Overview of the Lead-Lithium Ceramic Breeder (LLCB) Test Blanket Module (TBM) activities in India

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Lead-Lithium cooled Ceramic Breeder (LLCB)

- U-shaped First wall
- Box structure
- Top Plate
- Support
- He Purge Outlet
- He Purge Inlet
- Shear Keys
- He Inlet
- He Outlet
- Pb-Li Inlet
- Pb-Li Outlet
- Bottom Plate
- Outer Back Plate
- Poloidal 1660
- Toroidal 480
- Radial 536
**LLCB Parameters:**
- Ceramic Breeder: Lithium Titanate
- Coolant, Multiplier: Pb-Li
- FW coolant: Helium, 80 bar, 300-525°C
- Pb-Li Mass flow: 42 Kg/s
- Velocity (ref): 0.2 m/sec
LLCB TBM Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural material</td>
<td>IN-RAFMS</td>
</tr>
<tr>
<td>Breeder</td>
<td>Pb-17Li, Li$_2$TiO$_3$</td>
</tr>
<tr>
<td>Neutron reflector / shield</td>
<td>SS 316 LN IG</td>
</tr>
<tr>
<td>MHD insulation</td>
<td>Al$_2$O$_3$ or Other choice</td>
</tr>
<tr>
<td>Primary coolant</td>
<td>Helium and Pb-Li</td>
</tr>
<tr>
<td>He inlet/outlet</td>
<td>350 / 480 °C</td>
</tr>
<tr>
<td>Helium pressure</td>
<td>8 MPa</td>
</tr>
<tr>
<td>He pressure drop in module</td>
<td>0.3 MPa</td>
</tr>
<tr>
<td>Pb-Li inlet/outlet</td>
<td>350/480 °C</td>
</tr>
<tr>
<td>Li-6 enrichment</td>
<td>90 %</td>
</tr>
</tbody>
</table>

Helium as Purge gas for Tritium extraction

1.66 m (h) x 0.484 m (w) x 0.54 m (t)
Developmental Activities

- Engineering Design
- Neutronic Design
- MHD Analysis & design
- Engineering Safety Analysis
- Tritium Extraction and Management
- Materials and related Technologies
- Quality Assurance
- Instrumentation, Control Systems and Diagnostics
- Remote Handling
The R&D Issues

• Materials
• Processes
• Other Requirements
• Installation and Integration with ITER
• Testing & Commissioning
• Operation & Maintenance
Materials

- **Structural : the RAFMS Steel**
  - Its making, working, heat treatments and metallurgical characterization
  - Its fabrication into components like the first wall of the TBM, the top and bottom plates, the back plate, the internal modules
  - Assembly of these into a TBM box as per design requirements and quality criterion set by ITER
### Reduced Activation Ferritic-Martensitic steels

**Modified 9Cr-1Mo steel**

- Replaced (Mo ➔ W, Nb ➔ Ta)
- Reduced (P, S)
- Restricted (Al, Si, O, B, Ni, Co)

**RAFM steels (wt.%)**

<table>
<thead>
<tr>
<th>Steel</th>
<th>Composition</th>
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</thead>
<tbody>
<tr>
<td>F82H</td>
<td>7.65Cr, 2 W, 0.02Ta, 0.09C, 0.2 V</td>
</tr>
<tr>
<td>Eurofer 97</td>
<td>8.9Cr, 1.1 W, 0.14Ta, 0.11C, 0.14 V</td>
</tr>
<tr>
<td>JLF-1</td>
<td>8.9Cr, 2 W, 0.098Ta, 0.098C, 0.20 V</td>
</tr>
<tr>
<td>ORNL</td>
<td>9Cr, 2 W, 0.07Ta, 0.10C, 0.2 V</td>
</tr>
<tr>
<td>CLAM</td>
<td>9Cr, 1.4W, 0.14Ta, 0.10C, 0.2 V</td>
</tr>
<tr>
<td>Rusfer-EK 181</td>
<td>12Cr, 1.3 W, 0.15Ta, 0.16C, 0.4 V</td>
</tr>
</tbody>
</table>
Development of Indian RAFM Steel - Selection of composition range

