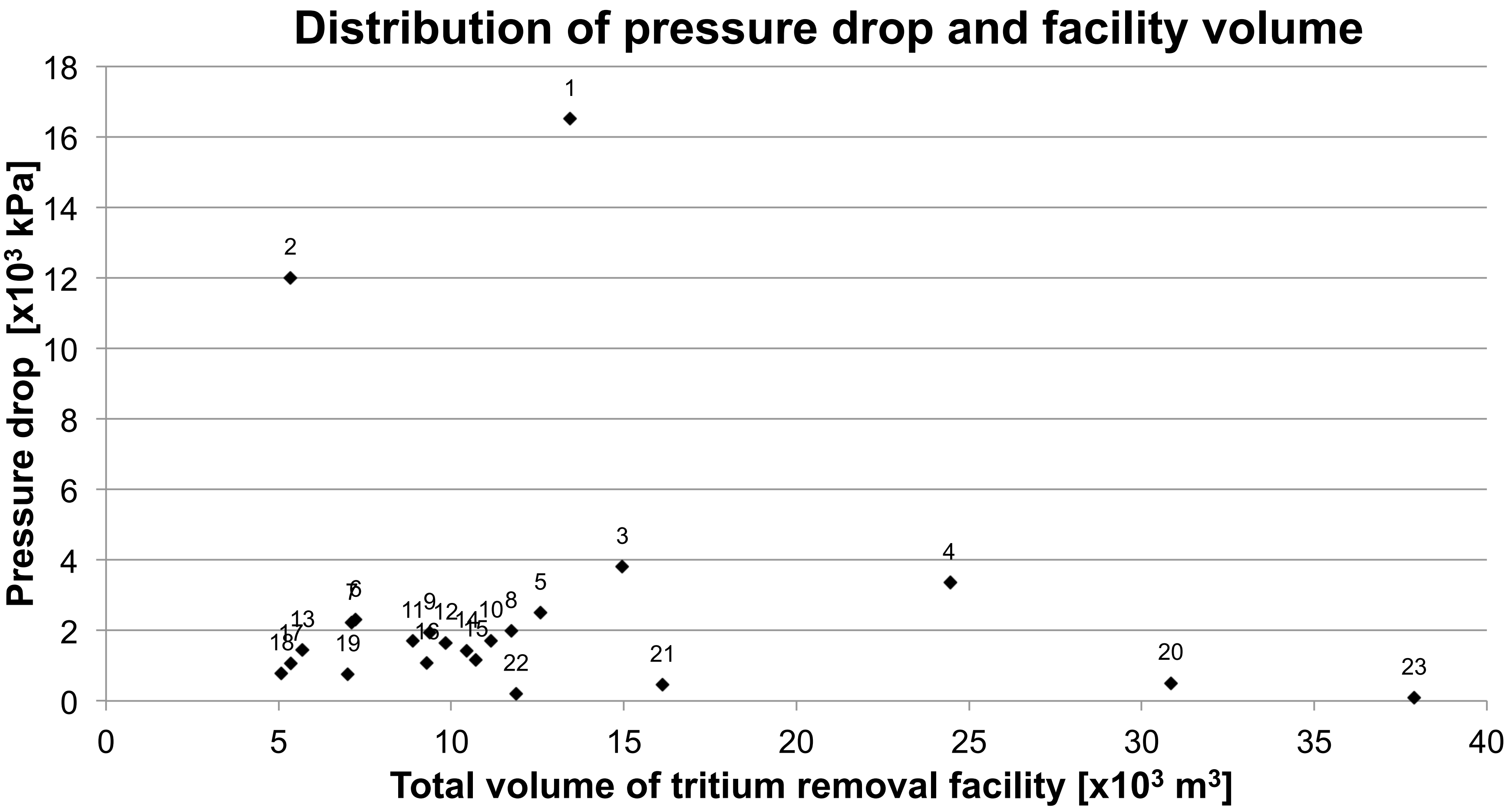




- Plot of Salt Flow Streamlines
  - Main streamlines are splitted each time as they meet the next row of tubes
- Plot of H_2 Concentration Distribution in the Molten Salt
  - Transport coefficients of H_2 instead of T_2 in FLiBe used due to the lack of data
  - H_2 concentration decreases quickly along the salt flow path

