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The potential synergies in fission - fusion fuel cycle

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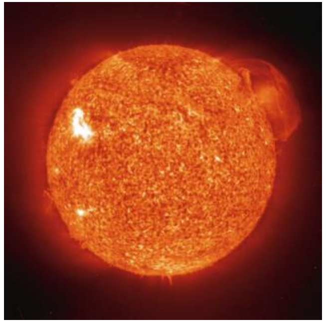
The energy of the nuclei can be tapped in two ways: fission and fusion

By splitting large nuclei into smaller ones: nuclear fission energy

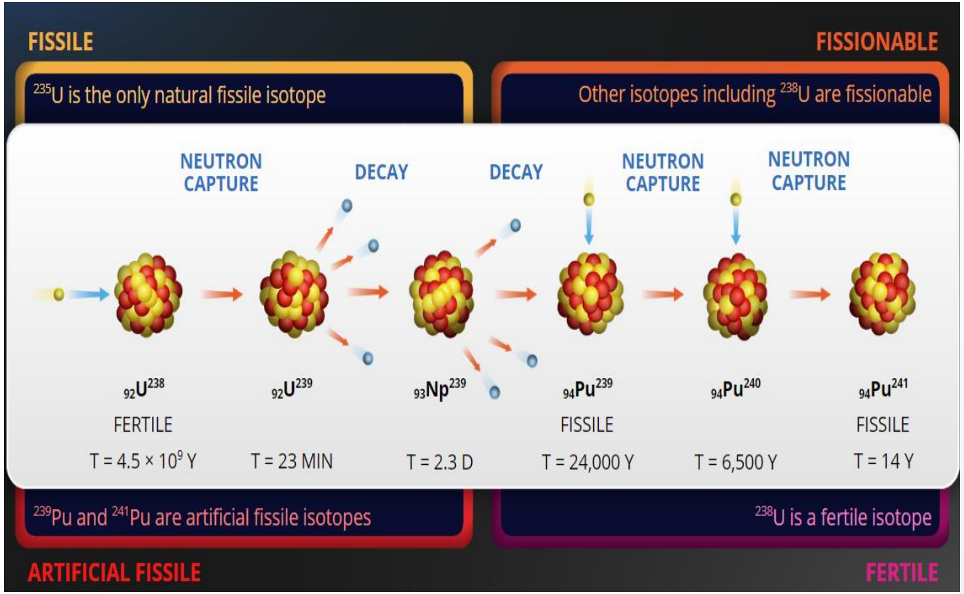
Fission is a well-developed technology

By combining small nuclei into larger ones: fusion energy



Fusion energy is basically solar power, since that is the way the sun and stars generate their energies

Fission energy



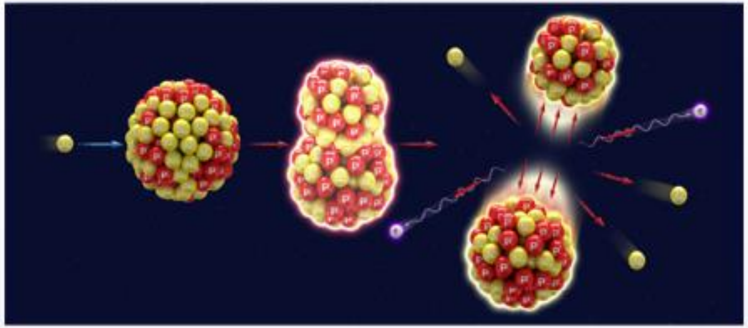
^{235}U is the only natural fissile isotope

