A Quantitative Case for Direct Internal Recycle of Deuterium & Tritium Through Permeation

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ISFNT 2023, Gran Canaria, Spain

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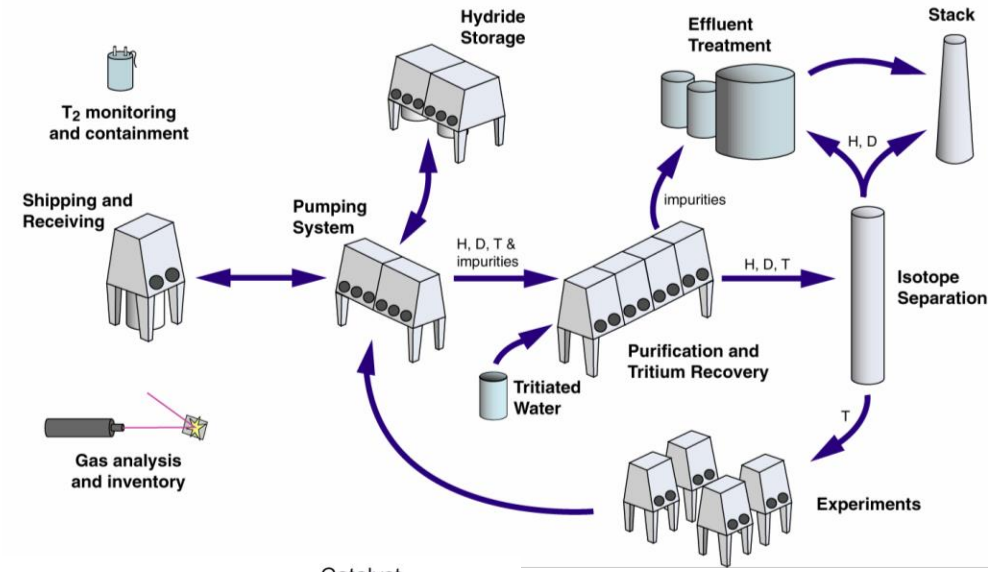
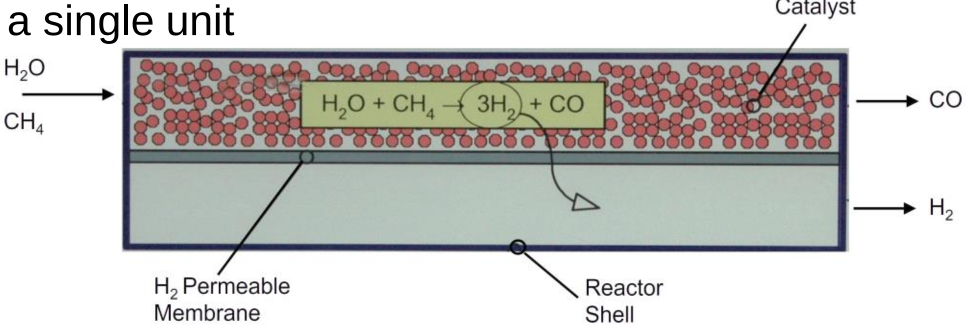
LANL fusion fuel cycle background

Tritium Systems Test Assembly (1977-2008)

- “Everything but the reactor”
  - Storage, processing, pumping
  - Investigated all tritium streams
  - Processing sized at 1/10th ITER scale
- Palladium Membrane Reactor
  - Developed at LANL
  - Combines hydrogen removal & separation into a single unit

