Thorium Molten Salt Reactor Energy System (TMSR) Program Update

Shanghai Institute of Applied Physics

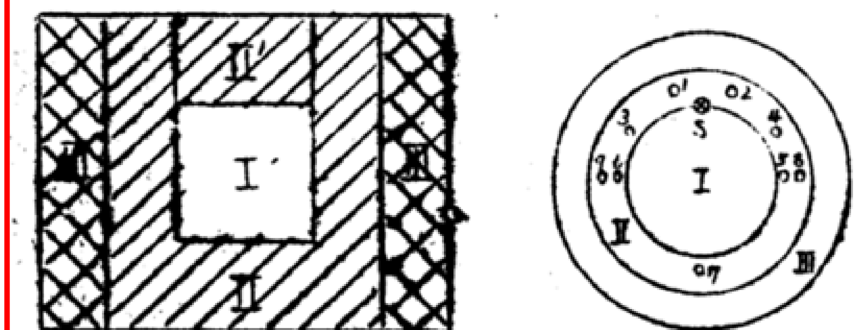
Chinese Academy of Sciences

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.



Ⅰ - core
Ⅱ - reflector
Ⅱ ′- reflector cover
Ⅲ - protection wall
S- neutron source (100mCi Ra-Be)

1-2- safety rod
3- regulating rod
4- shim rod
5-6- backup safety rod
7-8-9- BF_3 neutron counter

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.

