Technical Meeting on the Status of Molten Salt Reactor Technology (622-I3-TM-52244)， IAEA Headquarters， Vienna, Austria

Thorium Molten Salt Reactors (TMSR) Development in China

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Shanghai Institute of Applied Physics, Chinese Academy of Sciences

Outline

TMSR Program Overview

Team & Collaboration

TMSR Research Progress

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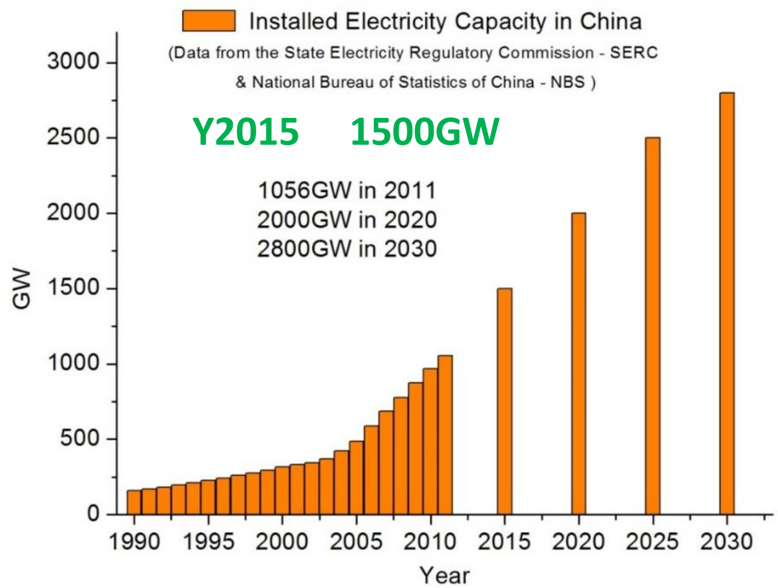
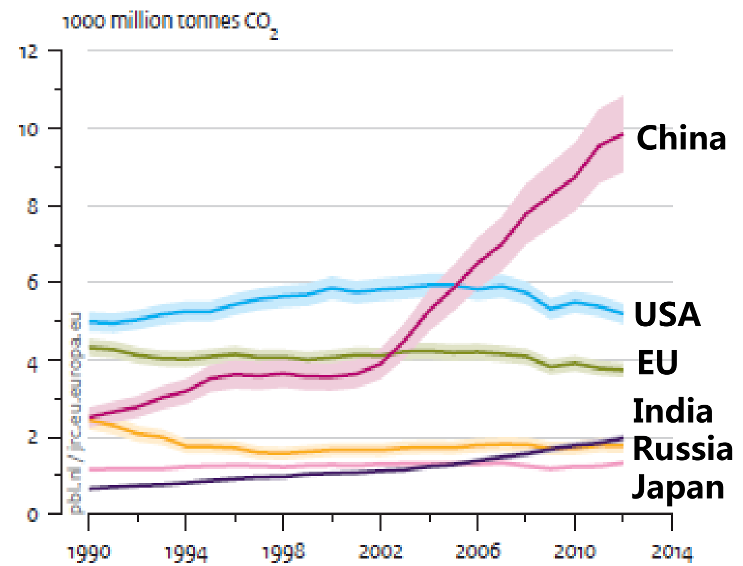
TMSR Research Progress

Energy Demand and CO_2 Emission of China





- **By year 2030, about 3000 GW-level electricity capacities are needed**
- Chinese electricity generation is dominated by fossil sources, coal (~70%)

Consumption of fuel produces large amount of CO_2 → greenhouse effect

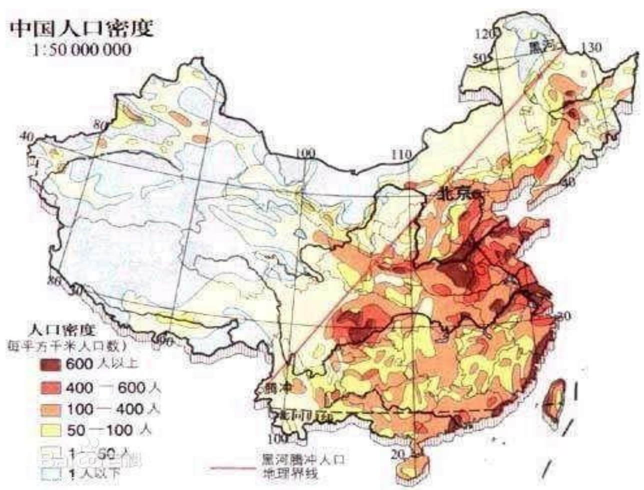
Burning coal produces airborne particles → frequent haze in China

2012: China became the top CO_2 emission Country

- **The Solution is developing Nuclear Energy**

Development of NPPs in China

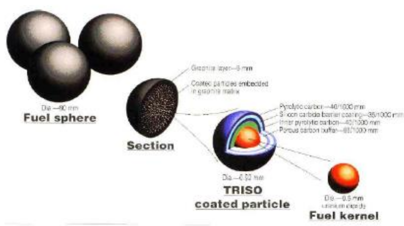
- **Up to May, 2016, there are 32 NPPs being operable, 22 NPPs under construction and 42 NPPs planned.**
- **Most of these NPPs are PWR , which consume lot of water.**
- **Water Scarcity in China, NPPs based on PWR are located along the coast, the total capacity is limited and can not satisfy the clean energy demand.**
- **Solution is to develop advanced non-water nuclear reactor**

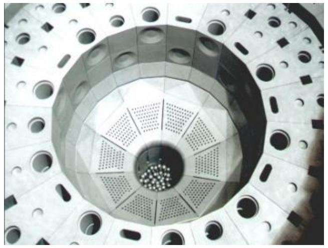


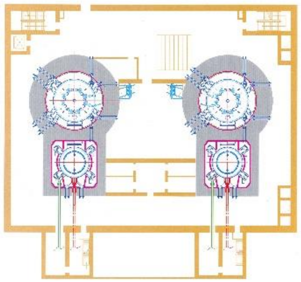
water scarcity by
province in China

R&D of Advanced Nuclear Reactor in China

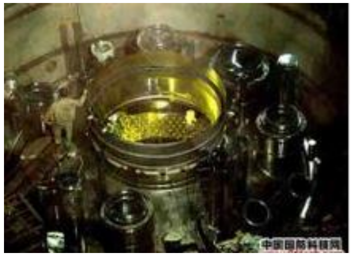
- Qinghua University: HTR-10 & HTR-PM (~200MWe)







- China Institute of Atomic Energy, CNNC: CEFR (65MWth SFR)



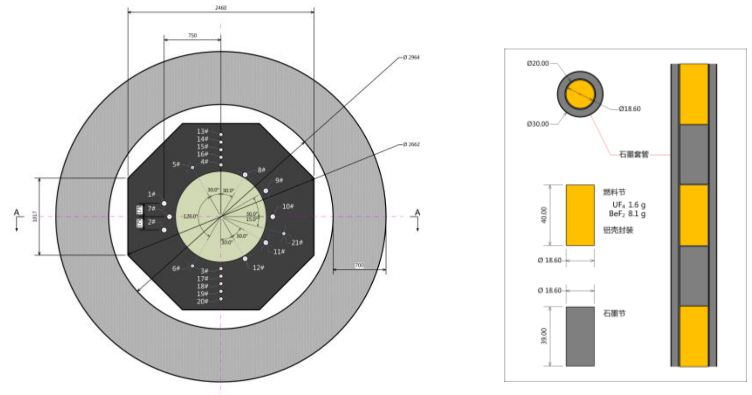
- SINAP (ANEI), CAS: TMSR
- IMP, IHEP&INEST, CAS: ADS (LFR)

Why TMSR?

- Fuel Supply: Thorium is 3 to 4 times more abundant than Uranium, especially China lack of Uranium but rich of Thorium.
- Nuclear Proliferation: Difficult to make weapon usable materials because of 232U (Gamma-irradiation) .
- Nuclear Waste: More than 90% reduction of long term radio-toxicity of spent fuel.
- MSR is suitable for thorium utilization, Thorium Molten Salt Reactor Energy System (TMSR).
- TMSR with Air-cooling Brayton Cycle is suitable for the mid and west of China & others where water is lacking.

Early Efforts for TMSR in China

- 1970, China started NPP Project in Shanghai, and its original goal is to build 25 MWe TMSR
- 1971.9.13, a zero-power MSR was built and reached critical in SINAP, but it was shutdown at the end of 1971.
- 1972-1975, the goal was changed to the Qinshan 300 MWe (Qinshan NPP-I), which has been operating since 1991.



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

7-8-9- BF_3 neutron counter

China Restarted TMSR Program

- January, 2011, Chinese Academy of Sciences (CAS) initiated (restarted) "Thorium Molten Salt Reactor Nuclear Energy System" (TMSR) Strategetic Pioneer Sci.&Tech. Project.
- August, 2013, TMSR was one of the National-Energy Major R&D projects of Chinese National Energy Administration (CNEA)。
- May, 2015, TMSR was one of the Major S&T Projects by Shanghai Local Government for "Development of Global S&T Innovation Center" .

The Aims of TMSR Program

- The Aims of TMSR Program is to develop Th-Energy, Non-electric application of Nuclear Energy based on Liquid-Fuel TMSR and Solid-Fuel TMSR during coming 20-30 years.
  - ➢ Liquid-Fuel TMSR (TMSR-LF)--- MSRs
  - ➢ Solid-Fuel TMSR (TMSR-SF)--- FHRs

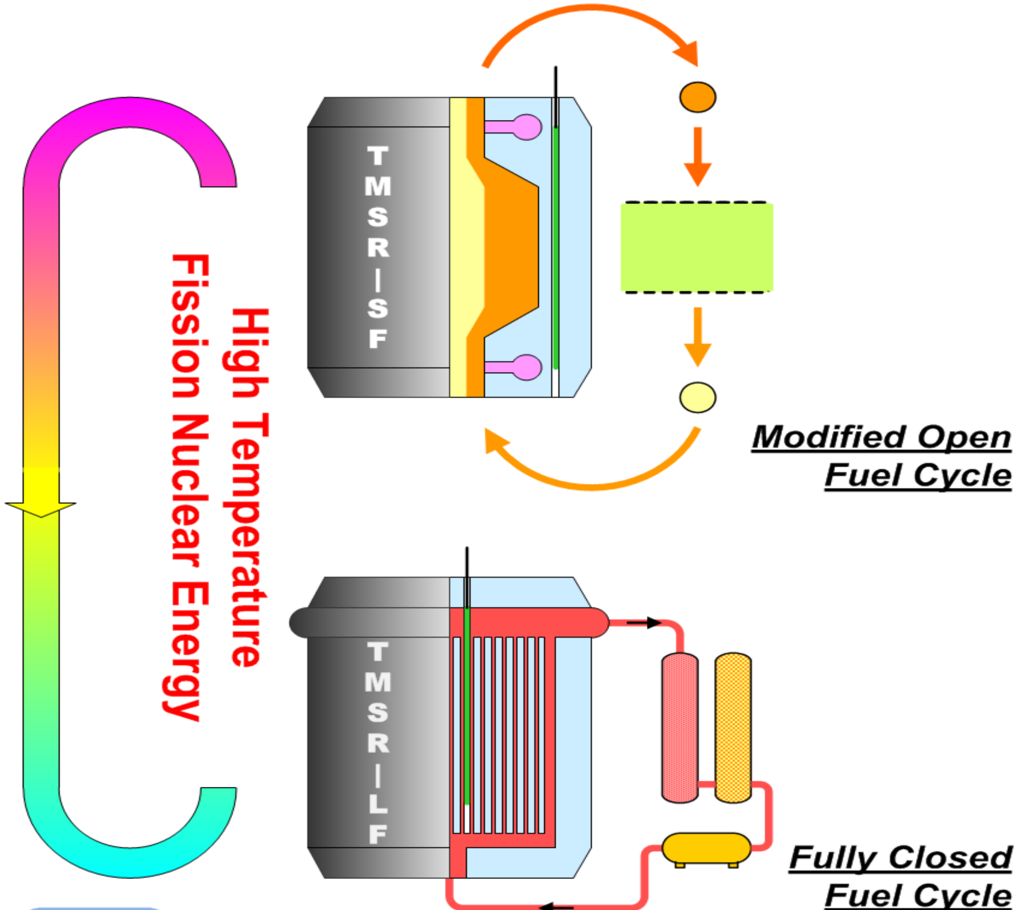
TMSR-LF: Optimized for utilization of Thorium.

