Activation characteristics of the fusion power plant coolants He, water, Pb-Li and aspects of tritium extraction techniques

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Outline

• Introduction
• EU DEMO fusion power plants
• Computational approach for activation calculations
• Activation characteristics of coolants He, H₂O, and Pb-Li
  – Specific activities, dominant radio-nuclides
  – Contact dose rates
• Aspects of T extraction techniques
• Conclusions
Introduction

• European Fusion Roadmap
  – Realization of fusion as energy source for electricity by 2050
    ⇒ Fusion Power Plant (FPP) providing electricity to the grid

• “Horizon 2020” research framework programme
  – Conceptual design of a fusion power demonstration plant (DEMO)
  – Power Plant Physics and Technology (PPPT) programme conducted by EUOFusion Consortium for the Development of Fusion Energy

• DEMO power plant
  – Conceived as single step between ITER and commercial FPP
  – Relies on technically mature breeder blanket providing Tritium for self-sufficiency and producing heat for conversion into electricity
  – Four different design concepts are under investigation for DEMO

⇒ Related issues addressed in several PPPT projects including design activities, safety & supporting R&D
**EU DEMO Baseline**

**“EU DEMO1 2015”**

<table>
<thead>
<tr>
<th>Main reactor parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of TF coils</td>
<td>18</td>
</tr>
<tr>
<td>Major radius [m]</td>
<td>9.072</td>
</tr>
<tr>
<td>Minor radius [m]</td>
<td>2.927</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>3.1</td>
</tr>
<tr>
<td>Plasma elongation, $\kappa_{95}$</td>
<td>1.59</td>
</tr>
<tr>
<td>Plasma triangularity, $\delta_{95}$</td>
<td>0.33</td>
</tr>
<tr>
<td>Average neutron wall loading [MW/m²]</td>
<td>1.05</td>
</tr>
<tr>
<td>Fusion power [MW]</td>
<td>2037</td>
</tr>
<tr>
<td>Net electric power [MW]</td>
<td>500</td>
</tr>
</tbody>
</table>

⇒ 18 torus sectors of 20°
Breeder Blanket Design

- Breeder blanket concepts considered for DEMO in PPPT programme:
  - Helium Cooled Pebble Bed (HCPB) blanket, Beryllium as neutron multiplier and He gas as coolant,
  - Helium Cooled Lithium Lead (HCLL), Pb-Li breeder and He gas as coolant,
  - Water Cooled Lithium Lead (WCLL), Pb-Li as breeder and water as coolant,
  - the Dual Coolant Lithium Lead (DCLL), Pb-Li as breeder and coolant, and He gas as coolant for the structure.

- Eurofer steel as structural material
- Multi-module segment (MMS) scheme for blanket arrangement and management

- **Considered in this work for activation analyses:**
  - HCPB DEMO ---> He coolant
  - WCLL DEMO ---> Water coolant
  - DCLL ---> Pb-Li coolant
HCPB DEMO Model

CAD neutronics model
with blanket module segmentation

MCNP model

HCPB blanket module

Vertical cut

Horizontal cut

10 ° torus sector

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Workshop Challenges for coolants in fast systems,
IAEA, Vienna, July 5-7, 2017
Computational approach

- **Coupled Monte Carlo transport – activation calculations**
  - MCNP code for particle transport simulations
    ⇒ *neutron flux spectra*
  - FISPACT code for activation
    ⇒ *nuclide inventories & derived quantities*
  - **MCNP-FISPACT coupled through automated interfaces**
  - Use of full and detailed 3D models of DEMO – as developed for nuclear design analyses
  - Nuclear data:
    - JEFF-3.1 for transport calculations
    - EAF-2010 for activation calculations

This work: Activation of coolants in first wall (HCPB, WCLL) or front liquid metal channel (DCLL), at outboard mid-plane

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## Irradiation scenario

### Scheduled DEMO operation scheme:

- 20 calendar years (CY) at average availability of 30%.
  - DEMO plant lifetime: 6 full power years (FPY).
- Two operation phases:
  - First phase lasting 5.2 CY (1.57 FPY).
    - Assumes deployment of a starter blanket with a maximum displacement damage of 20 dpa in the steel of the first wall.
  - Second phase lasting 14.8 CY (4.43 FPY)
    - Assumes deployment of another blanket that can withstand at least 50 dpa.