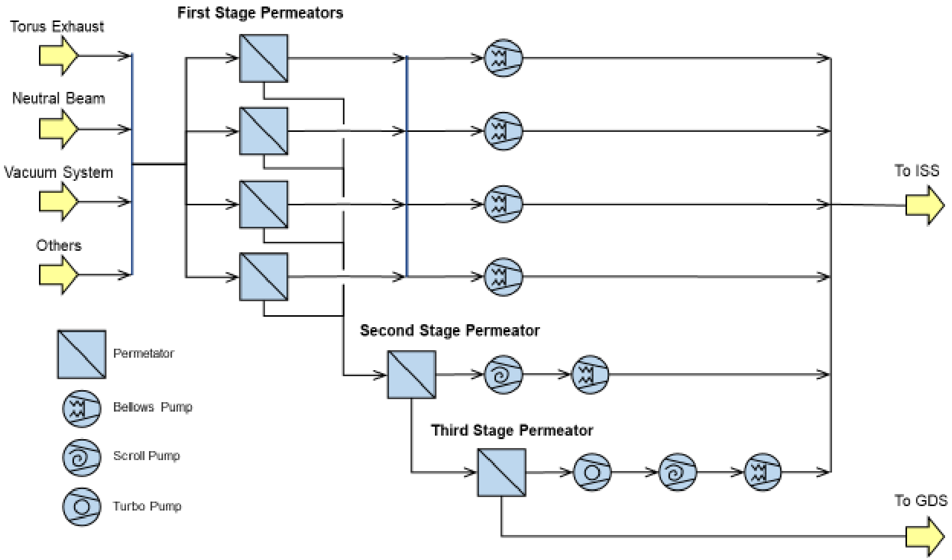




LANL fusion fuel cycle background

Tokamak Exhaust Processing System for ITER: Preconceptual Design

- Dynamic ASPEN models for TEP system design & sizing
- R&D for:
  - Catalyst selection
  - Permeators, Cat beds, Palladium Membrane Reactor
- Tritium-compatible vacuum pump models that could be combined into a pump train
- Lab-validated unit operations models specific to the ITER fuel cycle



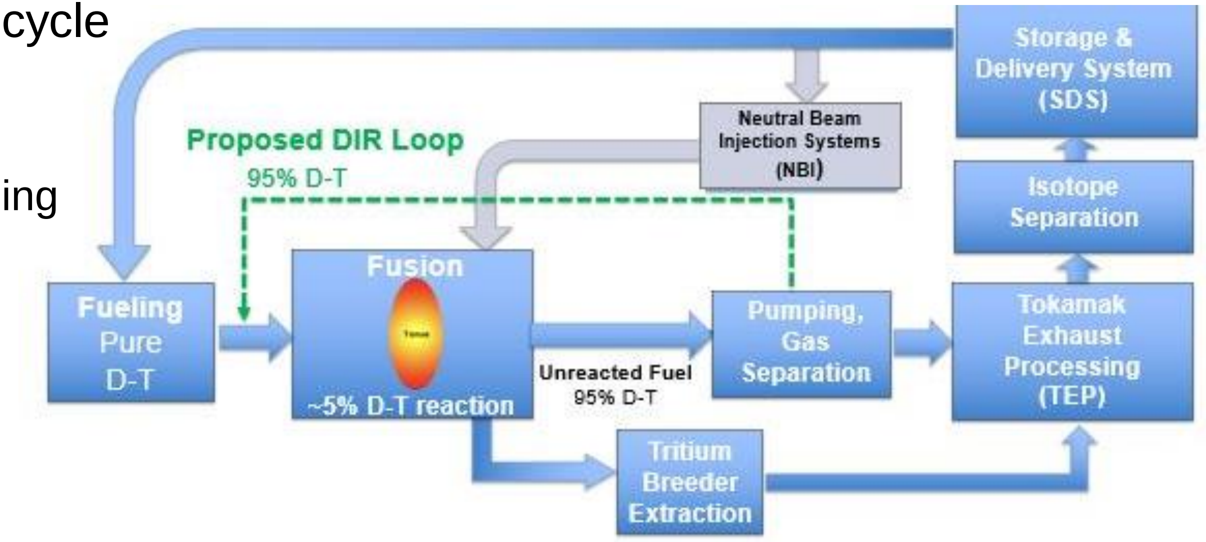
Fuel cycle design: Outstanding challenges

- Closing the fuel cycle
  - Minimizing any tritium losses from and holdup within the system
    - Cost of tritium ($30,000/gm US – € 27,800)
    - Scarcity
    - Safety concerns
  - Improving process definition & increasing technical readiness level (TRL)
  - Low plasma burnup = high available recycle fraction
- Tritium inventory management, operations with Q_2 (H/D/T)
- Tritium breeding – *highly needed!!!!*

More detail is needed for an eventual FPP/DEMO design, and overall tritium inventory is no small factor!

