Closing the fuel cycle

2020 Introduction to Fusion Energy and Plasma Physics Course

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Public information from:
2010 Tritium Conference Tutorial Lectures, Nara, Japan , 2010.10.29, five tutorial lectures taught by T. Tanabe (Kyushu university, Japan), M. Glugla (ITER), T. Yamanishi (JAEA), S. Willms (LANL, now with ITER), S. Konishi (Kyoto University, Japan);
Various public presentations with credits to: K. Heroux, G. Staack, M. Morgan, B. Garcia-Diaz, J. Klein, and D. Babineau at SRNL;
Th. Giegerich, Chr. Day, R. Knitter, N. Osman and F. Cismondi at KIT; I. Castillo at AECL EACL; C. Forsberg at MIT.

T and D as fuels for fusion reactions

$D + T \longrightarrow {}^{4}He + n + 17.6MeV$ (1)

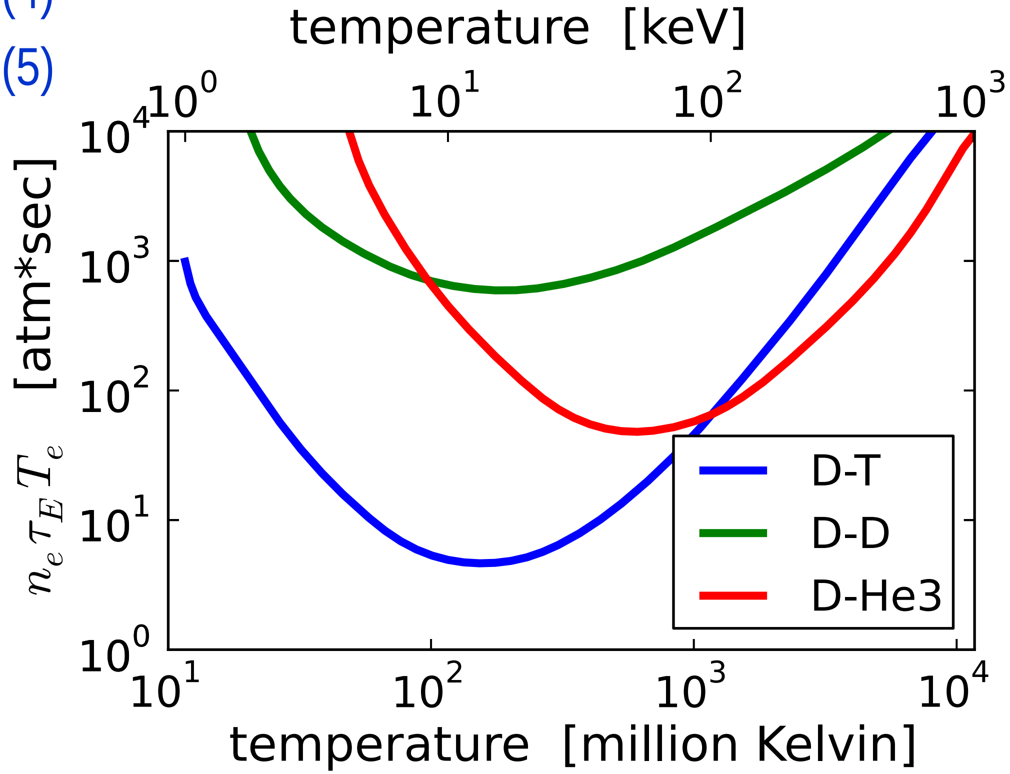
$D + D \longrightarrow T + H + 3.98M$ (2)

$D + D \longrightarrow {}^{3}He + n + 3.25MeV$ (3)

$T + T \longrightarrow {}^{4}He + 2n + 11.3MeV$ (4)

$D + {}^{3}He \longrightarrow {}^{4}He + H + 18.3 MeV$ (5)

The fusion triple product condition for three fusion reactions.



DT fusion (1) is the most suitable fusion reactions

The D + ^{3}He reaction is attractive for no neutron production, though accompanying DD reactions do produce it.

Tritium resource is very limited → need breeding

$D + T \rightarrow {}^{4}He\ (3.5MeV) + n(14.1MeV)$

plasma heating Energy and T breeding

– Deuterium: Vienna Standard Mean Ocean Water (VSMOW) is 155.76 ppm

– Tritium must be produced or bred internally from lithium

- 56 kg tritium per GW year (thermal) of fusion power
- About 100 g tritium produced per year in a standard CANDU fission reactor
- 20 to 25 kg tritium available (mainly in Canada) for ITER startup
- Tritium must be bred by reactions in blanket systems

$${}^{6}Li + n \rightarrow T + {}^{4}He + 4.8MeV$$
$${}^{7}Li + n \rightarrow T + {}^{4}He + n - 2.5\ MeV$$
$${}^{9}Be + n \rightarrow 2n + 2\ {}^{4}He - 2.5\ MeV$$
$${}^{a}Pb + n \rightarrow 2n + {}^{a-1}Pb - 7\ MeV$$

- Overall breeding ratio is expected to be above ~1.1 (not easy to achieve)

Deuterium

Property	D_2O (Heavy water)	H_2O (Light water)
Freezing point (°C)	3.82	0.0
Boiling point (°C)	101.4	100.0
Density at STP(g/mL)	1.1056	0.9982
Temp. of maximum density (°C)	11.6	4.0
Viscosity (at 20°C, mPa·s)	1.25	1.005
Surface tension (at 25°C, µJ)	7.193	7.197
Heat of melting (cal/mol)	1,515	1,436
Heat of vaporisation (cal/mol)	10,864	10,515

Source: in seawater at a D/H ratio of 156 ppm

Used: in nuclear energy (e.g. D_2O in CANDU reactors)

Production methods (D_2O): e.g. Girdler-Sulfide Process (isotope exchange column) + vacuum distillation

Estimated earth availability: $5*10^{16}$ kg (in oceans)

Sufficient for several billion years !!

F. Cismondi, Basics of breeding blanket technology, KIT

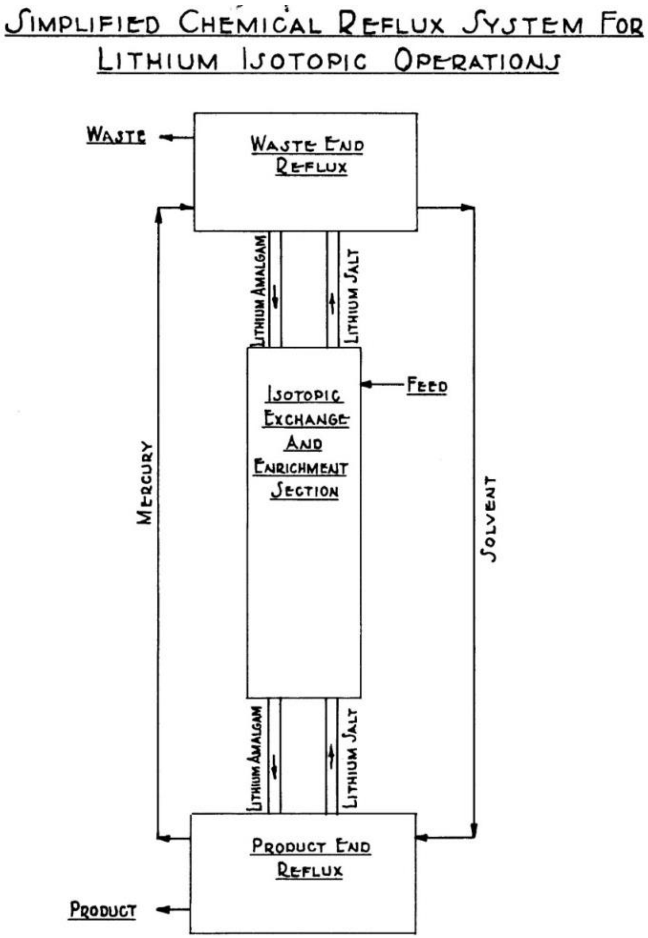
^{6}Li Enrichment

COLEX process

- Counter-current flow of a LiOH solution (OREX: LiCl in PDA) and lithium amalgam, ^{6}Li accumulates in the amalgam phase
- Production between 1955 and 1963 in the Y12 plant in Oak Ridge, Tennessee.

Other concepts:

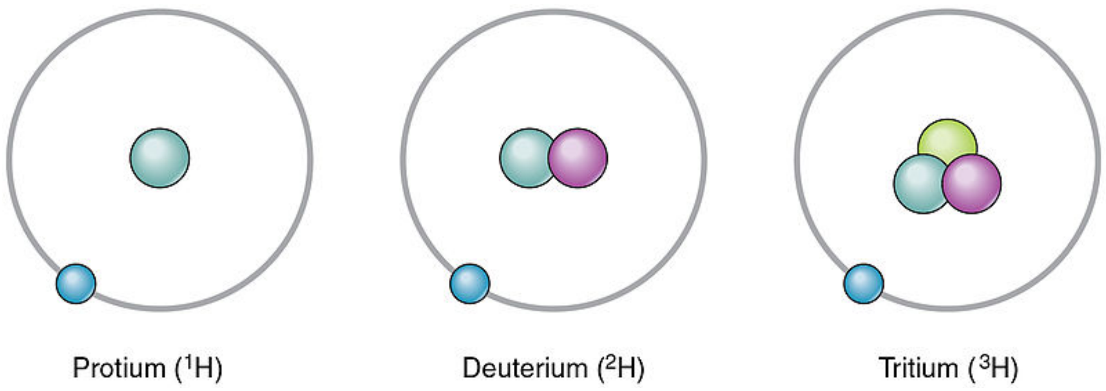
- Displacement chromatography
- Ion exchange methods
- Intercalation methods
- Electrolysis
- Electrophoresis
- Electromigration
- Crown ether complex
- Liquid ammonia methods
- Electromagnetic separation
- Laser based separation methods



Source: Separation Science and Technology, 20 (9-10), 633–651 (1985).

