Savannah River National Laboratory

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SRNL Fusion Capabilities for INFUSE and PPP Programs

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American Physical Society – Department of Plasma Physics, Mini-Conference PPP

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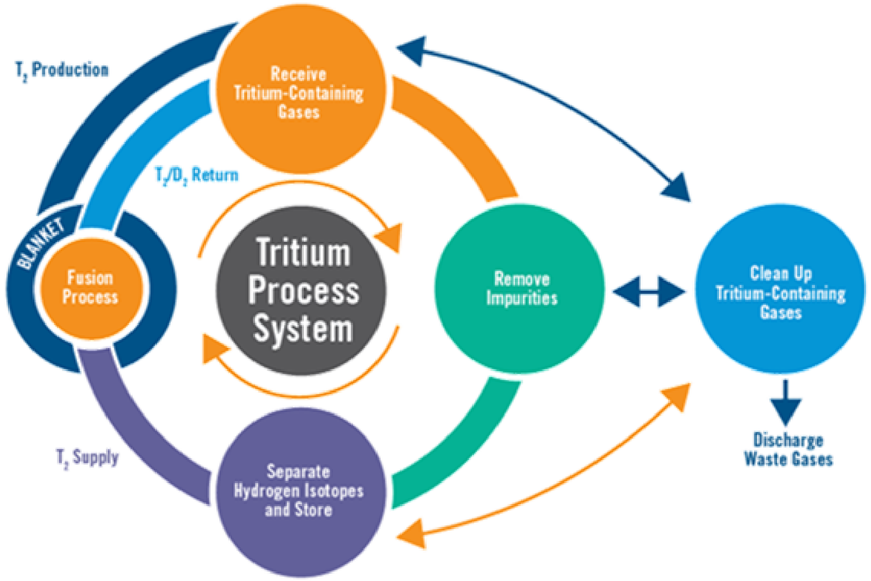
Five Tritium Research Topics to Enable Fusion Energy

- **System Modeling, Process Control, & Simulation** – Define models to advance & optimize system design, monitor operation, control the process and simulate performance during normal and off-normal operation
- **Tritium Inventory Reduction & Improved Process Technologies** – Improve tritium processing to reduce the inventory needed and lower the radioactive source term. This includes developing advanced designs such as direct internal recycling
- **Isotope Supply, Tritium Breeding, and Tritium Extraction** – Define tritium/isotope supply source and processing, ensure tritium breeding ratio can be achieved, and minimize captive inventory

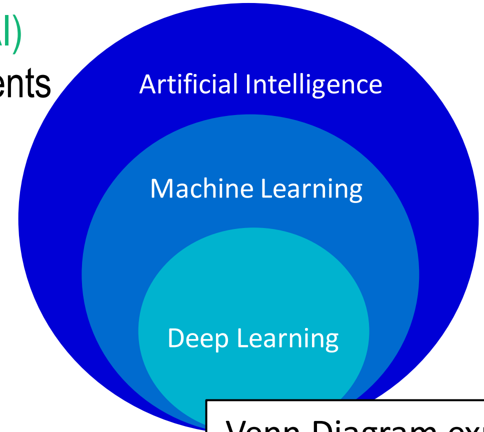


- **Tritium Confinement to Reduce Emissions and Support Safety Basis** – Develop advanced tritium wetted materials and confinement barriers, understand and mitigate tritium effects on plasma facing components, and improve tritium removal and recovery from secondary/tertiary confinements and effluent streams
- **Tritium Accountability and Tritium Analytical/Diagnostic Capabilities** – Develop rapid, high-accuracy/precise accountability measurement instruments and techniques to measure tritium and account for it in different parts of the system

System Modeling, Process Control, & Simulation

Automation Modeling Projects

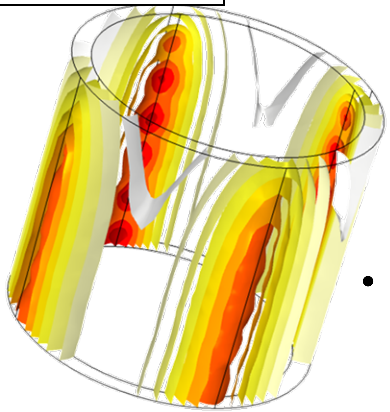
- Machine Learning (ML)/ Artificial Intelligence (AI)
    - Materials in complex chemical environments
    - Cyber-physical inspection
    - Material inspection automation
- Supply Chain Optimization models



