Thorium Molten Salt Reactor Energy System (TMSR) Program Update

Shanghai Institute of Applied Physics
Chinese Academy of Sciences

Generation IV International Forum
• TMSR is to develop the TMSR-LF and TMSR-SF in the next 20 to 30 years
  - Use thorium fuel and closed fuel cycle
  - Nuclear heat application
• TMSR-LF, a liquid fuel molten salt reactor or MSR
• TMSR-SF, a solid fuel molten salt reactor or FHR
• Program was initiated by the Chinese Academy of Sciences (CAS) in 2011
Early Efforts for MSR in China

1970 - 1971, SINAP built a zero-power (cold) MSR.

1972 - 1973, SINAP built a zero-power LWR.

1970~1975, in SINAP about 400 scientists and engineers studied on the nuclear power plant. The original goal is to build 25 MWe TMSR. 1972-1975, the goal was changed to the Qinshan 300 MWe (Qinshan NPP-I), which has been operating since 1991.
TMSR Fuel Cycles and Applications

- Thorium Energy
- High Temperature H₂ Production
- Water-free Cooling
- Small Modular Design

High Temperature Fission Nuclear Energy

Modified Open Fuel Cycle

Fully Closed Fuel Cycle

Strategy of TMSR R&D

Long-term  Mid-long  Mid-term
TMSR Reactor Development Plan

2015

Simulator
TMSR-SF0

2020

10 MW Test Reactor
TMSR-SF1

2 MW Test Reactor
TMSR-LF1 + Th Fuel Cycle Test

2025

100 MW Demo Reactor
TMSR-SF2

10 MW Test Reactor
TMSR-LF2 + Th Fuel Cycle Demo
Thorium and $^7\text{Li}$ Extraction

Fluoride Salt Production and Purification

Nickel-based Alloy Production and Test

Pyro-Processing

Material Corrosion Control

Tritium Measurement and Control

Nuclear Graphite Production and Test

Reactor Design

Salt Loop

Th-U Fuel Cycle

Safety & Licensing
Fundamental Research Base at Jiading

- Power Room
- Factory logistics
- Nuclear Fuel
- Hydrogen production
- Neutron facility
- Material Lab.
- Office
- HTS and FLNK loops
- Irradiation facility
- Molten salt Chemistry
- Chemical Lab.

- Super Computer
- Hot Cells
- Material Testing Labs
- Salt Properties Labs
- β Irradiation Facility
~600 staffs and more than 200 graduate students, ~410 staffs and 120 students from TMSR Center

- TMSR center staff Average Age ~31
- Key personnel Average Age ~38
- Constructed high-temperature fluoride salt loops.
- Developed equipment to be used with fluoride salts, e.g., pump, heat exchanger, valve, seal, pressure meter, etc.

- Design and analysis methods for high-temperature fluoride salt loops
- Prototypes for pump, valve, heat exchanger, etc.
- Experience of loading and unloading of fluoride salts
- Experience of high-temperature fluoride salt loops operation and maintenance

High-temperature fluoride salt experimental loop
Prototypes of equipment
Hydraulic test of molten salt pump
Thermal hydraulic & mechanical test of loop
High-Temperature FLiNaK Test LOOP

Engineering specifications:
- **Coolant**: FLiNaK molten salt
- **Max. Working Temp.**: 650°C
- **Flux**: ≥15m³/h
- **Molten salt cover**: Argon
- **Main heater**: Ohm heating
- **Max. power**: 200kW
- **Molten salt charge**: gas pressure
Finish molten salt pump hydraulic experiment platform construction and experiment prototype hydraulic test

MSRE molten salt pump

FLiNaK loop pump (prototype)

TMSR-SF1 primary pump (engineering prototype)

It started in 2013

2012-2013

2014/3/10
- **Fluorination for U recovery:** Verification of process with in-situ monitoring, use of frozen-wall technique to mitigate corrosion, derived from high temperature, F₂ and liquid fluorides melt.
- **Distillation for carrier salt purification:** Demonstration of a controllable continuous distillation device, the distillation rate is about 6 Kg per hour, and the DF is > 10² for most neutron poisons.
- **Fluorides electrochemical separation for U recovery:** Electro-deposition of U metal from FLiBe-UF₄ melt and separation ratio > 99 %
• Established a thorium fuel utilization strategy in MSRs by evaluating the Th-U fuel cycle performance
• Created a reprocessing flow sheet and demonstrated it in cold, lab-scale facilities