TMSR-SF: Optimized for high-temperature (~700 °C) based hybrid nuclear energy application (Non-electric application).

Developing two-types MSR, Realizing four Application

---National Mission-Oriented

- 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 Development Strategy

R&D、Design、Licensing → Demonstration → Commercial

Simulator (2017)

Test Reactor (2020)

Demonstration Reactor (2025)

Commercial Reactor (2030)

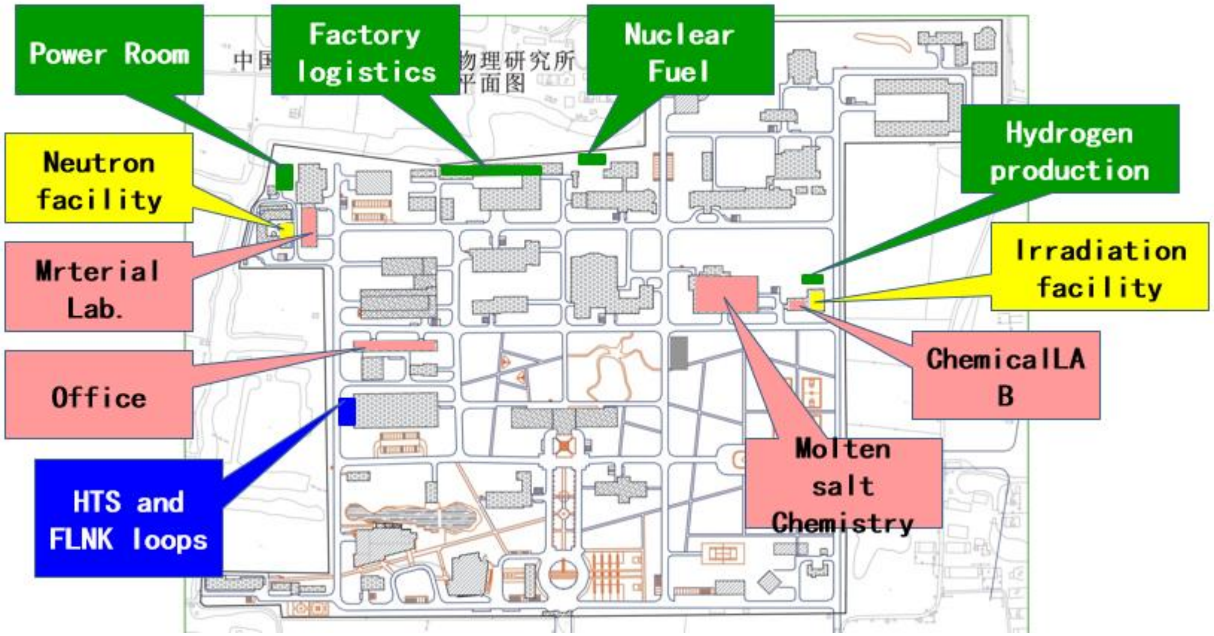
Simulator (2017)	Test Reactor (2020)	Demonstration Reactor (2025)
Key technology and component development, Simulator (mock-up) (TMSR-SF0)	2MWth liquid-fuel test reactor (TMSR-LF1) 10MWth Solid-fuel test reactor (TMSR-SF1)	168MWe liquid-fuel demonstration reactor (TMSR-LF2) 168MWe solid-fuel demonstration reactor (TMSR-SF2)

CAS TMSR Project (2011-2018): 2.17B RMB
Shanghai Local Government (2015-2017): 115M RMB

TMSR Research Bases

- **Fundamental research base at Jiading Campus of SINAP**
  - Material, Simulation, Thermal hydraulic, Safety facilities, Education and training et al., (without high radioactivity)
- **Nuclear R&D Park (TMSR Reactor Site)**
  - Experimental reactors, High radioactivity Lab., Chemical reprocessing Lab. et al.,

Fundamental research base in Jiading



Design Platform

Hot Cell

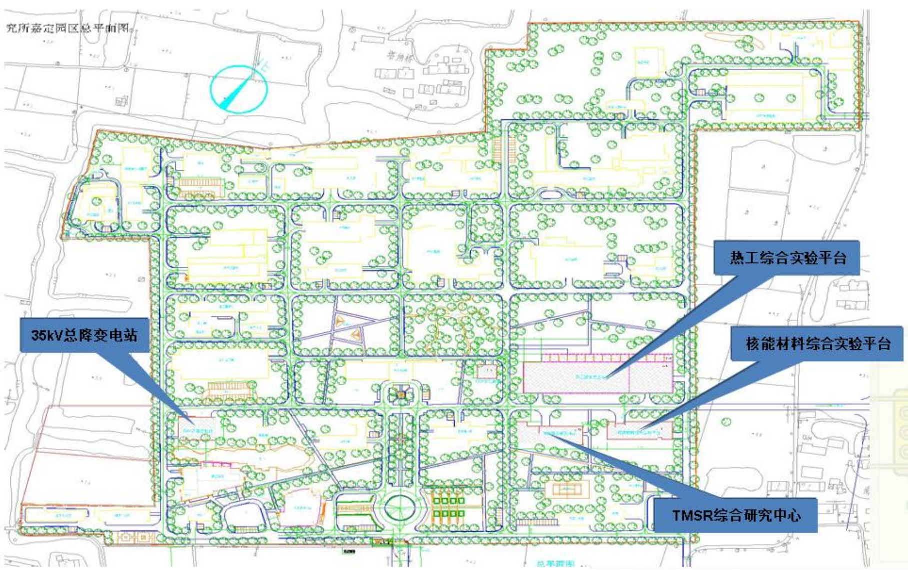
Material test Lab.

Molten salt measure Lab.

β Irradiation Facility

Fundamental research base in Jiading(II)

- 3 new building with 18000 m² has been finished in mid of 2016 at Jiading Campus of SINAP, which are Integrated Research Center, Thermo-tech Test Platform, Nuclear materials Test Platform



Thermo-tech Test Platform

Nuclear materials Test Platform

Integrated Research Center

TMSR Test Reactor Site

- **CAS and SPIC signed a science and technology collaboration agreement in March, 2016.**
  - Haiyang is now the candidate site for test reactors
  - CAS and SPIC are jointly developing a Nuclear R&D park in Haiyang

Two AP1000 units are under construction at Haiyang (right)

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

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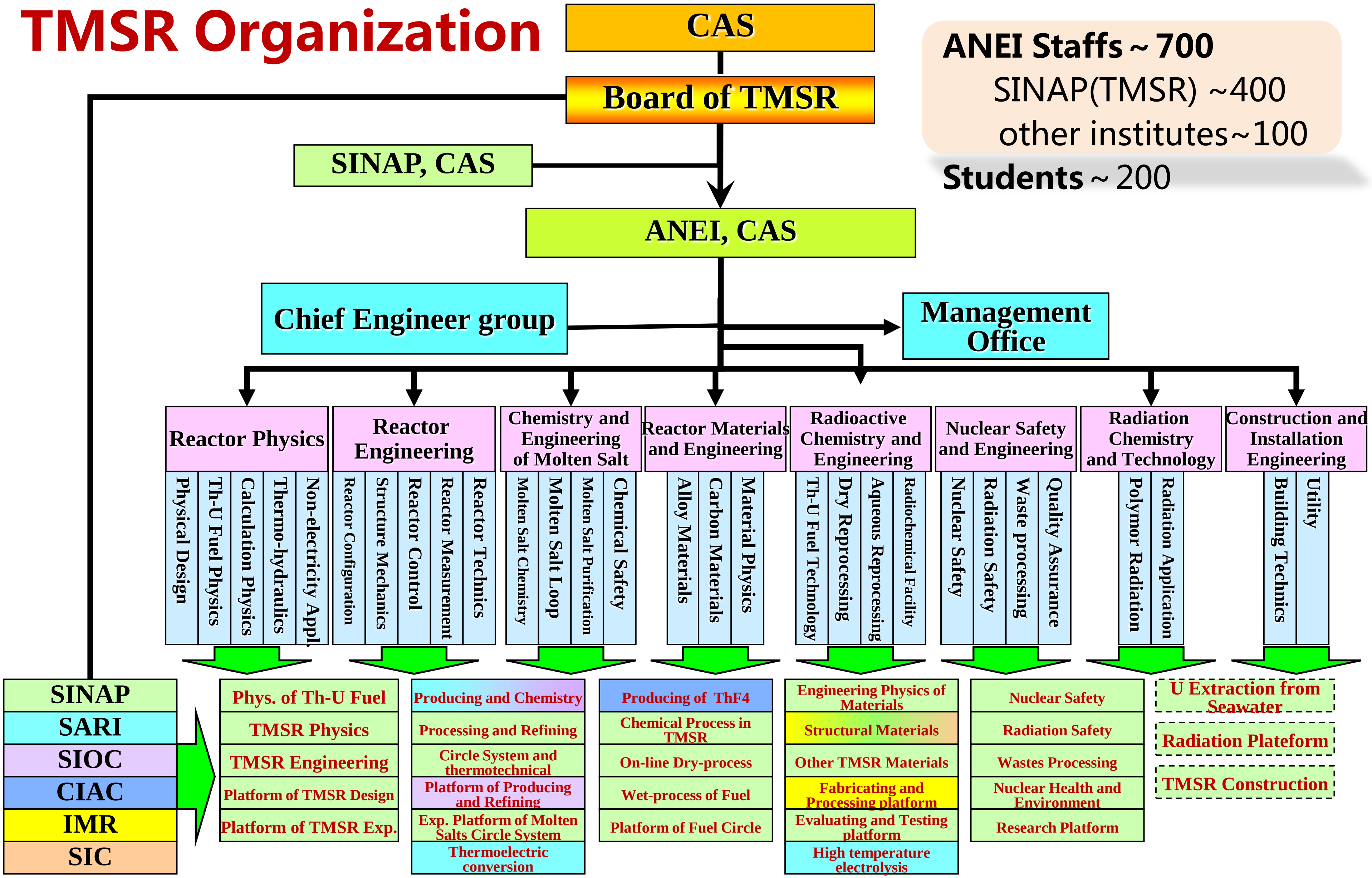
TMSR Organization

