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Tritium Processing and Material Research Needs for Fusion Energy

Brenda L. Garcia-Diaz, George Larsen, Jason Wilson, Dale Hitchcock, and Dave Babineau

DOE ARPA-E - Fusion Energy Workshop

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Five Tritium Research Topics where Advances Could Enable Fusion Energy

- **Tritium Inventory Reduction** – Improve tritium processing to reduce the inventory needed and lower the radioactive source term. This would also help to minimize releases.

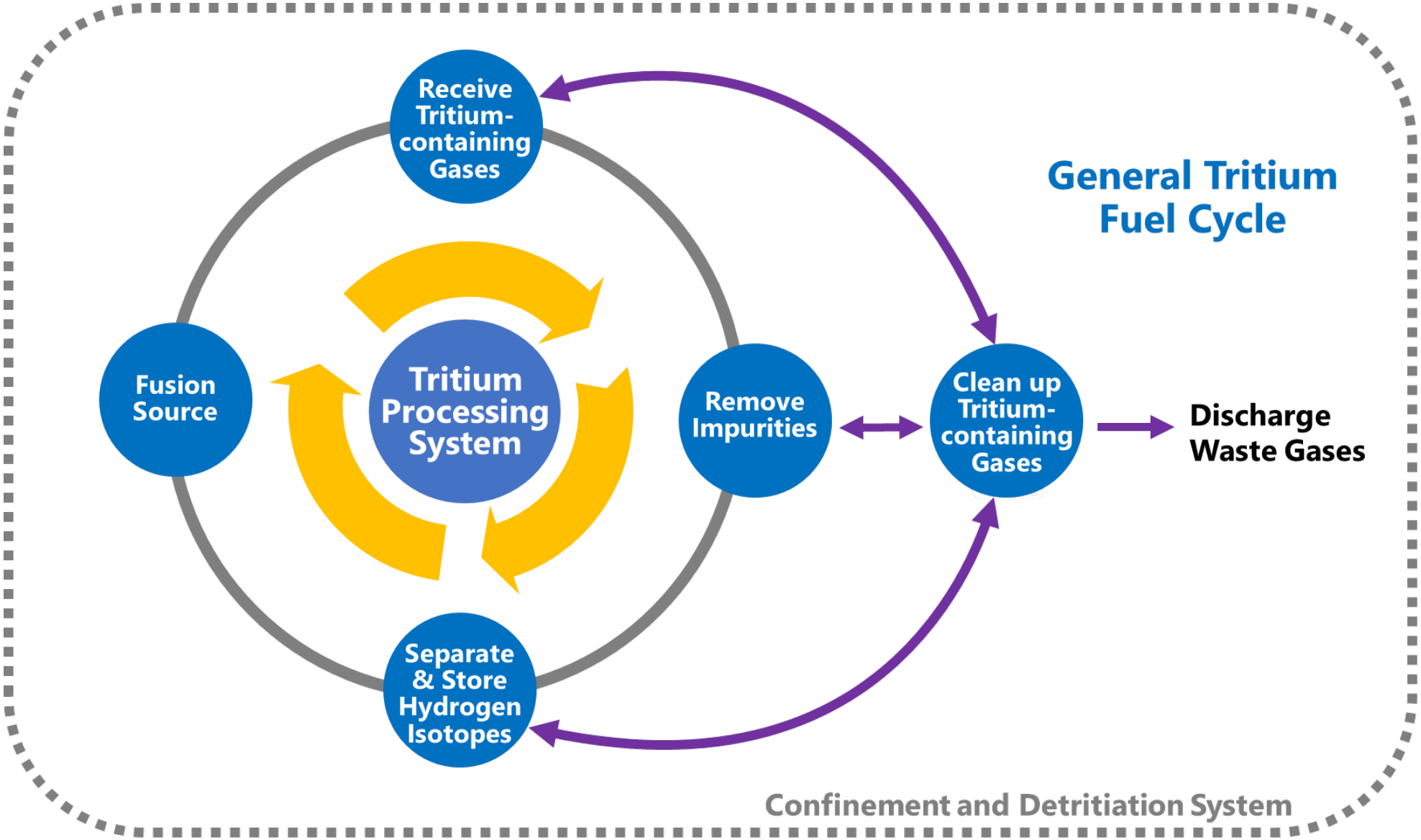
- **Tritium Process Technology Development** – Develop technologies and materials that assist with process intensification / scale-up of impurity removal, isotope separation, and storage and resolve process issues