Reference: Th. Giegerich, Chr. Day, R. Knitter, N. Osman, Lithium enrichment issues in the sustainable supply chain of future fusion reactors, KIT/ITEP, 05 May 2016

Tritium, one of the three hydrogen isotopes



– Tritium is the radioactive hydrogen isotope

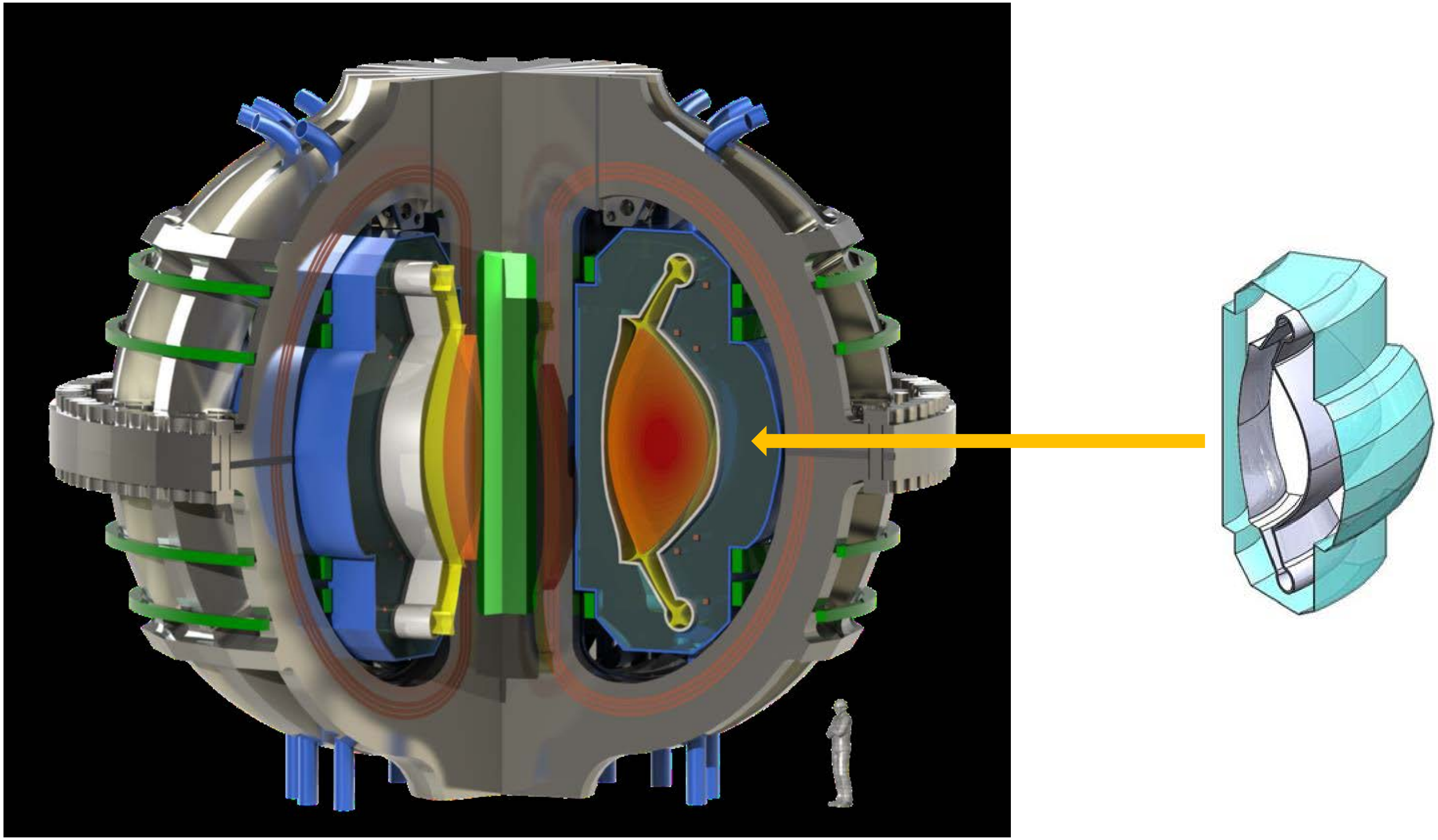
- decay: $^3T \rightarrow {}^3He + \beta$ electron + antineutrino
- 18.6 keV total (average 5.7 keV kinetic, + nearly undetectable antineutrino)
- decay heat: 324 mW/g
- half life: 12.32 years (loss ~5.5% per year)
- isotope mass: 3.0160492 u
- Shielding of tritium radiation is not really a issue (Except direct exposure of organs)
- HTO is > 10,000 times hazard than HT gas
- 9,650 Ci/g (3.57×10^{14} Bq/g)
- EPA drinking water standard: < 20 pCi/cc

Discovery

- deuterium 1931
- tritium 1934

Most of valves are not compatible with tritium because of polymer packing

Breeding blanket integrated with fusion reactor (example with ARC)



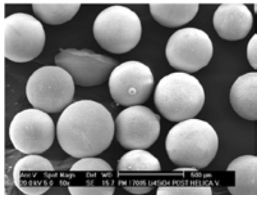
Fusion reactor

Breeding blanket

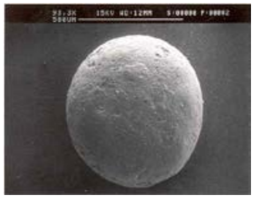
Source: Charles Forsberg, Molten Salt Liquid Blanket Integrated Validation Plan, Massachusetts Institute of Technology, Department of Nuclear Science and Engineering, December 6, 2019

Tritium breeding materials

Multiple solid and liquid breed concepts. Parts of these concepts have been tested. No realistic, integrated tests have been performed

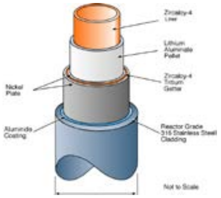


Li_4SiO_4 pebbles (FZK) 0.2- 0.4 mm



Li_2TiO_3 pebbles (CEA) 0.6 – 0.8 mm

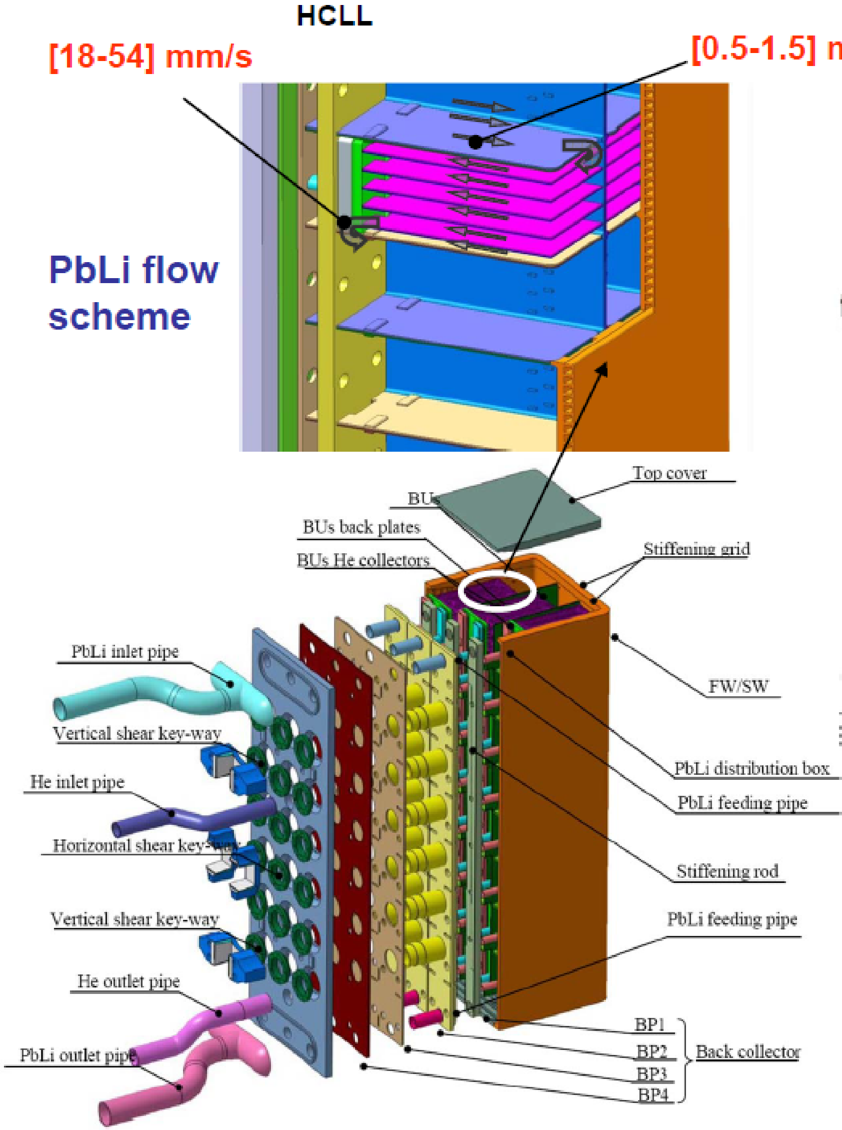
$LiAlO_2$ pellet

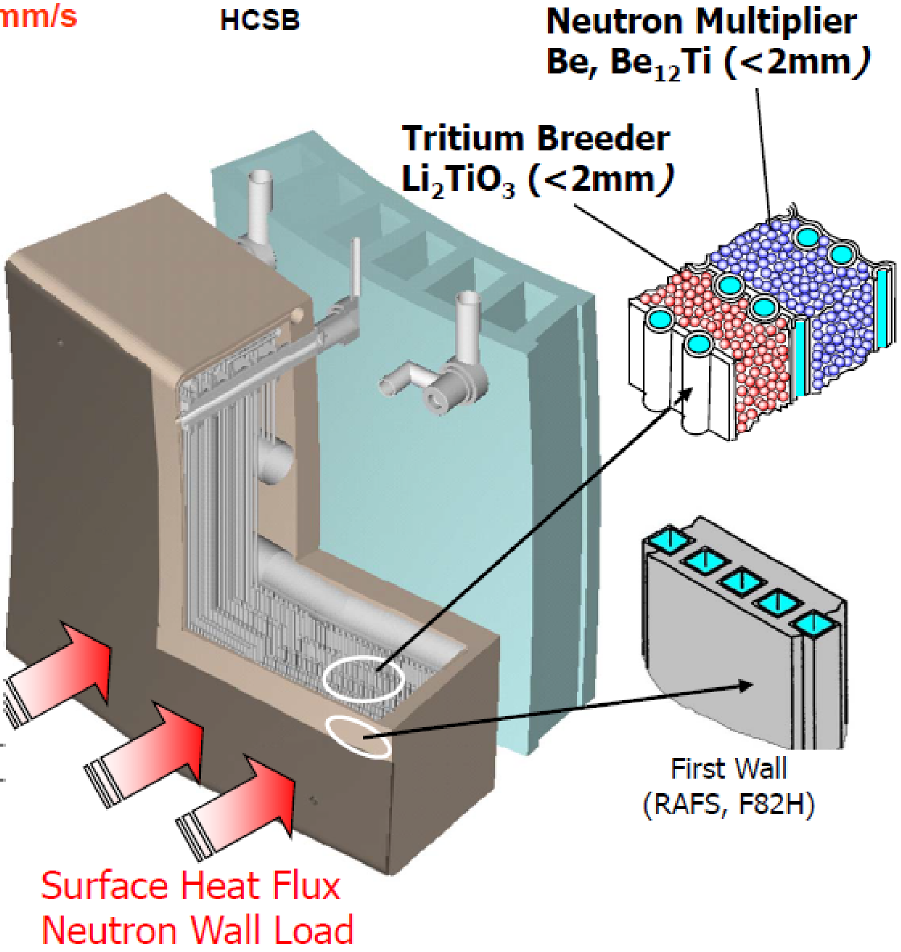


PbLi, work at 300-500°C

Li_2BeF_4(Flibe), m.p., 459°C

Blanket systems are complex and have many integrated functions, materials, and interfaces





Solid Breeder Blanket utilizes immobile solid lithium ceramic breeder and Be multiplier for tritium self-sufficiency

S. Willms, Tritium Science and Technology in the Future, 2010 Tritium Conference Tutorial Lectures, Nara, Japan , 2010.10.29

Tritium breeding technical challenges

- Tritium breeding blanket materials and configurations
- Blanket structural materials
- Blanket operations and control
- Blanket maintenance and disposal
- Blanket diagnostics
  - ❖ – Example:
    - ➢ For liquid breeding material, what characterizes the flow channel for the coolant blanket application, and how to maintain its function throughout blanket lifetime?
    - ➢ For solid breeding material: What radiation resistant properties should the solid breeder pebble have?

