The PPCS In-Vessel Component Concepts
(focused on Breeding Blankets)

Presented by

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Plan of the Presentation

1. Introduction on In-Vessel Components

2. Breeding Blankets
   1. Functions and Strategy
   2. Present Choices for EU PPCS and DEMO
   3. Design & Analyses Details of the EU PPCS Blankets
   4. Blanket Systems and Integration Issues (examples)
   5. R&D Issues (medium term, long term)

3. Divertors (short overview)
   1. Functions and Strategy
   2. Choices for EU PPCS

4. Conclusions
In-Vessel Components Location & Conditions

The most severe working conditions and requirements

- High surface heat flux: 0.5 (FW) → 5 MW/m² (div.)
- High neutron wall loading (FW): ~2.5 MW/m², ~150 dpa(Fe)
- Operation under void (plasma): → low coolant leakages
- High magnetic field (~7 Tesla): (high MHD effects)

Moreover: Remote access in high radiation field (maintenance, inspection, repairs, diagnostics, …)
Three crucial functions for a Power Plant

- **Convert** the neutron energy (80% of the fusion energy) in heat and collect it by mean of an high grade coolant to reach high conversion efficiency (>30%)
  - in-pile heat exchanger

- Produce and recover all **Tritium** required as fuel for D-T reactors
  - Tritium breeding self-sufficiency

- Contribute to neutron and gamma **shield** for the superconductive coils
  - resistance to neutron damages
**Tritium breeding self-sufficiency: a necessity**

- Main Tritium production reaction: $^6\text{Li} + n \rightarrow T + ^4\text{He} + 4.8\text{ MeV}$
- Typical T-production rate in dedicated fission reactor: $1-2\text{ kg T / GWth / y}$
- Typical T burn rate in a fusion reactor: $\sim 50\text{ kg T / GWth / y}$ ($\sim 150\text{ gT/GWth/day}$)
- Need to produce all T and collect it on-line (because of initial inventory and safety)

  $\Rightarrow$ Tritium Breeding Ratio, $TBR = \frac{T_{\text{prod}}}{T_{\text{burn}}} > 1$ (at least)

**Tritium breeding self-sufficiency: a severe constraint**

<table>
<thead>
<tr>
<th>$\text{D} + \text{T} \rightarrow ^4\text{He} + n$</th>
<th>$\text{Neutron Losses}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\uparrow 60-80%$</td>
<td>✓ n-leakage through ports, divertor region, gaps $\Rightarrow 10-20%$</td>
</tr>
<tr>
<td>$\downarrow$</td>
<td>✓ n-parasitic absorptions on other materials (structures) $\Rightarrow 10-15%$</td>
</tr>
<tr>
<td>$^4\text{He} + \text{T} \leftarrow ^6\text{Li} + n$</td>
<td>✓ blanket n-leakage (&lt;5%)</td>
</tr>
</tbody>
</table>

$\Rightarrow$ 20 to 40 % of neutrons are not available for T-production

**Neutronics requirements**

- *minimize n-losses*
- $\Rightarrow$ small gaps and openings, minimization of structures and coolant fractions

- *add a n-multiplier*
  - Pb or Be $(n,2n)$ or $\text{Li}^7 (n, n'T)$
Breeding blankets materials

Main available breeders (Li-based compounds)
- Liquid Lithium (7.5% $^6$Li)
- Eutectic Pb-17Li ($T_m$ 235°C)
- Molten Salts:
  - FLiBe, FLiNaBe
- Li-Ceramics:
  - $Li_4SiO_4$, $Li_2TiO_3$, $LiO_2$

Main Structural Materials
- Ferritic/Martensitic Steels
- Vanadium Alloys
- Composites SiC/SiC

Neutron multipliers
- $Be$ (n, 2n)
- $Pb$ (n, 2n)
- $^7Li$ (n, n'T)

Main Coolants for Nuclear (relevant $T$ for good efficiency))
- Pressurized Water (PWR)
- Helium
- Liquid Metals: Li (Na), Pb-17Li

A breeding blanket has to be designed using a combination of these materials. Best concepts are an optimum compromise between all constraints which has to take into account:
- temperature, pressure, loads levels
- compatibility between materials under the defined working conditions
- safety
- low activation/low radwaste characteristics
- performances (e.g., TBR)
- technology availability and manufacturing processes as a function of timescale
- reliability & others.....
### Breeding Blankets Development Timescale

