Ceramic Breeder Technology

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ENEA CR Casaccia, uts MAT
LITHIUM CERAMIC BREEDERS
State of art after 20 years of R&D

- Basic concepts
- Pellets functioning and radiation damage tested in fission reactors
- Pebbles fabrications
- Pebble beds testing in blanket modules
Breeding blanket primary functions

- 1 – tritium production
- 2 – heat generation
- 3 – neutron shielding
The tritium is mainly generated by the reaction

\[ ^6\text{Li} + n \rightarrow \text{T}(2.7 \text{ MeV}) + \text{He}(2.1 \text{ MeV}) \]

Neutrons are supplied by the D-T fusion

\[ \text{D} + \text{T} \rightarrow \text{He}(3.52 \text{ MeV}) + n(14.1 \text{ MeV}) \]

- Tritium generation rate \( G \) and its recovery rate \( R \) must satisfy self-breeding and start-up of other reactors, \( \text{TBR} > 1 \);
- \( \text{Be} \) as \((n.2n)\) neutron multiplier must be largely employed.
- Tritium inventory \( I = \int (G-R) \, dt \)
- Tritium residence time \( \tau = I/G \)

22/02/2005
Dimension of a 1000 MW Fusion Power Plant CONSUMPTION

- Deuterium $D_2$: ~0.7 Kg/day
- Tritium $T_2$: ~ 1 Kg/day
- $^6$Li isotope: ~ 2 Kg/day
- Inside the blanket during its life (4 years)
  - $^6$Li ~ 24,000 Kg
  - As fully enriched $\text{Li}_2\text{O}$ ~ 56,000 Kg
  - To be transformed in $T_2\text{O}$
$^{6}\text{Li}(n,\alpha)T$ transmutation

- Tritium generation rate
  \[ G = \int_V \int_E \varphi \rho \sigma \]
- Where $\varphi(E) =$ neutron flux density; $\sigma(E) =$ $^{6}\text{Li}$ cross section (decreasing with $\sim \sqrt{E}$); $\rho =$ $^{6}\text{Li}$ density; integrated over the energy $E$ and the space coordinates $V$
- Energy given per captured neutron: 4.8 MeV
- For each $\varphi(E)$, $G$ (and its power generation $P$) can be tailored by adjusting $\rho$ with appropriate $^{6}\text{Li}$ enrichment.
- Slow and fast neutron Fission reactors may reproduce the $G$ and $P$ values of DEMO power plant breeding blankets
DEMO neutron flux density as compared to those of the future D-Li stripping source (IFMIF) and of the existing fission reactor (HFR).
Li-ceramics testing in fission experimental reactors

Tritium and heat generation rate in Li-ceramics can be examined in fission neutron sources.

In fast-reactors the blanket fusion n-environment is reasonably reproduced for $^6$Li-tailored (enriched) oxides below 2MeV.

High Flux Fission Reactors may give $^6$Li transmutation rate (G) and amount ($^6$Li depletion or Li-burn-up (BU)) comparable to those of a DEMO-blanket.

The radiation damage (rate and dose) cannot be simultaneously and exactly reproduced.

A combination of differently tailored n-spectra and $^6$Li concentrations may help to reproduce the fusion breeding blanket radiation damage.
The recoiling of α and T from the $^6\text{Li}(n,\alpha)\text{T}$ reaction create a cascade of secondary recoil atoms from their interaction with atoms in the ceramics. Fast neutron interactions can also cause primary recoil atoms that also lead to a cascade of secondary recoil atoms. Both these processes lead to radiation damage characterized by the total number of displacements per atom (DPA). The Li transmutation leads to creation of Li-vacancies and build-up of He and T$_2$O, as measured by the Li burn-up (BU).

**BU effects might be more significant than stable products dpa in the evolution of property changes.**

$^6\text{Li}$-tailoring allows a reasonable reproduction of BU-DPA in high flux experimental fission reactors (much better if Fast Neutron Reactors (EBR-II and FFTF)) as envisaged to occur in a Fusion-DEMO breeding blanket.
Neutron spectrum and predicted radiation damage (DPA – BU combination) for Li-ceramics in DEMO

**Fig. 5.** HCPB Demo blanket: neutron flux spectra in Li$_2$O, Li$_4$SiO$_4$ and Li$_2$TiO$_3$.

**Fig. 6.** DPA accumulation vs. lithium burn-up for the breeder materials Li$_2$O, Li$_4$SiO$_4$ and Li$_2$TiO$_3$ in the HCPB Demo blanket.