Other isotopes including ^{238}U are fissionable

^{239}Pu and ^{241}Pu are artificial fissile isotopes

^{238}U is a fertile isotope

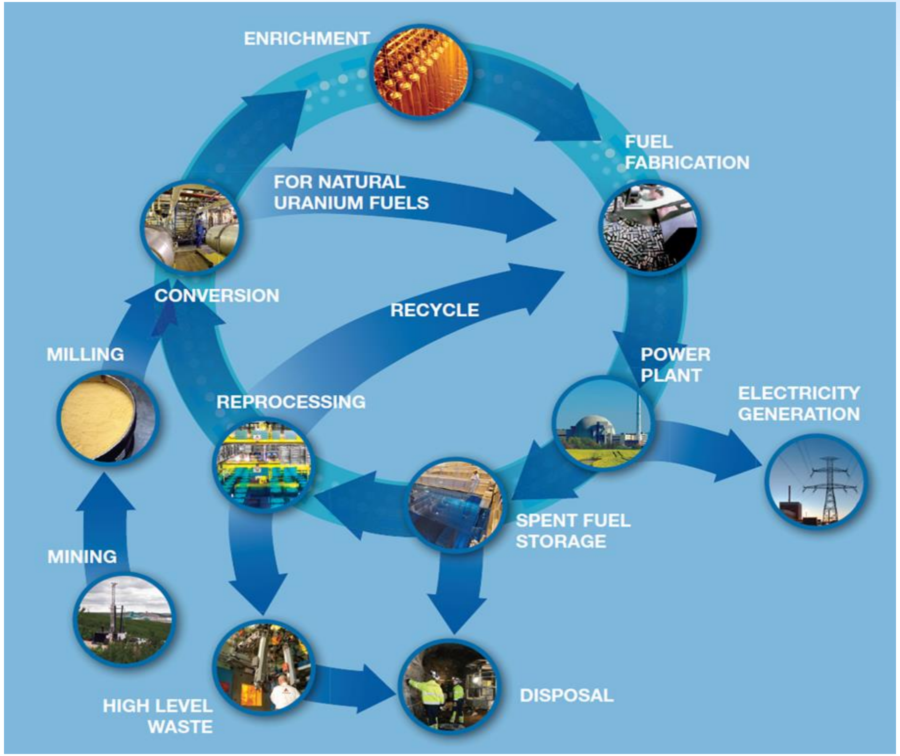
$$^{1}_{0}n + ^{235}_{92}U \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n + 200\ \text{MeV}$$



One fission, of one heavy atom releases between 200 and 211 MeV i.e. 3.2 to 3.4 × 10^{-11} J.

Fission nuclear fuel cycle

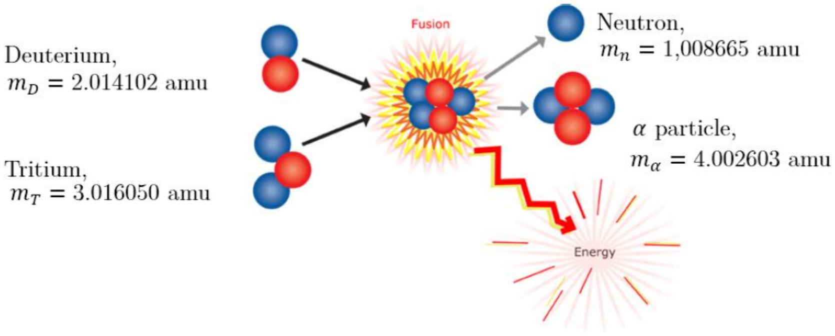
- Uranium Mining and Milling
- Uranium Conversion
- Uranium Enrichment
- Fuel Fabrication
- In-Reactor Fission
- Spent Fuel Management
- Spent Fuel Reprocessing and Recycling
- Disposal of HLW and Spent Fuel*