Venn Diagram expressing a high layer grouping of the different layers of AI

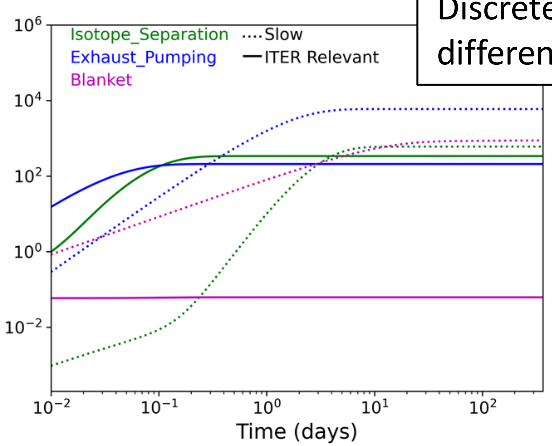
Isotope Separation & Heat Exchangers

Example of thermal modeling



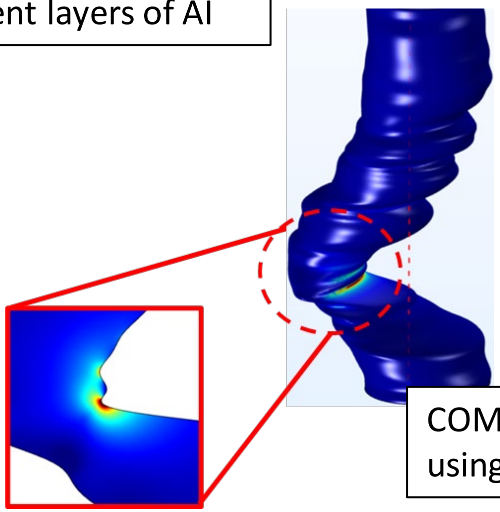
- SRNL can help develop **scaled-up** versions of the Mini TCAP that could be able to meet higher throughputs needed compared to Mini-TCAP
- SRNL can help to develop heating and cooling methods to **improve heat transfer**

Fuel Cycle Discrete-Time Model



Discrete-time model calculated Inventories for different sub-system processing times

- SRNL developed a discrete-time model based on processing times to calculate inventory
- The discrete model has been shown to support inventory reduction studies and real-time accountancy



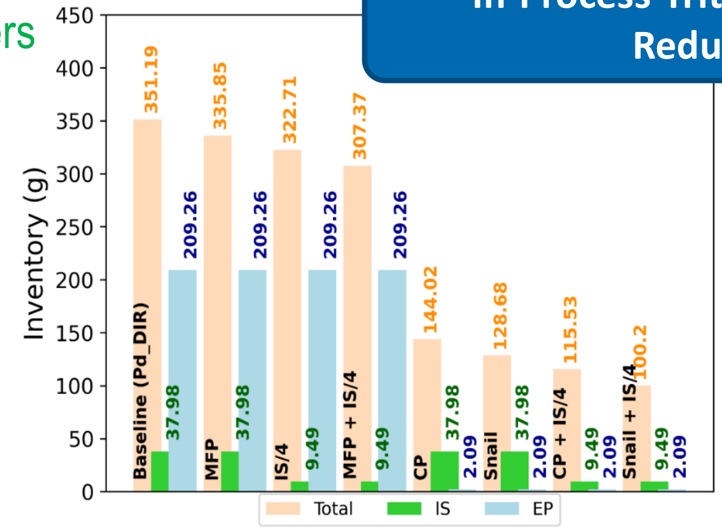
- SRNL developed LatticeJ©
- Strut specific data extracted from a Computed Tomography (CT) can be used to simplify Finite Element Analysis (FEA) and machine learning

COMSOL stress response of a 3D solid created using the SRNL developed LatticeJ© software

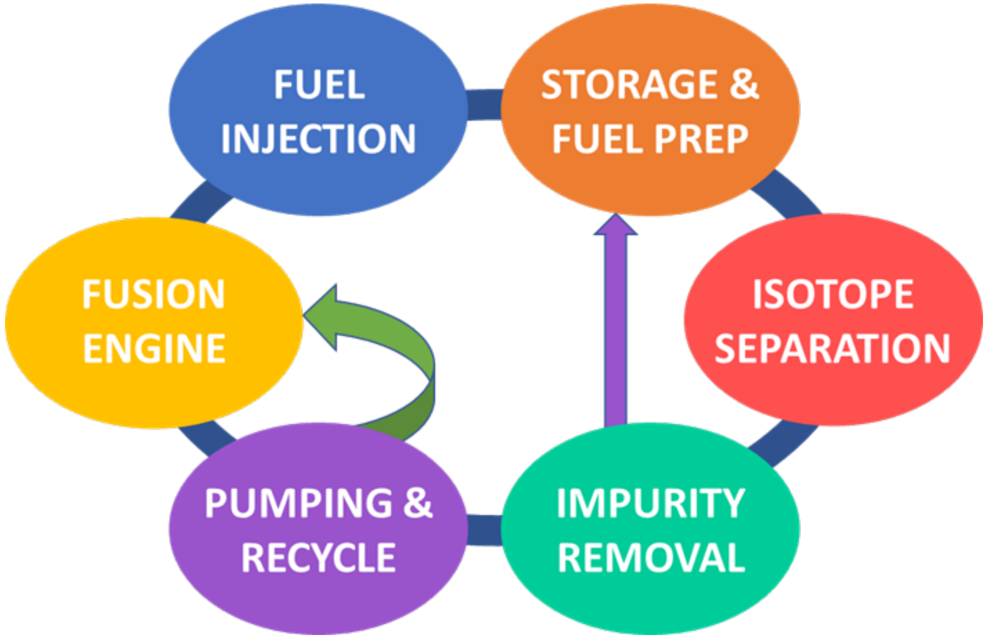
Tritium Inventory Reduction & Improved Process Technologies

- Simulated improvements and changes to the fuel cycle by adjusting parameters in the discrete-time model
  - Continuous pumping, Direct Internal Recycling (DIR), and improvement in Isotope Separation
  - In-process inventory was shown to be reduced > 50% with a maximum reduction of ~71%.