- **Tritium Breeding and Extraction** – Understand tritium breeding for fusion energy systems as well as methods to extract and recycle tritium back into the process are critical for self-sufficiency

- **Environmental Confinement of Tritium** – Reduce releases of tritium by at least 2 orders of magnitude over state of the art methods and current technologies

- **Development of Improved Materials for Fusion Energy Systems** – Develop materials with improved properties such as corrosion-resistance, tritium damage resistance, tritium permeation barriers, as well as maintenance of these material properties / function during radiation exposure

Tritium Fuel Cycle: Similar for All Applications



Key Processes in Tritium Fuel Cycle

Remove impurities

- **Impurity Removal**
  - Hydrogen separation from impurities
  - He-3 cleanup

Separate hydrogen isotopes and Store

- **Hydrogen Isotope Separation**
  - Thermal Cycling Absorption Process (TCAP)
- **Hydrogen Storage**
  - Metal hydride beds/tanks with varying capacities
  - Material options and vessel designs based on temperature/pressure/purity requirements

Clean up tritium-containing gases

- **Waste Gas/Tritiated Water Processing**
  - Glovebox atmosphere detritiation
  - Tritium recovery from water
  - Detritiation of process effluent gases

- **Secondary Confinement**
- **Pumping (Evacuation/Circulation)**
- **Analytical Systems**
- **Tritium Accountancy and Tracking**

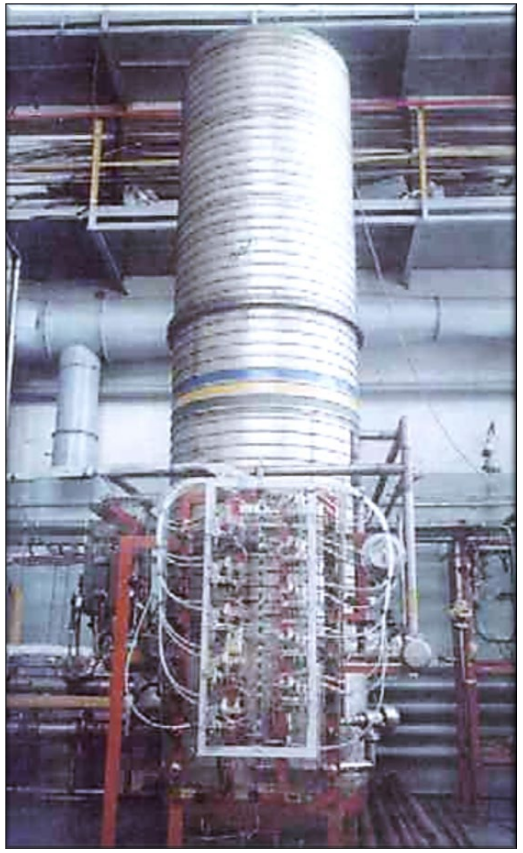
Tritium processing technology development is aimed at improving efficiency, decreasing operational costs, replacing aging technologies, reducing radiological footprint and tritium inventory, and allowing for more flexible operations to meet current and future demands.

Applied Research Center
Hydrogen Technology Research Laboratory

Process Intensification of Hydrogen Isotope Separation

Cryogenic Still (Second Generation Technology)

- 23 feet tall
- liquid helium refrigeration
- High maintenance



Thermal Cycling Absorption Process (TCAP): 1994

- About Three feet diameter and length
- 27X reduction in nuclear material at risk
- Size reduction allowed glovebox confinement that led to a 1000X reduction in environmental releases
- Higher Quality Gas

HT-TCAP: 2004

- Enhanced through-put saving $20M in project cost
- Reduced environmental release

Mini-TCAP

- Large briefcase
- >2X reduction in tritium process inventory
- 10X reduction in footprint
- 25% reduced heat load
- >2X throughput improvement
- Eliminates use of banned refrigerant

Micro-TCAP: 2014

- Further reduction in process inventory for small scale applications (LLE)

LLE Review Quarterly, Vol 144, DOE/NA/1944-1242, Jul–Sep 2015, Laboratory for Laser Energetics, Univ. of Rochester

