Tritium fueling, processing and handling

Heena K. Mutha, PhD

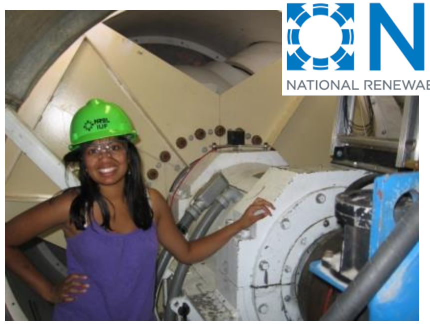
June 2021

Commonwealth Fusion Systems

My journey to fusion starts with wind turbines, micro-nanoengineering, and electrochemical systems

Olin College of Engineering

B.S. Mechanical Engineering

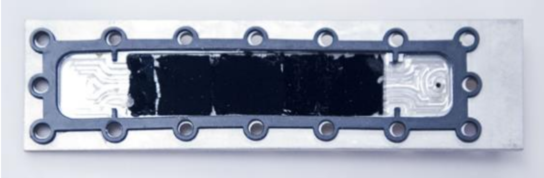


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

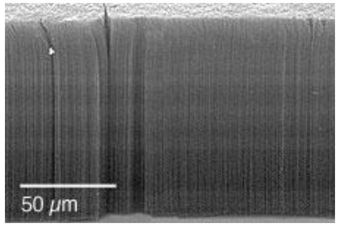
SULI

FULBRIGHT

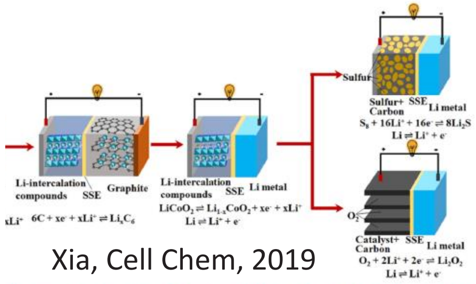
MIT



Stuart Darsch, MITEI News



M.S., PhD Mechanical Engineering minor in electrochemistry



Xia, Cell Chem, 2019

DRAPER

Senior Member of Technical Staff Materials and Devices

Transitioning my experience to CFS as the Fueling and Tritium System Responsible Officer

Experience:

- Worked on fluidic, biologic, chemical, and lithium metal-based systems
- Comfortable designing, analyzing, storing, and automating experiments and test data
- Coordinating multiple levels of staff and engineers to execute and drive projects
- Set up equipment, testing apparatus, systems, labs from scratch
- Comfortable moving between modeling, design, test, validation

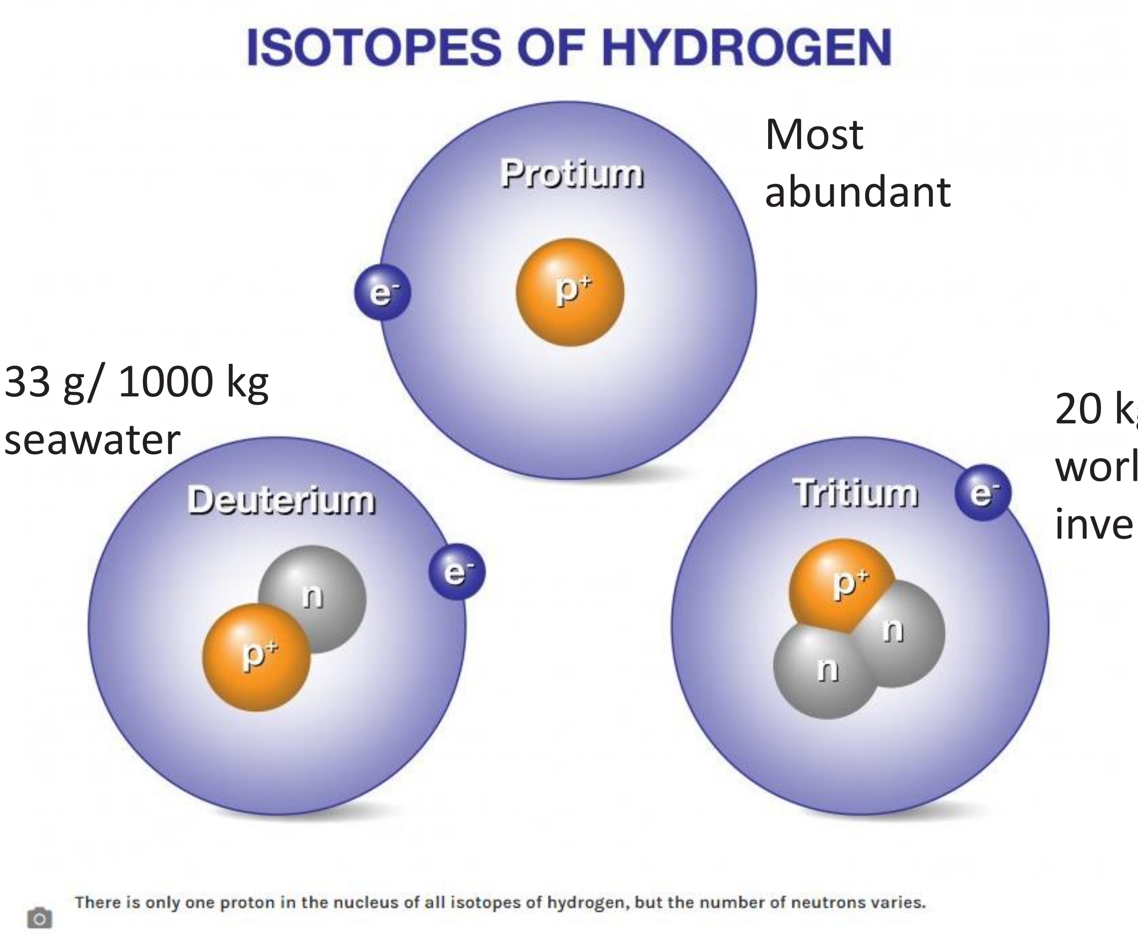
→

Fueling and Tritium SRO

- Excited and able to learn about tritium systems and transition existing know-how in-house to design, build, and test the tritium system
- Identify unknowns, required storage and flow specifications, operating pressures and temperatures
- Build a tritium team comprised of engineers, staff, co-ops
- Comfortable presenting and debating concepts with experts and engineering teams
- Able to develop schedules, budget, identify engineering challenges and maintain critical path

Fun fact: I pulled this from my CFS interview slide deck

Hydrogen isotopes: deuterium and tritium have been used to generate fusion energy



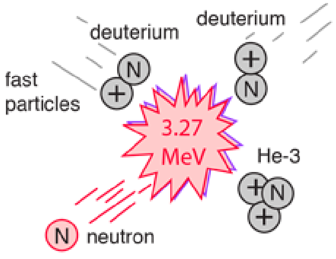
Most abundant

33 g/ 1000 kg seawater

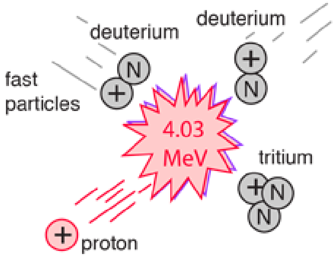
20 kg total world inventory

$${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n + 3.27\,MeV$$

Deuterium-deuterium Fusion

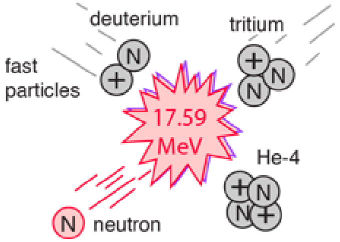


$${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{1}H + {}^{1}_{1}H + 4.03\,MeV$$



$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.59\,MeV$$

Deuterium-tritium Fusion



DT fusion generates more than **4x** more heat than DD fusion

Fusion is > 4 million times more energy dense than coal-fired power plants

DD fusion has allowed us to study many plasma properties, but moving fusion back towards DT enables high power fusion (Q>1)

DD fusion

General Atomics DIII-D

National Spherical Torus Experiment (NSTX-U) , PPPL

Alcator C-mod, MIT (1991-2016)

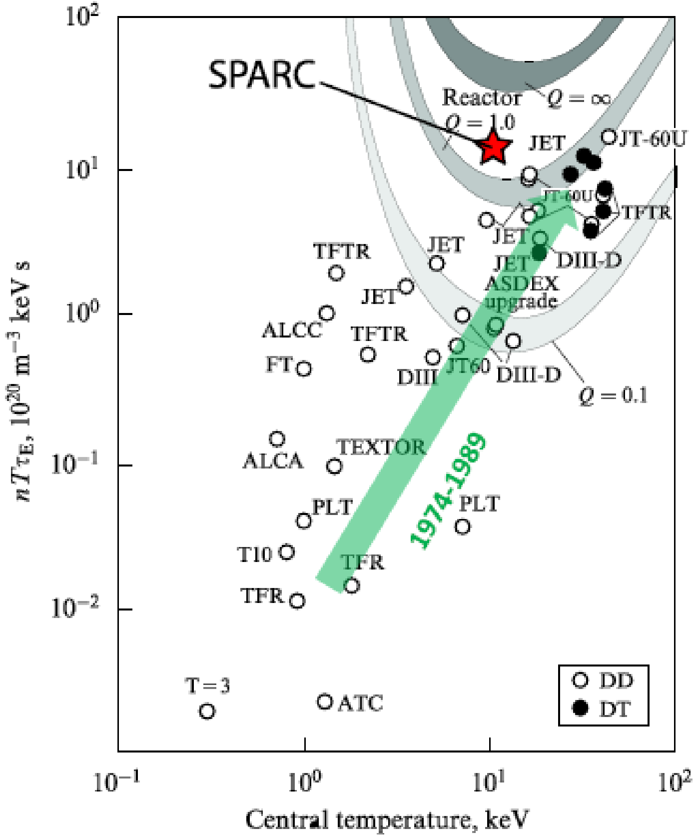
DT fusion

National Ignition Facility (LLNL)

