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LiPb TBM Program in China
(Progress in R&D Activities)

Presented by Yican WU

Contributed by FDS Team
Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
University of Science and Technology of China (USTC)
Outline

I. Development of LiPb Blanket Concepts

1. Reactor Concepts
   — FDS-I: Fusion-driven sub-critical system, for early application of fusion
   — FDS-II: Fusion power reactor, for advanced electricity generation
   — FDS-III: High temperature fusion reactor, for hydrogen production etc.
   — FDS-ST: Spherical tokamak-based reactor, to exploit innovative conceptual path

2. Blanket Concepts
   — DWT: Dual-coolant (He/LiPb) Waste Transmutation Blanket (temp.<450°C)
   — SLL: Single-coolant (He) Lithium-Lead Breeder Blanket (temp.~450°C)
   — DLL: Dual-coolant (He/LiPb) Lithium-Lead Breeder Blanket (temp.~700°C)
   — HTL: High Temperature Liquid Blanket (temp. ~1000°C)

II. Test Blanket Module Design & Development Strategy

   — Material R&D + Out-Of-Pile Mockup Test
   — TBM Test in EAST
   — TBM Test in ITER

III. R&D Activities

1. Hardware
   — RAFM steel (CLAM-CLChina Low Activation Martensitic)
   — LiPb loops (corrosion, MHD, dual-cooled)
   — Functional Materials (Al₂O₃ coating, SiCf/SiC FCI)
   — High Intensified Neutron Generator (HINEG)

2. Software
   — Codes & Data libraries
   — Integrated platform for design and simulation
I. Development of Concepts

1. Reactor Concepts
   - FDS-I : Fusion-driven sub-critical system, for early application of fusion
   - FDS-II : Fusion power reactor, for advanced electricity generation
   - FDS-III : High temperature fusion reactor, for hydrogen production
   - FDS-ST : Spherical tokamak-based reactor, to exploit innovative conceptual path

2. Blanket Concepts
   - DWT : Dual-coolant (He/LiPb) Waste Transmutation Blanket (temp. <450°C)
   - SLL : Single-coolant (He) Lithium Lead Breeder Blanket (temp. ~450°C)
   - DLL : Dual-coolant(He/LiPb) Lithium-Lead Breeder Blanket (temp. ~700°C)
   - HTL : High Temperature Liquid Blanket (temp. ~1000°C)
FDS Series Fusion Reactors & Blankets
Conceptual Design for DEMO

- **FDS-I**: Fusion-Driven Subcritical System
  for early applications of fusion (multi-function)
  e.g. waste transmutation, fuel breeding etc.

- **FDS-II**: Fusion Power Reactor
  for highly efficient electricity generation

- **FDS-III**: High Temperature Fusion Reactor
  for advanced applications, e.g. hydrogen production

- **FDS-ST**: Spherical Tokamak-based Reactor
  for exploiting and assessing innovative conceptual path

**In progress:**
- based on available or very limitedly extrapolated fusion and fission technologies

  - **FDS-EM**: A Fusion-Fission Hybrid reactor
    for energy production
  - **FDS-FB**: A Fusion-Fission Hybrid reactor
    for fuel breeding
  - **FDS-WT**: A Fusion-Fission Hybrid reactor
    for waste transmutation
  - **FDS-SFB**: A Fusion-Fission Hybrid reactor
    for spent fuel burner

**FDS-MF**: Multi-Functional Fusion-Fission Hybrid Concept

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Potential Advantages of lithium lead blankets

FDS focuses on the Liquid LiPb blanket concept.

- Good feasibility and relatively simple design;
- High heat removal;
- Adequate tritium breeding ratio;
- Good potential for getting higher outlet temperature;
- Fitting for fusion-fission hybrid system.
DWT Subcritical Blankets for FDS-I/ST

Blanket: He/LiPb Dual-cooled Waste Transmutation (DWT) blankets

Blanket design --- high energy multiplication

Emphasis on circulating particle or pebble bed fuel configurations considering geometry complexity of tokamak, frequency of fuel discharge and reload

Concept options:

DWT-CPL: the He&LiPb DWT blanket with Carbide heavy nuclide Particle fuel in circulating Liquid LiPb coolant.
DWT-OPG: Oxide heavy nuclide pebble bed fuel in circulating helium-Gas
DWT-NPG: Nitride heavy nuclide Particle fuel in circulating He-Gas.