*only when declared as waste

Fusion principle and fuel

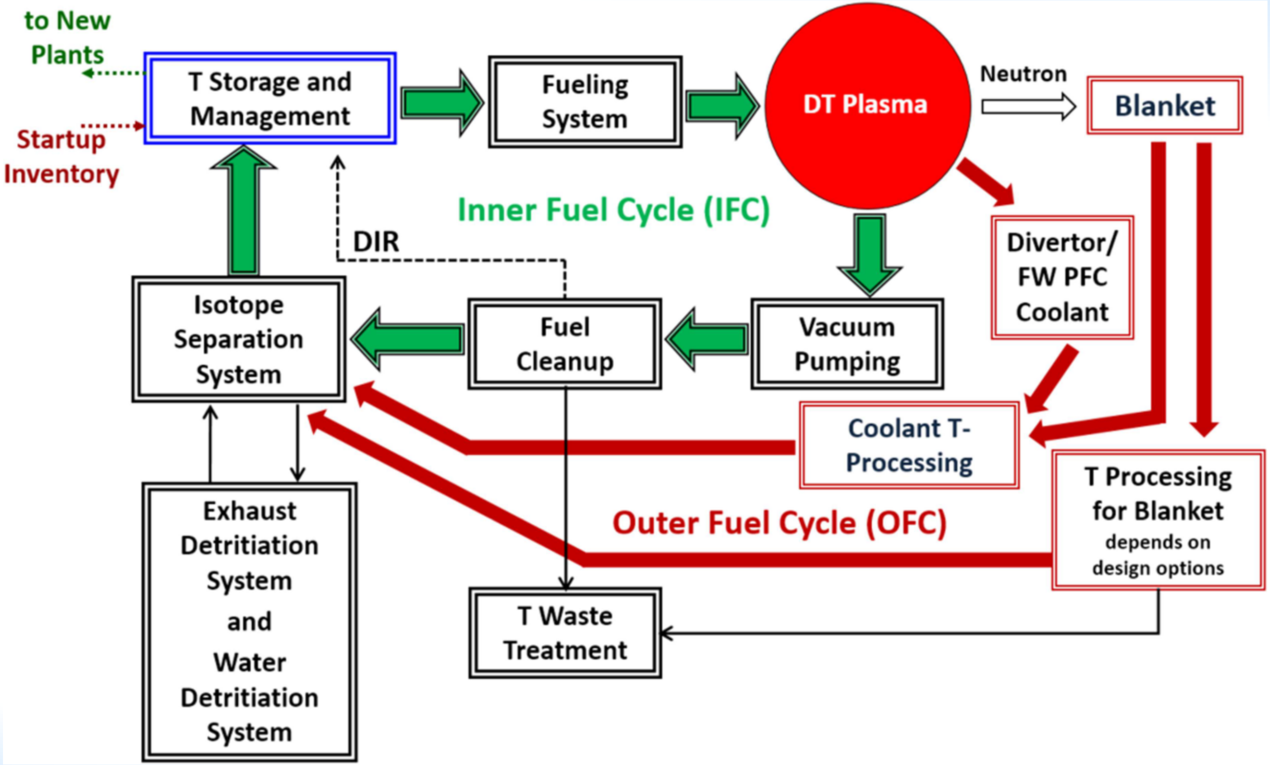
- Deuterium is abundant in nature: for example, it makes up 0.015 atomic percent of the hydrogen in seawater with a volume of about $1.35 \cdot 10^9\ \mathrm{km}^3$.
- Tritium can be produced in the mantel (breeding blanket) surrounding the area of the D-T fusion reactions.