Li-6 density is near the same for the different oxides.
DPA – BU combinations achievable (for both n-spectra and isotope tailored Li-ceramics) in high flux fission neutron reactors

Gray triangles refer to the DEMO fusion reactor
PELLETS are suitable forms to:

- ...investigate material properties (disks, rods, rings, etc.);
- ... be irradiated as cladded in instrumented fission reactor tubes/capsules,
- ... be used as tested in “Breeder In Tube” blanket concepts
- 

Pellets were candidate forms for the ENEA-CEA BIT- POLOIDAL He cooled European Blanket (1990-1995).
BEATRIX-I. Irradiation of Li-ceramic pellets in high flux fast neutron experimental reactor EBR-II

- Integrity and dimensional stability of pellets was tested
- Large pellets irradiated under high thermal gradients (~50 W/cm³)
- Small and large pellets up to high Li-BU
Li$_2$O pellets generated tritium at a rate $G = 1.2 \times 10^{14}$ atom/cm$^3$/s and power $P = 100$ w/cm$^3$ during irradiation exposure of $300 + 203$ effective full power days (EFPD, phase-I + phase-II).

Tritium recovery rate and temperature gradients were found stable up to 4.2% B.U., Data are directly applicable to the performance of Li$_2$O at EOL conditions.

During phase-II a Li$_2$ZrO$_3$ pebble bed was tested successfully (1994).


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Phase-I: thermal gradient under fast-flux irradiation of large Li$_2$O pellets was of 400 to 1000°C.

Phase-II: a Li$_2$ZrO$_3$ pebble bed canister was tested in similar conditions, the thermal gradient was of 440 to 1100°C.
BEATRIX-II phase II

- Main results for Li$_2$O big pellets (thermal gradient canister)
- Top temperatures inside the canister decrease slowly with BU and show stable gradient.
- Tritium release spikes as induced by thermal steps 530→640°C on thin annular pellets.
- This property remains good up to the EOL
PIE of $\text{Li}_2\text{O}$ pellets irradiated in FFTF

A central hole arised.

Composite photomicrograph of the post-irradiation temperature gradient specimen (BEATRIX-II, Phase I, 4.2% Li burnup), radial section.

Grains were found to grow as columnar (where the gradient is maximum) and as equiaxed (near the cold surface).

A situation similar to that of UO$_2$ fission fuel rod-pin section (~200 W/cm$^3$) at its End of Life (BU max).

As fabricated microstructure

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TRITIUM RECOVERY FROM Li-CERAMICS

- Pellets or pebbles are swept by He flowing during the reactor operation.
- Tritium in gaseous forms are carried by the He purge, adding \( \text{H}_2 \) (as isotope swamping) to He the removal rate is improved.
- \( \text{T}_2 \), DT (or HT in the experiments) are preferred to water vapor condensable forms \( \text{T}_2\text{O} \) or DTO (or HTO).
- He doped with \( \text{D}_2 \) (0.1\% as \( \text{H}_2 \) in the experiments) is the “reference” purge gas to get tritium in DT (or HT) form.

It is generally accepted that \( \tau < 1 \text{ day} \) states the minimum operative temperature \( \tau_{\text{min}} \).
Tritium generation and recovery is performed by inserting Li-ceramic specimens in instrumented vented capsules. Their rates G and R are measured in line. Irradiations are performed in high flux material testing fission reactors. Neutron flux, temperature, purge gas flow-composition are the main controlling parameters. The sketch shows the loop used in U.S. at the Fast Flux Test Facility (FFTF) reactor for the BEATRIX-II program (1990).
Li-CERAMICS TEMPERATURE WINDOWS

- The increase of temperature helps in power and tritium recovery at expense of the stability of ceramics.
- A compromise was stated.
- $T_{\text{min}}$ is stated by $\tau = 1$ day
- $T_{\text{max}}$ results from dimensional ($T_{1\text{max}}$), chemical, thermal and mechanical stability remaining acceptable as the durability ($T_{2\text{max}}$) under irradiation at extended burn-up
- A large data-base exist for pellets (density 70-80% of TD) tested by several tens of irradiation experiments performed in fission reactors.
- Microstructure (grain size) play an important role on $T_{1\text{max}} - T_{\text{min}}$ windows