<table>
<thead>
<tr>
<th>Reactors</th>
<th>JET, TFTR, JT60, Tore Supra Asdex, etc.</th>
<th>ITER (1) international</th>
<th>DEMO (1 or more ?)</th>
<th>1st Commercial Power Plant (1 or more ?)</th>
<th>10th of the kind ➔ PPCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Goals</td>
<td><strong>Plasma Physics</strong> <em>(control, stability, impurities, shutdown proc., heating, etc.)</em></td>
<td><strong>Plasma Ignition Long D-T Pulses Systems Integration</strong></td>
<td><strong>Tritium Breeding Self-sufficiency High Safety Standards</strong></td>
<td><strong>Electricity Production at Competitive Cost</strong></td>
<td><strong>Electricity Production at Competitive Cost</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Magnetic Field Advanced Systems</strong> <em>(e.g., super cond. coils)</em></td>
<td><strong>Test of DEMO Blanket Mock-ups (Test Module)</strong></td>
<td><strong>Electricity Production (high efficiency, but low reliability system)</strong></td>
<td><strong>High Reliability</strong></td>
<td><strong>Possible Advanced Reliable Technology</strong></td>
</tr>
<tr>
<td>Operation Years</td>
<td>~1980 - 2010</td>
<td>~2014 - 2034</td>
<td>~2030 - 2050</td>
<td>From ~2050</td>
<td>&gt; 2080</td>
</tr>
</tbody>
</table>

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## Breeding Blankets Concepts

<table>
<thead>
<tr>
<th>Basic Parameters</th>
<th>A</th>
<th>B</th>
<th>AB</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius (m)</td>
<td>9.8</td>
<td>8.7</td>
<td>9.1</td>
<td>7.5</td>
<td>6.1</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Plasma Current (MA)</td>
<td>33.5</td>
<td>28.1</td>
<td>29.2</td>
<td>20.1</td>
<td>14.1</td>
</tr>
<tr>
<td>Toroidal Field on axis (t)</td>
<td>7.3</td>
<td>6.9</td>
<td>6.8</td>
<td>6.4</td>
<td>5.6</td>
</tr>
<tr>
<td>TF on TF Coil Conductor (T)</td>
<td>12.9</td>
<td>13.1</td>
<td>13.6</td>
<td>13.6</td>
<td>13.4</td>
</tr>
<tr>
<td>Elongation (95% and separatrix)</td>
<td>1.7/1.9</td>
<td>1.7/1.9</td>
<td>1.7/1.9</td>
<td>1.9/2.1</td>
<td>1.9/2.1</td>
</tr>
<tr>
<td>Triangularity (95% and separatrix)</td>
<td>0.27/0.4</td>
<td>0.27/0.4</td>
<td>0.27/0.4</td>
<td>0.47/0.7</td>
<td>0.47/0.7</td>
</tr>
<tr>
<td>Q</td>
<td>21</td>
<td>15</td>
<td>16</td>
<td>30</td>
<td>35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Engineering Parameters</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Electrical Output (GW)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Fusion Power (GW)</td>
<td>5.5</td>
<td>3.4</td>
<td>4.0</td>
<td>3.4</td>
<td>2.5</td>
</tr>
<tr>
<td>P_{add} (MW)</td>
<td>265</td>
<td>234</td>
<td>234</td>
<td>112</td>
<td>71</td>
</tr>
<tr>
<td>Avg. Neutron Wall Load FW (MW/m²)</td>
<td>2.3</td>
<td>1.8</td>
<td>1.8</td>
<td>2.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Surface Heat Flux on FW (MW/m²)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Max. Divertor Heat Load (MW/m²)</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Selected Breeding Blanket Type</th>
<th>WCLL</th>
<th>HCPB</th>
<th>HCLL</th>
<th>DCLL</th>
<th>SCLL</th>
</tr>
</thead>
</table>

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PPCS Breeding Blankets Concepts

**Short Term Concepts**
(for models A, B, AB)

- **A** - Water-Cooled Lithium-Lead (WCLL)
  coolant $T_{in}/T_{out}$ 285/325°C, 15.5 MPa
- **B** - Helium-Cooled Pebble-Bed (HCPB)
  ceramic/Be blanket,
  coolant $T_{in}/T_{out}$ 300/500°C, 8 MPa
- **AB** - Helium-Cooled Lithium-Lead (HCLL)
  coolant $T_{in}/T_{out}$ 300/500°C, 8 MPa