DWT-CPL: The AC appears in the form of the TRISO(TRi-ISOtropic)-like carbide particles coated with SiC suspending in the LiPb slurry. The circulating fuel form has the advantages of good compatibility with complex geometry, easy control of fuel cycle and fast response to emergency fuel removal etc.

DLL/SLL Blankets for FDS-II

SLL: He-cooled Quasi-Static Lithium Lead Blanket
- Single Coolant: He-gas (R-T + P-directions)
- T-Breeder: Quasi-Static LiPb: (slowly flowing in P-direction, outlet temp.~450°C)
- Coating: to protect the steel structure and to reduce T-permeation and MHD effects.

DLL: He/LiPb Dual-cooled Lithium Lead Blanket
- Coolant 1: He-gas (R-T + P-directions)
- Coolant 2 & T-Breeder: LiPb (quickly flowing in P-direction, outlet temp.~700 °C)
- Thermal and electric insulators: to avoid RAFM working at high temp. 700 °C

The basic blanket structure using RAFM steel e.g. the CLAM steel.
DLL blanket as the main candidate blanket scheme: using Flow channel insert (FCI).
SLL blanket without FCI as backup scheme: relatively mature material technology, use quasi-static LiPb flow instead of fast moving LiPb in DLL.
HTL High Temp. Lithium Lead for FDS-III

— Materials:
• RAFM or ODS steel as structural material
• SiCf/SiC composite or other refractory materials as FCIs

— Blanket scheme:
Multilayer FCIs in LiPb channel:
• Increasing LiPb temp. above 900 °C
• Reducing interface temp. RAFM steel /LiPb below 500°C
• Limited temp. gradient across FCIs

— Hydrogen production technology:
Thermochemical I-S cycles

Great Challenges of CCP:
- Compact inboard space
- Serious radiation effects
- Large Joule losses

Requirements:
- Protect CCP against radiation
- Prolong lifetime of CCP
- Reduce Joule losses
- Must be replaceable, reliable, and maintainable

Four new concepts of CCP:
- Liquid Li/LiPb as conductor and coolant
- Solid Li/LiPb as conductor, water as coolant
- Cu as conductor, Li/LiPb as coolant
- Cu as conductor, water as coolant

### Features of China LiPb Blankets

The working conditions and performance requirements for blanket materials

<table>
<thead>
<tr>
<th>Function</th>
<th>Material candidates, working conditions &amp; performance requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structure</strong></td>
<td>RAFM ($T_{max}$~550°C, anti-irradiation, anti-corrosion)</td>
</tr>
<tr>
<td><strong>Tritium breeder</strong></td>
<td>lithium lead eutectic</td>
</tr>
<tr>
<td><strong>Coating</strong></td>
<td>Al-based coating or others ($T_{max}$~500°C, anti-irradiation, anti-corrosion, low $\sigma_e$)</td>
</tr>
<tr>
<td><strong>Coolant</strong></td>
<td>He &amp; LiPb (LiPb 450°C)</td>
</tr>
<tr>
<td></td>
<td>He (450°C)</td>
</tr>
<tr>
<td></td>
<td>He &amp; LiPb (LiPb 700°C)</td>
</tr>
<tr>
<td></td>
<td>He &amp; LiPb (LiPb 900~1000°C)</td>
</tr>
<tr>
<td><strong>FCI</strong></td>
<td>No/yes</td>
</tr>
<tr>
<td></td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>SiC_f/SiC or others ($T_{max}$~700°C, low $\sigma_{th}$ and low $\sigma_e$)</td>
</tr>
<tr>
<td></td>
<td>SiC_f/SiC or others ($T_{max}$~1000°C, low $\sigma_{th}$ and low $\sigma_e$)</td>
</tr>
<tr>
<td><strong>Fission fuel</strong></td>
<td>HLW/U/Pu</td>
</tr>
<tr>
<td></td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>No</td>
</tr>
</tbody>
</table>

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Common Features of Blanket Concepts

(DWT, DLL, SLL, HTL)

- **Structural Material:** RAFM (e.g. CLAM)/+ODS
- **Insulation/Anti-erosion/Anti-permeation coating:** Coating (Al-based) / insert (e.g. SiC)
- **Tritium Breeder/Neutron Multiplier:** LiPb
- **Coolant:** He or He/LiPb

To define TBM for Testing in ITER:
**Dual Function Lithium Lead liquid breeder TBM**

**DFLL:** SLL/DLL

Y. Wu, Nuclear Fusion 47(2007)1533-1539
Y. Wu, Fusion Engineering and Design 82 (2007) 1893-1903
II. TBM Design & Development Strategy

- Design and Performance/Safety Analysis
- Material R&D + Out-Of-Pile Mockup Test
- TBM Test in EAST
- TBM Test in ITER
Objectives and Features of DFLL-TBM

Objectives: To demonstrate the technologies of both SLL and DLL lithium lead DEMO blankets, and also to validate design and analysis tools.