Direct Internal Recycle Concept (DIR)

- Minimizing processing steps to reintroduce DT exhaust to fueling
- Reduces Q_2 inventory in steps like isotope separation, storage
  - Higher throughput = higher fraction of total inventory in use
  - Could reduce size & complexity of larger, more expensive systems such as ISS
- Select highest-volume, highest-Q_2 streams for immediate recycle
- Some proposed recycle concepts exhibit isotope selectivity
  - Increases processing time



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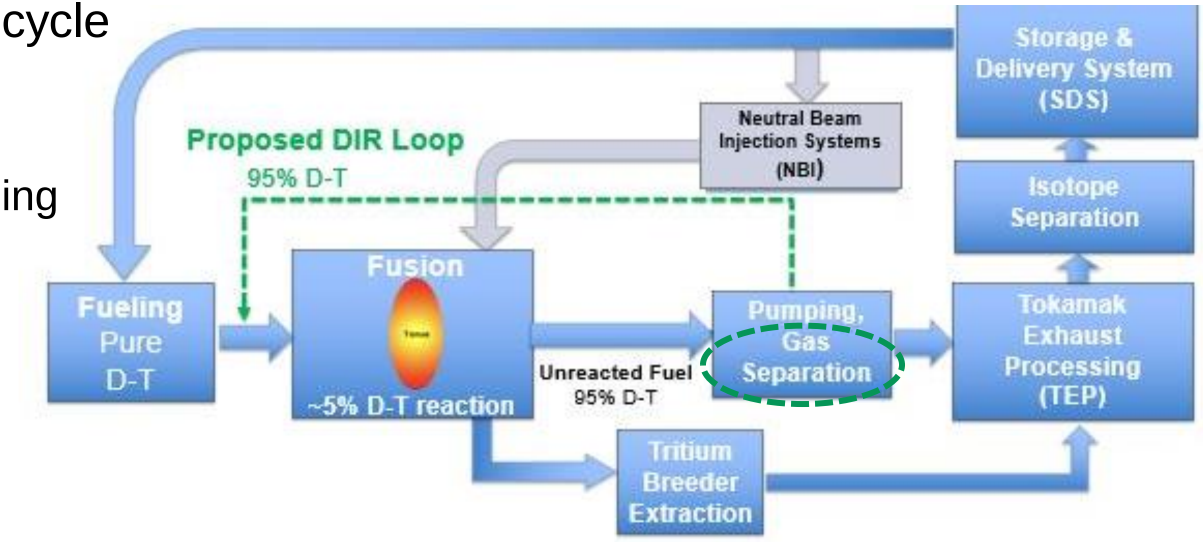
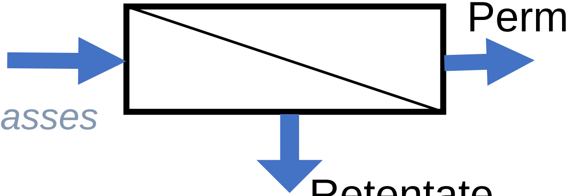


Permeation Through Q_2 Specific Membranes

- Permeation can accomplish the major function of DIR: hydrogen isotope separation
  - Removes non- Q_2 gasses, leaving pure Q_2 stream
    - Doping may be needed for 50:50 DT for fueling
  - High TRL at large scale
  - Commercially available
  - Fast response time
  - Continuous process
  - Scaleup: high throughputs possible