ANEI Staffs ~ 700
SINAP(TMSR) ~400
other institutes~100
Students ~ 200

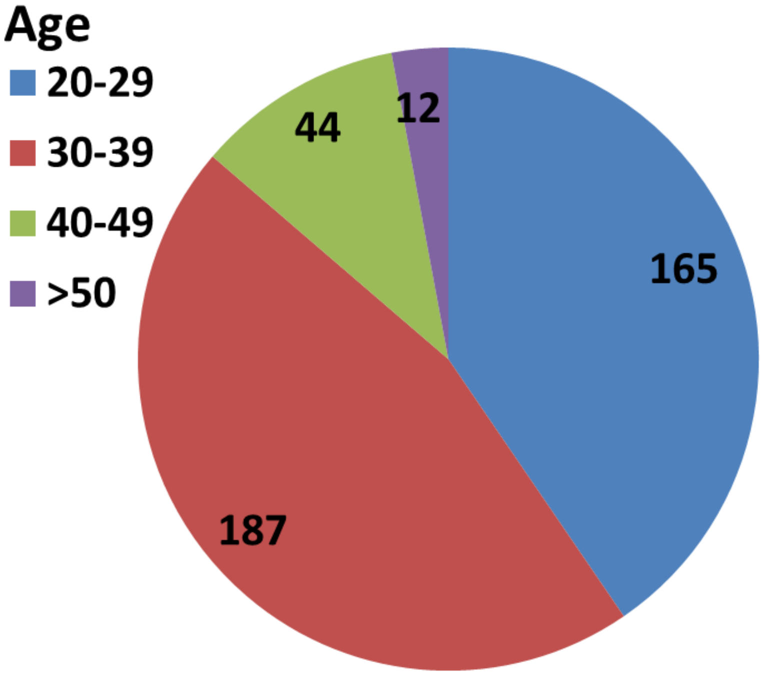


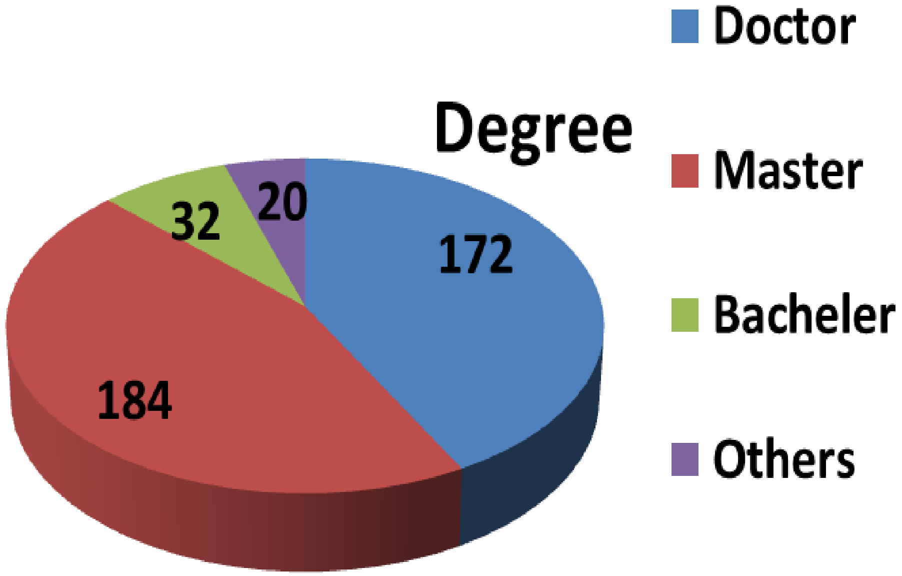
Institute of Advanced Nuclear Energy

- **The Institute of Advanced Nuclear Energy （ANEI）is an organization established by CAS for leading the TMSR program**
  - **There are 7 institutes of CAS involved in TMSR program**
  - **There are about 500 staffs and 200 graduatestudents of ANEI, in which ~400 staffs from SINAP and ~100 staffs from other institutes**

Research institutes	Tasks in TMSR program
Shanghai Institute of Applied Physics	● undertakes more than 80% of the R&D work with about 80% of the funding
Shanghai Institute of Organic Chemistry	● Extraction methods for lithium isotope separation
Shanghai Advanced Research Institute	● Thermal power conversion technology ● Production of methanol with CO_2
Institute of Metal Research	● R&D of nickel-based alloy with corrosion resistance to molten salt
Changchun Institute of Applied Chemistry	● Production of nuclear grade thorium
Shanghai Institute of Ceramics	● R&D of SiC-SiC composite materials and carbon-based materials
Institute of Coal Chemistry	● R&D of new grade of nuclear graphite

The SINAP TMSR Team





- ~400 employees with average age of 33.
- ~100 senior staffs (above subgroup leaders) with average age of 40.

TMSR Domestic Cooperation
With Univ./Institute

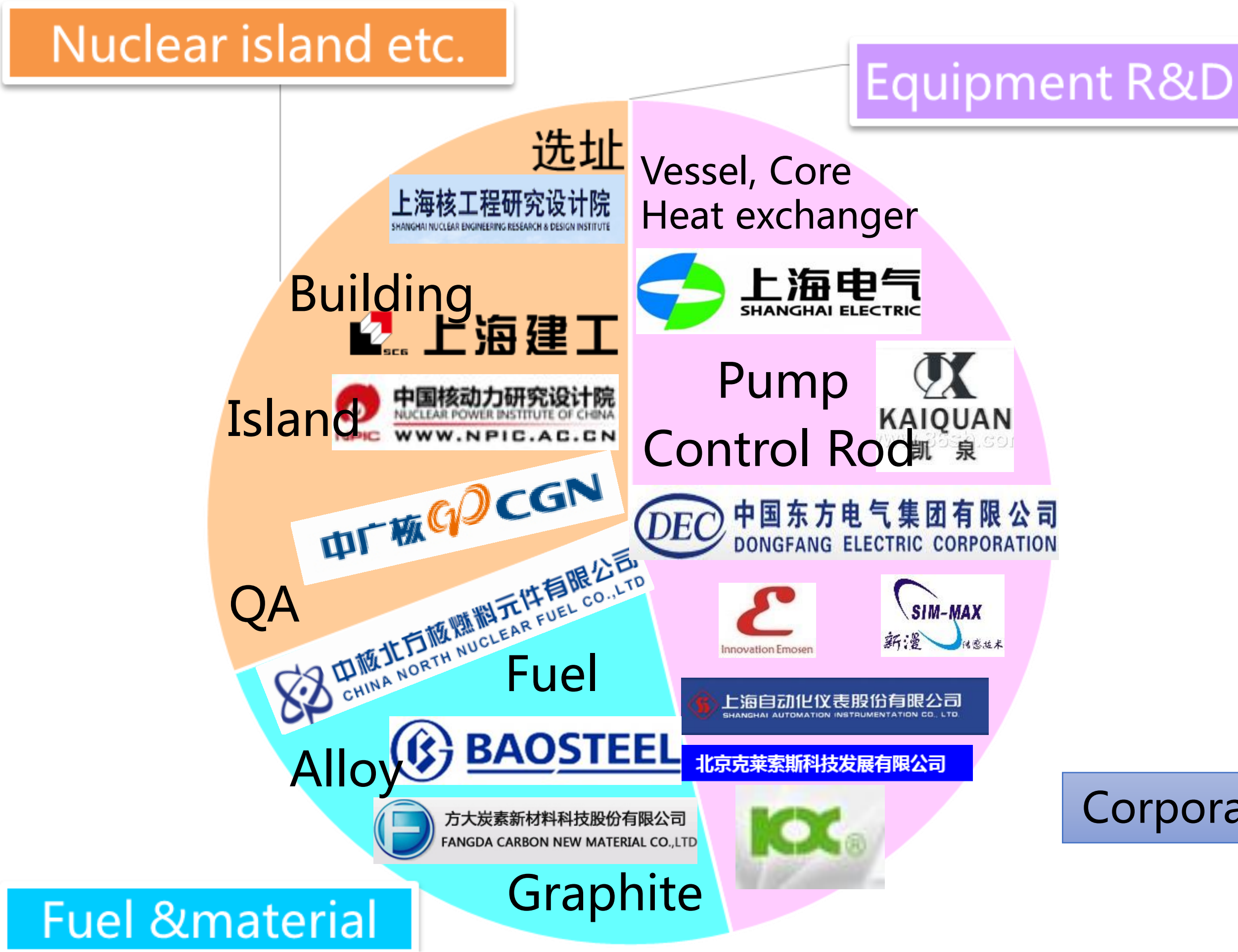
Research Fields：

- Fundamental research
- Data/method/software
- Specific technology R&D

Institutes (～10)

Universities (～20)

TMSR Cooperation With Domestic Corporation (Design/equipment manufacture)



Corporations（～15）

TMSR International Cooperation

- Th Utilization, Reactor Tech.
- Material, Molten Salt Tech,
- Pyro-processing
- Nuclear Safety Standards

Organizational Overview

The Chinese Academy of Sciences (CAS) and U.S. Department of Energy (DOE)
Nuclear Energy Cooperation Memorandum of Understanding (MOU)

MOU Executive Committee Co-Chairs

China – Mianheng Jiang (CAS)
U.S. – Pete Lyons (DOE)

GEN IV International Forum

Australia

ansto
Nuclear-based science benefiting all Australians

Future

- Russia
- EU
- Korea
- Japan
- others

Collaboration with USA-I

FHR Safety Standards
ANSI/ANS-20.1

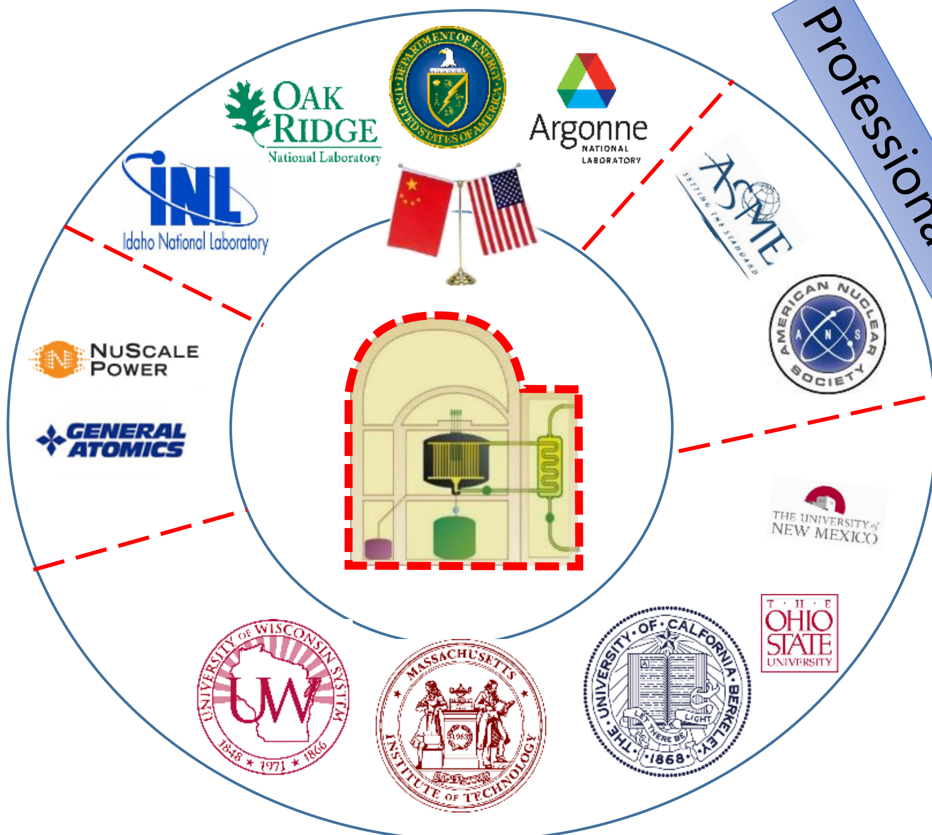
FHR technology
Pyro-processing

US DOE Labs

High-tem. Material
ASME

Professional Society

US Industry



US Universities

中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

Collaboration with USA-II

The CAS-DOE Nuclear Energy Sciences & Technologies Cooperation MOU signed in Nov. 2011.

