Progress of Materials R&D in TMSR Project

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Outline

- Overview of Thorium Molten Salt Reactor (TMSR) Project
- Materials R&D at SINAP
  - TMSR design and materials overview
  - Challenges and progress on alloy and graphite
  - Database construction
  - Basic science research in progress
- Summary
TMSR Reactor Development Plan

- Thorium Energy
- High Temperature \( \text{H}_2 \) Production
- Water-free Cooling
- Small Modular Design

High Temperature Fission Nuclear Energy

Strategy of TMSR R&D

- Long-term
- Mid-long
- Mid-term

Modified Open Fuel Cycle

Fully Closed Fuel Cycle
TMSR Reactor Development Plan

- Simulator TMSR-SF0
- 10 MW Test Reactor TMSR-SF1
- 2 MW Test Reactor TMSR-LF1 + Th Fuel Cycle Test
- 100 MW Demo Reactor TMSR-SF2
- 10 MW Test Reactor TMSR-LF2 + Th Fuel Cycle Demo

2015 2020 2025
## Materials

<table>
<thead>
<tr>
<th>Component</th>
<th>Candidate Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Vessel</td>
<td>N10003</td>
</tr>
<tr>
<td>Reactor Vessel Support</td>
<td>SA533</td>
</tr>
<tr>
<td>Graphite structure</td>
<td>Nuclear Graphite NG-CT-10</td>
</tr>
<tr>
<td>Core barrel</td>
<td>N10003, 316ss</td>
</tr>
<tr>
<td>Control Rod System</td>
<td>The rod- N 10003; seal cover-SA-508-3; gears-35SiMn/37SiMnV; spring-50CrVA; Gear box-ZG0Cr18Ni9Ti</td>
</tr>
<tr>
<td>Pebble injection Mechanism</td>
<td>N10003, 316ss</td>
</tr>
<tr>
<td>Pebble defuel Mechanism</td>
<td>N10003, 316ss</td>
</tr>
</tbody>
</table>

**Fuel**

- TRISO/ThF4/UF4

**Molten Salt**

- FLiBe /FLiNaK
Materials R&D for TMSR face the challenges from manufacture process as well as the service environments.
Challenges to Alloy

Alloy N (UNS N10003) including Hastelloy N and GH3535 is still considered as the best candidate, while 316 is also under review.

- **Scientific challenges**
  - High temperature strength (>700 ºC)
  - Neutron irradiation resistance (He/Te embrittlement, swelling)
  - Corrosion control

- **Technological challenges**
  - Large scale component fabrication
  - Welding procedure development

- **Challenges relevant to code & standard & data**
  - Most of the codes or standards do not exist to support the TMSR/FHR design
  - Alloy N faces big gaps in performance data for the ASME code case application
Progress in Alloy - Manufacture Capability

Current fabrication capacity of Alloy N components

<table>
<thead>
<tr>
<th>Type of materials</th>
<th>China</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingot</td>
<td>≤ 10 ton</td>
<td>≤ 3 ton</td>
</tr>
<tr>
<td>Plate</td>
<td>width ≤ 2200mm</td>
<td>width ≤ 1800mm</td>
</tr>
<tr>
<td>Rolled Ring</td>
<td>diameter ≤ 790mm</td>
<td>under development</td>
</tr>
<tr>
<td>Bar</td>
<td>diameter ≤ 240mm</td>
<td>diameter ≤ 240mm</td>
</tr>
<tr>
<td>Forging</td>
<td>≤ 1 ton</td>
<td>≤ 1 ton</td>
</tr>
<tr>
<td>Pipe</td>
<td>diameter ≤ 168.3mm</td>
<td>diameter ≤ 88.9mm</td>
</tr>
</tbody>
</table>

- Current fabrication ability of SINAP can fulfill the requirements of TMSR SF-1.
- The fabrication technology has come to a bottleneck, limiting the component scale.
Progress in Alloy – Mechanical Evaluation