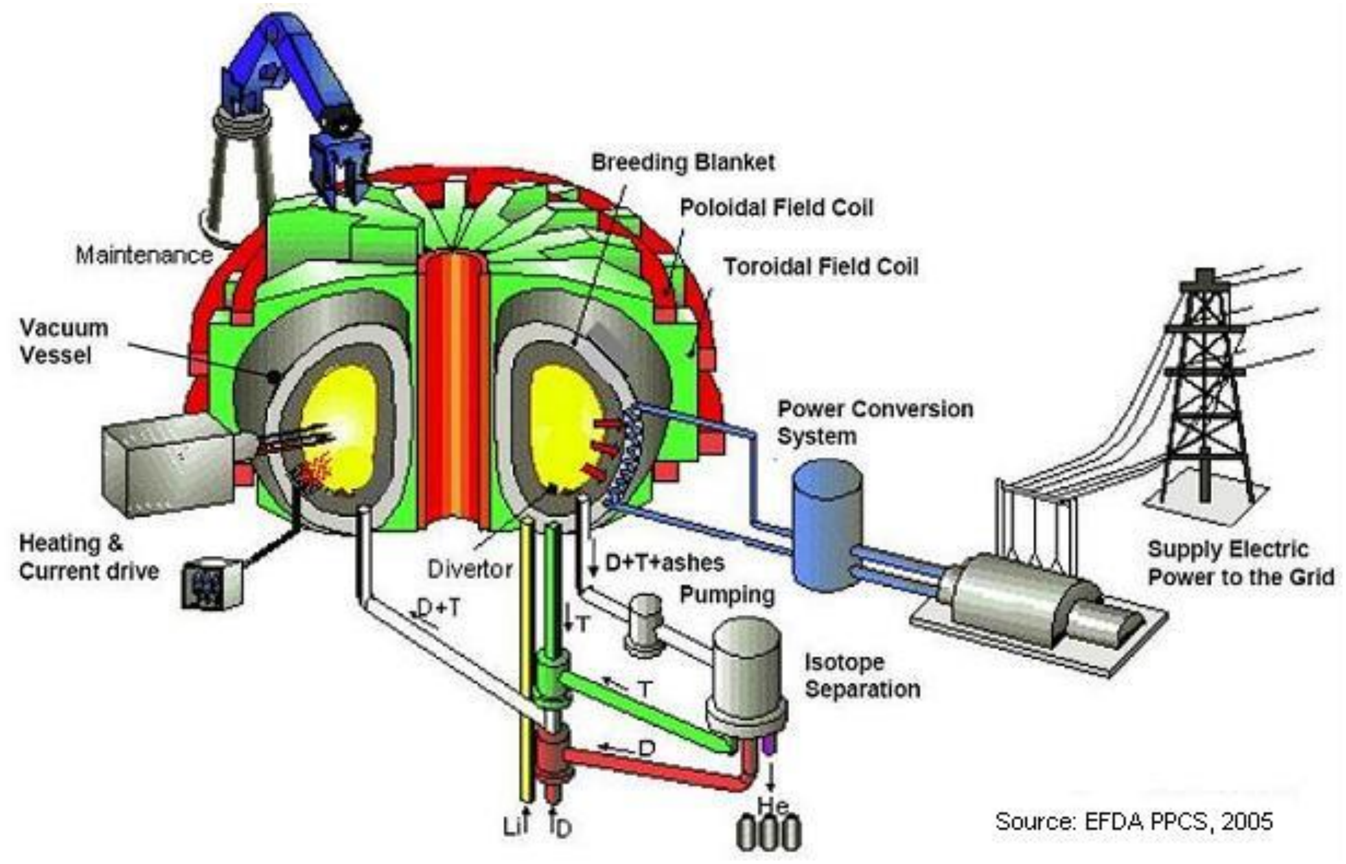
University of Rochester, LLE

Joint European Torus (JET), UKAEA

Tokamak Fusion Test Reactor (TFTR) (1989-1997)



The Deuterium-Tritium fusion gas cycle is designed for tritium recycling and reuse of fuel

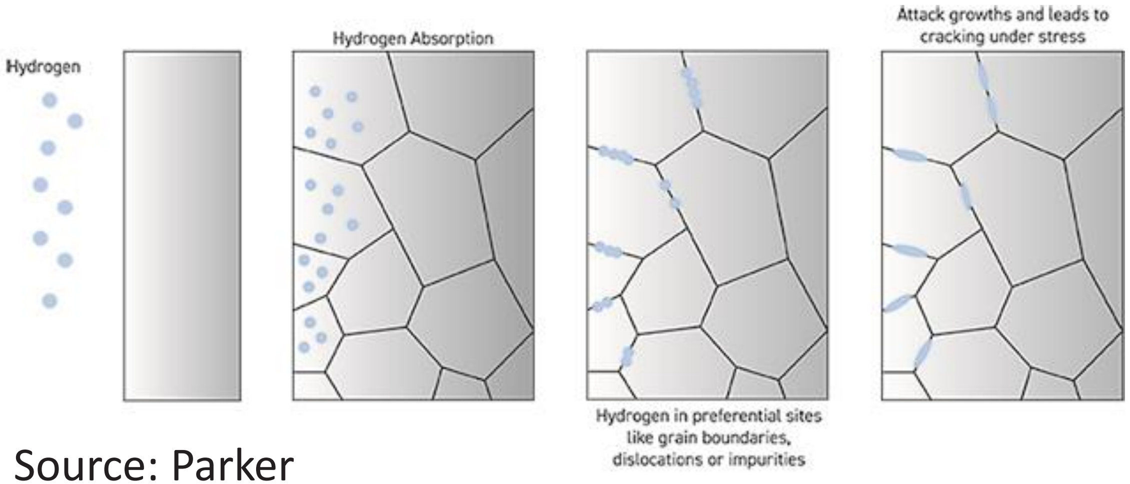


In a fusion power plant, neutrons will react with a lithium breeder blanket to generate tritium fuel which will be purified and recirculated into the fuel stream

Hydrogen systems are designed to prevent explosions (4% in air), while tritium systems are designed to minimize inventory and losses

- Hydrogen systems can use high concentration hydrogen, at high pressures, and are designed to prevent explosions
- Tritium systems are ~gram scale –never an explosion risk, and designed for vacuum operation
- Tritium is a weak beta emitter: decays to helium by releasing an energetic electron
  - Beta particles can only penetrate through 6 mm in air
  - Goal: keep concentrations as low as possible (1 ppm is a very high concentration)

Tritium systems are designed to minimize inventory, limit diffusion, reduce tritiation of compounds



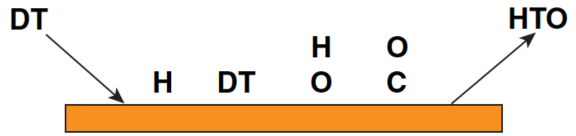
Source: Parker

Useful conversion factors:	
1 cc T_2 (STP)	2.588 Ci
1 ppm	2.588 Ci/m^3
1 gram of T_2	9615 Ci

The design of deuterium-tritium fusion facilities has unique considerations from deuterium-deuterium reactors

- The tritium inventory is collected, stored, and monitored. Over 99.99% of the tritium from the plasma fuel is recycled and purified
- Tritium is unique to deuterium because it has some beta energy and therefore exchanges with protium in many compounds
  - H2, D2, T2 can mix to become HT, DT, etc.
  - H20 can become HTO
  - Organics can swap H with T: elastomers corrode, oils can become tritiated

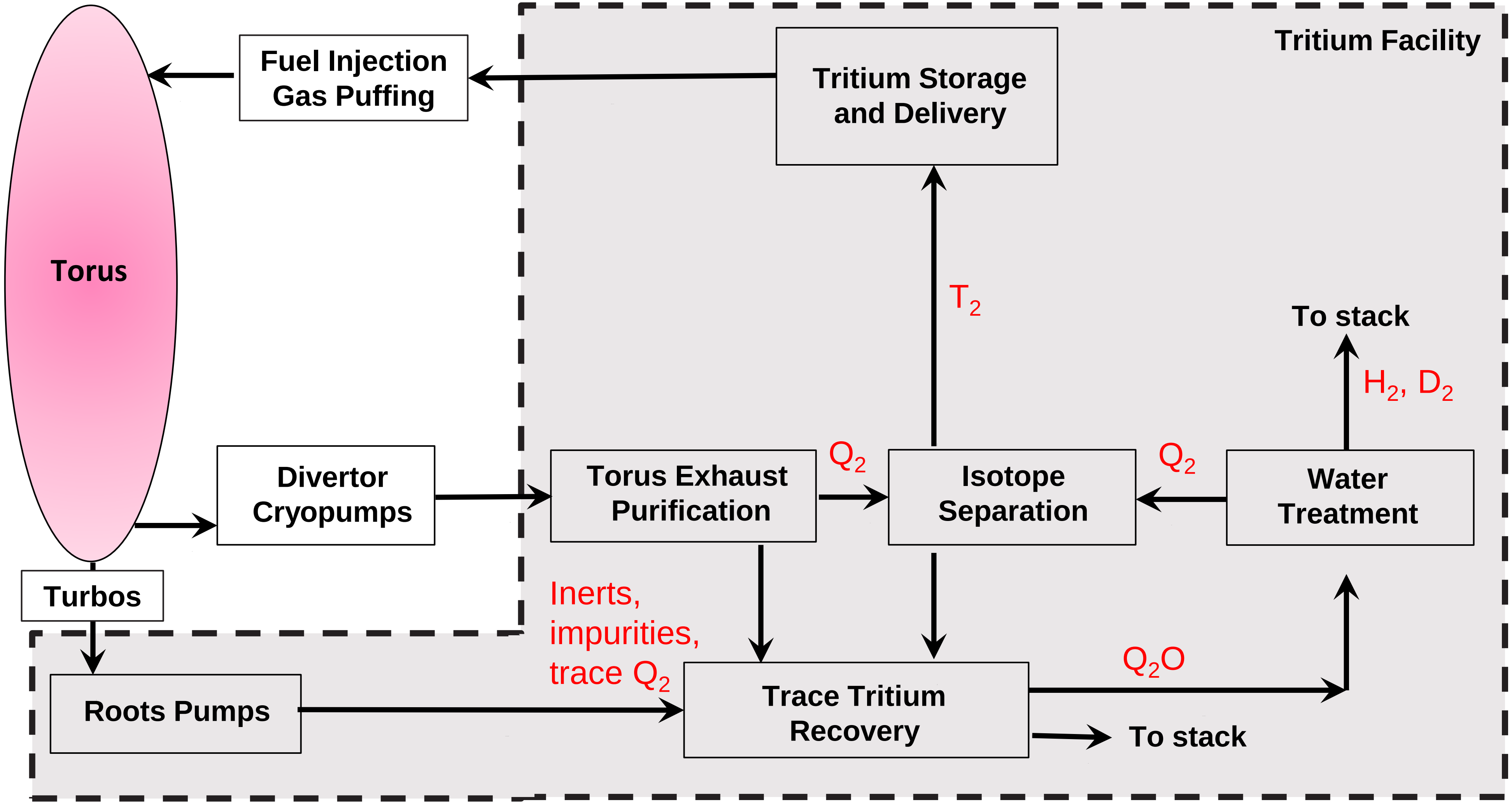
- **Elemental:** H_2, HD, HT, D_2, DT, T_2
  Water: H_2O, HDO, HTO, D_2O, DTO, T_2O
  Organic: CH_4, CH_3D, CH_3T, HCOOT, TCOOH



Credit: W. Shmayda

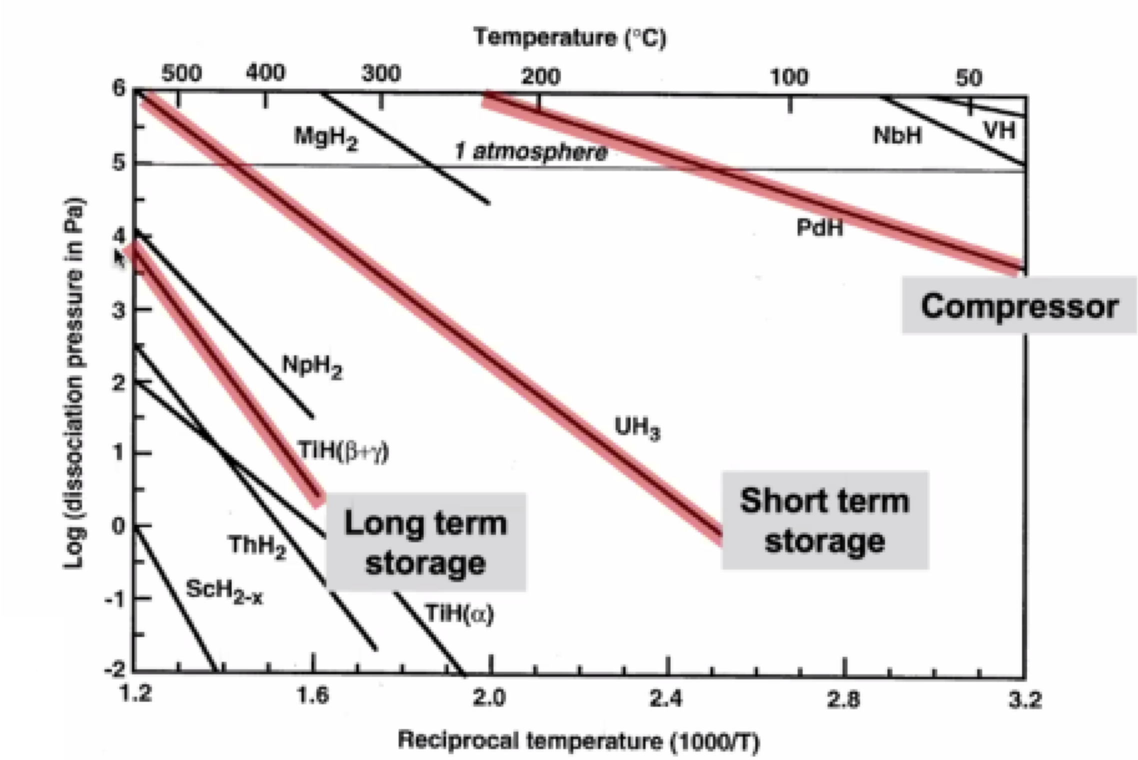
Tritium handling is designed with all-metal seals and take advantage of surface and bulk chemistry discoveries for managing tritium

