Italian National Agency for New Technologies, Energy and Sustainable Economic Development

# CROSS-CUTTING ISSUES IN FUSION AND FISSION TRITIUM MANAGEMENT

## Consultancy Meeting on Synergies in Technology Development between Nuclear Fission and Fusion for Energy Production

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# Introduction

- 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 2,000 $MW_{th}$ fusion power reactor **is 112 kg per full power year**, higher than the current global availability estimated at 20-30 kg.
- The 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 **fission** reactors, tritium can be produced:
  - By **ternary fissions** in the fuel pins, when during fission of $^{239}$Pu and $^{235}$U also one light nucleus, often alpha particles or tritium;
  - By **neutron activation** of $^{10}$B boron isotope present in control rods made of boron carbide ($B_4C$).
- Tritium then can diffuse through fuel claddings and through structural materials.

- Identify synergies with Fission program for detritiation system developed for High Temperature Gas Reactors (HTGRs) and CANDU Reactor is mandatory is order to accelerate Fusion program.

# Introduction

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.

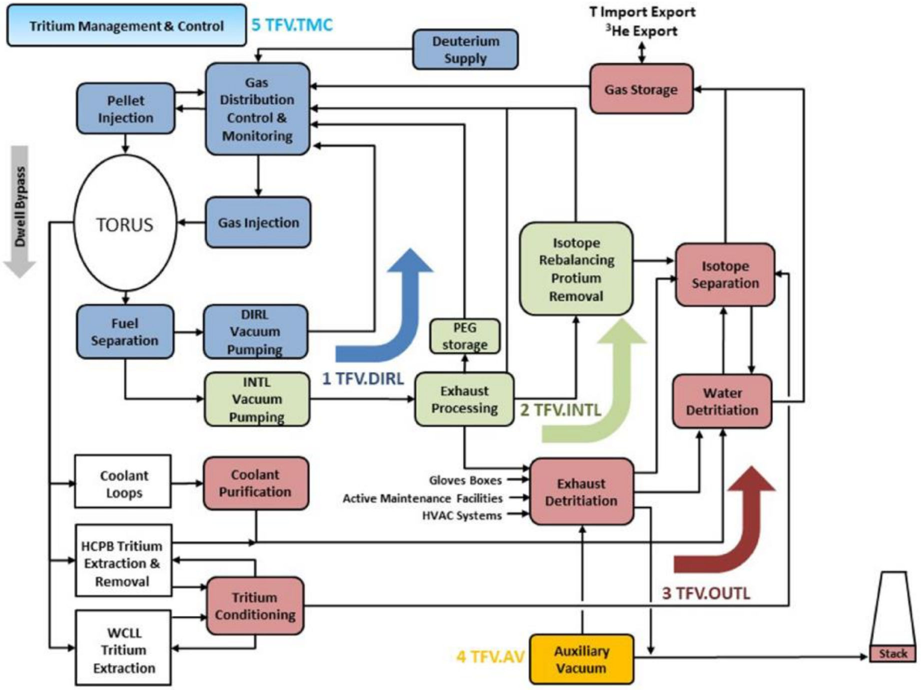
Two case studies were identified:

- ➢ Gas Detritiation system: HTGRs, SFR, LFR ⟷ Helium Cooled Pebble Bed (HCPB) BB
- ➢ Water Detritiation system: CANDU Reactor ⟷ Water-Cooled Lithium-Lead (WCLL) BB

# Tritium management for Fusion reactor

- The 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.

| # | Name | Classification ID |
|---|---|---|
| 1 | Direct Internal Recycling Loop | TFV.DIRL |
| 2 | Inner Tritium Plant Loop | TFV.INTL |
| 3 | Outer Tritium Plant Loop | TFV.OUTL |
| 4 | Conventional Vacuum Systems | TFV.CV |
| 5 | Tritium Management and Control | TFV.TMC |