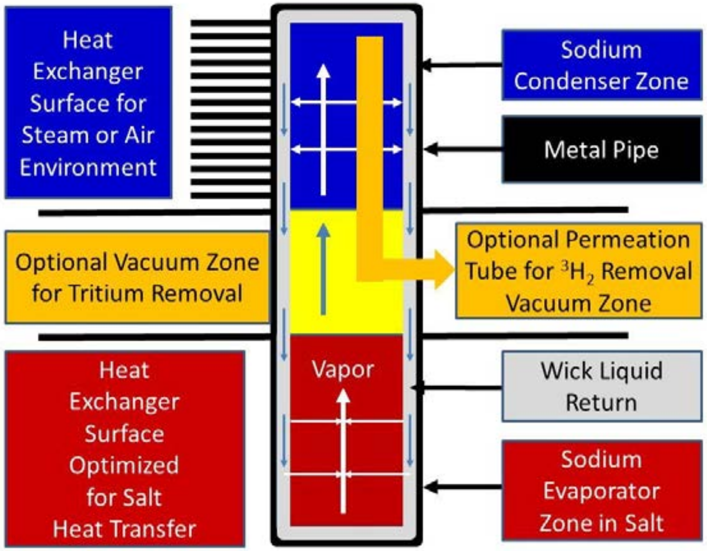
Tritium extraction

Tritium extraction from breeding materials

Tritium extraction from blanket coolants

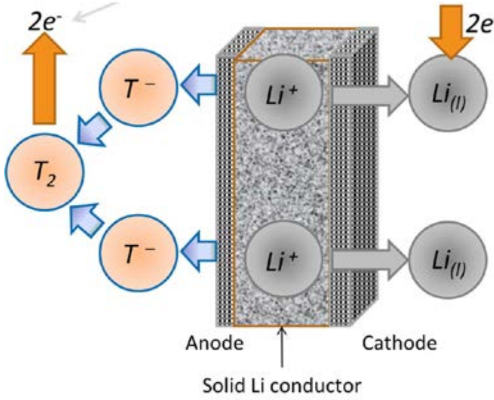
Tritium extraction diagnostics

Blanket systems tritium handling and containment



Thermal concept by ARC (MIT)

Electrochemical concept by SRNL



$2LiT \rightarrow 2Li^+ + T_2 + 2e^-$

$Li^+ + e^- \rightarrow Li$

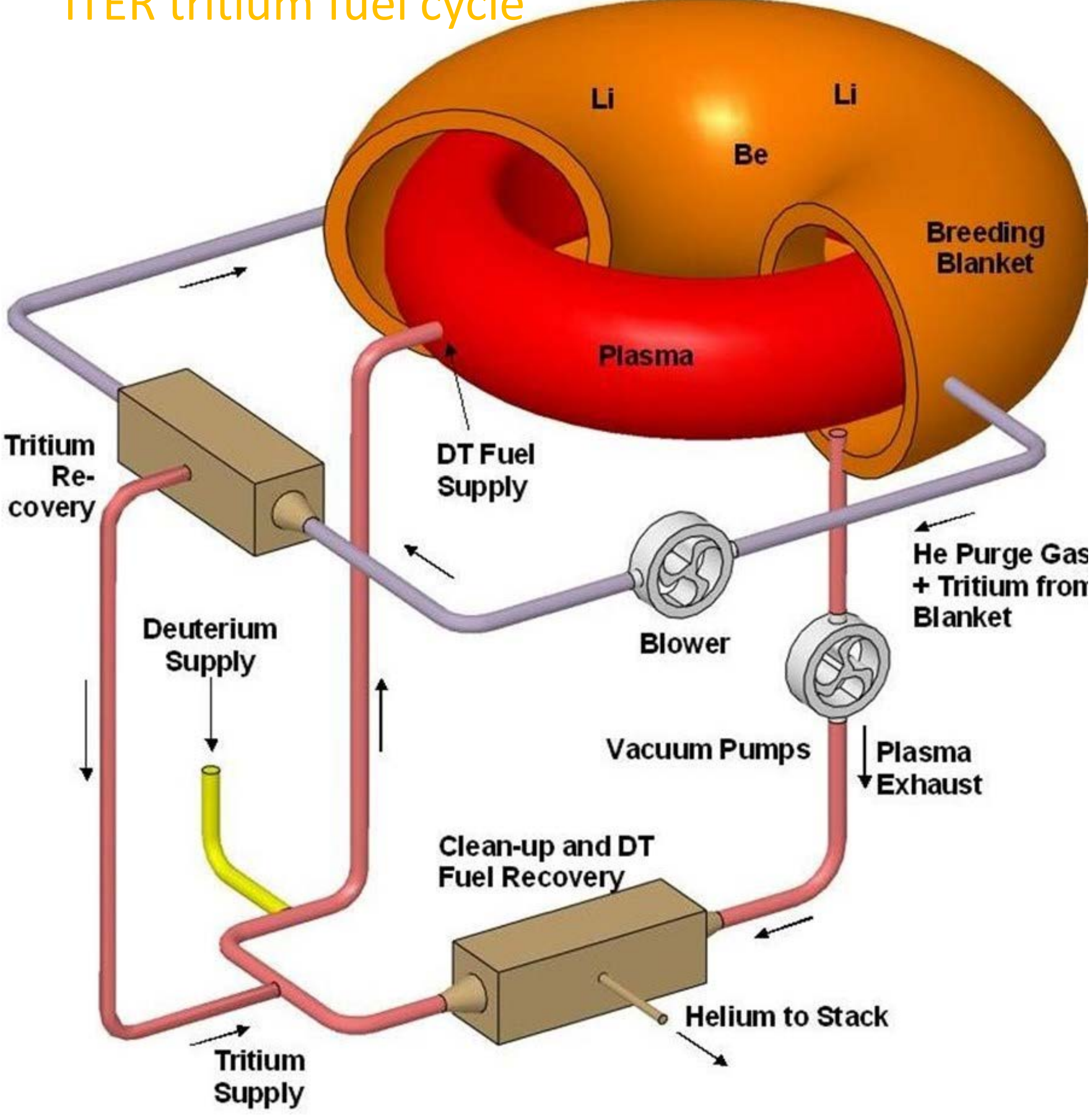
$E^0_{400°C} = -2.82$ V

$E^0_{400°C} = -3.22$ V

Tritium fuel processing

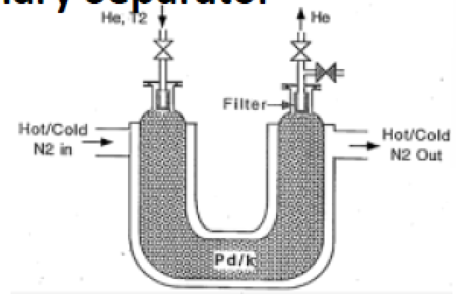
- Fuel cleanup
- Isotope separation
- Tritium storage and delivery
- Water detritiation
- Tritium pumping
- Confinement & detritiation
    - Process
    - Glovebox
    - Air
- Gas analysis
- Process control
- Tritium accountability

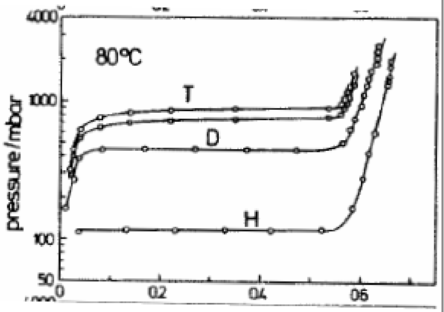
ITER tritium fuel cycle

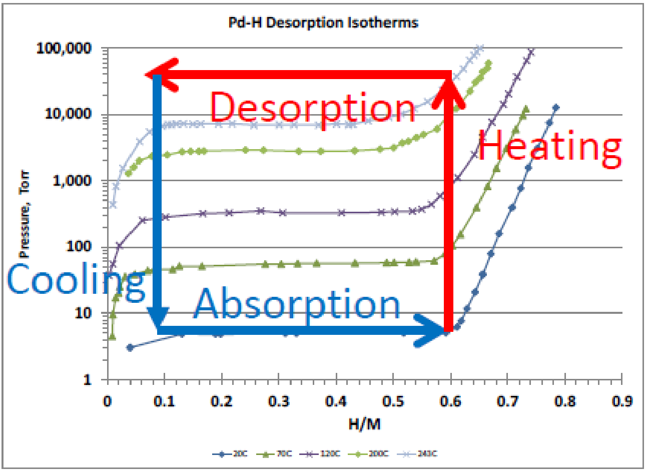


Impurity removal from bulk hydrogen isotopes (e.g., > 95%)

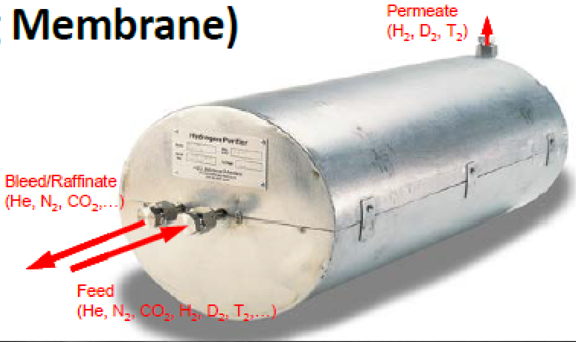
Flow-Through Bed/ Primary Separator

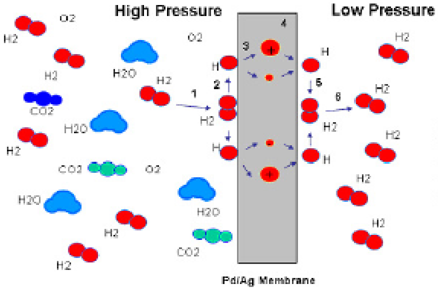




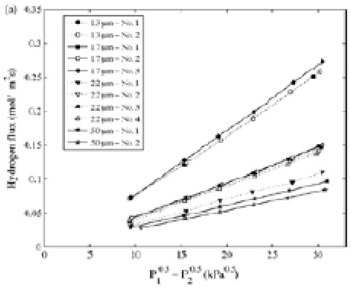


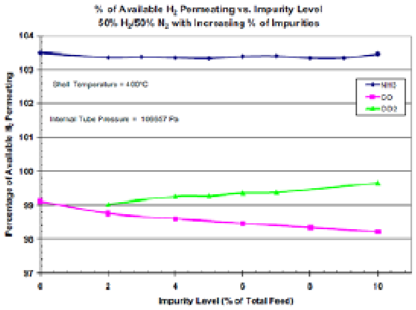
Diffuser/Permeator (Pd-Ag Membrane)