<table>
<thead>
<tr>
<th>Oxide (gLi/cc)</th>
<th>$T_{\text{min}}$</th>
<th>$T_{1\text{max}}$</th>
<th>$T_{2\text{max}}$</th>
<th>m.p.(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li$_2$O</td>
<td>0.93</td>
<td>320</td>
<td>750</td>
<td>1100</td>
</tr>
<tr>
<td>Li$_4$SiO$_4$</td>
<td>0.54</td>
<td>350</td>
<td>640</td>
<td>930</td>
</tr>
<tr>
<td>Li$_2$ZrO$_3$</td>
<td>0.33</td>
<td>300</td>
<td>850</td>
<td>1000</td>
</tr>
<tr>
<td>Li$_2$TiO$_3$</td>
<td>0.33</td>
<td>350</td>
<td>820</td>
<td>1000</td>
</tr>
<tr>
<td>LiAlO$_2$</td>
<td>0.27</td>
<td>420</td>
<td>850</td>
<td>1100</td>
</tr>
</tbody>
</table>

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### A Li-ceramic breeder ranking list based on main properties

<table>
<thead>
<tr>
<th>Items</th>
<th>Materials</th>
<th>Li$_2$O</th>
<th>Li$_2$TiO$_3$</th>
<th>Li$_2$ZrO$_3$</th>
<th>Li$_4$SiO$_4$</th>
<th>$\gamma$-LiAlO$_2$</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li Density (g/cm$^3$)</td>
<td></td>
<td>⁵ 0.94</td>
<td>³ 0.43</td>
<td>² 0.38</td>
<td>⁴ 0.51</td>
<td>¹ 0.27</td>
<td>×3</td>
</tr>
<tr>
<td>Thermal Conductivity (500°C)·(W/m·°C)</td>
<td></td>
<td>⁵ 4.7</td>
<td>² 2.4</td>
<td>¹ 0.75</td>
<td>⁴ 2.4</td>
<td>⁴ 2.4</td>
<td>×2</td>
</tr>
<tr>
<td>Thermal Expansion (500°C)·(DL/L$_0$%)</td>
<td></td>
<td>¹ 1.25</td>
<td>³ 0.8</td>
<td>⁵ 0.50</td>
<td>² 1.15</td>
<td>⁵ 0.54</td>
<td>×1</td>
</tr>
<tr>
<td>Reaction of Water</td>
<td></td>
<td>¹ very</td>
<td>⁵ less</td>
<td>⁵ less</td>
<td>³ little</td>
<td>³ little</td>
<td>×3</td>
</tr>
<tr>
<td>Residence Time (440°C)·(h)</td>
<td></td>
<td>⁵ 0.03</td>
<td>(5) (-)</td>
<td>⁵ 0.01</td>
<td>² 3.0</td>
<td>¹ 50</td>
<td>×4</td>
</tr>
<tr>
<td>Swelling* (DV/V$_0$%)</td>
<td></td>
<td>¹ 7.0</td>
<td>(5) (-)</td>
<td>⁵ &lt;0.7</td>
<td>³ 1.7</td>
<td>⁵ &lt;0.5</td>
<td>×1</td>
</tr>
<tr>
<td>Transmutation Nuclides</td>
<td></td>
<td>⁵ $^{16}$O(n,p):7s</td>
<td>⁴ $^{48}$Ti(n,p):84d</td>
<td>¹ $^{90}$Zr(n,p):64h</td>
<td>⁴ $^{28}$Si(n,2n):4s</td>
<td>³ $^{27}$Al(n,2n):6s</td>
<td>×3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>² $^{47}$Ti(n,p):3.4d</td>
<td>¹ $^{94}$Zr(n,2n):106y</td>
<td>⁴ $^{27}$Al(n,p):9.5m</td>
<td>³ $^{28}$Si(n,p):6m</td>
<td>³ $^{27}$Al(n,α):15h</td>
<td></td>
</tr>
<tr>
<td>Evaluation</td>
<td></td>
<td>65</td>
<td>(62)</td>
<td>56</td>
<td>54</td>
<td>43</td>
<td></td>
</tr>
</tbody>
</table>

* : $[^6]$Li Burn up] = 3atm% (500°C)

[Evaluation] = [point of item] × [Points]
Pebbles vs. pellets

- Large brittle ceramics are weaker than small ones.
- Single small pebbles (size below \( \sim 1 \) mm) get small thermal gradients as shared by a "pebble-bed" undergoing a large heat generation, their mechanical degradation should be reduced as compared to an equivalent geometric pile of pellets (dimensions \( \sim \) cm and above).
- Small spheres are easy movable and handled in (remote) plants.
Li-ceramics fabrications