The SPARC fuel cycle is designed for short pulse DT fusion for Q>1

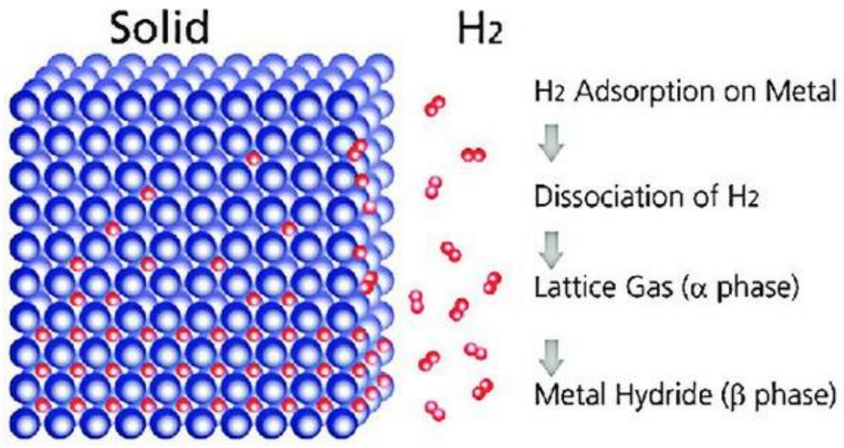


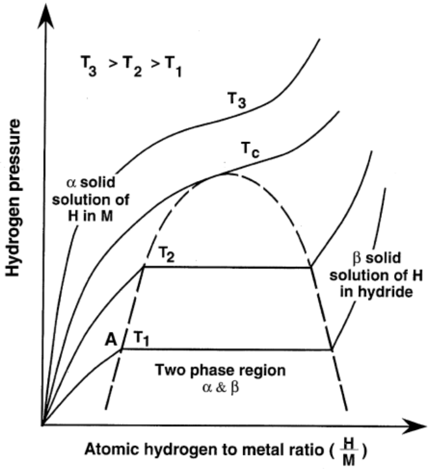
The tritium plant is designed to take tritiated process gas mixtures, separate and purify tritium, and minimize tritium emissions to trace quantities.

Tritium Storage: tritium is stored as a metal tritide (hydride)

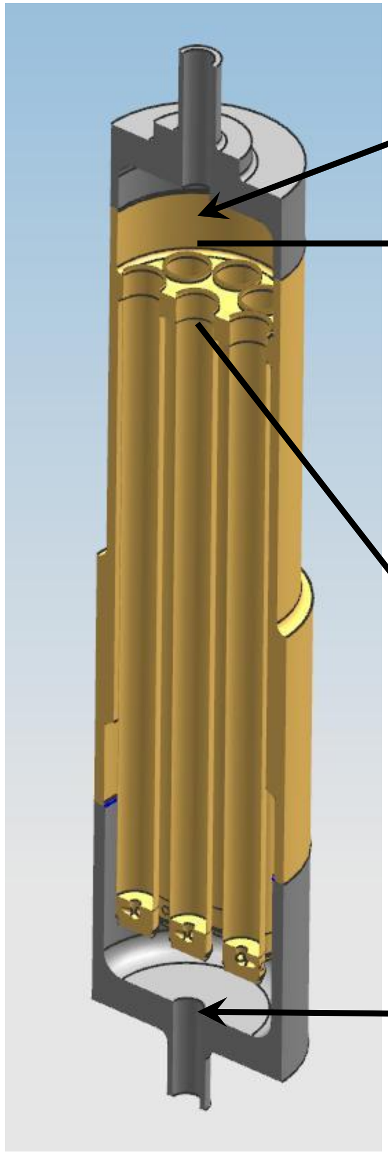


Shmayda, TRANSAT workshop 2021

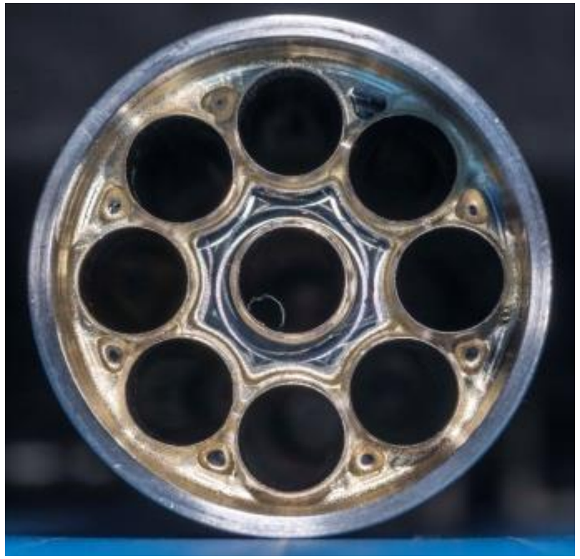




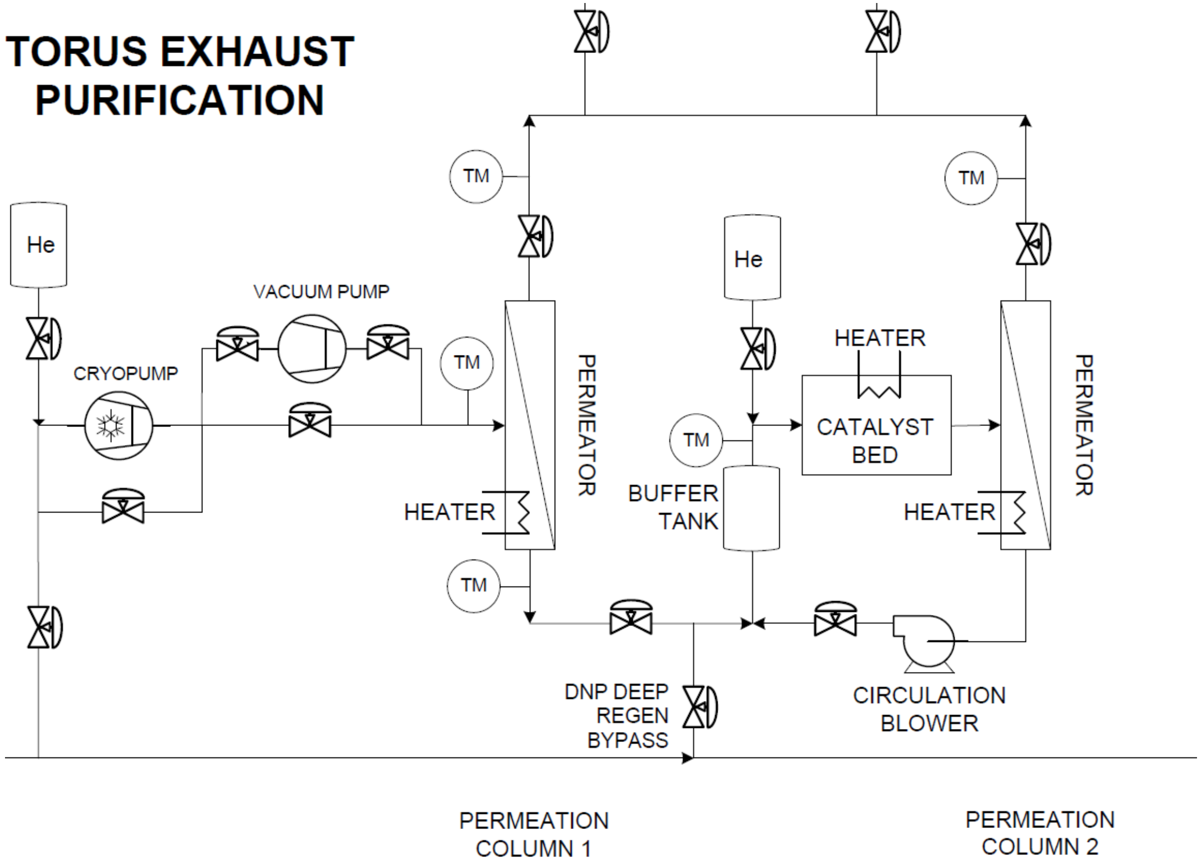
Torus Exhaust Purification collects high tritium concentration streams and uses a catalytic permeator to separate hydrogenics from other gas species