Flexible design:
- Similar structure and auxiliary systems.

SLL mode at the earlier stage
- LiPb: 1mm/s, 450°C,
- Without FCI in LiPb channels

DLL mode at the later stage
- LiPb: ~10mm/s, ~700°C,
- With FCI in LiPb channels
DFLL-TBM consists of four ‘act alike’ modules with similar structures, including EM-TBM, NT-TBM, TT-TBM and IN-TBM, which will allow to consecutively realize the objectives of DFLL-TBM during the first 10 years of ITER operation.

The He/LiPb auxiliary systems:

- Flexibility in adjusting coolants mass flow rates
- Achieving dual-functions.
Conceptual design of DFLL-TBM system has been finished.

Design for DFLL-TBS

To operate in SLL/DLL mode using basic similar structure.

SLL mode:
- LiPb: ~1mm/s up to 450°C, without FCI

DLL mode:
- LiPb ~10mm/s up to 700 °C, with FCI
Performance/Safety Analysis on DFLL-TBM

(1) Estimation of worker dose for replacement of DFLL-TBM

<table>
<thead>
<tr>
<th>Major activity</th>
<th>Description</th>
<th>Work effort (hr)</th>
<th>Dose rate (Sv/h)</th>
<th>Dose (Sv)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clear Post Cell</td>
<td>200.25</td>
<td>5</td>
<td>1101.25</td>
<td>Post cell</td>
</tr>
<tr>
<td>2</td>
<td>Remove R/BShield Block</td>
<td>45.1</td>
<td>5</td>
<td>215.3</td>
<td>Outside shield</td>
</tr>
<tr>
<td>3</td>
<td>Clear Post Interpipe</td>
<td>100.5</td>
<td>50</td>
<td>525</td>
<td>Post Interpipe</td>
</tr>
<tr>
<td>4</td>
<td>DFLL Removal/Replacement</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Post Interpipe</td>
</tr>
<tr>
<td>5</td>
<td>Reinstall R/BShield Block</td>
<td>100.5</td>
<td>50</td>
<td>502.5</td>
<td>Remote handling</td>
</tr>
<tr>
<td>6</td>
<td>Reinstall Interpipe sections</td>
<td>45.25</td>
<td>5</td>
<td>226.25</td>
<td>Post Interpipe</td>
</tr>
<tr>
<td>7</td>
<td>Reinstall post-EL pipings</td>
<td>200.25</td>
<td>5</td>
<td>1101.25</td>
<td>Post Interpipe</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>832.05</td>
<td></td>
</tr>
</tbody>
</table>

Note:
(1) During estimation of work effort, the operation activities include disconnecting and rehaling of the frame cooling pipe.

Accident Analysis
Occupational Radiation Exposure
FMEA
Activity

Preliminary safety analysis of DFLL-TBM has been finished in DDD
Main Interfaces Design

- AEU/TBM
- HCS piping layout in TCWS
- Main interfaces in Port Cells
- PIE equipment layout in Hot Cell
## Design Parameters of DFLL-TBM

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heat Flux Neutron Wall Load</strong></td>
<td>Ave.0.3MW/m², Max. 0.5 MW/m² 0.78 MW/m²</td>
</tr>
<tr>
<td><strong>Structural material</strong></td>
<td>China Low Activation Martensitic steel (RAFM Steel)</td>
</tr>
</tbody>
</table>
| **TBM dimensions**                             | Pol. 1660 mm × Tor. 484 mm × Rad. 585 mm  
Gap between TBM and Frame = 20 mm |
| **Total deposited power**                      | 0.66 MW                                         |
| **He coolant**                                 | T<sub>in/out</sub> = 340/402 °C; P<sub>in</sub> = 8 MPa; Q<sub>tot</sub> = 1.49 kg/s |
| **First Wall**                                 | U-shape; Toroidal He cooling; 4 paths; Thickness: 30 mm (5/15/10) 
Cooling channels: (15 x 20) mm², pitch 25 mm  
T<sub>in/out</sub> = 340 / 395 °C; V<sub>He</sub> = 50 m/s |
| **r-p Stiffening plate**                       | Thickness: 10 mm (3/4/3); Cooling channels: (4 x 9) mm², pitch 12 mm  
V<sub>He</sub> = 60 m/s; T<sub>in/out</sub> = 395/402 °C |
| **t-p Stiffening plate**                       | Thickness: 10 mm (3/4/3); Cooling channel: (4 x 8) mm², pitch 11 mm  
V<sub>He</sub> = 64 m/s; T<sub>in/out</sub> = 395/412 °C |
| **Cover**                                       | Thickness: 32 mm; 8 parallel cooling channels; (8 x 16) mm², pitch 13 mm  
V<sub>He</sub> = 60 m/s; T<sub>in/out</sub> = 395/400 °C |
| **He collector**                               | 3-stage collector; radial direction size: 20/20/10/20/10/20/20 mm |
| **Breeder/multiplier LiPb**                    | 2 rows poloidal flowing channel  
V<sub>LiPb</sub> = 14/5.5/5.5 mm/s  
V<sub>LiPb</sub> = 4.33 kg/s; T<sub>in/out</sub> = 480/700 °C |
Roadmap of Liquid TBMs to ITER