1. Adsorption
2. Dissociation
3. Ionisation
4. Diffusion
5. Recombination
6. Desorption





Diffusion vs. Permeation

Diffusion

Average velocity of gas molecules by Maxwell-Boltzmann's distribution

$$v = \sqrt{\frac{8kT}{\pi m}} = \sqrt{\frac{8RT}{\pi M}}; \quad v_H/v_D = \sqrt{2}; \quad v_H/v_T = \sqrt{3}; \quad v_D/v_T = \sqrt{3/2}$$

Molecular kinetics gives incident flux to wall surface under pressure P

$$J = nv = \frac{P}{\sqrt{2\pi mkT}}; \quad J_H/J_D = \sqrt{2}; \quad J_H/J_T = \sqrt{3}; \quad J_D/J_T = \sqrt{3/2}$$

Permeation

Sieverts' law - a rule to predict the solubility of gases in metals

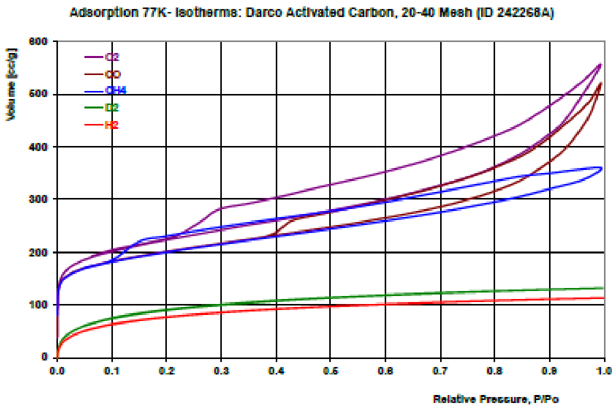
$$H_2\ (molecular\ gas) \leftrightarrow 2\ H\ (dissolved\ atoms);\ K = \frac{c_{at}^2}{P_{mol}}; \quad c_{at} = \sqrt{KP_{mol}}$$

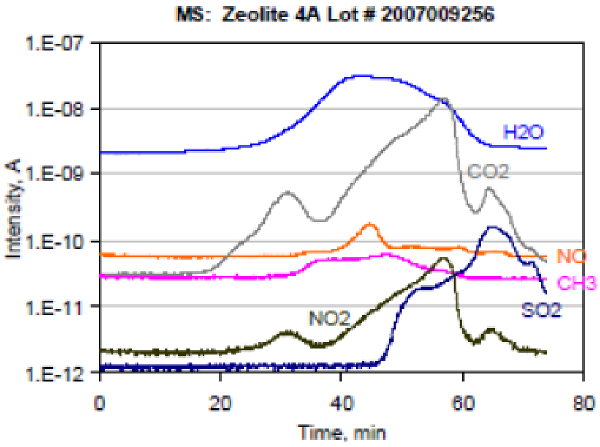
Permeation flux

$$F = \phi \frac{\sqrt{P_{up}} - \sqrt{P_{down}}}{\delta} A; \quad \phi_{HD}/\phi_{H_2} = 0.9;\ \phi_{HD}/\phi_{D_2} = 1.1$$

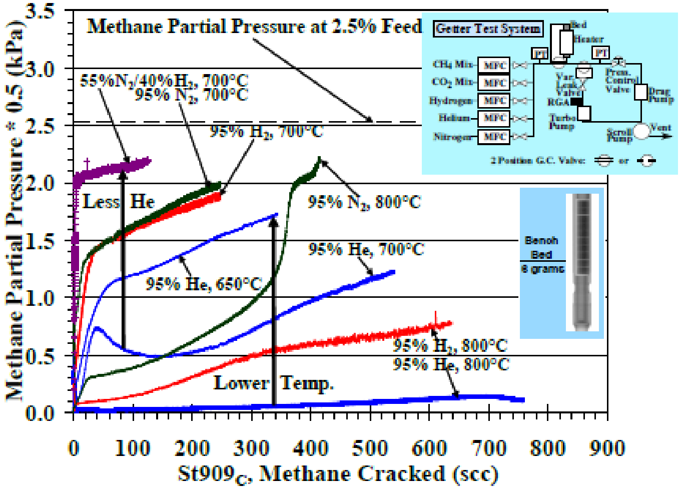
Tritium recovery from bulk impurities (e.g., > 95%)

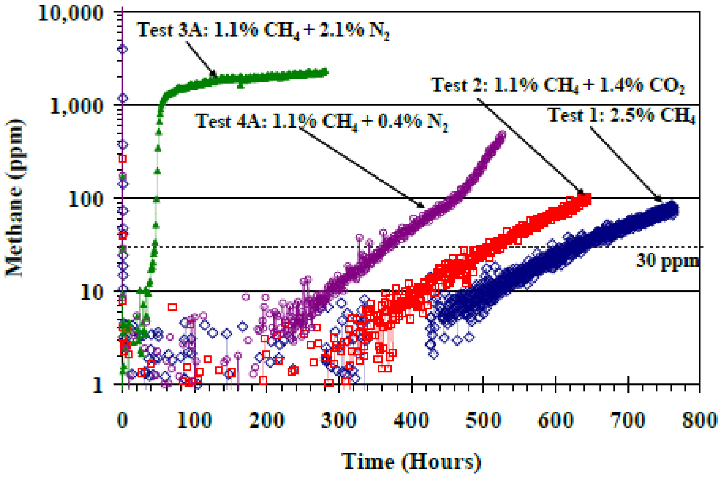
Activated Carbon/ Molecular Sieve



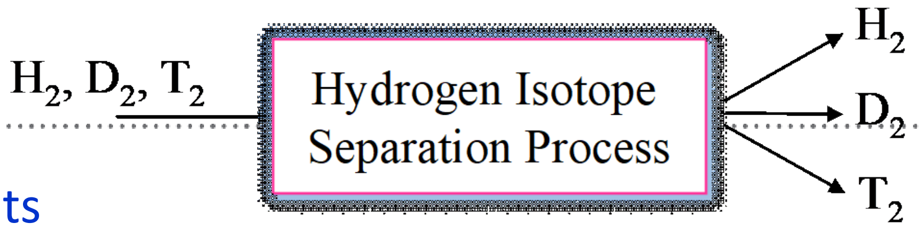


Non-Evaporative Getters (NEG)





Isotope separation



H_2, D_2, T_2

Hydrogen Isotope Separation Process

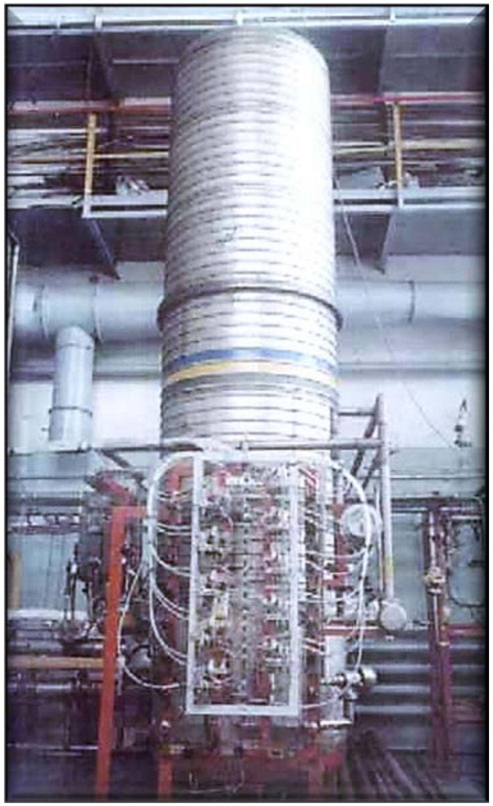
H_2

D_2

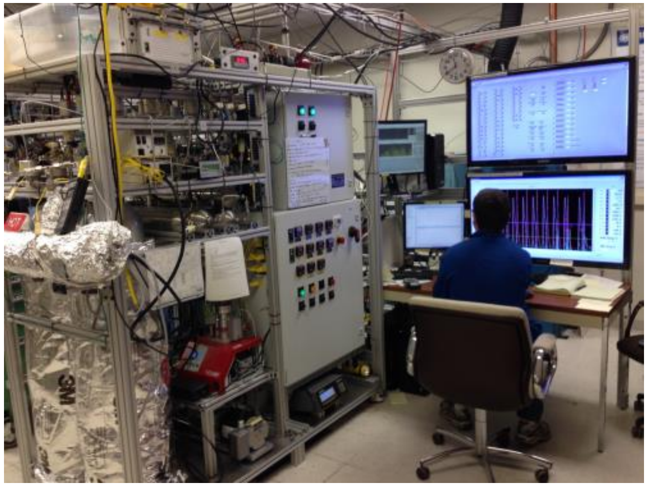
T_2

- Six species with different boiling points

Species	H_2	HD	HT	D_2	DT	T_2
Boiling Point, Kelvin	20.7	22.1	23.5	23.8	25	25.5

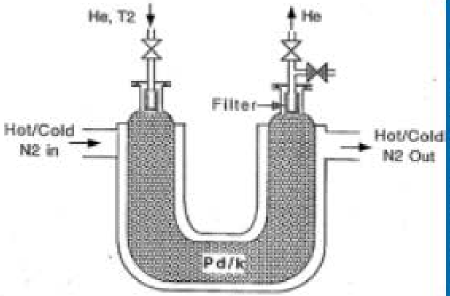


Cryogenic Distillation

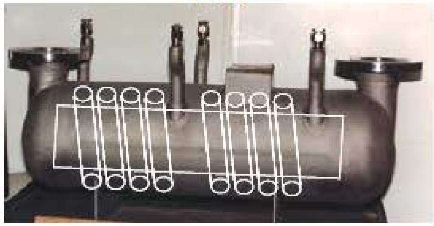


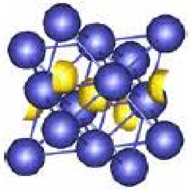
TCAP - Thermal Cycling Absorption Process (palladium has the highest isotopic effect)

TCAP development for isotope separation



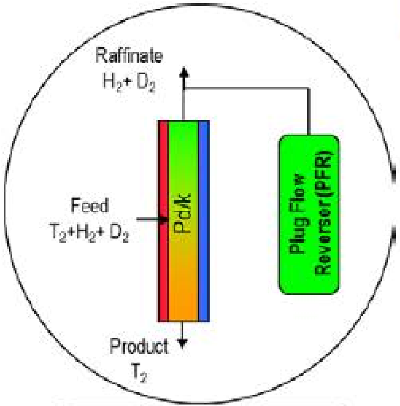
First Tritium Production TCAP
1994

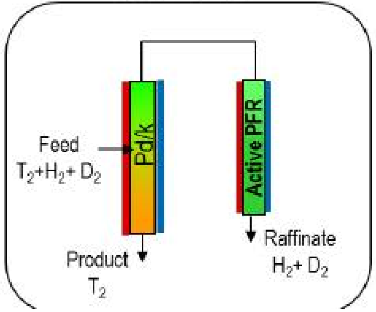




Palladium favors lighter hydrogen isotope, especially at low temperatures

Molecular Sieve favors heavier hydrogen isotope (active PFR)