Low Pressure Side
Volume 11 cc

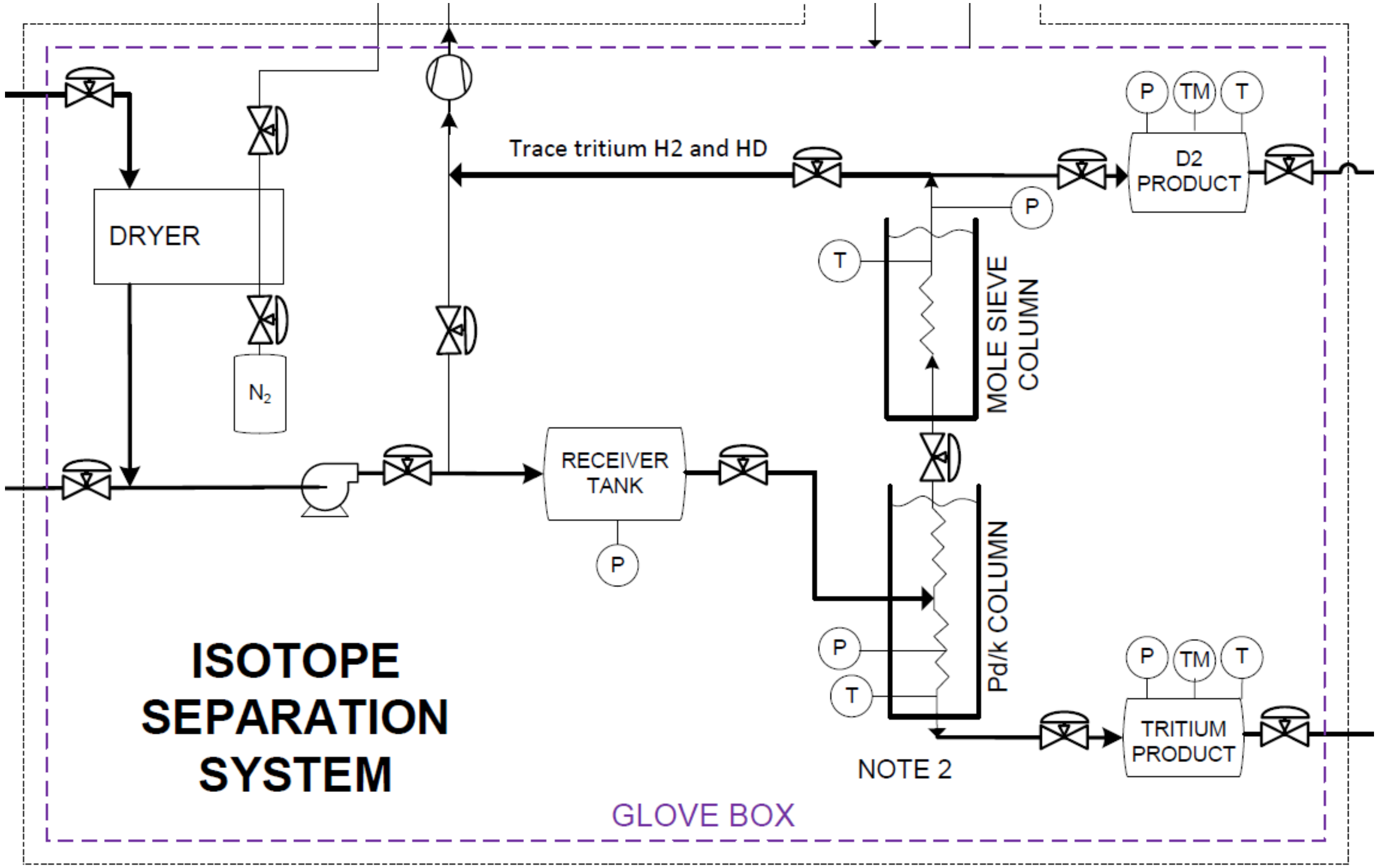


High Pressure Side
Volume 27 cc

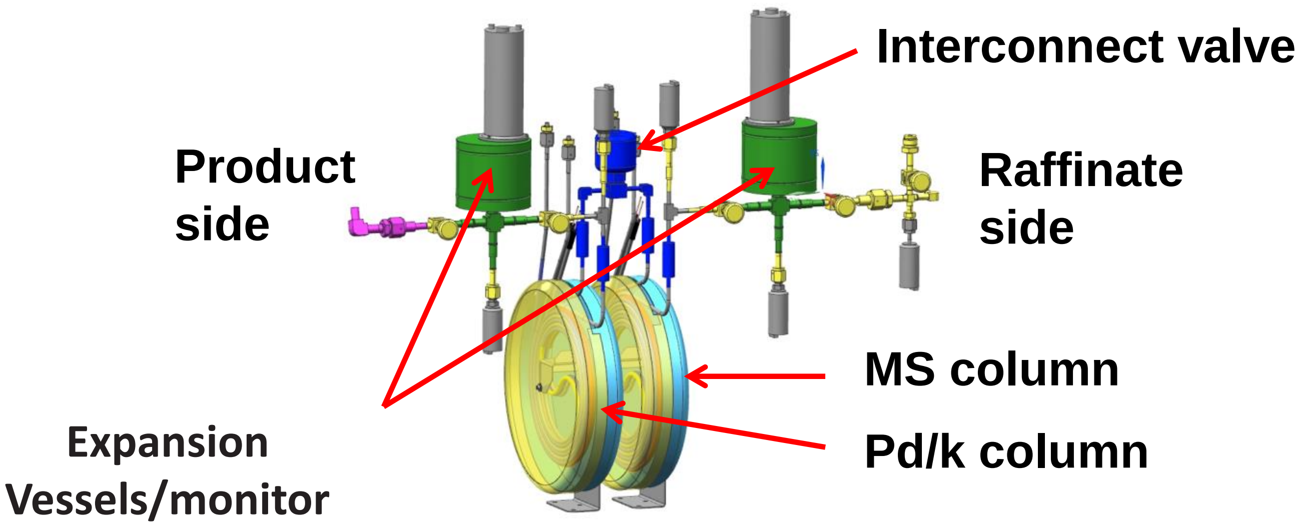


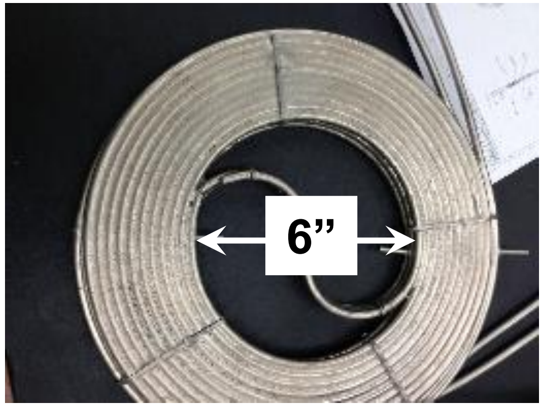
Isotope Separation Systems uses a combination of Pd/k and mole sieve columns to separate T from D and H

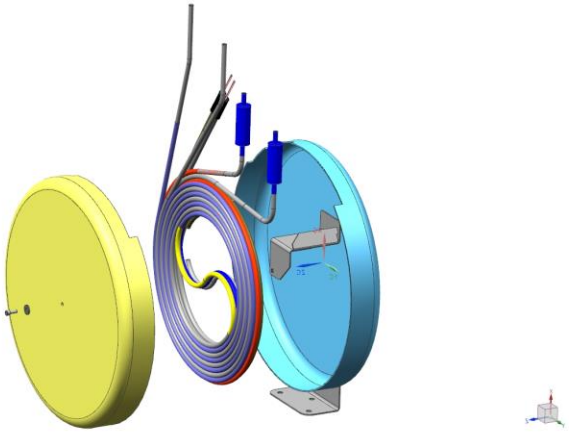
Credit: W. Shmayda

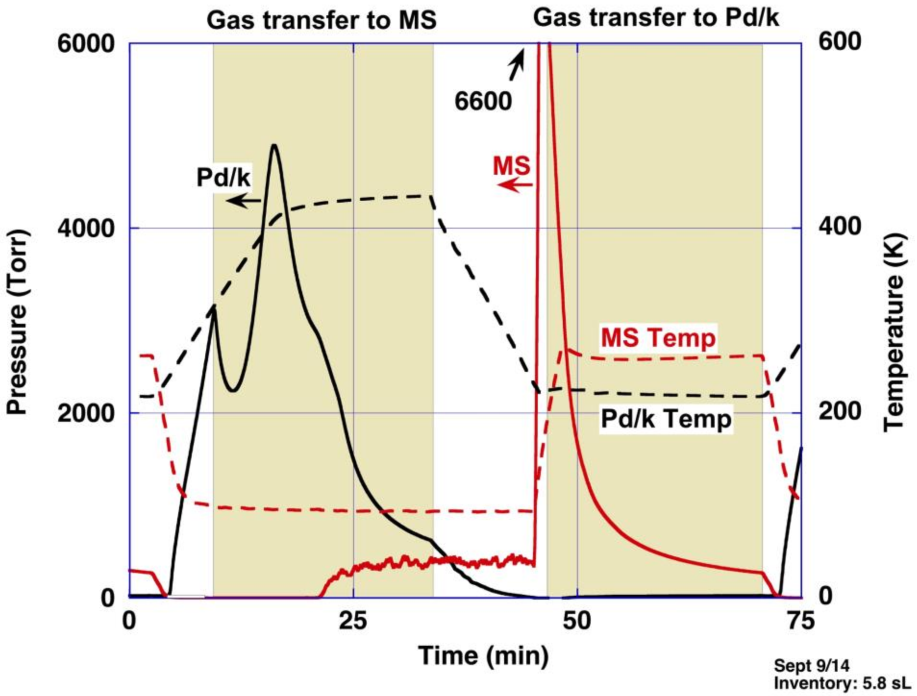


Isotope separation is based on shuffling elemental hydrogen between Pd/k and molecular sieve (MS) coils





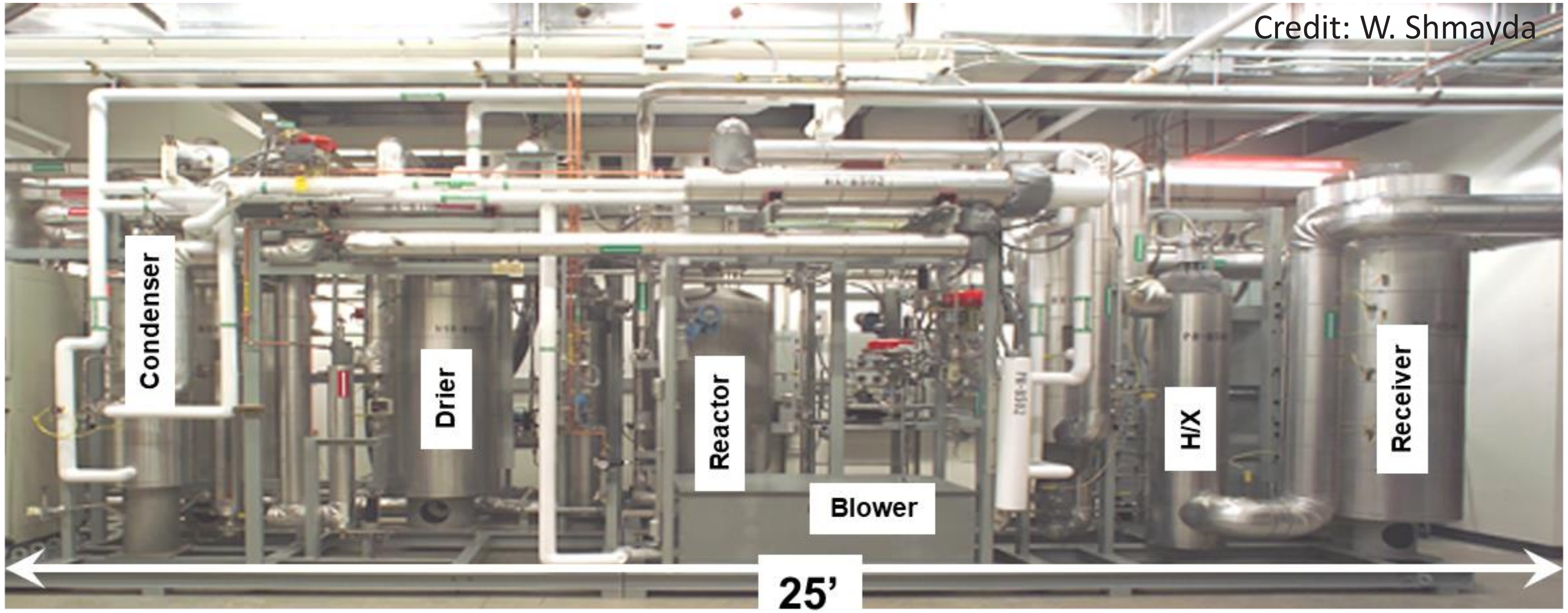




Credit: W. Shmayda

- The Pd/k coil sorts atomic hydrogen
- The MS coil sorts molecular hydrogen isotopologues
- Coil capacity 6.5 sL

Detritiation for further collection: combustion and water generation



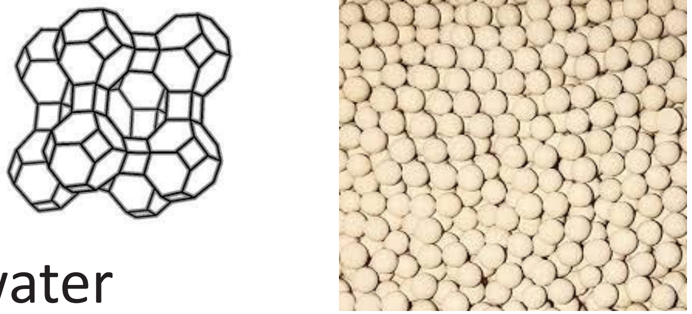
Combustion:

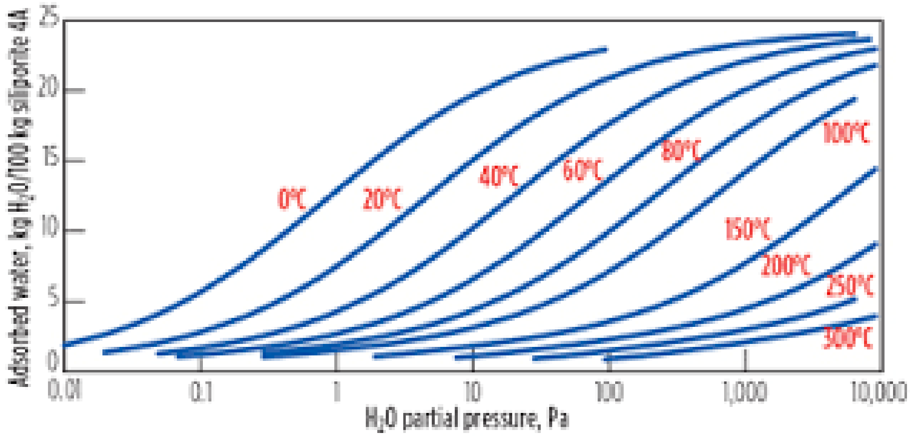
Tritiated organics + air

→ $CO_2 + Q_2O$

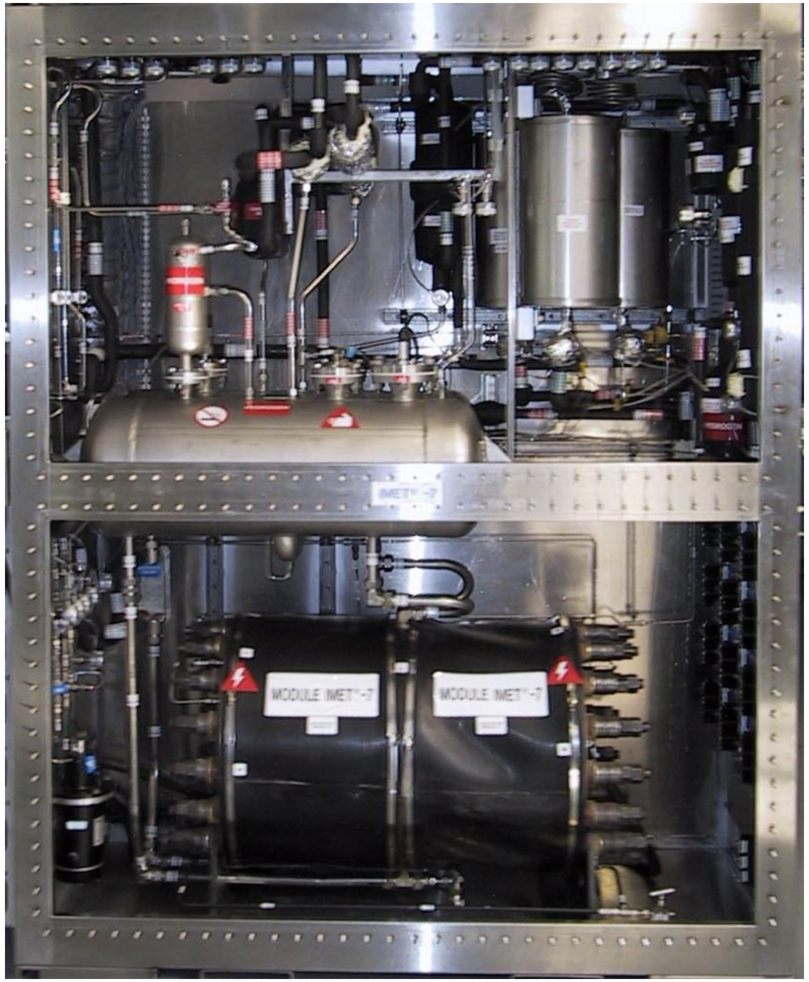
Drier (molecular sieve adsorbent):

Crystal structure size selective for trapping water

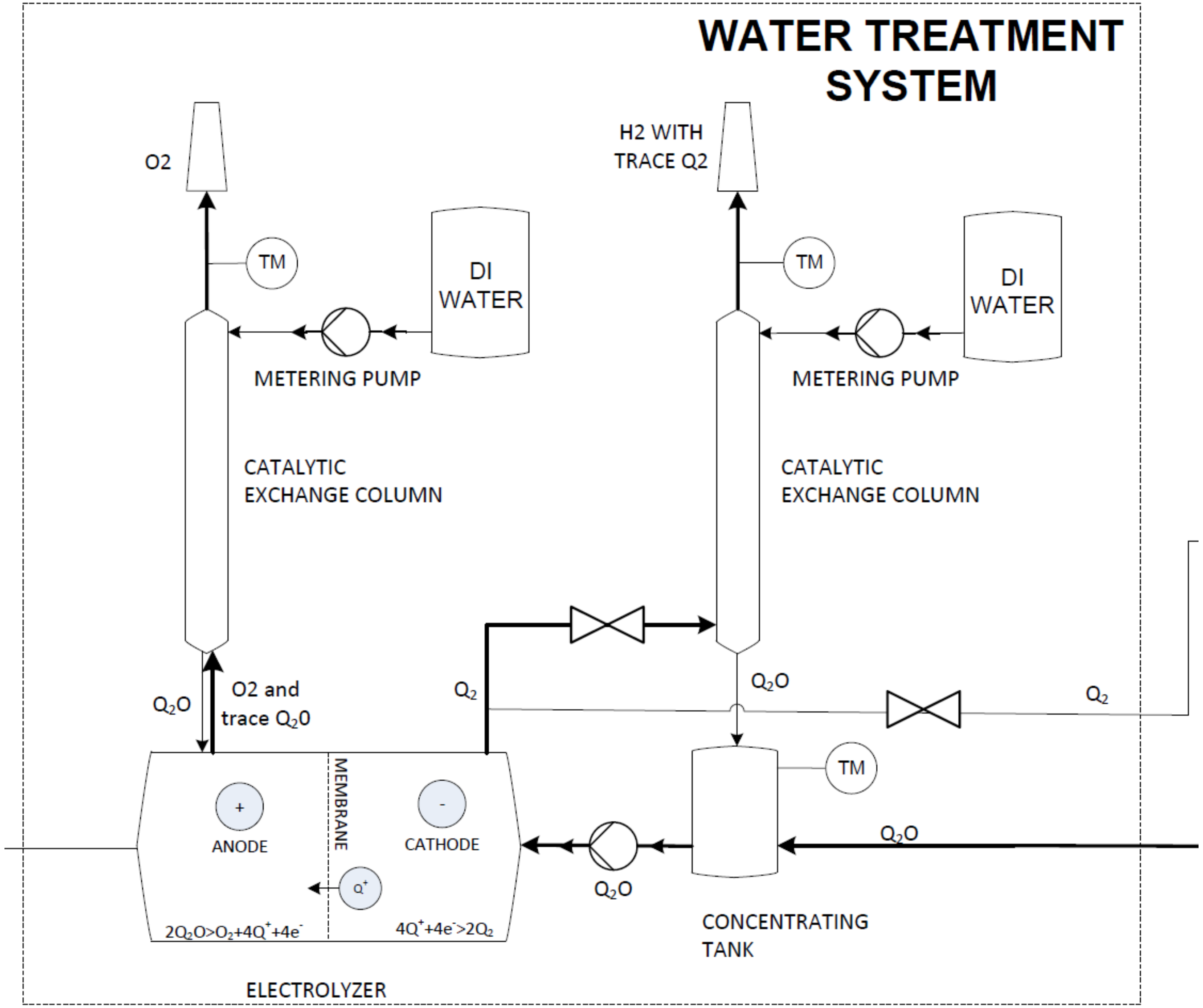




Detritiation for further collection: electrolysis to collect tritiated gas

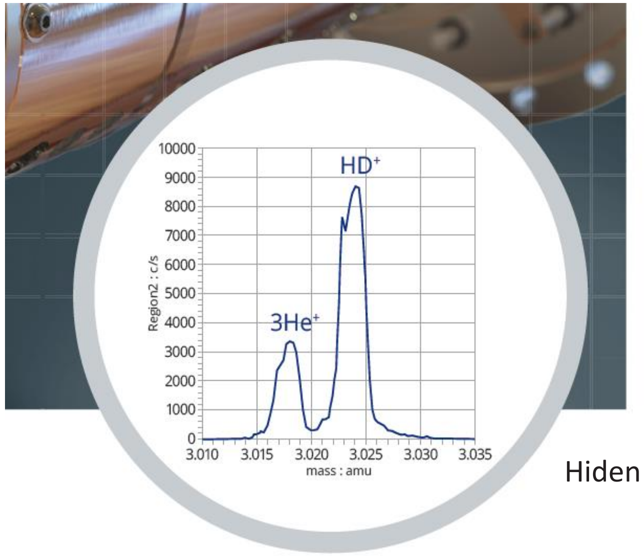


Credit: W. Shmayda

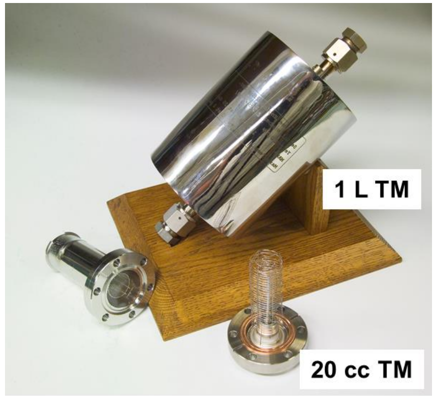


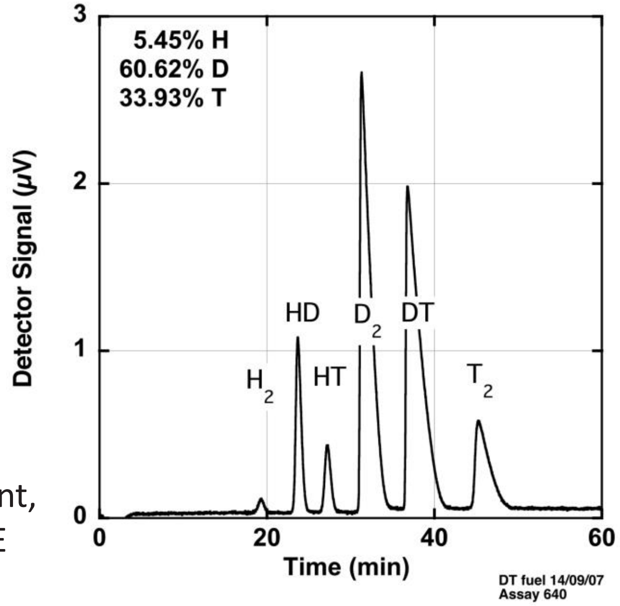
Tritium measurements and accounting

- Traditional gas techniques: mass, charge, gas laws
  - Mass spectrometery (AMU) (Residual gas analyzers)
  - Gas chromatography
  - Laser Raman Spectroscopy
  - PVT measurements
- Measurements from tritium's beta decay:
  - Calorimetry: measure tritium decay heat
  - Ionization Chambers



