Progress of TMSR in China

Jul. 08th, 2020. KNS workshop

Hongjie XU, Zhimin DAI, Hefei HUANG

TMSR Center of CAS/ SINAP

OUTLINE

What is TMSR

Motivation for TMSR

Progress of TMSR

Perspective on TMSR

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TMSR Project (Chinese Academy of Sciences)

中文名称：钍基熔盐堆核能系统

英文名称：Thorium Molten Salt Reactor Nuclear Energy System

Abbr. ：TMSR

Aims ：Develop Th-Energy, Non-electric application of Nuclear Energy based on TMSR during coming 20-30 years.

TMSR Development Plan

R&D、Design、Licensing	Demonstration	Commercial

Mock-up (2018)

Key technology and component development, mock-up (TMSR-0)

Test Reactor (2021)

2MWt liquid-fuel test reactor (TMSR-LF1)

Research Reactor (~2030)

10MWe liquid-fuel research reactor (smTMSR-Research Facility)

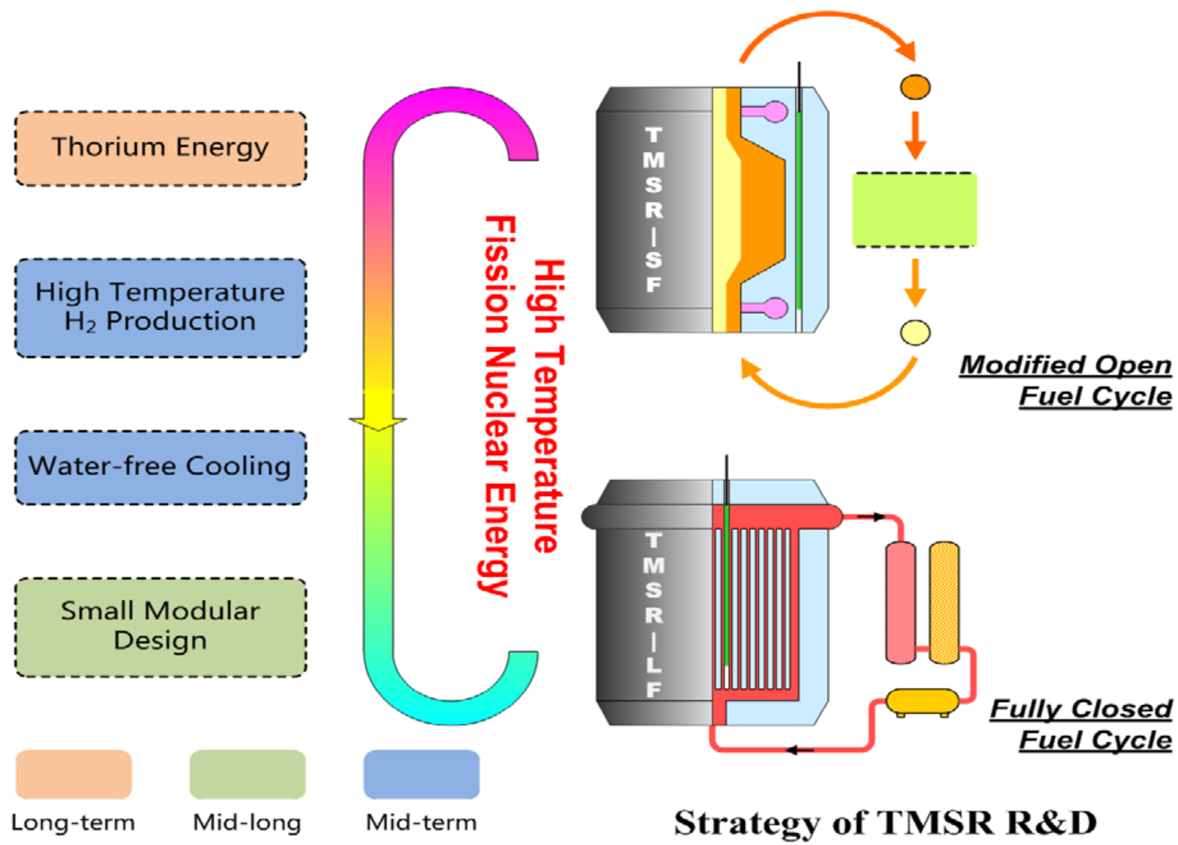
Demonstration Reactor (~2035)

100MWe grade liquid-fuel reactor

CAS TMSR Project (2011-2017): 2.17B RMB; (2018-2020)500M RMB

Shanghai Project (2015-2017): 115M RMB; (~2025)~800M RMB

TMSR Reactors and Applications



Strategy of TMSR R&D

Th Energy:

- Long-Term Supply of Nuclear Fuel

MSR:

- Elevated Safety
- Efficiency
- Nonproliferation

- Optimized for high-temperature based hybrid nuclear energy application.
- Optimized for utilization of Th with Pyroprocessing.

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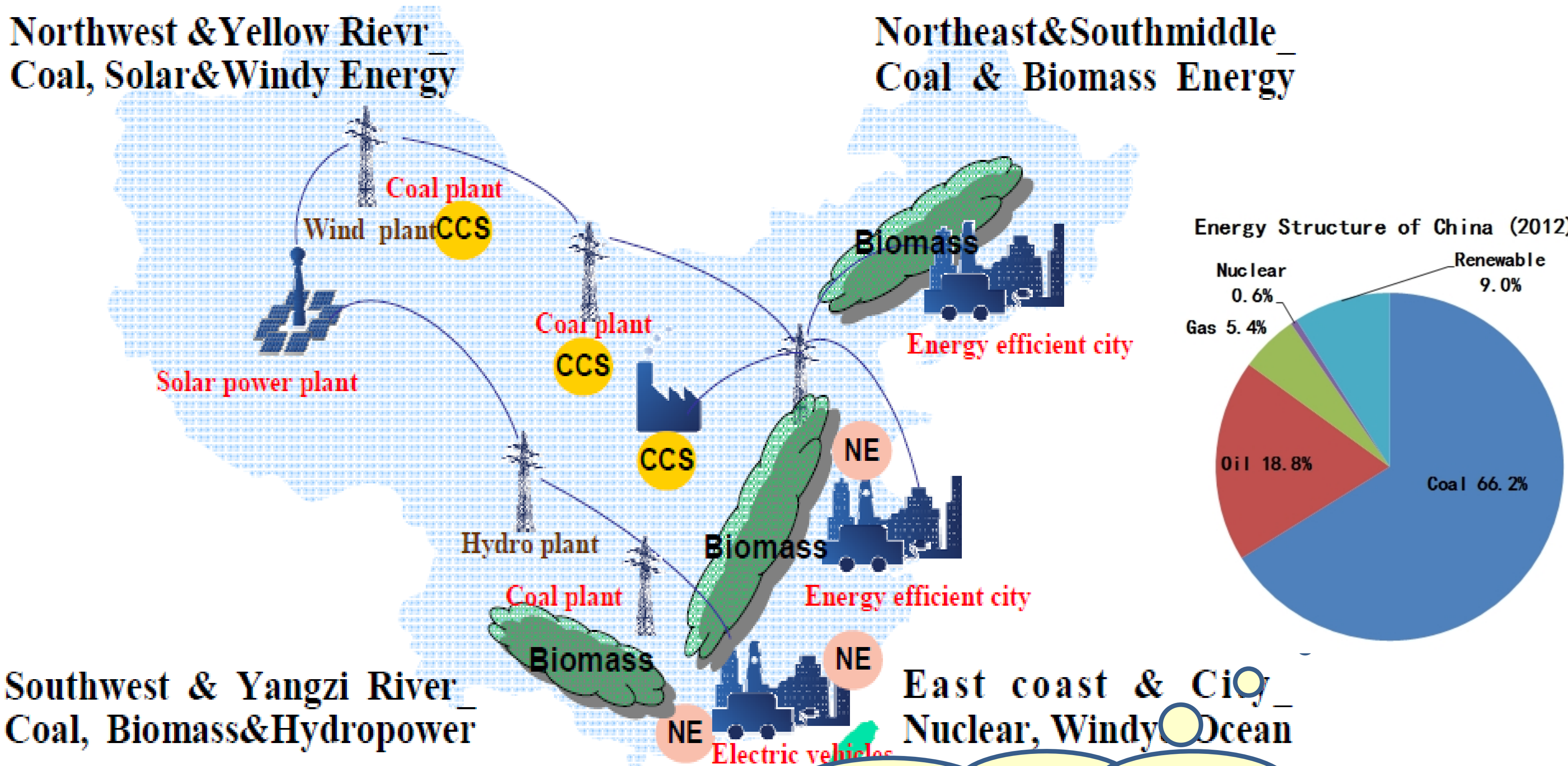
Coal dominates primary energy consumption of China

