Pressurized Helium as coolant of fusion reactor breeding blankets: focus on the Purification Technologies
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- Functions and Description of the Coolant Purification System
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Functions of the Breeding Blanket

A. Tritium breeding for tritium self-sufficiency
B. Nuclear power conversion and heat extraction
C. Neutron/γ-ray shielding

Any Breeding Blanket (BB) consists of:

- breeding material (solid or liquid, containing Li)
- neutron multiplier (solid or liquid, containing Be or Pb)
- structural material (RAFM steel, Composite SiC/SiC, ODS, Va alloys)
- coolant (pressurized water, supercritical water, pressurized He, Pb-16Li)

Any combination must satisfy:

- safety requirements
- performance requirements

Breeder/Structural Material/Coolant combinations are not all compatible, neither result in same performance level and development needs.
Breeding Blanket Functions and Options /2

Options for the Breeding Blanket

- Helium-Cooled Pebble-Bed
- Helium-Cooled Ceramic Breeder
- Helium-Cooled Ceramic Reflector
- Lead-Lithium Ceramic-Breeder
- Water-Cooled Ceramic Breeder
- Helium-Cooled Lead-Lithium

- Four out of six TBS are cooled by pressurized Helium
- Operative conditions foreseen for HCLL and HCPB-BB:
  - Pressure: 8 MPa
  - Inlet/outlet Temperature: 300 °C to 500 °C
  - Mass flow-rate to TBM: 1.3 kg/s

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## Main Pros and Cons

A. Excellent compatibility with materials at high temperature

B. Potential for high plant efficiency

C. No radiation effects

D. No chemical reactivity

E. No neutron absorption

F. High pumping power required

G. Compared with water or liquid metals, He coolant requires much bigger heat exchange surfaces and consequently bigger cooling system volume

H. Reduced technological maturity (i.e. He circulator) at high power scale

I. Permeated tritium from the breeding modules into the coolant generates a significant tritium partial pressure with the consequent tritium permeation into the cooling system vault which, depending on the conditions, can exceed the limits imposed by the nuclear authorities

J. Potential high leakage rate (tritiated He) into the cooling system vault due to the intrinsic physical characteristic of He molecule
I. Permeated tritium from the breeding modules into the coolant generates a significant tritium partial pressure with the consequent tritium permeation into the cooling system vault which, depending on the conditions, can exceed the limits imposed by the nuclear authorities.

J. Possible high leakage rate (tritiated He) into the cooling system vault.

I and J can be mitigated keeping at the lowest possible value the tritium partial pressure in He coolant.

- The minimization of the tritium source = tritium permeation into the coolant. This requires the development of tritium permeation barriers to be applied on BB modules.
- The operation of a system, directly connected to the primary coolant, able to extract tritium at high rate and efficiency. This system is the CPS “Coolant Purification System”.

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The **Coolant Purification System (CPS)** developed in EU for the Helium Cooled Test Blanket Systems implements the following functions:

1. **to extract tritium permeated from the TBM into HCS**

2. **to concentrate tritium and to route it to Tritium Plant Processing Systems**

3. **to remove impurities generated in He**

- CPS is fed by a small portion of the He flow-rate in the HCS (Helium Cooling System).
- The extracted tritium is sent in concentrated form to the tritium accountancy (TAS) and then to TEP (Tokamak Exhaust Processing System) for the final purification.
- The removed impurities are sent to Detritiation System (VDS). Both TEP and VDS belong to the Tritium Plant.
**Tritium Extraction**

**Needed CPS flow-rate** $\Gamma_{\text{cps}}$ to keep a given tritium partial pressure/concentration $C_o^T$ in the coolant in presence of a given tritium permeation rate $P$ from the breeding modules into the coolant.

\[
\Gamma C_o^T = \Gamma C_i^T + P
\]

\[
\Gamma C_o^T + \Gamma_{\text{cps}} C_u^T = \left(\Gamma + \Gamma_{\text{cps}}\right) C_i^T
\]

\[
\eta_{\text{cps}} = \frac{C_i^T - C_u^T}{C_i^T}
\]

\[
\Gamma_{\text{cps}} = \frac{\Gamma P}{\eta_{\text{cps}} \left(\Gamma C_0^T - P\right)} \approx \frac{P}{\eta_{\text{cps}} \cdot C_0^T}
\]
Coolant Purification System /3