Hiden Analytical



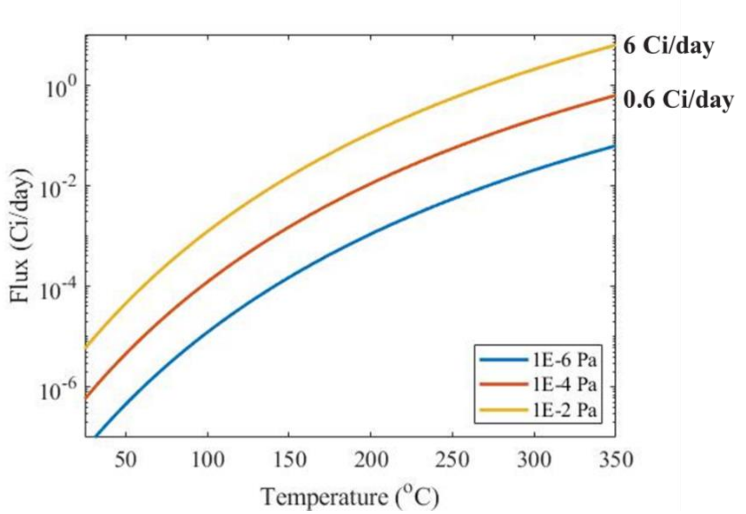


GC measurement,
W. Shmayda LLE

Open research for the design of systems for tritium compatibility

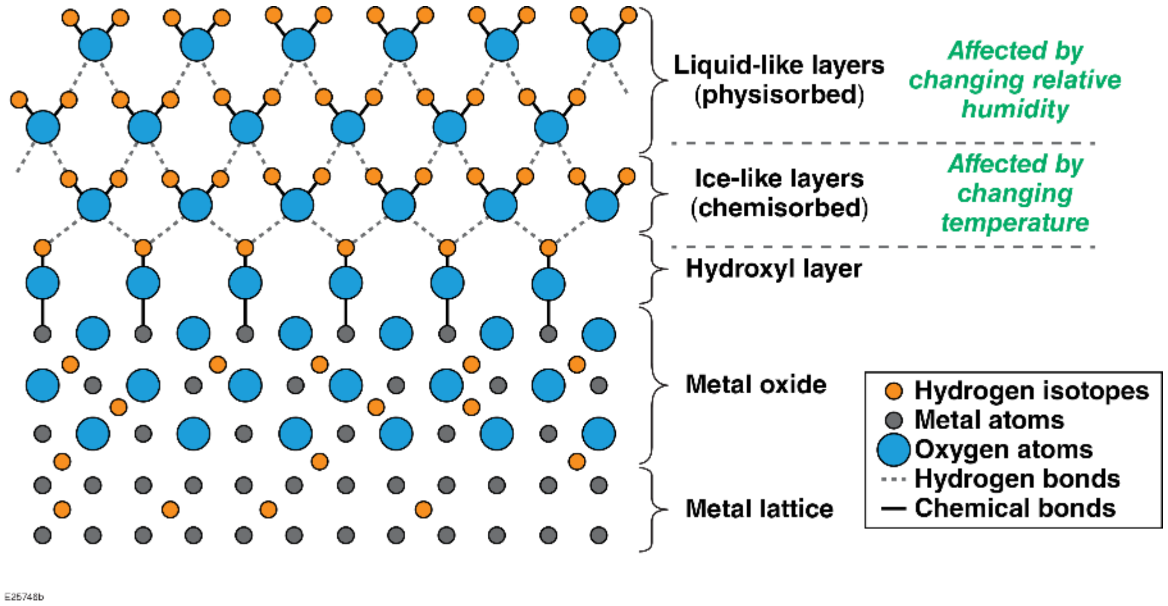
- Studies on tritium diffusion through metals
- Tritium uptake and retention in plasma facing components
- Technology development:
  - Fueling valves and vacuum pumps for tritium operation
  - Tritium pellet injection
  - Processing tritiated ammonia for plasmas using nitrogen
- Corrosion at high tritium activities
  - 10s of % starts to react (liquids/compounds)

Diffusion through metals and surface water formation leads to outgassing of T_2



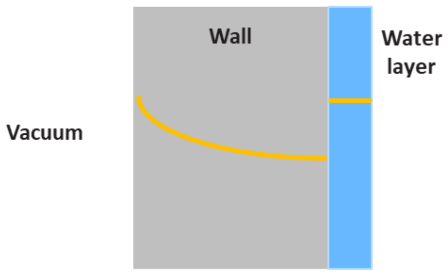
Flux through SS for varying $P(T_2)$

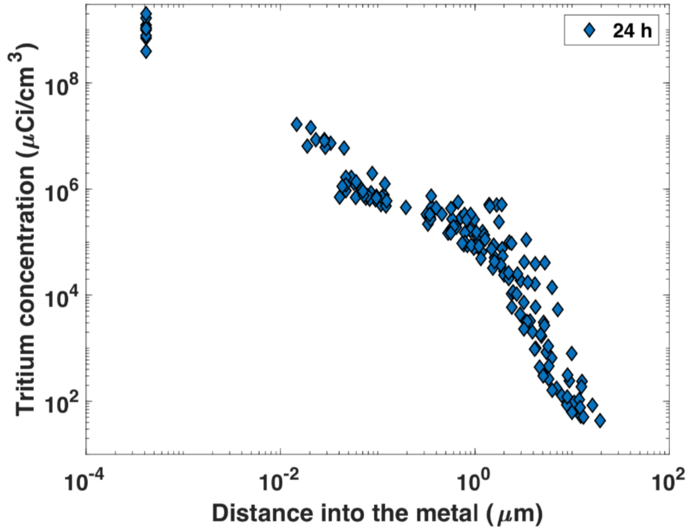
Surface water layer: Isotopic exchange to form HTO



Flux= diffusivity * concentration gradient

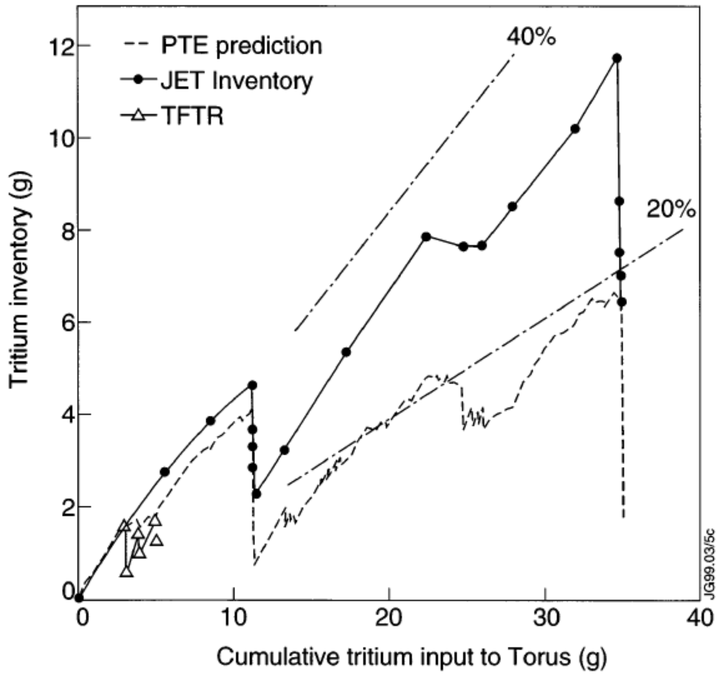
Ongoing studies for permeation through metals, surface chemistry, and metallic structure





Tritium retention and recovery from plasma-facing components

- Significant tritium inventory has been adsorbed by carbon PFCs in previous tokamaks
- As tokamaks move to metal walls (tungsten, beryllium) the retention is likely reduced but very limited studies
- Mechanisms for uptake, mitigations, and recovery are all of interest



Andrews, *FED* (1999)

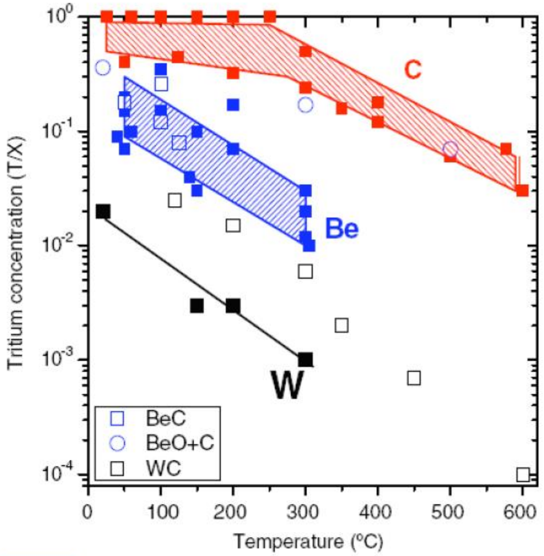


Figure 3.4.1: Data for retention of D co-deposited with C, Be and W.

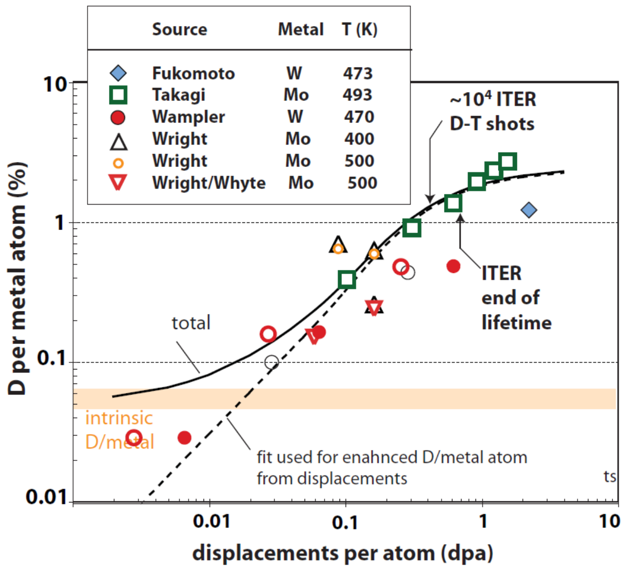


Figure 4.1.1. The **increase** in deuterium concentration due to damage from ion irradiation in tungsten [48-49] and molybdenum [29, 50-51].

Lipschultz, B., et al. "An assessment of the current data affecting tritium retention and its use to project towards T retention in ITER." (2010).

Tritium fueling: modules, valves, and pellet injectors

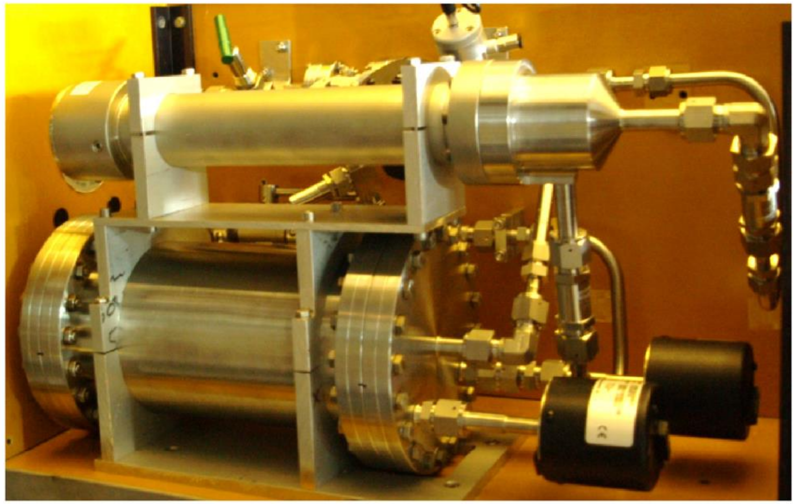


Fig. 5. GIM3 as installed on the machine. 5L reservoir on bottom and piezoelectric valve on top.