Permeator/Diffuser



Feed

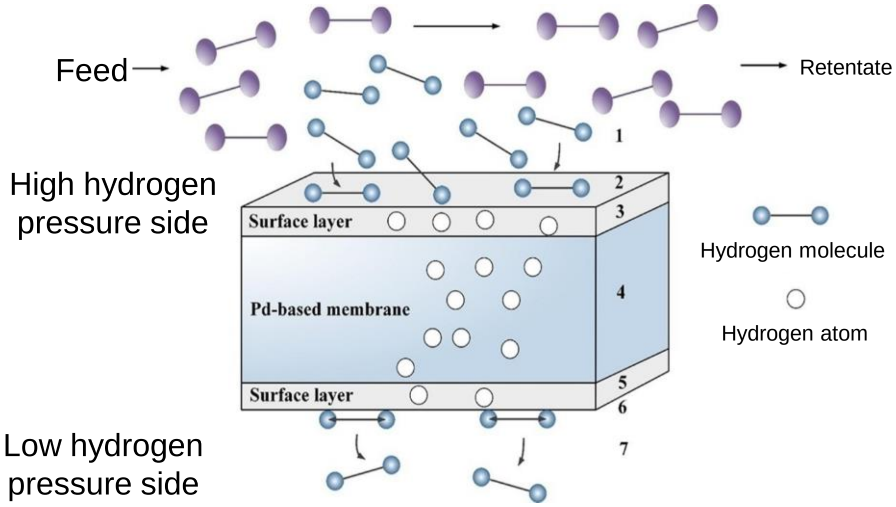
Q_2 + *Other gasses*

Permeate

Q_2

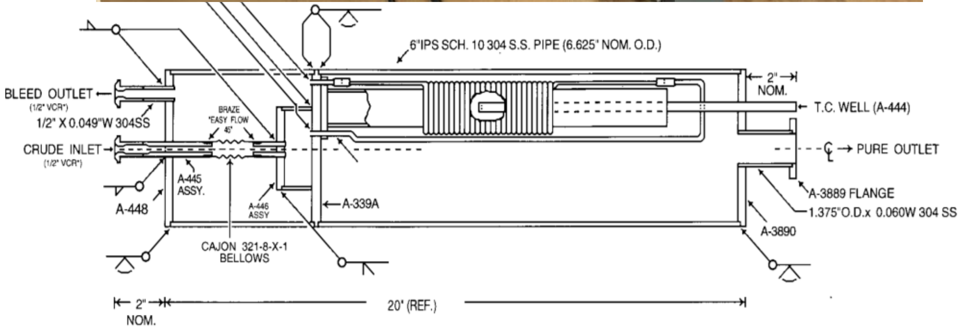
Retentate

Other gasses



https://doi.org/10.1016/j.cep.2017.07.021

LANL permeator & experiment design



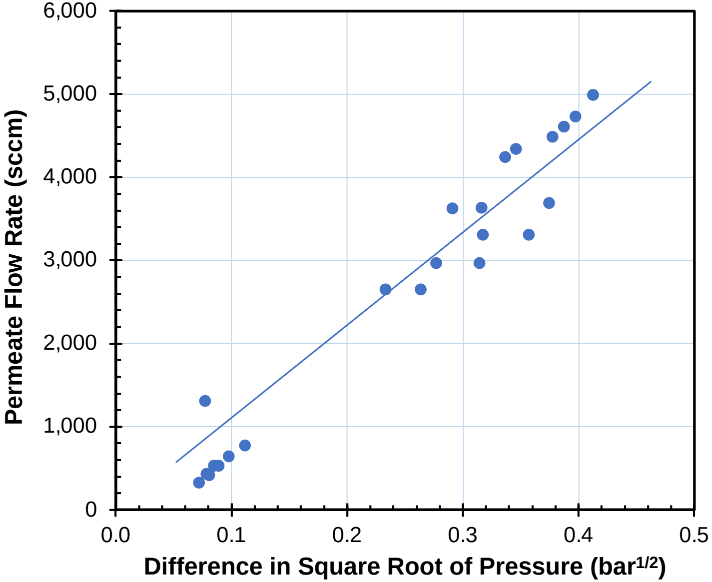
- **RSI model RS-3870 Permeator**
- PdAg membrane (0.47 m^2)
- Operated at 350 ºC
- Testing between 15-95% H_2 in Argon
  - Broad range of burnup fractions
  - Permeation of remaining hydrogen for direct recycle to fueling
- Tested with tritium-compatible pumps
  - Metal Bellows
  - All-Metal Scroll (Normetex)
- Data generated to validate permeator models for DIR calculations