In-Process Tritium Inventory Reduction



2.) (Accepted) “Fusion Fuel Cycle Inventory Reduction Studies using a Processing Time based Discrete-Time Interval Model” in a Special Edition of Fusion Science and Technology, Young Investigators of Fusion



- Fusion Engine Development Occurs in Concert with Fuel Cycle Development
  - Fusion engine is still determining tolerable levels of impurities, operating conditions, and fueling rates, which affects possible recycle and bypass flows in the fuel cycle
  - Technology selection occurs with engine design so that operating conditions lead to tractable tritium inventories and manageable fuel cycle footprints
  - Technology evaluation depends on engineering models requiring bulk material quantities such as viscosity, heats of adsorption and vaporization, interaction parameters, etc.

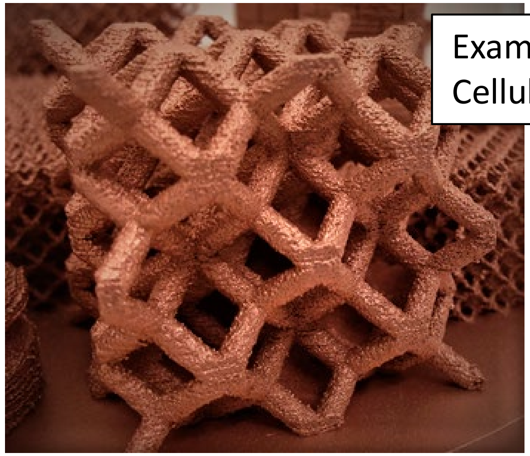
Tritium Inventory Reduction & Improved Process Technologies - Hydrogen Storage & Pumping

The Hydrogen Storage and Pumping R&D re-design the current methods of storing, compressing, mixing, and transporting hydrogen isotopes

Hydride Bed Development

Hydride Beds Development

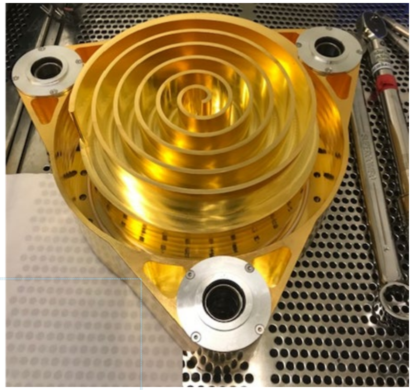
- In-process regeneration of hydride beds would ***reduce large tritium heel***, lowering unusable tritium inventory, and extend bed life

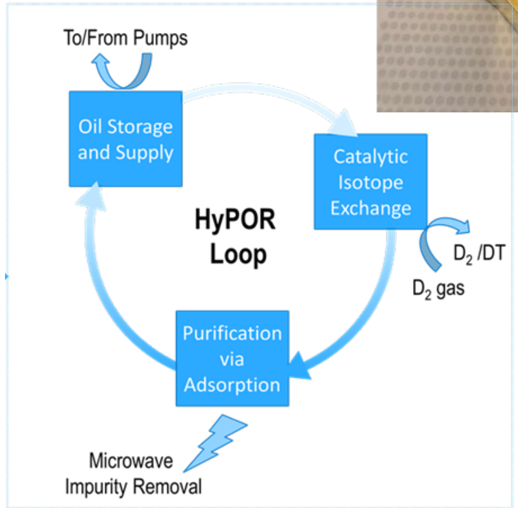


Example of Additively Manufactured (AM) Cellular Structure for Hydride Bed Heat Transfer

- Use of lattice structures to confine particles in a bed could **allow flow-through operations**
- Improved heat transfer can help to improve the response times of beds to desired changes in process conditions

Alternative Pumping Technologies



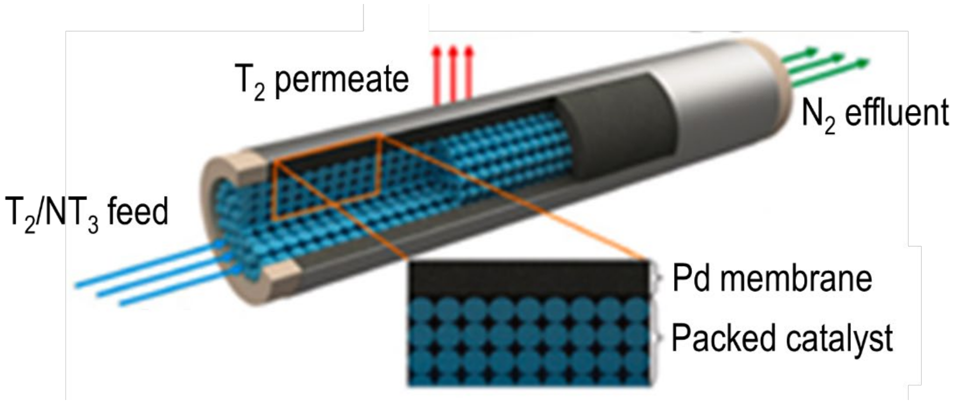


- Redesign pumping components and development of new systems **for tritium service**

Tritium Inventory Reduction & Improved Process Technologies - Impurity Removal

The Impurity Removal R&D tasks address the issues caused by accumulation of gaseous impurities.