Carvalho, Fus. Engr Des. 2017

JET Tritium Injection Modules are 0.8 bar pressure vessels with ~2g 10L systems

High inventory and pressure systems

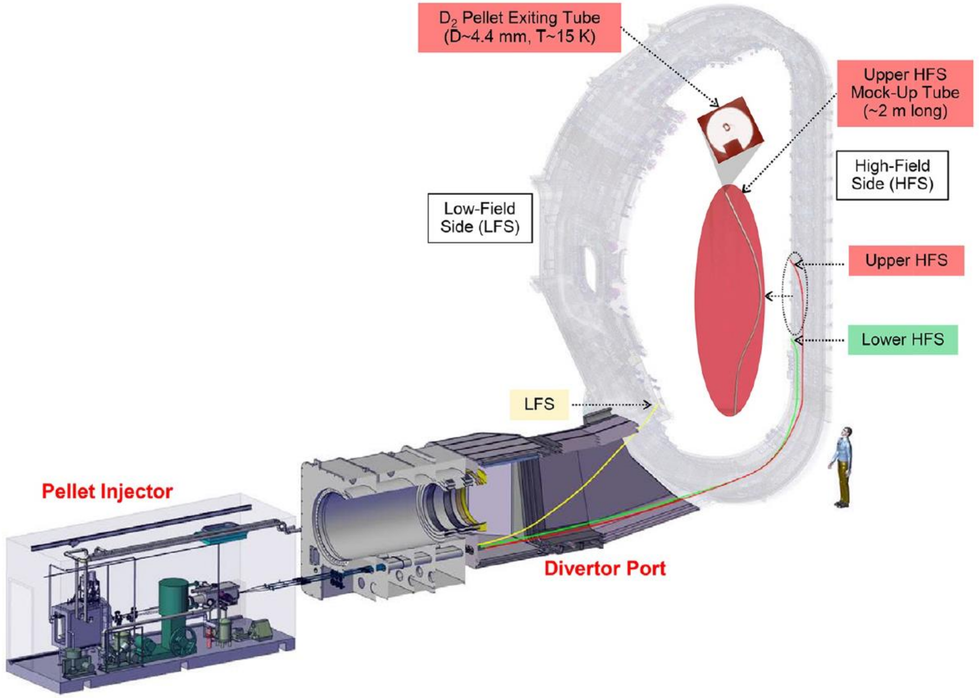


Fig. 12. Design schematic of the ITER pellet injection system; three curved guide tubes are used to transport pellets for injection at three wall locations.

Combs and Baylor, OSTI, 2018

Minimize tritium inventory, recirculate gas, eliminate failure points, confined system

Processing tritiated ammonia to allow for nitrogen seeding of plasmas

- Impurity seeding is typically used to manage heat fluxes in divertor region and reduce sputtering of wall material into plasma, N_2 is one candidate gas
- Previous works shows nitrogen adsorbs on tungsten wall
- This adsorbed nitrogen can exchange with tritium to form tritiated ammonia compounds
- Tritiated ammonia can poison getter beds and many components in the tritium facility
- Pre-processing to crack ammonia needed
  - Hydrogen fuels industry looking at cracking but technology needs to be adapted for tritium

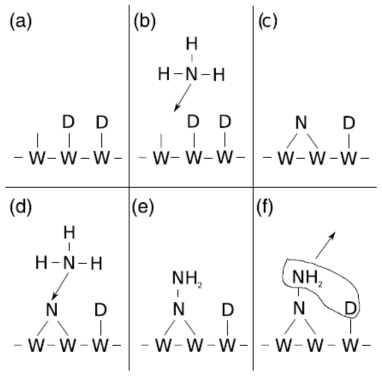
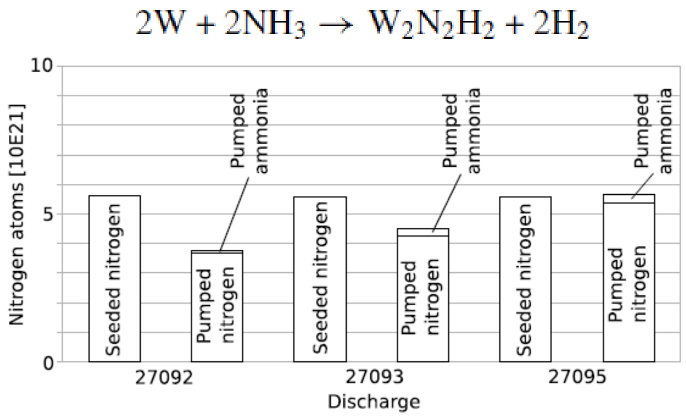
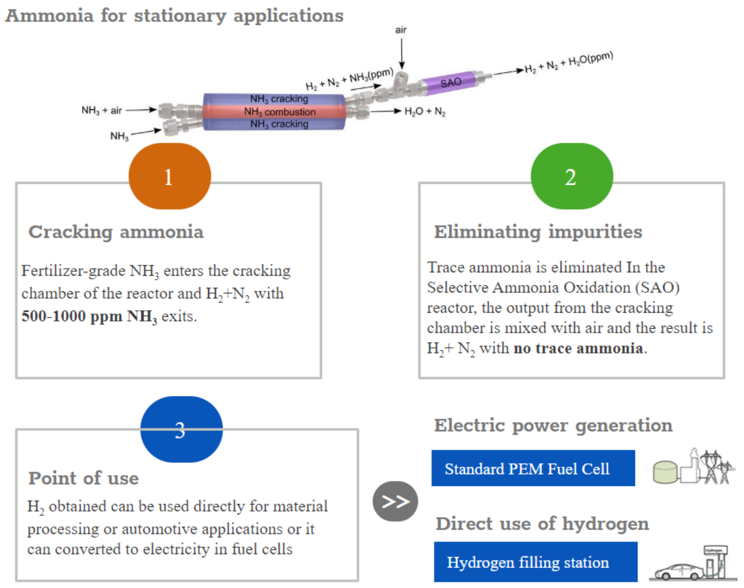


Figure 3. Six-step model of the interaction of ammonia with the tungsten surface of the AUG plasma vessel.



D Neuwirth *et al* 2012 *Plasma Phys. Control. Fusion* **54** 085008

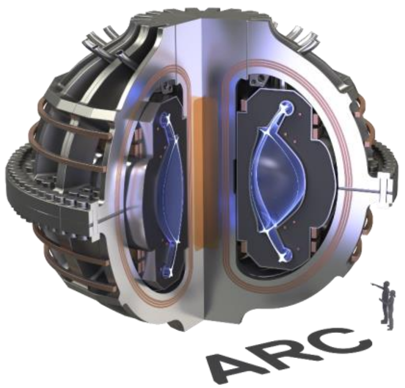


https://rencat.net/

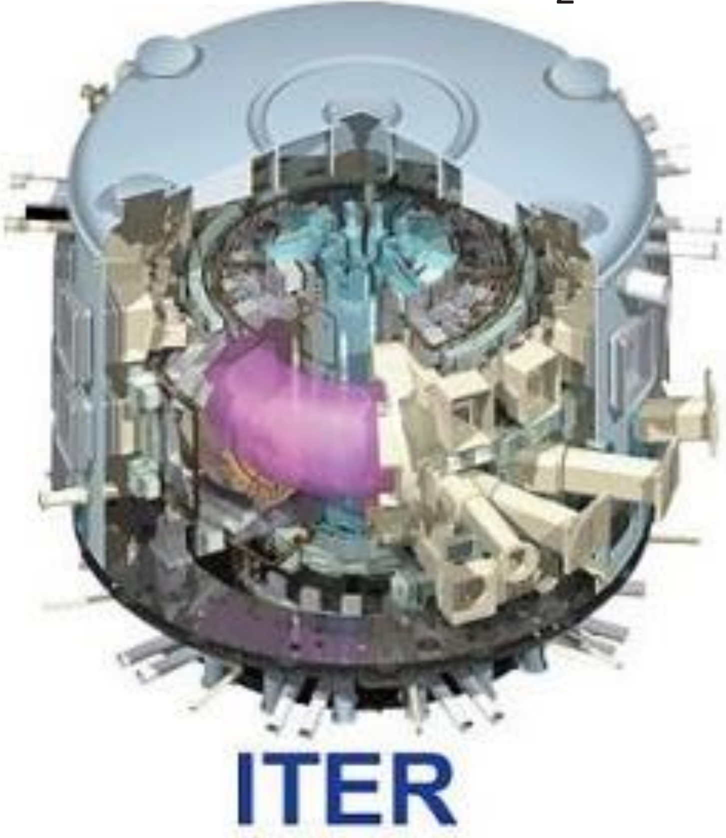
Tritium inventories: CFS scaling compared to ITER

- SPARC is 1/40th the size of ITER
- ARC is planned to be 1/15th the size of DEMO
- Tritium inventory required for fueling scales with plasma volume

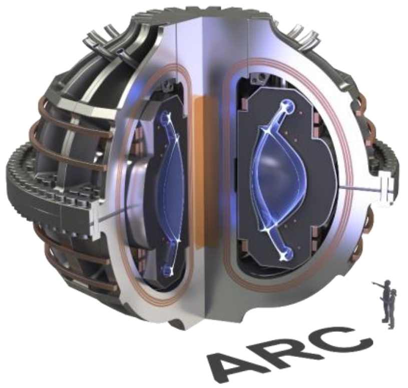
10 g T_2

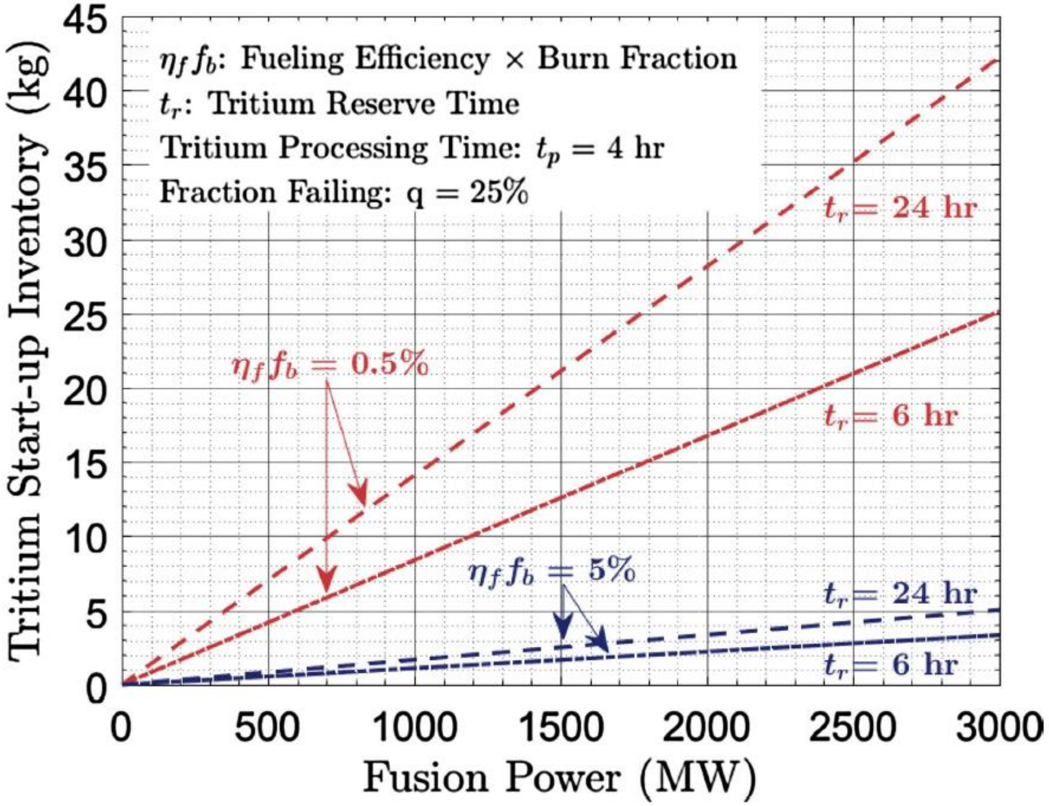


2000-3000 g T_2



DEMO fuel cycle could require up to 40 kg of tritium inventory, greater than the world's tritium stores today.