SRNL Leverages Tritium Processing Expertise for a Variety of Applications including Fusion Energy

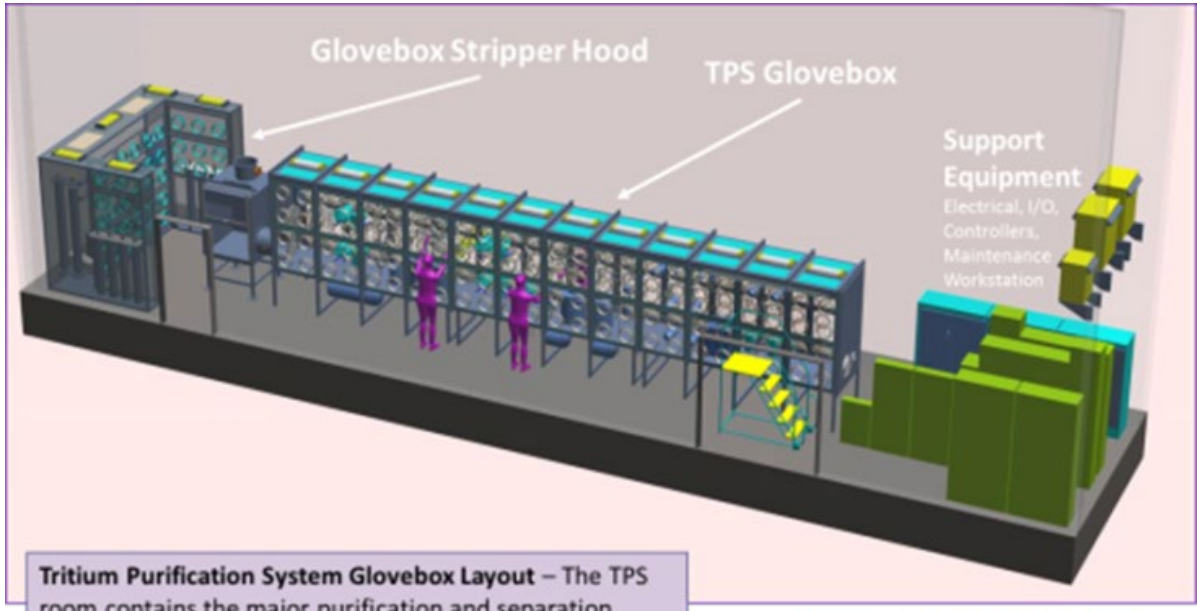
- **Tritium Processing at SRS**
  - Tritium Sustainment (NA-19)
    - » *Required Minimum Inventory (RMI), gas process modeling efforts, next generation tritium facility*
  - Facility Support (MR&R, RTBF), PDRD, LDRD
    - » *Bed life extension, hydride aging studies, tritium accountability, component testing, water splitting*
- **Fusion Energy Programs Support**
  - US ITER – Tokamak Exhaust Processing (TEP)
  - National Ignition Campaign (Rochester LLE, NIF – LLNL)
- **Commercial Accelerator Technology for Mo-99 Medical Isotope Production**
  - SHINE® Medical Technologies (NA-231)
    - » *Tritium Purification System*
    - » *SHINE TCAP (isotope separation) System*
    - » *Accelerator-Target System Interface*
- **Other Programs**
  - Nuclear Safety R&D (NSR&D) - Highly Tritiated Water, Tritium Oxidation
  - Thomas Jefferson National Accelerator Facility (TJNAF)

