Progress and Status of ITER Solid Breeder Test Blanket Module in China

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Outline

I. Background
II. Progress and Status
III. R&D Plans
IV. Summary
I. Background

- Development and test different ideas of ITER-TBM, it should be one of the aims of the ITER Project.

- China plans to develop own TBM concept for testing during ITER operation period based on China’s DEMO definition and development strategy.

- The preliminary design and performance analysis of HC-SB TBM have been carried out. The final DDDs have been finished, moreover, related R&D plans are proposed.
Two options of breeding blanket with ceramic and lead lithium-lead breeders might be chosen as China’s DEMO blanket concepts.
Selected HCSB-DEMO Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion power/electric power, (MW)</td>
<td>2000 / ~ 600MWe</td>
</tr>
<tr>
<td>Major radius, (m)</td>
<td>7.0 m</td>
</tr>
<tr>
<td>Minor radius, (m)</td>
<td>2.0-2.5 m</td>
</tr>
<tr>
<td>Neutron wall load, (MW/m²)</td>
<td>~ 2.0</td>
</tr>
<tr>
<td>Surface heating, (MW/m²)</td>
<td>~0.3-0.5</td>
</tr>
<tr>
<td>Tritium breeding ratio, (TBR)</td>
<td>&gt;1.1</td>
</tr>
<tr>
<td>Availability, (%)</td>
<td>50-70</td>
</tr>
<tr>
<td>Divertor peak load, (MW.a/m²)</td>
<td>8.0 (water-cooled)</td>
</tr>
<tr>
<td>Plasma operation mode</td>
<td>Continuous</td>
</tr>
</tbody>
</table>
Basic Options on China TBM

- Solid Breeder Blanket might be a basic option and first candidate in China. The lithium-lead breeding blanket is also recommendable concept.

- We are also interested in other TBM concepts, such as, water-cooled solid breeder concept, etc.

- China is proposing two TBM concepts (HCSB, DFLL) to be tested in one port, with a unified design of auxiliary systems.
II. Design Progress of CH HC-SB ITER-TBM
Originally Design of CH HC-SB TBM

2004 Version, ¼ Port, Integration design

- Be pebble bed
- Top plate
- Purge gas inlet
- Cooling plane
- Fix point
- He coolant inlet/outlet
- Purge gas outlet
- Side plane
- Coolant manifold
- First Wall
1-beryllium armor, 2-multiplier zone, 3-sidewall, 4-U-shaped shell, 5-cooling pipes, 6-breeder zone, 7-backplane, 8-He coolant (hot leg), 9-measure access, 10-attachment, 11-purged, 12-He coolant (cold leg)

Outline view for CH originally HCSB-TBM design
Modified Design of HC-SB TBM
(2005 Version, 3x3 Modularization Design)

Configuration: BOT
Be armor: 2 mm
Max Temp. 514°C
First wall thickness: 30 mm
Material: LAFM
Max T: 506°C
Cooling tube: 18x14.5mm
Unit cells: 3x3 sub-modules
He pressure: 8 MPa
Modification Design of HCSB-TBM
2006, ½ Port, 3x6 Modularization Design
Connection of Components, gap

Gap structure

Cross-section of Sub-module
Assembly of HC-SB TBM in port frame
Schematic views of Coolant flow

Fig. 2.3-1 Flow scheme of the test module

Coolant Flow Direction

Coolant flow in the sub-module
HCSB TBM integrated assembly
(Common share the ancillary system)
HC-SB TBM Auxiliary Sub-system Design

Helium Cooling System (HCS)

Draft layout of the helium cooling subsystem in the TCWS

Flow scheme of the HCS system

HCS

Tritium Measurement System (NMS)

The schematic of the gas flow calorimeter

Flow chart of the TMS

Layout of the TMS

TMS

Tritium Extraction Subsystem (TES)

Flow chart of the TES sub-system

Layout of the TES sub-system

Space Requirement:
The TES system must be installed in a glove box.
The size of the Glove Box is: 5.5m x 1.2m x 5.5m (L x W x H).

TES

Coolant Purification System (CPS)

Flow chart of the CPS

Layout of the CPS

CPS

Neutron Measurement System (NMS)

Schematic diagram of neutron fluxes and spectra measurement system

NMS

Space Arrangement in TCWS for HCS subsystem

TCWS
Neutronics Measurement System (NMS)

Schematic diagram of neutron diagnostic system

Micro-fission chamber assembly
Tritium Measurement System (TMS)