Process Flow Diagram

Three-stage process
1. $Q\_2$ ($Q=H, D, T$) oxidation to $Q\_2O$
2. $Q\_2O$ trapping
3. Impurity removal

Legenda
- **TSA**: Temperature Swing Adsorption
- **OX**: Oxidizer
- **HG**: Heated getter
- **RB**: Reducing bed
- **HC**: He compressor in HCS
- **EC**: Economizer
- **HT**: Heater
- **BL**: Blower of the TSA regeneration loop

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Coolant Purification System /4

Technologies

- **Oxidation**: the conversion of Q$_2$ to Q$_2$O and, of CO to CO$_2$ is accomplished by a **Cu oxide reactor** working at 250 °C in normal operation. The Cu oxide reactor can be regenerated using a purge gas of N$_2$ or He with a low oxygen content (1-2%) to avoid excessive temperature increase.

- **Q$_2$O Trapping**: this function is implemented by a **TSA (Temperature Swing Adsorption) with 13X zeolite** as adsorbent material. TSA consists of two adsorbent beds operated in parallel, one working in adsorption at room temperature and high pressure and the other one regenerated at high temperature and lower pressure, in a counter-flow configuration. Once the regeneration process is over, the main flow stream is switched towards the regenerated column, while the bed in parallel saturated by Q$_2$O is driven to the regeneration cycle for its desorption from the adsorbent material. The net effect of the TSA is to deliver a gas stream concentrated in Q$_2$O to TAS for tritium accountancy.

- **Reducing Q$_2$O to Q$_2$**: reduction of Q$_2$O into Q$_2$ is needed to assure reliable tritium accountancy, avoiding Q$_2$O adsorption on the piping wall connecting the CPS to the Tritium Plant where TAS (Tritium Accountancy Station) is assembled. The selected technology is currently based on the use of the **SAES Getter material St909 alloy (Zr-Fe-Mn alloy)** with a theoretical conversion performance of 30-40 torr Lt of oxygen/g of alloy, corresponding to 27 mg of O$_2$ absorbed per gram of alloy. The main issue of this technology is that this material cannot be regenerated. This implies the replacement of the reducing bed at the end of its lifetime with the consequent problems related to the maintenance tasks.

- **Impurity Removal**: for this function the technology of **heated getter** has been selected as reference solution. The getter material, based on a Zr alloy, is operated at a temperature of around 400°C. It removes the considered impurities, essentially O$_2$, CO, CO$_2$, N$_2$ at an overall concentration of 10 vppm, forming almost irreversible chemical bonds. A minimum of impurity removal efficiency of 90% is claimed by the supplier for this set of impurities. This material cannot be regenerated and, then, the same consideration done for the reducing bed applies also in this case.
Main Challenges and R&D needs

- Use of pressurized He as primary coolant of the breeding blanket of fusion reactors requires very low tritium partial pressure during normal operation (< 0.1 Pa). This is needed to avoid unacceptable tritium permeation and leakages into the reactor cooling vault.

- This low tritium partial pressure in He coolant can be achieved by the operation of an efficient CPS accompanied by tritium permeation barriers which have the function of reducing the tritium permeation into the He coolant from the breeding blanket modules.

- Intense R&D is needed to develop tritium permeation barriers with high performance (Permeability Reduction Factor >10) in relevant geometry and operative conditions. The objective to reduce the permeation rate into the coolant of at least one order of magnitude appears necessary to keep the CPS throughput at a reasonable level.

- For the proposed CPS process the biggest challenge is to find an efficient reducing bed material which can be fully regenerated, in alternative to the current Zr-Fe-Mn alloy (SAES getter ST-909).

- in view of the scaling to DEMO, it would be important to find alternatives to the CPS process here described, going in the direction of simplification and of more flexible technologies.

- Operation of He-Fus3 (ENEA-Brasimone, Italy) and HELOKA (KIT, Germany) pressurized He loops give the chance to progress at the correct speed on the development of He technologies.
Thank you for your attention

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