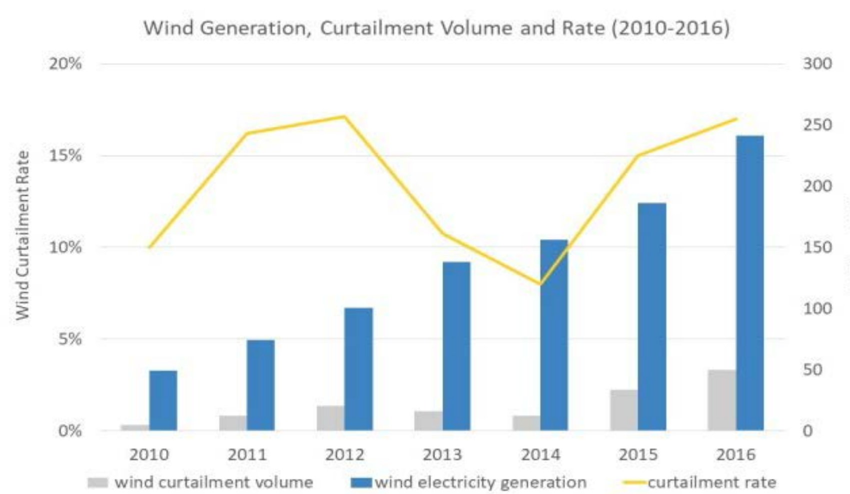


>620 coal-fired power plants

The coal accounts for about 66% China's 0f total energy consumption.

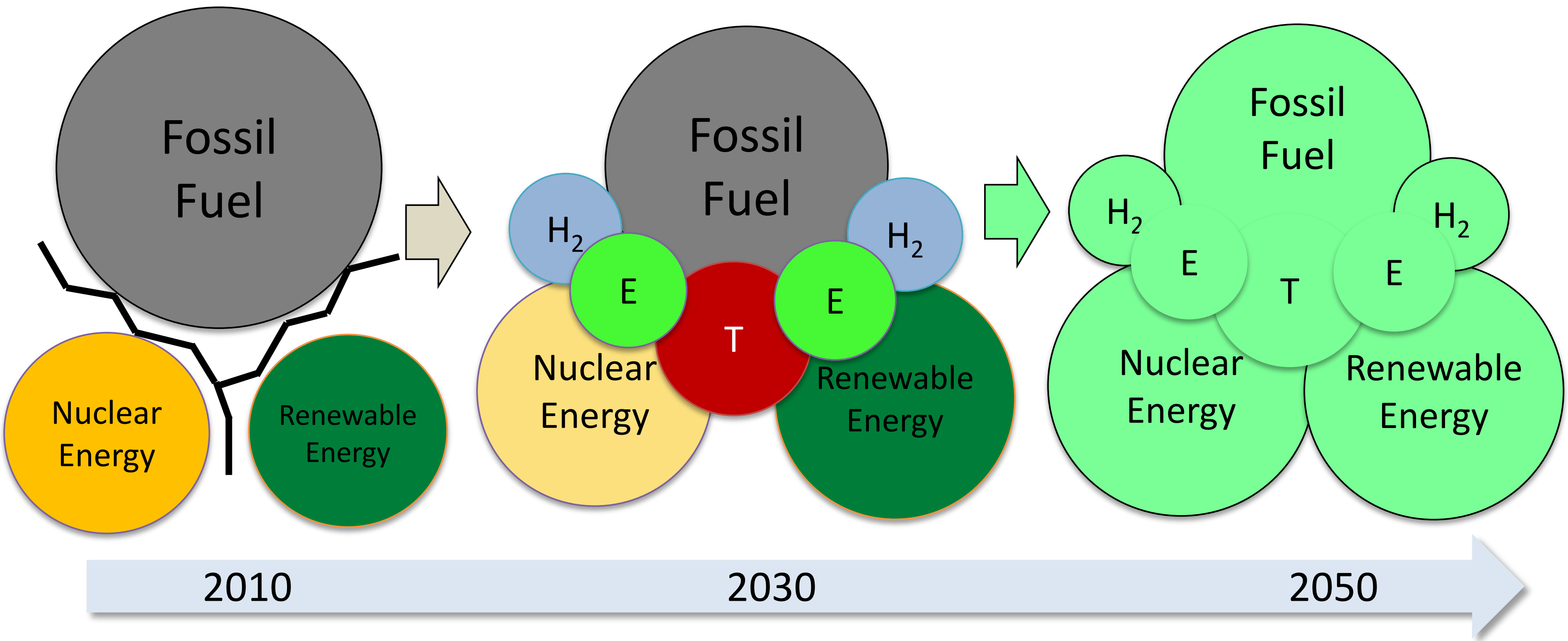
Wind abandoned in China

- Much of the electricity produced by vast wind farms goes unused, with grids unable to accommodate fluctuating sources of power and amid rising overcapacity in the country’ s total power generation.
- From 2010 to 2016, 150.4 million megawatt hours, or as much as 16 percent of overall wind generation, was abandoned. Over the last 6 years, the opportunity cost of wind power curtailment in China is estimated to exceed $1.2 billion.



Clean Energy System

- Nuclear energy system produces heat and/or electricity; renewable energy system produces electricity and/or heat; both of them can produce hydrogen for energy conversion and storage, which is also used for lower the CO_2 emission of fossil fuel.

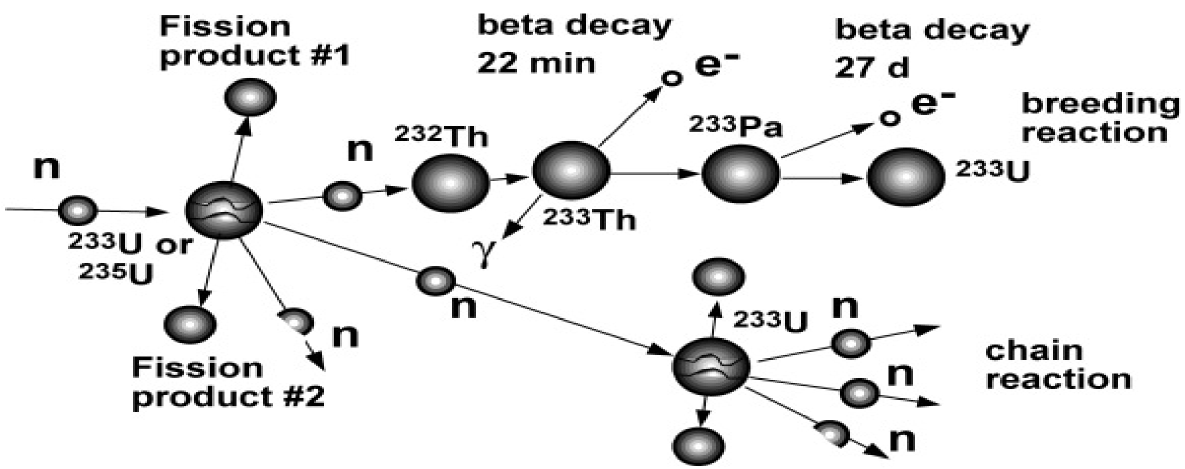


Overview of the Generation IV Systems

System	Neutron Spectrum	Fuel Cycle	Size (MWe)	Applications	R&D needed
Very-High Temperature Reactor (VHTR)	Thermal	Open	250	Electricity, Hydrogen, Process Heat	Fuels, Materials, H_2 production
Gas-Cooled Fast Reactor (GFR)	Fast	Closed	200-1200	Electricity, Hydrogen, Actinide Management	Fuels, Materials, Thermal-hydraulics
Lead-Cooled Fast Reactor (LFR)	Fast	Closed	50-150 300-600 1200	Electricity, Hydrogen Production	Fuels, Materials
Sodium Cooled Fast Reactor (SFR)	Fast	Closed	300-1500	Electricity, Actinide Management	Advanced recycle options, Fuels
Molten Salt Reactor (MSR)	Epithermal	Closed	1000	Electricity, Hydrogen, Actinide Management	Fuel treatment, Materials, Reliability

