Tritium Breeding and blanket technology

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Introduction: principle of a fusion power plant

\[
\begin{align*}
D + T & \rightarrow \text{He} + n + 17.6 \text{ MeV} \\
^6\text{Li} + n & \rightarrow \text{He} + T + 4.8 \text{ MeV} \\
^7\text{Li} + n & \rightarrow \text{He} + T + n' - 2.5 \text{ MeV}
\end{align*}
\]

\((1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J})\)

Annual consumption 1 GW\textsubscript{el} power plant \((\eta = 0.3)\): 100 kg D, 300 kg Li

Annual consumption 1 GW\textsubscript{el} coal power plant: \(3 \times 10^9\) kg coal
Fusion rates in a thermal plasma

Data: S. Bosch Nucl. Fusion 32 (1992) 611

\[ \langle \sigma v \rangle / m^3/s \]

\[ T / keV \]

- \( D + T \rightarrow ^4\text{He} + n \)
- \( D + ^3\text{He} \rightarrow ^4\text{He} + p \)
- \( D + D \rightarrow T + p \)
- \( D + D \rightarrow ^3\text{He} + n \)

\( \sim T^2 \) for 10 ... 20 keV
Blanket design

The blanket is a key component of a fusion reactor, with the following functions:

- Tritium breeding
- Power exhaust
- Radiation shielding

Important aspects for blanket design:

- Tritium breeding rate $\text{TBR} > 1$
- Structural integrity maintained for long operation (high neutron fluence)
- Efficient heat exhaust (high thermodynamic efficiency)
- Low activation
- Low tritium retention
- Good tritium confinement
Radial build of a tokamak reactor

Fusion power plant: distance between plasma edge and TF coil casing $b \sim 1.8\,\text{m}$. This number does not scale with reactor size $\rightarrow$ consequence for reactor size

$$B_0 = B_{\text{max}} \left( 1 - \frac{a+b}{R_0} \right)$$

(F. Cismondi, L. V. Boccaccini, KIT, PPCS Studie)
Tritium breeding blanket

Tritium ($t_{1/2} = 12.32$ years) is only scarcely available (from fission reactors) and hence it has to be produced in the fusion reactor („breeding“).

Natural Lithium consists of 7.42% $^6\text{Li}$ and 92.58% $^7\text{Li}$.

Possible breeding reactions:

\[
^6\text{Li} + n \rightarrow T + \alpha + 4.78\text{MeV} \\
^7\text{Li} + n \rightarrow T + \alpha + n - 2.47\text{MeV}
\]

The $^7\text{Li}(n;n'\alpha)t$ reaction is endothermic with an energy threshold of 2.8 MeV.

In steady state operation, a fusion reactor should reach a tritium breeding ratio ((TBR) > 1.

![Graph showing Li-6(n,alpha)t and Li-7(n,n,alpha)t Cross-Section](image)
Abschätzung der notwendigen Blanket-Dicke

Freie Weglänge (1/e) für die Abbremsung der Neutronen (after: J. Freidberg)

\[ \lambda_{SD} = \frac{1}{n_{Li} \sigma_{SD}} \approx 0.055 \text{m} \]

(Stoß-Querschnitt Neutronen-Kühlung \( \sigma_{SD} = 10^{-28} \text{m}^2 \))

Daraus folgt für die Energie der Neutronen folgender räumlicher Verlauf:

\[ \frac{dE}{dx} = - \frac{E}{\lambda_{SD}}, \quad \Rightarrow E = E_n e^{-\frac{x}{\lambda_{SD}}} \]

Wie dick muss der Li-Moderator sein, damit die Neutronen von der Anfangsenergie \( E_n = 14.1 \text{ MeV} \) auf thermische Energien (\( E_{th} = 0.025 \text{ eV} \)) abgebremst werden?

\[ \lambda_{SD} = \frac{1}{n_{Li} \sigma_{SD}} \approx 55 \text{ mm}, \quad \frac{E_n}{E_{th}} = \frac{14.1 \text{ MeV}}{25 \text{ meV}} = 5.63 \times 10^8 \Rightarrow x = \ln(5.63 \times 10^8) \lambda_{SD} \]

\( \rightarrow \) Es werden etwa 20 Abfall-Längen \( \lambda_{SD} \) benötigt, d.h. \( x = 1.1 \text{ m} \)

Berücksichtigt man zusätzlich die Brutreaktion, genügt eine Blanket-Dicke von etwa 0.7 ... 0.9 m
Neutron multiplication

A pure Lithium blanket cannot reach TBR > 1 due to unavoidable neutron losses:

- absorption in structural materials
- Geometric losses through divertor (no breeding blanket there)
- voids in the blanket needed for heating and diagnostic access

Endothermic reactions with Be or Pb are suited for neutron multiplication in the blanket → TBR > 1

In total, the blanket is producing extra energy due to the exothermic $^6\text{Li}$ reaction. The typical total energy yield per primary fusion reaction is about 20 MeV.