First meeting in Shanghai 2012

SINAP-ORNL CRADA
signed in July 2014

SINAP-MIT MRA
signed in March 2015

Review meeting for TMSR-SF1 in UCB

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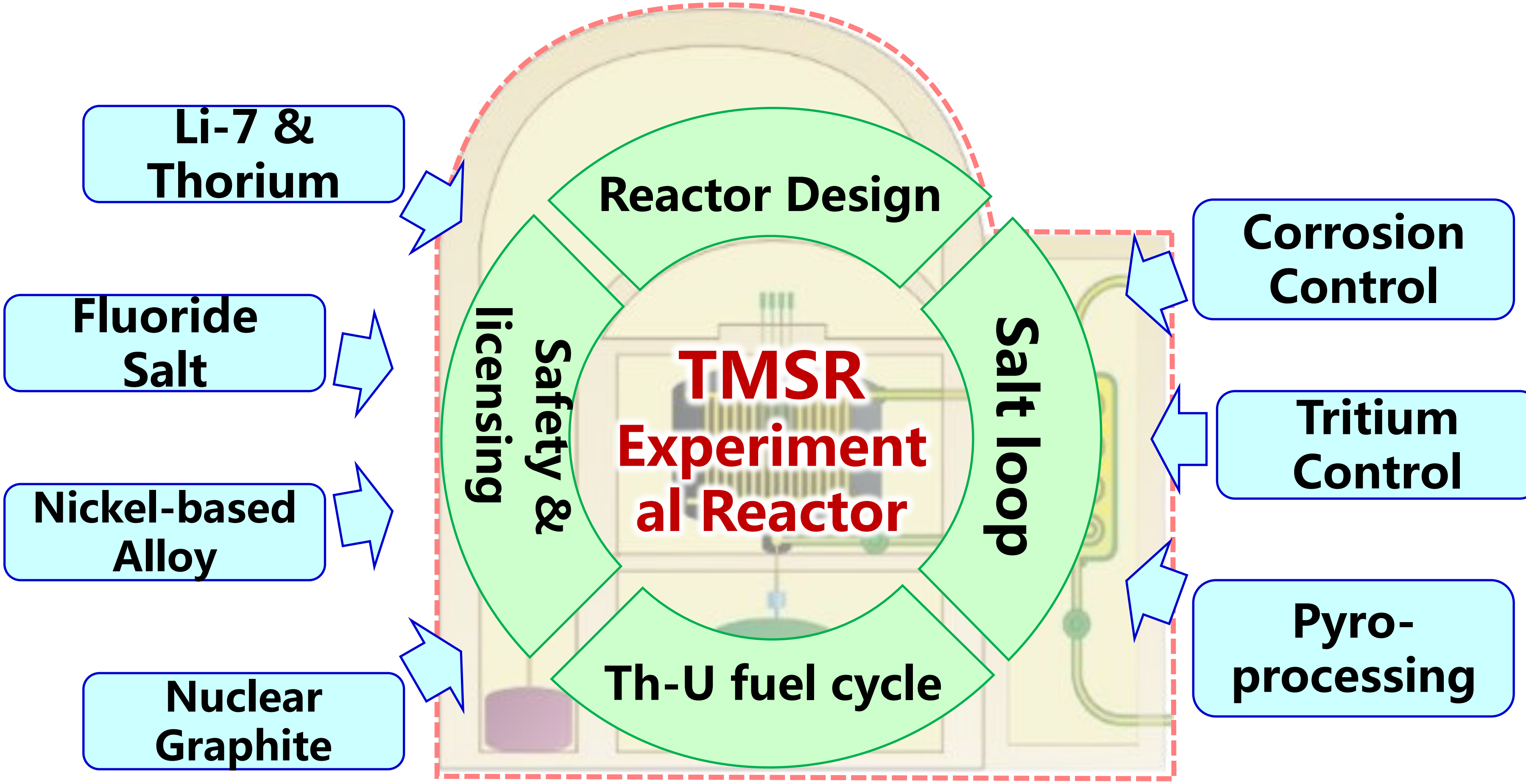
Prototype Systems and Key Techs @ TMSR



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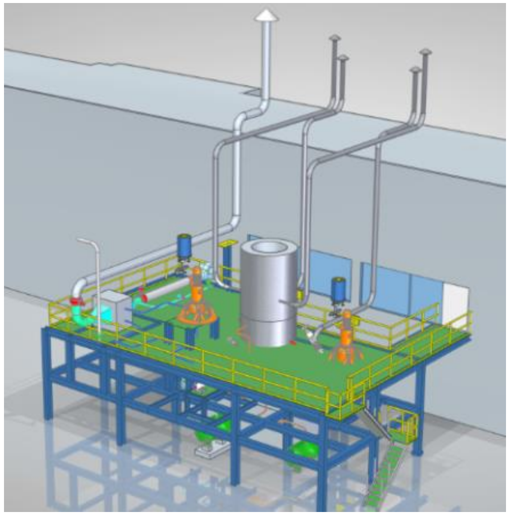
TMSR Research Progress

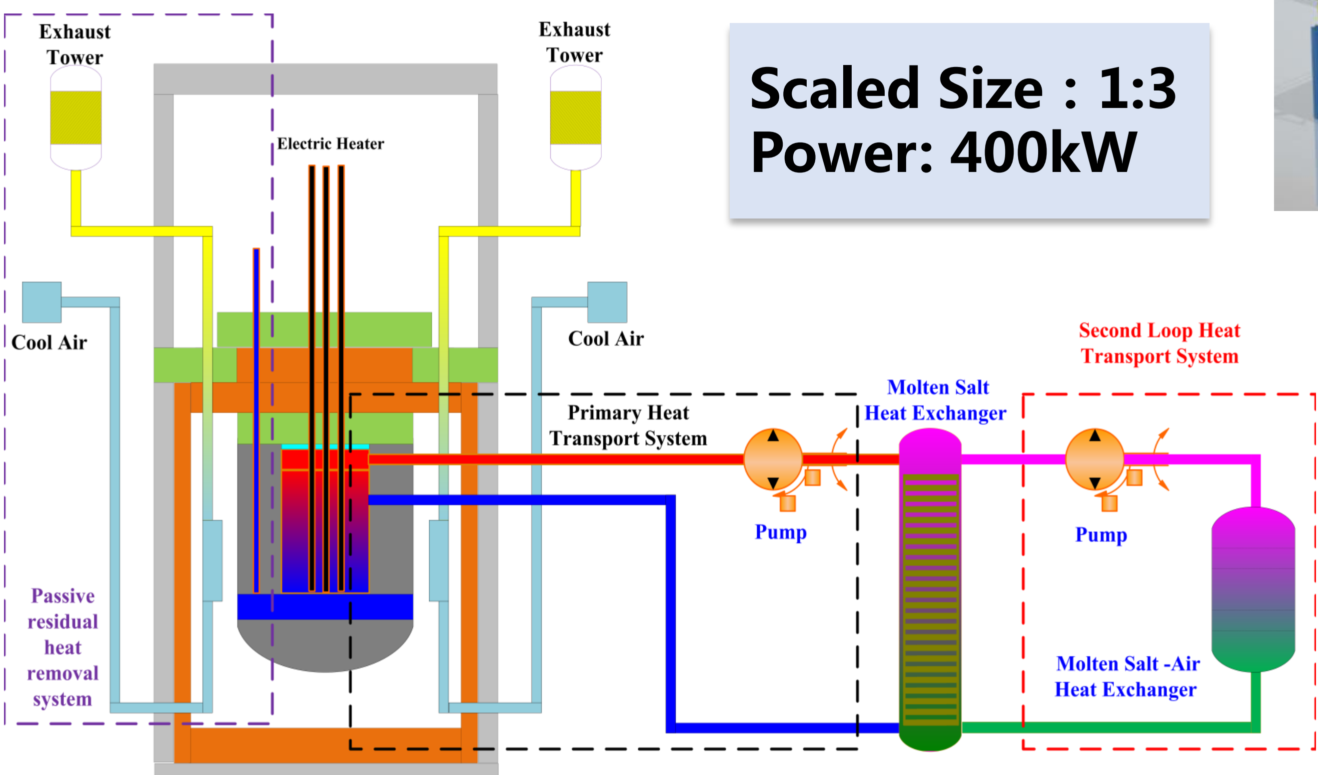
--Reactor Design

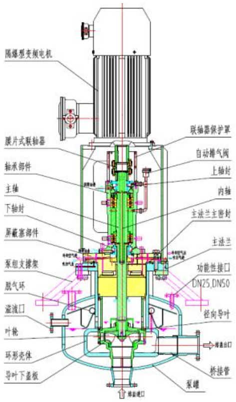
TMSR - SF0 (Mock-up)

- Integrated TH effect testing
- Key phenomena verifying
- Component and material testing
- Operator training