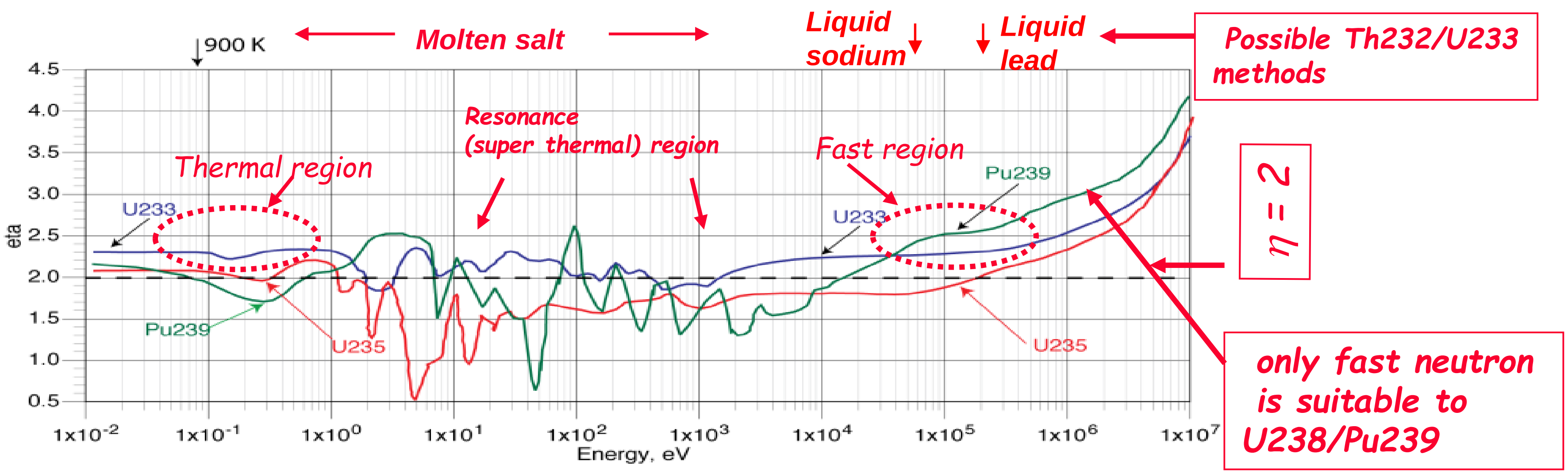
2016 US Edition

Th232/U233 and U238/Pu239 fuel cycles



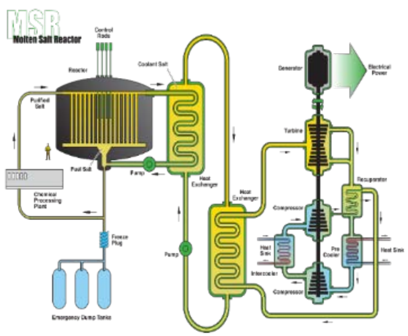
Mean released neutron number per fission η

η = 2 is the required condition for a sustain reactor



Molten Salt Reactor

Suitable for generate electricity, comprehensive utilization and modular design



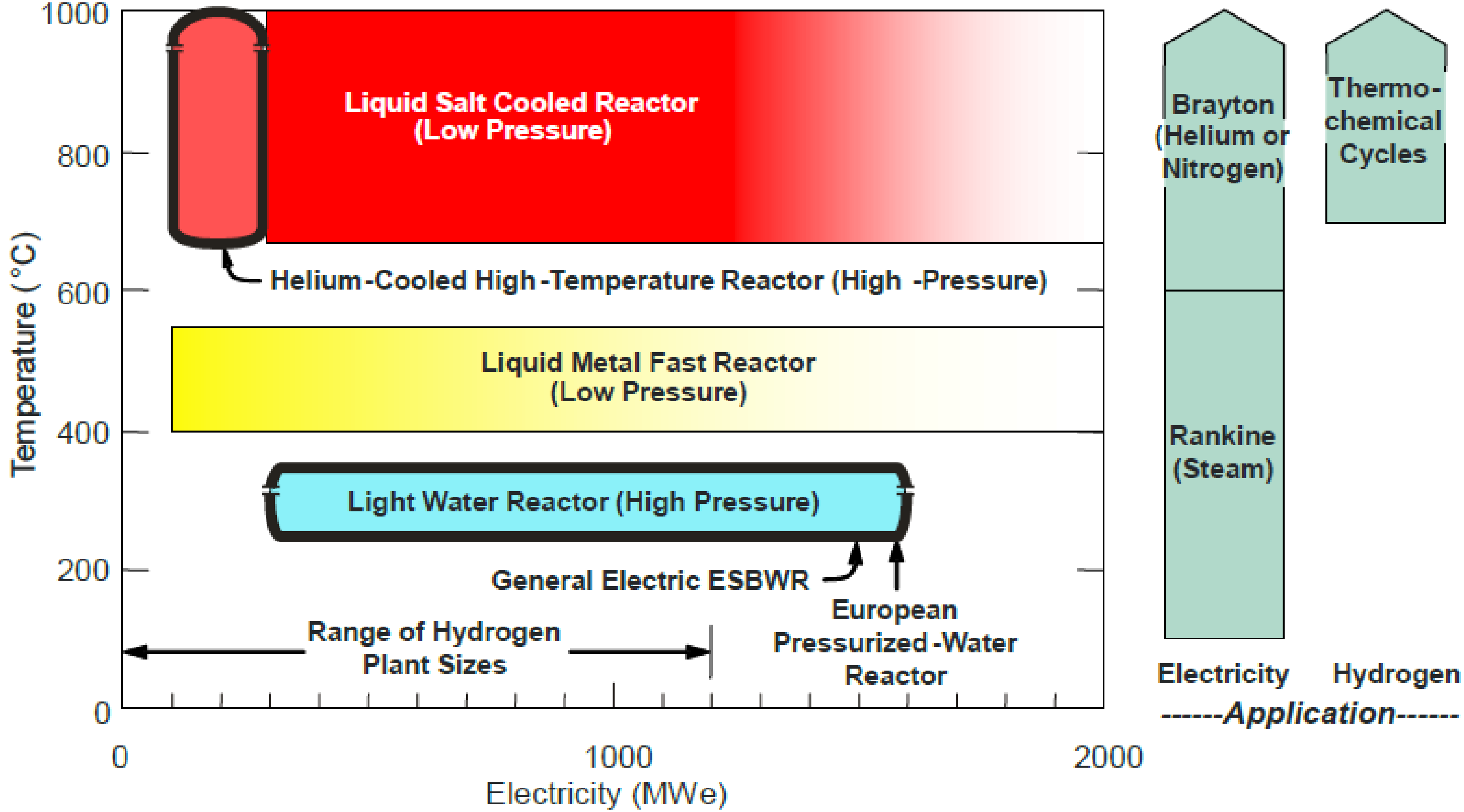
- **Th utilization:** Physical features applicable for Th fuel
- **Online refueling:** Refueling and reprocessing of fuel
- **Inherent safety:** Intrinsic safety features, can be built underground
- **Water-free cooling:** Applicable for inland arid area

Excellent properties of MSR coolant

	Outlet temperature (℃)	Pressure (atm)	Heat Capacity (kJ/m³℃)	Compatibility
Li_2BeF_4	1000	~2	4670	Good
Water	320	~150	4040*	Excellent
Na	545	~2	1040	Medium
He2	1000	~70	20*	Excellent