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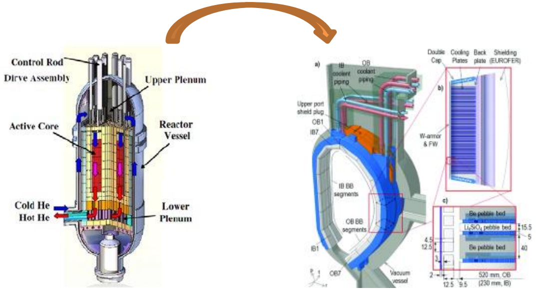
# Tritium Extraction System from Gas

The reference process for helium purification foresees three steps:

1. oxidation of $Q_2$ and CO into $Q_2O$ and $CO_2$, respectively using a copper oxide bed
2. adsorption of $Q_2O$ and $CO_2$, using a molecular sieve bed
3. adsorption of the remaining impurities, using a heated getter

These processes are used in the Coolant Purification Systems (CPSs) of **High Temperature Gas Reactors (HTGRs) and it was adopted in Helium Cooled Pebble Bed (HCPB) BB DEMO and TBM ITER**.

A preliminary design of CPS to be tested in ITER, was carried out in and characterized in HYDREX facility.




G-IV HTGRs

DEMO-HCPB BB

# Tritium Extraction System from Gas

- HYDREX (HYDRogen EXtraction) is an experimental facility, located in ENEA Brasimone Research Centre, having the scope to test processes, components and materials considered of interest for tritium extraction/purification from helium and for the purification systems of the cover gas of liquid metal cooled fast reactors.

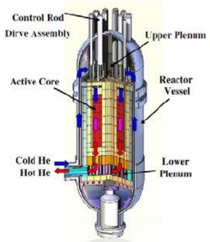
- The performances of different types of molecular sieves, included in a PTSA column, can be studied in conditions characterized by different temperatures and pressures.

- The trapped water, released during the regeneration of the molecular sieves, can be directed to a RB, in which the performances for the reduction of $H_2O$ into $H_2$ of the selected metallic getter can be studied.

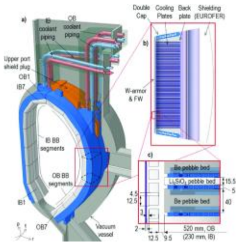
HYDREX Experimental Facility

# Tritium Extraction System from Gas

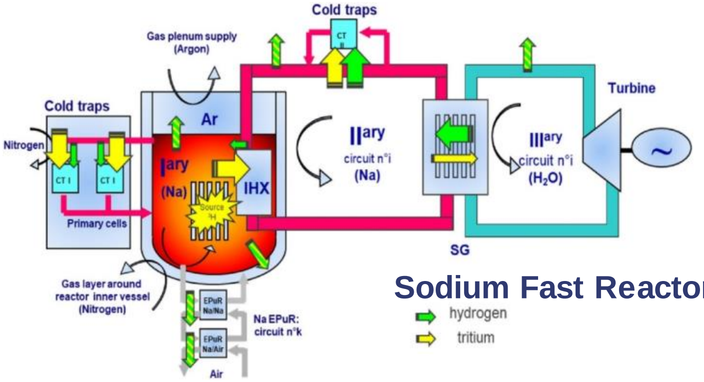
In the past, the tritium concentration in the primary cover gas of **Sodium Fast Reactors** (SFRs) was considered very low in the reactors due to the efficiency of the **cold traps for the tritium removal**. However a small amount of tritium permeates into the water of the steam generator. In the last years, the evolution of the industrial techniques and the application of optimization principles developed in Fusion application have allowed the design of systems that allow the reduction of the releases in the environment.




HTGRs



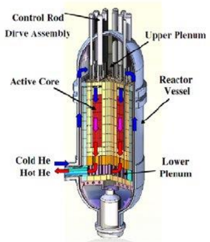
DEMO-HCPB BB



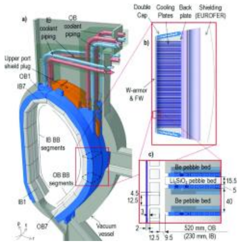

Sodium Fast Reactor

# Tritium Extraction System from Gas

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.