Stage I: Out-of-pile Test (1/3 size)
- R&D on materials (RAFM, Coating and FCI) and fabrication technology
- Diagnostic and measurement
- Out-of-pile test of 1/3 mockup etc.
- MHD

Stage II: Test in EAST (1/2 size)
- 1/2 mockup test in EAST
- EM and thermo-mechanics, partially neutronics performances
- Influence on plasma
- MHD

Stage III: Test in ITER (full size)
- To confirm results of EM/Thermo-mechanics test in EAST,
- To test neutronics, tritium and integration performances in ITER
Stage I: Out-Of-Pile Small Mockup Test

Objectives:
- Validation of the fabrication route and techniques
- Validation of performances
- Assessment of reliability and safety with regard to ITER standards.

Test Items:
- Leak and pressure test.
- MHD and heat removal from FW.
- Mock-up connected to LiPb loop
- Hydrogen control and extraction to simulate tritium extraction
- Irradiation performance
Stage II: Test in EAST

(1/2 Size-reduced TBM)

Objectives:
- Preliminary validation of design codes and data
- Checking of feasibility & availability of auxiliary system
- FM Influence on Plasma

EAST-TBM Test in EAST:
- ElectroMagnetic performance (MHD pressure drop, influence on plasma)
- Thermo-mechanics/Thermofluid dynamics performances
- Partially neutronics performance (DD neutrons), Diagnostic instruments

<table>
<thead>
<tr>
<th>Device</th>
<th>EAST</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>DD</td>
<td>HH</td>
</tr>
<tr>
<td>R (m)</td>
<td>1.95</td>
<td>6.2</td>
</tr>
<tr>
<td>A (m)</td>
<td>0.46</td>
<td>2</td>
</tr>
<tr>
<td>Bt (T)</td>
<td>3.5-4.0</td>
<td>5.3</td>
</tr>
<tr>
<td>Neutron rate (n/s)</td>
<td>10^{15}~10^{17}</td>
<td>1.77x10^{20}</td>
</tr>
<tr>
<td>Avg.HF(MW/m^2)</td>
<td>0.1~0.2</td>
<td>0.11</td>
</tr>
<tr>
<td>Port Size</td>
<td>0.97m x 0.53m</td>
<td>2.2 m x 1.7m</td>
</tr>
<tr>
<td>Pulse (sec)</td>
<td>~1000</td>
<td>100-200</td>
</tr>
</tbody>
</table>
Design of EAST-TBM

- Structure and cooling scheme similar to ITER-TBM, Size: 280 (r) × 308 (t) × 960 (p) mm³
- Thermo-mechanics and neutronics performance analyses have been done.
- Installation by means of cantilever
## Main Design Parameter of EAST-TBM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat flux</td>
<td>Ave. 0.15 MW/m², Max. 0.2</td>
</tr>
<tr>
<td>Structural material</td>
<td>RAFM steel, e.g. CLAM steel</td>
</tr>
<tr>
<td>Size</td>
<td>Pol. 960 mm × Tor. 308 mm × Rad. 280 mm</td>
</tr>
<tr>
<td>Heat power</td>
<td>0.05 MW</td>
</tr>
<tr>
<td>Helium coolant</td>
<td>He: Tin/out = 340/377 °C; Pin = 8 MPa;</td>
</tr>
<tr>
<td>FW</td>
<td>U-shape; Toroidal He cooling; 4 paths; Thickness: 30 mm (5/15/10)</td>
</tr>
<tr>
<td></td>
<td>Cooling channels: (15 x 20) mm², pitch 25 mm</td>
</tr>
<tr>
<td></td>
<td><em>tpSP</em>; rpSP Thickness: 10 mm (3/4/3); Cooling channels: (4 x 8) mm², pitch 11 mm</td>
</tr>
<tr>
<td>Cover</td>
<td>Thickness: 32 mm; 4 parallel cooling channels; (8 x 16) mm², pitch 17.5mm</td>
</tr>
<tr>
<td>He collector</td>
<td>3-stage collector; radial direction size: 20/20/10/20/10/20/20 mm</td>
</tr>
<tr>
<td>LiPb</td>
<td>2 rows poloidal flowing channel, $V_{LiPb}=3$ mm/s; $T_{in/out}=377 /377$ °C</td>
</tr>
</tbody>
</table>