Th-U Fuel Cycle System

Fuel cycle mode

Th-U Fuel Cycle System

Flow sheet design

Thorium utilization strategy in MSRs
- $^{235}\text{U}$ to $^{233}\text{U}$ transition
- Minor actinides transmutation

Flow sheet combines on-line and off-line processing
- On-line for U and carrier salt
- Off-line for Th and minor actinides

Consistency of on-line reprocessing in cold, lab-scale
- Recovery rate of U > 95%
- Recovery rate of carrier salt > 90%

Process Consist.
Frozen-wall experimental equipment ready for research

A frozen-wall between vessel surface and liquid flow might serve as a protecting surface

Purpose of the equipment:
---developing techniques for determining and controlling of frozen-wall thickness
---studying the effect of formation of frozen-wall on the corrosion control

Preliminary results
✧ A frozen-wall of 2~10mm was formed during operation
✧ Temperature gradient obtained by thermocouples could be used to speculate the thickness of frozen-wall
**Experimental results of gas extraction (Bubbler + Gas separator) for separating the gas from water environment**

Negative Press: 0.009 MPa  
Balance: 0.012 MPa  
Positive Press: 0.030 MPa

Discovering separation efficiency of separator relating with the outlet pressure
A 3-step Strategy for Th-U Fuel Cycle

Step 1: batch process
- Fuel: LEU+Th
- Online refueling and removing of gaseous FP
- Discharge all fuel salt after 5 years and extract U and Th
- FP and MA for temporary storage

Step 2: batch process + fuel reload
- Batch process to recycle residual salt, U and Th from FP and MA
- Reloading of $^{233}$U and Th to realize thorium fuel cycle
- FP and MA for temporary storage

Step 3: continuous process
- Continuous process to recycle residual salt, U and Th from FP and MA
- Improved thorium fuel cycle
Tritium Measurement and Control

- On-line tritium monitoring
- Tritium stripping using bubbling, tritium separation with cryogenics, and tritium storage

<table>
<thead>
<tr>
<th>Tritium stripping with bubbling</th>
<th>Tritium separation with cryogenics</th>
<th>Tritium alloy storage</th>
<th>On-line tritium monitoring</th>
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<tbody>
<tr>
<td>Bubble-size control, degassing efficiency &gt; 95%</td>
<td>Kr(\text{Xe} &lt; 1 \text{ ppb and } \text{H}_2 &lt; 1 \text{ ppm in the off gases}</td>
<td>Zr(_2)Fe alloy (Hydrogen partial pressure ratio &lt; 0.1 ppm)</td>
<td>On-line monitoring of HTO, HT, K and Xe,</td>
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• Succeed in obtaining high purity thorium and enriched $^7$Li using extraction technology

- **Enrichment of $^7$Li**: As a green technology, centrifugal extraction method was developed to replace mercury method to obtain $^7$Li. High efficient extractants were synthesized. Counter current extraction experiment was conducted and a 99.99 % abundance of $^7$Li was achieved.

- **High purity thorium**: High efficient extraction system was developed to obtain the high purity thorium. A 99.99 % purity of thorium was achieved in batches.

Small/medium (20 kg/a by design) scale centrifugal extractor cascade demonstrations

- PWR pH control (abundance ≥ 99.9 %)
- MSR coolant (abundance ≥ 99.99 %)
Li-7 Extraction Separation Investigation Progress

- 160 stages 20 mm centrifugal extractor device cascade separation system (Intelligent operation, high-precision control)
- Li-7 accumulation \(99.957\% \rightarrow 99.9912\%\) (run 600 h continuously, obtain 1.68 g Li-7)
Li-7 Extraction Separation Key Instrument Development Progress

- Centrifugal extractor test prototype development (rotator diameter 350 mm, electromotor power 5.5kw)
- Centrifugal extractor hydraulic test platform (global flux 8m³/h, separation factor ≥500)
Fluoride Salts Production and Purification

- High purity FLiNaK batch production, characterization and purification
- Synthesis of FLiBe and beryllium control method
- Establishing FLiBe-Th-U fuel salts thermodynamics database

- Synthesis technology of nuclear grade FLiBe with boron equivalent < 2 ppm
- Purification technology of high purity FLiNaK with total oxygen < 100 ppm
- High purity FLiNaK batch production of 10 tons per year
- Capability of fluoride salt physical properties measurement