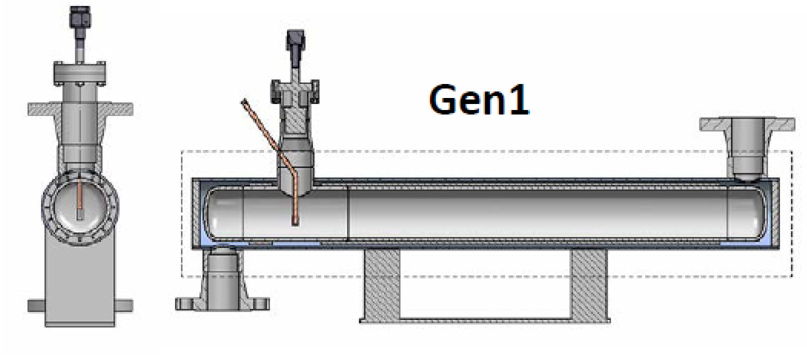




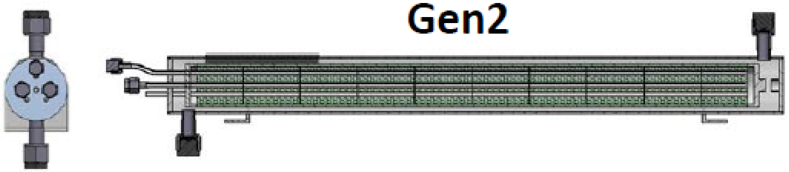
Rochester LLE TCAP - 2014

Hydride bed design for tritium storage

Gen1

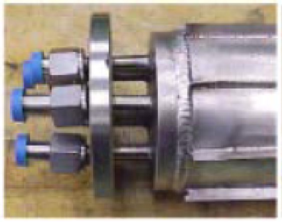


Gen2



Gen3

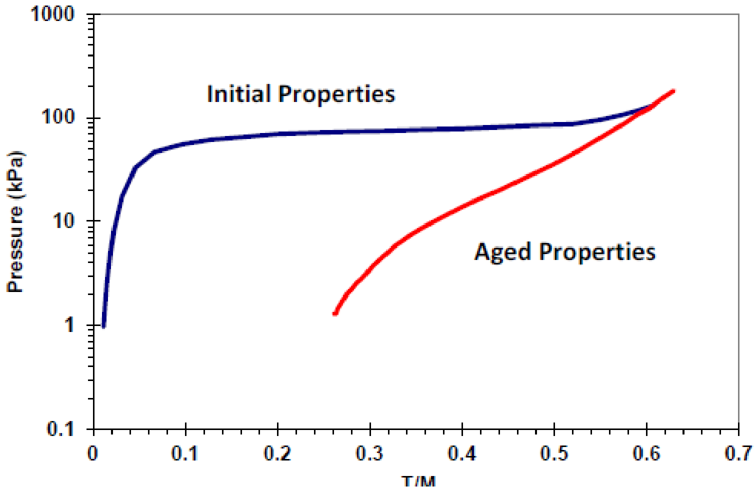
Fully Assembled End View

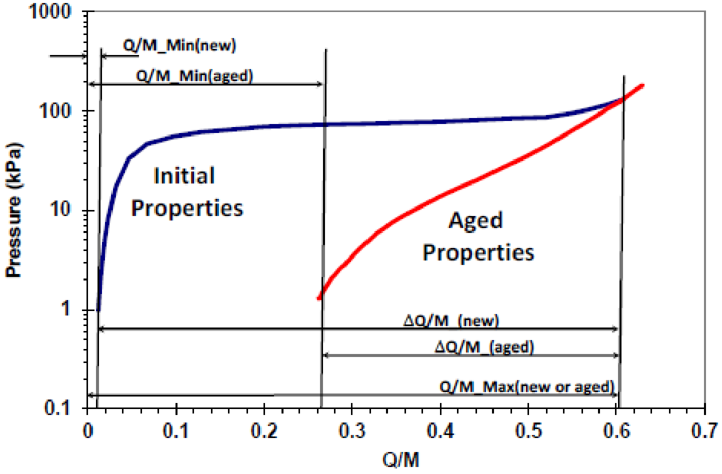


Fully Assembled End Cap detail

Fully Assembled General View

Fully Assembled Process Vessel Side View

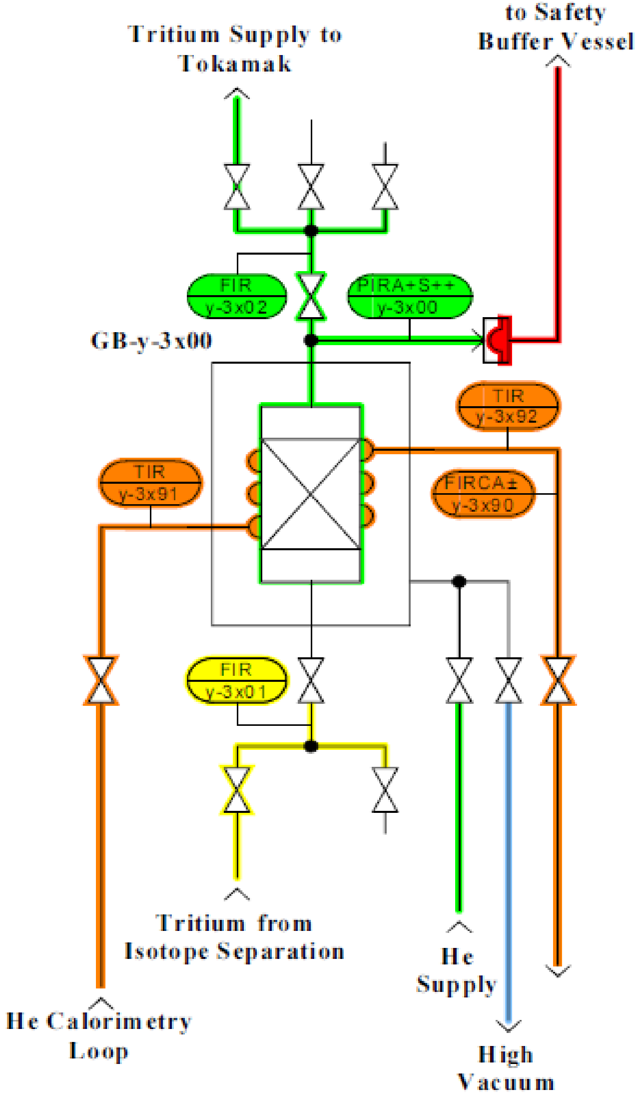




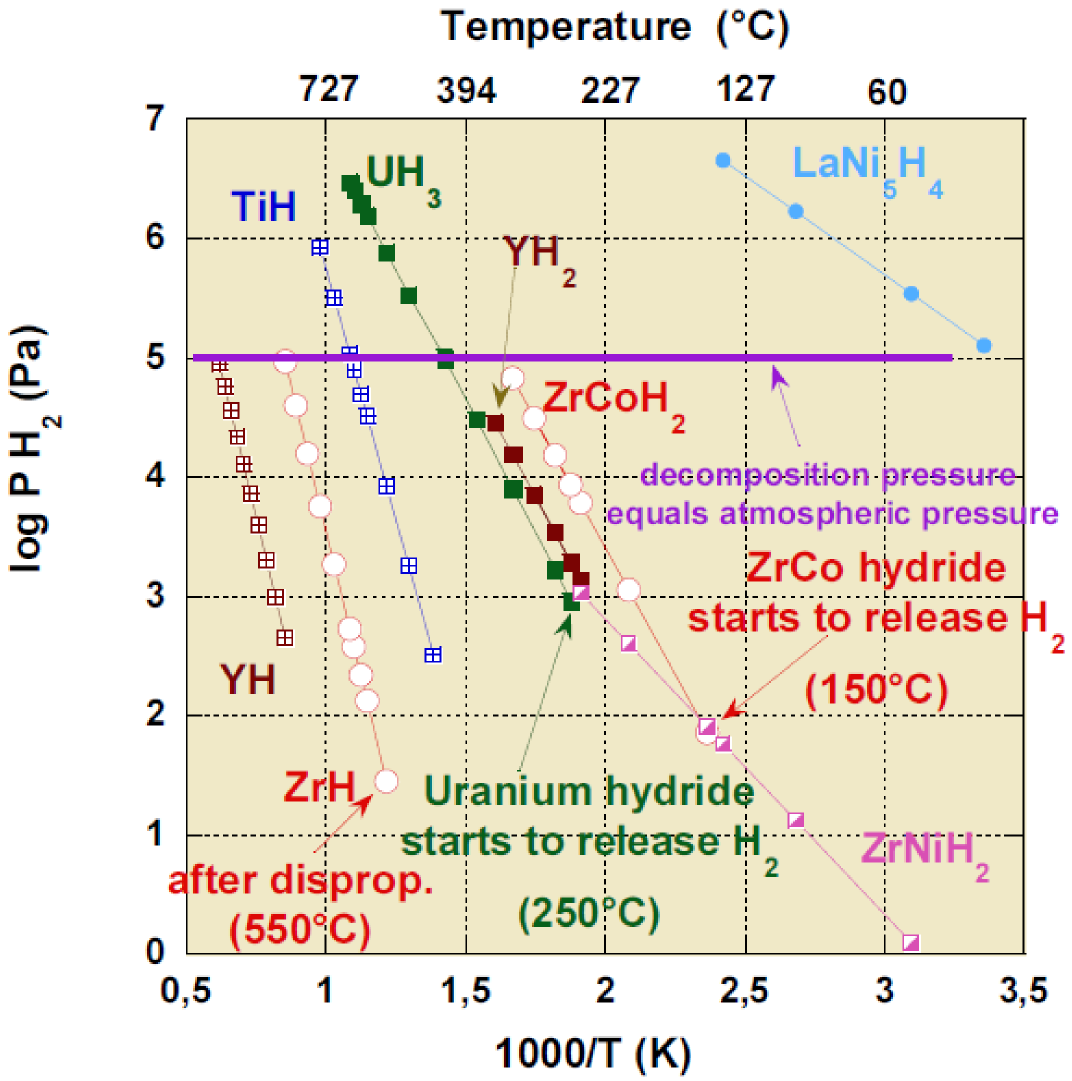
Three Generations of Metal Hydride Storage Bed Development

Example - Storage and Delivery - Jacketed Vessels, Hydride Selection

Typical Hydride Bed

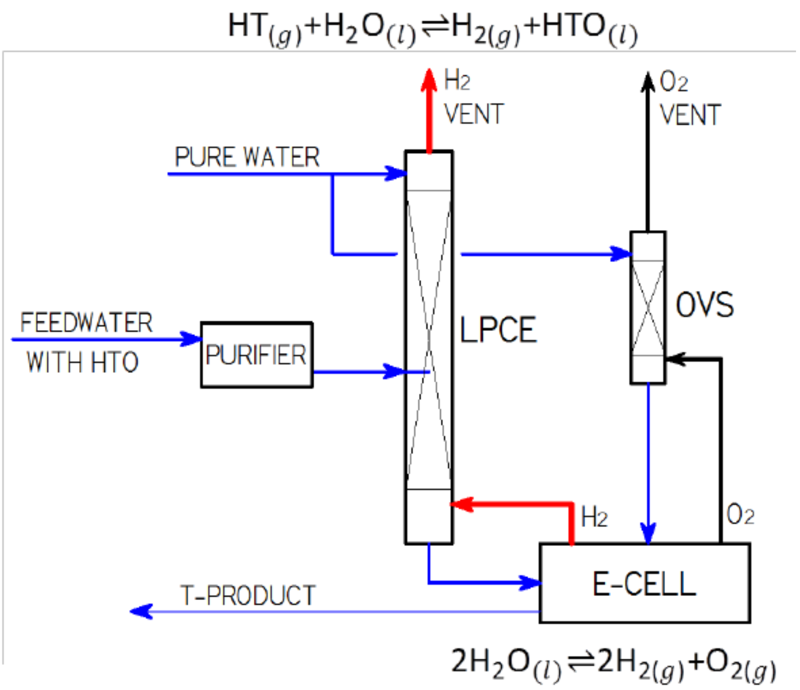


Van't Hoff Diagram for Various Hydrides



David Babineau, at al., Review of the ITER Fuel Cycle, 23rd IAEA FEC, 2010.