- Classical routes for powders: (for all the Li oxides)
  - Calcining, a solid state reaction induced by carbonates decomposition under annealing to get the needed compounds as fine powder;
  - examples:
    - $\text{Li}_2\text{CO}_3 + \text{TiO}_2 \rightarrow \text{Li}_2\text{TiO}_3 + \text{CO}_2$
    - $\text{Li}_2\text{CO}_3 \rightarrow \text{Li}_2\text{O} + \text{CO}_2$
  - Forming: powders are cold pressed in dyes of the needed shape (pellets); pebbles are obtained by extruding-cutting-spheronizing or by powders agglomeration in a rotating device.
  - Sintering: high temperature annealing-sintering at the needed density (% of TD)

- Melt-spraying: A molten compounds mixture is sprayed in drops solidifying during their flight;

- example: molten $\text{Li}_2\text{CO}_3$ and $\text{SiO}_2$ to fabricate $\text{Li}_4\text{SiO}_4$ pebbles

- Wet or Sol-Gel routes: “drops” of a solution of Li and Metal salts are “gelled”, then dried and sintered in nice spheres

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Fabrication of Li-Orthosilicate at Schott Glas

R. Knitter, G. Piazza, J. Reimann, P. Risthaus, L. V. Boccaccini (FZK)

Aim

\[ \text{Li}_4\text{SiO}_4 + 2.5 \text{ wt}\% \text{ SiO}_2 \]

Raw Materials

- \[ \text{Li}_4\text{SiO}_4 + \text{SiO}_2 \]
- \[ \text{Li}_2\text{CO}_3 + \text{SiO}_2 \]
- \[ \text{LiOH} + \text{SiO}_2 \]

\[ 1450 ^\circ C \]

\[ \sim 1350 ^\circ C \]
Melt-Spraying Facility at Schott Glas, Mainz

Production: 2 x 1.5 kg per day
Yield of screened pebbles: 50% (250 – 630 µm)
200 – 300 kg per year

Drawbacks:
- Batch processing
- Limited control of fabrication parameters
- Variation of batch properties

Advantage: Recycling of material

pebbles cross section

Dendritic structure
Li₄SiO₄
Li₆Si₂O₇
micropores

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Crush Load OSi 03 ex hydroxide

Pebble diameter 500 µm (dried at 300°C)

Batch 1-3
10.1 ± 2.8 N

OSi 03/1-3

Crush Load (N)

Number of Particles
Thermomechanical Tests on Pebble Beds

R. Knitter, G. Piazza, J. Reimann, P. Risthaus, L. V. Boccaccini (FZK- Karlsruhe)

Stress-strain dependence for $T = 25^\circ C$ and $T = 850^\circ C$

Thermal creep, an irreversible behavior to be known and controlled for the HCPB blanket design
Li$_4$SiO$_4$ pebbles fabrication

Conclusions

• material meets the specification of HCPB
• single process for all required $^6$Li enrichments
• low impurities by high-purity raw material
• rejections and irradiated material can be recycled
• variation in batch properties are due to batch processing and will be reduced by a continuous process

Fabrication of lithium orthosilicate pebbles using LiOH and SiO$_2$ as raw materials in a melt-spraying process

R. Knitter, G. Piazza, J. Reimann, P. Risthaus, L. V. Boccaccini (FZK)
EXTRUSION-SPHERONISATION-SINTERING PROCESS

The process can be adapted to a range of pebbles specifications (pebble size, pebble density, grain size).
The purity level of the pebbles is very good.
The current facility at CTI (Caramiques Techniques et Industrielles) allows to produce 150 kg/year of Li₂TiO₃ pebbles.
Pebble size from 0.6 to 1.2 mm with density ranging about 90% of TD and an average crash load of about 30 N.
## INVESTIGATION OF 0.6-0.8 mm Li₂TiO₃ PEBBLES