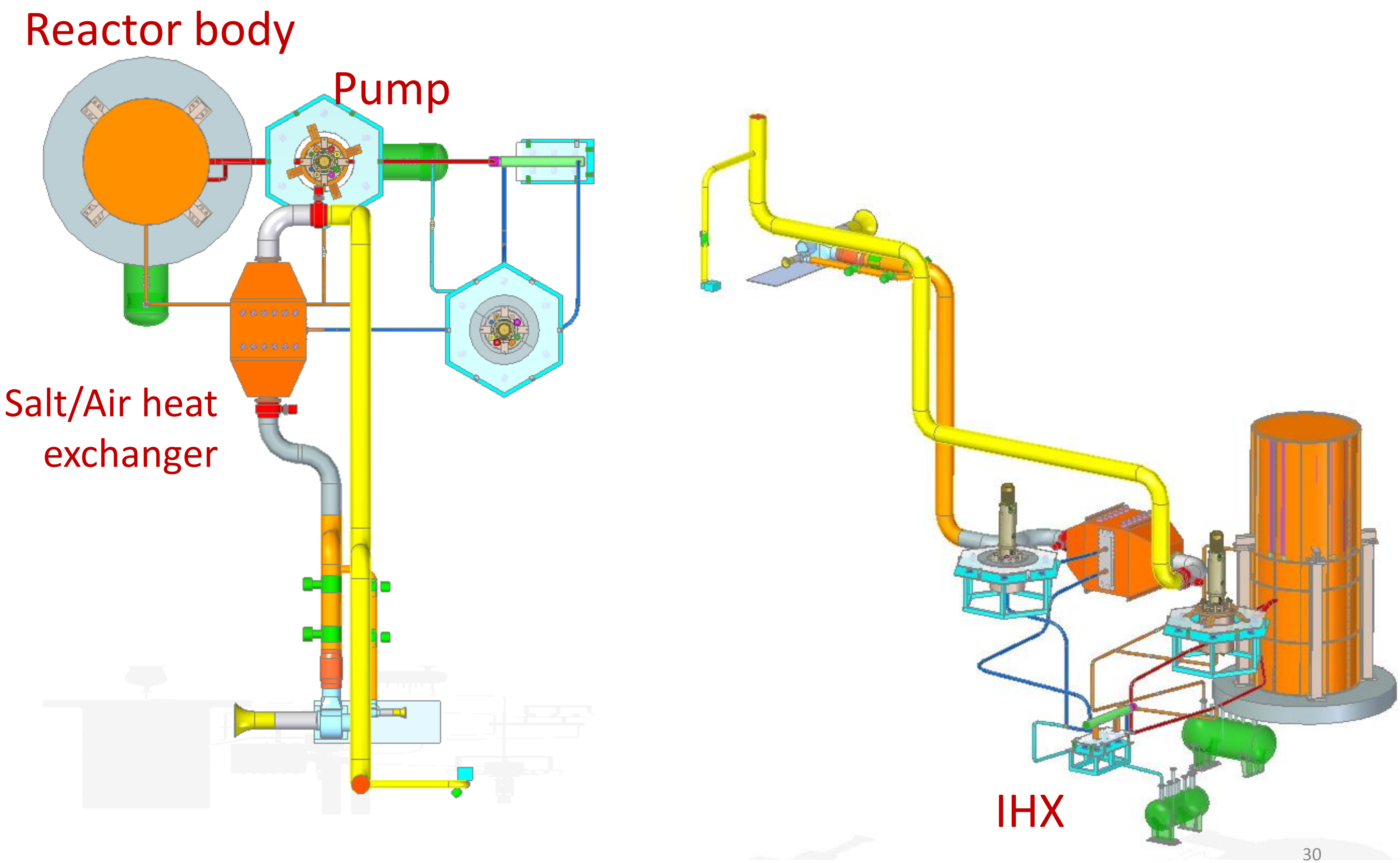
Scaled Size : 1:3
Power: 400kW





Molten Salt Pump

TMSR-SF0 Layout



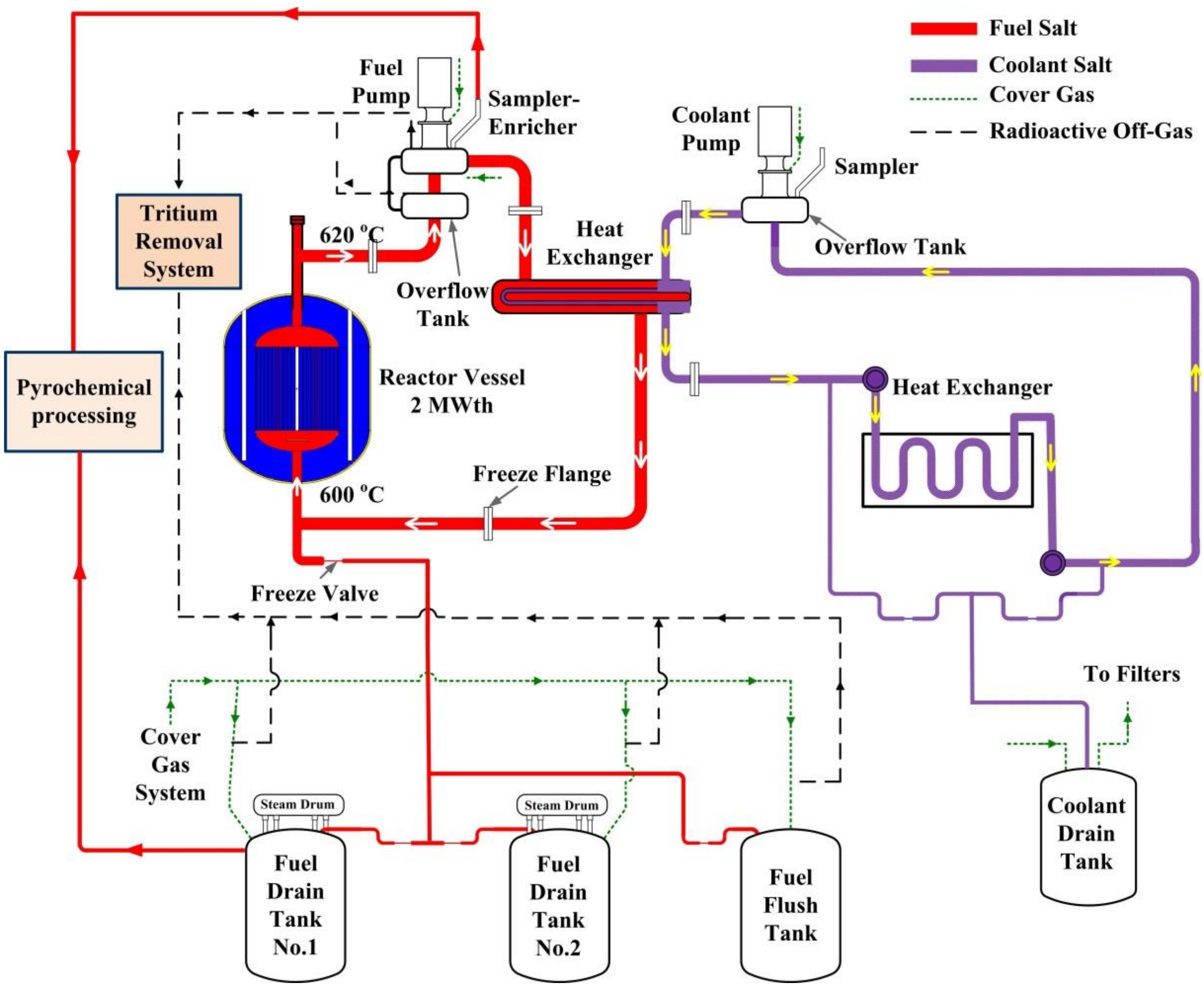
TMSR-LF1 (liquid-fuel)

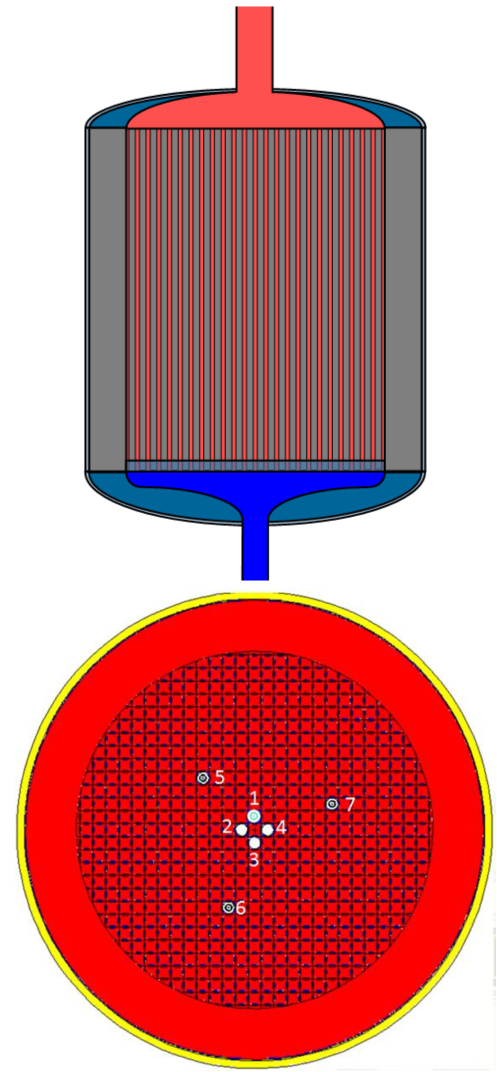
Goals of TMSR-LF1

- Verifying the concept of liquid-fuel MSR with pyro-processing.
- Research on the Th-U cycle and its features.
- Experimental platform for future reactors and Th-U cycle development.

Parameters	Value	Parameters	Value
Thermal power	2 MWth	Candidate salts	LiF-BeF_2-UF_4-ThF_4
Inlet temperature	600 ℃	Outlet temperature	650 ℃
Number of Loops	2		

TMSR-LF1 Schematic layout



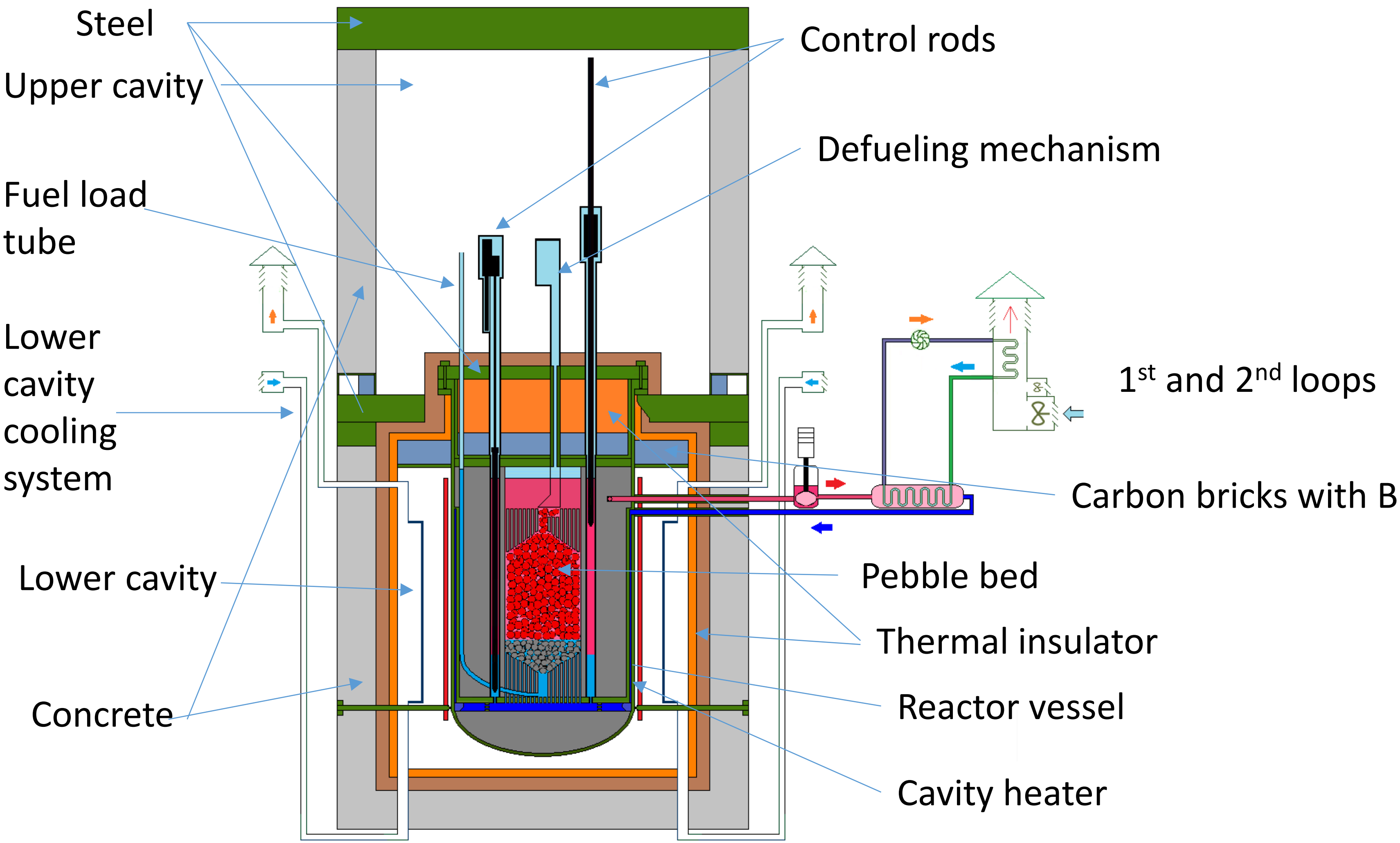


TMSR-SF1 (Solid-fuel)