<table>
<thead>
<tr>
<th>Property</th>
<th>Requirements in ASME 2015</th>
<th>Data Completeness</th>
<th>Current status</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus</td>
<td>25-700°C, 50°C Interval</td>
<td>Complete</td>
<td>finished</td>
<td>ASME II, Haynes</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>25-700°C, 50°C Interval</td>
<td>Incomplete</td>
<td>1 batch finished</td>
<td>ASME II ID</td>
</tr>
<tr>
<td>Density</td>
<td>25-700°C, 50°C Interval</td>
<td>Complete</td>
<td>finished</td>
<td>SINAP</td>
</tr>
<tr>
<td>Plastic modulus</td>
<td>25-700°C, 50°C Interval</td>
<td>Complete</td>
<td>finished</td>
<td>ASME II ID</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>25-700°C, 50°C Interval</td>
<td>Complete</td>
<td>finished</td>
<td>ASME II ID</td>
</tr>
<tr>
<td>Linear expansion coefficient</td>
<td>25-700°C, 50°C Interval</td>
<td>Incomplete</td>
<td>Lack of data above 400°C, and 400-900°C data</td>
<td>ASME II, Haynes</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>25-700°C, 50°C Interval</td>
<td>Complete</td>
<td>finished</td>
<td>ASME II ID</td>
</tr>
<tr>
<td>Base metal 50</td>
<td>25-700°C, 50°C Interval</td>
<td>Complete</td>
<td>finished</td>
<td>ASME II ID</td>
</tr>
<tr>
<td>Base metal 55</td>
<td>25-700°C, 50°C Interval</td>
<td>Complete</td>
<td>finished</td>
<td>ORNL</td>
</tr>
<tr>
<td>Base metal 30</td>
<td>450-700°C, 50°C Interval/ Up to 300000h</td>
<td>Incomplete</td>
<td>650°C Cup to 300000h ; 700°C Cup to 30000h</td>
<td>SINAP</td>
</tr>
<tr>
<td>Base metal 35</td>
<td>450-700°C, 50°C Interval/ Up to 300000h</td>
<td>Incomplete</td>
<td>650°C Cup to 300000h ; 700°C Cup to 30000h</td>
<td>SINAP</td>
</tr>
<tr>
<td>Weldment Smt</td>
<td>450-700°C, 50°C Interval/ Up to 300000h</td>
<td>Incomplete</td>
<td>650°C Cup to 300000h ; 700°C Cup to 30000h</td>
<td>SINAP</td>
</tr>
<tr>
<td>Weldment St</td>
<td>450-700°C, 50°C Interval/ Up to 300000h</td>
<td>Incomplete</td>
<td>650°C Cup to 300000h ; 700°C Cup to 30000h</td>
<td>SINAP</td>
</tr>
<tr>
<td>Weldment R</td>
<td>450-700°C, 50°C Interval/ Up to 300000h</td>
<td>Incomplete</td>
<td>650°C Cup to 300000h ; 700°C Cup to 30000h</td>
<td>SINAP</td>
</tr>
<tr>
<td>Bolt 50</td>
<td>25-700°C, 25°C Interval;  Up to 300000h</td>
<td>Complete</td>
<td>finished</td>
<td>ASME II ID</td>
</tr>
<tr>
<td>Bolt Smt</td>
<td>450-700°C, 50°C Interval/ Up to 300000h</td>
<td>Incomplete</td>
<td>650°C Cup to 300000h ; 700°C Cup to 30000h</td>
<td>SINAP</td>
</tr>
<tr>
<td>Isochronous stress-strain curves</td>
<td>450-700°C, 50°C Interval/ Up to 300000h</td>
<td>Incomplete</td>
<td>650°C Cup to 300000h ; 700°C Cup to 30000h</td>
<td>SINAP</td>
</tr>
<tr>
<td>Designed fatigue strain curves</td>
<td>25°C, 600°C, 650°C, 700°C , 730°C ; Fatigue rupture cycles : 10⁸ ~ 10⁹</td>
<td>Incomplete</td>
<td>650°C Cup to 300000h ; Confidential curve , fatigue rupture cycles up to 10⁹</td>
<td>SINAP</td>
</tr>
<tr>
<td>Creep-fatigue envelope</td>
<td>No defined requirements</td>
<td>Incomplete</td>
<td>650°C, 1% strain</td>
<td>SINAP</td>
</tr>
<tr>
<td>Yield stress</td>
<td>25-700°C, 50°C Interval</td>
<td>Complete</td>
<td>finished</td>
<td>ASME II, SINAP</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>25-700°C, 50°C Interval</td>
<td>Complete</td>
<td>finished</td>
<td>ASME II, SINAP</td>
</tr>
<tr>
<td>Yield strength reduction factor</td>
<td>650°C, 700°C, 1000°C, 10000h</td>
<td>Incomplete</td>
<td>650°C, 700°C Cup to 10000h</td>
<td>SINAP</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>650°C, 700°C, 1000°C, 10000h</td>
<td>Incomplete</td>
<td>650°C, 700°C Cup to 10000h</td>
<td>SINAP</td>
</tr>
</tbody>
</table>