### Assumed irradiation scenario:

- 5.2 years (CY) minus 10 days: continuous operation at 30% of the nominal fusion power
- Last 10 days: Pulsed operation with 48 pulses of 4 h at full power and 1 h dwell time in between.
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Mass densities:
- Pb-Li: 9540 kg/m³
- He: 4.9 kg/m³
- Water: 725 kg/m³
Coolant activity of He, water and Pb-Li

Specific activity [Ci/m³] as function of cooling time

- Pb-Li shows highest activation level
- He activation level very low (³H)
- Water activation level high at short term (and during plant operation), very low afterwards
He coolant activity in HCPB DEMO

Specific activity [Bq/kg] as function of cooling time

- Activity only due to $^3$H generated by $^3$He(n,p)$^3$H
- He density: 4.92 kg/m$^3$ (8 MPa, 500 °C)
- Natural $^3$He abundancy: 1.38 appm
- Specific activity of $^3$H: $3.57 \times 10^{14}$ Bq/g
- $^3$H beta decay: no emission of gamma radiation

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Pb-Li coolant activity in DCLL DEMO with tritium

Specific activity [Bq/kg] as function of cooling time

- PbLi serves (primarily) as breeder material
- Activity in reactor dominated by $^3$H
- $^3$H is extracted (externally) from Pb-Li for re-fuelling of plasma

$\Rightarrow$ PbLi activity to be considered without $^3$H
Specific activity [Bq/kg] as function of cooling time

- Activity largely dominated by Pb activation products
  - $^{207m}\text{Pb} \quad (T_{1/2}=0.8 \text{ s})$
  - $^{203}\text{Pb} \quad (T_{1/2}=51.9 \text{ h})$
  - $^{204}\text{TI} \quad (T_{1/2}=3.78 \text{ y})$

$\Rightarrow$ To be considered:
Generation and activation of corrosion products in Pb-Li (no assessment available)
Specific activity [Bq/kg] as function of cooling time

- High activity level at short times due to generation of $^{16}\text{N}$ via $^{16}\text{O}(n,p)^{16}\text{N}$ ($T_{1/2} = 7.13$ s).
  
  \[ \Rightarrow \text{During plant operation permanent } \gamma\text{-radiation source (6.13 & 7.12 MeV) in circulating water!} \]

- Low activity level at longer cooling times due to small amounts of $^3\text{H}$ and $^{14}\text{C}$ produced from $^2\text{H}$ and $^{16,17}\text{O}$, respectively.
  
  \[ \Rightarrow \text{To be considered:} \]
  (i) $T$ permeation into water

  (ii) Activated corrosion products
Activated Corrosion Products in water (WCLL)

- Assessment performed by L. Di Pace (ENEA) for WCLL using PACTITER V2.1 and representative DEMO irradiation scheme.
- Resulting conservative estimates for First Wall loop of WCLL DEMO(*):
  - ACP deposit mass = 10 kg
  - ACP mass in coolants: 20 g (⇒ *Used as “upper” value in activation calculations*)
  - Average surface activity (“out-of flux”): 10 GBq/m²

Coolant activity [GBq/t] as function of irradiation time, predicted by PACTITER v2.1 (Courtesy L. di Pace, ENEA)

Activity level in water coolant ≃ 0.1 GBq/t = \(10^5\) Bq/kg

(*) Total water mass is ≃ 200 tons
Contact gamma dose rates

Semi-infinite slab approximation for activated material as provided by FISPACT for contact dose rate as function of cooling time

- Water (WCLL): Dose rate level high at short times (and plant operation), low after longer (> 10 yr) cooling times
- Pb-Li (DCLL): Dose rate at high level
- He (HCPB): No emission of γ-radiation

Note:
- Hands-on limit: 10 μSv/h = 10⁻⁵ Sv/h
- Recycling limit: 10 mSv/h = 10⁻² Sv/h
Contact gamma dose rate of Pb-Li (DCLL)

Semi-infinite slab approximation for activated material as provided by FISPACT for contact dose rate as function of cooling time

- Dose rate level at short times (< month) dominated by Pb activation products, afterwards by ACP $^{54}$Mn
- Radiation dose rate from $^{210}$Po, generated through sequence $^{208}$Pb$\rightarrow^{209}$Bi$\rightarrow^{210}$Po, not significant

$\Rightarrow$ Strong radiation hazard arises from release of gaseous Po and potential inhalation (strong $\alpha$-radiation).
Contact gamma dose rate of water (WCLL)

Semi-infinite slab approximation for activated material as provided by FISPACT for contact dose rate as function of cooling time

- High radiation level at short times due to $^{16}\text{N}$ ($T_{1/2} = 7.13 \text{s}$).

  \[ \Rightarrow \text{Dominates radiation level around water coolant pipes at plant operation (outside irradiation zone)!} \]

- At decay times > 5 mins dose rate level significantly lower, dominated by ACPs

- After 10 y hands-on level reached

  \[ \Rightarrow \text{Note: } ^{17}\text{N } \gamma\text{-dose rate level is low, but } ^{17}\text{N} (T_{1/2} = 4.17 \text{s}) \text{ emits (delayed) neutrons (}\beta n\text{-decay) which activate coolant pipes outside the irradiation zone!} \]
Conclusions on Activation Characteristics

- **He coolant**
  - Low level activity due to T generated from $^3\text{He}$; no $\gamma$-radiation