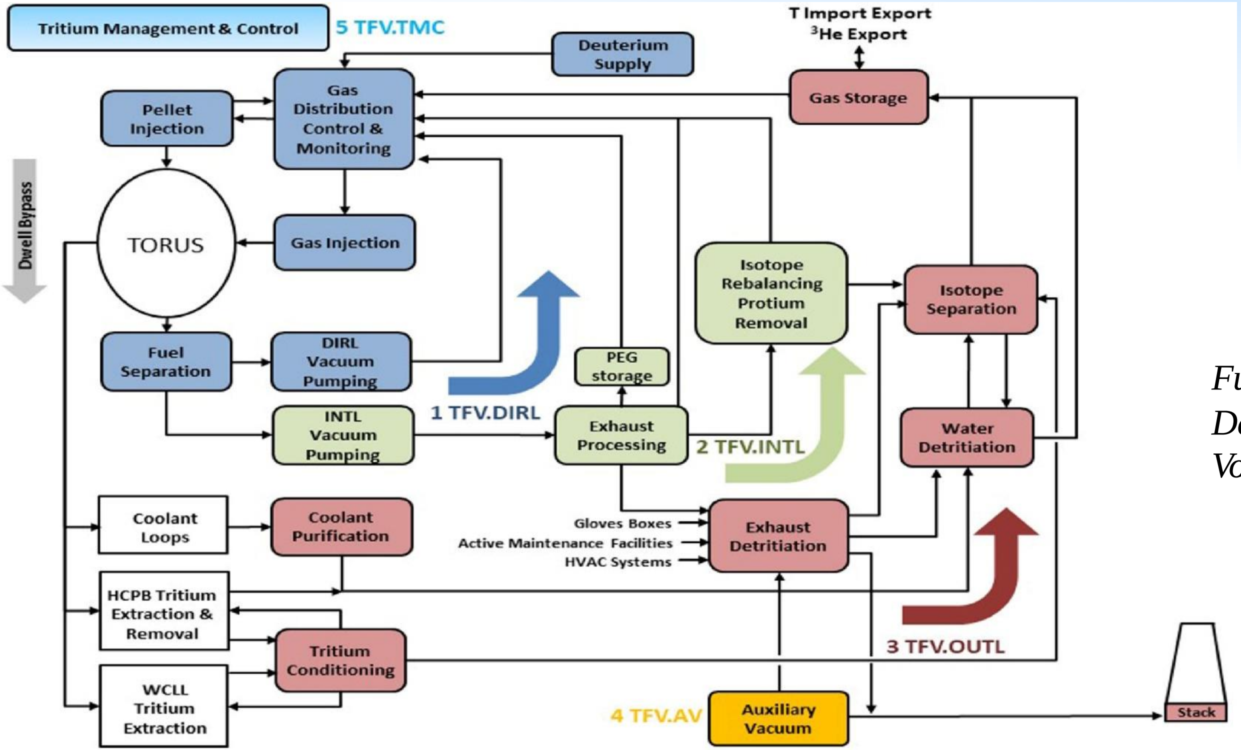
$$
\begin{aligned}
{}^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n(slow)} &\longrightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{T} + 4.9\,\mathrm{MeV} \\
{}^{7}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n(fast)} &\longrightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{T} + {}^{1}_{0}\mathrm{n} - 2.5\,\mathrm{MeV}
\end{aligned}
$$

The first equation generates energy, while the second consumes energy. The Li-6 reaction consumes one slow neutron and produces tritium, and it is easier to initiate this reaction with respect to the second.

Fusion fuel cycles components: inner and outer



DEMO Fuel Cycle



Fusion Engineering and Design
Volume 179, June 2022, 113139

"Cross-cutting issues in fusion and fission. Tritium management" M. Utili, C. Alberghi, L. Candido, D. Diamanti, F. Papa, A. Venturini

Fuel cycle concepts of DT-FC developed in RF

Beam isotope composition	Tritium plant, g	NBI-system, g	Fueling systems and vacuum chamber, g	Total inventory, g
D+T (current FC architecture)	25	20	180	180-220
D (current FC architecture)	30	0	160	160-190
D (full exhaust separation)	35	0	180	215
T (current FC architecture)	40	40	40	145-170
T (full exhaust separation)	100	40	30	175
T (NBI gas support optimisation)	165	15	30	215-220

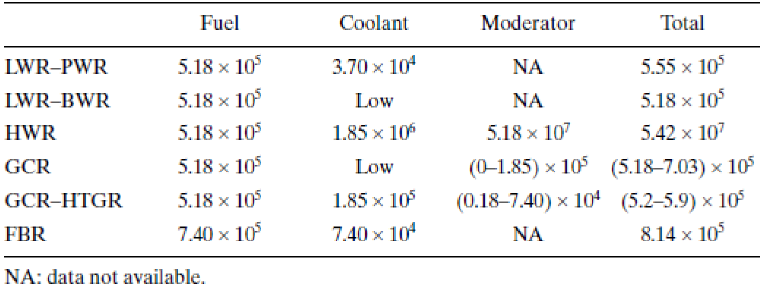
Tritium locations in FC systems and the total inventory for various NBI gas support scenarios (in gram)

- The integrated model for simulating processes in the plasma fueling cycle systems (FC) of DEMO-FNS tokamak
- Interaction of FC with core and divertor plasmas employs the SOLPS, ASTRA, and FC-FNS codes