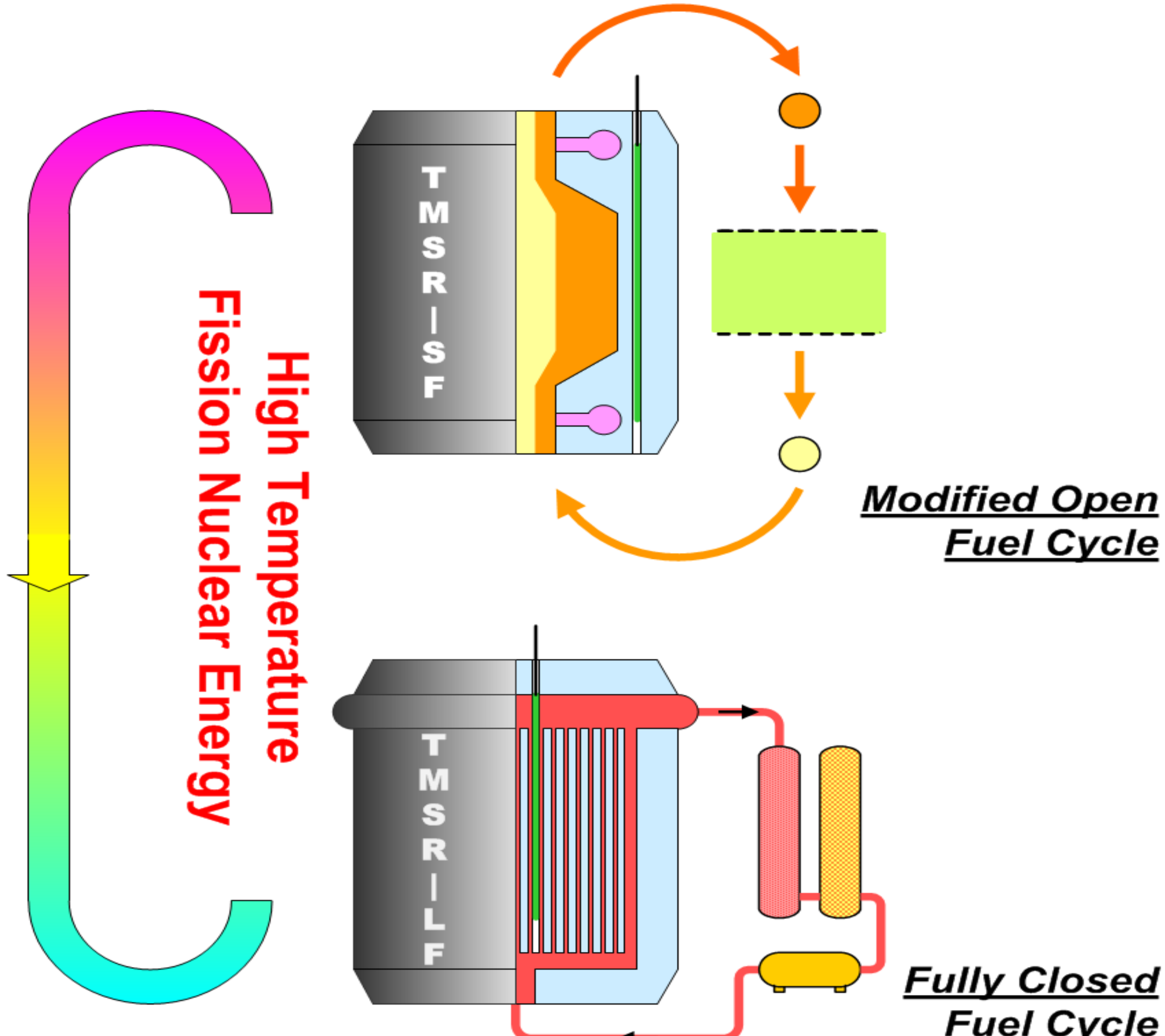
TMSR Fuel Cycles and Applications

Thorium Energy

High Temperature H_2 Production

Water-free Cooling

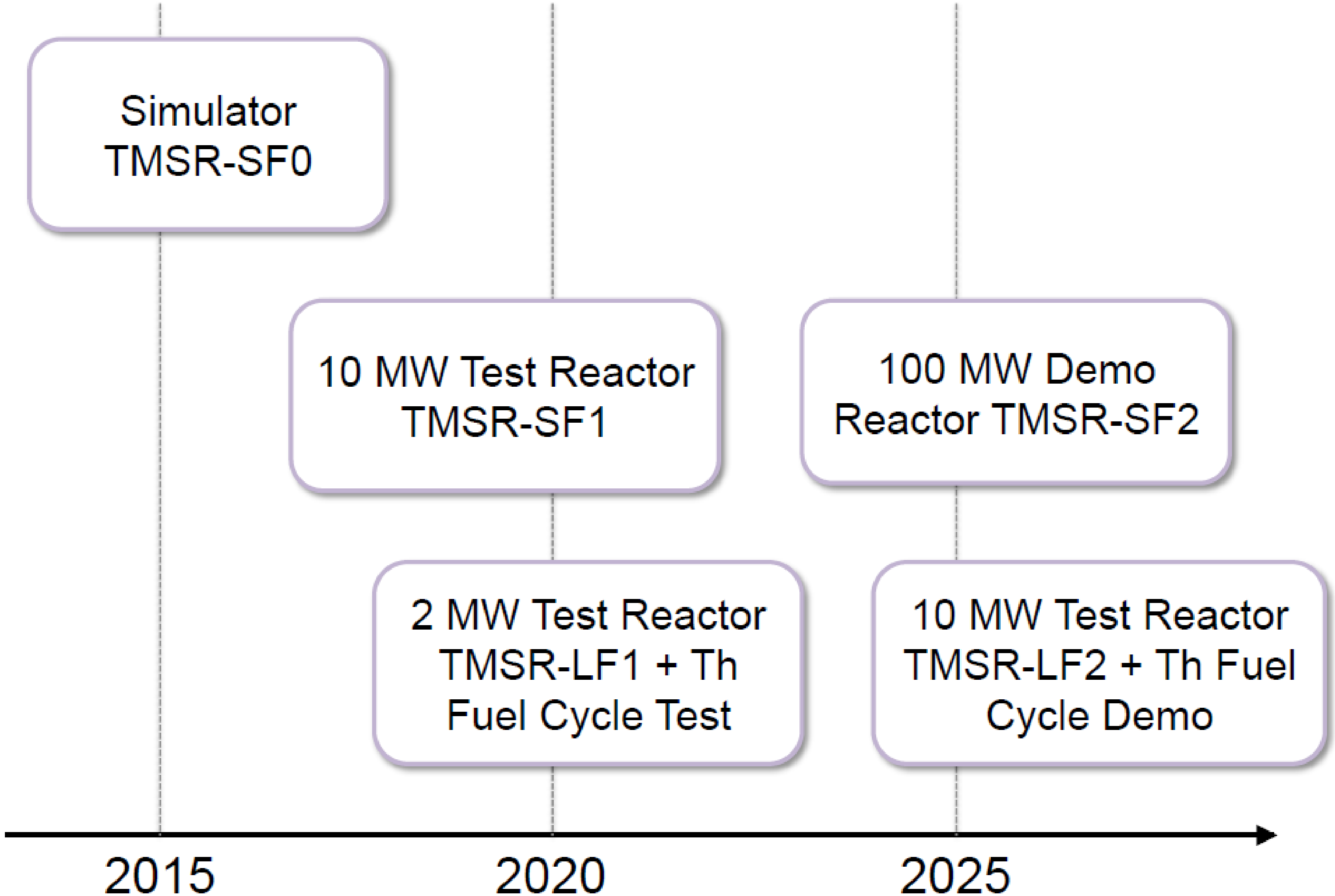
Small Modular Design



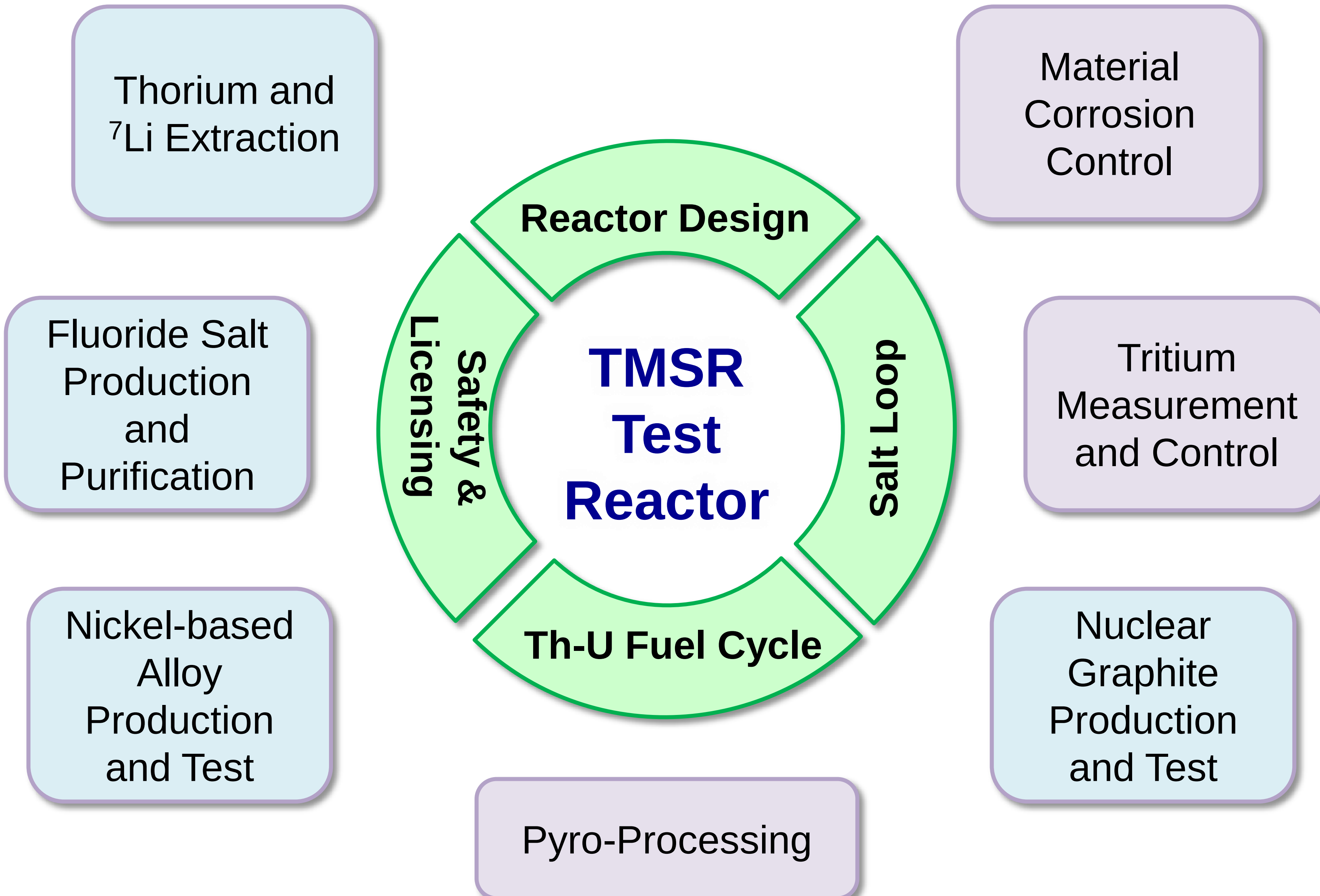
Long-term | Mid-long | Mid-term

Strategy of TMSR R&D

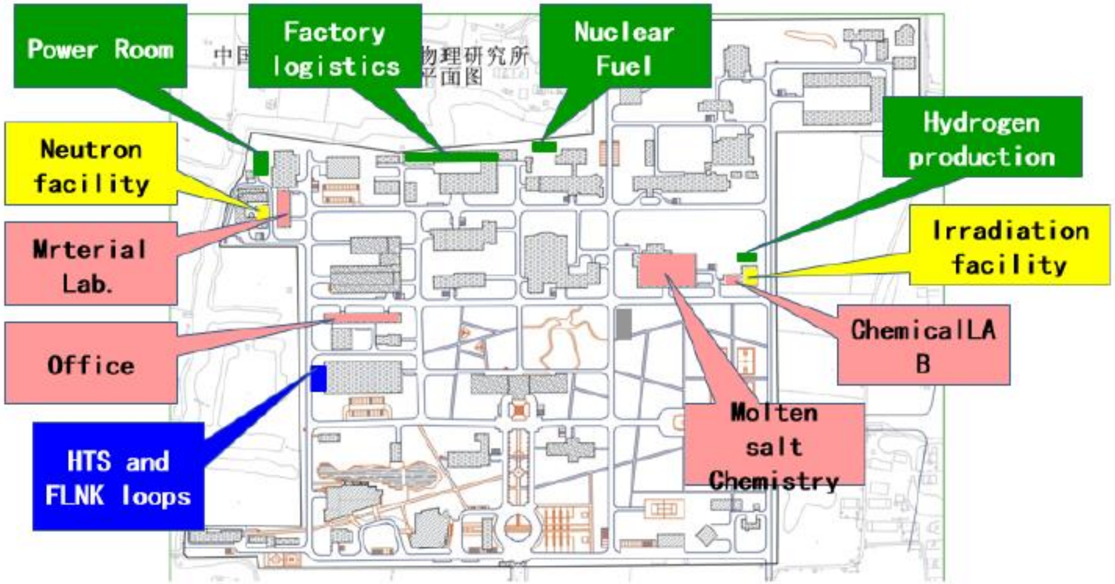
TMSR Reactor Development Plan



Systems and Techs of TMSR



Fundamental Research Base at Jiading




Super Computer


Hot Cells

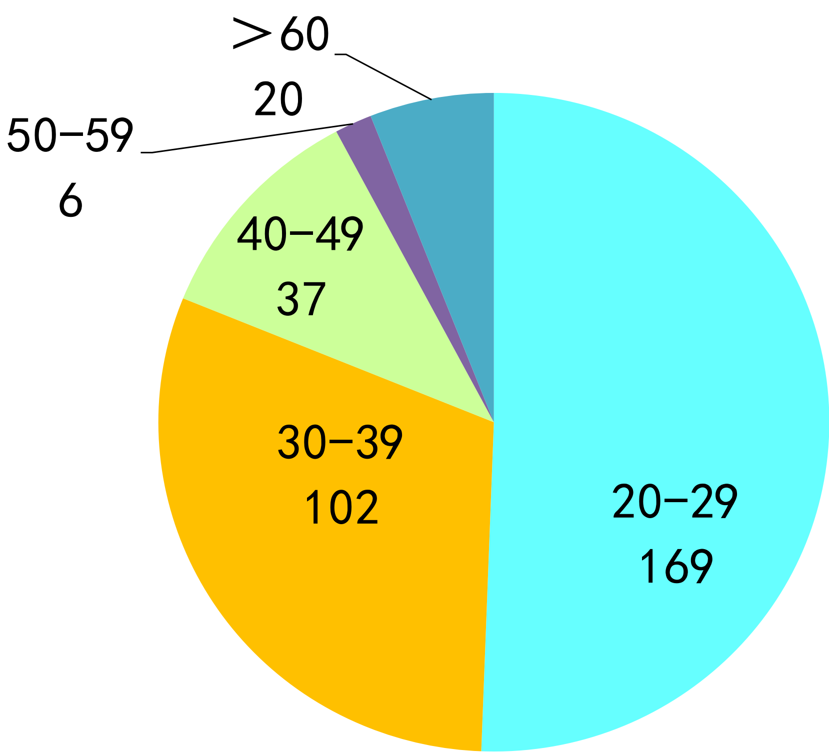

Material Testing Labs

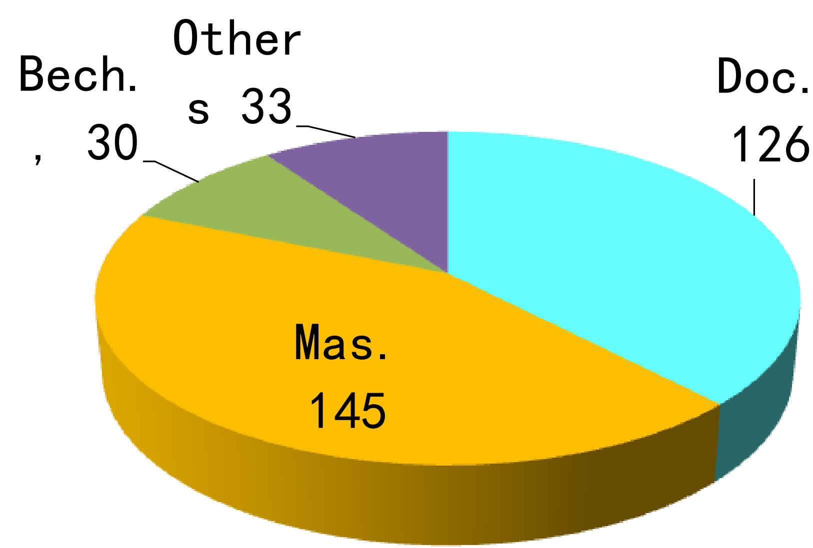

Salt Properties Labs


β Irradiation Facility

TMSR Team Structure

- ~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

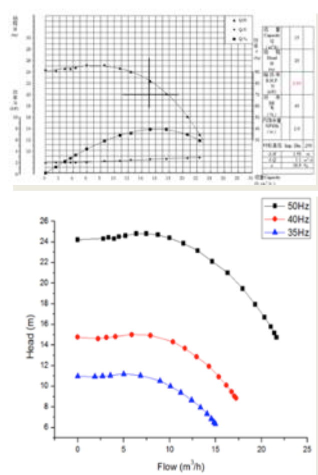
Fluoride Salt Loops

- Constructed high-temperature fluoride salt loops.
- Developed equipment to be used with fluoride salts, e.g., pump, heat exchanger, valve, seal, pressure meter, etc.

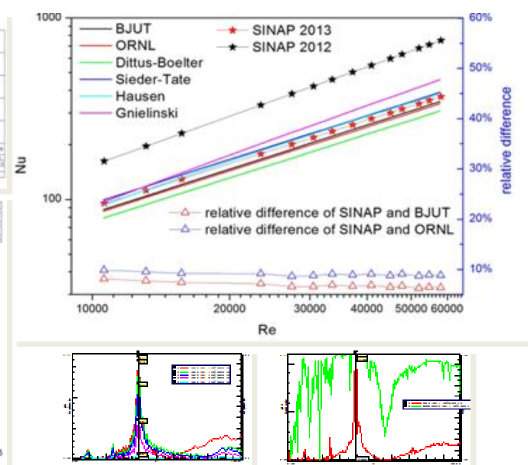
- Design and analysis methods for high-temperature fluoride salt loops
- Prototypes for pump, valve, heat exchanger, etc.