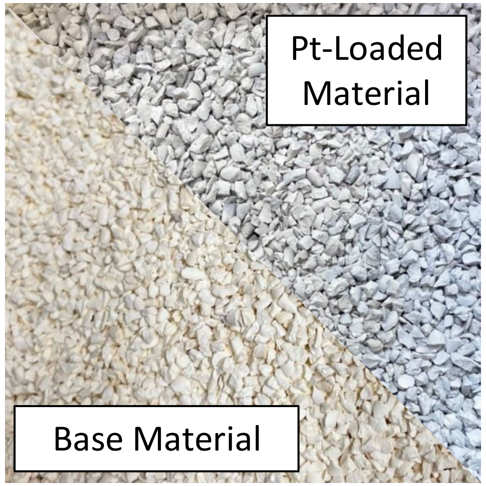
Ammonia Decomposition and Processing



Permeation Membrane Reactor (PMR) Packed With Ammonia Decomposition Catalyst.

- Development of novel trimetallic **catalysts for ammonia decomposition** could be used to re-design diffusers
- As ammonia is cracked into tritium and nitrogen, tritium permeates out of the reactor through the palladium (Pd) walls for further purification
- Nitrogen and tritium cannot recombine since the tritium is removed

Tritiated Water Processing



- Development of **water vapor detritiation unit** for the passive (i.e., ambient condition) **recovery of accumulated tritium** present in the moisture of a glovebox atmosphere

Impurity Trap Material Development

Cryocooler With Sample Loaded

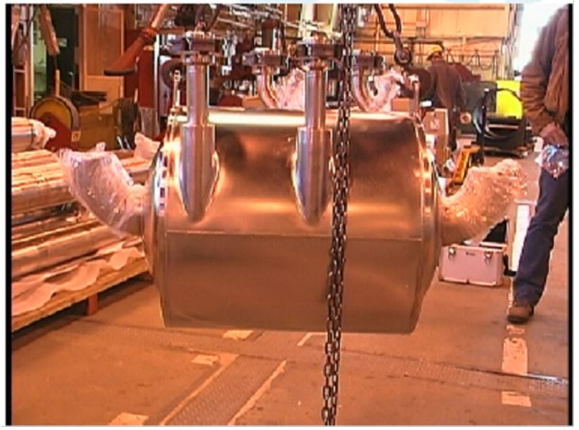
- Development of **absorbent and cryogenic beds** to selectively **remove impurities** from a hydrogen isotope process stream

Tritium Inventory Reduction & Improved Process Technologies - Isotope Separations

The Isotope Separation R&D improves and scales up TCAP and other advanced isotope separation technologies

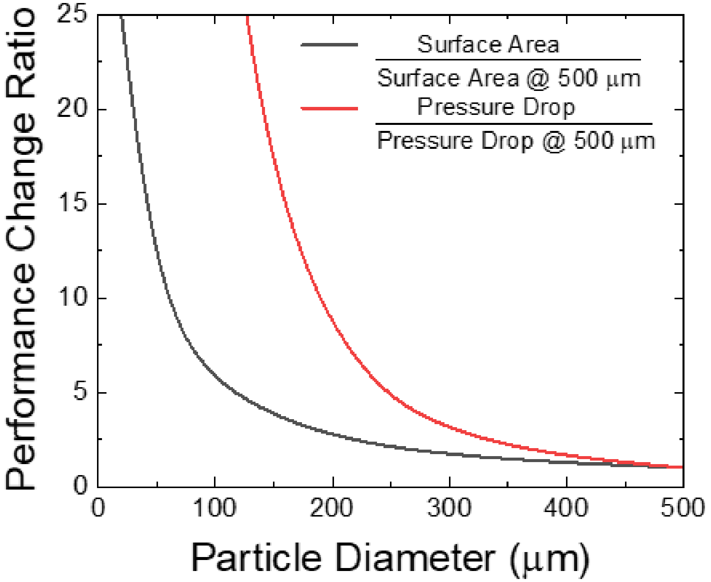
Advanced TCAP Development

Mini-TCAP System



- Mini-TCAP design occupies a significantly **smaller footprint with double the throughput** and 1/3 the tritium working inventory of the currently deployed TCAP system

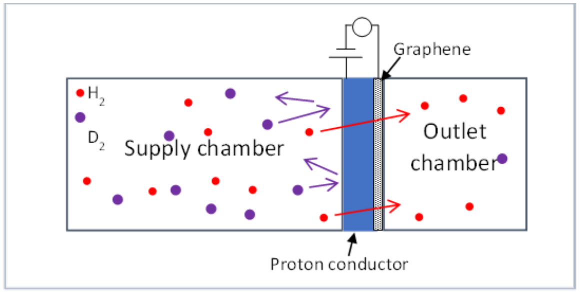
TCAP Column Material Development



Performance versus particle diameter of packed column containing 500 µm particles as a baseline

- Development of new Pd-based and other hydride and non-hydride materials to **improve absorption kinetics and mass transfer** in TCAP columns

2D material-based Isotope Separation



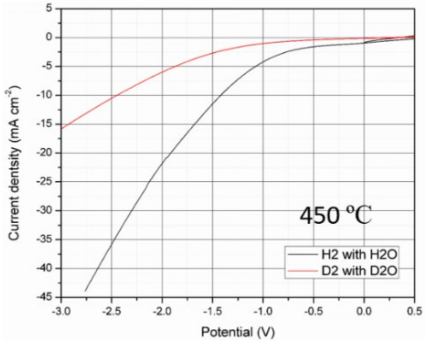


Figure 2. IV curve of graphene coated BCZYYb at 450 °C.