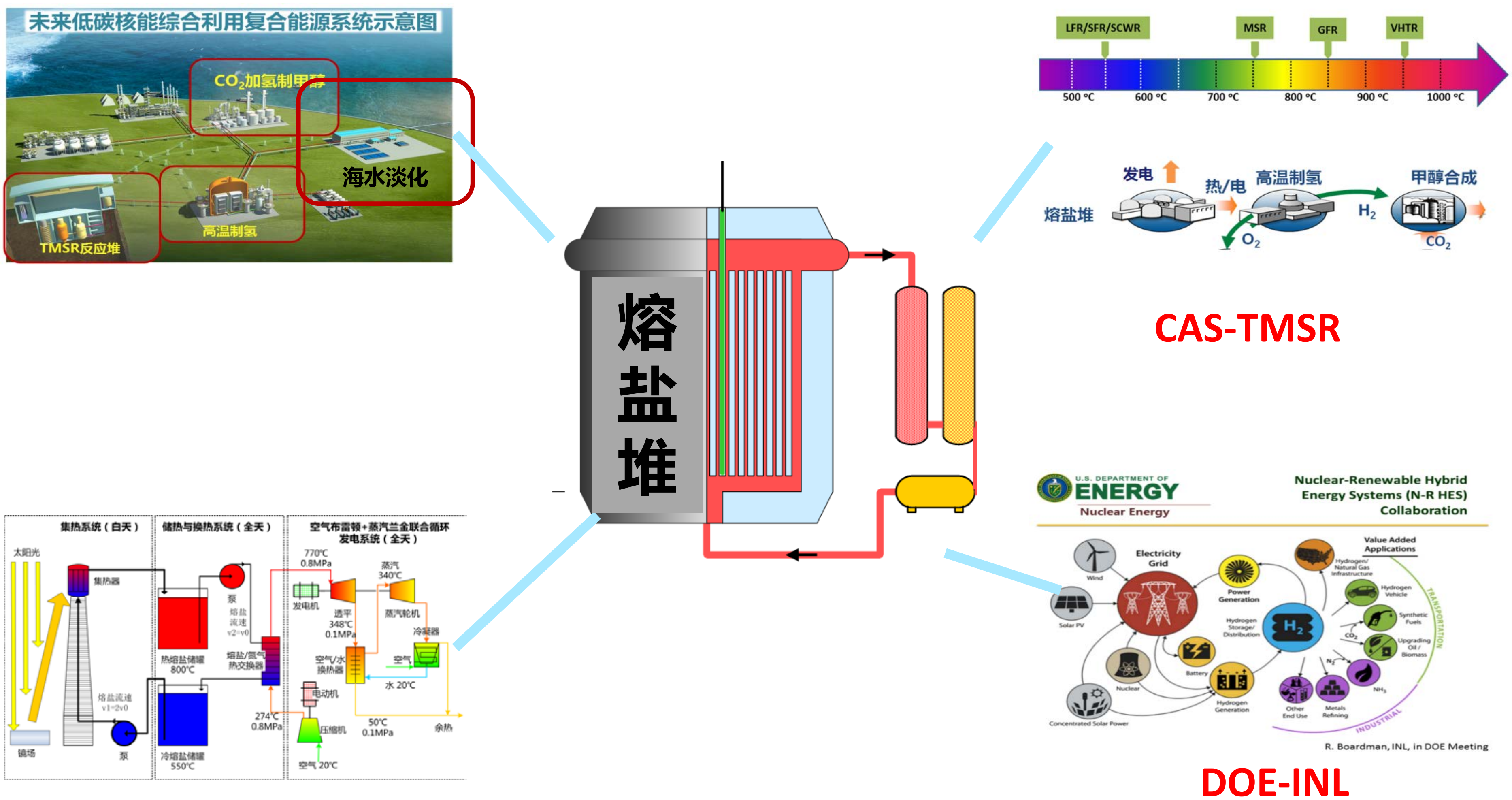
*@75 atm

MSR has obvious advantages in high temperature comprehensive utilization



Solution of low carbon new energy

High temperature TMSR+ hybrid-energy utilization



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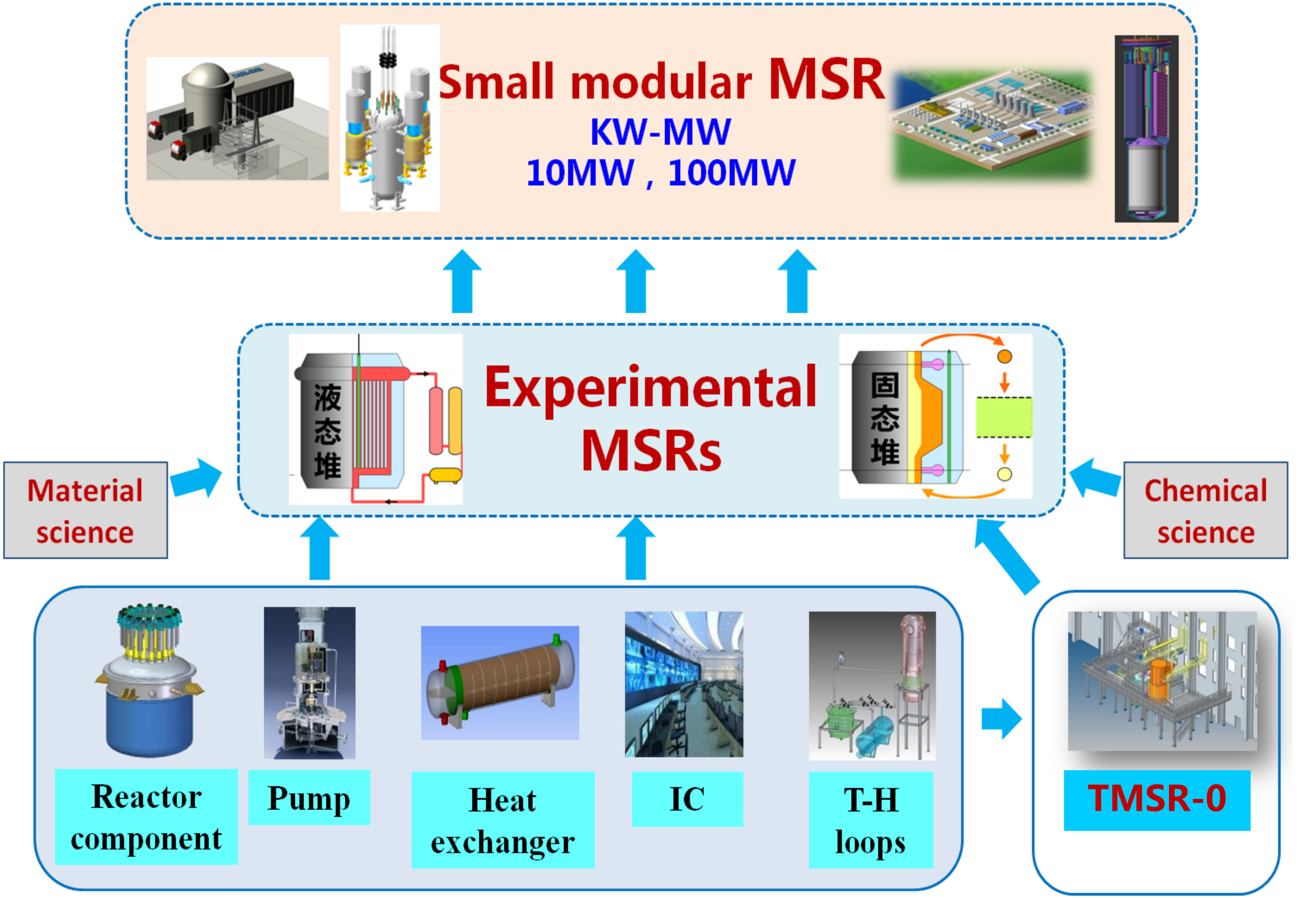
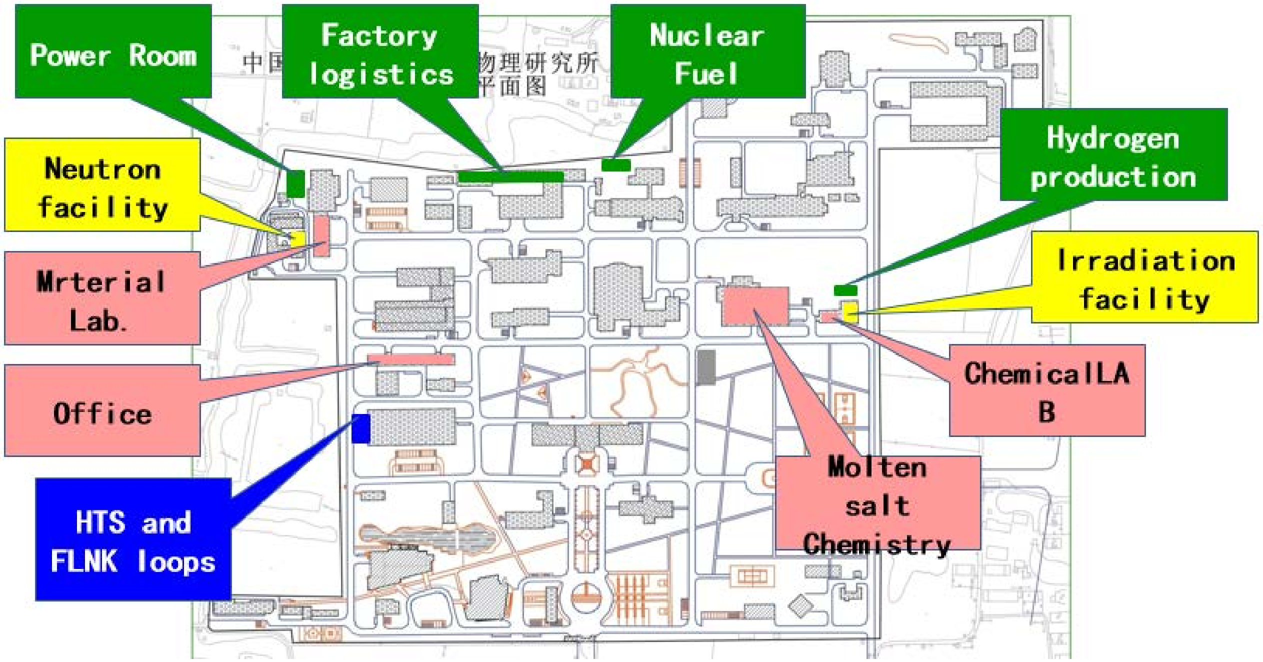
Roadmap of Technologies R&D