- Experience of loading and unloading of fluoride salts
- Experience of high-temperature fluoride salt loops operation and maintenance

High-temperature fluoride salt experimental loop

Prototypes of equipment

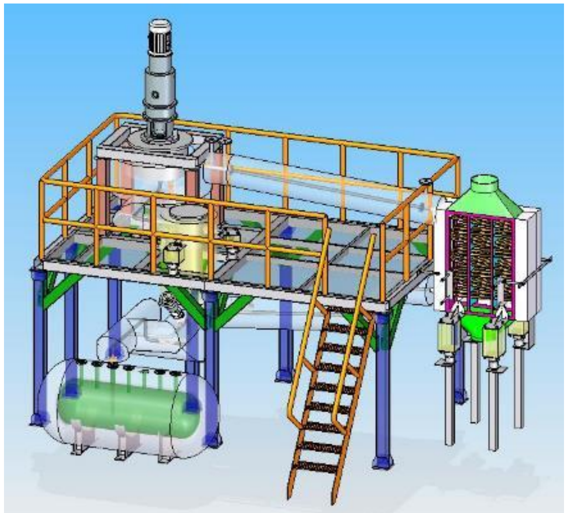


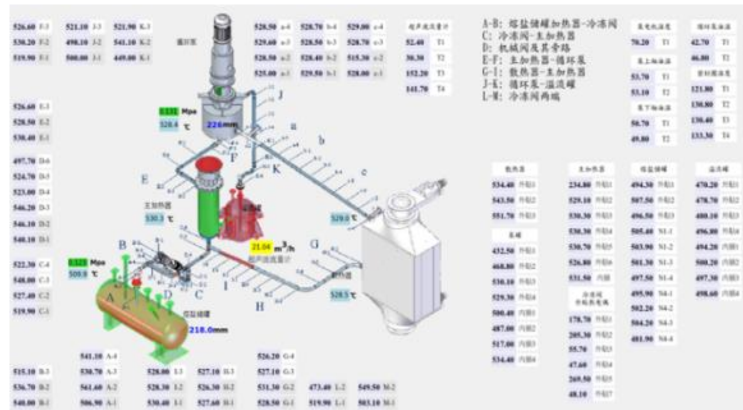
Hydraulic test of molten salt pump



Thermal hydraulic & mechanical test of loop

High-Temperature FLiNaK Test LOOP





Engineering specifications:

- ➤Coolant: FLiNaK molten salt
- ➤Max. Working Temp.: 650℃
- ➤Flux: ≥15m^3/h
- ➤Molten salt cover: Argon
- ➤Main heater: Ohm heating
- ●Max. power: 200kW
- ➤Molten salt charge: gas pressure

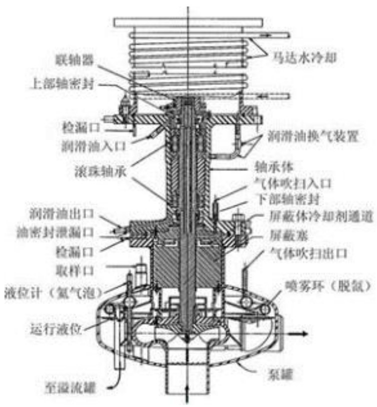
Loop key equipment development

- Finish molten salt pump hydraulic experiment platform construction and experiment prototype hydraulic test

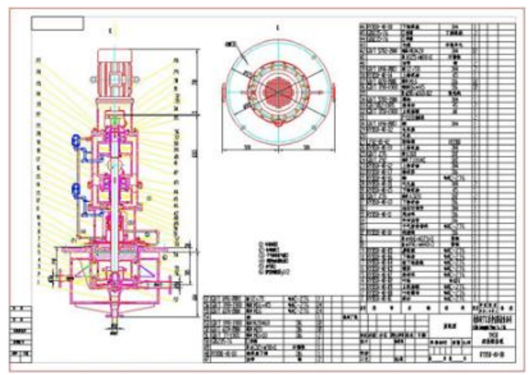
Pump

2012-2013

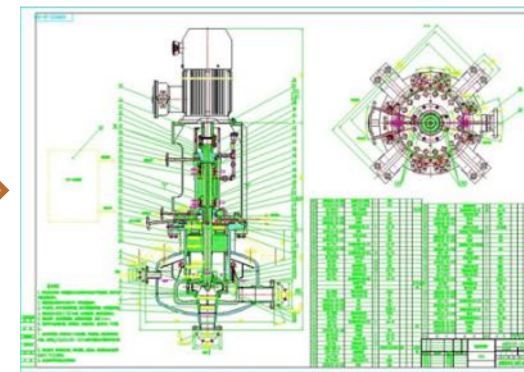
It started in 2013



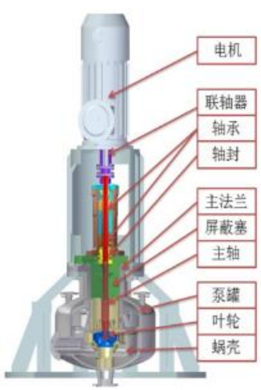
MSRE molten salt pump

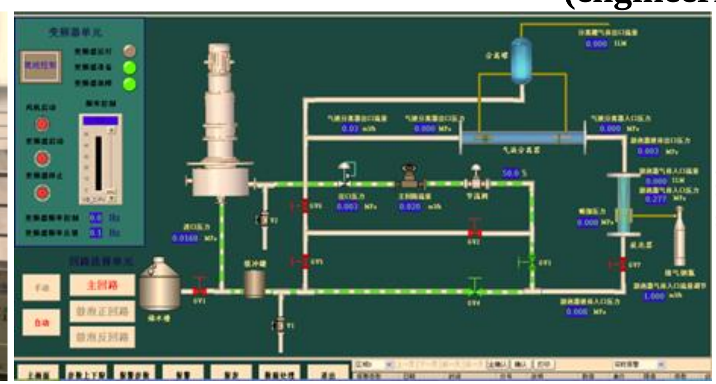


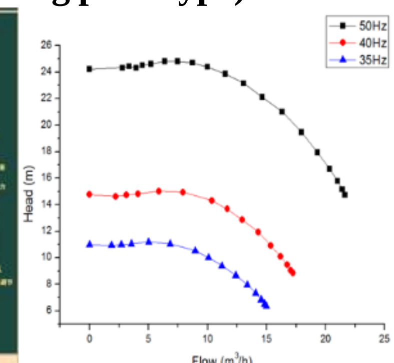
FLiNaK loop pump (prototype)