- Developing novel isotope separation methods based on 2D materials

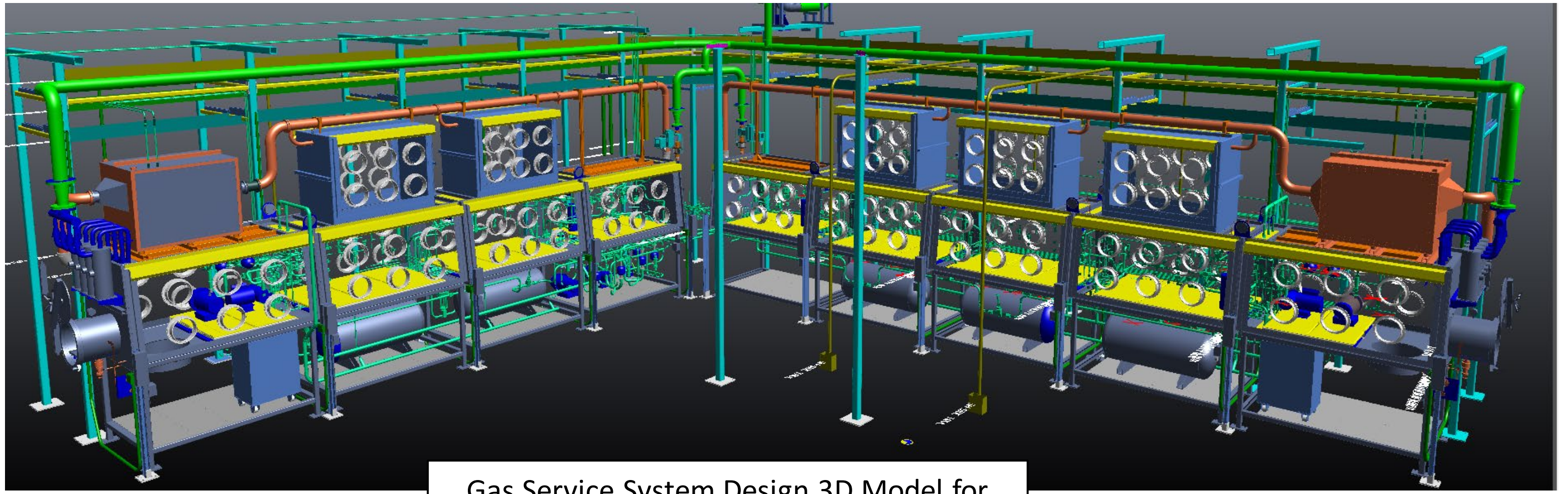
Tritium Inventory Reduction & Improved Process Technologies - Integrated R&D Capabilities

Fusion Fuel Cycle Integrated R&D Capabilities advance radiological and non-radiological R&D capabilities required to address the risk of inserting new technologies into fusion fuel cycles

Hydrogen Processing Demonstration Systems (HPDSs)

- SRNL has constructed HPDS for defense applications to **facilitate tritium process research and maturation** efforts by integrating technologies prior to insertion into the Tritium Facility

- Having HPDS systems for the fusion fuel cycle would provide valuable **hands-on training** for researchers/operators and **maintain/grow core competencies** and expertise in tritium processing



Gas Service System Design 3D Model for an HPDS glovebox system

Glovebox interior provide abundant space to test individual tritium processing components as well as integrated systems testing

Tritium Laboratory/Facility

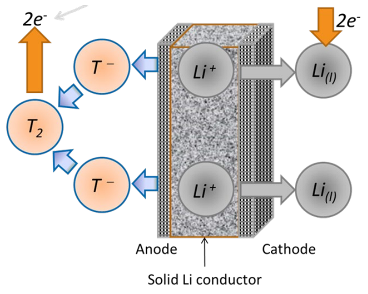
- SRNL is exploring the creation of a tritium laboratory in its existing lab facilities that can handle small quantities of tritium and also new tritium R&D facilities to enable fuel cycle integration research

Isotope Supply, Tritium Breeding, and Tritium Extraction

Direct LiT Electrolysis for tritium extraction from lithium alloys

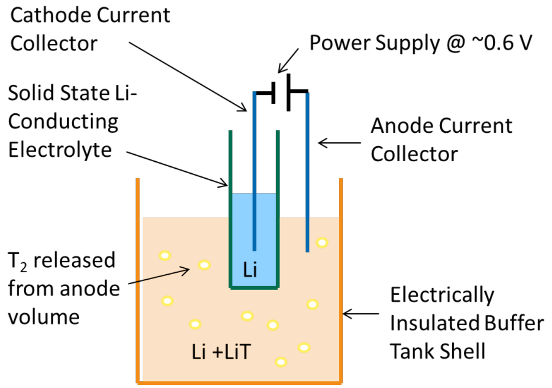
Lithium Conducting Electrolyte

$2LiT \rightarrow 2Li^{+} + T_2 \uparrow + 2e^{-} \qquad Li^{+} + e^{-} \rightarrow Li$