Results from COMSOL

- Comparison of Tritium Removal Facility Models
- Main Variables
  - Tube size
  - Tube pitch
  - Salt inlet flow velocity

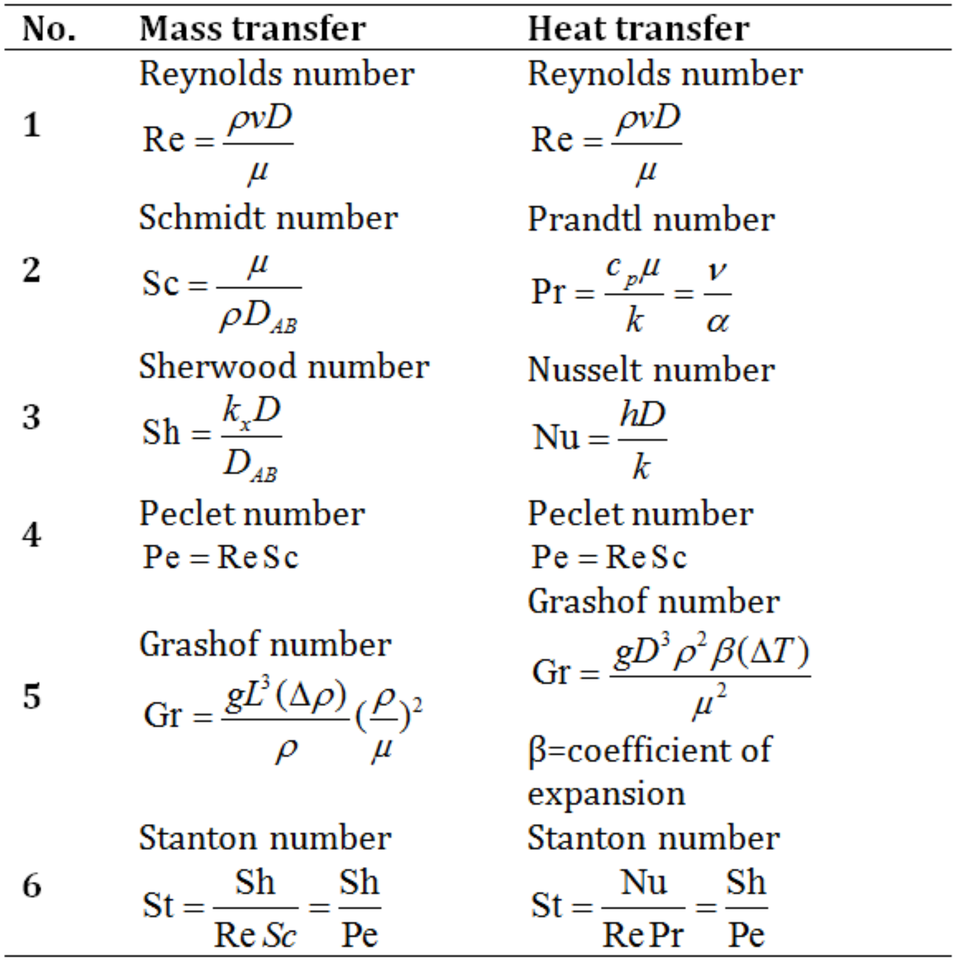

Distribution of pressure drop and facility volume

Code Calculation Using MATLAB

- Overall Mass Transfer Coefficient k_o

$$\left(\frac{1}{k_o H_s}\right)^{\sqrt{2}} = \left(\frac{1}{k_s H_s}\right)^{\sqrt{2}} + \left[\frac{t_w}{K_w}\,\frac{(p_{1,in}^{0.5}-p_2^{0.5})-(p_{1,out}^{0.5}-p_2^{0.5})}{\ln\left(\frac{p_{1,in}^{0.5}-p_{2,in}^{0.5}}{p_{1,out}^{0.5}-p_{2,in}^{0.5}}\right)}\right]^{\sqrt{2}}$$