Fundamental Research Base at Jiading



Super Computer

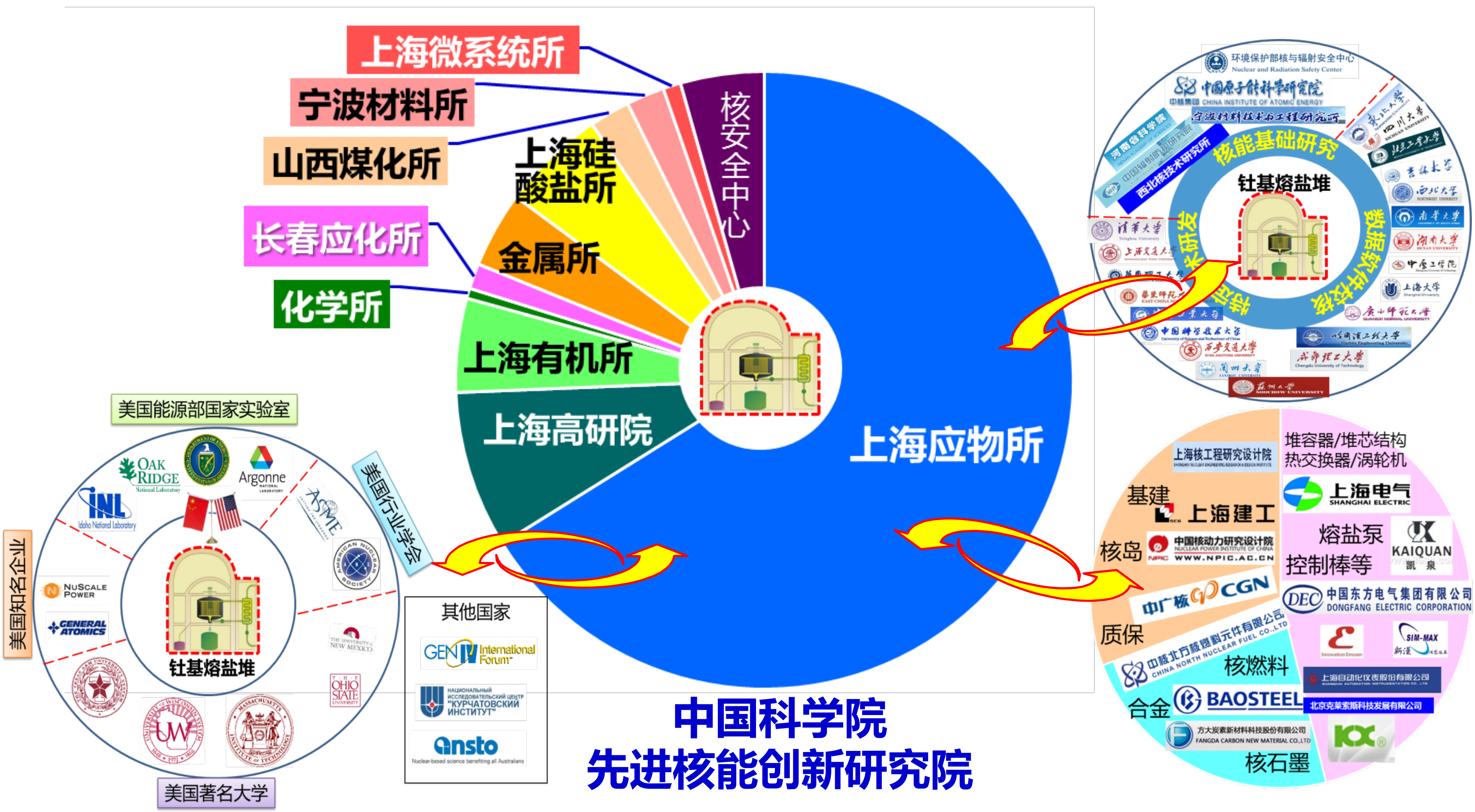
Hot Cells

Material Testing Labs

Salt Properties Labs

β Irradiation Facility

International and Domestic Collaborations

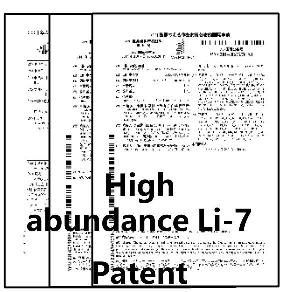


TEAMS: Staffs ~600; Graduate students ~200

^{7}Li and Thorium Extraction and Separation

Succeed in obtaining nuclear grade thorium and high abundance Li-7 using extraction technology

- **High abundance Li-7**: As a green technology, centrifugal extraction method was developed instead of mercury method to obtain Li-7. Counter current extraction experiment was achieved and 99.99% Li-7 was obtained for the first time. High efficient extractants were synthesized.
- **Nuclear grade thorium**: High efficient extraction system was developed for the separation and preparation of the nuclear grade thorium. The 99.999% purity thorium was obtained in batches.



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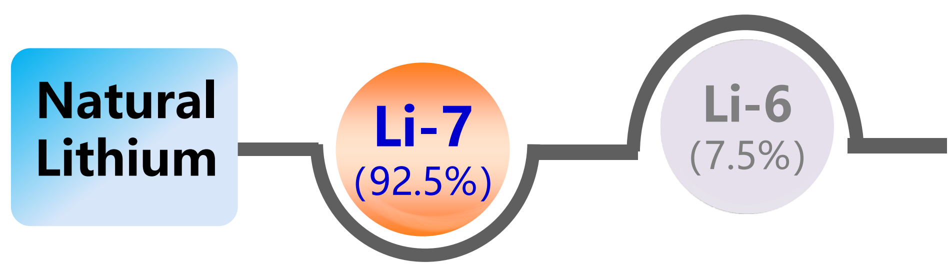


- **PWR pH control (abundence≥99.9%)**
- **MSR coolant (abundence≥99.99%)**

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

Molten salt

Prototype for molten salt production (10ton/y)

FLiBe

Physical properties determination lab

Patent obtained：CN103219052A, CN103606385A,CN203440069U, CN103601222A,CN104147929A, CN104140379A,CN103572318A, CN104344120A,CN104214420A, CN203083132U,CN104089917A, CN104407011A,CN202460640U, CN202926703U,CN102878109A

15 Chinese patents

Nickel-based alloy

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

GH3535: A nickel-based alloy with an outstanding corrosion resistance in molten salts

- Technologies for smelling (10 tons), processing & welding; performance comparable to Hastelloy N
- Deformation processing technologies for nickel-based alloys with high Mo, the largest UNS N10003 seamless pipes.

hot extrusion

pipe processing

Welding

Capability	China	US Haynes
Pipe Diameter	141.3mm	<88.9mm

seamless alloy pipes for the primary loop of MSR

Performance Test Report

Chinese Patent CN103966476 A (under review)

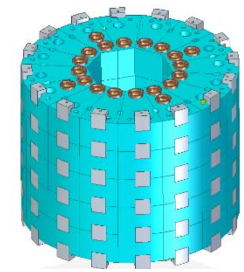
Component (head)