Flow chart of the TMS

The schematic of the gas flow calorimeter
## Design parameters for the HC-SB TBM

<table>
<thead>
<tr>
<th>Items</th>
<th>NT-TBM</th>
<th>EM-TBM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>BOT (Breeder Out of Tube)</td>
<td>Modules: 3×6 Sub-modules</td>
</tr>
<tr>
<td>First wall area</td>
<td>0.4844 m(W)×1.7600 m(H)</td>
<td>0.803 m².</td>
</tr>
<tr>
<td>Neutron wall loading</td>
<td></td>
<td>0.78 MW/m²</td>
</tr>
<tr>
<td>Surface heat flux</td>
<td></td>
<td>0.3 MW/m² (normal condition)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5 MW/m² (extreme condition)</td>
</tr>
<tr>
<td>Total heat deposition</td>
<td>surface heat flux included</td>
<td>0.76 MW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.177 MW</td>
</tr>
<tr>
<td>Globe TBR</td>
<td>Lithium orthosilicate, $\text{Li}_4\text{SiO}_4$</td>
<td>0.63 (3-D), 80% Li-6</td>
</tr>
<tr>
<td>Tritium production rate</td>
<td>ITER operation condition</td>
<td>$1.70 \times 10^{-2}$ g/d</td>
</tr>
<tr>
<td>Sub-module dimension</td>
<td>(P)×(T)×(R)</td>
<td>253 mm×130mm×420 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>253 mm×130mm×420 mm</td>
</tr>
<tr>
<td>Ceramic breeder (Li₄SiO₄)</td>
<td>One size</td>
<td>Diameter: 1 mm, pebble bed</td>
</tr>
<tr>
<td></td>
<td>Thickness</td>
<td>90 mm (four zones)</td>
</tr>
<tr>
<td></td>
<td>Max. Temperature</td>
<td>742</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SiC pebble bed, 01 mm</td>
</tr>
<tr>
<td>Neutron multiplier (Beryllium)</td>
<td>Two size</td>
<td>Diameter: 0.5–1 mm, Pebble bed</td>
</tr>
<tr>
<td></td>
<td>Thickness</td>
<td>200 mm(five zones)</td>
</tr>
<tr>
<td></td>
<td>Max. Temperature</td>
<td>613</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al pebble bed, 0.5–1 mm</td>
</tr>
<tr>
<td>Be armor</td>
<td>Thickness</td>
<td>2mm</td>
</tr>
<tr>
<td></td>
<td>Max. Temperature</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>514</td>
</tr>
<tr>
<td>Structure Material</td>
<td>Ferritic steel</td>
<td>LAFM</td>
</tr>
<tr>
<td></td>
<td>Max. Temperature</td>
<td>537</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LAFM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>506</td>
</tr>
<tr>
<td>Coolant helium (He)</td>
<td>Pressure</td>
<td>8 MPa</td>
</tr>
<tr>
<td></td>
<td>Pressure drop</td>
<td>0.22 MPa</td>
</tr>
<tr>
<td></td>
<td>Temperature range (inlet/outlet)</td>
<td>300/500</td>
</tr>
<tr>
<td></td>
<td>Mass flow</td>
<td>0.99 kg/s</td>
</tr>
<tr>
<td></td>
<td>Diameter (OD/ID)</td>
<td>85/80 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.051 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300/411</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.62 kg/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>85/80 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>He purge flow (He)</td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>0.12 MPa</td>
</tr>
<tr>
<td></td>
<td>Pressure drop</td>
<td>0.02 MPa</td>
</tr>
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III. Performance Analysis
for HCSB ITER-TBM
3-D MCNP Model for Neutronics Calculation

ITER side view

TBM ITER side view

planform view

20° planform view
Performance Analysis for HC-SB TBM

Temperature distribution of FW

Temperature distribution of sub-module

Temperature on Flow Channel

Stress distribution of FW

Stress distribution of sub-module

The stress distribution
At shutdown, the total decay heat is $9.77 \times 10^2$ MW with a contribution of $8.71 \times 10^2$ MW and $6.36 \times 10^2$ MW from structure material and Li$_4$SiO$_4$, respectively. A total activity of $5.43 \times 10^5$ Ci is attained at shutdown with a contribution of $5.39 \times 10^5$ Ci from the structure, $3.7 \times 10^3$ Ci from the Li$_4$SiO$_4$.

At shutdown, the total decay heat is $8.77 \times 10^{-3}$ MW with a contribution of $8.71 \times 10^{-3}$ MW and $6.36 \times 10^{-5}$ MW from structure material and Li$_4$SiO$_4$, respectively.

LOCA analysis shows depressurization of the TBM helium coolant occurs within 10 to 15 s. Contribution to the pressure build-up in the VV is small ($17.8 \times 10^2$ kPa). Tritium and activation products released from the TBM into the VV are insignificant compared to the total amount mobilized from non-TBM components. The TBM FW temperature can be kept, after the disruption burst has decayed variant to the reference case, with postulated unlimited steam access to the pebble beds, the estimated hydrogen production is the order of g only and the chemical heat is negligible.