### Characteristics of Li₂TiO₃ pebbles

<table>
<thead>
<tr>
<th>Reference of batch</th>
<th>Pebble size (mm)</th>
<th>Open porosity (%)</th>
<th>Closed porosity (%)</th>
<th>Bed density (g/cm³)</th>
<th>Grain size (µm)</th>
<th>Cr. load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTI 1532 Ti 1100 CEA</td>
<td>0.8 - 1.2</td>
<td>6.0</td>
<td>5.8</td>
<td>1.82</td>
<td>1.5 - 5</td>
<td>30 ±15</td>
</tr>
<tr>
<td>CTI 942 Ti 1100 CEA</td>
<td>0.6 - 0.8</td>
<td>2.0</td>
<td>4.9</td>
<td>1.91</td>
<td>1 - 4</td>
<td>30 ±15</td>
</tr>
</tbody>
</table>

- *CTI 1532 Ti 1100 CEA*:
  - 88.7% of T.D.
- *CTI 942 Ti 1100 CEA*:
  - 93.1% of T.D.
SOL GEL fabrication routes

Comparison between Old and New Methods on Pebble Fabrication

Fabrication of Tritium Breeders

Gelling drops of syrup

Sintered Pebbles

1. Li₂TiO₃ solution

Concentration to a syrup

2. Precipitate Li₂CO₃

3. Li₂TiO₃ powder*

Reprocessing of Tritium Breeders

New Method (One Step)

By H₂O₂ to form soluble peroxo-titanium complex

Old Method (Three Steps)

Solution by acid

[Working Group F]

* : Preparation of Li₂TiO₃ powder (Solid-solid reaction between Li₂CO₃ and TiO₂)
Objectives and Implementation Sharing of Working Group F

The objectives of new task are as follows:
1) Development of small-scale fabrication confirmation by direct wet process
   (including recycling confirmation of $^6$Li in Li$_2$TiO$_3$ solution)
2) Characterization of Li$_2$TiO$_3$ pebbles.

<table>
<thead>
<tr>
<th>Fabrication of Tritium Breeder Pebbles</th>
<th>JAERI</th>
<th>ENEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication of Li$_2$TiO$_3$ pebbles by direct wet process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Fabrication of Li$_2$TiO$_3$ pebbles (kg scale fabrication)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Study on recycling confirmation of $^6$Li in the solution</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characterization of Tritium Breeder Pebbles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication and delivery of Li$_2$TiO$_3$ or oxide-doped Li$_2$TiO$_3$ pebbles (or disks)</td>
</tr>
<tr>
<td>- Selection of oxide for doping</td>
</tr>
<tr>
<td>Tritium release property of Li$_2$TiO$_3$ or oxide-doped Li$_2$TiO$_3$ pebbles (or disks)</td>
</tr>
<tr>
<td>- Post-irradiation tritium release by TPD tests</td>
</tr>
<tr>
<td>Solid-gas chemical interaction of Li$_2$TiO$_3$ or oxide-doped Li$_2$TiO$_3$ pebbles (or disks)</td>
</tr>
<tr>
<td>- H$_2$ consumed by the reaction of the specimen with Ar+H$_2$ purge</td>
</tr>
<tr>
<td>Kinetics on reduction and tritium release of Li$_2$TiO$_3$ or oxide-doped Li$_2$TiO$_3$ by calculation code developed in ENEA</td>
</tr>
</tbody>
</table>
Wet chemical fabrication route of \( \text{Li}_2\text{TiO}_3 \) pebbles

- In ENEA-Casaccia a density varying from 60\% (code FN-1) to 92\% of TD (code FN-5) were obtained.
- Grain size was 20 ± 10 µm
- FN-5 meets the HCPB specifications and was tested in EXOTIC-8.9 experiment
TRITIUM RELEASE from Li$_2$TiO$_3$ pebble bed (FN-5). Effect of the average temperature

- EXOTIC-8.9 irradiation in HFR-Petten (440 FPD). Cycle 00-02.
- $R, I = \int (G-R) \, dt$ and $\tau = I/G$, are evaluated by step-changing the temperature, purge gas He+0.1%H$_2$
- Arrhenius type $\tau$ activation heat=111 kJ/mol

- $T_{min} = 410^\circ C$ for $\tau = 1$ day
- Note the increase of $\tau$ in pure He

\[ \tau \sim 520^\circ C \quad \text{in pure He} \]

\[ \text{He+0.1%H}_2 \quad \text{1 day} \]
TRITIUM RELEASE from Li$_2$TiO$_3$. Effect of the H$_2$ in the He purge gas

- EXOTIC-8.9, Cycle 00-07.
- R, hence $\tau$ changing with H$_2$ concentrations in He at 471°C.
- Plot of $\tau$ vs. H$_2$ concentration
FZK - BOT blanket concept evolved in European HCPB Blanket for DEMO and ITER-BM