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Y. Wu et al, the 24th SOFT, Warsaw, Poland (2006)
## Stage III: Test in ITER

**Full size TBMs**

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>DD</td>
<td>DD</td>
<td></td>
<td>EAST : DD</td>
<td>HH</td>
<td>HH</td>
<td>DD</td>
<td>DD</td>
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<td>DT</td>
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<td></td>
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<td>ITER Commissioning</td>
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</tr>
</tbody>
</table>

**EAST-TBM (DLL-function)**

- **In EAST:**
  - D-plasma(1000sec, 10^{15-17}n/s)
  - Thermo-mechanics/Thermofluid dynamics performances
  - FCI & MHD Test
  - Partially neutronics
  - Diagnostic instruments

**EM-TBM (SLL-function):**

- ElectroMagnetics-Test:
  - To confirm results of EM/Thermo-mechanics test in EAST
  - Auxiliary system

**NT-TBM (SLL-Function):**

- Neutronics Test:
  - Neutronics performance
  - N-fluence&gamma spectra
  - Nuclear heat T-breeding Code &Data

**TT-TBM (DLL-Function):**

- ThermoDynamics&Tritium Behavior Test:
  - Tritium recovery
  - FCI performance
  - Thermofluid MHD Code &Data

**Integrated Test:**

- On-line tritium extraction
- Synergic nuclear effects
- MHD integrated effects
- Reliability and Safety

**TBM installation**

- Qualification test

**Mat.R&D Out-of-pile**

- EAST-TBM
  - FM-Influence on plasma
  - Thermo-mechanics/Thermofluid dynamics performances
  - EM & MHD Test
  - Corrosion and Coating Test
  - Auxiliary system

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**ITER Commissioning**

- IN-TBM
  - TBM installation Qualification test

**ITR Commissioning**

- DD

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ASIPP • USTC

### ITER Stage III: Test in ITER (Full size TBMs)
III. Status of R&D
(hardware and software)

- Blanket Material and Technology R&D
- Design & Analysis Tools R&D
R&D Experiments
( Hardware)

1. China Low Activation Martensitic Steel (CLAM) and TBM Fabrication

2. Liquid LiPb Loops (DRAGON-I, II, III, IV, ST, RT)

3. Functional Materials and components:
   Anti-corrosion/tritium barrier/electrical insulation;
   SiC$_f$/SiC composite (FCI/Loop)

4. High Intensified Neutron Generator (HINEG)

Key Technologies for Blankets
Ton Level Melting of CLAM Steel

- **Main compositions**

<table>
<thead>
<tr>
<th>Elements</th>
<th>Fe</th>
<th>C</th>
<th>Mn</th>
<th>Cr</th>
<th>W</th>
<th>V</th>
<th>Ta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content (wt%)</td>
<td>Bal.</td>
<td>0.10</td>
<td>0.45</td>
<td>9.0</td>
<td>1.5</td>
<td>0.20</td>
<td>0.15</td>
</tr>
</tbody>
</table>

- **1.2 ton ingot smelting**

- **Microstructures**

- **Mechanical properties**

<table>
<thead>
<tr>
<th>Room temperature</th>
<th>Rp0.2</th>
<th>Rm</th>
<th>A/%</th>
<th>Z/%</th>
<th>Akv(J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>533.65</td>
<td>658.11</td>
<td>20.40</td>
<td>70.99</td>
<td></td>
<td>240, 225, 248</td>
</tr>
<tr>
<td>533.96</td>
<td>660.33</td>
<td>24.20</td>
<td>76.38</td>
<td></td>
<td></td>
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<tr>
<td>541.51</td>
<td>663.72</td>
<td>21.20</td>
<td>72.97</td>
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<td></td>
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</table>