“The concept of Tritium Fuel cycle for a Tokamak based fusion neutron sources in the Russian Federation“, S.S. Ananyev, B.V. Ivanov, A.S. Kukushkin, M.R. Nurgaliev, B.V. Kuteev

Tritium is generated by the nuclear fission industry

Estimated tritium production rates (in GBq per GW(e) per year) in various types of reactor
(1 GBq (^{3}H) = 27 mCi (^{3}H) ~ 27 g (^{3}H))



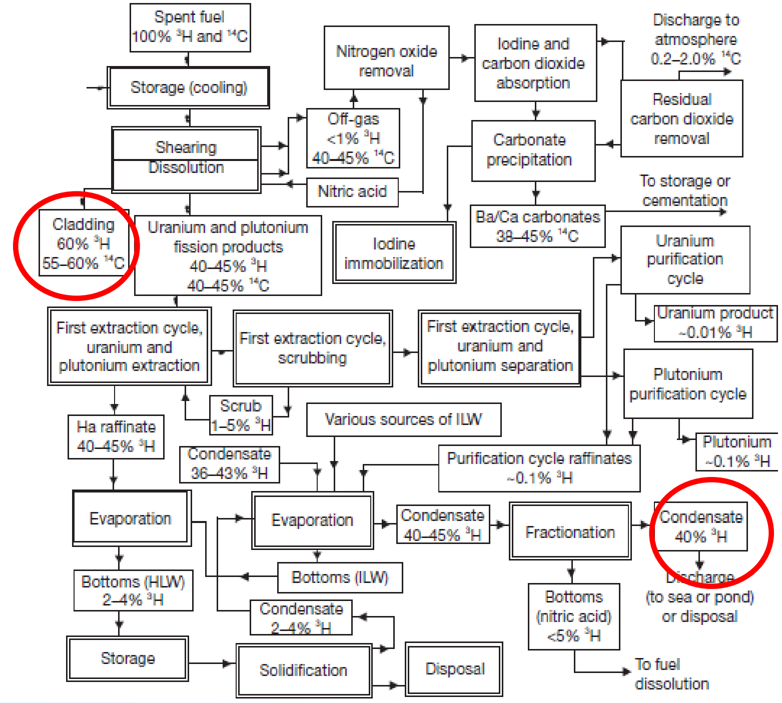
	Fuel	Coolant	Moderator	Total
LWR–PWR	5.18×10^5	3.70×10^4	NA	5.55×10^5
LWR–BWR	5.18×10^5	Low	NA	5.18×10^5
HWR	5.18×10^5	1.85×10^6	5.18×10^7	5.42×10^7
GCR	5.18×10^5	Low	$(0–1.85) \times 10^5$	$(5.18–7.03) \times 10^5$
GCR–HTGR	5.18×10^5	1.85×10^5	$(0.18–7.40) \times 10^4$	$(5.2–5.9) \times 10^5$
FBR	7.40×10^5	7.40×10^4	NA	8.14×10^5

NA: data not available.

Tritium is formed in the following fission reactor components:

- LWRs: coolant–moderator (water)
- HWRs: coolant and moderator (heavy water)
- HTRs: coolant (helium)
- Many types of reactors: control rods (boron)
- PWRs, HTRs: dissolved boric acid in the moderator
- GCRs, HTGRs: graphite moderator (lithium impurity for GCRs)
- FBRs: UO_2/PuO_2 core and UO_2 breeder fuel (lithium and boron impurities)

Flow diagram of a typical LWR fuel reprocessing plant and typical tritium distribution



The tritium contents in the process products

For a LWR fuel reprocessing plant, with a capacity of 1400 t/a of heavy metal (serving 50 GW(e) of electric production capacity), the tritium release is estimated at around (1.85–3.70) × 10^7 GBq/a (0.5–1.0 MCi/year or 50–100 g/year)