National Nuclear Security Administration

SAVANNAH RIVER TRITIUM ENTERPRISE

iter
china eu india japan korea russia usa

NIF

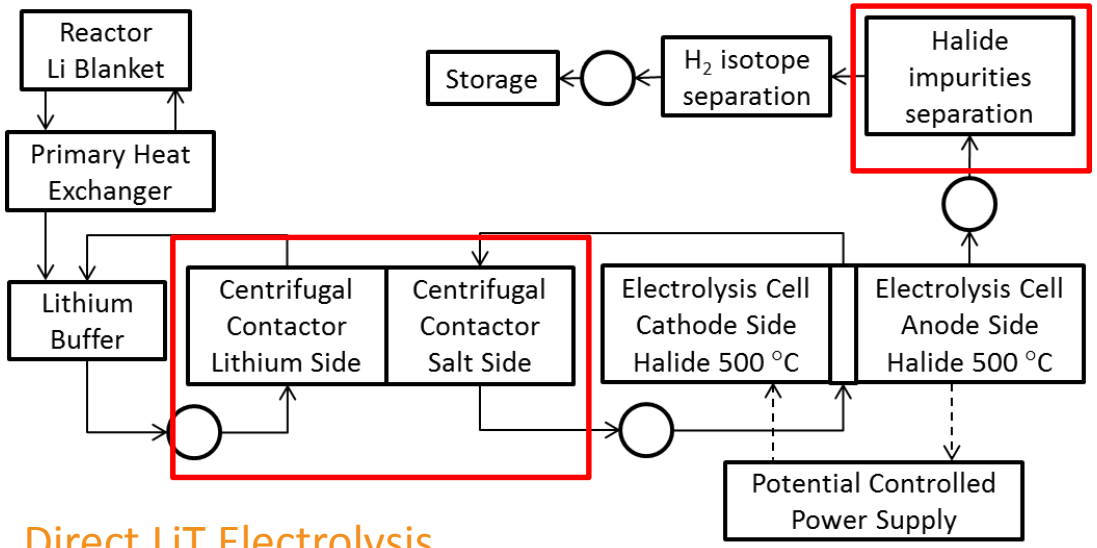


Tritium Purification System Glovebox Layout – The TPS room contains the major purification and separation components, including a glovebox stripper system.

SHINE Medical Technologies

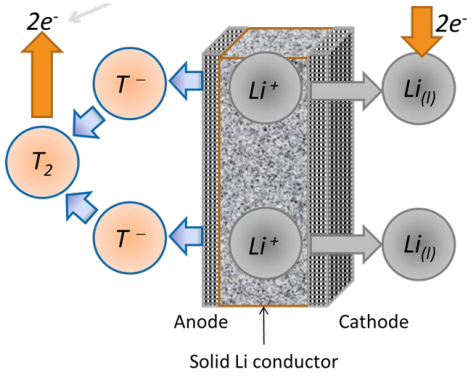
SRNL Direct LiT Electrolysis Process Flow Diagram

Maroni Process

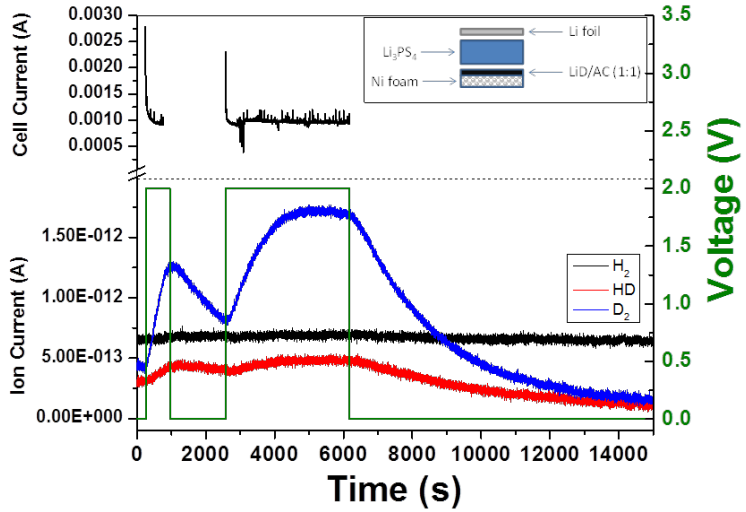


Lithium Conducting Electrolyte

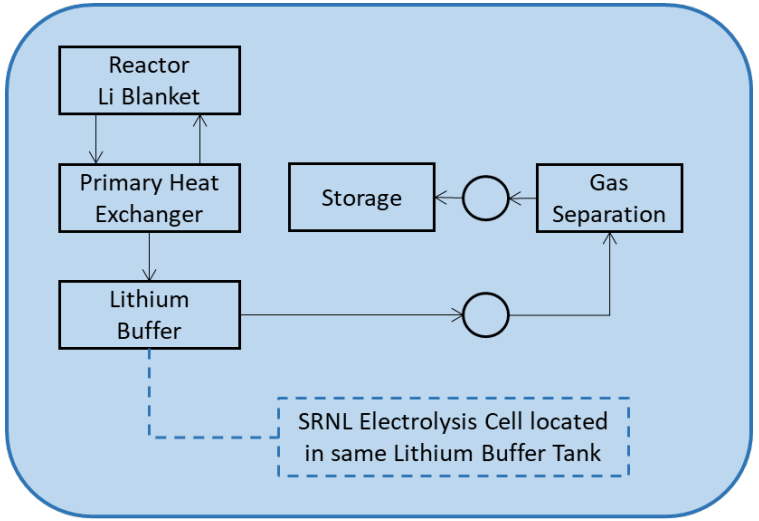
$$2LiT \rightarrow 2Li^{+} + T_2 \uparrow + 2e^{-} \qquad Li^{+} + e^{-} \rightarrow Li$$