<table>
<thead>
<tr>
<th>High temperature</th>
<th>Rp0.2</th>
<th>Rm</th>
<th>A/%</th>
<th>Z/%</th>
<th>Akv(J)</th>
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<tbody>
<tr>
<td>306.68</td>
<td>349.29</td>
<td>20.00</td>
<td>78.97</td>
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<td>319.42</td>
<td>362.10</td>
<td>20.80</td>
<td>86.34</td>
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<tr>
<td>312.28</td>
<td>350.97</td>
<td>24.00</td>
<td>85.23</td>
<td></td>
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</tr>
</tbody>
</table>

Composition and mechanical properties agree with the requirements of design
Following the design & test strategy of DFLL-TBM, exploration for the fabrication and manufacture technique of TBM are being performed.

- **Exploration for fabrication of the FW and CP by HIP welding**
  - Fabrication of the special pipe → HIP welding → CLAM

- **Exploration for assembly of the key components by EB Welding**
  - CP-FW → CP-CP → CLAM

**Small mockups**
- 1/5 TBM of 316SS
- 1/3 TBM of P91
Irradiation Test of CLAM steel

High Flux Engineering Test Reactor (HFETR) in China

Neutron Irradiation tests (~1 dpa, ~300°C) are underway.

Irradiation Temp.: 250°C. DPA: 0.02

Tesile properties

Charpy impact properties

Spallation Neutron Source, SINQ, in PSI, Switzerland

Spallation irradiation tests (10~20 dpa, 100~500°C) was finished.

PIE is underway.

Ion and electron irradiation tests were also done to investigate irradiation effects.
# Development of DRAGON Series LiPb Loops

<table>
<thead>
<tr>
<th>Loop name</th>
<th>Type</th>
<th>Function</th>
<th>Temperature</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAGON-I</td>
<td>TC*</td>
<td>Material Compatibility</td>
<td>420-480°C</td>
<td>2001-2005</td>
</tr>
<tr>
<td>DRAGON-II</td>
<td>TC</td>
<td>Compatibility</td>
<td>550-700°C</td>
<td>2004-2006</td>
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<tr>
<td>DRAGON-III</td>
<td>TC</td>
<td>Compatibility</td>
<td>800-1000°C</td>
<td>2007-2009</td>
</tr>
<tr>
<td>DRAGON-SI</td>
<td>Static</td>
<td>Compatibility</td>
<td>250-1000°C</td>
<td>2008-2009</td>
</tr>
<tr>
<td>DRAGON-RII</td>
<td>Flowing</td>
<td>Compatibility</td>
<td>450-600°C</td>
<td>2009</td>
</tr>
<tr>
<td>DRAGON-IV</td>
<td>FC</td>
<td>Material Compatibility, Thermal-hydraulics, MHD, Purification of LiPb, etc.</td>
<td>480-800°C</td>
<td>2007-2009</td>
</tr>
<tr>
<td>DRAGON-V</td>
<td>FC</td>
<td>Dual-coolant test for TBM, MHD test for the complex ducts</td>
<td>300-700°C</td>
<td>2010-2012</td>
</tr>
<tr>
<td>DRAGON-VI</td>
<td>FC</td>
<td>Auxiliary system for EAST-TBM</td>
<td>-</td>
<td>2012-2015</td>
</tr>
<tr>
<td>DRAGON-VII</td>
<td>FC</td>
<td>Auxiliary system for ITER-TBM</td>
<td>-</td>
<td>2015-2018</td>
</tr>
<tr>
<td>DRAGON-VIII</td>
<td>FC</td>
<td>Auxiliary system for DEMO blanket</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
DRAGON-IV: Forced Convection LiPb Loop

Experiments:
- High temperature corrosion (800°C)
- Stress corrosion (480°C, 4KN)
- MHD (350°C; 2T; 1m/s)
- Test Blanket Mockup (1/5-size-reduced)
- LiPb eutectic purification

Components:
- Figure-of-eight type loop with a central heat exchanger, a hot leg and a cold leg;
- Hot leg contains Corrosion test section, MHD test section, Mini-blanket, etc;
- The cold leg contains the pump, flow meter and cold trap.

Size: 7 × 5 × 4 m³
Liquid PbBi eutectic was the target and coolant for ADS.

PbBi loops are the necessary devices to investigate the key technologies of materials technology and thermal-hydraulics challenges, etc.