The potential fission - fusion crosscutting areas Waste minimization approaches

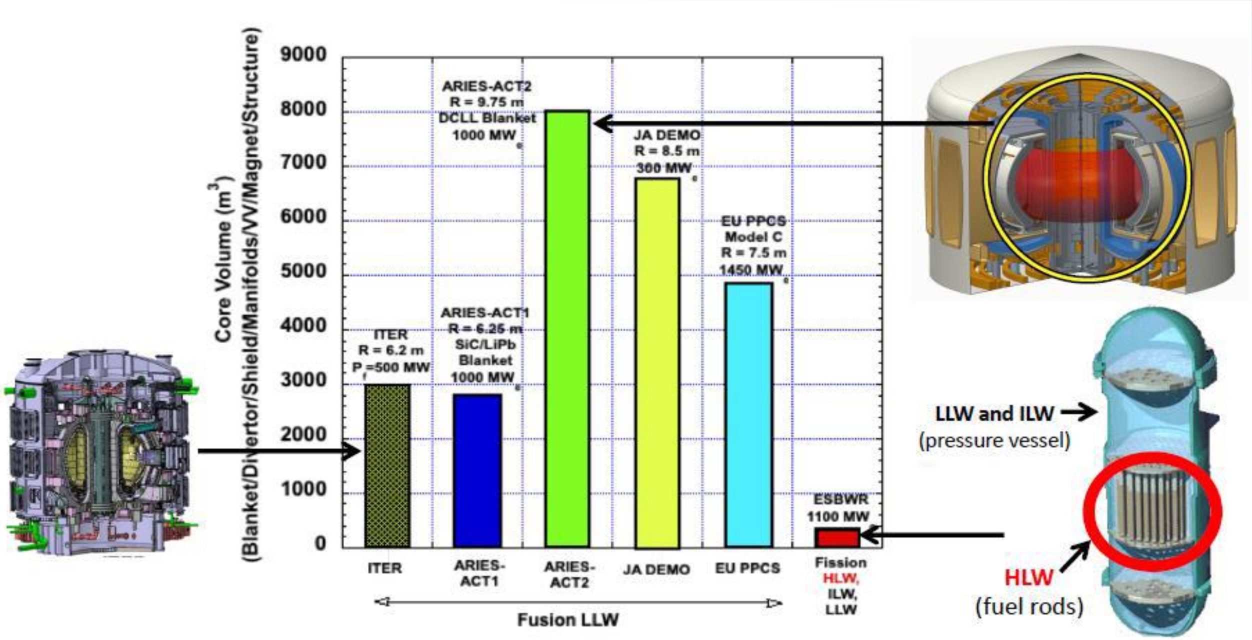
Lessons learned from NPP waste management and from ITER licensing applied to DEMO and fusion power plant RWM requirements on the design needs to include:

- Minimization of operational and dismantling radwaste production with careful choice of materials, optimized layout and shielding aspect.
- Segmentation of Component design to prolong service lifetime, possible dismantling of elementary parts in order to separate them according to their content of radioactivity (and reusability).
- Maximization of recycling and clearance.
- Minimization of ultimate waste disposal. For fission such an approach may include closed fuel cycle with minor actinide separation and transmutation for the DGR footprint reduction.

Overall conceptual approach that needs to be adopted in DEMO and fusion power plant RWM

Sehila M. Gonzalez de Vicente et al 2022 Nucl. Fusion 62 085001

Comparison the waste inventories in Fusion and Fission



Fusion Core Volumes of several Nuclear Fusion Plants and ESBWR (US waste estimation). It is noted that this is the core volumes and not the lifetime waste generation including decommissioning waste and balance of plant.

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Comparison the waste inventories in Fusion and Fission

Fusion power plant radioactive wastes are significantly different from wastes of fission NPPs, i.e., much larger quantities, large amount of tritium, different radioisotopes, no-transuranic elements, lower decay heat to be removed and lower radioactivity content overall.

The dominant fusion wastes are mainly composed of structural materials (steels, e.g. AISI 316L and ferritic martensitic steels, like EUROFER97 and F82H) and functional materials (such as tritium breeders, magnet constituents, etc.).

The relevant long-lived radioisotopes generated in fusion (from impurities) after irradiation can include isotopes of niobium, molybdenum, nickel, carbon, copper, and aluminium and material impurities (such as Co, K, Ag), that might preclude disposal in LLW repositories.