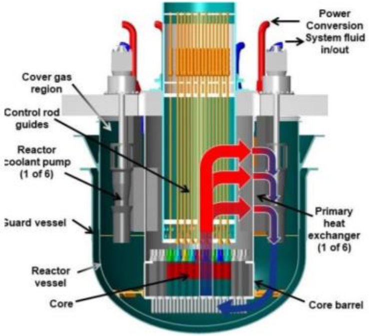


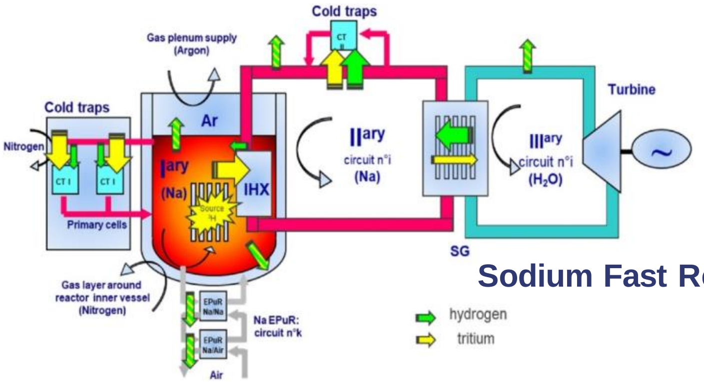

HTGRs



DEMO-HCPB BB

Lead Fast Reactor



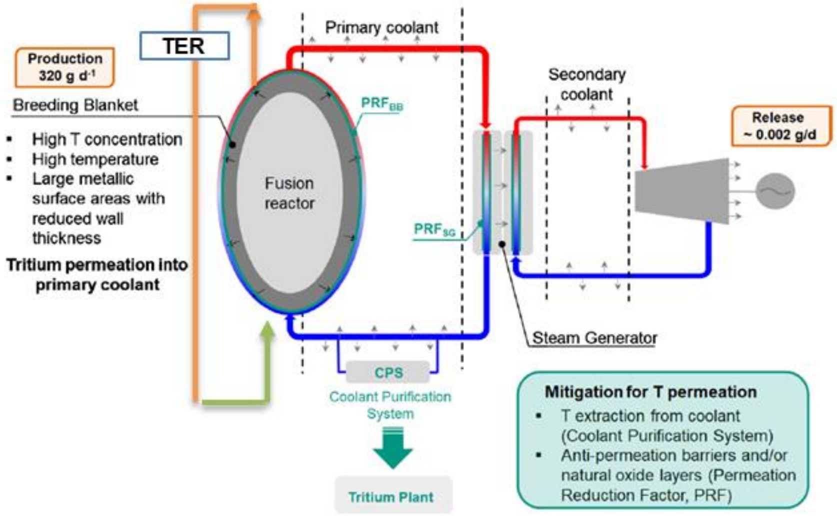




Sodium Fast Reactor

# Tritium Extraction System

In the WCLL BB concepts the critical aspect is the tritium extraction from the water by the **Tritium Coolant Purification System** (CPS).

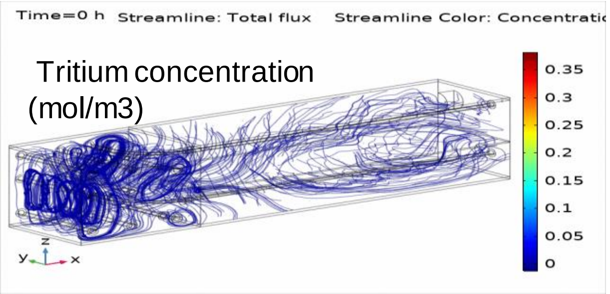
**The CPS** has to be devoted to remove tritium from the primary coolant (H2O) with an efficiency **> 90%.**