The KYLIN series of PbBi loops are being designed and constructed in ASIPP, CAS. KYLIN-I (the first PbBi loop in China) and the rotating corrosion test device (KYLIN-RT) have been completed for thousands of hours corrosion test for CLAM steel and 316L, etc.

Some Liquid Metal Technologies may be shared
Design and Construction of LiPb Purging Bubbler

CAEP contributed
Development of Functional Coatings

Functions:
- Tritium permeation barrier;
- Electrical insulator to reduce MHD pressure drop;
- Corrosion barriers against liquid LiPb.

Progress:
- High quality aluminide coatings of uniform thickness and composition are produced by a pack cementation vapor processes.
- >1um Al₂O₃ coating were obtained by in-situ oxidation on the aluminide coating.

SEM photo of coating

Line-scan of electron spectrum

CIAE contributed
Fabrication of SiC_f/SiC Composites

**Requirements:**
- Low / high thermal conductivity
- Low electrical conductivity
- Good compatibility with LiPb under elevated temp.
- Stable under neutron irradiation

**Key issues:**
- Fabrication of SiC_f/SiC pipe
- Fabrication of FCI
- Bonding technology of SiC_f/SiC composites

**SiC_f/SiC composites**
- SiC fiber
- SiC fiber felt
- SiC fiber cloths
- Continuous SiC fiber reinforced ceramic matrix composites
  - Strength of Continues SiC fiber reach 2.8-3.0GPa

**Loop Technology**
- Fiber 3D braid preform
- SiC fiber braid tube
- Connection of metal and SiC composite

SiC_f/SiC composites were fabricated by CVI + PIP + CVD.

CVI---Chemical Vapor Infiltration
PIP---Polymer Infiltration and Pyrolysis
CVD---Chemical Vapor Infiltration

Φ 80mm × 800mm
Design and Construction of High Intensified Neutron Generator

HINEG: D-T neutron rate: $10^{10}$~$10^{13}$ n/sec

(1) Fusion neutronics Integrated Testing of Materials and Components, e.g. Blankets

(2) Validation of Codes and Data libraries

Intensity meter
Bonner spectrum meter
Neutron dose detector
Portable neutron detector
Design and Analysis Tools Development (Software)

1. Physics and Engineering Calculation PEC
   • Multi-functional neutronics calculation & analysis system: VisualBUS
   • Multi-physics (neutronics/thermalhydraulics/MHD) coupling simulation codes: NTC/MTC
   • System (safety/economy) analysis codes: TAS, RiskA, SYSCODE
   • Liquid TBM accident analysis code based on RELAP5

2. Computer Modeling and Simulation CMS
   • Automatic Modeling Codes: MCAM/SNAM/RCAM/HUMOP
   • Visualization/Virtual Roaming/Virtual Assembling Codes: SVIP/RVIS/FVAS

3. Database Management System DMS
   • Plasma/Nuclear/Material/Component data libraries: FusionDB

4. Integrated Design & Simulation Platform 4DS
   • Virtual Fusion Reactor (application of 4DS)

Key Tools for Reactor Design and Analysis

> 50~100 man-years each program
Main Functions

I. 4D: Automatic Modeling
   • Monte Carlo (MC) geometries
   • Discrete Ordinates (SN) geometries
   • MC-SN coupled geometries
   • Human dosimetry models reconstructed

II. 4D: Coupled Calculation
    • Particle Transport
    • Fuel Isotope Burnup
    • Material Activation & Irradiation Damage
    • Radiation Dose
    • Fuel cycle management

III. 4D: Visualized Analysis
     • Static / dynamic physical data fields
     • Virtual roaming and dosimetry assessment
     • Virtual assembly of component models

- Multi-functions in One System
- Convenient Operation
- Easy-Upgrading / Integration
MTC/NTC: Multi-Physics Coupling Programs

• MTC (Magnetic - Thermohydraulics Coupled Simulation Program)
  - MTC-F 1.0/2.0: Developed base on the B-formulation
    - MHD effects: FLUENT +User-routine
    - Exact solution on the condition: Ha<500
  - MTC-H 1.0: Developed base on the $\phi$-formulation
    - Good accuracy for low magnetic Reynolds numbers
    - Consistent and conservative scheme
    - Exact solution for high Ha~10000

• NTC (Neutronics - Thermohydraulics Coupled Simulation Program)
  - Safety analysis
    - Design basic accidents analysis
    - Severe accident analysis
  - Advanced reactor design
    - Advanced fission reactor design
    - Advanced fusion reactor design
TAS: Tritium Analysis Program for Fusion System