(1 barn = $10^{-28}$ m$^2$)
Overview: European blanket concepts for DEMO

(L. Boccaccini, KIT)
Helium-gekühltes „Pebble-Bed“-Blanket

**HCPB Konzept (KIT):**

- Keramische Kugel-Schüttungen mit Li und Be; **Verbrauch ca. 1 cm/Jahr**
- Helium-Kühlung (hohe Abgangstemperatur; Sicherheit)
- Komplett-Austausch von Blanket + erster Wand nach einigen Jahren

- benötigt sehr hohe Pumpleistungen
- T-Inventar in den Li₄SiO₄ Kugeln (Ausgasrate ist temperaturabhängig)
- Versprödung der keramischen Kugeln

![Diagram of HCPB blanket with helium cooling](image)

*q*<sub>max</sub> = 3 MW/m<sup>2</sup>

(F. Cismondi, KIT, 2008)
HCPB Blanket (Helium Cooled Pebble Bed)

Main features

- Large modules (up to 1 m x 2 m)
- EUROFER as structural material; protective tungsten layer at the front side
- He at 8MPa, Tinl/Tout = 300/500 °C coolant
- Ceramic Breeder (CB): Li$_4$SiO$_4$ in form of pebble bed at 50% 6Li. Li$_2$TiO$_3$ is an alternative candidate.
- Beryllium as multiplier in form of a pebble bed
- T extraction (Be and CB) through low pressure purge He (few bars)
Operational conditions in a ceramic type blanket

High temperature operation needed
1. to ensure that the Tritium can outgas from the ceramic pebbles fast enough,
2. to allow for a high thermodynamic efficiency of electrical power generation

Note that high temperature operation is demanding for the materials requirements.
HCLL Blanket Concepts (Helium Cooled Lithium Lead)

Main features

- Large modules (~ 2 m x 1.5 m)
- EUROFER as structural material
- He at 8MPa, Tinl/Tout = 300/500 °C coolant
- Pb-Li (Li at 90% in 6Li ) breeder, neutron multiplier and tritium carrier
- PbLi slowly re-circulating (10/50 rec/day)
- T extraction from Pb-Li outside the blanket

G. Aiello et al. Development of the Helium Cooled Lithium Lead Blanket for DEMO, ISFNT-11
Flüssig-PbLi Blanketprinzip

Self-cooled PbLi blankets

**Poloidal flow concept**
PbLi as breeder and coolant

**Advantages:**
- only one fluid
- simple design

Schwierigkeiten:
- Strömung eines elektrisch leitfähigen Mediums senkrecht zum Magnetfeld, daher hoher Druckabfall
- Korrosion in den Leitungswegen

a) Blanket cross section  b) Reactor sector
The ARIES-RS Blanket and Shield are Segmented to maximize Component Lifetime

Outer blanket detail

- Blanket and shield consists of 4 radial segments.
- First wall segment, attached to the structural ring, is replaced every 2.5 FPY.
- Blanket/reflector segment is replaced after 7.5 FPY.
- Both shield segments are lifetime components:
  * High-grade heat is extracted from the high-temperature shield;
  * Ferritic steel is used selectively as structure and shield filler material.
Pumping liquid metals

Current source $U[V]$

J. Hartmann 1918

MHD DC pump

(after L. Bühler, KIT)
Flow of electrically conducting fluids in a magnetic field

Poiseuille – Hartmann flow

Exact solution

\[ u = U \left(1 - \frac{\cosh Ha y}{\cosh Ha}\right) \]

Hydrodynamic flow for \( Ha < 1 \)

Plug flow for \( Ha \gg 1 \)

Formation of thin boundary layers

Balance between pressure and Lorentz force

\[ Ha = LB \sqrt{\frac{\sigma}{\rho \nu}} \]

For applications in fusion blankets: \( Ha > 10^4 \), \( \delta \ll 1 \)
Optimisation of TBR is possible via

1. enrichment of $^6\text{Li}$
2. mass ratio between neutron multiplier and breeding materials
The Blanket systems: segmented design

- Blanket replacement concept based on the Vertical Maintenance Concept
- Design of the blanket segment based on the Multi Module Design

Blanket Box

Back Supporting Structure

16 TF -> 16 Blanket Sectors

3 OB + 2 IB Blanket Segments

(slide from L. Boccaccini, KIT / Eurofusion)
Fusionsreaktor: Gefäß-Komponenten und deren Integration