Our modeling approach

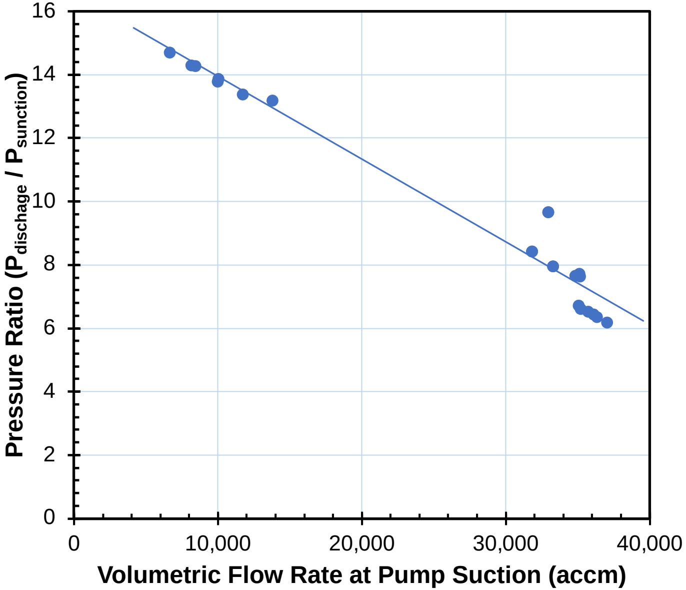
- **Goal Unit operations simulation for fuel cycle design**
  - Physics-based chemical engineering models of each operation
  - Generate flexible software tools for user-specific design
    - Generate models that are readily accessible to businesses and universities
  - HPL laboratory capability/permeators able to test/validate/refine models
- **Permeator modeling**
  - Emphasizes on steady-state model permeator design
    - Explicit treatment of hydrogen isotopes and disproportionation reactions
    - Includes retentate pressure drop and heat transfer
    - Define the relationship between permeator geometry & performance
  - Coupling permeator & pump models
    - Predicts pump train performance from individual pump models
    - Predicts permeate pressures based on pump models
  - Using CAPE-Open standard for inter-platform compatibility

Data Summary

Permeate Flow Rate as a Function of the Difference in Square-Root of Hydrogen Partial Pressures