- To be tested in ITER (B & AB)
- Can be used for DEMO (after selection)
- Use of martensitic/ferritic steel structures
  (low activation EUROFER)

**Medium Term Concept (model C)**

- **C** - Dual-Coolant Lithium-Lead (DCLL)
  & He $\Rightarrow$ He $T_{in}/T_{out}$ 300/480°C, 8 MPa
  LiPb $T_{in}/T_{out}$ 480/700°C

- Need SiC/SiC insulators + high Temp. HX
- Can be used in DEMO at later stage?
- Use of martensitic/ferritic steel structures
  (low activation EUROFER)

- Significant R&D required, relatively long time is required

**Long Term Concept (model D)**

- **D** – Self-Cooled Lithium-Lead (SCLL)
  LiPb $T_{in}/T_{out}$ 700/1100°C

- Use of SiC/SiC structures
- Need very large & lengthy R&D (50 y?)
- Very good efficiency & safety standard

- Attractive but high development risk

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Blanket Concept A: Water-Cooled LiPb

Module inlet
Module outlet

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Blanket Concept A: Water-Cooled LiPb

**Used Calculation Models**

- Double Walled Tube
- First Wall Tube
- Stiffener
- Back plate
- Lithium-lead

For 2D CASTEM Thermo-mechanical Analyses

For 3D MCNP Montecarlo Neutronics Analyses

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Blanket Concept A: Water-Cooled LiPb

Main Analyses Results

- **Mechanics:** the modules box resists to 15.5 MPa in accidental conditions (RCC-MR)

- **Thermo-mechanic:** acceptable T (< 550°C in FW steel, < 480°C on Pb-17Li interface), acceptable stresses and deformation (RCC-MR)

- **Neutronics:** 3-D TBR = 1.06 at 90 at% ⁶Li enrichment, 30 dpa/y in FW steel, 850 appm H/y, 300 appm He/y

- **Tritium:** maximize confinement and extraction (LiPb at ~2 mm/s to avoid MHD pressure drops)
Blanket Concept B: Helium-Cooled Ceramic/Be

Modular Concept for HCPB/HCLL blankets

- He-cooled stiffening grid
- He-collectors back-plates
- He-cooled FW & Box
- Breeder Unit

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Blanket Concept B: Helium-Cooled Ceramic/Be

Stiffening Grid (details)

HCPB Breeder Unit

- Ceramic container with He cooling channel system
- Central He cooling channel system
- Ceramic breeder bed
- HCPB jacket
- Top Inlet He collector
- Welding Line for evacuated HCPB jacket
- HCPB carrier backplate
- Top Outlet He collector
- Inlet/Outlet He collector
- Bottom Outlet He collector
- Bottom Inlet He collector
- Beryllium pebble bed

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Blanket Concept B: Helium-Cooled Ceramic/Be

**Scheme of the He-flow path in each module**

FW/SW (alternating flow)

- Breeder unit
- Stiff. grid
- Cap
- In-/Outlet
- Back wall manifolding

**Scheme of a possible module attachment to the back shield**
Blanket Concept B: Helium-Cooled Ceramic/Be

3D Monte Carlo Neutronics Analyses (MCNP)

- Breeder: $\text{Li}_4\text{SiO}_4 (^{6}\text{Li} \text{30\%})$
- Blanket thickness (inb/outb): 41/51 cm
- Tritium Breeding Ratio: 1.12
- Neutron multiplication: 1.78
- Deposited Nuclear Power
  - whole blanket: 3000 MW
  - Vacuum Vessel & Shield: 310 MW
- Energy multiplication: 1.38
Blanket Concept AB: He-Cooled Lithium-Lead

Modular Concept for HCPB/HCLL blankets: details of the HCLL Breeder Unit

He in/out unit manifolds
He unit inlet
He unit outlet
Unit backplate
Cooling Plates (CPs)
Front
Blanket Concept AB: He-Cooled Lithium-Lead

**HCLL Breeder Unit & Module: LiPb flow path**

Stiffening plates (SPs) frontier

FW frontier (FW not shown here)

PbLi inlet

PbLi outlet

pol

rad

tor
Blanket Concept AB: He-Cooled Lithium-Lead

HCLL Module: Helium flow path

Module top view

80% He in FW

100% He in BUs

20% He in SPs

Stage #3:
- Breeder unit return
- Main He outlet

Main He outlet

Main He inlet
Scheme for Tritium control in blanket modules and associated circuits: List of T-sources, possible T-permeation flux and leakages

Some Questions
- Need of T-permeation barriers?
- Extraction & purification efficiency?
- He-chemistry?