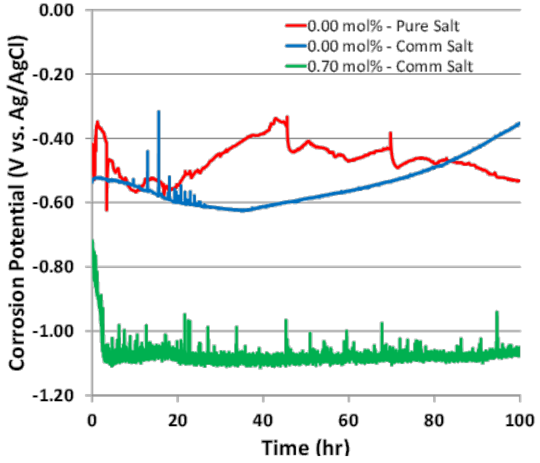
$E^{0}_{400°C} = -2.82V \qquad E^{0}_{400°C} = -3.22V$

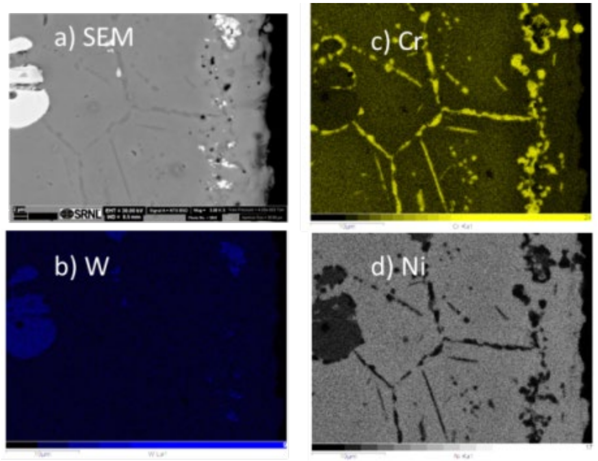
Lithium Buffer Tank



Scale-up with ARPA-e GAMOW

Corrosion mitigation and control in FLiBe Blankets





INFUSE with CFS

Isotope Supply (T_2, Li-6, B-11)

- SRNL helps manage the NNSA tritium supply chain and could help with tritium supply issues and needs for the fusion community
- SRNL has previously developed and funded Li-6 enrichment concepts and is looking at multiple concepts in this area due to renewed interest from fusion
- SRNL is also developing concepts around B-11 enrichment that can leverage SRNL expertise in nuclear separations

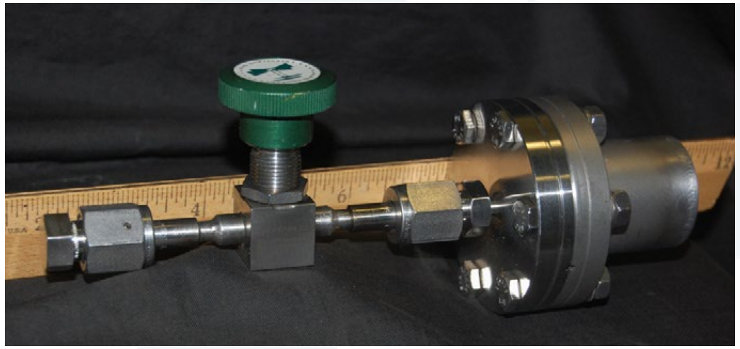
Tritium Extraction from FLiBe

In Progress and Coming Soon!

Tritium Accelerated Aging of Materials

Soft materials (beta decay dominated)

