Challenges and R&D Needs for PbLi Coolant and Breeder for Fusion Applications

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FUSION REACTION

\[ \text{D} + \text{T} \rightarrow ^4\text{He} (3.5 \text{ MeV}) + \text{n} (14.1 \text{ MeV}) \]

The eutectic alloy Pb16Li enriched at 90% in 6Li as breeder can be used as coolant and breeder of Thermonuclear Tokamak Fusion Reactor.

EU DEMO BBs concepts:

- Dual Coolant Lithium Lead (DCLL): uses Pb-16Li as breeder, neutron multiplier, tritium carrier and coolant, and Helium as additional coolant
- Helium Cooled Lithium Lead (HCLL): uses Pb-16Li as breeder, neutron multiplier and tritium carrier, and Helium as coolant
- Water Cooled Lithium Lead (WCLL): uses Pb-16Li as breeder, neutron multiplier and tritium carrier, and water at typical PWR conditions as coolant
Technological issues

The main technological issues with Lead Lithium to be managed

- **Material Compatibility:**
  - Corrosion Issue and development of Anti-corrosion coating
  - Removal of corrosion product (Cr, Fe, Ni, …)
- **Magnetohydrodynamic (MHD) issues**
- **Tritium:**
  - Tritium mass transfer characteristic parameters (Diffusivity, Sievert constant, …)
  - Tritium inventory in the materials
- **Irradiated Pb-16Li:**
  - He generated in PbLi to be removed
  - Activated products to be removed
- **Safety:** PbLi/water interaction
- **Instrumentation:** due to the melting point of Pb-16Li (234°C), corrosion/erosion characteristic, opacity and height density the conventional instrumentation cannot be used for measure the pressure, mass flow rate, velocity, level, temperature and chemistry
### Operative conditions

<table>
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<th>Parameters</th>
<th>DCLL BB</th>
<th>WCLL BB</th>
<th>HCLL BB</th>
</tr>
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<tr>
<td>Pb-16Li volume BB total (m³)</td>
<td>891</td>
<td>844</td>
<td>743</td>
</tr>
<tr>
<td>Pb-16Li mass flow BB total (kg/s)</td>
<td>26466</td>
<td>956</td>
<td>894</td>
</tr>
<tr>
<td>Recirculation/day</td>
<td>265</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Pb-16Li velocity (m/s)</td>
<td>0.005-0.17</td>
<td>0.005-0.01</td>
<td>0.005-0.01</td>
</tr>
<tr>
<td>Pb-16Li Temperature out BB [°C]</td>
<td>530/550</td>
<td>326</td>
<td>300</td>
</tr>
<tr>
<td>Max T PbLi/Eurofer interface [°C]</td>
<td>530/550</td>
<td>350-450°C</td>
<td>540°C</td>
</tr>
<tr>
<td>HT pressure [Pa]</td>
<td>&lt;0.1</td>
<td>50-80</td>
<td>~30</td>
</tr>
<tr>
<td>PbLi Operative pressure [MPa]</td>
<td>0.3-3.0</td>
<td>0.3-3.0</td>
<td>0.3-3.0</td>
</tr>
<tr>
<td>Corrosion rate [µm/y]</td>
<td>~ 240 (540°C)</td>
<td>1.58 (330°C)</td>
<td>0.95 (300°C)</td>
</tr>
<tr>
<td>BB Lifetime [year]</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
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In despite of the design of a water or gas facility, for the design of a lead lithium loop the following additional remarks must be taken into account:

- **Material compatibilities with lead lithium:** due to the high solubility of Nickel in Pb-16Li it is not possible to use AISI 316 as structural materials for piping and main components. Chromium steel or compatible material with lead lithium must be used, which required post-welding treatment.

- **The structural material used** is a reduced activation ferritic-martensitic steel, **Eurofer** (a Reduced Activation Ferritic/Martensitic steel – RAFM steel).
The corrosion rate of RAFM steels in PbLi depends strongly on **temperature**, velocity, **impurities** and **flow regime**. The corrosion phenology is due to dissolution of alloying elements in PbLi. The driving force for corrosion of elements (W<<Fe, Cr<Ni) is the chemical potential.

\[ \mu_i = \mu^\circ + RT \ln \left( \frac{C_i}{C_{is}} \right) \]

The larger \( C_{is} \) - the stronger the dissolution attack.