TMSR-SF1 primary pump (engineering prototype)







Pyro-processing Techniques

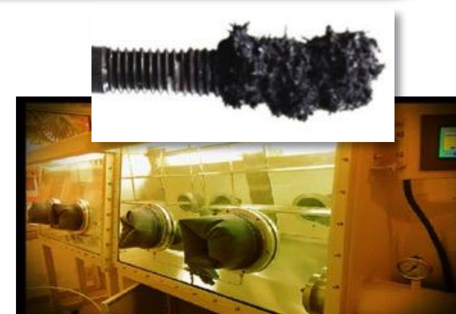
- Fluorination and distillation of fluoride salts in cold experiments
- Developing fluorides electrochemical separation techniques

- **Fluorination for U recovery:** Verification of process with in-situ monitoring, use of frozen-wall technique to mitigate corrosion, derived from high temperature, F_2 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 > 10^2 for most neutron poisons.
- **Fluorides electrochemical separation for U recovery:** Electro-deposition of U metal from FLiBe-UF_4 melt and separation ratio > 99 %

Fluorination experimental set-up

Frozen-wall test

Distillation experimental set-up



Electrochemical experimental set-up

Thorium-Uranium Fuel Cycle

- 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

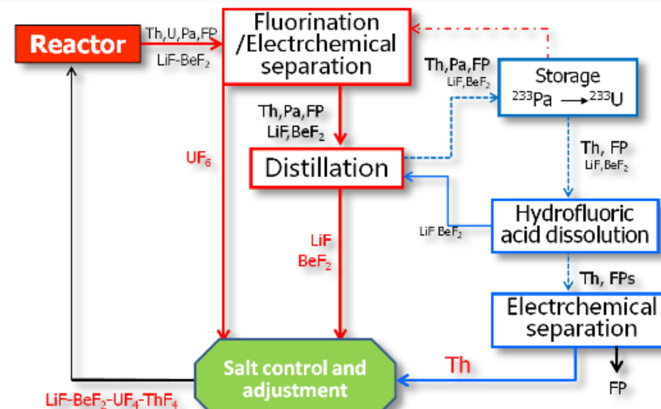
Thorium utilization strategy in MSRs
- ^{235}U to ^{233}U transition
- Minor actinides transmutation

Flow sheet design

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

Process Consist.

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



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:

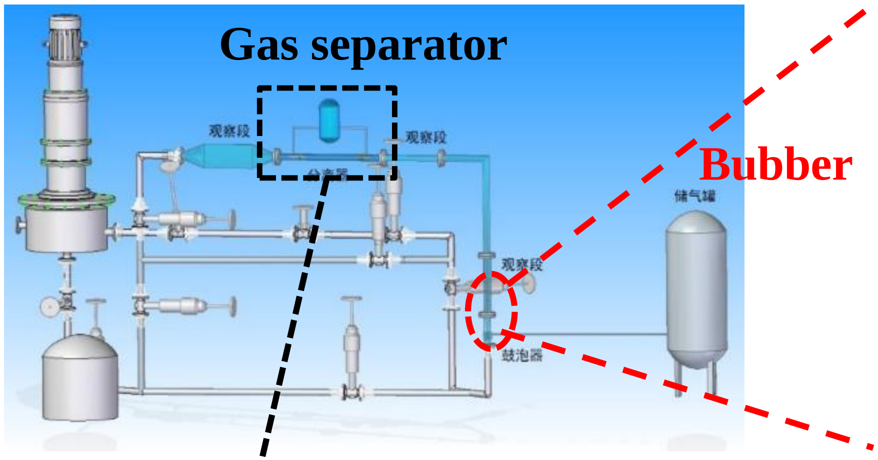
---developing techniques for determining and controlling of frozen-wall thickness

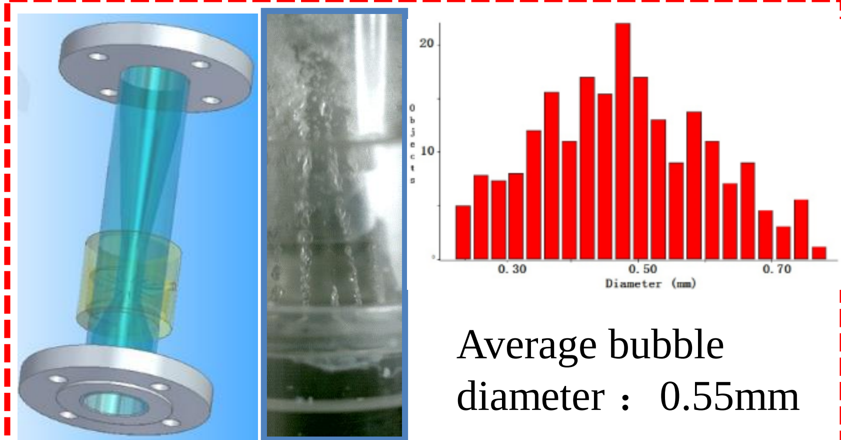
---studying the effect of formation of frozen-wall on the corrosion control

Preliminary results

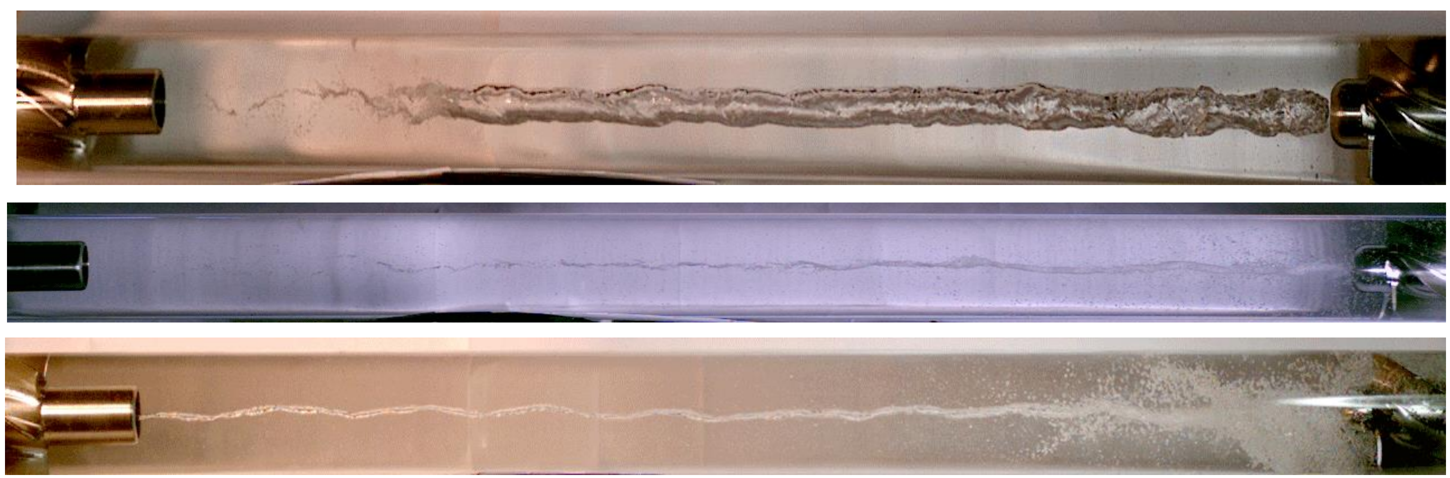
- ✧ A frozen-wall of 2~10mm was formed during operation
- ✧ Temperature gradient obtained by thermocouples could be used to speculate the thickness of frozen-wall

Experimental results of gas extraction （Bubbler + Gas separator ） for separating the gas from water environment