Water Detritiation System



$HT_{(g)}+H_2O_{(l)} \rightleftharpoons H_{2(g)}+HTO_{(l)}$

$2H_2O_{(l)} \rightleftharpoons 2H_{2(g)}+O_{2(g)}$

H. Boniface, A Practical Process for Light Water Detritiation at Large Scales, Pacific Basin Nuclear Conference, 2014

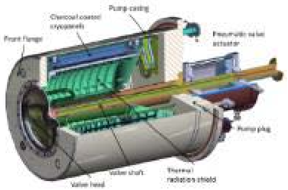
Information from: Ian Castillo, Overview of AECL's Tritium Compatible Electrolyser Program, Tritium Focus Group Meeting, Idaho National Lab, 2014 Sep 24-25

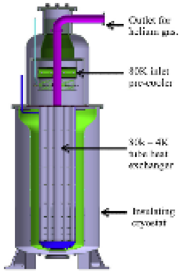
Small CECE Process at AECL

C. Muirhead, et al., Advanced Combined Electrolysis & Catalytic Exchange (CECE) Process for Hydrogen Isotope Separation in Water Decontamination Applications, 64th Canadian Chem. Eng. Conf. Niagara Falls, 2014

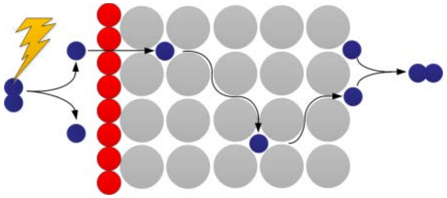
Vacuum and pumps

Cryosorption pumps



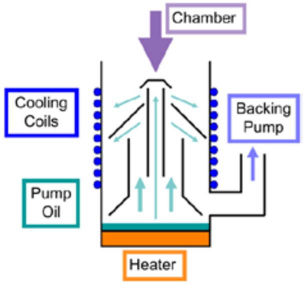


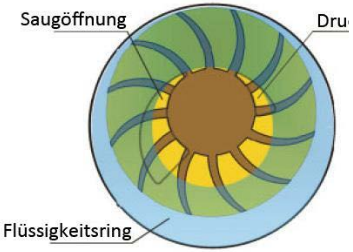
Snail pump under test at LANL.



Metal Foil Pump (MFP)

Vapor diffusion pump



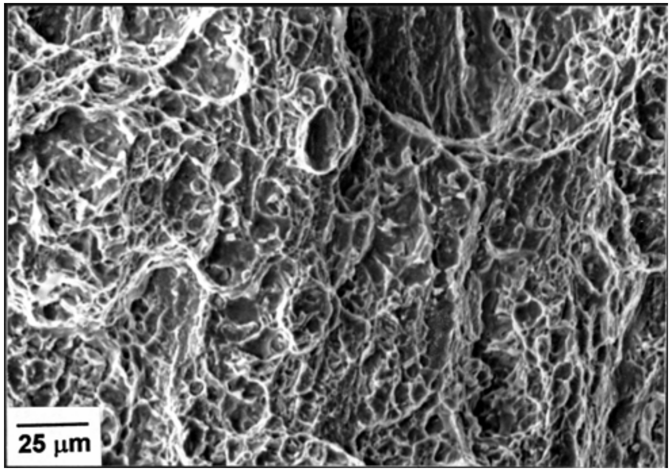


Liquid ring pumps (LRPs)

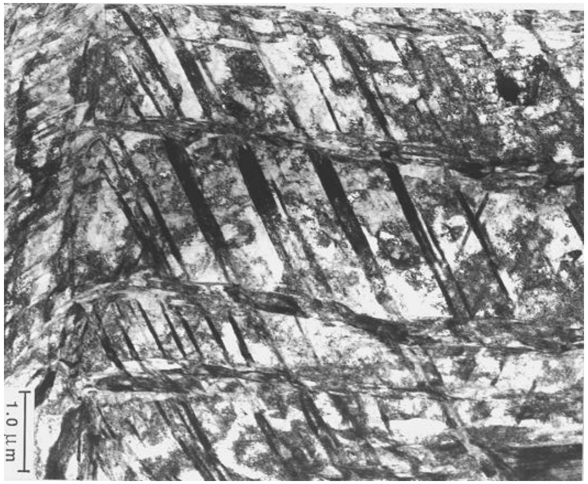
discontinued Normetex – complete dry and fluid tight vacuum pump

Th. Giegerich, Chr. Day, Tritium processing technology developments at KIT for nuclear fusion reactor, KIT/ITEP, 15 May 2018
S. Willms, Tritium Science and Technology in the Future, 2010 Tritium Conference Tutorial Lectures, Nara, Japan , 2010.10.29

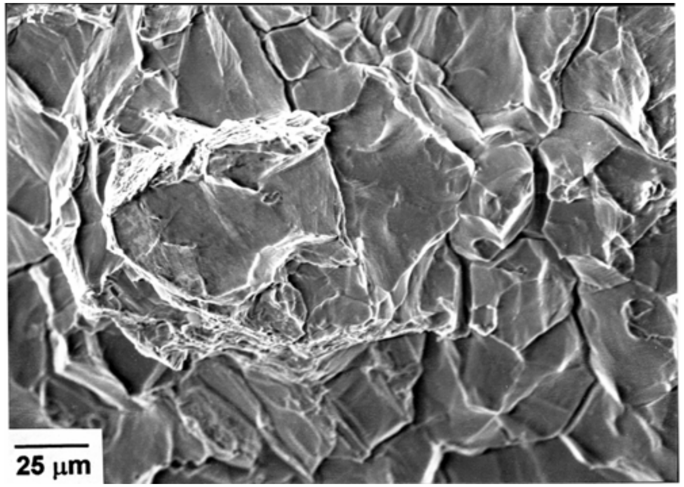
Tritium material compatibility evaluation



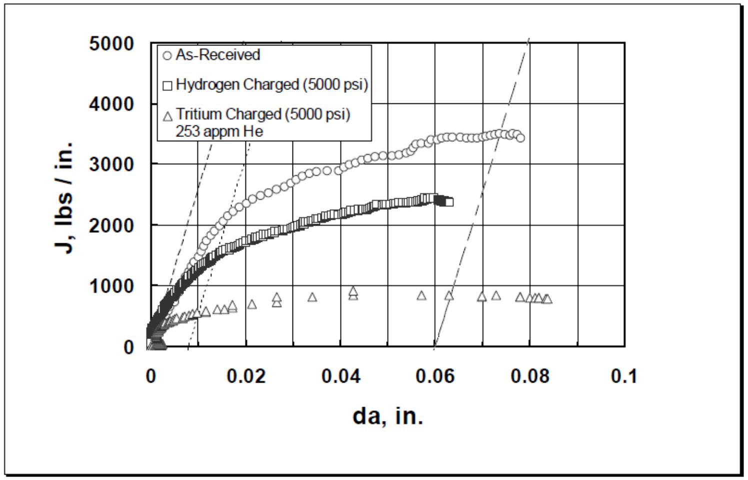
Unexposed stainless steel



Helium Hardened Microstructure



Tritium-Exposed & Aged



Conventionally Forged Type 21-6-9 Stainless Steel

Michael Morgan, "Effect of Forging Process on Tritium Compatibility of Stainless Steel", Hydrogen and Helium Isotopes in Materials, February 6-7, 2008, Sandia National Laboratory, Albuquerque, NM

Tritium Interaction with Metal Surface

H_2O always exists in H_2

Any “clean” hydrogen includes more than a few ppm of H_2O

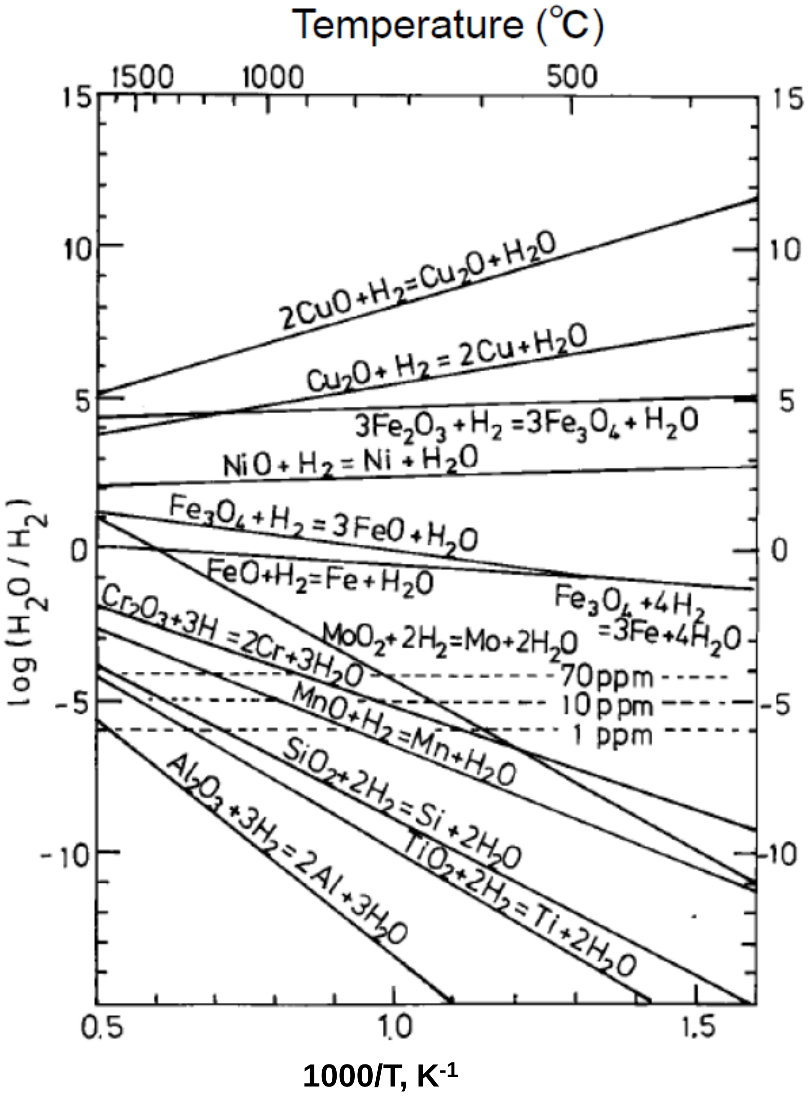
Oxidation and reduction on metal surface