The velocity and temperature profile in BB is influenced by Magnetohydrodynamic phenomena and buoyancy effect:

\[ \mathbf{j} \times \mathbf{B} \]

\[ \mathbf{j} = \sigma (-\nabla \phi + \mathbf{v} \times \mathbf{B}) \]
The database is not available, such that extrapolating these data to different blankets conditions is hardly possible.
Breeder blanket is an extremely complex component in which a coating is necessary to tackle 4 main issues:

- Electrical Insulation
- Compatibility With Pb-Li
- T permeation
- Thermal mechanics load

Anti corrosion/anti permeation coating
Two kinds of coatings are under development in the EU BB project:

- Al-based corrosion barriers - electrochemical ECX process (KIT)
- Al2O3 coating developed by Pulsed Laser Deposition (PLD) (IIT-ENEA)

Different coatings methods produce important modifications in coatings that can affect the compatibility with the liquid breeder.

In the *Pulsed Laser Deposition (PLD)* technique, a high-power pulsed laser beam is focused inside a vacuum chamber to strike a target of the material that is to be deposited. Al is vaporized from the target and as result, a high homogeneous layer of alumina is deposited on the Eurofer. The interphase is well defined and the external surface is smoothies.

The ECX process is based on the electrodeposition of aluminum from an ionic liquid for the fabrication of Fe-Al barriers. Al is diffused gradually into the Eurofer. The roughness of the external surface is high.
Preliminary characterization for coatings developed by ENEA and KIT

Characterization of the developed coating in flowing Pb-16Li in LIFUS II facility (Pb-16Li velocity 0.01 m/s, 0.1 m/s and 1 m/s at 550°C with chemistry control) and KIT coating in PICCOLO loop.

Coatings qualification after corrosion tests in PbLi

Permeation test on developed coating

Thermal cycle characterisations

Coatings qualification after ion irradiation

Corrosion experiments in samples previously degraded by ion irradiation

Degraded coatings qualification after corrosion tests in PbLi

Characterize the developed coating under gamma rays and measure the tritium permeation with Van De Graff accelerator.

Experimental validation of neutron activation of breeder using 14MeV neutron generator

Coating irradiation in Pb-16Li capsule in Fission reactor LVR-15 (CVR)
Al2O3 coating - Pulsed Laser Deposition (PLD)

- Permeation Reduction Factor (PRF)
- Corrosion Tests:
  - 1,000 h @ 550 °C in static Pb-16Li

ALD coating:
- Internal side of Pipes
- Complex geometry
- Preliminary coating was produced and characterize

ECX coating:
- Corrosion characterization
  - Microstructure remains columnar
  - No penetration of Pb-15.7Li into the Fe-Al layer observed

50 cycles from 250°C to 550°C up to 4°C min⁻¹ in fluxed Ar 6.0 and 2hr of dwelling time.

Eurofer exposed in flowing Pb-15.7Li: 2,224 h (left) and 4,026 h (right).
A dedicated experimental activities are ongoing in Europe in the Frame of BB – WPB5 EUROFUSION project in order to qualify the developed barrier.

- **Permeation Tests:**
  1. Without irradiation (ENEA coating)- Temperature range: 250-650°C (*PERI II facility* - ENEA)
  2. with electro irradiation (ENEA/KIT coating): Temperatre range 20-250°C *Van De graf accelerator* – *CIEMAT*
  3. Coating Characterisation (CIEMAT): **Techniques:** XRD; Confocal microscopy; SEM/EDX; SIMS

- **Irradiation Tests:**
  1. With ion irradiation (ENEA/KIT coating): 10-30 dpa, CIEMAT facility
  2. With neutro irradiation (ENEA/KIT coating): *IPP-CR LVR-15 reactor*: $4.5 \times 10^{14} \text{n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1} (E > 0.1 \text{MeV})$ and $2 \times 10^{14} \text{n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1} (E > 1 \text{MeV})
Coating Irradiation

- Permeation under electro irradiation
- Thermal desorption spectroscopy (TDS)

- 5 µm PLD-coating
- T 450°C
- Ionizing dose rates of 200-400 Gy/s 1.8 MeV electron irradiation

The PLD coating reduces about 1000 times permeation

PLD Electrical conductivity: $10^{-13}$ and $10^{-11}$ S/m at 450°C

=> Electrical Isolator
Helium Production in BB

\[ ^6\text{Li} + (n) \rightarrow ^3\text{H} + ^4\text{He} \]

- To produce 1 gram of tritium, 2.33 g of Li-6 must be consumed and 1.33 g of He is released. He daily production will be more than 500 g.
- Depending from PbLi mass flow rate, Temperature, pressure, helium will be leaving the module as dissolved gas or, if the solubility limit is exceeded, as a gas bubble.