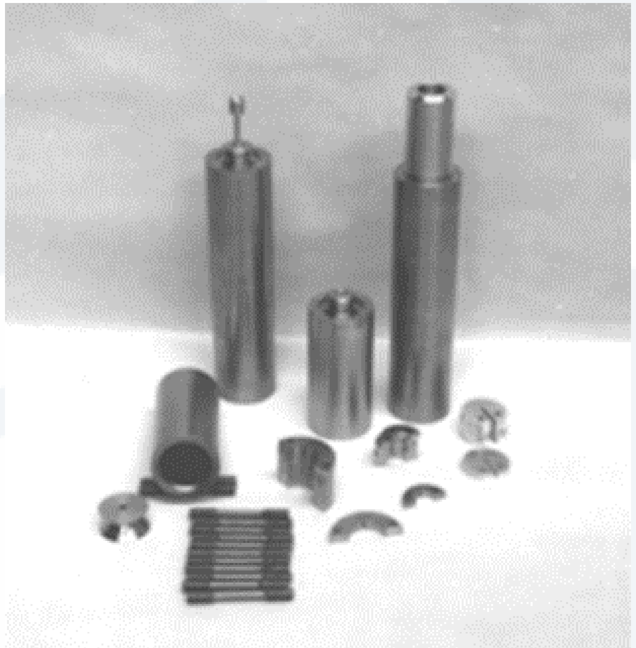
Polymers

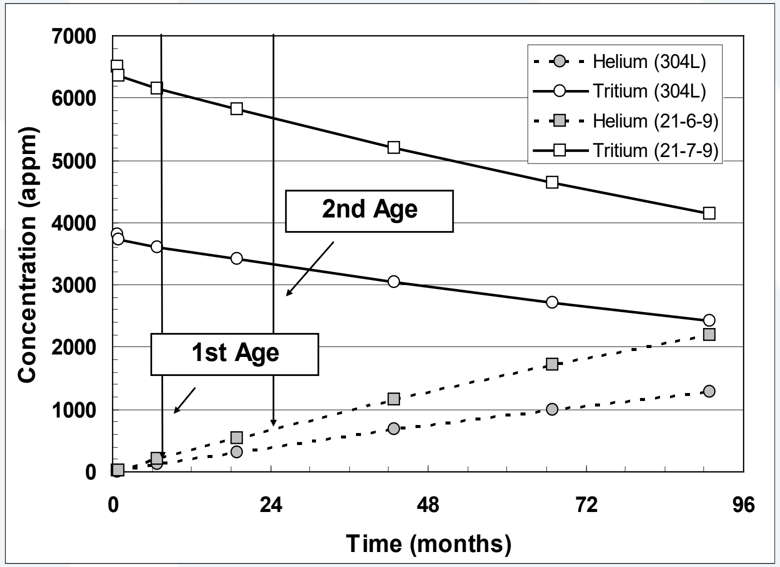


Tritium gas exposure containers
There is no substitute for bulk T_2 exposure

Hard materials (He ingrowth dominated)

Structural Materials

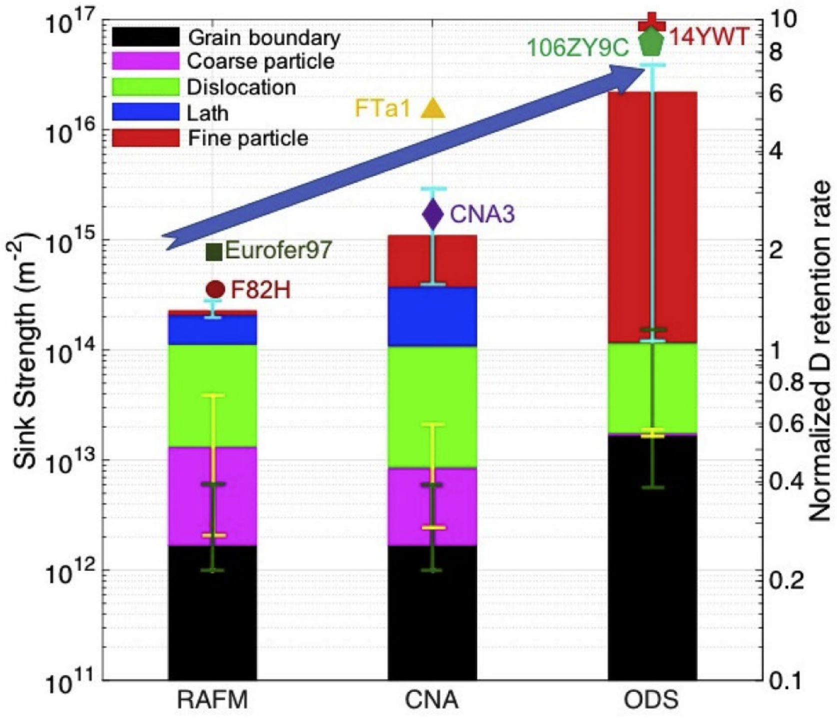




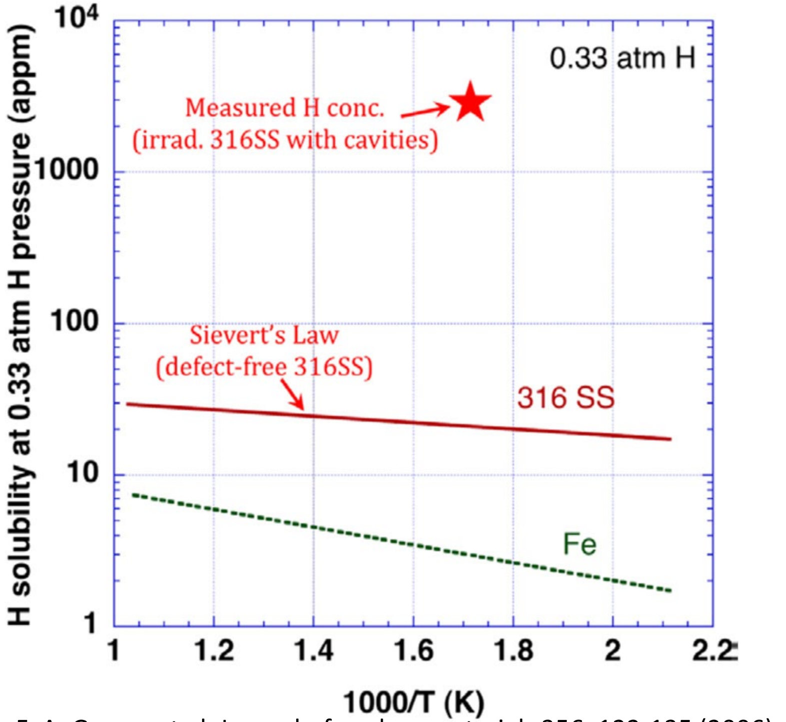
Hydrogen/Tritium Exposure at elevated temperature and pressure followed by low temperature aging to build-in helium Without Losing Tritium.