Average bubble diameter： 0.55mm



Negative Press 0.009MPa

Balance 0.012MPa

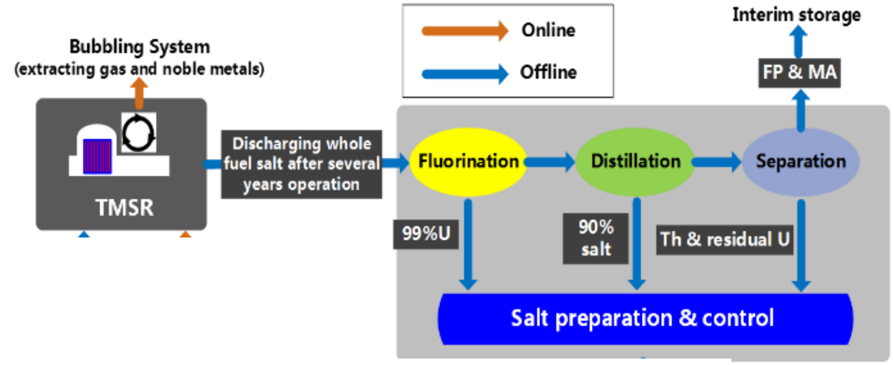
Positive Press 0.030MPa

Discovering separation efficiency of separator relating with the outlet pressure

A 3-step Strategy for Th-U Fuel Cycle

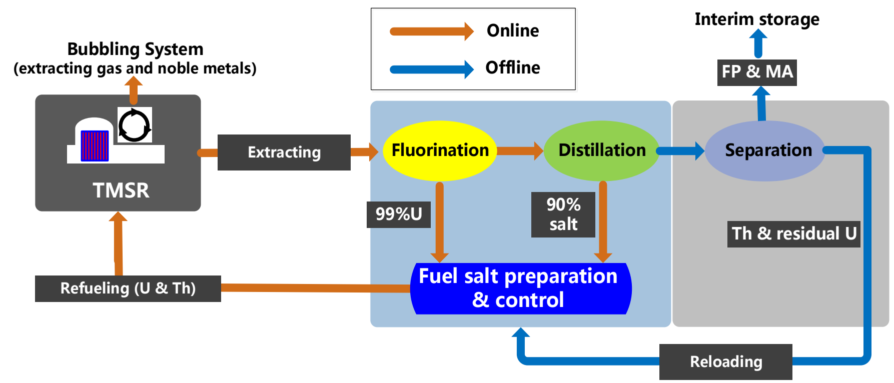
Step 1: batch process

- 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



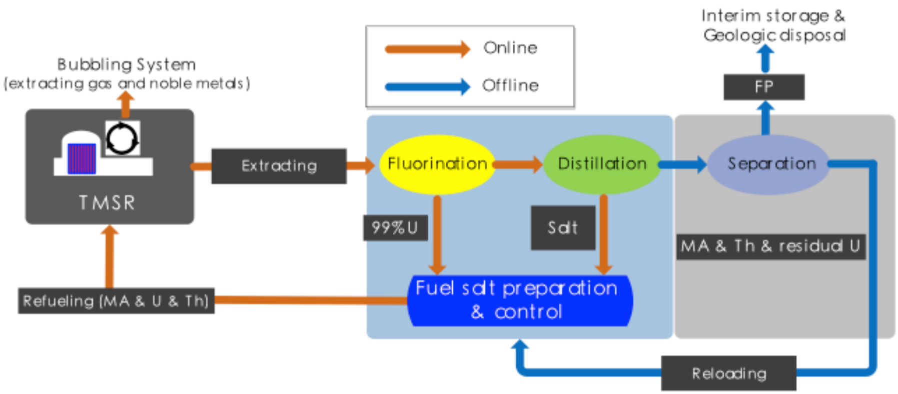
Step 2: batch process + fuel reload

- 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



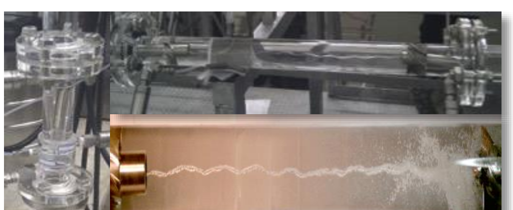
Step 3: continuous process

- 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

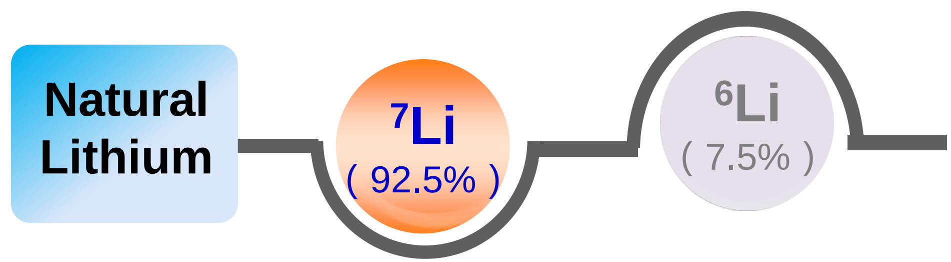
Tritium stripping with bubbling	Tritium separation with cryogenics	Tritium alloy storage	On-line tritium monitoring
Bubble-size control, degassing efficiency > 95%	Kr\Xe < 1 ppb and H_2 < 1 ppm in the off gases	Zr_2Fe alloy (Hydrogen partial pressure ratio < 0.1 ppm)	On-line monitoring of HTO, HT, K and Xe,
		  	

^{7}Li and Thorium Extraction and Separation

- 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.

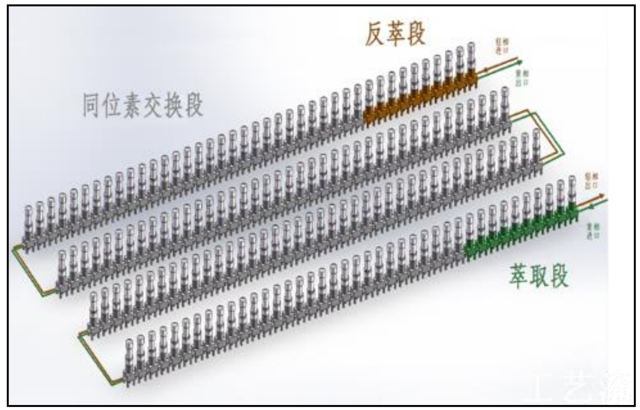
Small/medium (20 kg/a by design) scale centrifugal extractor cascade demonstrations



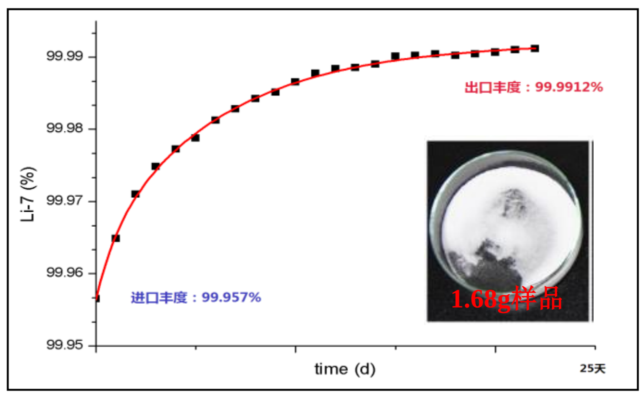
- PWR pH control (abundance ≥ 99.9 %)
- MSR coolant (abundance ≥ 99.99 %)

Li-7 Extraction Separation Investigation Progress

- 160 stages 20 mm centrifugal extractor device cascade seperation system (Intelligent operation, high-precision control)
- Li-7 accumulation **99.957%→99.9912%** (run 600 h continuously, obtain 1.6 8g Li-7)



Centrifugal extraction cascade separation experiment system

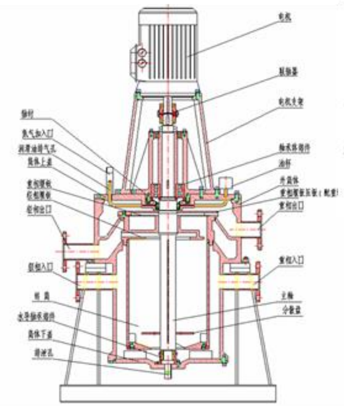
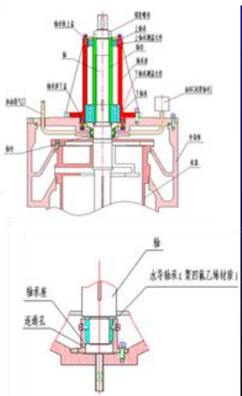
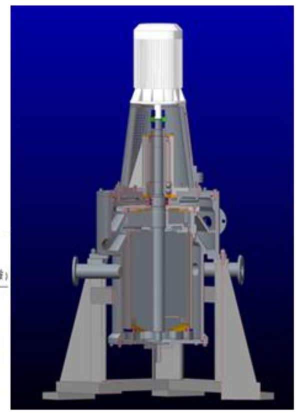


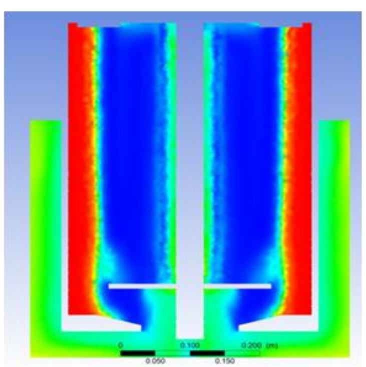
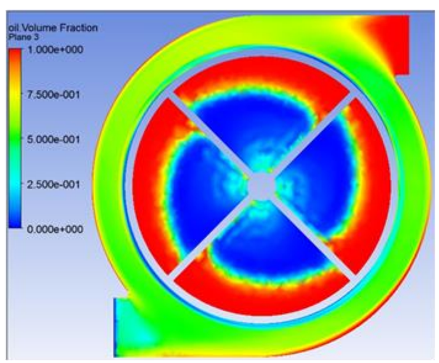
Li -7 extraction separation experiment results