Abdou et al. *Nucl. Fus.* 2021

The CFS ARC team is developing breeding blankets to reduce inventory. Combined with an efficient tritium fuel processing loop, ARC should be well below what ITER and DEMO require

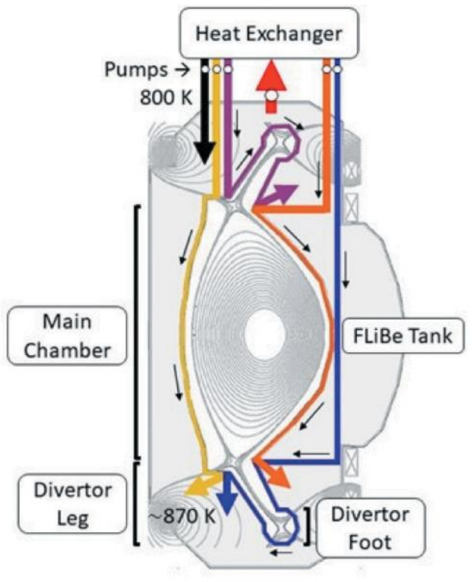
For continuous operation of a DT fusion power plant, tritium can be generated from lithium breeder blankets

$$ {}^{6}_{3}\mathrm{Li} + \mathrm{n} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{H} + 4.8\mathrm{MeV}; $$

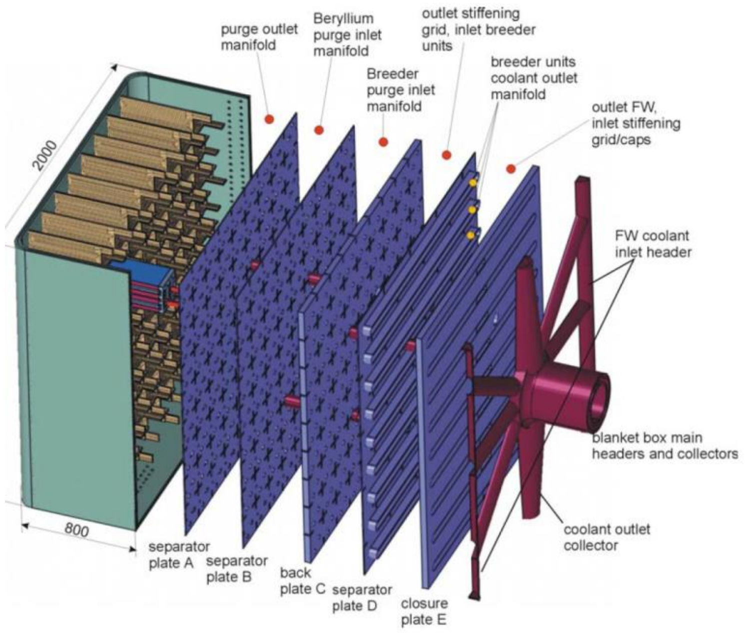
Self-cooled:
FLiBe

Separately-cooled:
Pb-Li/He coolant

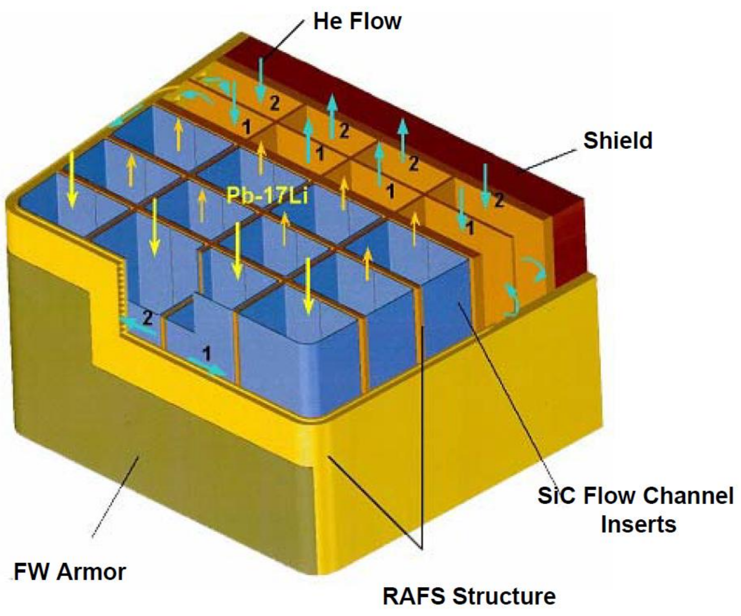
Dual-cooled:
Pb-Li/He coolant



C Forsburg, Nuclear Fusion 2019



EU-PPCS B



Research areas for breeder blankets

- Efficient breeding of tritium from blanket materials
- Developing channels and pumps for efficient circulation of FLiBe coolant
- Handling of tritiated fluorides and separation of tritium from TF
- Corrosion resistance materials for coolant loop

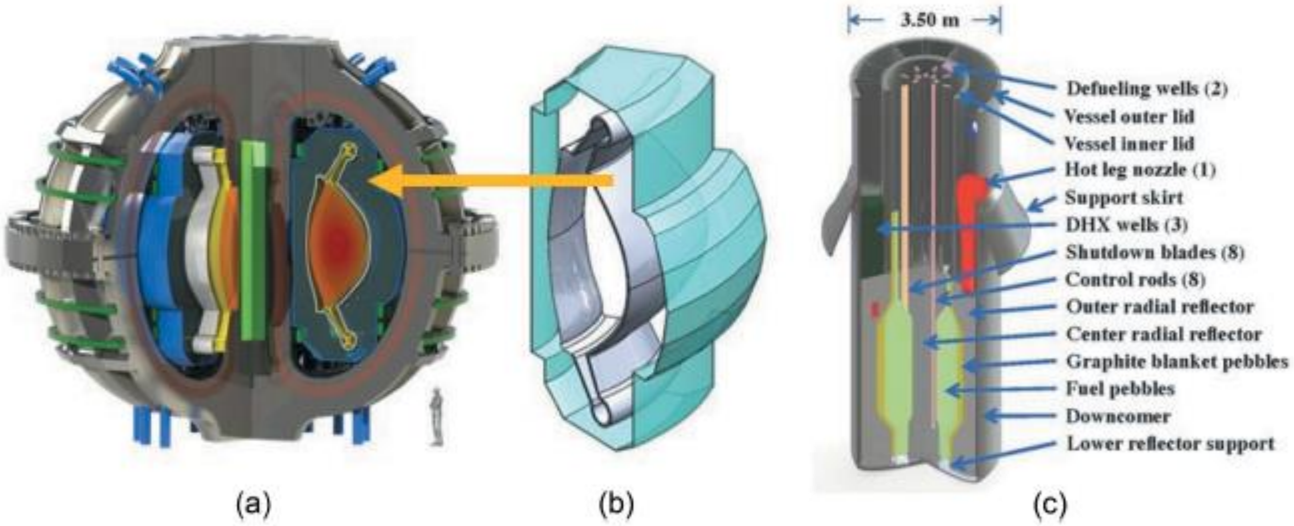


Fig. 1. (a) ARC fusion system, (b) flibe fusion blanket for ARC, and (c) FHR fission system.

C Forsburg, Nuclear Fusion 2019

The SPARC FUEL team is comprised of many scientists and engineers with collaborations among fusion facilities

Corinne Mitchell,
Corporate Radiation
Protection Manager

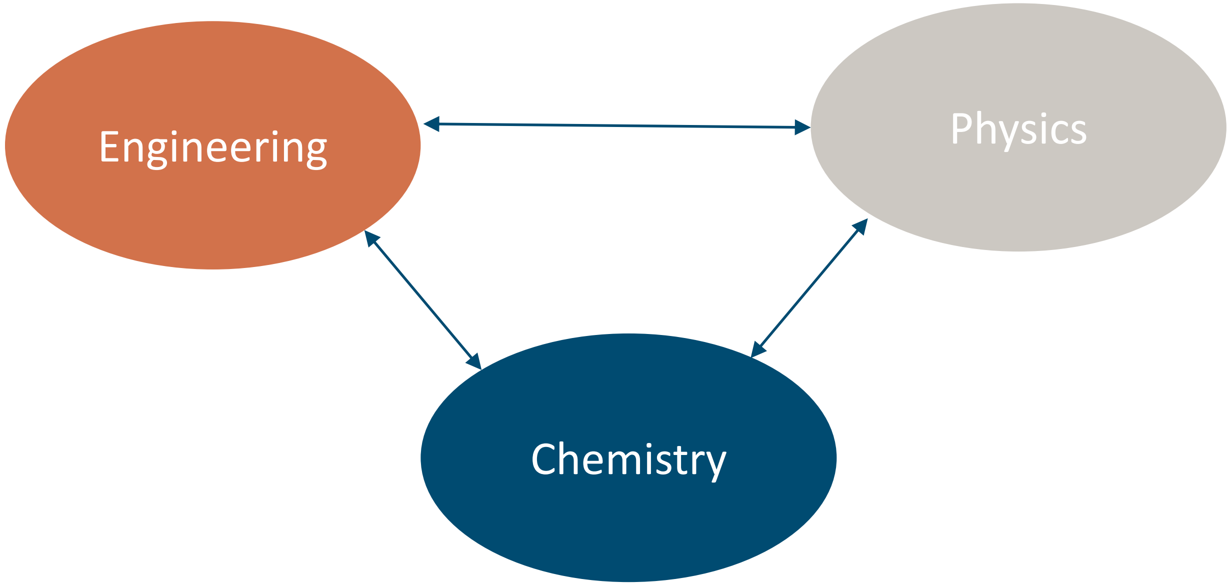
Dr. Walter Shmayda
University of Rochester, LLE
Faculty and RSO

Dr. Valeria Riccardo
Head of Mechanical
Engineering

ChemE, MechE, Vacuum systems, tokamak physicists, lab scientists, postdoctoral researchers, tritium experts

Tritium engineering builds from skills in many fields and there are many opportunities along the full R&D spectra

- Skills: labwork, attention to detail, modeling, programming, data analysis
- Attitude: push to enable fusion, contribute to a culture of trust, transparency, and safety, and always strive to design systems to minimize fuel needs outside the fuel cycle



- Plasma physics
- Vacuum systems
- Semiconductors
- Micro-nano phenomena
- Fuel cells and electrochemistry

Overview of ongoing tritium projects at UofR LLE

- Tritium extraction from air using a platinized molecular sieve

- Evaluation of flow through palladium permeators

- Process torus exhaust using asymmetric permeation

- Tritium beta induced isotopic exchange with protons on 316 SS surfaces

Walter Shmayda

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SULI on-site lab opportunity
Graduate research opportunities

Questions?

Contact: hmutha@cfs.energy

Subject: SULI PPPL 21