Reaktor-Komponenten:
- Vakuum-Gefäß + Ports
- Blanket
- Divertor
- Magnetensystem
- Anschlüsse und Rohre
- Abschirmung, Isolation

Wichtige Reaktor-Systeme:
- Kühlssystem
- Stromerzeugung
- Tritium-Erzeugung und Auskopplung
- Komponenten-Austausch-System
- Plasma-Heizung und Stromtrieb
- Plasma-Kontrolle

D. Filsinger, L. V. Boccaccini, et al. (KIT)
Konzept für Wartung und Austausch von Komponenten (Vertikaler Port)

Regelmäßiger Austausch von Wand-Komponenten und Blanket ca. alle 2 - 4 Jahre

D. Filsinger, L. V. Boccaccini, et al. (KIT)
<table>
<thead>
<tr>
<th>Blanket Name</th>
<th>IP</th>
<th>Coolant</th>
<th>Breeder materials</th>
<th>Additional features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium Cooled Lithium Lead (HCLL)</td>
<td>EU</td>
<td>helium</td>
<td>PbLi</td>
<td></td>
</tr>
<tr>
<td>Helium Cooled Pebble Bed (HCPB)</td>
<td>EU</td>
<td>helium</td>
<td>Ceramic Breeder + Be</td>
<td></td>
</tr>
<tr>
<td>Water Cooled Ceramic Breeder (WCCB)</td>
<td>JA</td>
<td>water</td>
<td>Ceramic Breeder + Be</td>
<td>T-permeation barrier should be tested</td>
</tr>
<tr>
<td>Helium Cooled Ceramic Reflector (HCCR)</td>
<td>KO</td>
<td>helium</td>
<td>Ceramic Breeder + Be</td>
<td>Reflector of graphite pebbles coated with SiC.</td>
</tr>
<tr>
<td>Helium Cooled Ceramic Breeder (HCCB)</td>
<td>CHI</td>
<td>helium</td>
<td>Ceramic Breeder + Be</td>
<td>Be as binary bed and T Permeation barriers.</td>
</tr>
<tr>
<td>Lithium Lead Ceramic Breeder (LLCB)</td>
<td>IN(RF)</td>
<td>helium / PbLi</td>
<td>Ceramic Breeder + PbLi</td>
<td>Electrical insulating coatings for PbLi flow</td>
</tr>
<tr>
<td>[Dual Coolant Lithium Lead (DCLL)]</td>
<td>US</td>
<td>Helium / PbLi</td>
<td>PbLi</td>
<td>SiC/SiC inserts as electrical insulator for PbLi flow</td>
</tr>
</tbody>
</table>

All the Blankets use a RAFM stell as structural material (in EU the steel is EUROFER-97)
## Blanket concepts for a DEMO reactor