- Time independent data are nearly complete, except for Poisson's ratio and a few stress data
- Time dependent data are ~ 30% completed
Progress in Alloy – Irradiation Test

✓ Finish irradiation test on Hastelloy N @ T=650 °C, dose=2.5E19. PIE indicates that after irradiation the yield strength slightly increases, whereas the elongation keeps stable.

✓ Finish Irradiation test on Hastelloy N and GH3535 (base metal & weld metal) @ T=25 °C, dose=2.5E19 & 1E20

● High Dose (3-15 dpa) test to be conducted in 2018 @ PSI
3000 hrs static corrosion test suggests corrosion depth of Alloy N in FLiNaK less than 20 um

Comparison between the base metal and weld zone suggests that the welding process does not affect the corrosion degree of Alloy N in FLiNaK
Challenges to Graphite/Carbon Based Composite

**Manufacture**
- Manufacturing large block of ultrafine grain graphite is challenging.
- The fracture toughness and thermal conductivity need to be improved.
- The uniformity and reproducibility are critical to nuclear graphite.

**Compatibility**
- The infiltration/diffusion of molten salt need to be studied.
- Fission produce/tritium absorption in graphite affects the neutron economy.
- Impurities in salt could enhance the corrosion of graphite.

**Irradiation**
- The irradiation behaviors of ultrafine grain graphite could be different.
- The irradiation data collection is a time and money consuming effort.
- The molten salt and graphite interface could affect the irradiation behavior of graphite.

**Design Code**
- Design code is needed for commercializing TMSR.
- Fully understanding the behavior of graphite is essential for design code development.
Progress in Graphite – Manufacture & Salt Infiltration

1400×600×350mm

Tests on candidate graphite NG-CT-50

- Manufacture capability – size up to 1400 x 600 x 350 mm
- Smaller size compared to common commercial graphite
- FLiBe infiltration test done – low permeation for molten salt under reactor pressure
Progress in Graphite – Irradiation Test

- Irradiation Test @ T=650 °C, dose=5\times10^{20} to be done by June, 2017. PIE to be done by 2018.

<table>
<thead>
<tr>
<th>Test issues</th>
<th>NG-CT-50</th>
<th>NG-CT-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>Splitting tensile</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>Bending strength</td>
<td>24</td>
<td>16</td>
</tr>
</tbody>
</table>

- Irradiation Test in MS @T=700 °C, dose=4\times10^{20} to be done by Dec. 2016. PIE to be done in 2017.
Material Database Construction

- Covers a wide range of materials for TMSR including alloys, graphite, ceramics and composites
- Source includes experimental data by TMSR, qualified data from other expert groups (ORNL etc.), and Journal Publication
- Full traceability from material property data to experimental data and reports
Basic Science Research in Progress

Material Structural Studies Using Synchrotron X-ray
- In situ observing load allocation in alloy
- Molten salt distribution in graphite and composite
- Element tracing in irradiated/corroded samples
- Radioactive material studies with dedicated beam line

Ion beam simulates neutron irradiation
- He embrittlement in Ni based alloy
- Synergy effect of multiple ion species
- New methodology to compare ion and neutron irradiated samples

Simulation and Modeling
- Irradiation effect on Ni based alloy
- Intergranular embrittlement by fission products
- MD simulation on molten salt and its interaction with materials
Collaboration to Move MSR Forward

- Material R&D for TMSR benefit from the rich heritage left by MSRE.

- Challenges to Material R&D for modern MSR require the application of modern technologies.

- Collaboration between SINAP and international universities and institutes will propel TMSR/FHR to success.