Plasma disruption: in-vessel TBM coolant leaks

This figure shows temperature changes of materials after the end of blow-down. When heat radiation emissivity of material is 0.7, the peaking value of FW is about 623 °C at the transient time of about 1s.

This figure shows temperature changes of materials after the end of blow-down. When heat radiation emissivity of material is 0.3, the peaking value of FW is about 623 °C, too, at the transient time of about 1s. But curves have different change trends after 1000s.
Safety analysis /RELAP5 Application

Piping hydrodynamic model
Piping between HCS components

5. Results of in-box LOCA for EM HCSB TBM

- Pump velocity of in-box LOCA
- Mass flow rate of in-box LOCA

4. Results of Steady State EM HCSB TBM

- Temperature of Steady State
- Pressure of Steady State
MCNP-FDKR
3-D Activation Calculation Code
VI. R&D Plans on HCSB-TBM
Relevant R&D plans

System Integration, Out-pile R&D
- Module fabrication technology
- Thermo-mechanical integrity of module
- Thermo-mechanical performance
- Thermal hydraulic research

In-pile R&D
- Breeder/multiplier development
- Irradiation technology development
- Irradiation tests of blanket partial mockup

Tritium Recovery System Development
- Process and system development for hydrogen pump,
- Coolant purification system

Material Development
- Irradiation data of structure materials (CLAF), etc.
- Environmental effect, etc.

Neutronics / Tritium Production Tests with 14MeV neutrons
- Neutronics performance of blanket mockup and improvement of analysis accuracy
Development Strategy for the structural materials

- Two sorts of structural materials will be focused on:
  - **RAFM for ITER-TBM and DEMO-TBM**
    (1) Data base to support the design,
    (2) Goal: support the fabrication in future
  - **Low activation V-based alloys**
    (1) For advanced fusion reactor blanket concept
    (2) Basic study on mechanism

- **Budget** (Total is about 4 M$)
  - A small part is from the Nuclear Energy Project.
  - Others will be supported by the MOST, as one of the projects in ITER program.

- **Collaborations**
  - SWIP and ASIPP will be the leading institutes in China
  - CIAE, IMR, NPIC and Universities will join.
  - International, join IFMIF.
R&D of China RAFM CLF-series

(1) Chemical Composition, wt%

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>Cu</th>
<th>W</th>
<th>O</th>
<th>N</th>
<th>Ta</th>
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</thead>
<tbody>
<tr>
<td>CLF-1</td>
<td>0.037</td>
<td>0.10</td>
<td>0.0006</td>
<td>0.0041</td>
<td>8.32</td>
<td>0.023</td>
<td>0.009</td>
<td>0.16</td>
<td>0.02</td>
<td>&lt;0.02</td>
<td>-</td>
<td>0.0016</td>
<td>0.002</td>
<td>-</td>
</tr>
<tr>
<td>(F82)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLF-2</td>
<td>0.025</td>
<td>0.28</td>
<td>0.0006</td>
<td>0.0040</td>
<td>8.69</td>
<td>-</td>
<td>-</td>
<td>0.18</td>
<td>-</td>
<td>&lt;0.02</td>
<td>1.11</td>
<td>0.005</td>
<td></td>
<td></td>
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<tr>
<td>(Eurofer97)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<td>0.002</td>
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</tbody>
</table>

(2) Mechanical property

<table>
<thead>
<tr>
<th>Type</th>
<th>Tensile strength $\sigma_b$ (MPa)</th>
<th>Yield strength $\sigma_{0.2}$ (MPa)</th>
<th>Tensile ductility $\delta$ (%)</th>
<th>Impact ductility, $A_k$ (J/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLF-1 (~15%CW)</td>
<td>495.0</td>
<td>365.0</td>
<td>33.2</td>
<td>&gt;300</td>
</tr>
<tr>
<td>CLF-2 (~15%CW)</td>
<td>528.3</td>
<td>435.0</td>
<td>25.8</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>
Development of Neutron Multiplier (Be)

Main Chemical Composition of CH 2# and US S-65C**

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Be</th>
<th>BeO</th>
<th>Fe</th>
<th>C</th>
<th>Al</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 2# (CH)</td>
<td>99</td>
<td>0.80</td>
<td>0.05</td>
<td>-</td>
<td>0.075</td>
<td>0.015</td>
</tr>
<tr>
<td>S-65C VHP (US)</td>
<td>99</td>
<td>1.0</td>
<td>0.08</td>
<td>0.1</td>
<td>0.060</td>
<td>0.060</td>
</tr>
</tbody>
</table>

- China has also large yielding capacity of Be and relevant experiences of neutron multiplier.
- China has built Be fabrication and manufactory in Ningxia Orient Non-ferrous Metal Group Co.
- A new project, to develop high quality Be in China, is being implemented for ITER project.
Solid Breeder Technology

China has studied tritium-processing technology supported by national fusion program for many years. Knowledge accumulated in this field is useful for the TBM tritium technology.

