KO Programme on Liquid Metal Breeder Blankets

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Outline

1. Overview on fusion technology development in KO
   - Roadmap of nuclear fusion technology development
   - KO position on ITER TBM program

2. KO Activities for developing the liquid metal breeder blanket
   - Codes development and validation
   - Fabrication technology
   - Cooling technology
   - Liquid breeder technology
   - Tritium extraction technology

3. Gen-IV reactor development in KO
   - Overview of the GEN-IV reactor development in KO
   - SFR development plan and R&Ds
   - VHTR development plan and R&Ds

4. Conclusions
1. Overview on fusion tech. development in KO

- Development path to fusion plant in KO

- Integrated Technology for Fusion Plant
  - TOKAMAK Technology
  - BOP Technology

- Portfolio investment into KSTAR, ITER, Fusion Nuclear Technology in KO
- Utilization of the existing nuclear plant technology in KO
1. Overview on fusion tech. development in KO

- **Fusion energy development roadmap**

<table>
<thead>
<tr>
<th>Fusion Energy Development Enhancement Plan</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>2007</td>
<td>2008</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>2011</td>
<td>2012</td>
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<td></td>
<td>2013</td>
<td>2014</td>
<td>2015</td>
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<tr>
<td></td>
<td>2016</td>
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<td>2033</td>
</tr>
<tr>
<td></td>
<td>2034</td>
<td>2035</td>
<td>2036</td>
</tr>
</tbody>
</table>

- **Devices**
  - DEMO: Conceptual Design -> Engineering Design -> Ready for Construction
  - ITER: Construction -> Operation Phase 1
  - KSTAR Operation: Phase 1 -> Phase 2 -> Phase 3 -> Phase 4

- **Fusion Nuclear Technology**
  - Breeding Blanket Buildup: Design, Fabrication, Core Technology
  - TBM: Test Test-1, TBM Test-2 (Partnership), TBM Test-3 (Own Concept)
  - Breeding Blanket Concept: Design, Fabrication, Core Technology

- **Fuel Cycle**
  - Tritium Fuel Cycle System Concept and Design
  - DEMO Breeding Blanket Design, Fabrication Technology Verification

- **Material**
  - Material Evaluation
  - Commercial Reactor Material Development

- **Power Conversion**
  - Power Conversion System Design
  - DEMO Thermal Energy Removal and Power Conversion System Design and Fabrication
KO position on ITER TBM program

Leadership (Partnership) [from TBM-PC-03]
- KO is interested in the exploring partnerships with TBM concept leaders rather than being a TBM concept leader.
- KO will participate in both ceramic breeder and PbLi based blanket concepts.
- Even though we will not take any leadership of KO TBM concept for Day-One, we would like to have possibility of testing our TBM concept in the later phase.

KO status for developing the TBMs
- NFRI (National Fusion Research Institute)
  has developed ceramic breeder blanket and operated KSTAR.
- KAERI (Korea Atomic Energy Research Institute)
  has developed PbLi(or Li) based breeder blanket and Gen.-IV reactors.
1. Codes development and validation

(1) Design and safety analysis

- Based on the nuclear technologies (e.g. GEN-IV) of Very High Temperature Reactor System (VHTR) and Sodium-Cooled Fast Reactor System (SFR), KO is developing an integrated design tool for fusion reactor.

### System Codes Development

- **For Coolant (He)**
  - MARS-GCR
  - GAMMA

- **For Breeder (Li, PbLi)**
  - MARS-LMR
  - MARS-FR

- **For Tritium**
  - TRITGO
  - MARS-T

- **Integration**
  - MARS-FR
  - GAMMA-FR

### Separate Code Verification

- **For MHD**
  - CFX EM module

- On verifying with exp. Data
1. Codes development and validation

(2) MHD analysis

- CFX EM module has been being verified with the previous works
2. KO Activities for liquid metal breeder blanket

2. Fabrication technology

(1) For joining FMS to FMS
- HIP (hot isostatic pressing) and PHHT (post HIP heat treatment) conditions were developed and verified through the thermal fatigue test (1.0 MW/m² for 1000 cycles, no failure)

- Developed HIP & PHHT conditions
- Fabricated mockup & KoHLT-2
- Tested mockup & measured temperature during the last 30 cycles
2. Fabrication technology

(2) For joining Be to FMS

- HIP (hot isostatic pressing) conditions were developed and one of them was verified through the thermal fatigue test.
- Interlayers (Ti/Cr/Cu and Cr/Cu) and Cu layers in FMS (or SS) were tried for Be joining.
- Mockup with Cr/Cu interlayer and explosive welded Cu layer survived up to 1000 cycles under 0.5 MW/m² heat flux.