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**Blanket Concept AB: He-Cooled Lithium-Lead**

**Computation procedure to be used for the estimation of T-permeation in a blanket module**

- **LiPb flow and T convection via cast3m_fluid**
- **T diffusion and permeation via cast3m_fluid (heat-like)**

**Neutron code (Tripoli)**

- **Tritium production rate (at/cm³ neutron)**

**Thermal-mechanical code (cast3m)**

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<table>
<thead>
<tr>
<th></th>
<th>HCLL</th>
<th>HCPB</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBR [breeder zone thickness]</td>
<td>1.15 [55 cm]</td>
<td>1.14 [46 cm]</td>
</tr>
<tr>
<td>Coolant (He): $T_{\text{min}}$ - $T_{\text{max}}$ °C</td>
<td>300-500</td>
<td>300-500</td>
</tr>
<tr>
<td>Coolant passes Temperature:</td>
<td>- FW: 300– 410</td>
<td>- FW: 300 – 363</td>
</tr>
<tr>
<td></td>
<td>- BU: 410 – 500</td>
<td>- Grid: 363 – 400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- BU: 400 – 500</td>
</tr>
<tr>
<td>Coolant (He): pressure MPa</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Breeder [$^6$Li enrichment]</td>
<td>PbLi$_{\text{eu}}$ [90%]</td>
<td>Li$_4$SiO$_4$ [40%] or Li$_2$TiO$_3$ [~70%]</td>
</tr>
<tr>
<td>Multiplier</td>
<td>-</td>
<td>Be</td>
</tr>
<tr>
<td>EUROFER: $T_{\text{min}}$ - $T_{\text{max}}$ °C</td>
<td>300-550</td>
<td>300-550</td>
</tr>
<tr>
<td>Breeder: $T_{\text{min}}$ - $T_{\text{max}}$ °C</td>
<td>400-660</td>
<td>400-920</td>
</tr>
<tr>
<td>Multiplier: $T_{\text{min}}$ - $T_{\text{max}}$ °C</td>
<td>-</td>
<td>400-650</td>
</tr>
</tbody>
</table>
Blanket Concept C: Dual-Coolant (He & LiPb)

**Blanket Design Scheme and Main Features**

**Main features:**
- Helium-cooled RAFM steel structures (EUROFER)
- ODS plated FW to use the high-temperature strength of ODS
- Self-cooled breeding zone with Pb17Li as breeder and coolant
- SiCf/SiC flow channel inserts as electrical (MHD) and thermal insulators leading to high exit temperature and high thermal efficiency

<table>
<thead>
<tr>
<th>Dual Coolants</th>
<th>T_{inlet} (°C)</th>
<th>T_{outlet} (°C)</th>
<th>ΔT (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium (8 MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall blanket</td>
<td>300</td>
<td>480</td>
<td>180</td>
</tr>
<tr>
<td>FW</td>
<td>300</td>
<td>450</td>
<td>150</td>
</tr>
<tr>
<td>Grids</td>
<td>450</td>
<td>480</td>
<td>30</td>
</tr>
<tr>
<td>Pb-17Li</td>
<td>480</td>
<td>700</td>
<td>220</td>
</tr>
</tbody>
</table>

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Blanket Concept C: Dual-Coolant (He & LiPb)

Outboard Module Horizontal Cross-section

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**Used Neutronic 3D Model and Main Results**

**TBR = 1.15**

(90% $^6$Li, inb/outb breeder zone thk: 50.5/85.5 cm)

- **Blanket Concept C: Dual-Coolant (He & LiPb)**
- Neutron Flux Profile in Inboard mid-plane

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Blanket Concept D : SiC/SiC - LiPb Self-Cooled

Design Rational (maximization of efficiency & safety)

- **Structural Material**: SiC/SiC (low afterheat, high temperature)
- **Blanket working principle**: co-axial Pb-17Li flow to maximize outlet temperature
- **Pb-17Li external circuits location**: horizontal deployment, to minimize pressure
- **Blanket remote maintenance procedure**: segment geometry, maintained through vertical ports after Pb-17Li draining
- **Potential reduction of waste quantities**: separation of outboard blanket in two zones in order to minimize radioactive waste (depending on lifetime evaluations)
- **Magnet system**: possibility of high T superconductors (77 K)
- **Plasma heating system**: acknowledge of need but not evaluated
- **Advanced conversion systems**: potential for H-production
### Blanket Concept D: SiC/SiC - LiPb Self-Cooled