Li isotope analytical platform

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 $8m^3/h$, separation factor $\geq$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）

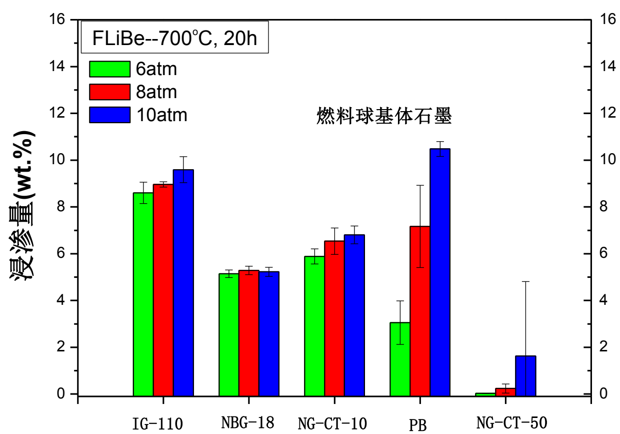
Production of Nuclear Grade Graphite

- 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

Parameters	NG-CT-50	IG-110
Pore Dia. (mm)	0.74	2
Boron (ppm)	< 0.05	0.1

Comparison of graphite



FLiBe salt infiltration

Ultrafine grain nuclear graphite

Material Corrosion Control

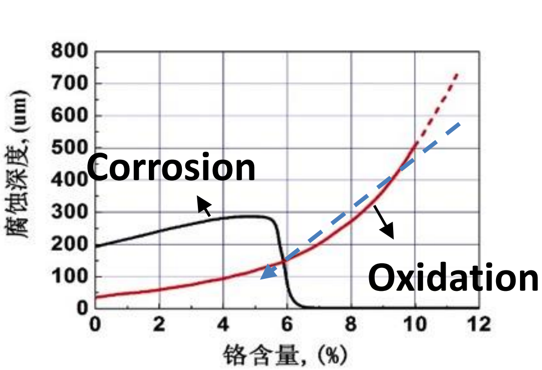
- Control the structural material corrosion by alloy composition optimization, salt purification and surface treatment
- Building a test loop for dynamic corrosion tests

Investigating Corrosion Mechanism

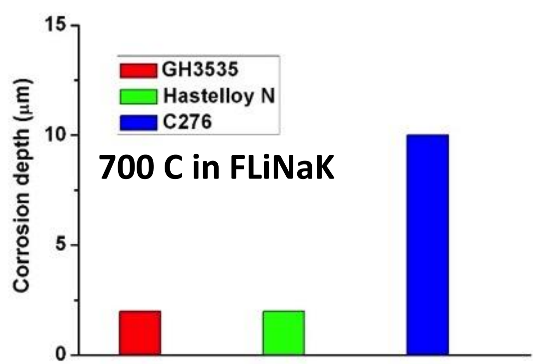
- Salt impurities
- Elements diffusion
- Mass transfer

Developing Corrosion Control Technologies

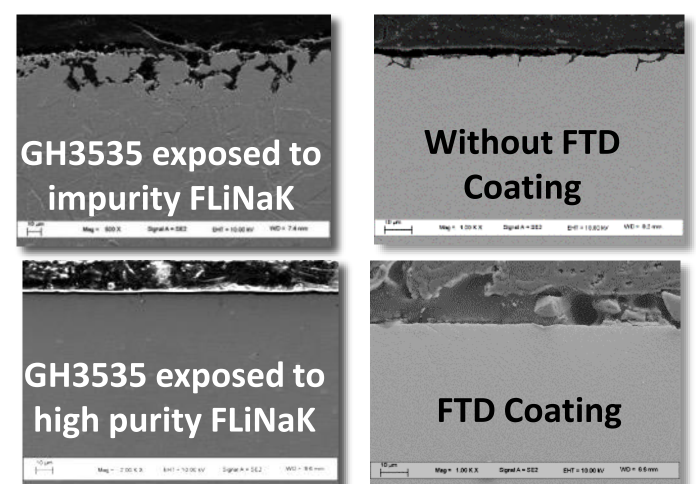
- Optimize the composition of alloy, diffusion of Cr
- Improve purification technology, minimize impurities
- Fluoride salt thermal diffusion coating



Composition Optimization (Cr)



Corrosion Depth (μm/y)



Reactor Design and Components Development

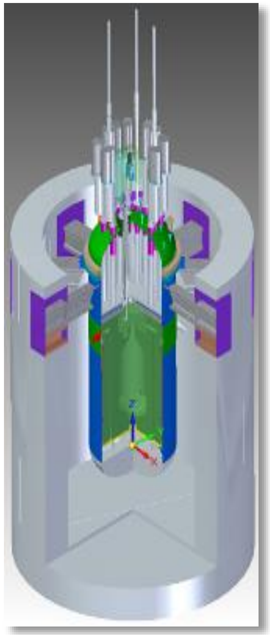
- Development of design and analysis methods and tools
- Development of technology and equipment used for high-temperature fluoride salts
- Design of the 2 MW TMSR-LF1 and the 10 MW TMSR-SF1
- Design of the "simulator" TMSR-SF0

- Development of design and analysis tools
- Evaluation of H-T nuclear data
- Thermal hydraulics experiments
- Reactor core modeling and analysis

Conceptual Design

Preliminary Design

Engineering Design



- Vessel and core structure design
- Control rods
- Fueling and defueling machine
- Neutron detectors
- H-T Flowmeter, pressure sensor, thermometer, level gauge
- Digital reactor protection and control system

Nuclear Safety and Licensing

- 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

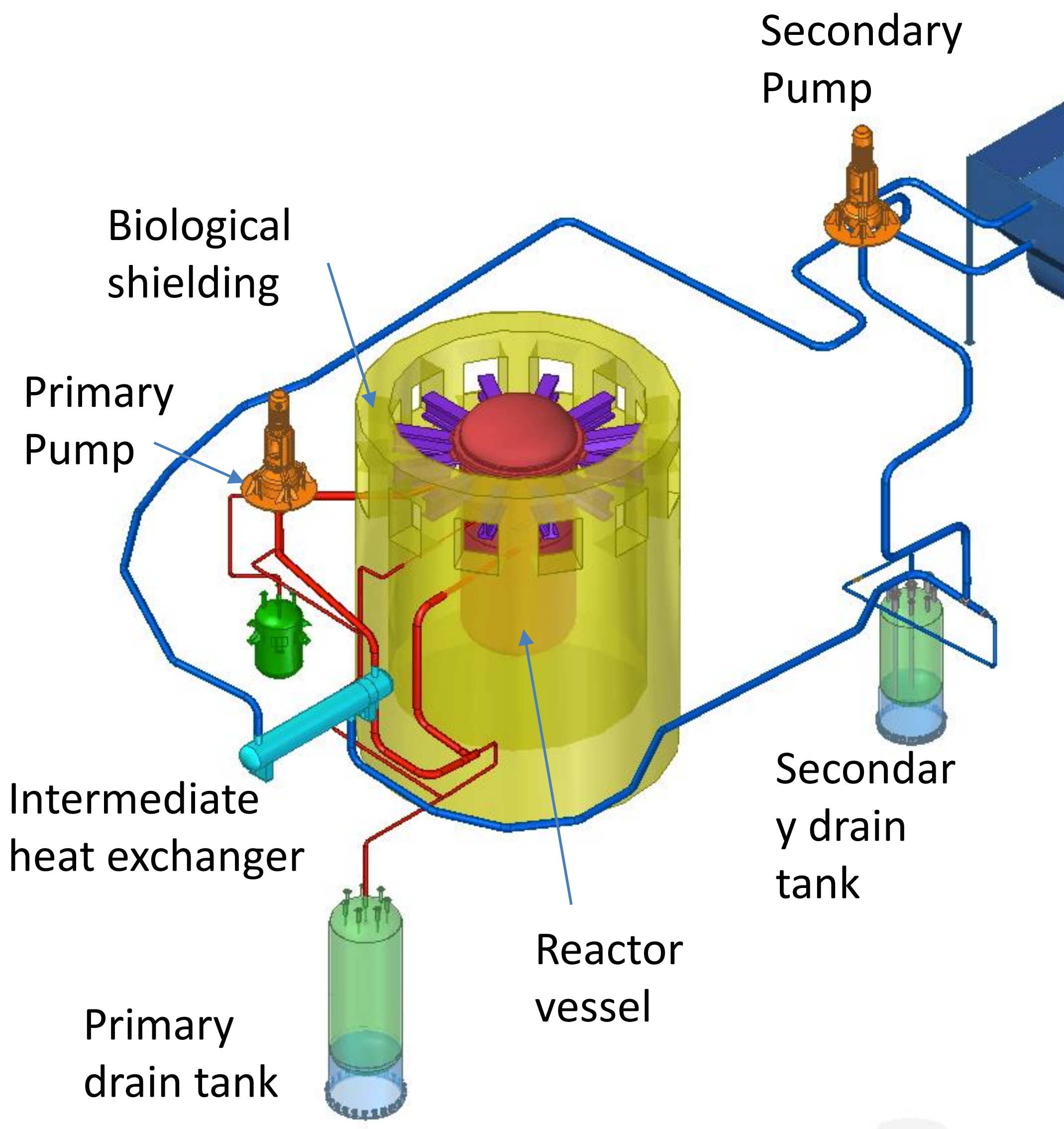
- Completing preliminary safety analysis report (PSAR)
- Safety design criteria were reviewed and accepted by the review team designated by the National Nuclear Safety Administration (NNSA)
- Safety classification analysis of the TMSR-SF1 and TMSR-LF1 were reviewed and accepted by NNSA, both were classified 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