### Fabricated mockups & conditions

<table>
<thead>
<tr>
<th>ID</th>
<th>Interlayer</th>
<th>Tile size</th>
<th>Materials</th>
<th>Shear strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>#49</td>
<td>1T1 / 0.5Cr / 5Cu</td>
<td>80 x 80 mm²</td>
<td>Be (SB) / Cu(0.3) / SS</td>
<td>190 MPa</td>
</tr>
<tr>
<td>#56</td>
<td>1T1 / 0.5Cr / 5Cu</td>
<td>50 x 80 mm²</td>
<td>Be (SB) / Cu(0.3) / T91</td>
<td>167 MPa</td>
</tr>
<tr>
<td>#57</td>
<td>1Cr / 5Cu</td>
<td>80 x 80 mm²</td>
<td>Be (SB) / Cu(0.3) / T91</td>
<td>177 MPa</td>
</tr>
</tbody>
</table>

### KoHLT-1

UT & DT results after HHF test

Measured temperature during the last 50 cycles
2. KO Activities for liquid metal breeder blanket

2. Fabrication technology

(3) For joining W to FMS
- HIP (hot isostatic pressing) conditions has been developed
- The interlayers of Ti films were used to reduce the difference in thermal expansion of W and FMS
- The interlayers of Cu films were used to form diffusion bonding between W and Cu

**TEST MATRIX**

<table>
<thead>
<tr>
<th>Interlayer</th>
<th>Shear Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 um Ti film</td>
<td>57 MPa</td>
</tr>
<tr>
<td>5 um Ti coating</td>
<td>96 MPa</td>
</tr>
<tr>
<td>5 um Ti + 10 um Cu film</td>
<td>75 MPa</td>
</tr>
<tr>
<td>2 um Cr + 50 um Cu film</td>
<td>166 MPa</td>
</tr>
<tr>
<td>2 um Cr + 10 um Ti film</td>
<td>Int test</td>
</tr>
<tr>
<td>2um Cr + 50 um Ti film</td>
<td>Int test</td>
</tr>
<tr>
<td>2um Ti + 50 um Ti film</td>
<td>Int test</td>
</tr>
</tbody>
</table>
2. KO Activities for liquid metal breeder blanket

2. Fabrication technology

(3) Heat load test facilities for fabrication technology development

- For thermal fatigue test, KoHLT-1 & 2 (Korea Heat Load Test facilities) were developed
- E-beam facility will be prepared by the end of 2013 (300kW/EH800V)
3. Cooling technology

(1) He supplying system for KoHLT-2 (by Jan. 2011)
- to test TBM FW (10 Channels) up to 0.73 kg/s

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working fluid</td>
<td>He gas</td>
<td></td>
</tr>
<tr>
<td>He temperature [°C]</td>
<td>300~500</td>
<td>&lt; 550 (by FMS)</td>
</tr>
<tr>
<td>He system pressure [MPa]</td>
<td>8.0</td>
<td>Operation P</td>
</tr>
<tr>
<td>Expected pressure drop [MPa]</td>
<td>0.12 + margin</td>
<td>0.012 MPa for SC</td>
</tr>
<tr>
<td>Coolant mass flow rate [kg/s]</td>
<td>0.73</td>
<td>Total: 1.46 kg/sec V at SC = 60 m/sec</td>
</tr>
</tbody>
</table>

objectives
1. He gas supplying to KoHLT-2
2. HX experiment (He/water HX, PCHE)
3. design the HCS for TBM (ITER)
2. KO Activities for liquid metal breeder blanket

3. Cooling technology

(2) TH test for codes validation using High pressure (6 MPa, 900 °C) gas loop (N2, He) at KAERI Loops developed for HTGR project

- CFD code (CFX-11), MARS-GCR, GAMMA code was simulated with the same test condition
2. KO Activities for liquid metal breeder blanket

3. Cooling technology

(3) Heat Exchanger Development
- PCHE (Printed Circuit Heat Exchanger) for He/He and He/Water
- PHE (Printed Heat Exchanger) for He/H2SO4
4. Liquid breeder technology