- Cr: 8.8 to 9.2
- W: 0.9 to 2.1
- Ta: 0.06 to 0.14
- S: < 0.002
- P: < 0.002
- Si: < 0.05
# Chemical composition of melted steels

<table>
<thead>
<tr>
<th></th>
<th>Targeted (Eurofer 97)</th>
<th>Heat #1 (G3445)</th>
<th>Heat #2 (G3463)</th>
<th>Heat #3 (G3535)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr (8.80-9.20)</td>
<td>9.07</td>
<td>9.04</td>
<td>8.98</td>
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<tr>
<td>C (0.08-0.12)</td>
<td>0.093</td>
<td>0.08</td>
<td>0.09</td>
<td></td>
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<tr>
<td>Mn (0.40-0.60)</td>
<td>0.56</td>
<td>0.55</td>
<td>0.51</td>
<td></td>
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<tr>
<td>V (0.18-0.24)</td>
<td>0.22</td>
<td>0.22</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>W (0.90-1.10)</td>
<td>1.01</td>
<td>1.00</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Ta (0.06-0.08)</td>
<td>0.06</td>
<td>0.06</td>
<td>0.07</td>
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<tr>
<td>N (0.02-0.04)</td>
<td>0.02</td>
<td>0.0226</td>
<td>0.0266</td>
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<tr>
<td>O (0.01 max)</td>
<td>0.0046</td>
<td>0.0057</td>
<td>0.0019</td>
<td></td>
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<tr>
<td>P (0.02 Max)</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>S (0.02 Max)</td>
<td>0.002</td>
<td>0.002</td>
<td>0.0008</td>
<td></td>
</tr>
<tr>
<td>B (0.01 Max)</td>
<td>0.0005</td>
<td>0.0005</td>
<td>0.0003</td>
<td></td>
</tr>
<tr>
<td>Ti (0.005 Max)</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Nb (0.001)</td>
<td>0.001</td>
<td>0.001</td>
<td>0.0019</td>
<td></td>
</tr>
<tr>
<td>Mo (0.002)</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Ni (0.005)</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Cu (0.002 Max)</td>
<td>&lt; 0.001</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Al (0.005 Max)</td>
<td>0.004</td>
<td>0.004</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Si (0.05 Max)</td>
<td>0.09</td>
<td>0.09</td>
<td>0.069</td>
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<tr>
<td>Co (0.005 Max)</td>
<td>&lt; 0.002</td>
<td>0.004</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>As+Sn+Sb+Zr (0.03 Max)</td>
<td>&lt; 0.03</td>
<td>&lt; 0.03</td>
<td>&lt; 0.005</td>
<td></td>
</tr>
</tbody>
</table>
Melting, thermo-mechanical processing and final heat treatment

- Melting process:
  - Vacuum Induction Melting (VIM)
  - Vacuum Arc Refining (VAR)

- Thermo-mechanical processing
  - Forging: 1140 – 1160 °C
  - Rolling: 1100 – 1120 °C

- Final heat treatment
  - Normalizing: 980 – 1000 °C for 30 minutes
  - Tempering: 760 – 765 °C for 90 minutes
Heat to heat variation as well as plate thickness have no effect on impact energy.
Tensile properties of Indian steel compared with internationally developed RAFM steel (Alloy 1)

1.0% W
0.06% Ta

Indian RAFM steel has YS and UTS comparable to those developed internationally

Tensile ductility of Indian RAFM steel (Alloy 1)

Creep rupture strength of Indian RAFM steel

Indian RAFM steel has creep rupture strength comparable to that of the internationally developed RAFM steels.