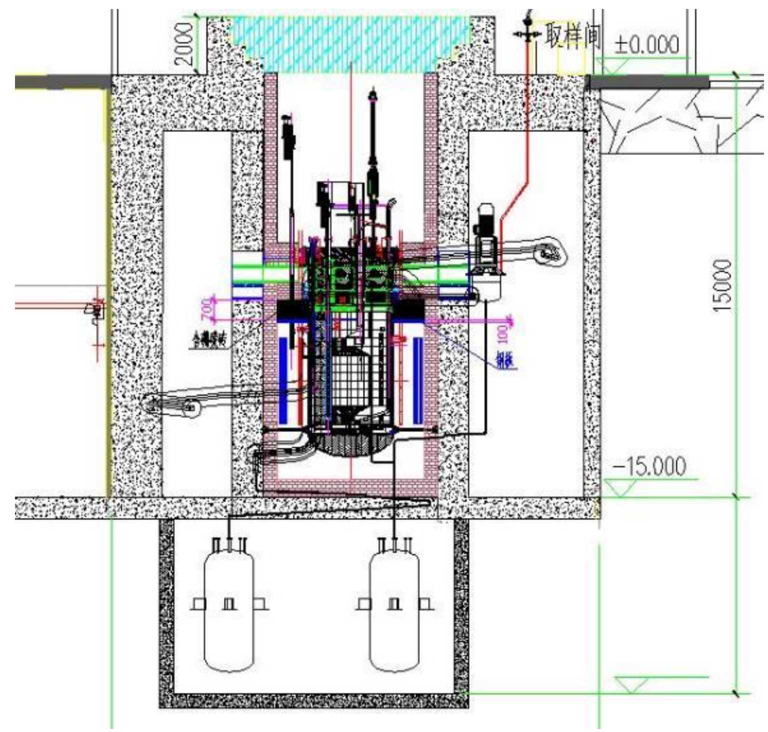
PSAR → Construction Permit

FSAR → Fuel Loading Permit

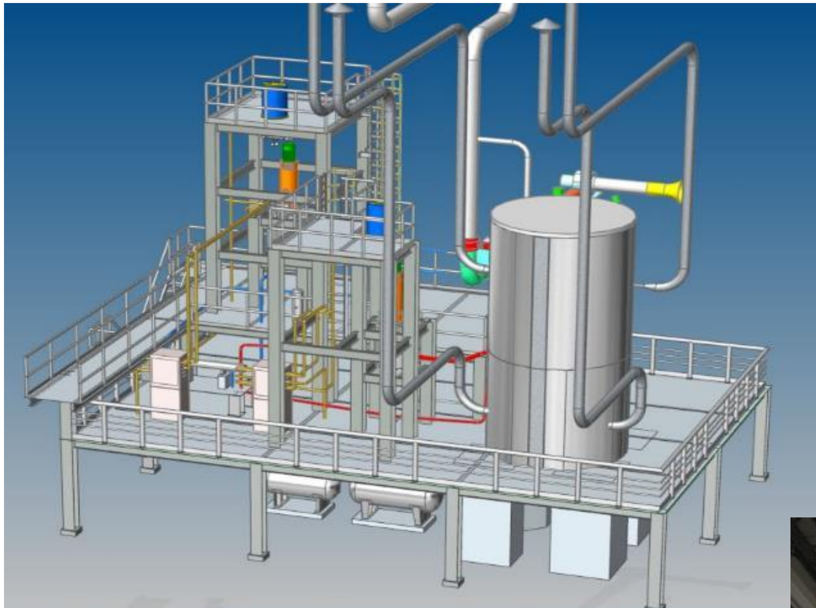
FSAR Rev. → Operation Permit

Completion of the TMSR-SF1 Design

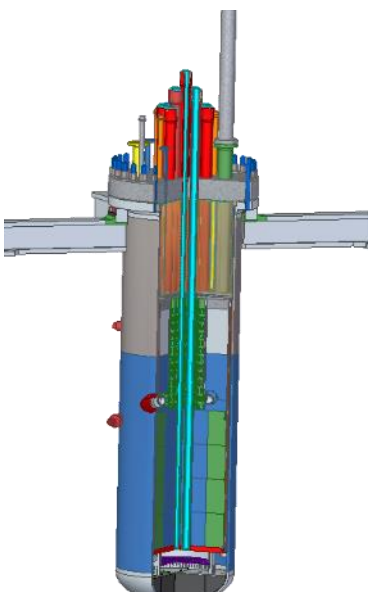




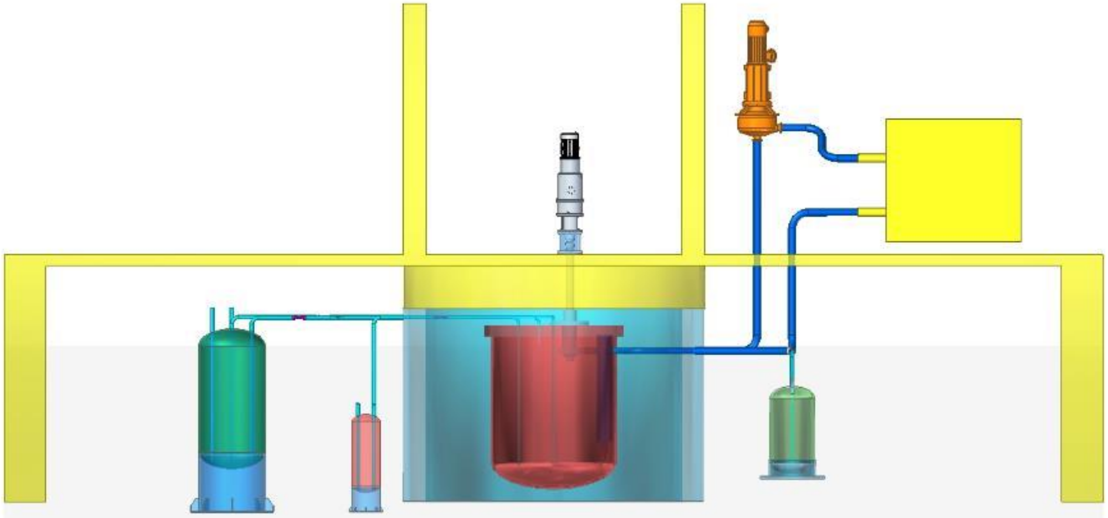
Progress of the TMSR-SF0 Construction

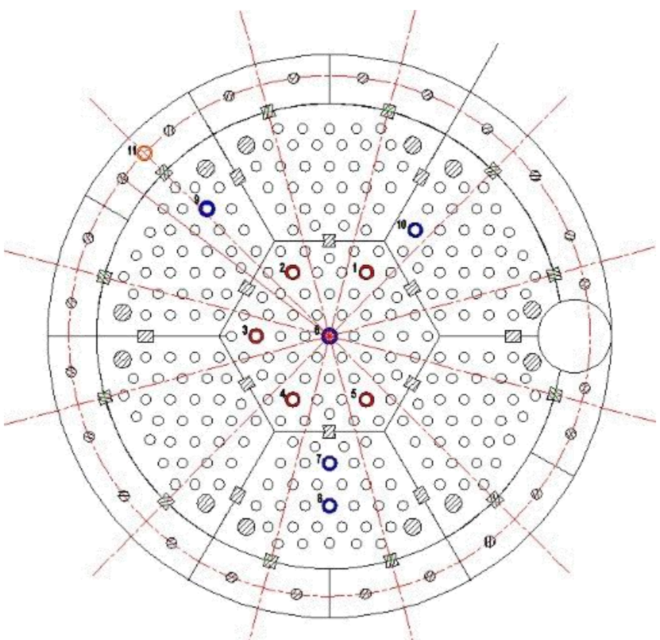


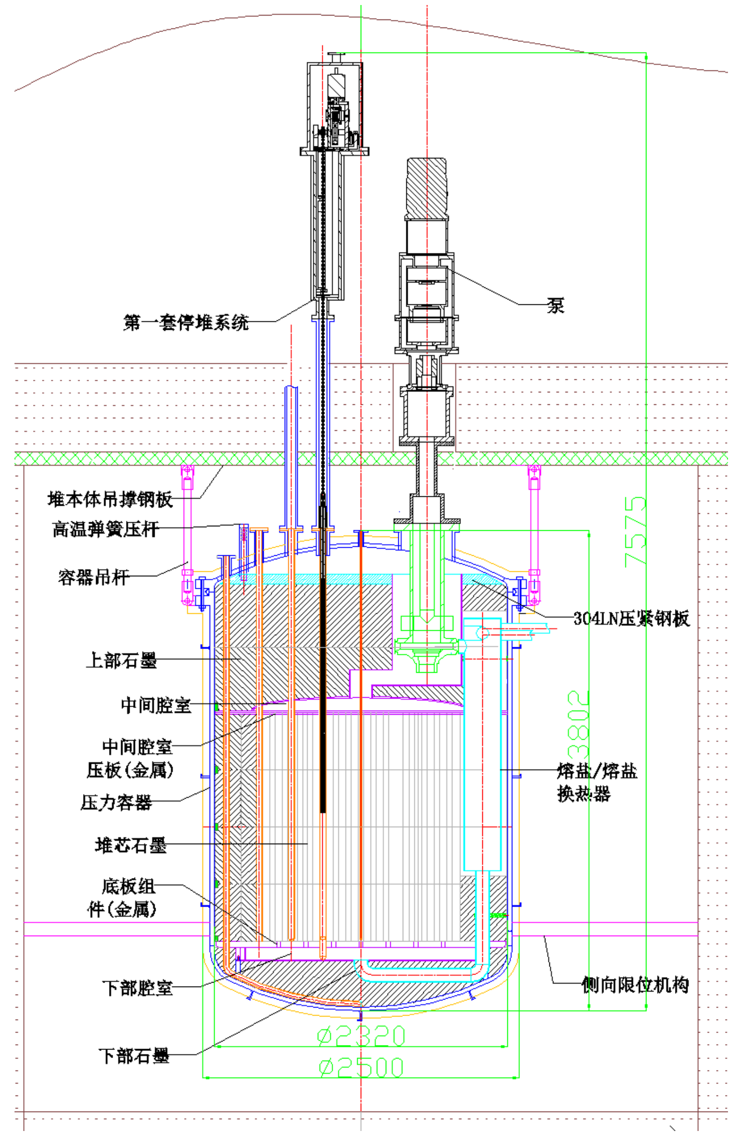
- The engineering design was complete and major components was ordered
- Steel frames were constructed
- Installation of major components is expected to start in mid of 2018
- A practice for the future test reactor construction



Progress of the TMSR-LF1 Design