Two kinds of ceramic breeder (Li$_4$SiO$_4$, Li$_2$TiO$_3$), are developing in China.
Fabrication and Experiment of Ceramic Pebbles

- **Diameter**: 1~5mm
- **Relative density**: 60~80% T.D.
- **Crushing load**: 30~70N

- **γ-LiAlO$_2$**
- **Li$_4$SiO$_4$**
- **Li$_2$ZrO$_3$**

*Contributed from CAEP*
Irradiation Test on High Flux Reactors

China has built a High Flux Engineering Test Reactor (HFETR) in the China Institute of Nuclear Power (CINP). HFETR is a largest one in Asia.

- Neutron Flux:
  - Thermal neutrons: $6.2 \times 10^{14}$ n/cm²•sec; (E<0.625eV)
  - Fast neutrons: $1.7 \times 10^{15}$ n/cm²•sec; (E>0.625eV)

- Total power:
  125 MW (th)

In addition, there are two sets experiment reactors with power of 20MW and 40MW are constructing in CIAE and CAEP of China.

- These facilities and their ability are useful for the irradiation experiment of the TBM structure materials, tritium breeders, neutron multiplier etc.
Optical pyrometer (300-3000)

Main parameters:
- Pressure: 1-2×10⁻³ Pa (e-gun chamber), 2-4×10⁻³ Pa (main chamber).
- Power: max. 3kW (60kV, 50mA).
- E-beam: Gaussian distribution, max. spot: ~φ20mm (ellipse).
HIP Technology development

CuCrZr/316L-HIP weld module

- The technology is based on drilling holes and HIPing.
- Tensile strength is more than 260MPa.

Supersonic wave detector

1. NDT method for flat interface of Cu-SS
2. NDT method for the interface of Cu-SS tube
A High Temperature He Experiment Loop (HTHEL) with 700 °C and 8-10 MPa, which is useful for HC-SB TBM design and R&D activities, is proposed to be built in SWIP.

He Test Loop for HTGR
Temp.: 900 °C, Total Power: 10MW, Pressure: 3 MPa
### Proposed test facilities prior to TBMs installation in ITER

<table>
<thead>
<tr>
<th>Facilities name</th>
<th>Main objectives</th>
<th>Parameters</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>A high temperature He Experiment Loop based on China HTGR technologies.</td>
<td>TBM mock-ups test</td>
<td>500-700 °C and 8-10 MPa (adjustable)</td>
<td>SWIP/ Under construction</td>
</tr>
<tr>
<td>A facility for high heat flux properties test</td>
<td>Evaluation of plasma facing materials and components</td>
<td>Max. power density: 20 MW/m², Active cooling, control of the temperature of coolant from RT-150</td>
<td>SWIP/ Under construction</td>
</tr>
<tr>
<td>High Flux Engineering Test Reactor (HFETR)</td>
<td>Materials Test</td>
<td>Thermal neutrons : $6.2 \times 10^{14}$ n/cm²·sec; (E&lt;0.625eV)</td>
<td>CINP/ (existing)</td>
</tr>
<tr>
<td>Facilities of tritium extraction, purification, permeation, and test</td>
<td>Tritium extraction and recovery experiment from the purge gas and coolant.</td>
<td>TBD</td>
<td>CAEP, CIAE &amp; SWIP (planning)</td>
</tr>
</tbody>
</table>
Expected Collaboration on R&D

- **Tritium technologies**
  - Tritium extraction & purification
  - Tritium control and ISS
  - Tritium loop qualification
  - Tritium permeation barriers

- **Ceramic breeder technologies**
  - Fabrication;
  - Performance test;
  - Simulation and modeling;
  - Irradiation test.

- **Thermo-mechanics and helium flow test**
  Test of on the pebble bed thermo-mechanics and helium flow stability and distribution by means of a high temperature, high pressure He test loop.
IV. Summary

- Solid Breeder Blanket should be the basic option and first candidate in China. *The progress and status of CH HC-SB TBM since 2004 are introduced briefly.*

- *Under the cooperation with domestic institutes, a update design description document (DDD) have been completed. The preliminary safety analysis reports will be submitted by the end of this year.*

- *Preliminary R&D program as well as the collaboration expected with other Parties are presented.*

- *Some key technologies are to be implemented, such as high temperature He experimental loop, Low-activation material (CLF), high qualified beryllium, HIP welding technology, optimized lithium ceramic breeder, etc.*

- *Relevant R&D on the key techniques are being preformed intensively and systematically with the cooperation of domestic and international institutions and companies.*
Thank you for your attention!
21th IAEA FEC Conference will be hold in Chengdu International Conference Center, Oct.16-20, 2006