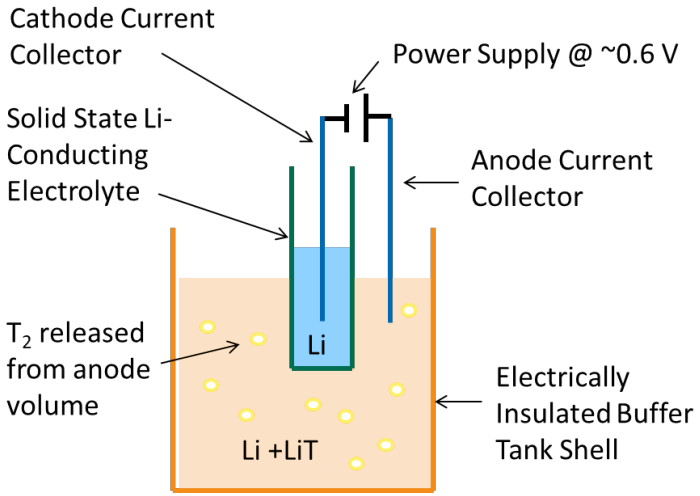
$$E^{0}_{400°C} = -2.82V \qquad E^{0}_{400°C} = -3.22V$$

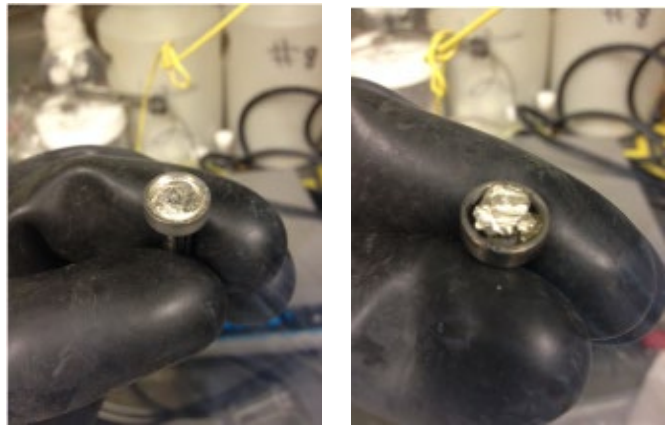


Direct LiT Electrolysis



Lithium Buffer Tank

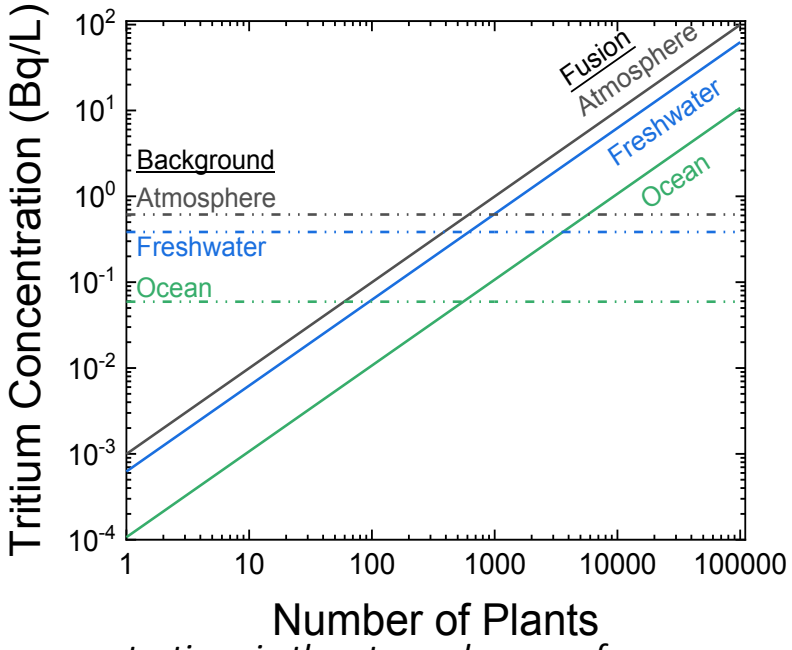




J. A. Teprovich, H. R. Colon-Mercado, L. Olson, P. Ganesan, D. Babineau, B. L. García-Díaz, "Electrochemical extraction of hydrogen isotopes from Li/LiT mixtures," *Fusion Engineering and Design*, 139, 1-6, 2019.

Potential Environmental Impact Modeling of Fusion Due to Tritium Emissions

- On the global scale, tritium is only removed slowly via decay and diffusion into ocean depths (dilution)
- The increase in global tritium from fusion will be detectable above background
  - *Developed a global hydrological model to begin investigating the effects of widespread tritium emissions from fusion*
- As few as 5 fusion plants could increase tritium levels by 1% over background levels



Tritium concentrations in the atmosphere, surface freshwater, and ocean surface water versus number of 500 MW fusion plants releasing 1 gram/yr into the atmosphere.