Alloy 1
1.0% W
0.06% Ta
Fabrication of First Wall, the Back Plate and Top & Bottom Plates of the TBM

- Fabrication of First Wall
- Fabrication of Other Components Like Back Plates, Solid Breeding Modules, Top and Bottom Plate Assembly
- Integration of the Sub-Components to Fabricate Complete LLCB TBM

All the Process Development Work is being Carried out on Surrogate Material ASTM A387 Grade 91 to Conserve the Actual Material Indian RAFMS (IN-RAFMS)
Important Steps Involved in FW Fabrication

1. Machining of Square Channels & Other Shapes
2. Bending of Plates with Square Channels
3. Fusion Welding for Channel Construction & Assembly of Sub Components
Fabrication of First Wall

1. Fabrication of Linear Square Channels (20x20 mm) by Machining in 28 mm Thick Plate
2. Bending of the Plates with Square Channels
3. Stress Relieving

Plates (Straight as well as with L-Bend) with 500 mm Long Square Channels

Different Views Showing Undulation Free Bend
Square Channel Construction by Welding

1. Fabrication of Rectangular Channels Open to Surface by Machining
2. Insertion of Strips of Suitable Size
3. Fusing Along the Seam to Make Square / Rectangular Channels
4. Laser Beam Welding (as it leads to low distortion)

Before Welding  Top & Isometric View After Welding
Square Channel Construction by Laser Welding

• Weld Bead Profile Showing Full Penetration (5 mm)
• No Defect and Little Distortion
Materials

 ✓ **Functional:** the coatings, the ceramic breeders and the Pb-Li eutectic

 ➢ Development of coatings on the RAFMS to reduce the MHD drag and prevent permeation of tritium

 ➢ Making of ceramic pebbles of lithium titanate or/and lithium ortho-silicate

 ➢ Making of the lead-lithium eutectic alloy
Development of Coatings on the RAFMS to Reduce the MHD Drag and Prevent Permeation of Tritium

Method 1

Hot Dip Aluminising (HDA) followed by Oxidation

Method 2

Pack Cementation Process

Layers being attempted by this route are aluminide as well as SiC on FMS

Method 3

Electrochemical
Pb-Li Alloy Preparation

**COMPOSITION**
- Lead : 83 % (mole) & Lithium : 17 % (mole)

**PREPERATION**
- Pb-Li alloy of desired composition has been prepared in lab-scale

**CHARACTERIZATION**
- Characterization of the prepared alloy has been carried out
- Scale-up of the process
Other R&D Activities

• Development of Pb-Li loops for corrosion and MHD studies, including development of electromagnets

• Development of 550 degrees C /80 bar He-cooling loops, including development of circulators

• Development of sensors and diagnostic tools

• Gadgets and tools for remote assembly and disassembly of the TBS and its integration with ITER
**Velocity**: 6 cm/s  
**Hot leg temp**: 500°C  
**Cold leg temp**: 400°C

*Lead - Lithium Buoyancy loops have been developed with samples of 9 Cr- Mo placed inside for corrosion studies.*
Electromagnetic Pump for forced circulation loop

Indigenously Developed
Pump driven loops for lead-lithium have been installed and run successfully with test section temperatures at 550°C.
Mercury facility for MHD studies under construction

Major Components

- Mercury-TBM
- Electro magnet (~ 2.0 T)
- Variable speed Pump
- Heat exchanger
- Dump tank
- Special Diagnostics
- Control & instrumentation
- Primary water coolant circuit
- Nitrogen gas for loading mercury into the loop
- Safety Enclosure
- Scrubber (Hg filter)
B = 4T

Pb 83%-Li -17% (enriched 90% of Li6)

Ti = 380 0C,
v = 0.1m/s

**Actual TBM**

<table>
<thead>
<tr>
<th></th>
<th>TBM</th>
<th>Mercury-TBM</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>~4T</td>
<td>~1.8 T</td>
</tr>
<tr>
<td>Ha</td>
<td>~18500</td>
<td>~5500</td>
</tr>
<tr>
<td>Re</td>
<td>~ 50,000</td>
<td>~24500</td>
</tr>
<tr>
<td>N</td>
<td>~ 6700</td>
<td>~1200</td>
</tr>
<tr>
<td>Ha/Re</td>
<td>~0.36</td>
<td>~0.22</td>
</tr>
</tbody>
</table>
MHD – Experiments at IPUL, Latvia