<table>
<thead>
<tr>
<th>Key SiC/SiC Properties and Parameters *</th>
<th>Assumed values [1] in the design analyses</th>
<th>Typical measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>~ 3000 kg/m³</td>
<td>~ 2500 kg/m³</td>
</tr>
<tr>
<td>Porosity</td>
<td>~ 5%</td>
<td>~ 10%</td>
</tr>
<tr>
<td>Young's Modulus</td>
<td>200-300 GPa</td>
<td>~ 200 GPa</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.16-0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Thermal Expansion Coefficient</td>
<td>~ 4 x 10⁻⁶/°C</td>
<td>4 x 10⁻⁶/°C</td>
</tr>
<tr>
<td>Specific heat</td>
<td>190 J/kg·K</td>
<td>190 J/kg·K</td>
</tr>
<tr>
<td>Thermal Conductivity in Plane (1000°C)</td>
<td>~ 20 W/m·K (EOL)</td>
<td>~ 15 W/m·K (BOL)</td>
</tr>
<tr>
<td>Thermal Conductivity through Thickness (1000°C)</td>
<td>~ 20 W/m·K (EOL)</td>
<td>~ 7.5 W/m·K (BOL)</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>~ 500 /Ωm (under irradiation, EOL value)</td>
<td>~ 500 /Ωm (before irradiation)</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>300 MPa</td>
<td>300 MPa</td>
</tr>
<tr>
<td>Trans-laminar Shear Strength</td>
<td>-</td>
<td>200 MPa</td>
</tr>
<tr>
<td>Inter-laminar Shear Strength</td>
<td>-</td>
<td>44 MPa</td>
</tr>
<tr>
<td>Maximum allowable tensile Stress</td>
<td>Not used*</td>
<td>Unknown*</td>
</tr>
<tr>
<td>Max. Allowable Temperature (Irradiation Swelling basis)</td>
<td>~ 1000 °C</td>
<td>~ 1000 °C</td>
</tr>
<tr>
<td>Maximum Allowable Interface Temperature with breeder</td>
<td>~ 1000°C (flowing)</td>
<td>~ 800°C (static)</td>
</tr>
<tr>
<td>Min. Allowable Temperature (Thermal conductivity basis)</td>
<td>~ 600 °C</td>
<td>~ 600 °C</td>
</tr>
<tr>
<td>Cost</td>
<td>$400/kg</td>
<td>~ 10 times larger</td>
</tr>
</tbody>
</table>

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Blanket Concept D: SiC/SiC - LiPb Self-Cooled

Design Scheme - Banana shaped Modules (poloidal Cross-Section)
Blanket Concept D: SiC/SiC - LiPb Self-Cooled

Design Scheme – Banana shaped Modules (Horizontal Cross-Section)
Blanket Concept D: SiC/SiC - LiPb Self-Cooled

Design Scheme – Banana shaped Modules (Outboard Module cross-section)
Banana shaped Module Replacement Procedure (through vertical ports)
Blanket Design Point

- segment: SiC\textsubscript{f}/SiC box acting as Pb-17Li container, 2 mm W protection
- use of 3D (industrial) SiC\textsubscript{f}/SiC 3D, extensive use of brasing
- Pb-17Li: \(T_{\text{inlet/outlet}}\) 700°C/1100°C (\(\text{div: } 600/990°C\)), max. speed \(\sim 4.5 \text{ m/s}\)
- dimensions outboard (front) segments: 5 modules \(h=8\text{m}, w=0.3\text{m}, \text{thk}=0.3\text{m}\)
- High T Shield: Pb-17Li-cooled WC, SiC\textsubscript{f}/SiC structures (energy recovered)
- Low T Shield: He-cooled WC with B-steel structures (as for VV)