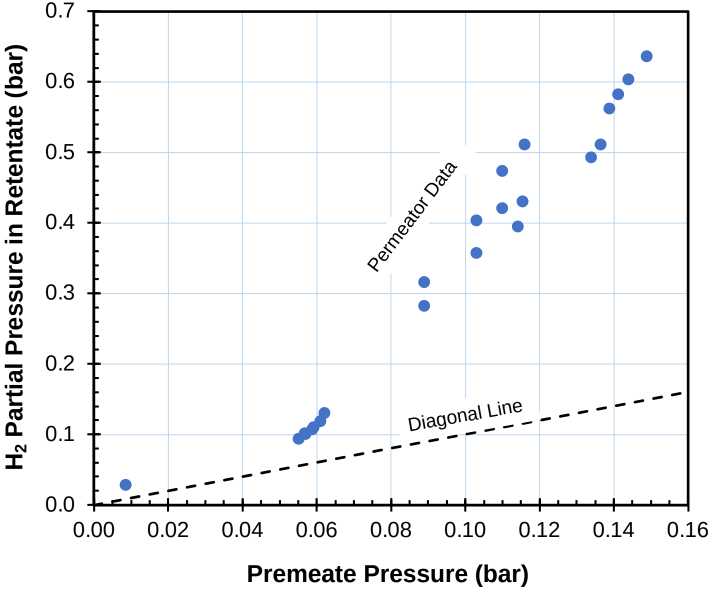


Experimental Pump Curve for MB-601 Metal Bellows Pump

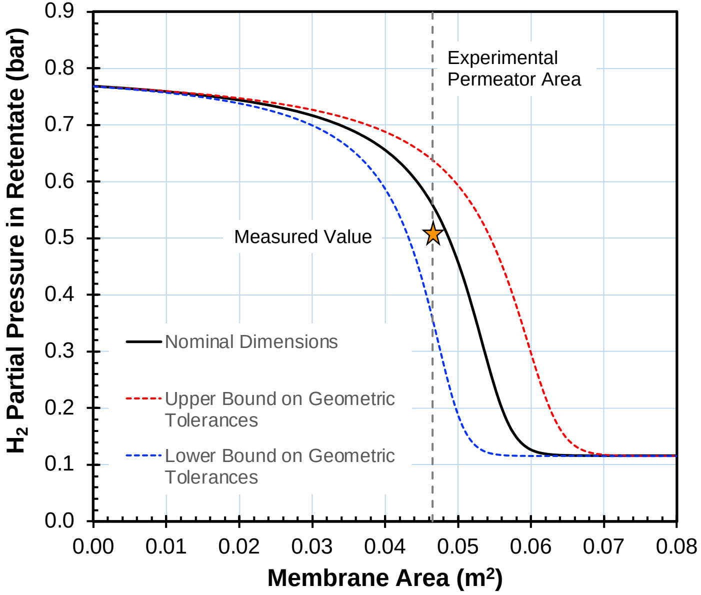


Experiments Conducted Under Breakthrough Conditions

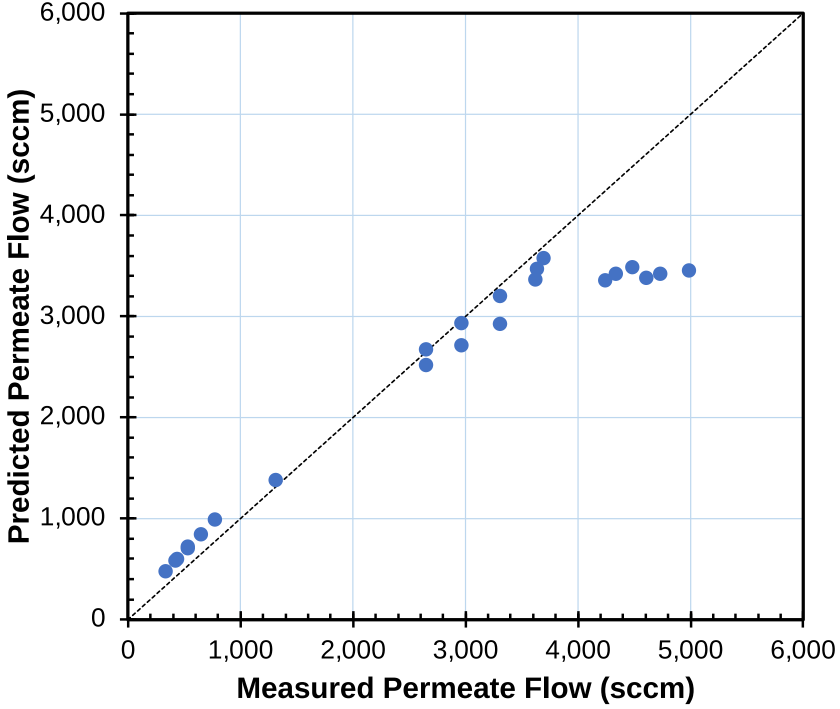
Hydrogen Partial Pressure in the Retentate as a Function of Permeate Pressure