<table>
<thead>
<tr>
<th>Label</th>
<th>Class of concept</th>
<th>Structure</th>
<th>Coolant</th>
<th>Breeder</th>
<th>Multiplier</th>
<th>Tritium removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>WCSB (JA)</td>
<td>Water Cooled Solid Breeder</td>
<td>RAFM</td>
<td>Water @ 285-325°C, 15.5 MPa Opt: @ 280/510°C, 25 MPa,</td>
<td>Li₂TiO₃</td>
<td>Be</td>
<td>Separated Tritium / Heat removal loops</td>
</tr>
<tr>
<td>WCLL (EU)</td>
<td>Water Cooled Lithium Lead</td>
<td>RAFM</td>
<td>Water @ 285-325°C, 15.5 MPa</td>
<td>PbLi</td>
<td>PbLi</td>
<td>Separated Tritium / Heat removal loops</td>
</tr>
<tr>
<td>HCPB (EU)</td>
<td>Helium Cooled Solid Breeder</td>
<td>RAFM</td>
<td>Helium @ 300-500°C, 8 MPa</td>
<td>Li₄SiO₄ (Li₂TiO₃)</td>
<td>Be</td>
<td>(Be12Ti) Separated Tritium / Heat removal loops</td>
</tr>
<tr>
<td>HCCB (CHI)</td>
<td>Helium Cooled Solid Breeder</td>
<td>RAFM</td>
<td>Helium @ 300-500°C, 8 MPa</td>
<td>PbLi</td>
<td>PbLi</td>
<td>Separated Tritium / Heat removal loops</td>
</tr>
<tr>
<td>HCCR (KO)</td>
<td>Helium Cooled Lithium Lead</td>
<td>RAFM</td>
<td>Helium @ 300-500°C, 8 MPa</td>
<td>PbLi</td>
<td>PbLi</td>
<td>Combined Tritium / Heat removal loops</td>
</tr>
<tr>
<td>HCLL (EU)</td>
<td>Helium Cooled Lithium Lead</td>
<td>RAFM</td>
<td>Helium @ 300-500°C, 8 MPa</td>
<td>Li</td>
<td>(Be)</td>
<td>Combined Tritium / Heat removal loops</td>
</tr>
<tr>
<td>DCLL (US, EU,CHI)</td>
<td>Dual Coolant Lithium Lead</td>
<td>RAFM</td>
<td>Helium @ 300-500°C, 8 MPa PbLi @ 500-700°C</td>
<td>PbLi</td>
<td>PbLi</td>
<td>Combined Tritium / Heat removal loops</td>
</tr>
<tr>
<td>FFHR (JA)</td>
<td>FLiBe Self Coolant</td>
<td>RAF V (alloy)</td>
<td>FLiBe @ 450-550°C</td>
<td>FLiBe</td>
<td>FLiBe + Be</td>
<td>Combined Tritium / Heat removal loops</td>
</tr>
<tr>
<td>Li/V-SC (US)</td>
<td>Li/V Self Coolant</td>
<td>V (alloy)</td>
<td>Li @ 650-700°C</td>
<td>Li</td>
<td>(Be)</td>
<td>Combined Tritium / Heat removal loops</td>
</tr>
<tr>
<td>AHCPB (KIT-EU)</td>
<td>Advanced HCPB</td>
<td>SiC_f/SiC</td>
<td>Helium@ 350-750°C, 8 MPa</td>
<td>Li₄SiO₄</td>
<td>Be</td>
<td>Separated Tritium / Heat removal loops</td>
</tr>
<tr>
<td>SCLL (US, EU)</td>
<td>Self Coolant Lithium Lead</td>
<td>SiC_f/SiC</td>
<td>PbLi @ 700-1100°C</td>
<td>PbLi</td>
<td>PbLi</td>
<td>Combined Tritium / Heat removal loops</td>
</tr>
<tr>
<td>TAURUS (CEA-EU)</td>
<td>High temperature Solid Breeder</td>
<td>SiC_f/SiC</td>
<td>Helium @ 600-900°C, 10MPa</td>
<td>Li₂TiO₃</td>
<td>Be</td>
<td>Combined Tritium / Heat removal loops</td>
</tr>
<tr>
<td>Dream (JA)</td>
<td>Advanced HCPB</td>
<td>SiC_f/SiC</td>
<td>Helium@ 350-750°C, 8 MPa</td>
<td>Li₄SiO₄</td>
<td>Be</td>
<td>Separated Tritium / Heat removal loops</td>
</tr>
<tr>
<td>EVOLVE (US)</td>
<td>Evaporating Li</td>
<td>W (alloy)</td>
<td>Li @ 1200°C (boiling)</td>
<td>Li</td>
<td>none</td>
<td>Combined Tritium / Heat removal loops</td>
</tr>
</tbody>
</table>

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**Legend:**
- **RAFM:** Real Alloy Fuels Module
- **SiC_f/SiC:** Silicon Carbide
- **PbLi:** Lead-Lithium
- **Li:** Lithium
- **Li₂TiO₃:** Titanium Oxide
- **Be:** Beryllium
- **none:** No specific material mentioned
- **Self Coolant:** Self-cooled blanket
- **Combined:** Combined Tritium/Heat removal loops
- **Separated:** Separated Tritium/Heat removal loops
- **Evaporating Li:** Evaporating lithium
- **Opt:** Optimum
- **Boiling:** Boiling temperature

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26 Sept 2014 | Wolfgang Biel | Diagnostics and control of fusion plasmas | DPG school „The physics of ITER“ | No 23
Zusammenfassung zur Blanket-Auslegung für einen Fusions-Reaktor

- In der Brutzone laufen die Prozesse von Moderation der Neutronen, Tritium-Brüten und Neutronenvervielfachung parallel ab; einschließlich Strukturmaterial und Kühlung ist eine Dicke von etwa 1 m notwendig.
- Falls wir einen zu häufigen Austausch des Blankets vermeiden wollen, dann muss entsprechend eine „Verbrauchsschicht“ zugegeben werden, hierfür genügen etwa +10 cm (> 10 Jahre).
- Eine Feinabstimmung der Brutrate (TBR) oder geringe Reduzierung der Blanketdicke kann durch Anreicherung von $^6$Li erfolgen.
- Die Magnetfeldspulen benötigen eine Abschirmung gegenüber der verbleibenden ionisierenden Strahlung sowie eine thermische Abschirmung (+30 .. 40 cm).
- Ein doppelwandiges Vakuumgefäß ist für den sicheren Einschluss des Tritium-Inventars nötig (+30 .. 40 cm).
- Insgesamt ergibt sich auf der Innenseite des Torus ein Mindestabstand zwischen Plasmarand und TF-Spulen von $b = 1.8 \ldots 2.0$ m.