Main Analyses Results

- Neutronics: \(TBR = 1.12\) (0.98 blankets, 0.125 divertor, 0.015 HT shield)
- Thermal results: \(T_{\text{max}} \sim 1100°C\) (if \(\lambda =20 \text{ W/mK}, \text{thk. FW } 6 \text{ mm}\))
- Acceptable stresses (see criteria details) for Hydr. pressure = 0.8 MPa
- Acceptable MHD pressure drops
- 1 independent cooling circuit for divertor, 4 for blanket, \(\varepsilon = 61 \% \) \(P_{\text{ef}}/P_{\text{fus}}\)
- \(T\)-extraction performed on the cold leg (Pb-17Li renewal \(\sim 1100\) times/day)
Blanket Concept D: SiC/SiC - LiPb Self-Cooled

Scheme of the LiPB External Circuits–Banana shaped Modules

L. Giancarli, The PPCS In-Vessel Components Concepts, Erice Summer School, July 26 – August 1, 2004
Main Blanket R&D Issues

Short Term Concepts
(for models A, B, AB)

- Further development of EUROFER (irrad.)
- Further development of structures manufacturing process (HIP, welds, etc…)
- Supporting systems, collectors and piping routes, remote mounting/dismantling
- Interaction LiPb/water & DWT (A)
- Tritium Management and Control (A, AB, B at lower extend)
- Permeation Coatings (A and AB) (irrad.)
- LiPb compatibility with EUROFER (A, AB)
- Ceramic and Be behavior under irradiation, T-inventory in Be (B)
- Pebbles beds behavior (B)

Promising on-going R&D

Medium Term Concept (model C)

- SiC/SiC related issues: FCI design (out of the main body), irradiation, compatibility LiPb
- MHD: modeling of 3D inertial flow in expansion
- ODS: fabrication of ODS plated FW, irradiation
- Heat Exchanger Technology for High T LiPb
- T-recovery and purification (high LiPb flowrate)
- Integration aspects as for Short Term concepts

Long Term Concept (model D)

- SiC/SiC related issues requiring structural functions: irradiation (thermal conductivity, burn-up, lifetime), manufacturing ( joints, pipe connections), reliability, modeling, compatibility with very high v & T LiPb
- MHD: modeling of 3D inertial flow in expansion
- T-recovery and purification (high LiPb flowrate)
- Heat Exchanger Technology and other components for High T LiPb
- Integration aspects as for Short Term concepts
PPCS Proposed Divertor Concepts

Main Functions *(ref. others speakers)*

- To control Plasma Boundary Conditions
- To divert magnetic lines to extract ashes and other impurities from the plasma

Vertical Targets are submitted to:

- very high heat fluxes (up to 15 MW/m²)
- interaction with plasma ions/neutrals

**Vertical Targets Designs**

- studied only for ITER, performances TBD
- Additional requirements in a Power Plant: account for neutron irradiation (~10 dpa/y), use of high T-coolant for acceptable power conversion efficiency, lifetime, …

W-alloy appears to be the only acceptable armor material *(interaction with plasma)*
**PPCS Divertor: Water-cooled concepts**

**Low-temperature concept**
- $T_{\text{inlet}} = 150^\circ\text{C}$
- Pressure: 4 MPa

**Main features**
- Derived from ITER divertor studies
- W-alloy monoblocks
- CuCrZr tubes
- OFHC compliance layer
- CuCrZr Temp. limited to 400°C

**Performances**
- Heat flux up to 15 MW/m²
**High-temperature concept**

$T_{\text{outlet}} = 325^\circ\text{C}$  
Pressure : 15.5 MPa

**Main features**

- derived from low-T concept  
- W-alloy monoblocks  
- EUROFER tubes  
- Papyex compliance layer  
- Thermal barrier in the front part

**Performances**

*Heat flux up to 15 MW/m$^2$*
**PPCS Divertor: Helium-cooled concepts**

**Target-Plate Modular concept**
- $T_{\text{inlet}} = 600^\circ C$
- $T_{\text{outlet}} \approx 680^\circ C$
- He P: 10 MPa

**Main features**
- W-alloy tiles
- W-alloy & ODS-steel structures

**Performances**
- Heat flux $10 \text{ MW/m}^2$

**Divertor cartridge (RAFM)**
- Divertor target plates with modular thermal shield (W alloy)
- Dome and structure (ODS RAFM)
**Principle of the target plate modular concept**

1. High flux components
2. Thimble
3. Structure with manifolds
4. Tile
Conceptual designs the vertical target and He-flow path

Various design principles:
- HETS (ENEA)
  Jet impingement
- HEMP/HEMS (FZK)
  Flow promoter (pin, slot arrays)
### PPCS Divertor: Helium-cooled concepts