A Sample Comparison of Experimental Data to Model Predictions



Comparison of Model Prediction to Experimental Results

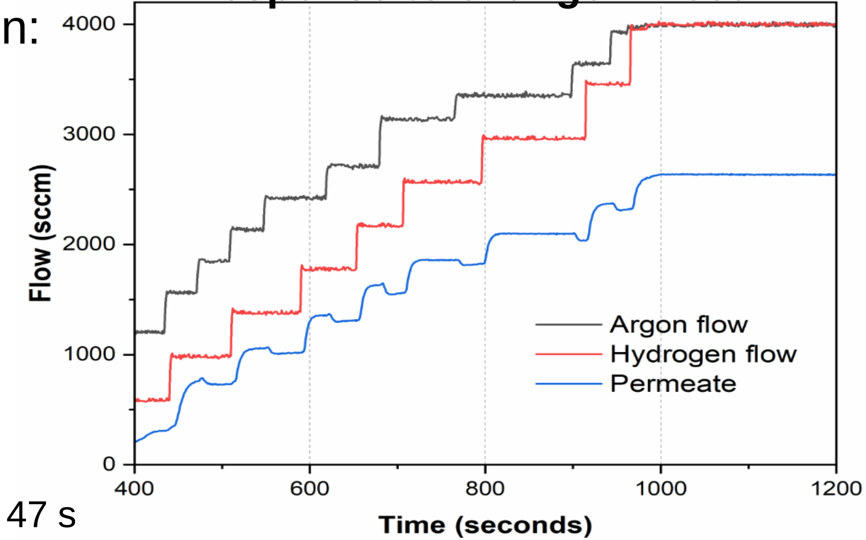


- Data obtained with flows greater than breakthrough flow most useful for evaluating models
  - Flows less than the are insensitive to permeability
  - Excessively large flow rates do not test ability of model to predict breakthrough
- Model predicts permeate flow rate for over 70% of the data
  - Still need to resolve differences for high permeate flow data

Dynamic behavior

- Observed permeate dynamics depend on:
  - Lag between flow controllers and permeator
  - Volume of the permeator inlet plenum
  - Dynamics of the membrane
  - Pump-down time of permeate plenum
- Estimated time response for tests
  - Permeator feed lag: 0.5 – 0.9 s
  - Inlet plenum response: 2.5 – 5 s
  - Permeate plenum pump down: 7 – 41 s
  - Overall response less membrane response: 11 – 47 s
- Membrane response on the order of a few seconds
  - Membrane response time increase with square of thickness
  - Increasing membrane unlikely to impact permeator response time

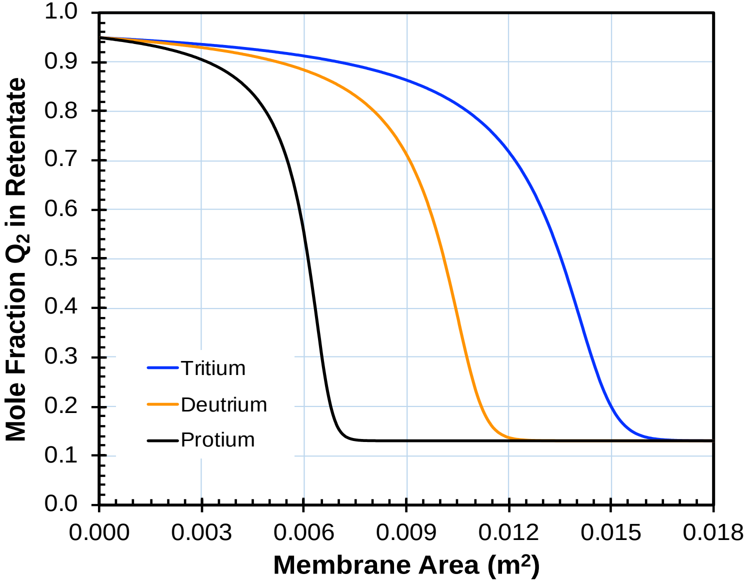
Change in permeation in response to change in feed