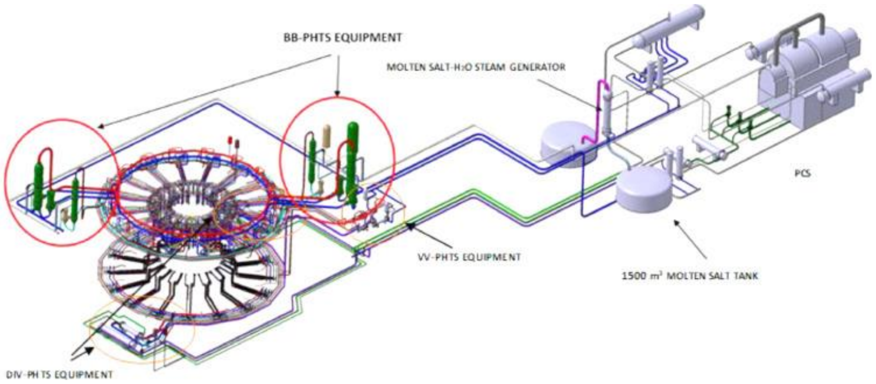
# Tritium balance in WCLL BB TER

## Water Cooled Lithium Lead (WCLL) BB – CPS Operative conditions

| Design Inputs CPS - WCLL | | |
|---|---|---|
| Parameter | Value | unit |
| Inlet Tritium concentration in LiPb | 0.014 | $mol/m^3$ |
| T perm. rate from plasma | 150 | mg/d |
| Water Flow rate | 20-360 | kg/h |




## WCLL BoP reference configuration: direct coupling design with small energy storage system, 3D CAD model.

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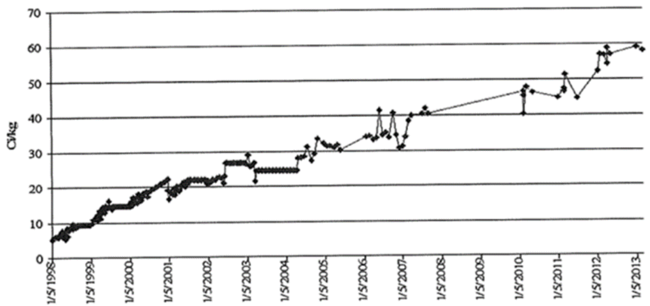
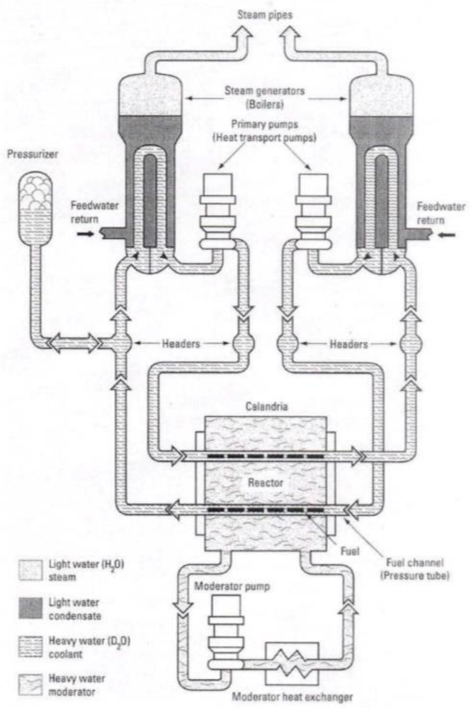
# Water Coolant Purification System

- Heavy Water Reactors (HWR) use $D_2O$ as neutron moderator and reactor coolant due to the very small absorption cross section for thermal neutrons compared to light water
- In HWR, tritium is directly generated from neutron absorption (even if it is small) by the deuterium atoms in heavy water; therefore the coolant and moderator will be contaminated with tritium
- In a CANDU 600 NPP, the HW inventory is >450,000 kg divided between moderator and coolant. The growth of tritium activity in the moderator of NPP Cernavoda Unit 1 is shown in figure.