#### Materials & Temp. Windows

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Min Temp.</th>
<th>Max Temp.</th>
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<tbody>
<tr>
<td>Tiles</td>
<td>W</td>
<td>tbd (600°C) DBTT</td>
<td>2500°C Melting temp. 3410°C</td>
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<tr>
<td>High heat flux structure</td>
<td>W-alloy</td>
<td>600°C DBTT</td>
<td>1300°C re-crystallisation</td>
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<tr>
<td>(high P He-containment)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Structure and manifolds</td>
<td>W-alloy ODS, ...</td>
<td>600°C DBTT</td>
<td>1300°C re-crystallisation 700-750°C strenght limits</td>
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#### Design Point

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</thead>
<tbody>
<tr>
<td>HETS</td>
<td>35</td>
<td>600-669</td>
<td>10</td>
<td>30</td>
<td>~ 30</td>
<td>0.063</td>
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<tr>
<td>HEMP/HEMS</td>
<td>16</td>
<td>600-679</td>
<td>10</td>
<td>6.0</td>
<td>~ 30</td>
<td>0.11</td>
</tr>
</tbody>
</table>

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**PPCS Divertor: LiPb-cooled (SiC/SiC) concept**

**Very high-T concept**

- $T_{\text{outlet}} = 1000^\circ\text{C}$
- Low pressure (MHD)

**Main features**

- Derived from ARIES-ST studies
- W-alloy tiles
- High velocity LiPb in the toroidal direction (to limit MHD)
- SiC/SiC thin structures (R&D)

**Performances**

- Heat flux up to ~5 MW/m$^2$
PPCS Proposed Divertor Concepts - Summary

Surface heat-flux in a reactor: TBD
15 MW/m² ➔ 10 ➔ 5 (long term) ??

Water-cooled Concepts

1 - Low-Temp. (as ITER, 150°C)
✓ Known manufacturing (as ITER)
✓ Achieve heat flux of 15 MW/m²
✓ Lifetime of Cu-alloy under irradi. TBD
✓ Deposited Power not used for Power conversion ➔ low reactor efficiency
   ➔ Low R&D but low performances

2 - High-Temp. (as WCLL, 325°C)
✓ Achieve heat flux of 15 MW/m²
✓ Lifetime of Papyex & th. Barrier, especially under irradiation TBD
✓ Manufacturing of interface TBD
   ➔ Significant R&D for the steel/W joint

He-cooled Concepts
✓ Achieve heat flux of 10 MW/m² (or more)
✓ Allow high T He-coolant (high efficiency)
✓ Avoid use of water with He-cooled blankets
✓ Development of W-alloy and ODS-steel manufacturing processes TBD
✓ Behavior of W-alloy under irradiation TBD
✓ Exp. demonstration of P-drops and heat transfer
✓ Joint W-alloys/steel TBD
   ➔ Significant R&D on Materials

LiPb-cooled Concepts
✓ Interesting concept if used jointly to the SCLL blankets, same R&D long term issues (SiC/SiC structures), reliability, modeling, compatibility with very high v & T LiPb TBD
✓ MHD: modeling of 3D inertial flow in expansion TBD
✓ Low achieved heat flux : 5 MW/m², large progress expected in divertor physics TBD
   ➔ Very large R&D (including physics)

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Overall Conclusions

- **Breeding Blankets**: a major new technological challenge for Fusion towards DEMO
  - Five blanket lines considered in the EU PPCS studies after a selection among the different possible options & materials combinations
  - The blanket concepts corresponding to three of these lines (Water-cooled LiPb, He-cooled Ceramic/Be pebble beds, He-cooled LiPb) requires technologies which can be developed for DEMO (short term). In particular, several mock-ups of the two He-cooled concepts will be tested in ITER.
  - The short term concepts show an acceptable efficiency (30-40%). Major design uncertainties are linked with reactor integration issues (module attachment, pipes routes, connection/disconnection, blanket coverage)
  - Medium and long-term concepts (Dual-Coolant and LiPb Self-cooled SiC/SiC structures) show large attractiveness by higher development risk

- **Divertor**: a major technological improvement from ITER towards DEMO
  - Design and R&D performed for ITER. Additional requirements for DEMO and a Power Plant have to be taken into account. Possible solutions have been evaluated with EU (PPCS). Results will be used as a basis for launching appropriate R&D.