$$MO + H_2 \leftrightarrow M + H_2O - \Delta G$$

$$\Delta G = -RT lnK$$

$$= -RT \left[\frac{P(H_2O)}{P(H_2)} \frac{\alpha(M)}{\alpha(MO)} \right]$$

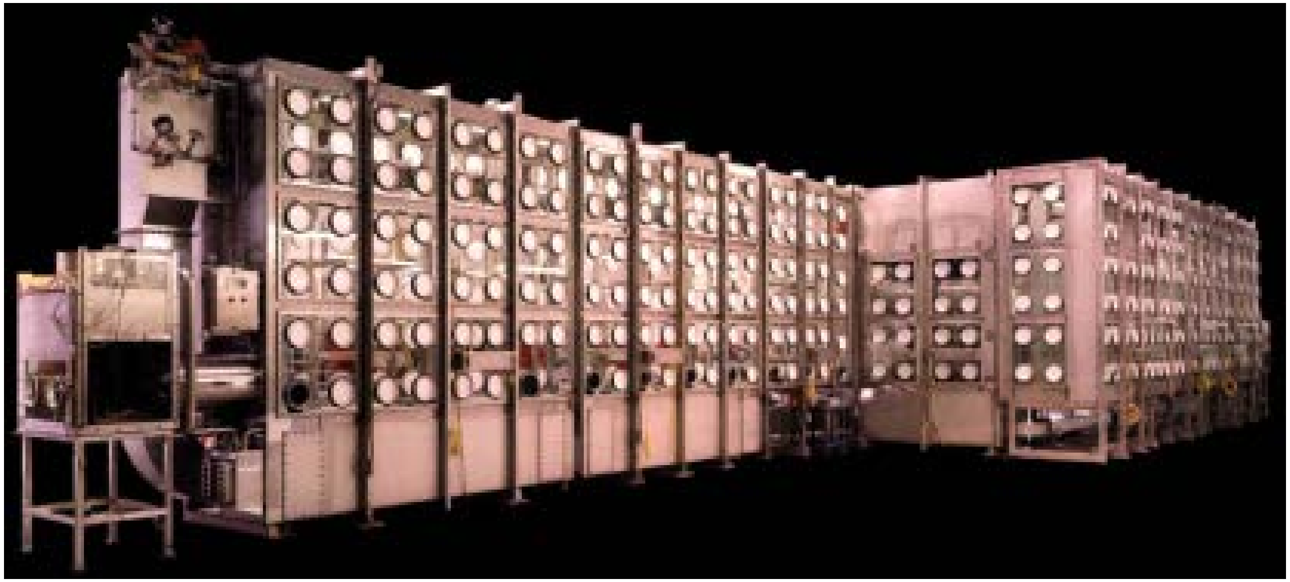
$$\approx -RT \left[\frac{P(H_2O)}{P(H_2)} \right]$$



T. Tanabe, What is tritium, 2010 Tritium Conference Tutorial Lectures, Nara, Japan , 2010.10.29

Tritium confinement and radiological safety

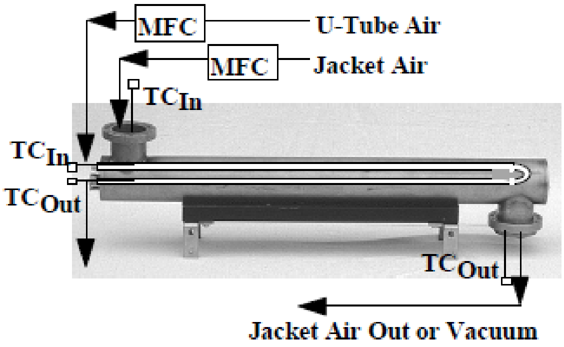
- Primary, secondary and tertiary confinement
- Area monitor and personnel surveillance
- Permeation barriers
- Occupational and environmental tritium monitoring
- Maintenance systems
- Waste handling, characterization and processing
- Decontamination and decommissioning
- Personnel protection equipment
- Best practice and safety culture



Tritium Accountability

State-of-the-Art

- – P-V-T Composition: 2% or less
- – Dedicated calorimeters: ± 0.25% in 6-8 hours
- – In-bed accountability (IBA): 1-2%



Non-distructive Detection of Hydrogen in Solids

- Direct: Nuclear reaction, Ion beam analysis, diffraction (neutron, ion, X-ray, electron) (Only for hydrogen in near surface layers)
- Electron transition: EELS, UPS, LIF
- Vibrational and rotational transition: IR, Raman, Low energy EELS (Limited to surface or transparent materials)
- Diffraction, Channeling: Neutron, Ion, Electrton
- Magnetic moment: NMR, ESR
- Indirect: Elastic energy (Internal Friction, Gorsky effect)
- Electronic and Mechanical property change
- All are not applicable at higher temperatures
- And few methods can be applied in vessel tritium analysis

Tritium Waste Disposal

State-of-the-Art

- – (see Safety and Environmental presentation)

Demo Function/Requirements

- – Some type of on-site or permitted disposal site will be needed

Gaps

- – Assurance that fusion will not suffer from “Yucca Mountain syndrome”
- – Recycle option from “Safety and Environmental” presentation needs to include tritium recovery functionality in project scope

S. Willms, Tritium Science and Technology in the Future, 2010 Tritium Conference Tutorial Lectures, Nara, Japan , 2010.10.29

Areas to further improve / develop

- Fuel Cleanup: Technology improvement
- Isotope Separation: Tritium inventory and technology improvement
- Tritium Storage and Delivery: Technology and assaying improvement
- Water Detritiation: Technology improvement. Need low-level tritiated water processing system.
- Pumping: Need larger capacity pumps
- Effluent Detritiation: Would benefit from system which does not produce water
- Gas Analysis: Technology improvement
- Process Control: Duty cycle and flowrate will require better control
- Modeling: Accurate, easy-to-use models will be essential

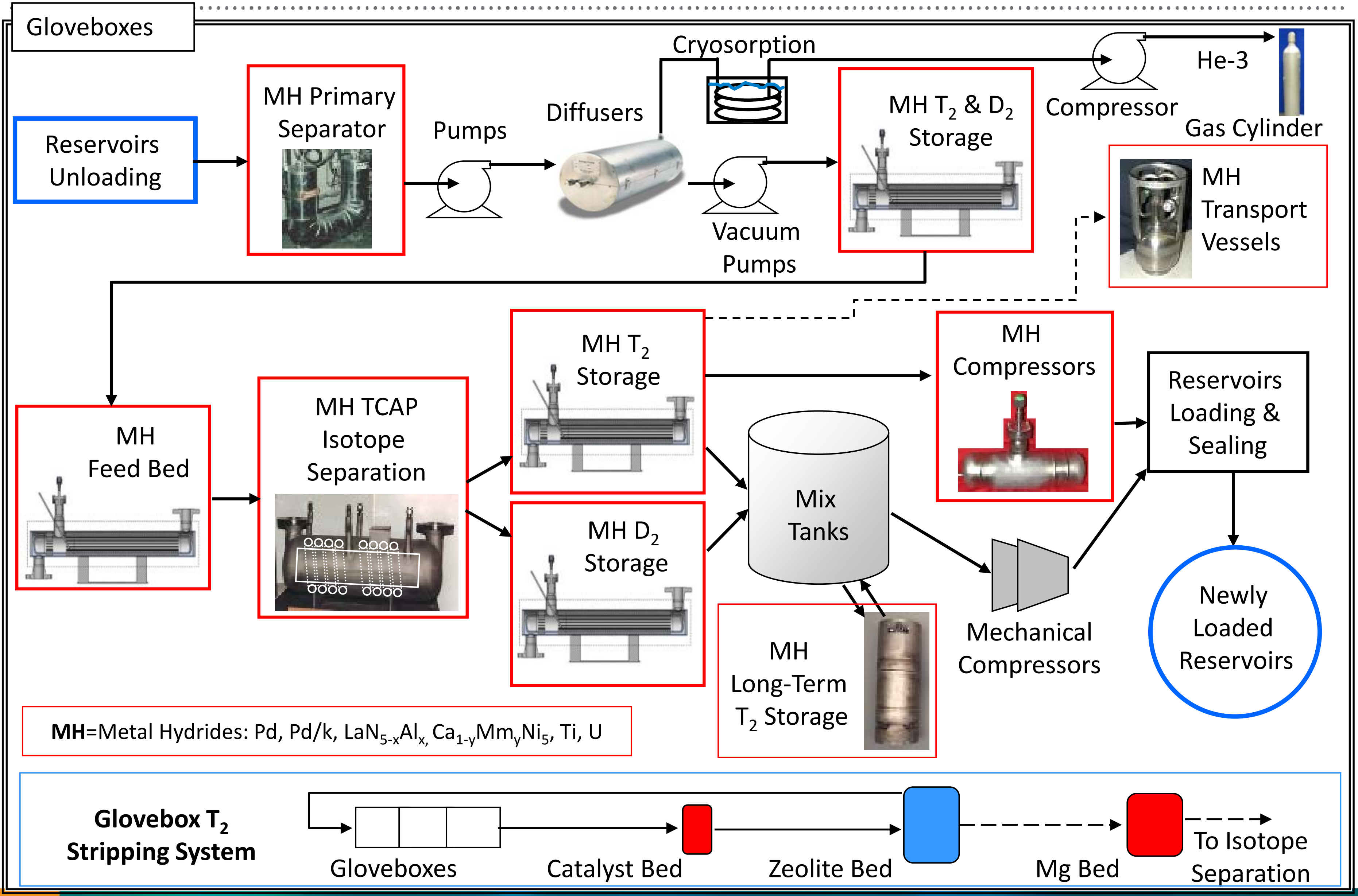
S. Willms, Tritium Science and Technology in the Future, 2010 Tritium Conference Tutorial Lectures, Nara, Japan , 2010.10.29

Additional Issues

- Tritium recovery in waste components
  - ✓ ITER: high temperature bake out in tritium controlled hot cell
- Hold-up in hidden and cooler areas (gaps, ducts, behind in vessel components such as RF launchers, etc.)
  - ✓ – Maintain similar temperature in these components
- Wall conditioning produced tritium stream
  - ✓ – ITER: use available tritium exhaust and recovery system
- Impurities introduced into vessel due to abnormal or accidental conditions including from auxiliary systems such as NBI (SF_6 insulator)
  - ✓ – Limit material choices for in-vessel and auxiliary systems