- For common steel alloys ~350 °C and 35 MPa is high enough for to saturate samples with tritium but low enough to minimize any change in microstructure.
- Age at -50 °C to limit tritium off gassing and build in varying levels of T_2 decay He.

Characterization of Tritium Retention & Permeation in Advanced Materials



Xunxiang Hu et al. Journal of Nuclear Materials, 2018. 516: p. 144-151.



F. A. Garner et al. Journal of nuclear materials 356, 122-135 (2006).

S. J. Zinkle et al. Nuclear Fusion 53, 104024 (2013).

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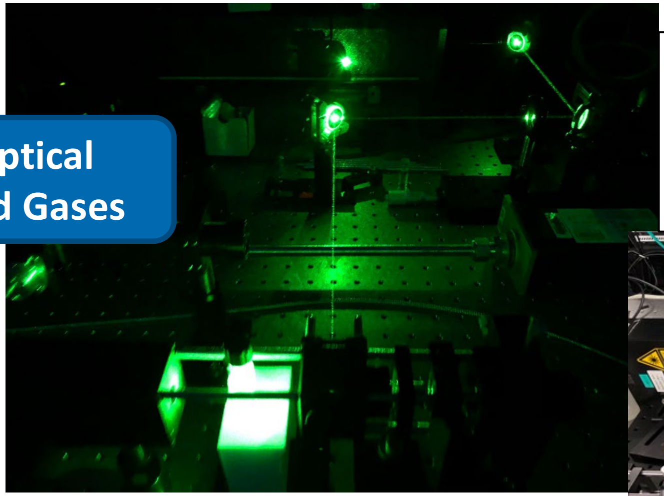
- SRNL starting an FES project studying tritium retention and permeation structural alloys
- Tritium permeation and holdup may be significantly larger in modern low activation alloys than austenitic steels generally preferred for tritium service
- Tritium retention may also be steels significantly enhanced after irradiations at energy-relevant elevated temperatures

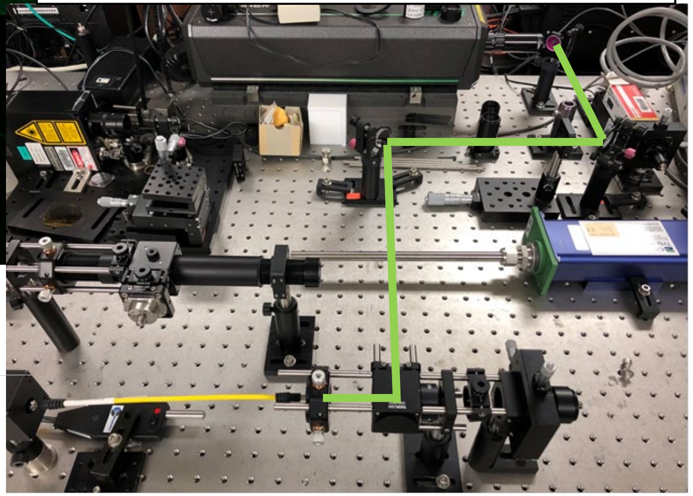
Tritium Accountability and Tritium Analytical/Diagnostic Capabilities

Tritium Analytical Systems R&D advanced instrument design and operation for compatibility in tritium processing systems.

Next Generation Optical Detection of Tritiated Gases

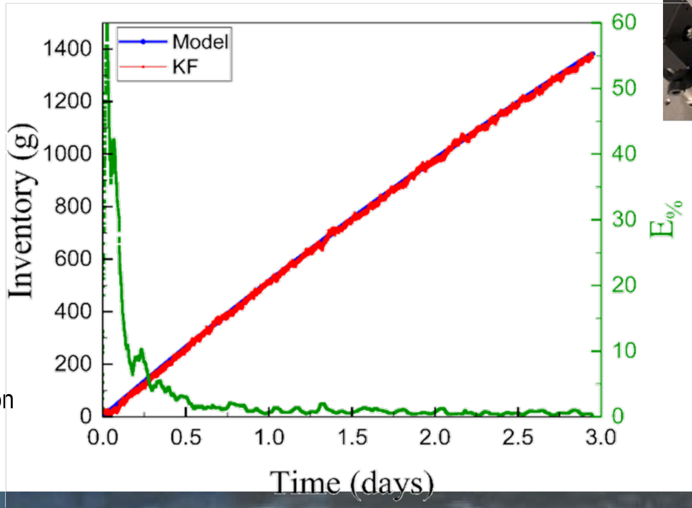


SRNL has multiple test beds and instrumentation for analytical characterization of tritium process gases and impurities.



- Development of advanced analytical **monitoring system for X_2 and other tritium-containing trace gas species**.
- Developing components for tritium analytical systems that can provide ~100 ppm sensitivity for X_2 isotopologues.

Real-Time Tritium Accountancy



1.) Flynn, H. B., and George Larsen. "Investigating the application of Kalman Filters for real-time accountancy in fusion fuel cycles." *Fusion Engineering and Design* 176 (2022): 113037.

- Demonstrated the capability of the Kalman Filter for real-time tritium accountancy
  - Simulated sensor measurements and processed through Kalman Filter
  - Sensor measurement error was reduced from 60% to near 0.001%

Questions?