- Corresponding Dimensionless Groups of Mass and Heat Transfer



No.	Mass transfer	Heat transfer
1	Reynolds number $\mathrm{Re} = \frac{\rho v D}{\mu}$	Reynolds number $\mathrm{Re} = \frac{\rho v D}{\mu}$
2	Schmidt number $\mathrm{Sc} = \frac{\mu}{\rho D_{AB}}$	Prandtl number $\mathrm{Pr} = \frac{c_p \mu}{k} = \frac{\nu}{\alpha}$
3	Sherwood number $\mathrm{Sh} = \frac{k_x D}{D_{AB}}$	Nusselt number $\mathrm{Nu} = \frac{hD}{k}$
4	Peclet number $\mathrm{Pe} = \mathrm{Re}\,\mathrm{Sc}$	Peclet number $\mathrm{Pe} = \mathrm{Re}\,\mathrm{Sc}$
5	Grashof number $\mathrm{Gr} = \frac{gL^3(\Delta\rho)}{\rho}\left(\frac{\rho}{\mu}\right)^2$	Grashof number $\mathrm{Gr} = \frac{gD^3\rho^2\beta(\Delta T)}{\mu^2}$ β=coefficient of expansion
6	Stanton number $\mathrm{St} = \frac{\mathrm{Sh}}{\mathrm{Re}\,Sc} = \frac{\mathrm{Sh}}{\mathrm{Pe}}$	Stanton number $\mathrm{St} = \frac{\mathrm{Nu}}{\mathrm{Re}\,\mathrm{Pr}} = \frac{\mathrm{Sh}}{\mathrm{Pe}}$

  - Sherwood number is calculated using the correlations for Nusselt number: heat transfer coefficient *h* replaced with mass transfer coefficient k_x and thermal conductivity *k* replaced with diffusivity D_{AB}
  - The concept of heat transfer resistance is applied to mass transfer using corresponding parameters

Facility Design Comparisons

	Dimension Set A	Dimension Set B
Mass flow rate of molten salt [kg/s]	11190.8	
Tritium inlet concentration [mol/m³]	1.8×10^{-6}	
Tritium outlet concentration [mol/m³]	1.62×10^{-6}	
Tritium removal rate [mol/s]	1.8×10^{-7}	
Tube OD [in]	1.050	1.315
Tube ID [in]	0.824	1.049
Tube wall thickness [in]	0.113	0.133
Tube bank pitch [in]	1.31 (Pitch/OD = 1.25)	1.64 (Pitch/OD = 1.25)
Tube length [in]	18	18
Tube number	49971	41365
Molten salt inlet frontal velocity [m/s]	1.0	1.0
Re	4.64×10^{4}	5.82×10^{4}
Molten salt inlet flow area [m²]	5.54 (2.35 × 2.35)	5.54 (2.35 × 2.35)
Total mass transfer area [m²]	9.85×10^{3}	1.02×10^{4}
Molten salt flow length estimated [m]	20.61 (in the direction normal to the tube bank)	26.72 (in the direction normal to the tube bank)
Molten salt frictional pressure loss [kPa]	197	189

- Fluoride salt flow rate from the AHTR preliminary design
- Tritium inlet concentration is raised to 10 times of that equivalent to the tritium production rate in the core

Contact Information

- Georgia Tech:
  - Timothy Flaspoehler
  - Email: timothy.flaspoehler@gatech.edu

  - Bojan Petrovic
  - Email: bojan.petrovic@gatech.edu

- Ohio State University
  - Xiaodong Sun
  - Email: sun.200@osu.edu