Nuclear Graphite

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

Nuclear graphite：moderator/reflector

- Industrial production technologies of Chinese ultrafine-grain nuclear graphite **NG-CT-50**
- Pore diameter<1μm, ensured better infiltration resistance than existed nuclear graphite
- Establishing database of its performance & deep involvement in Intl. Std. for MSR nuclear graphite

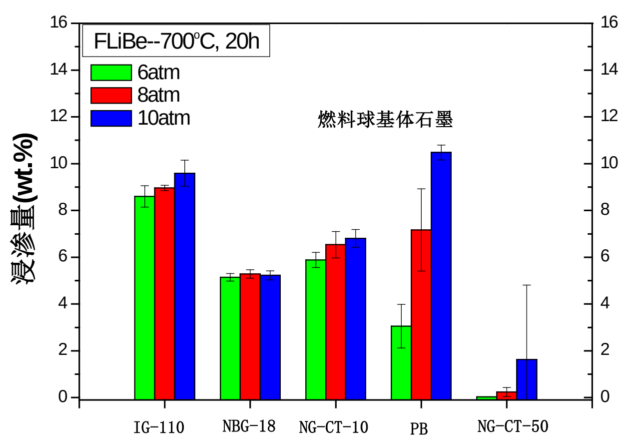


Graphite Core

Ultrafine grain Nuclear Graphite

Parameters	NG-CT-50 (China)	IG110 (Japan)
Pore Dia. (μm)	0.74	2
B Equiv. Cont. (ppm)	<0.05	0.1

Comparison between different nuclear graphite



Molten Salt Infiltration in nuclear graphite

ASME
SETTING THE STANDARD

Two Park Avenue
New York, NY
10016-5990 U.S.A.

tel +1.212.591.8500
fax +1.212.591.8501
www.asme.org

August 21, 2014

Zeng Guang Li
SINAP
2019 Jialuo Road
Jiading District, Shanghai 37831
People's Republic of China

Dear Dr. Zeng,

The ASME BPV III Subgroup on Graphite Core Components intends to consider the improvement of the provisions for fine-grain graphite in ASME BPV Section III, Division 5. As a research organization prominent in the field of nuclear graphite material, the Shanghai Institute of Applied Physics (SINAP) is positioned to assist the Subgroup in this endeavor.

Provision for ASME code

Corrosion Control

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

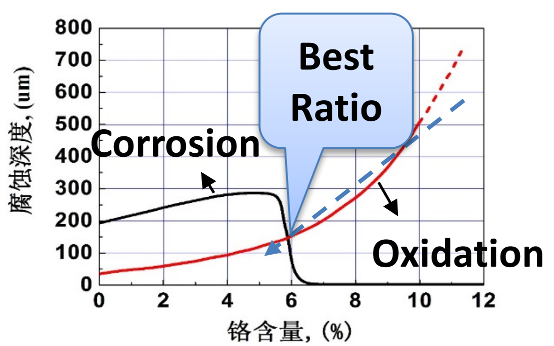
Investigating Corrosion Mechanism

- Salt impurities;
- Elements diffusion;
- Mass transfer;

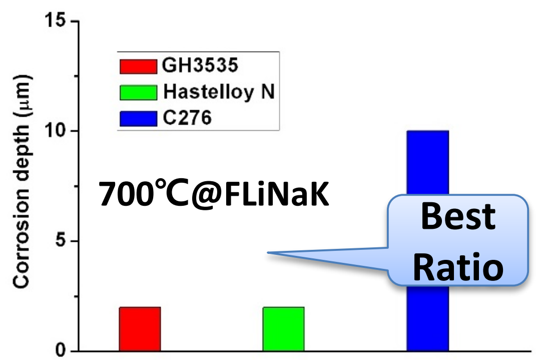
Developing Corrosion Control Technology

- **Design Optimization :** Optimize the composition of alloy, degrade diffusion of Cr;
- **Salt Purification:** Modify purification technology, control the impurities content;
- **Surface modification:** FTD coating, improve the corrosion resistance;

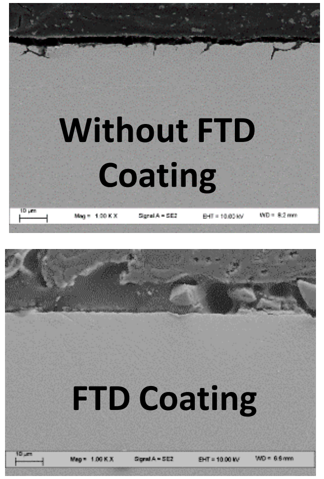
Solving the corrosion control in fluoride salt (GH3535 static corrosion rate < 2μm/y)！



Composition Optimization of Alloy (Cr)



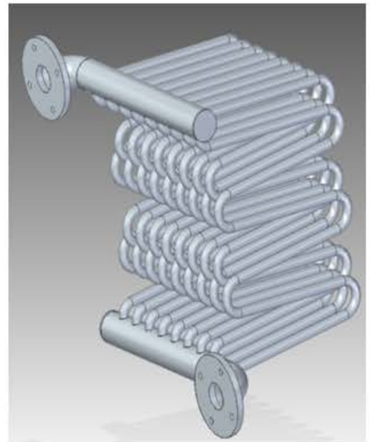
Corrosion Depth (μm/y)



R&D of Components

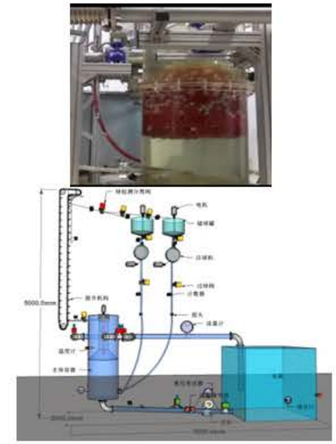
Salt pump

Freezing valve



Heat exchanger

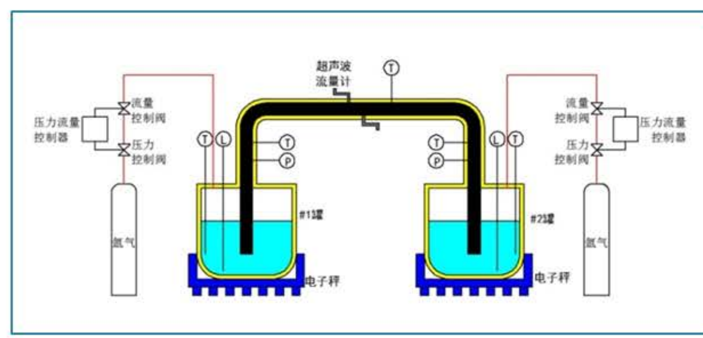
Control rod test facility



Fuel sphere Loading facility

Graphite structure test facility

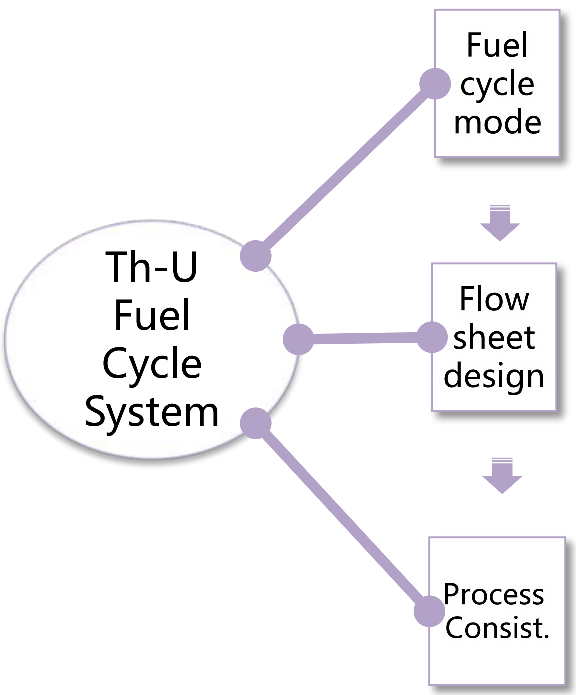
Pressure meter film



Ultrasonic flowmeter benchmark platform

Thorium-Uranium Fuel Cycle Researches

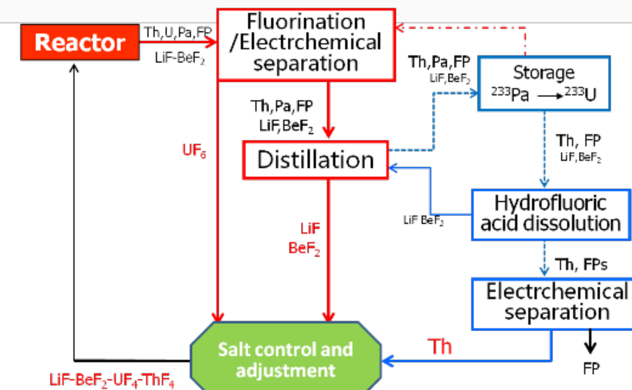
- Established a thorium fuel utilization strategy in MSRs by evaluating the Th-U fuel cycle performance
- Created a reprocessing flow sheet and demonstrated it in cold, lab-scale facilities