(1) Li & PbLi Reaction test

- Li melting and reaction with water/air were performed
- reaction control with nano-particle was confirmed
- PbLi melting test was performed before inserting in the ELLI
2. KO Activities for liquid metal breeder blanket

4. Liquid breeder technology

(2) PbLi loop (ELLI, Experimental Loop for Liquid breeder)
- early 2010, ELLI was constructed and operation was started
- objectives: EM pump design verification, MHD test, flow-corrosion test

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breeder</td>
<td>Pb-15.7Li</td>
</tr>
<tr>
<td>Melting point</td>
<td>235 °C</td>
</tr>
<tr>
<td>Temperature</td>
<td>~ 550 °C</td>
</tr>
<tr>
<td>Pressure</td>
<td>0.5 MPa in operation</td>
</tr>
<tr>
<td>Flow rate</td>
<td>Operation 5.5 lpm (10 cm/s) Max. 60 lpm (110 cm/s)</td>
</tr>
<tr>
<td>EM Pump</td>
<td>60 lpm @PbLi (16.8 kW)</td>
</tr>
<tr>
<td>Sump tank</td>
<td>163 liter (50kW)</td>
</tr>
<tr>
<td>Magnet</td>
<td>~ 2.2 T (12 kW) Pole gap: 30 mm</td>
</tr>
</tbody>
</table>
2. KO Activities for liquid metal breeder blanket

4. Liquid breeder technology

(3) Compatibility test

Corrosion test of FMS in static Pb-Li

- Objective: Investigate the corrosion behavior of FMS in Pb-Li
- FMS was corroded preferentially along the grain boundaries as well as martensite lath boundaries
- Oxide coating (Al₂O₃) protected FMS surface from corrosion

Static Corrosion
FMS: Grade 91
Pb-Li: Pb-15.7Li
Test Temp.: 450°C
Test Duration: 3000 h

Corrosion Barrier Coating

- substrate without heating (cf. 1200°C was required)
- annealing at above 950°C resulted in crystallization of Al₂O₃

- preferred corrosion at grain boundaries
- absence of corrosion on Al₂O₃ coated surface
- dissolution of Al₂O₃ (in 3000 h)
- loss of protectiveness
5. *Tritium extraction technology*

(1) Study for gas-liquid contactor and design of the batch type facility

- Installation in 2010 (Batch Type), 2011 (Loop)
- Extraction method of liquid-gas contactor was considered
3. Gen-IV reactor development in KO

1. Overview


(1) Objectives
- **Expansion of Nuclear Energy**: Energy security while addressing climate change issues
- **Improved Transparency**: Peaceful use of nuclear energy
- **Establishment of National Roadmap**: Long-term milestones

(1) Major R&D topics
- **SFR** and **Pyroprocess**: for proliferation resistant spent fuel management
- **VHTR**: for efficient hydrogen production
3. Gen-IV reactor development in KO

1. Overview

THE NATIONAL LONG-TERM DEVELOPMENT PLAN FOR THE FUTURE NUCLEAR ENERGY SYSTEM

DEMO '26-'28
2. SFR development

- **Goal**
  - Construction of demo. SFR by 2028

- **Work Scope**
  - Advanced design concept development
  - Design validation
  - Metal fuel development

- Proliferation resistant core without blankets
- MA bearing metal fuel
- Enhanced safety with passive systems

3. Gen-IV reactor development in KO

- KALIMER-150 Conceptual Design
- KALIMER-600 Conceptual Design
- Advanced SFR Concept
- Sodium T/H Experiment Facility
- Standard Design Approval
- Demonstration SFR

- '92 '97 '02 '07 '11 '15 '20 '28
2. SFR development

- Advanced Concept Design Studies
  - Sustainable and proliferation resistant core
  - Design improvement of fluid and structural system

- Development of Advanced Technologies
  - PDRC experiment
  - S-CO\textsubscript{2} Brayton cycle system
  - Na-CO\textsubscript{2} interaction test
  - Metal fuel technologies
  - Under-sodium viewing technique

- Development of Basic Technologies
  - System analysis code development
  - Sodium technology development