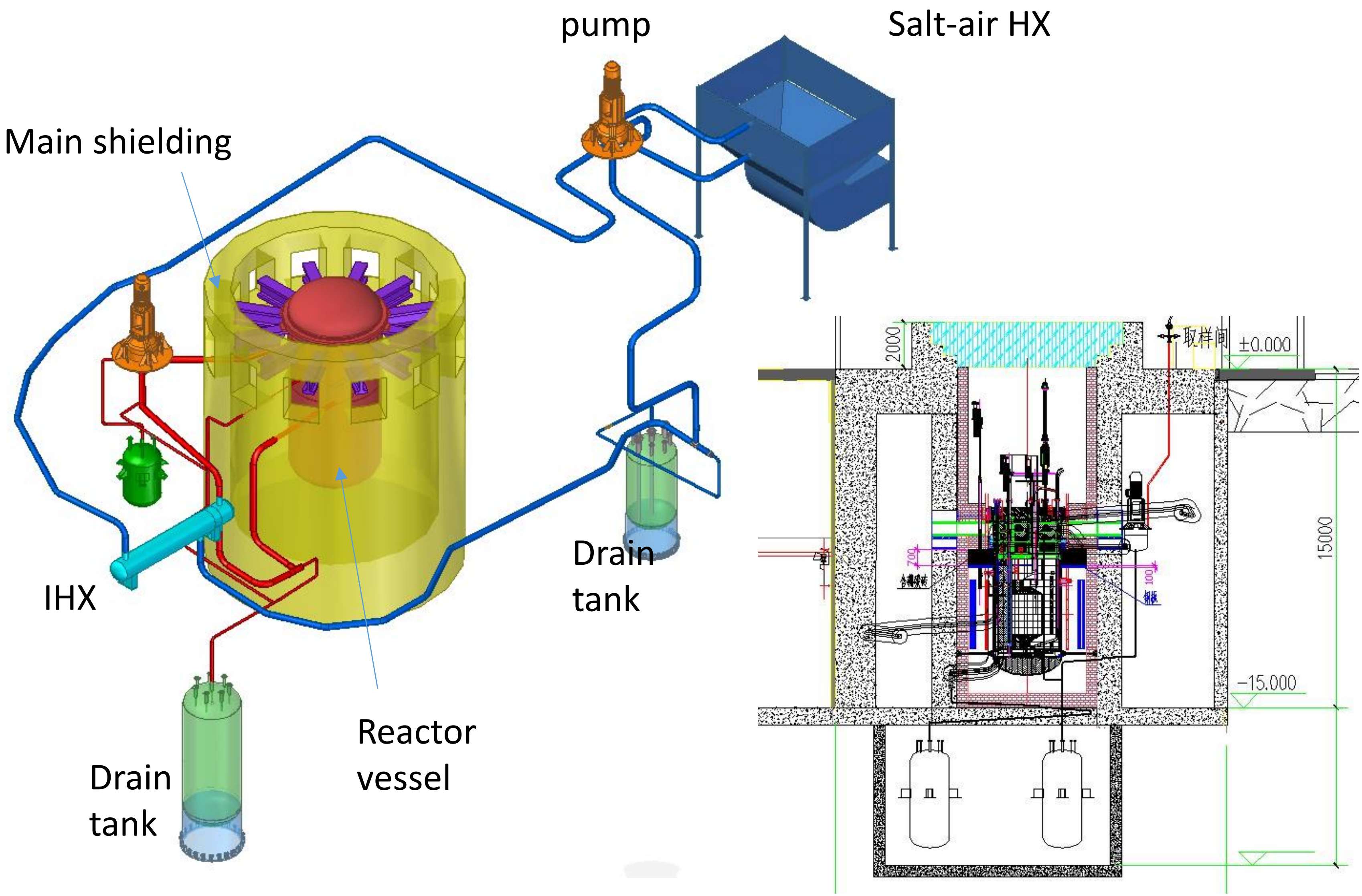
- **Goals of TMSR-SF1**
- Verifying the concept of solid-fuel MSR.
- Experimental platform for future solid-fuel TMSR development: Reactor physics research, design, benchmark of modeling codes, technology and components test, materials and fuel (component) irradiated properties, etc..

Parameters	**Value**	**Parameters**	**Value**
Thermal power	10 MWth	Candidate salts	LiF-BeF_2
Inlet temperature	600 ℃	Outlet temperature	650 ℃
Number of Loops	2	Fuel element:	TRISO fuel

TMSR-SF1 Schematic layout



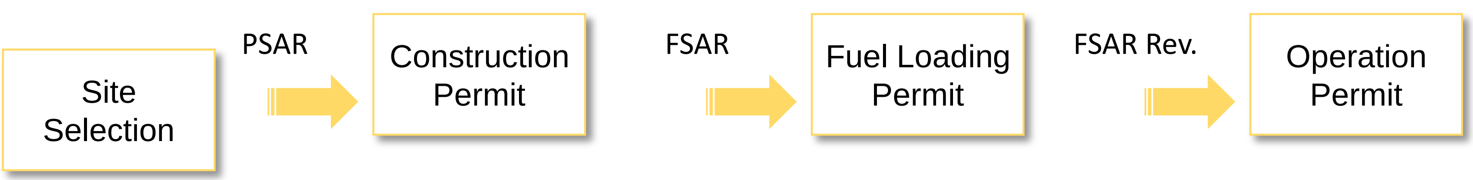
TMSR-SF1 system layout



Nuclear Safety and Licensing

- Developing safety analysis methods and codes
- Developing safety design criteria and completing safety system design
- 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 experiments for code validation



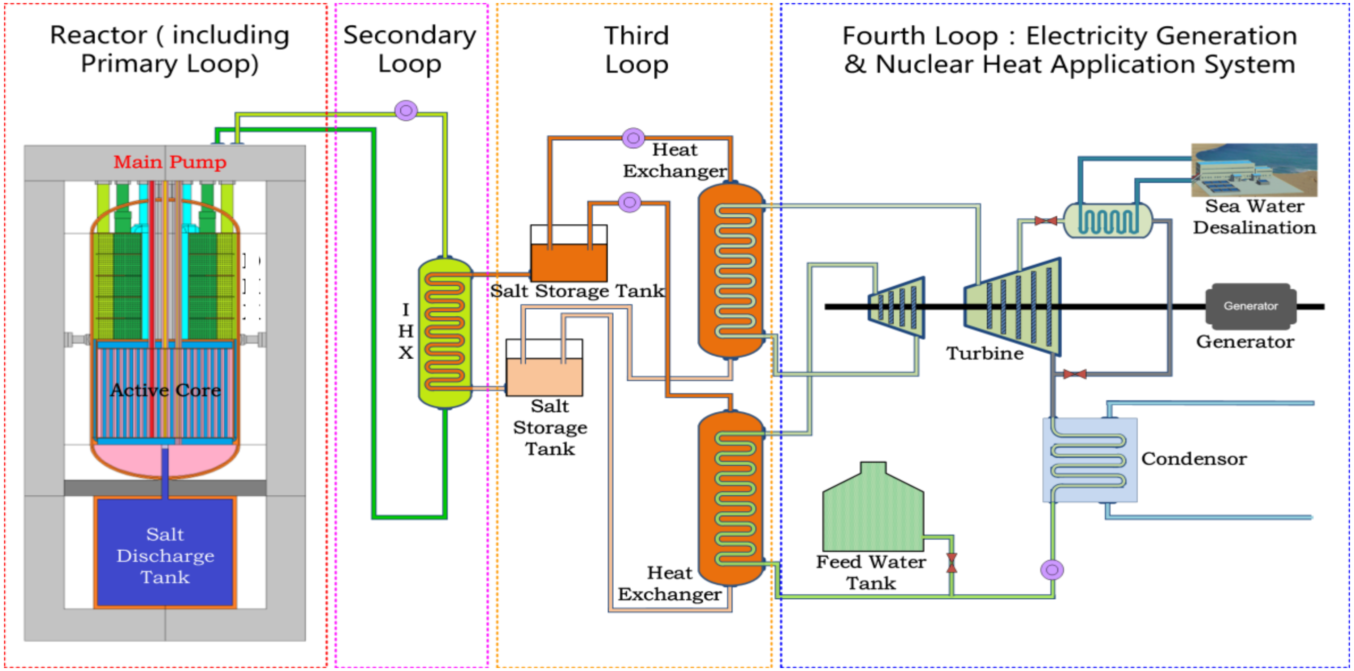
A review meeting for test reactor site is planned at the end of 2016

Small Modular TMSR-LF2

■ A multi-purpose clean energy supplier

- Electricity production
- Seawater desalination
- Hydrogen or methyl alcohol production
- Steam supply