S. Willms, Tritium Science and Technology in the Future, 2010 Tritium Conference Tutorial Lectures, Nara, Japan , 2010.10.29

Tritium Processing at SRS - The Largest Metal Hydride Based Tritium Facility in the World



Gloveboxes

Reservoirs Unloading

MH Primary Separator

Pumps

Diffusers

Cryosorption

Vacuum Pumps

MH T_2 & D_2 Storage

Compressor

He-3

Gas Cylinder

MH Transport Vessels

MH Feed Bed

MH TCAP Isotope Separation

MH T_2 Storage

MH D_2 Storage

Mix Tanks

MH Compressors

Reservoirs Loading & Sealing

Mechanical Compressors

Newly Loaded Reservoirs

MH Long-Term T_2 Storage

MH=Metal Hydrides: Pd, Pd/k, $LaN_{5-x}Al_{x}$, $Ca_{1-y}Mm_{y}Ni_{5}$, Ti, U

Glovebox T_2 Stripping System

Gloveboxes

Catalyst Bed

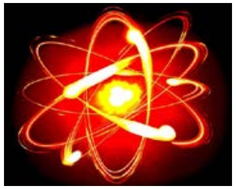
Zeolite Bed

Mg Bed

To Isotope Separation

The Fusion Fuel Cycle

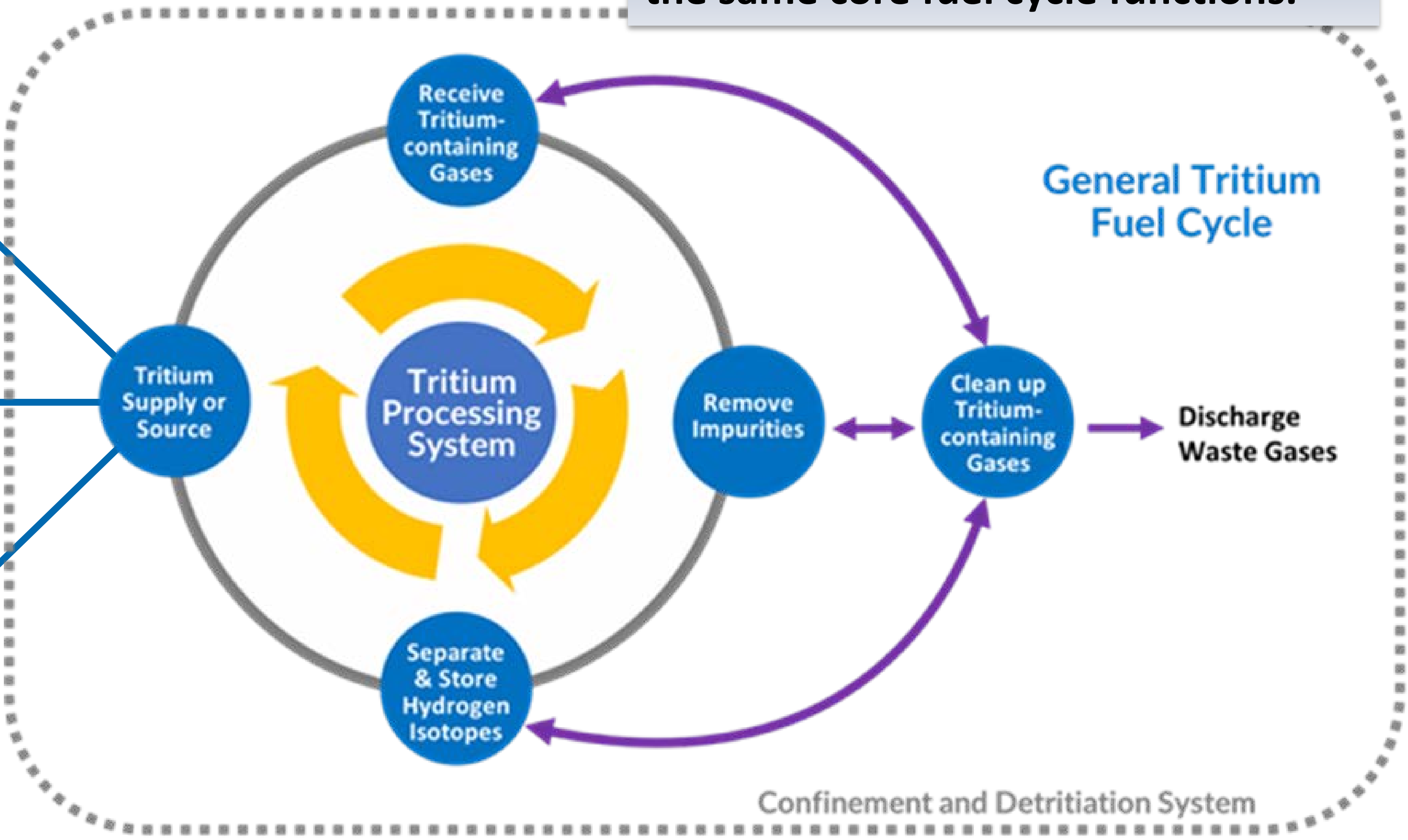
All tritium processing systems contain the same core fuel cycle functions.



POWER

DEFENSE

COMMERCIAL



General Tritium Fuel Cycle

Tritium Processing System

Receive Tritium-containing Gases

Tritium Supply or Source

Remove Impurities

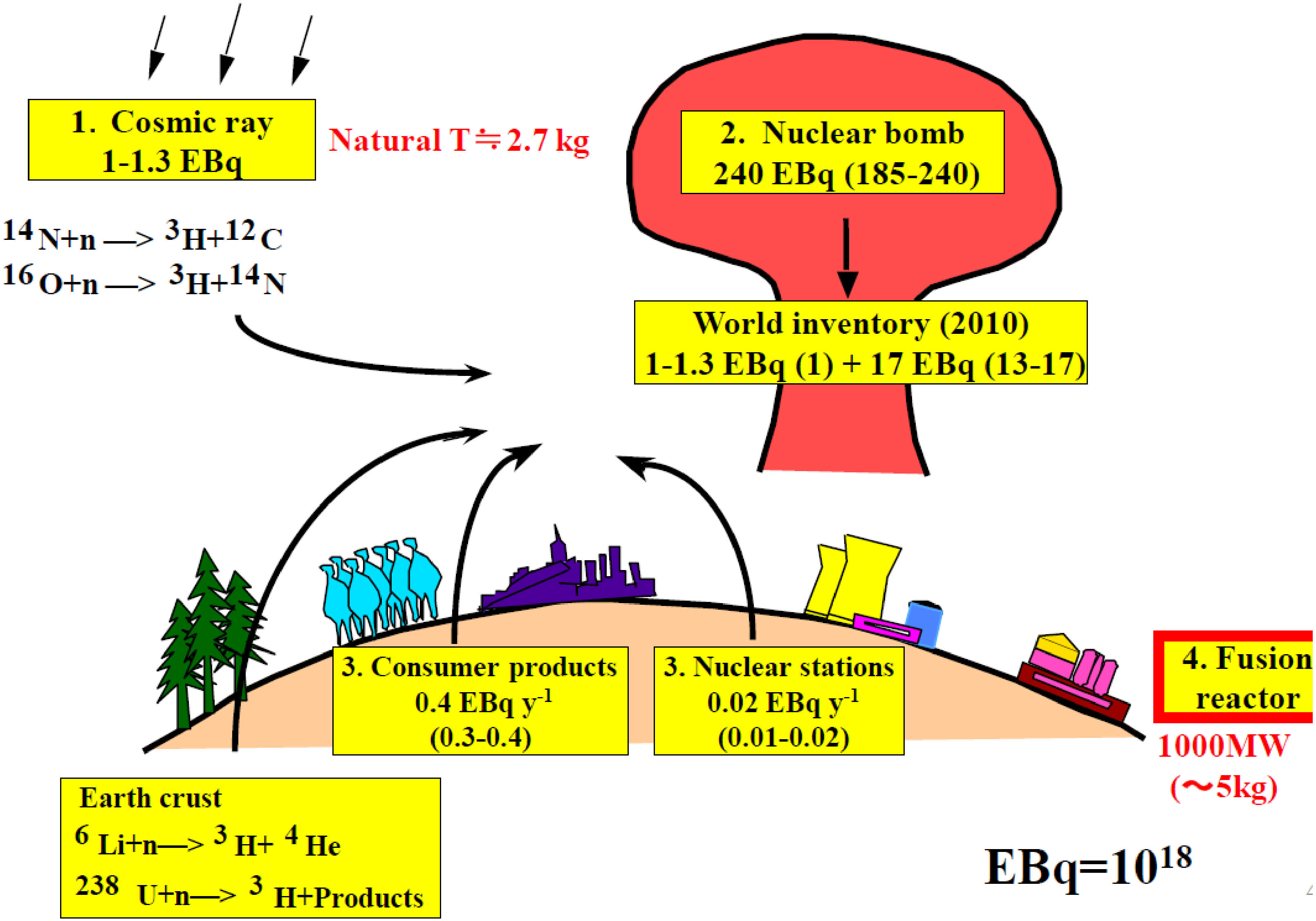
Separate & Store Hydrogen Isotopes

Clean up Tritium-containing Gases

Discharge Waste Gases

Confinement and Detritiation System

Tritium and environment



1. Cosmic ray
1-1.3 EBq

Natural T≒2.7 kg

$^{14}N+n \rightarrow {}^{3}H+{}^{12}C$

$^{16}O+n \rightarrow {}^{3}H+{}^{14}N$

2. Nuclear bomb
240 EBq (185-240)

World inventory (2010)
1-1.3 EBq (1) + 17 EBq (13-17)

3. Consumer products
0.4 EBq y^{-1}
(0.3-0.4)

3. Nuclear stations
0.02 EBq y^{-1}
(0.01-0.02)

4. Fusion reactor

1000MW
(～5kg)

Earth crust
$^{6}Li+n \rightarrow {}^{3}H+{}^{4}He$
$^{238}U+n \rightarrow {}^{3}H+\text{Products}$

EBq=10^{18}

Source: S. Konishi, TRITIUM and Environment, 2010 Tritium Conference Tutorial Lectures, Nara, Japan, 2010.10.29

Useful References for Tritium System Design

- DOE-STD-1129-2015 “DOE Handbook Tritium Handling and Safe Storage”, 2015
- William W Weaver et al, DOE/EH-0417, Technical Notice Issue No 94-01, “Guidelines for Valves in Tritium Service”, 1994
- F Mannone, Springer, Editor, "Safety in Tritium Handling Technology", Kluwer Academic Publishers, 1993
- International Atomic Energy Agency, "Safe Handling of Tritium: Review of Data and Experience", Vienna, 1991
- ASME B31.3 process piping code, ASME Boiler and Pressure Vessel Code Section VIII and Section II