TMSR Test Reactor Candidate Site

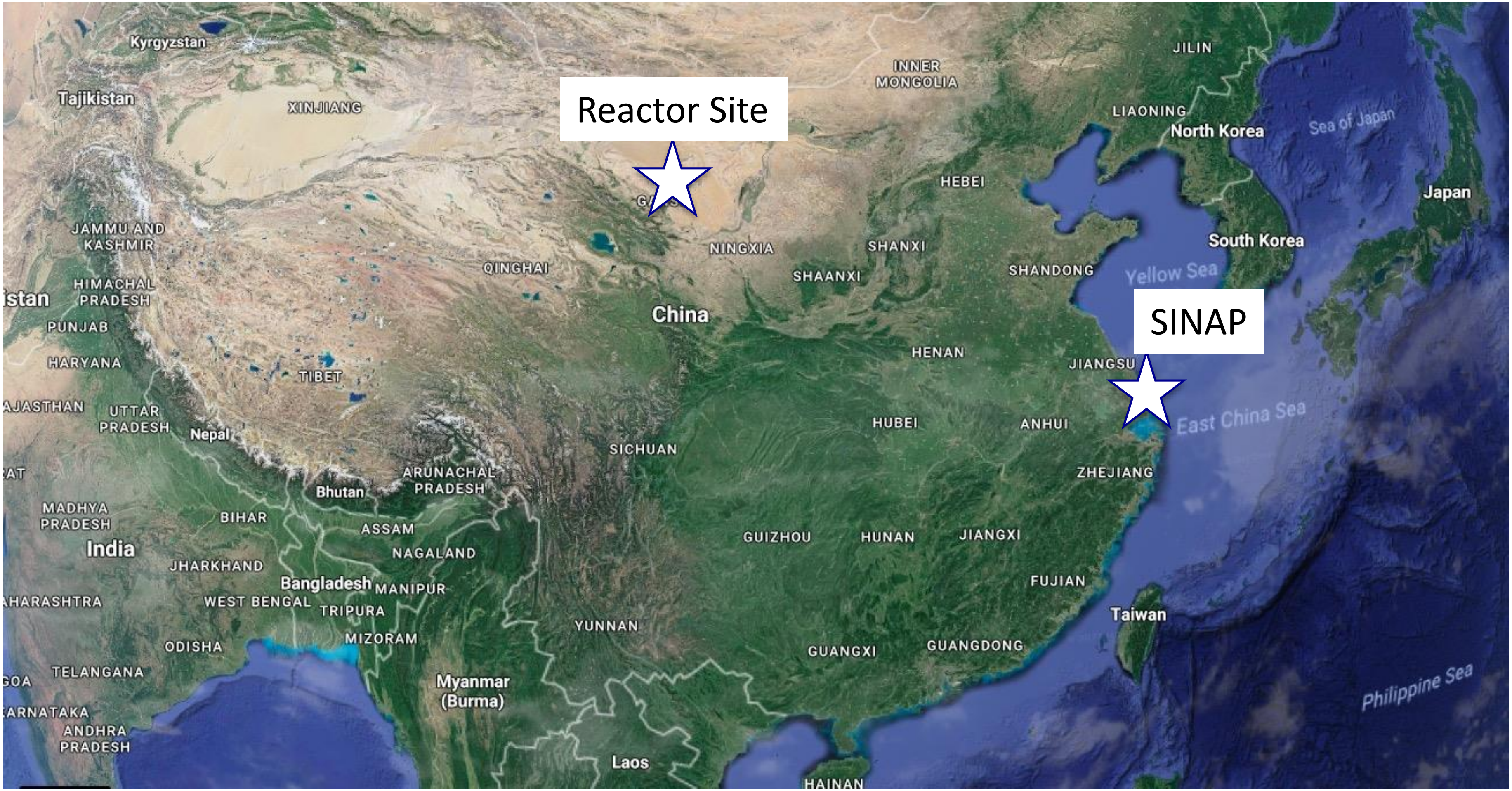
- State Power Investment Corporation (SPIC) was newly established through the merger of China Power Investment Corporation (CPI) and State Nuclear Power Technology Corporation (SNPTC)

- CAS and SPIC signed a science and technology collaboration agreement in March, 2016

Two AP1000 units are under construction at Haiyang (right)

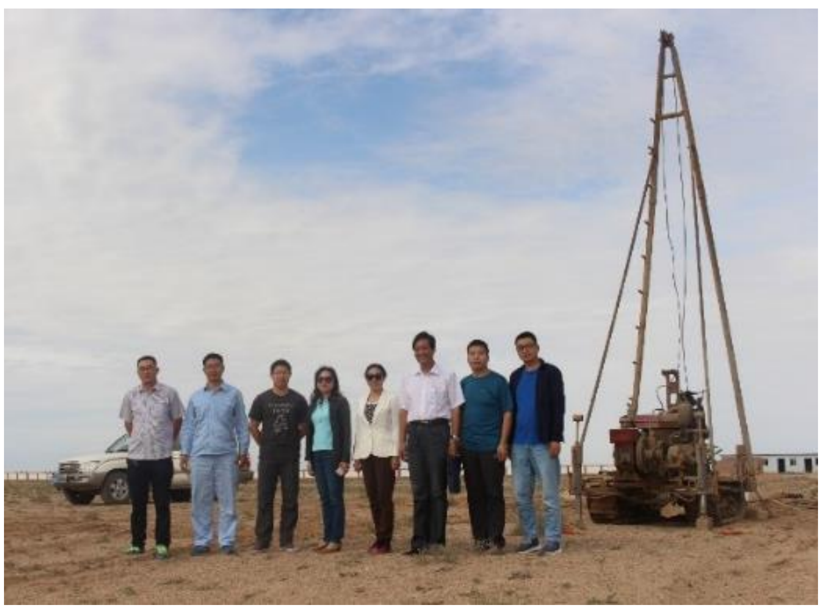
- Haiyang is now the candidate site for TMSR test reactors
- CAS and SPIC are jointly developing a Nuclear R&D park in Haiyang

New Candidate Site of the TMSR-LF1



- 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