■ Demonstrate economical utilization of Th in MSR



Main Features of TMSR-LF2

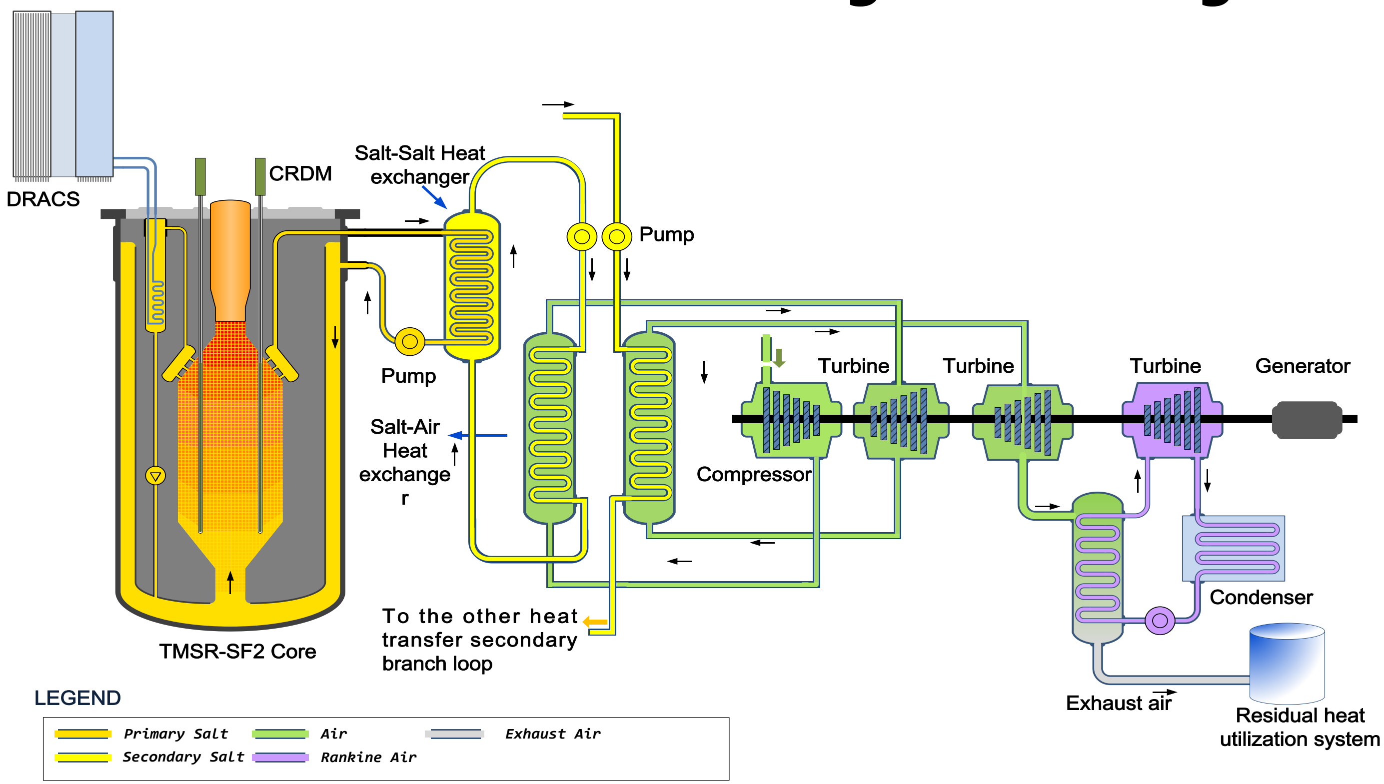
Reactor type	Small modular liquid-fueled Molten Salt Reactor
Power of one unit	373MWth / 168 MWe
In / Out temperature	600 / 700 ℃
Generator	Open Air Brayton Cycle & Super CO_2 cycle, et.al.
Fuel salts	$LiF-BeF_2-UF_4-ThF_4$ (19.75% U-235)
Moderator	Graphite
Structural material	Nickel-based alloy， stainless steel
Processing for Fuel cycle	Online degassing (Xe, ke, T), off-line remove solid fission products
Residual Heat removal	Whole passive residual heat removal system

Small Modular TMSR-SF2

■ A multi-purpose clean energy supplier

- ➢Electricity production
- ➢Seawater desalination
- ➢Hydrogen or methyl alcohol production
- ➢Steam supply

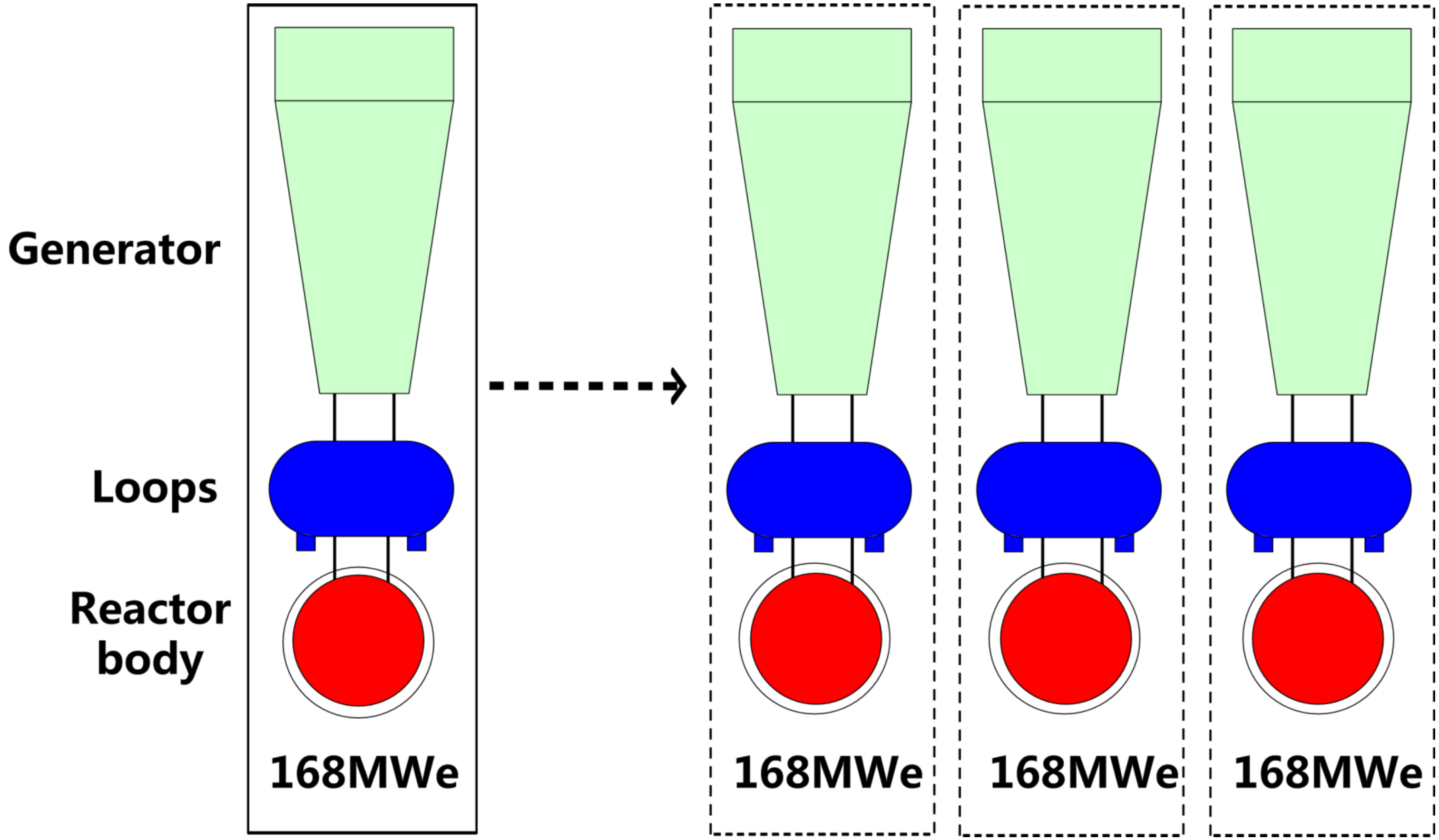
■ A desired reactor for in-land region with high safety



Main Features of TMSR-SF2

Reactor Type	Solid-fueled Molten Salt Reactor
Residual Heat Removal System in accidents	Passive residual heat removal system
Generator	Air-Brayton power generator Water-free cooled
Power	384MWth / 168 MWe
In / Out temperature	600 / 700 ℃
Fuel	4cm Triso particle sphere
Coolant	FLiBe （99.995% Li-7）

Scale up for different power requirements



Typical deployment for a station

One unit, two units, six units (GW level)

Outline

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TMSR Research Progress

--Key Component Development & test

Molten Salt Loops & Key Equipments

Pump

Chemical Pump

Prototype Nuclear-Grade Pump

- **Parameters**

Temp：550~700℃
Flow：300m^3/h
Lift：~20m
Rot Speed：1480r/min

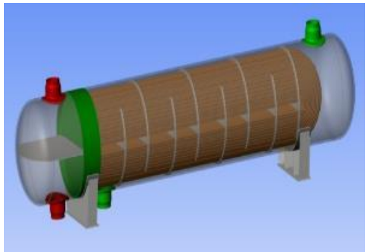
Valve

Principle prototype

Pre-engineering prototype

Heat Exchanger

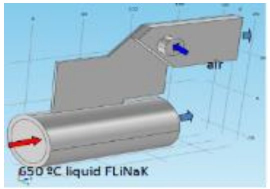
Salt – Air HX



Salt – Salt HX

Instrumentation

Pressure gauge

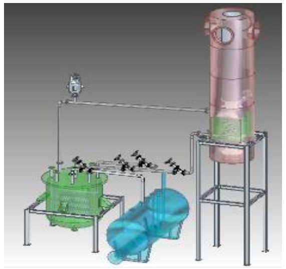


HT ultrasonic flowmeter

Loop

Nitrate test loop

FLiNaK test loop



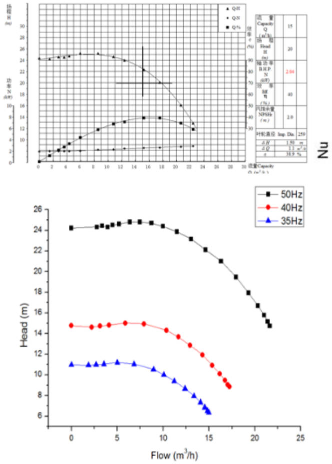
Natural circulation test loop

中国科学院上海应用物理研究所

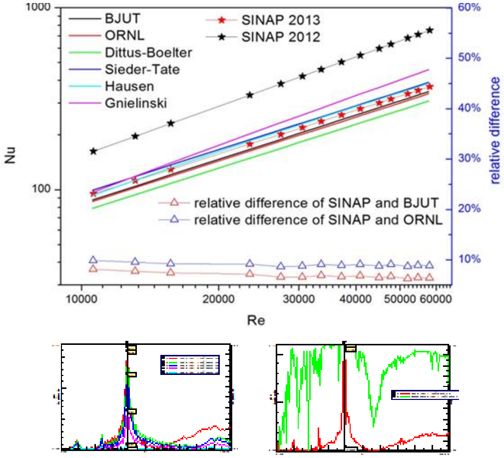
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

SINAP

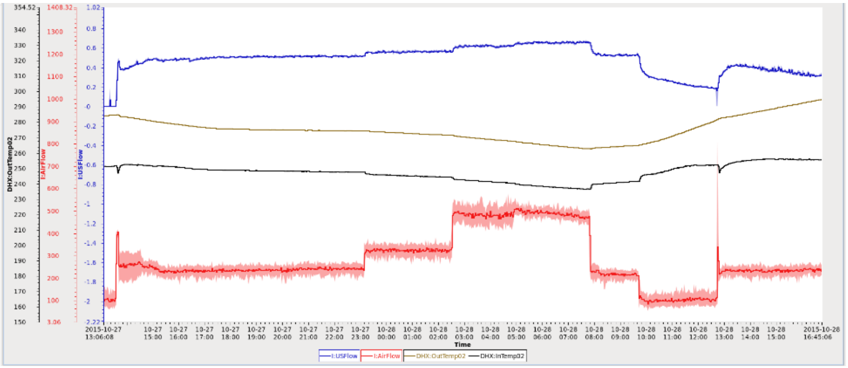
High-temperature molten-salt Loop & test