*Babcock & Wilcox Canada – Cernavoda Steam Generators Design - Project No. 7505/7506.*

➡ Adoption of **Water Detritiation System (WDS)**



# Water Coolant Purification System

The general procedure to recover tritium from water foresees three processes:

- **front-end process** in which the tritium is transferred from the aqueous into a hydrogen gas stream (several processes available: direct electrolysis, CECE, LPCE, VPCE)

This can be performed either through chemical exchange in the presence of a platinum-based catalyst:

$$HTO + H_2 \leftrightarrow H_2O + HT$$

or through the decomposition of water:

$$2HTO \rightarrow 2\,HT + O_2$$

- **back-end process** for the separation of the hydrogen isotopologues (cryogenic distillation)


*Darlington Tritium Removal Facility*

- A means of stabilizing the concentrated tritium and **storing it safety**. Uranium metal is used if storage is temporary; titanium is mainly employed for long term storage.

Current WDS for CANDU reactors manage water flow rates up to 360 kg $h^{-1}$ (Darlington Tritium Removal Facility DTRF). Tritiated water is processed off-line

# Water Coolant Purification System

**ITER, CFETR and DEMO WDS:**

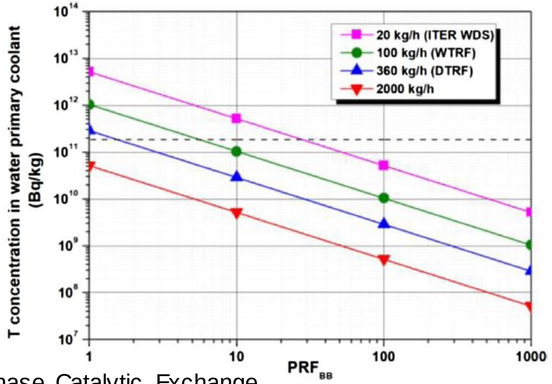
- In future, **ITER WDS** could be based on **CANDU WDS** design. It will process a flow rate of 20 kg $h^{-1}$ adopting as front-end process the Combined Electrolysis and Catalytic Exchange (CECE)
- **Chinese Fusion Engineering Test Reactor (CFETR**) WDS will be based on CECE process. It will process around 500 kg $h^{-1}$ for water-cooled BB.
- **DEMO WDS** in the case of WCLL BB must process few thousands kg $h^{-1}$ to ensure, without anti-permeation barriers, a tritium concentration in the coolant below $1.85 \times 10^{11}$ Bq $kg^{-1}$

# Conclusion

In the case of DEMO, from a technological point of view, a process able to decontaminate such large amount of tritiated water is very energy consuming.

Tritium permeation should be reduced with permeation barriers

*A. Santucci, Fusion Engineering and Design 158 (2020) 111759*




WTRF = Liquid Phase Catalytic Exchange
DTRF = Vapour Phase Catalytic Exchange

| Parameter | WCLL Case-0 | Min/ Inter. | Max |
|---|---|---|---|
| CPS by-pass flow rate [kg/h] | 0 | 20 | 360 |
| TER efficiency [%] | 82 | 80 | 95 |
| T perm. rate from plasma [mg/d] | 0 | 0 | 20 |
| PRF in BB [-] | 100 | 1 | 1000 |
| $H_2$ concentration in water [ppm] | 8 | 8 | 100 |
| PRF in PbLi loop[-] | 1 | 100 | 1000 |
| $H_2O$ leak rate from HXs [kg/h] | 0 | 0.3 | 0.6 |

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# Conclusion

- The management of tritium in both fission and fusion reactors share common strategies and common engineering solutions.
- It is necessary to **developed a collective database** for: Engineering Design, infrastructure, experimental facilities, instrumentations with focus on possible synergies between Gen-IV and Fusion power plant application.
- A common research, validation program between EUROFUSION and European Joint Program (EJP) SRA related **Helium coolant purification Technologies** is mandatory
- In CANDU reactor and ITER, the tritiated water is processed off-line. From a technological point of view, a process able to decontaminate such a large amount of tritiated water is almost impossible to realize and it would be very energy-consuming. Common R&D program has to be developed for **Water Detriation System** to confine the tritium generated at a level as low as reasonably achievable.
- **To strengthen**: synergies among research Teams in order to promote exchange of knowledge and experience.

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