- DCLL no He bubble
- Remove all He solubilised in PbLi

WCLL, PbLi flow rate: 833 kg/s

Max value of He gaseous production Volume in 1 module/h = 0.04l/h
=> 350L in 1 year

Effect of liquid flow rate

Effect of total pressure (depth)
The corrosion behavior of Breeding Blanket materials is influenced by irradiation, because irradiation changes the material properties, the chemistry of PbLi and the tritium behavior in PbLi.

- Main activated product: Hg, Po
- R&D required: Verification of a neutron spectra produced by a D–T reaction using a neutron generator
- Calculations of the reaction rates for activation products

**Reactant** | **Reaction type** | **Products** |
---|---|---|
Li6 | n, T | H3, He4 |
Li7 | n, 2n | Li6 |
Li7 | n, g | Li8 |
Li7 | n, d | He6 |
Pb204 | n, n’ | Pb-204m |
Pb204 | n, 2n | Pb203 |
Pb204 | n, p | Tl204 |
Pb206 | N, T | Tl204 |
Pb206 | N, A | Hg203 |
Pb206 | n, g | Bi-207 |
Pb208 | n, g | Bi 209 |
Pb208 | N, 2N+A | Hg203 |

**Species** | **Half time** | **Specific activity after irradiation [Bq/kg]** |
---|---|---|
³H | 12.32 y | 8.89 \(10^{12}\) |
²⁰³Hg | 46.6 d | 2.41 \(10^{10}\) |
²⁰⁴Tl | 3.78 y | 6.91 \(10^{9}\) |
²⁰²Tl | 122.2 d | 1.16 \(10^{9}\) |
²¹⁰Po | 138 d | 5.49 \(10^{8}\) |
²⁰³Pb | 51.9 h | 2.37 \(10^{7}\) |
²¹⁰Bi | 5.01 d | 5.86 \(10^{6}\) |
²⁰⁵Pb | 1.5 \(10^7\) y | 4.61 \(10^6\) |
²⁰⁷Bi | 32.2 y | 6.95 \(10^5\) |
²⁰⁸Bi | 3.7 \(10^5\) y | 3.79 \(10^4\) |
²¹⁰Pb | 22.3 y | 6.92 \(10^3\) |
²⁰⁹Po | 102 y | 5.14 \(10^3\) |
²⁰⁶Bi | 6.24 d | 1.53 \(10^3\) |

**Typical irradiation products and their activity after 2.5y irradiation**

**Gas saturator + cold trap** is the proposed solution in order to remove activation products (Hg, Po, He etc.).

**GRADEL: 14MeV Neutron generator**
- DD 2.5 MeV neutron yield: >1 \(10^8\) n/s output
- DT 14 MeV neutron yield (65x DD): >5 \(10^9\) n/s
- TT 0.5-9.5 MeV neutron yield: ~3x DD
- Non-pulsed continuous operation
Conceptual design of LiPb breeder loops concepts auxiliary systems: Integration of PbLi loop in Tokamak Building and procedure to be adopted for normal and abnormal operations (LOCA and LOFA in/ex Vessel)

PbLi Main component:
- Storage tank
- Pumping system
- Heat Exchanger
- Buffer Tank
- Charge Tank
- Purification system
- Tritium Extration and Removal System (TER):
  - PAV/VST
- Safety/Expansion Tank
PbLi Loop Design & Integration

Integration PbLi loops in tokamak building

TER – DCLL BB

- Design and integration of PbLi loops and main component (storage tank, expansion tank) in the tokamak building for each BB concepts;
- Integration of TER, storage tank, system developed in order to remove activation products, helium generated in the BB;
- Mitigation system in case of In-box LOCA, LOFA, etc
The Design of PbLi and auxiliaries systems are performed with the support of:

- **EXPERIMENTAL ACTIVITIES**
- **MODELING & SIMULATION ACTIVITIES**

RELAP5-3D code is used in order to perform the thermodynamic design of PbLi loops and to analyse transient conditions during operation and safety analysis.

Benchmark of Relap5-3D code with experimental results in IELLLO loop.
Conclusions

- Investigate MHD effect on corrosion rate, heat transfer and tritium transport => developed dedicated tools;

- **Material corrosion database development:** Experimental and numerical Analysis of RAMF steel corrosion rate with chemistry control in flowing (up to 1m/s) PbLi at 550°C-500°C;

- **Development and Characterization of Antipermeation and anticorrosion barrier:**
  - Characterization process with and without **Tritium**;
  - Thermo-mechanical analysis;
  - Characterization under gamma, electron and neutron irradiation;
  - Long time Corrosion characterization;

- **Analysis of PbLi corrosion products in flowing PbLi loops**;

- **Experimental and Numerical analysis of PbLi activated product** => High Neutron Energy source is required to irradiated PbLi/water;

- **Scale up of the developed Technologies**
Thank You