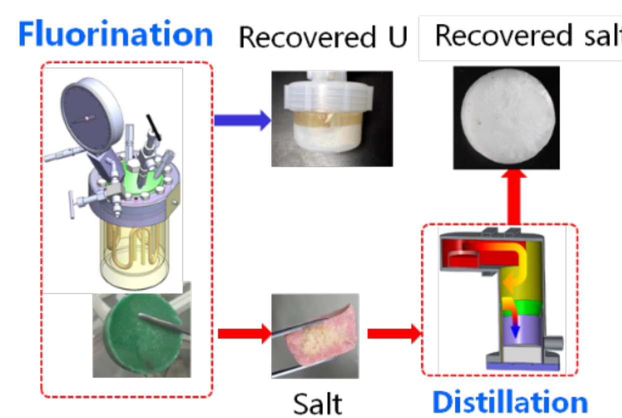


Fuel cycle mode: Thorium utilization strategy in MSRs
- ^{235}U to ^{233}U transition
- Minor actinides transmutation

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%





Pyro-processing Techniques

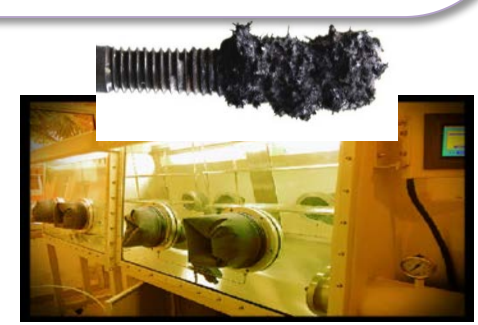
- Fluorination and distillation of fluoride salts in cold experiments
- Developing fluorides electrochemical separation techniques

- **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



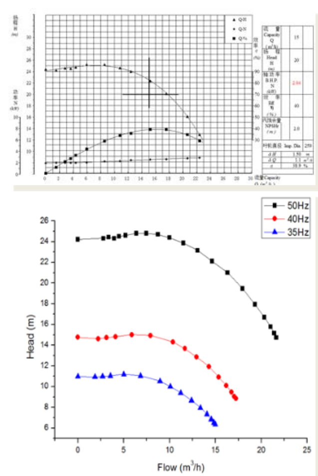
Electrochemical experimental set-up

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

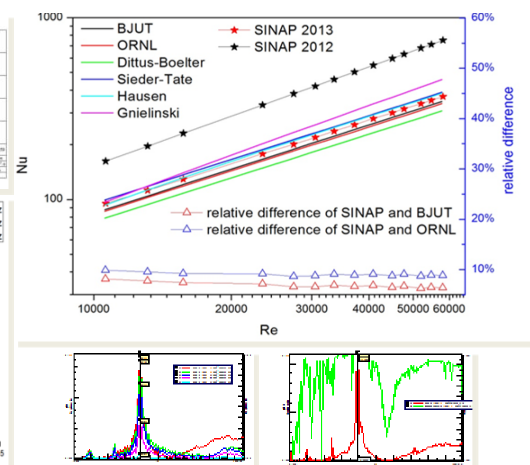
- Design and analysis methods for high-temperature fluoride salt loops
- Prototypes for pump, valve, heat exchanger, etc.
- Experience of loading and unloading of fluoride salts
- Experience of high-temperature fluoride salt loops operation and maintenance

High-temperature fluoride salt experimental loop

Prototypes of equipment



Hydraulic test of molten salt pump

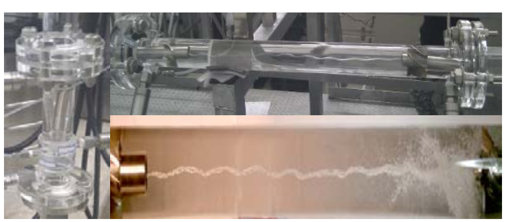


Thermal hydraulic & mechanical test of loop

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,

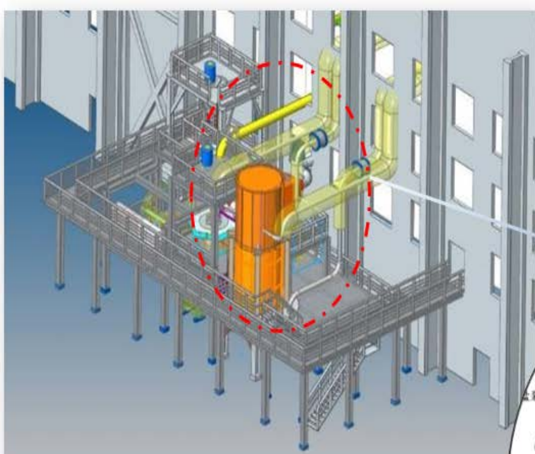


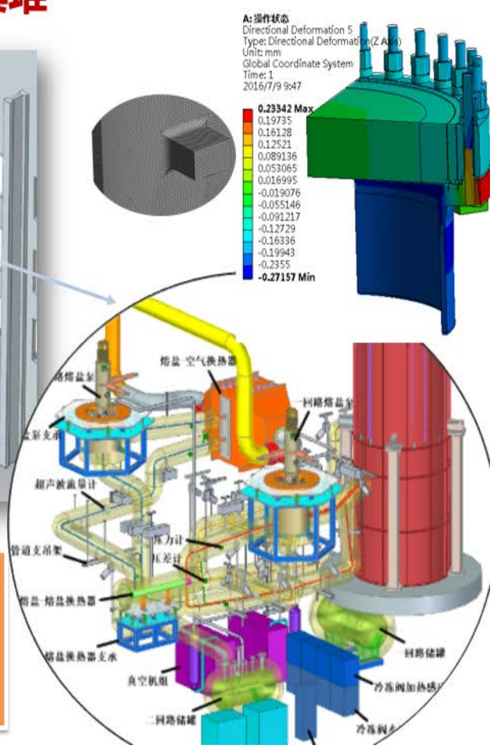



General description of TMSR-0

- Integrated facility via scaling methods
- Key facility for design validation and licensing
- Simulation for operation and training operators.

TMSR缩比仿真堆





◆ 2016-7月中旬完成初步工程设计评审，形成109份设计报告；
◆ 2016-8月缩比仿真堆由设计阶段转入采购、加工制造阶段

	TMSR	TMSR-0
Coolant	FLiBe	FLiNaK
Temperature	600℃-650℃	
Size ratio	1:3	
Area ratio	1:9	
Volume ratio	1:27	
Power	10 MW	370 kW
Salt speed	84 kg/s	3.9 kg/s
Heating	nuclear	electricity

Construction of TMSR-0

- A practice for the future test reactor construction
- Installation of is finished in June. 2019
- Verification experiment of 2MW TMSR-LF1 design has been done.