Several options have been analysed to recover valuable elements (i.e., tritium, T) and separate long-lived radionuclides (i.e., C-14, Nb-94, and/or Mo-99), to define an optimal set of process conditions depending on the final destination of the material (disposal, recycling, or clearance).

Specific materials from the tritium fuel cycle also need to be considered as well as those from general operation and maintenance of the nuclear fusion facilities.

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The potential fission - fusion crosscutting areas: Technologies for detritiation

One of the most ambitious goals of fusion energy is to ensure fuel self-sufficiency of future D-T fusion power plants. **Tritium consumption** for a 2000 MWth fusion power reactor **is 112 kg per full power year**, higher than the current global availability estimated at 20-30 kg. It is clear, therefore, that efficient characterization of the processes and engineering solutions to **manage and control tritium transfer** and release is a critical factor in the success of fusion electricity deployment.

In the G-IV reactors in general, tritium is produced in the core by ternary fissions and by nuclear transmutation of boron used in the control rods and can then diffuse through fuel claddings and through structural materials.

A common approach for the tritium management for fission and fusion systems is to use a combination of these techniques:

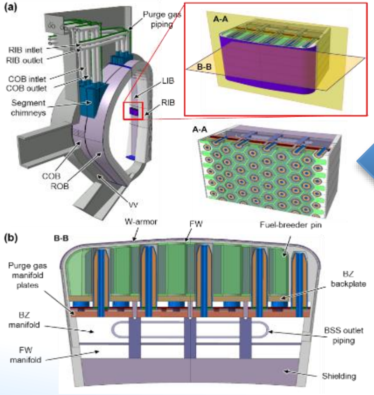
- ☐ Developing coating barriers to prevent the tritium permeation;
- ☐ Removing tritium from the liquid metal or the cover gas;
- ☐ Monitoring the tritium concentration in the reactor.

"Cross-cutting issues in fusion and fission. Tritium management" M. Utili, C. Alberghi, L. Candido, D. Diamanti, F. Papa, A. Venturini

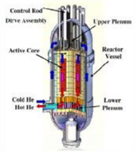
Detriation system

Two case studies were identified:

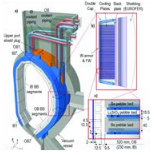
Water Detritiation systems based on CANDU Reactor technologies



Gas Detritiation system

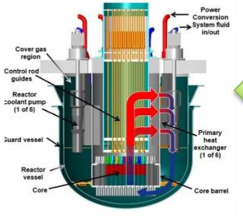


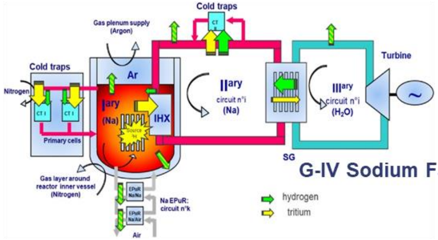
G-IV HTGRs



DEMO-HCPB BB

G-IV Lead Fast Reactor





G-IV Sodium Fast Reactor

On the basis of experience developed in Fusion application and HTGR it is proposed to size the LFR tritium removal system from the cover gas.

"Cross-cutting issues in fusion and fission. Tritium management" M. Utili, C. Alberghi, L. Candido, D. Diamanti, F. Papa, A. Venturini

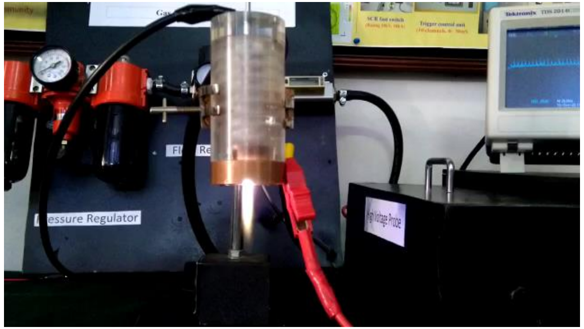
Technologies for detritiation

“Extraction and separation of tritium, the nuclear fusion fuel and the by-product of fission” (E. Pajuste, G. Vaivars, I. Reinholds, A. Lescinskis, A. S. Teimane, A. Kizilovs, R. Zabolockis)

The development of an installation for the separation of tritium from both water and gas.