Hydraulic test of molten salt pump



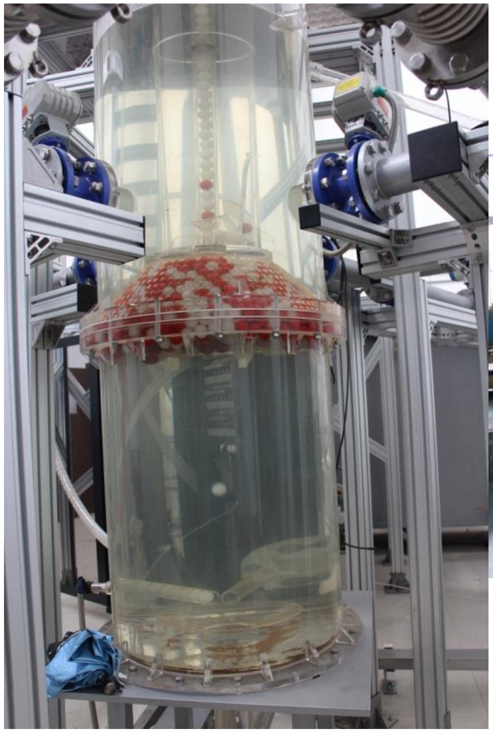
Thermal hydraulic & mechanical test of loop



Molten salt natural circulation test (Passive safety)

Prototypes & test platforms

Control Rod prototype and its test platform



Simulator of pebble recirculation system

fuel order

Outline

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--Key technology Development

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 recovery > 92%

Fluorination experimental set-up

Frozen-wall test

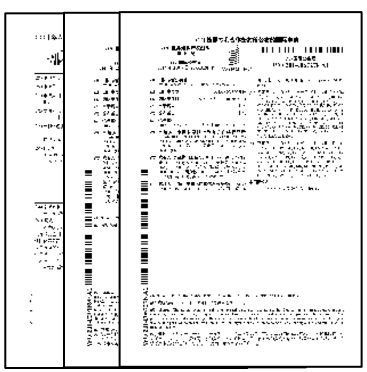
Distillation experimental set-up

Electrochemical experimental set-up

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 99.999 % purity of thorium was achieved in batches.



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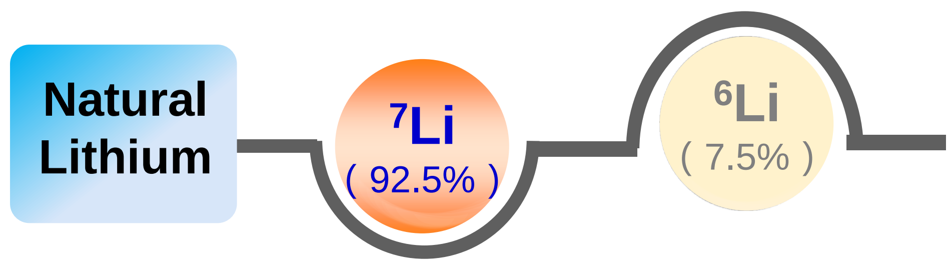
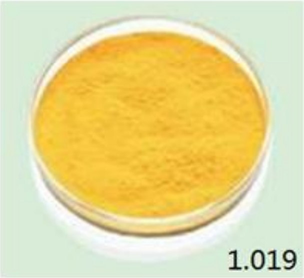
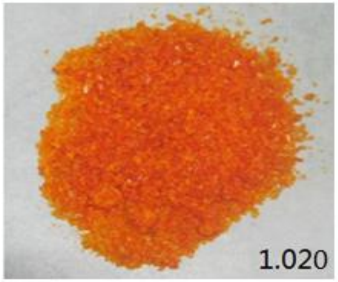


- PWR pH control (abundance ≥ 99.9 %)
- MSR coolant (abundance ≥ 99.99 %)

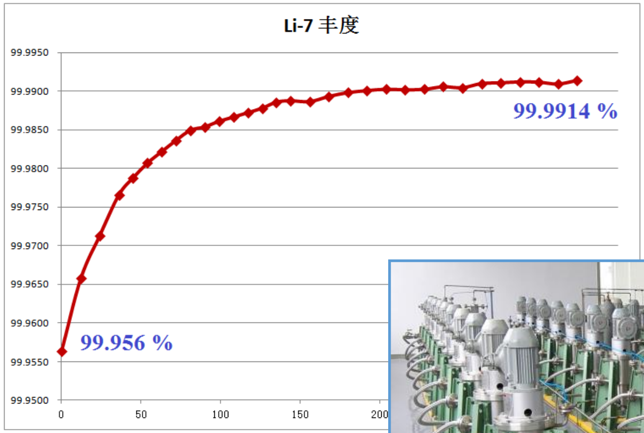
Cascade Enrichment of Lithium-7

- The 160-stages cascade extraction process with ϕ 20 mm centrifugal extractor
- Cumulative operating time > 1000 h
- The abundance of lithium isotope was enriched from 99.956% to 99.9914%





Extractants



- Designed the cascade process flow diagrams
- Be Setting up the 40-stage ϕ 100 mm centrifugal extractor

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

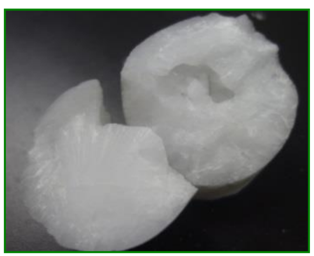
Fluoride salt

Salt production of 10 tons per year

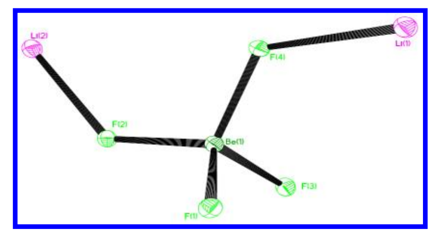
FLiBe Salt

Preparation and Purification of FLiBe

Equipment for the preparation of FLiBe (10kg scale)



FLiBe molten salt (left: 1kg; right: 10 kg)

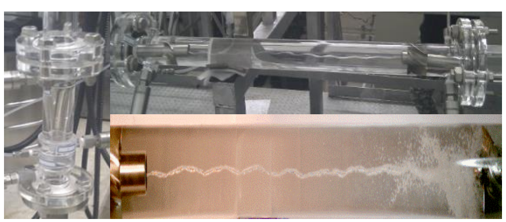


FLiBe single crystal structure

	Na	Mg	Ca	Al	P	S	Si	Cr	Fe	Ni	Cu	Cd	Pb	B
ANEI	4.4	10	15	2.3	7	1.6	64	0.5	<0.2	5.3	<0.2	<0.02	<0.6	0.7
ORNL[a]	-	-	-	-	-	<5	-	19	166	26	-	-	-	-

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,
		  	

Nickel-based Alloy

- Technologies for the smelling, processing, and welding of a Nickel-based alloy, UNS N10003, China standard GH3535

- Smelling 6&10 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)

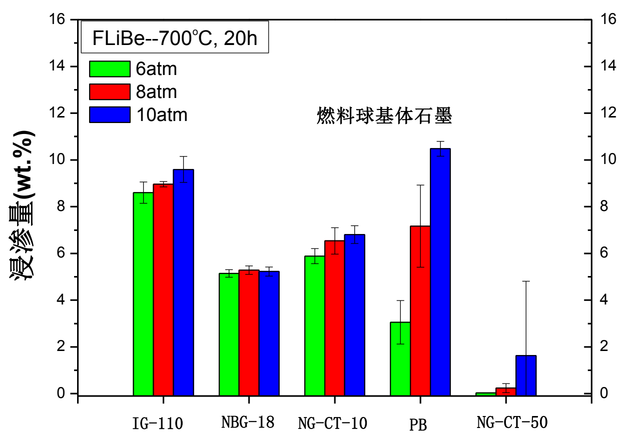
Nuclear Grade Graphite

- 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. (um)	0.74	2
Boron (ppm)	< 0.05	0.1

Comparison of graphite



FLiBe salt infiltration

Ultrafine grain nuclear graphite

Material Corrosion Control

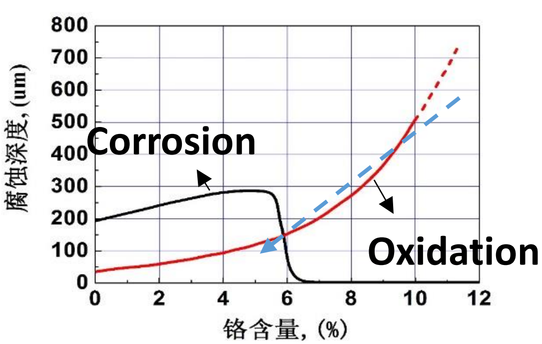
- Control the structural material corrosion by alloy composition optimization, salt purification and surface treatment

Investigating Corrosion Mechanism

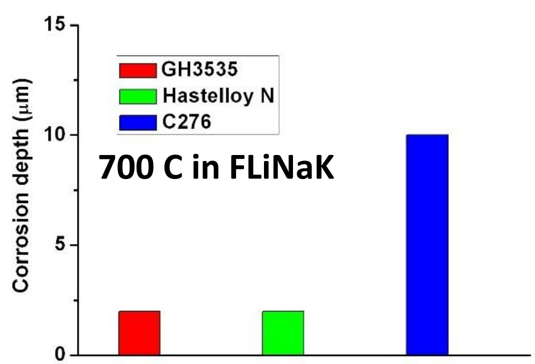
- Salt impurities
- Elements diffusion
- Mass transfer

Developing Corrosion Control Technologies

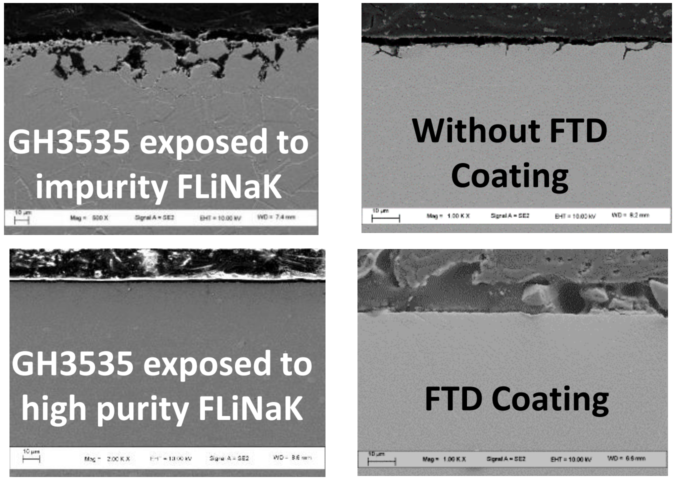
- Optimize the composition of alloy, diffusion of Cr
- Improve purification technology, minimize impurities
- Fluoride salt thermal diffusion coating



Composition Optimization (Cr)



Corrosion Depth (μm/y)




Thanks