- If fusion power accounts for a large portion of the baseload power, environmental tritium targets may be exceeded without significant technology improvements
  - *Assuming 50% of the installed electrical capacity of the seven members of ITER (50% 13.2 billion kW)*
  - *Tritium is released either to the atmosphere or to surface freshwater*

Surface Freshwater Release Fraction	Tritium Concentration (Bq/L)						
	Atmosphere	Surface Soil	Deep Ground	Surface Freshwater	Inland Seas	Ocean Surface	Deep Ocean
0	13.15	10.37	0.53	8.23	0.24	1.41	0.0015
0.2	10.80	8.52	0.44	31.52	0.20	1.38	0.0014
0.4	8.45	6.66	0.34	54.80	0.15	1.34	0.0014
0.6	6.10	4.81	0.25	78.09	0.11	1.31	0.0013
0.8	3.75	2.96	0.15	**101.38**	0.068	1.27	0.0013
1	1.40	1.11	0.057	**124.66**	0.025	1.23	0.0013

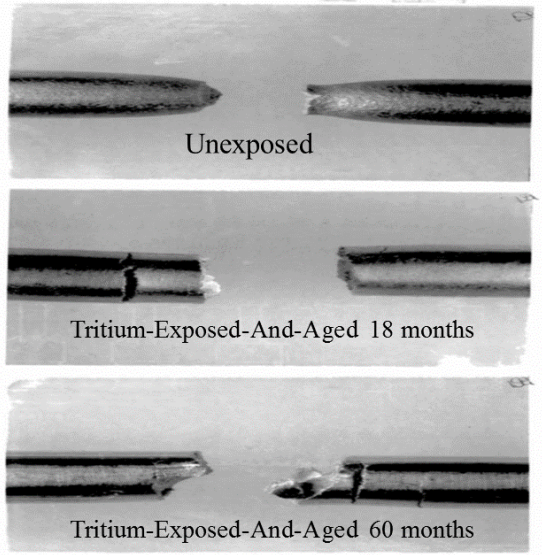
Tritium concentrations for increasing surface freshwater tritium effluents. The values in bold exceed the European Union drinking water limits (100 Bq/L)

Note: WHO considers ~10000 Bq/L safe. But, California EPA has a 14.8 Bq/L target; Ontario - recent push for 20 Bq/L

Larsen, G. and Babineau, D., "An Evaluation of the Global Effects of Tritium Emissions from Nuclear Fusion Power", *Fusion Engineering and Design*, In Preparation.