Method is based on technique using graphene based – electrochemical pumping. The membrane-electrode assembly consists of two catalytic electrodes deposited on a proton conducting membrane. Hydrogen gas or water is split on one side to the proton and electron, which recombines on the other side of the membrane. NAFION® (sulfonated tetrafluoroethylene-based copolymer) is used as the proton exchange membrane coated with graphene layer

The potential fusion-fission synergy: Technologies of waste management



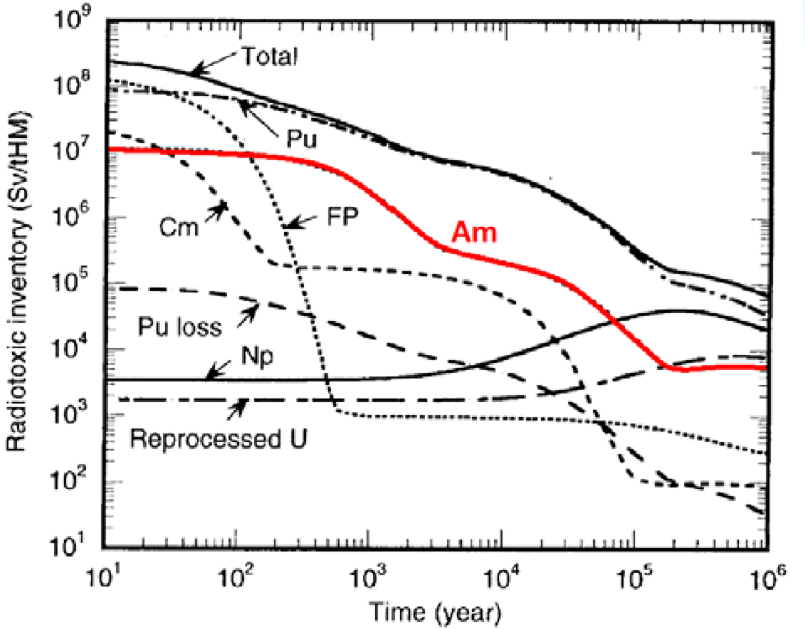
"Synergy between nuclear fusion and fission technology for developments of reactor's materials and waste management",
S. Hussain, Z. Ahmad and R.Khan

- Thermal plasma processing for fission RW management
- The vitrification of LLW and ILW through high power plasma torches (converts electrical energy into thermal up to 10000^{o}C) to reduced in volume by ~50 times
- A prototype plasma torch (250 W, 4kV DC & Temp. ~500 ^{o}C) has been developed for demonstration

Transmutation of Minor actinides as Fusion neutron beans application

Impact of minor actinides (Am, Cm, Np) on the waste inventory:

- Radiotoxicity of actinides
- Contribution to the thermal of the final package and impact on the size of waste storage ultimate



"Synergy of Fission and Fusion: the path to clean nuclear energy system" (V.V. Artisyuk)

The outline of the 3.5 section on Fuel Cycle (NES document)

1. **Fusion and fission fuel cycles: the fuel material production**
    - a. **Fission fuel cycle** (mining, enrichment, fuel fabrication, spent fuel management, waste management)
    - b. **Fusion fuel cycle**
        - a. Achieving tritium self-sufficiency within the fusion system
        - ○ *Inner fuel cycle*, i.e., fuel separation, vacuum pumping, plasma exhaust processing, gas distribution control and monitoring, and fuelling systems
        - ○ *Outer fuel cycle*, i.e., coolant purification, tritium extraction system from the breeding, isotope separation, exhaust detritiation (treating the streams from active ventilation, glove boxes and HVAC), water detritiation and isotope separation system providing a tritium inventory for the initial start-up of a fusion facility, minimizing the tritium inventory in the system
    - c. **Potential fission - fusion crosscutting areas** (tritium generation at NPP and technologies for detritiation, waste minimization approaches)

2. **Ultimate waste management**
    - a. Comparing the waste inventories in fusion and fission
    - b. Potential synergy: the waste management technologies in fission, that can be implemented in fusion
    - c. Transmutation of Minor actinides as Fusion neutron beans application

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Thank you…