- Analysis on T fuel circulation system
  - T self-sufficiency analysis
  - T system safety analysis
  - T fuel management

- Analysis on T flow in liquid breeder blanket system
  - T partial pressure
  - T distributing
  - T extraction and permeation
Risk and Economy Analysis Programs

**RiskA: Probabilistic Safety Assessment Program**
- FMEA (Failure Mode and Effects Analysis)
- FTA (Fault Tree Analysis)
- ETA (Event Tree Analysis)
- Importance Analysis
- Uncertainty and Sensitivity analysis
- Optimization of reliability parameters

**RiskAngel: Risk Monitor for Nuclear Power Plants (Qinshan nuclear power plant)**
- Instantaneous risk calculation
- Component OOS / restore
- Schedules optimization
- Evaluation of AOT/ACT

**SYSCODE: System Analysis Program for Parameter Optimization and Economical Assessment of Fusion Reactor**
- Physical engineering design
- Economic evaluation
- Design optimization
- Sensitivity & Uncertainty analysis

Liquid TBM accident Analysis codes based on RELAP5

To develop accident safety analysis code for dual-coolant liquid TBM

- Complex TBM structure model
- Dual coolant (Helium gas/ Liquid LiPb)
- New thermophysical properties for LiPb
- New heat transfer characteristics of LiPb
Automatic Modeling Programs

MCAM: Monte Carlo Automatic Modeling Program

- Passed ITER QA verification & validation
- Selected as “ITER reference code”
- Created the 3D “ITER reference neutronics model”
- Applications: > 100 users; > 60 international institutes/companies

SNAM: SN Automatic Modeling Program (CAD↔SN)

RCAM: MC-SN Coupled Automatic Modeling Program (CAD↔MC-SN)

HUMOP: Human Automatic Modeling Program
Visualization & Virtual Simulation Programs

**SVIP: Scientific Visualization Program**
- 4D visualized data analysis for VisualBUS / MCNP / TORT...
- Various visualization functions (Iso-surface, volume rendering, ...)
- Visualized data analysis coupled with geometries

**RVIS: Radiation Virtual Simulation System**
- Flexible & realistic virtual roaming
- 4D visualization of dynamic spatial radiation field
- Real-time & accurate evaluation of human & organ dose
- Good compatibility & excellent expansibility

**FVAS: Fusion Virtual Assembly System**
- Automatic/semi-automatic/manual virtual manipulation interfaces
- Real-time simulation & accurate collision detection
- Flexible virtual roaming based on multi-viewpoints
- Supporting record & replay of assembly processes
FusionDB: Database Management System for Fusion (China Fusion Data Library)

- **Fusion data management**
  
  (Plasma, nuclear, material, component……)

- **Data processing software**
  
  (visualization, model auto-conversion……)

**Data sources:**

- EAST data
- ITER data
- FDS data
- …

- **1. Plasma data**
  
  ~$10^9$°C

- **2. Nuclear data**
  
  $10^2$°C

- **3. Material data**
  
  ~$-200$°C (80k)

- **4. Component data**
  
  $-269$°C (4k)
4DS: a 4-Dimensional System for Integrated Design and Simulation of Advanced Reactors

- 4D accurate calculation based on multi-physics coupling concept
- Auto-modeling & visualized analysis
- Integration of design & operational simulation
- Auto coupling of multi-processes
- Virtual roaming & assembly
- Easy to integrate new-developed codes, due to hierarchical design
- Serve to Design & Simulation of advanced reactors
Virtual Fusion Reactor

Parametric Design; Auto-Modeling / Coupled Calculation / Visualized Analysis; Virtual Assembly & Dose Evaluation ➔ Application of 4DS

Neutronics Analysis

System Analysis/Virtual Simulation

Thermo & Safety Analysis
Summary

- **Designs** of four concepts of fusion power reactors, four concepts of blankets with LiPb tritium breeder, three kinds of TBMs (Out-of-pile mockup, EAST-TBM and ITER-TBM) and the related evaluation of safety, economy and environmental impact are being performed in parallel. The designs are still evolving.

- **Development strategy and time schedule** of TBMs including related material R&D have been developed.

- **R&D on RAFM steel, LiPb loops, Coating/FCIs, D-T Neutron Source** are ongoing.

- **R&D on design & analysis tools** are being performed by making full use of advanced computer technologies including CG, IC and Network technologies etc..

The End

Thanks for your attention!

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