Tritium Effects on Materials

- **Tritium embrittlement discovered at Savannah River Lab (SRL) in 1979**
- **In metals tritium embrittlement is a combination of hydrogen and helium embrittlement effects**
- **At SRNL we have studied tritium effects on a wide range of materials including polymers structural materials, hydrogen storage materials and polymers**
- **We mainly study tritium effects on materials using an accelerated aging technique**

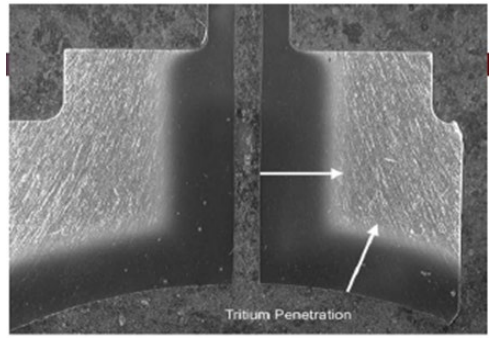


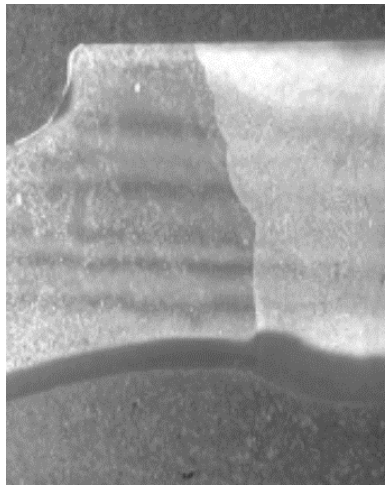
Source: SRL Notebook Dave Rawl, 11/7/79

Fusion related materials

These effects are particularly important in two classes of fusion related materials materials :

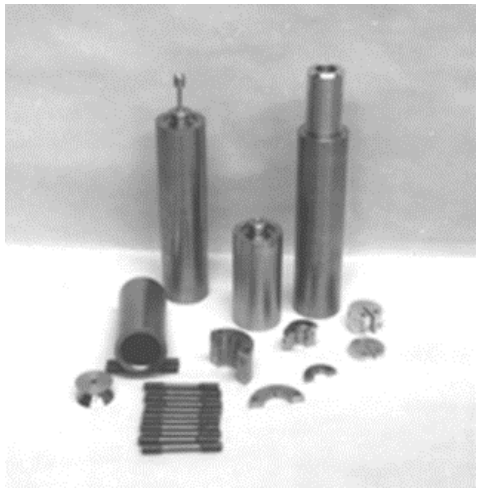
1. **Hydrogen/^{3}He embrittlement effects on tritium facing process materials (pipes valves, pumps, etc.):** Outside the reactor and blanket tritium embrittlement will be a major factor in the lifetime of tritium facing process components
2. **^{3}He retention and embrittlement in PFCs:** The majority of the ^{3}He present in tungsten PFCs will be due to tritium decay unlike other reactor and blanket materials where neutron interactions lead to significant ^{3}He production. To simulate this effect tritium accelerated aging is needed because it cannot be replicated with a neutron fluence. Of interest are both the structural effects of ^{3}He as well as the T/^{3}He trapping behavior





Tritium Autoradiography Reveals Penetration in Stainless Steel and Welds

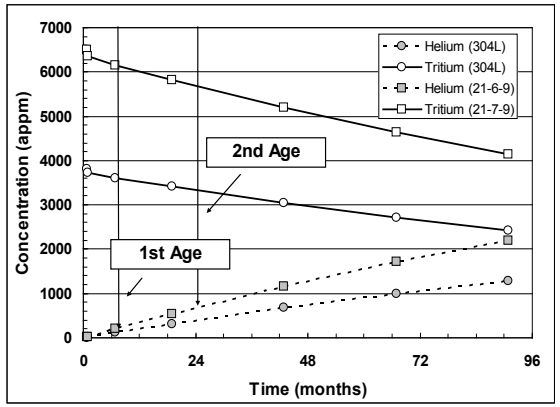
Tritium Accelerated Aging of Materials



Exposure

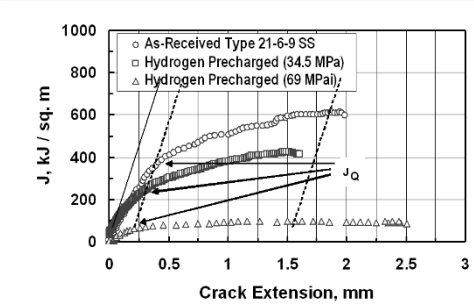
Hydrogen/Tritium Exposure at elevated temperature and pressure followed by low temperature aging to build-in helium Without Losing Tritium.