- 4 Test-sections with & without electrical insulation
- Liquid Metal: Pb-Li
- Operating temperature: 350°C
- Magnetic field: 4T
- Flow velocity: 0.1 m/s (nominal)

Various test-sections

Schematic of the IPUL MHD Loop
Corrosion Experiments at IPUL, Latvia

- P91 samples (flat and tensile) placed in and without magnetic field
- Liquid Metal: Pb-Li
- Operating temperature: ~550°C
- Magnetic field: 1.8T
- Flow velocity: 0.15 m/s (nominal)

Schematic of the IPUL Corrosion Loop
3D MHD Codes for High Hartmann numbers are under development.

Velocity profile across the side wall for $Ha=25000$ for various wall conductivity cases.
The assembled core of the electromagnet (Photograph at the shop floor)
Electromagnetic pump based on permanent magnets

Features

- Cylindrical rotor with rare earth permanent magnets
- Rotating magnetic field is generated in the cylindrical cavity containing liquid metal
- Axial eddy currents are induced in the conducting liquid metal
- Azimuthal lorentz forces are exerted on the liquid metal conductor
- A mass flow rate of 20 kg/min achieved in the prototype
Development of Li$_2$TiO$_3$ Pebbles

PROCESS DEVELOPMENT FOR THE SYNTHESIS AND FABRICATION OF PEBBLES TO MEET THE SPECIFICATIONS FOR TBM AND CHARACTERIZATION

Process for Li$_2$TiO$_3$ Synthesis & Pebble Fabrication

1. SOL-GEL PROCESS
2. SOLUTION COMBUSTION PROCESS
3. SOLID STATE REACTION, EXTRUSION & SPHERODIZATION
Sol-gel process has been standardized for preparation of Li$_2$TiO$_3$ pebbles having specified characteristics.

- **LiCl/LiNO$_3$ + TiOCl$_2$**
- **HMTA, Urea solution**
- **0 to - 5°C**

Flow sheet of sol-gel process (Internal Gelation Process)
Photomicrograph of Li$_2$TiO$_3$ after sintering at 1250°C, 4 hours, by SOL-GEL Process:

Photomicrograph of Li$_2$TiO$_3$ after sintering at 900°C, 6 hours, by Solid-State reaction Process:
CHARACTERIZATION

X-ray diffraction patterns of the final reaction product obtained. Synthesized and fabricated by a Solid State reaction process.

SEM analysis of Li$_2$TiO$_3$ pebbles (by the process route, 'mixing and milling, classification, sample preparation and calcination, milling and re-calcination, pebble fabrication, and sintering' (sintering temperature: 900°C, time: 6 hours).

SEM photograph of fractured Li$_2$TiO$_3$ pebble synthesized and fabricated by sol-gel process and sintered to 1250°C, for 4 hours.

Backscattered electron image of Li$_2$TiO$_3$ microspheres produced by a solid-state reaction process.
Li$^6$ Enrichment Plant
Tritium Extraction System

- PbLi Coolant Circulation
- Tritium Transfer to Helium
- He Coolant Gas
- He Coolant Circulation
- He Transfer Gas
- He Purge Gas
- Purge Gas TRS
- Coolant Bleed
- CPS TRS
- Tritium
Tritium Extraction System (TES) for Indian LLCB TBM

Purge gas
He Coolant
Pb-Li
Summary

• LLCB TBM will be developed and installed in ITER for testing from day one.

• Discussion with RF for TBM Partnership to develop and test LLCB TBM in ITER is in progress.

• Bilateral collaborations with other institutes are being implemented.
  • Corrosion and MHD studies at IPUL, Latvia

• Discussions with EU, US are in progress for collaboration
Thank You