$$\tau = \frac{D_Q \times t}{x^2}$$

τ – time constant
D_Q – diffusion coefficient
x – membrane thickness
t - time

Validity of Experiments with Protium


Typical Q_2 Concentration Profiles in the Retentate

Dimensionless Permeator Equation

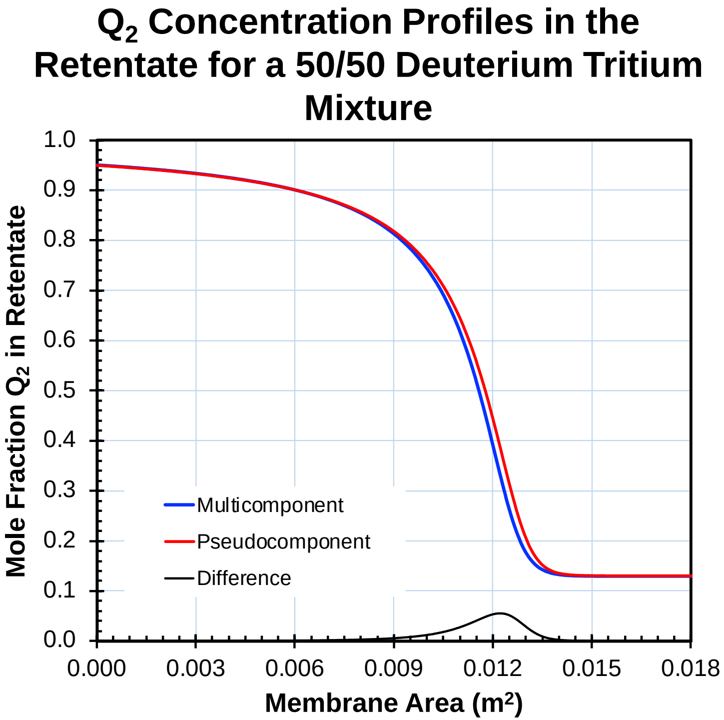
$$\frac{d\Pi}{dx} = -\Gamma \cdot \left(\sqrt{\Pi} - \sqrt{\Pi_{perm}}\right) \cdot (1 - \Pi)$$

Dimensionless Parameters

- Q_2 partial pressure $\Pi = \frac{P_{Q_2}}{P_{ret}}$
- Membrane area $x = \frac{A}{A_{total}}$
- **Permeability** $\boldsymbol{\Gamma = \frac{k_p \cdot A_{total} \cdot \sqrt{P_{ret}}}{F_{inert} \cdot \delta}}$
- Permeate pressure $\Pi_{perm} = \frac{P_{perm}}{P_{ret}}$

- **Smaller membrane area required for experiments with H_2**
- **H_2 representative D_2 and T_2 if dimensionless permeability is the same**

Applicability of Protium Experiments to Isotopic Mixtures



- Assuming disproportionation reaction are in equilibrium, mixture permeability can be estimated using a linear mixing rule

$$k_{p,mix} = k_{p,H} \cdot X_H + k_{p,D} \cdot X_D + k_{p,T} \cdot X_T$$

- A model representing a D-T mixture as a pseudo-component closely approximates an exact model
- Permeator experiments with protium are applicable to isotopic mixtures

Conclusions & Future work

- Permeation may be a promising solution for DIR if isotope resolution is not fully necessary
  - Higher TRL than alternatives
- Models generated for permeators predict performance for 70% of dataset
- A thorough understanding of operating conditions needed will give the most efficient, specific design
  - *True for all unit ops AND whole-plant design*
- Future work:
  - Goal: implement unit operations in system models to discuss broader impacts
  - Isotope effects: further investigation & validation
    - Change in permeate composition because of change in feed composition
  - Opportunity: enhanced membrane design

Acknowledgements

Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of the U.S. Department of Energy (DOE) under Contract No. 89233218CNA000001. This work was partially supported by the U.S. DOE Office of Science, Fusion Energy Sciences, LANL2020FES2- FESS Tritium Plant Modeling.

Thank you!

How to reach out: hpl@lanl.gov

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LANL contributions to the Fusion Fuel Cycle

Hydrogen storage in uranium beds

Alternatives to Normetex: Airsquared pump test report

The Fusion Fuel Cycle

- Major challenges for tritium use
  - – Retention/permeation through materials at high temperature [DOE tritium standard]
  - – β-radiation & decay
  - – Safe storage & accountancy of large quantities of gas
  - – Isotope exchange with protium (water, hydrocarbons)
    - $H_2O+T_2 \longrightarrow$ HTO
- Tritium handling best practices:
  - – Pressure cascade
  - – Secondary containment
    - Gloveboxes
    - Double-walled piping
  - – Isolatable volume limits
  - – Minimizing processing temp