Equatorial He coolant flow
Important role of the design

$^{6}\text{Li}$ increase gives higher heat deposited in layers

Layer thickness is limited by $T_{\text{max}}$

Enrichment of individual layers adjusted to keep heating and upper temperature within limits

High nuclear heating at front implies thin Be and SB layers
NGK Beryllium Pebbles Realize Power Generation in Fusion Reactor

Advantage of NGK Beryllium Pebbles as Neutron Multiplier
- Small swelling under neutron irradiation
- Good sphericity and smooth surface
- Easy recycling
- Good productivity

(Rotating Electrode Method)

NGK Beryllium Pebbles leads total recycling system

NGK Beryllium Pebbles (BP-1: Standard grade) have been selected as International Standard Material for Neutron Multiplier
- Reference Material for EU HCPB
- Reference Material for JA Solid Blanket

NGK INSULATORS, LTD.
http://www.ngk.co.jp/english/
Out-of-pile testing of small-scale and medium-scale HCPB blanket mock-ups are carried-out at:

1) FZK Karlsruhe – HEBLO facility
2) ENEA Brasimone – HE-FUS3 facility

OBJECTIVE:
thermal-mechanical behaviour of the pebble beds. The mock-ups represent portions of blanket segment with adequate adjustment of temperatures, temperature gradients, coolant temperature and flow distribution. Steady state as well as cyclic power and accidental situations are investigated. Internal heat sources are simulated by flat electrical heaters.
HELICHETTA experiment (ENEA-Brasimone) simulated HCPB thermal cycling of Li$_4$SiO$_4$ pebble-beds (top temperature 600-650°C). Powders were released from the cells during the pebble discharging (7%). SEM examination of the pebbles confirmed the pebble necking and superficial fragmentation.
Tritium Breeding Modules (TBM) tests in High Flux Fission Reactors

- TBM with $^6$Li-tailored ceramics are being irradiated in representative environment (neutron flux, dose, BU and dpa)
- In EU (in HFR-Petten): and
- In JAERI (in JMRT-Oarai)
HICU (High neutron fluence Irradiation of pebble stacks for fusion)

- Effect of neutron irradiation on the thermal-mechanical pebble bed at DEMO representative levels of temperatures and defined thermal-mechanical loads
- Li-isotope compositon in Li₂TiO₃ and Li₄SiO₄ pebbles and neutron spectrum tailored to have in the High Flux Reactor HFR-Petten a
- Fast neutron rate allowing DEMO relevant target dose of 20 dpa, dpa/BU ratio as well as 10-15% BU
Current He-Cooled Ceramic Breeder Blanket Module

Module design
- Dimension up to 4m x 2m x 0.8m
- Box design with an array of stiffening grids (~20 cm spacing) to withstand coolant pressurization

CB (Li₂TiO₃ or Li₄SiO₄) and Be in form of pebble beds, FS as structural material

Cool. T<sub>in</sub>/T<sub>out</sub> = 300/500°C
Cool. P = 8 MPa
Max FS Temp. < 550°C
Max. Be Temp. < 750°C
Max CB Temp. < 920°C
Energy Multip. = 1.25
TBR = 1.14
Cycle Eff. ~ 37% (Rankine)
Lifetime = 15MW-a/m²


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Li-ceramic breeder R&D started 20 years ago, when by the “TRIO” experiment resulted that

*fusion fuel can be bred and recovered safely*


Data-bases of lab-scale fabricated pellets have been achieved by tens of materials-irradiations matrix tests for Li$_2$O, LiAlO$_2$, Li$_2$ZrO$_3$, Li$_4$SiO$_4$, Li$_2$SiO$_3$ performed by U.S., Canada, Japan and EU co-operation (BEATRIX programs) finished in 1995, accompanied by the EBR-II and FFTF fast breeder reactors final shut-down.

Now pre-industrial-scale batch-production of ceramic pebbles is “optimized” and R&D for industrial continuous production may start.

- Li$_4$SiO$_4$ (FZK-Schott)
- Li$_2$TiO$_3$ (CEA-CTI, JAERI-NGK)
- Be and berillides (NGK)

The pebble beds of these materials are being tested in mock-ups or modules in thermal fission reactors (HFR-Petten and JMRT) by Li-isotope and neutron spectrum tailoring allowing relevant simulation of DEMO fusion reactors and supply of data for the ITER BM designs.