Cross-cutting area with NTFR
2. SFR development

PDRC (Passive Decay-heat Removal Circuit) development

- Key design parameters of the facility

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scaling Ratio (Model/Prototype)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference reactor (Prototype)</td>
<td>KALIMER-600</td>
</tr>
<tr>
<td>Working fluid</td>
<td>Sodium</td>
</tr>
<tr>
<td>Sodium mass</td>
<td>17 ton</td>
</tr>
<tr>
<td>Core power</td>
<td>1.9 MW</td>
</tr>
<tr>
<td>Reactor vessel height</td>
<td>3.7 m</td>
</tr>
<tr>
<td>Reactor vessel diameter</td>
<td>2.3 m</td>
</tr>
<tr>
<td>Temperature distribution</td>
<td>1:1</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>1 bar</td>
</tr>
</tbody>
</table>

- Key design parameters of the facility

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scaling Ratio (Model/Prototype)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length Ratio</td>
<td>1/5</td>
</tr>
<tr>
<td>Area Ratio</td>
<td>1/25</td>
</tr>
<tr>
<td>Volume Ratio</td>
<td>1/125</td>
</tr>
<tr>
<td>Temperature Rise/Drop Ratio</td>
<td>1</td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>1/2.24</td>
</tr>
<tr>
<td>Time Ratio</td>
<td>1/2.24</td>
</tr>
<tr>
<td>Gravity Acceleration Ratio</td>
<td>1</td>
</tr>
<tr>
<td>Core Power Density Ratio</td>
<td>2.24</td>
</tr>
<tr>
<td>Power Ratio</td>
<td>1/55.9</td>
</tr>
<tr>
<td>Flow rate Ratio</td>
<td>1/55.9</td>
</tr>
<tr>
<td>Pressure Drop Ratio</td>
<td>1/5</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>1</td>
</tr>
</tbody>
</table>
3. Gen-IV reactor development in KO

3. VHTR development

VHTR technology and hydrogen production technology

- VHTR Design Tech.
- Material & Component
- TRISO Fuel
- Coupling Tech.

SI Hydrogen Production

- HI Decomposition Bunsen
- Sulfuric Acid Decomposition
3. VHTR development

- Advanced Concept Design Studies
  - Block and pebble type of 950 °C
  - Development of cooled vessel design concept

- Development of Advanced Technologies
  - Materials & component development
  - High temperature experiment

- Development of Basic Technologies
  - Nuclear Design System code development
  - Safety analysis code development
  - GUI development

- Cross-cutting area with NTFR
  - TRISO fuel technologies
  - Graphite Oxidation
  - Material Test (He)
4. Cross-cutting area and collaboration

There are many technology challenges that advanced fission reactors (Gen-IV) and fusion have in common.

Examples of the overlap are:
- Design tools
- Power conversion technologies; Brayton cycle
- High temperature materials design rules
- Materials corrosion: high temperature materials and coolant compatibility
- Materials response under neutron irradiation
- Welding and joining technologies
- First-principles materials modeling
- Tritium/hydrogen behavior in materials

<table>
<thead>
<tr>
<th>Structural alloy maximum temperature</th>
<th>Fission (Gen. I)</th>
<th>Fission (Gen. IV)</th>
<th>Fusion (Demo)</th>
<th>JIMO space react.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural alloy maximum temperature</td>
<td>&lt;300°C</td>
<td>500-1000°C</td>
<td>550-1000°C</td>
<td>~1000°C</td>
</tr>
</tbody>
</table>

| Max dose for core internal structures | ~1 dpa | ~30-100 dpa | ~150 dpa | ~10 dpa |
| Max transmutation helium concentration | ~0.1 appm | ~3-10 appm | ~1500 appm (~10000 appm for SiC) | ~1 appm |
| Coolants | H₂O | He, H₂O, Pb-Bi, Na | He, Pb-Li, Li | Li, Na, or He-Xe |
| Structural Materials | Zirconal, stainless steel | Ferritic steel, SS, superalloys, C- composite | Ferritic/martensitic steel, V alloy, SiC composite | Nb-1Zr, Ta alloy, Mo alloy |
4. Conclusions

- KO has been developed liquid metal breeder blanket for fusion reactor
- We have participated ITER TBM program and related R&Ds have been performed;
  - Codes development and validation,
  - Fabrication technology,
  - Cooling technology,
  - Liquid breeder technology, and
  - Tritium extraction technology.
- Gen-IV technologies have been developed, which can be the cross-cutting area with fusion field.
- We hope to have chances to collaborate with you.
Thanks for your attention.

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