Fluoride salt  Salt production of 10 tons per year  FLiBe Salt
Production of Nickel-based Alloy

- Technologies for the smelting, processing, and welding of the Nickel-based alloy (UNS N10003, China standard GH3535).
  - Smelting 12 tons of alloy, developed technologies for processing and welding, performance is comparable to Hastelloy N
  - Deformation processing technologies for nickel-based alloys with high Moly, manufactured large UNS N10003 seamless pipes

- Hot extrusion
- Pipe processing
- Welding
- Component (head)
Production of Nuclear Grade Graphite

- Development of the ultrafine grain nuclear graphite for MSR, involved in the establishment of ASME code of MSR nuclear graphite

- Industrial production of ultrafine-grain nuclear graphite NG-CT-50
- Pore diameter < 1 μm, ensured better FLiBe salt infiltration resistance than existing nuclear graphite
- Establishing performance database for NG-CT-50 graphite
- Participating in the international standards development of MSR nuclear graphite

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<th>Parameters</th>
<th>NG-CT-50</th>
<th>IG-110</th>
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<tbody>
<tr>
<td>Pore Dia. (mm)</td>
<td>0.74</td>
<td>2</td>
</tr>
<tr>
<td>Boron (ppm)</td>
<td>&lt; 0.05</td>
<td>0.1</td>
</tr>
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Comparison of graphite

FLiBe salt infiltration
Material Corrosion Control

- Control the structural material corrosion by alloy composition optimization, salt purification and surface treatment
- Building a test loop for dynamic corrosion tests

**Investigating Corrosion Mechanism**
- Salt impurities
- Elements diffusion
- Mass transfer

**Developing Corrosion Control Technologies**
- Optimize the composition of alloy, diffusion of Cr
- Improve purification technology, minimize impurities
- Fluoride salt thermal diffusion coating

![Composition Optimization (Cr)](image1)

![Corrosion Depth (μm/y)](image2)

**GH3535 exposed to impurity FLiNaK**

**GH3535 exposed to high purity FLiNaK**

**Without FTD Coating**

**FTD Coating**
Reactor Design and Components Development

- Development of design and analysis methods and tools
- Development of technology and equipment used for high-temperature fluoride salts
- Design of the 2 MW TMSR-LF1 and the 10 MW TMSR-SF1
- Design of the “simulator” TMSR-SF0
- Developed safety analysis codes (RELAP-MS, etc.)
- Developed safety design criteria and completing safety system design
- Established multiple test loops for safety code validation
- Participating in the development of ANSI/ANS-20.1 and 20.2

- Completing preliminary safety analysis report (PSAR)
- Safety design criteria were reviewed and accepted by the review team designated by the National Nuclear Safety Administration (NNSA)
- Safety classification analysis of the TMSR-SF1 and TMSR-LF1 were reviewed and accepted by NNSA, both were classified as Class II research reactors
- Release of cover gas was determined as the MCA
- Conducting salt natural circulation, Dowtherm A and water experiments for code validation
Completion of the TMSR-SF1 Design

Primary Pump

Intermediate heat exchanger

Biological shielding

Primary drain tank

Secondary Pump

Salt-air heat exchanger

Secondary drain tank

Reactor vessel
Progress of the TMSR-SF0 Construction

- The engineering design was complete and major components was ordered
- Steel frames were constructed
- Installation of major components is expected to start in mid of 2018
- A practice for the future test reactor construction
Progress of the TMSR-LF1 Design
TMSR Test Reactor Candidate Site

- State Power Investment Corporation (SPIC) was newly established through the merger of China Power Investment Corporation (CPI) and State Nuclear Power Technology Corporation (SNPTC)
- Two AP1000 units are under construction at Haiyang (right)
- Haiyang is now the candidate site for TMSR test reactors
- CAS and SPIC are jointly developing a Nuclear R&D park in Haiyang
- CAS and SPIC signed a science and technology collaboration agreement in March, 2016
The candidate site is located in Wuwei (武威), Gansu Province, about 2000 Km from Shanghai, the annual precipitation is 128 mm and the annual average temperature is 8.3 °C.
Survey of the Candidate Site

- Onsite survey completed in August
- Application for the site permit to be submitted to government this year.
Thank you