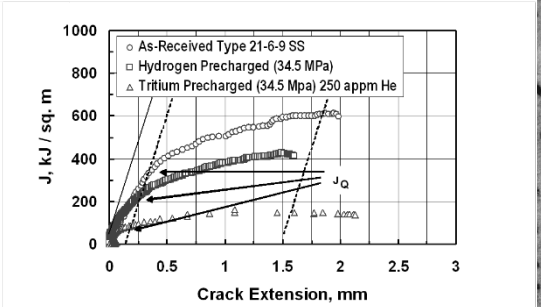
- For common steel alloys ~350 °C and 35 MPa is high enough for to saturate samples with tritium but low enough to minimize any change in microstructure.
- Age at -50 °C to limit tritium off gassing and build in varying levels of T_2 decay He.



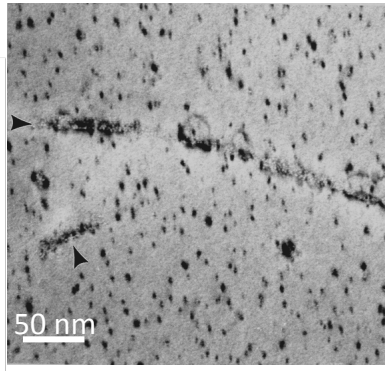
Characterization

Mechanical testing performed in a tritium hood for off-gassing containment





- J-Integral fracture toughness properties are decreased with increasing hydrogen exposure pressures.
- Properties decrease further with aging from build in of decay helium.



Nanometer sized bubbles randomly distributed and clustered on defects

Tosten, M. H. and M. J. Morgan (2009). *Transmission Electron Microscopy Study of Helium Bearing Fusion Welds.* 2008 Int. Hydrogen Conf. - Effect of Hydrogen on Materials, Materials Park, OH

Conclusions

The Tritium Fuel Cycle will be an Important Need in Fusion Energy Facility Design

- Tritium processing needs for fusion energy are similar to other systems utilizing a tritium fuel cycle
- Five Main Research Needs to Enable Commercialization of a Compact System
  - Tritium Inventory Reduction
    - *More closely match tritium processing rates to tritium feed rate into the fusion machine*
  - Improvement and Intensification of Tritium Process Technologies
    - *Improvement of tightly coupled heat and mass transfer limited systems such as TCAP for isotope separation*
  - Tritium Breeding and Extraction
    - *Ensure breeding ratio can be achieved and that tritium can be extracted from blanket at a rate that will sustain the fusion economy*
  - Environmental Tritium Confinement
    - *Reduce tritium emissions by improving facility-wide tritium confinement*
  - Development of Advanced Tritium Wetted Materials
    - *Develop tritium permeation barriers, tritium resistant materials, and corrosion-resistant materials / coatings*
- SRNL has unique capabilities, technologies, and experience in tritium and is willing to partner in developing fusion energy technologies

SRNL Capabilities and Expertise

- **Design and Testing of Tritium Processing Systems**
  - Design & testing of hydrogen isotope separation processes, impurity removal, and tritium storage systems
  - Tritium analytical characterization and tritium accounting
  - Development of novel materials for tritium processing
- **Testing of Tritium Effects on Materials**
  - Accelerated Aging
  - Mechanical testing of tritiated sample
  - Characterization of tritiated samples (e.g. – TEM, SEM/FIB)
  - Hydrogen isotope permeation of materials
- **Metallurgy / Additive Manufacturing**
  - Welding / joining for tritium applications
  - Characterization of AM components
- **High Temperature Corrosion and Electrochemistry**
  - Testing of material durability with exposure to lithium alloys, molten salts, or other aggressive environments
  - Development of high temperature electrolytes and electrodes for electrochemical processes / characterization
- **Advanced Spectroscopy for Tritium Applications**
  - Application of spectroscopy for tritium applications
    - *Ultrafast Raman, IR, Cavity Ringdown, GC/DID, MS*
  - Development of sensors for tritium applications
    - *QEPAS, Ion Chambers, Calorimeters*
- **Modeling / Simulation**
  - Systems Engineering, Modeling, and Analysis
    - *Discrete Event Modeling*
  - Multi-physics modeling / CFD modeling
  - Ab-initio modeling
  - Flowsheet modeling (e.g. ASPEN)
  - Neutronics modeling