- **Water coolant**
  - Very high activity and $\gamma$-radiation level during plant operation and shortly (few minutes) after shut-down due to $^{16}\text{N}$ generated from $^{16}\text{O}$ (shielding of water pipes required); (delayed) neutron radiation from $^{17}\text{N}$ further issue of concern
  - Low activity and $\gamma$-radiation level at longer cooling times, due to T generated in water and ACPs assumed in water

  *To be further considered:*
  - $T$ permeation into water coolant, ACPs, radiolysis, water chemistry

- **Pb-Li coolant**
  - Activity level dominated by T generated in Pb-Li (acting as breeder)
  - High activity and dose rate levels during operation and at shut-down due to Pb activation products

  *To be further considered:*
  - Activation of corrosion products, $^{210}\text{Po}$ generation and Bi/Po extraction
Aspects of T extraction techniques for Water, He, Pb-Li
Parametric studies carried out to investigate the tritium release from turbine loop:

- Tritium extraction (TES) efficiency;
- Coolant purification (CPS) efficiency;
- Water fraction to CPS
- Permeation Reduction Factor (PRF) blanket
- PRF steam generator

Average tritium concentrations [ppb] in Pb-Li loop, coolant and steel structure
Main references for tritium removal facility from cooling water

- Estimated tritium concentration in the coolant: ~ 0.5 ppm
- Coolant flow rate: 10,500 kg/s
- Parametric studies show that 0.1% of the coolant flowrate shall be processed in the CPS; the required CPS efficiency is minimum 60%
- The throughput of the water detritiation facility strongly depends on the allowable tritium concentration in the coolant
- The following technologies have been investigated and show potential for industrialization at DEMO conditions:
  - Water distillation under vacuum with heat pump in combination with the CECE process for large throughputs
  - Direct electrolysis followed by tritium recovery in DEMO Tritium Plant for moderate throughputs of the water detritiation facility

Block diagram of the water detritiation facility consisting of water distillation under vacuum and Combined Electrolysis Catalytic Exchange (CECE) processes.
Tritium Transfer and Extraction from He coolant in HCLL DEMO

- All inventories reach very fast the steady state (in almost 1 hour)
- Estimated tritium inventories:
  - PbLi = 4.6 g
  - He coolant = 2.5 g
  - In steels = 2.5 g

Parametric studies carried out to investigate the tritium release from turbine loop:
- Tritium extraction (TES) efficiency;
- Coolant purification (CPS) efficiency;
- Water fraction to CPS
- Permeation Reduction Factor (PRF) blanket
- PRF steam generator

Tritium inventory [g] in Pb-Li breeder, He coolant, and steel structures (HCLL DEMO)
Estimated tritium concentration in the coolant: \( \sim 1 \) ppm

Coolant flow rate: 2,500 kg/s

Parametric studies show that 1% of the coolant flowrate shall be processed in the CPS; the required CPS efficiency is minimum 60%

The following technologies have been investigated

- Oxidation, trapping and tritium recovery by isotopic exchange with swamping deuterium
- Tritium recovery in permeation cascade

Tritium recovery in a permeation cascade is very complex as far as control and configuration are concerned, and high energy consumption; therefore the tritium recovery based on conversion to tritiated water followed by isotopic exchange on a reactive molecular sieve with deuterium and further processing in the DEMO Tritium Plant can be considered as option for DEMO.
Reference Technologies for tritium removal from helium used as coolant for the DCLL DEMO

- Estimated tritium concentration in the coolant: 1 – 10 ppb
- Coolant flow rate: 26,500 kg/s
- Parametric studies show that 1% of the coolant flowrate shall be processed in the CPS; the required CPS efficiency is minimum 60%
- The following technologies have been investigated
  - Permeation against vacuum
  - Vacuum sieve trays
- Modelling of the tritium transport in the “vacuum chambers” of the VST and PAV and the definition of the requirements for the vacuum systems in view of qualification for tritium service are the main challenges of the processes
Conclusions on tritium extraction techniques

- Significant efforts made to enhance the tritium transport and permeation models aiming at an accurate predict the tritium concentration and inventories in the coolants;

- The experimental data base for tritium permeation to coolants in DEMO like operation conditions is very limited and the experimental procedures are not well harmonized;

- The selection/development of the tritium removal technologies from coolants strongly depend on the allowable tritium concentration in the coolants;

- The lessons learns from the licensing and the operation of the CANDU nuclear reactors can be used as reference for defining allowable tritium concentration in the coolants;

- Available detritiation technologies provide a good basis for the development of the tritium removal process from the coolants of WCLL, HCLL and HCPB blankets; as far as DCLL is concerned, the technologies are under development and the validation at relevant DEMO conditions shall be the priority for the upcoming years.

⇒ For more information on tritium extraction techniques, see I. Cristescu, Tritium Transfer and Extraction from Water, He, and PbLi Coolants, poster session Topic 1: Coolant characteristics under irradiation