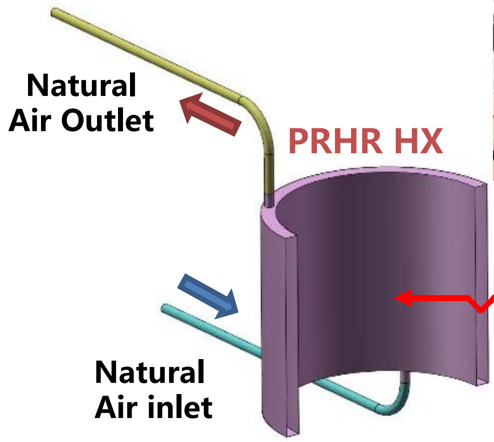
Vessel body

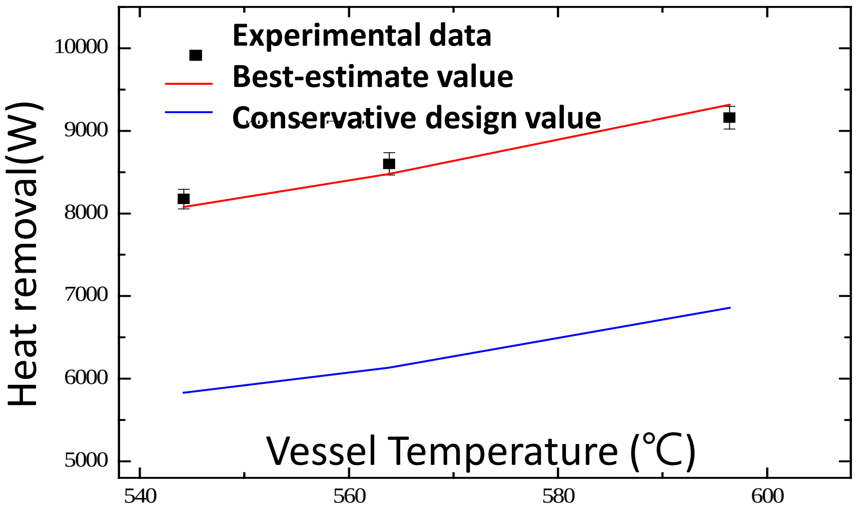
Graphite Components

Graphite Core

Test of Passive Residual Heat Removal System of TMSR-0

- Scaling analysis is used to build similarity between TMSR-0 and TMSR-LF1.
- Results: Best-estimate value are in accord with Experimental data, which supports safety licensing of LF1.



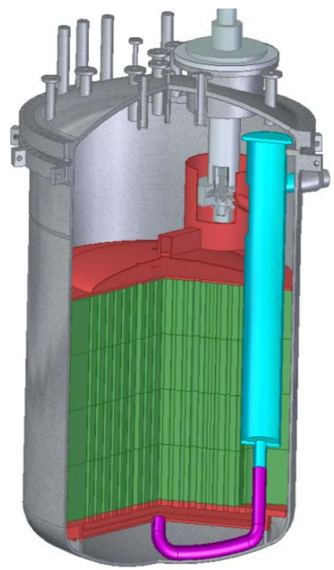


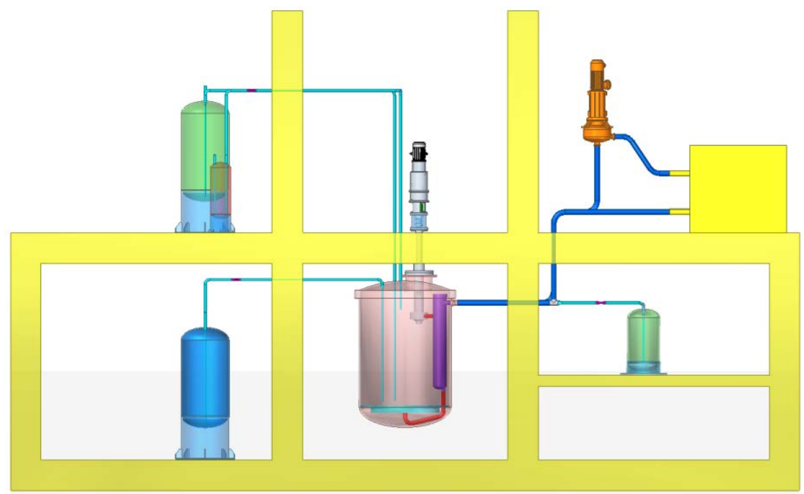
2MWt TMSR test reactor (TMSR-LF1)

- **Demonstrate concept of MSR with liquid fuel.**
- **Demonstrate Th-U cycle and its features.**
- **Platform for future reactors and Th-U cycle R&D.**

Heat Power	2MWt
Temperature	630 ℃ / 650 ℃
Fuels	$LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4\text{-}ThF_4$
Residual heat removal	Passive air natural circlation system

Integrated design





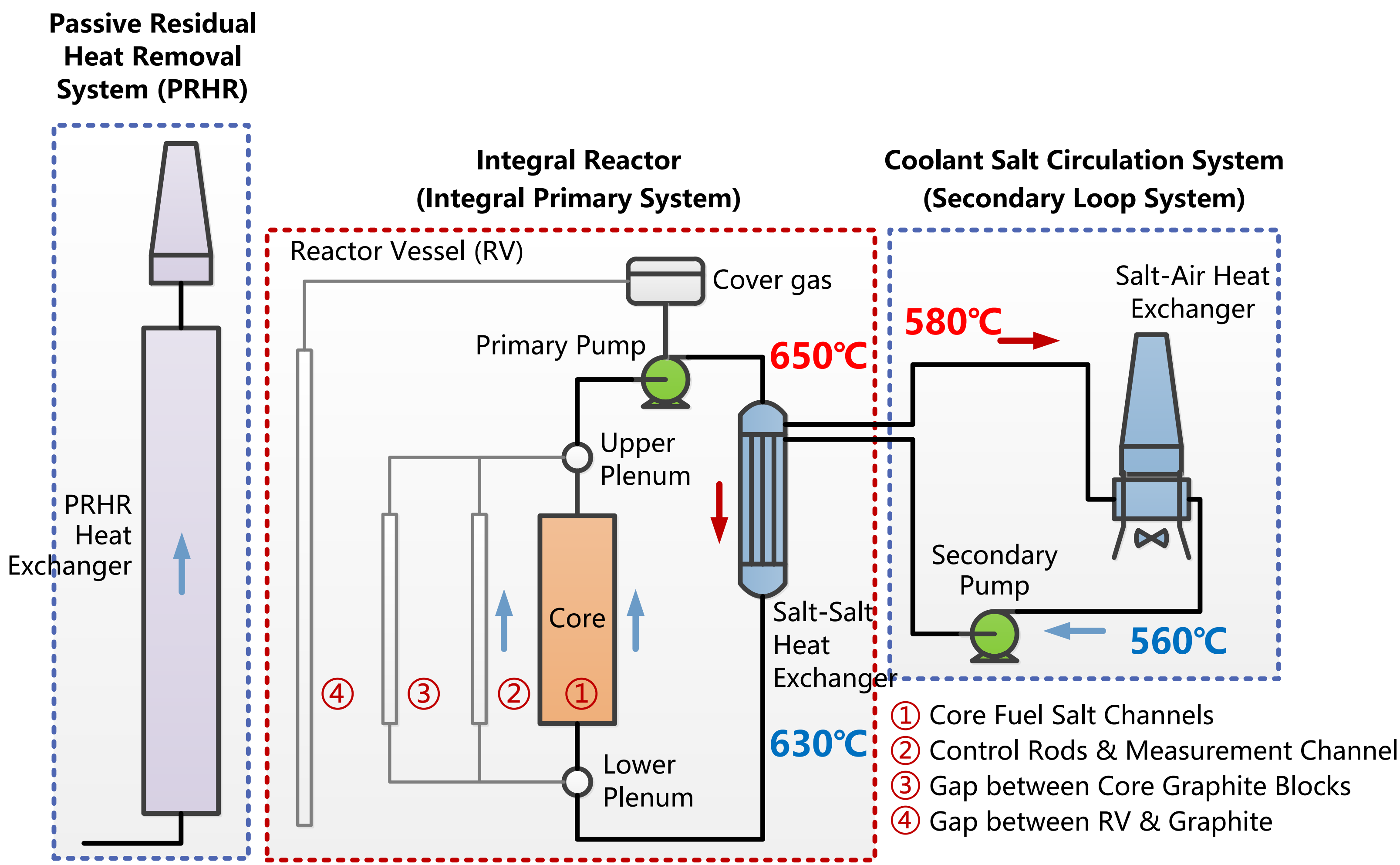
Main parameters

Reator type	Liquid-fueled molten salt reactor
Heat Power	2MW
Temperature	630℃ / 650 ℃ (inlet/outlet)
life	10 years
Fuel salt	LiF-BeF_2-ZrF_4-UF_4-(ThF_4)
U-235 enrichment	19.75%
Thorium	~30kg in whole reactor
Coolant salt	LiF-BeF_2 (2rd loop)

General Description

- **Fuel**： LiF-BeF_2-ZrF_4-UF_4 (+ThF_4),
- **Structural Materials**: UNS N1003 alloy， superfine particle graphite made in china.
- **Systems**：
  - Heat generation (reactor body)
  - Heat transfer (loops, air cooling system)
  - Cavity: structure support and maintain
  - Cover gas and off-gas processing system
  - Controlling and instrumentations
  - Etc.

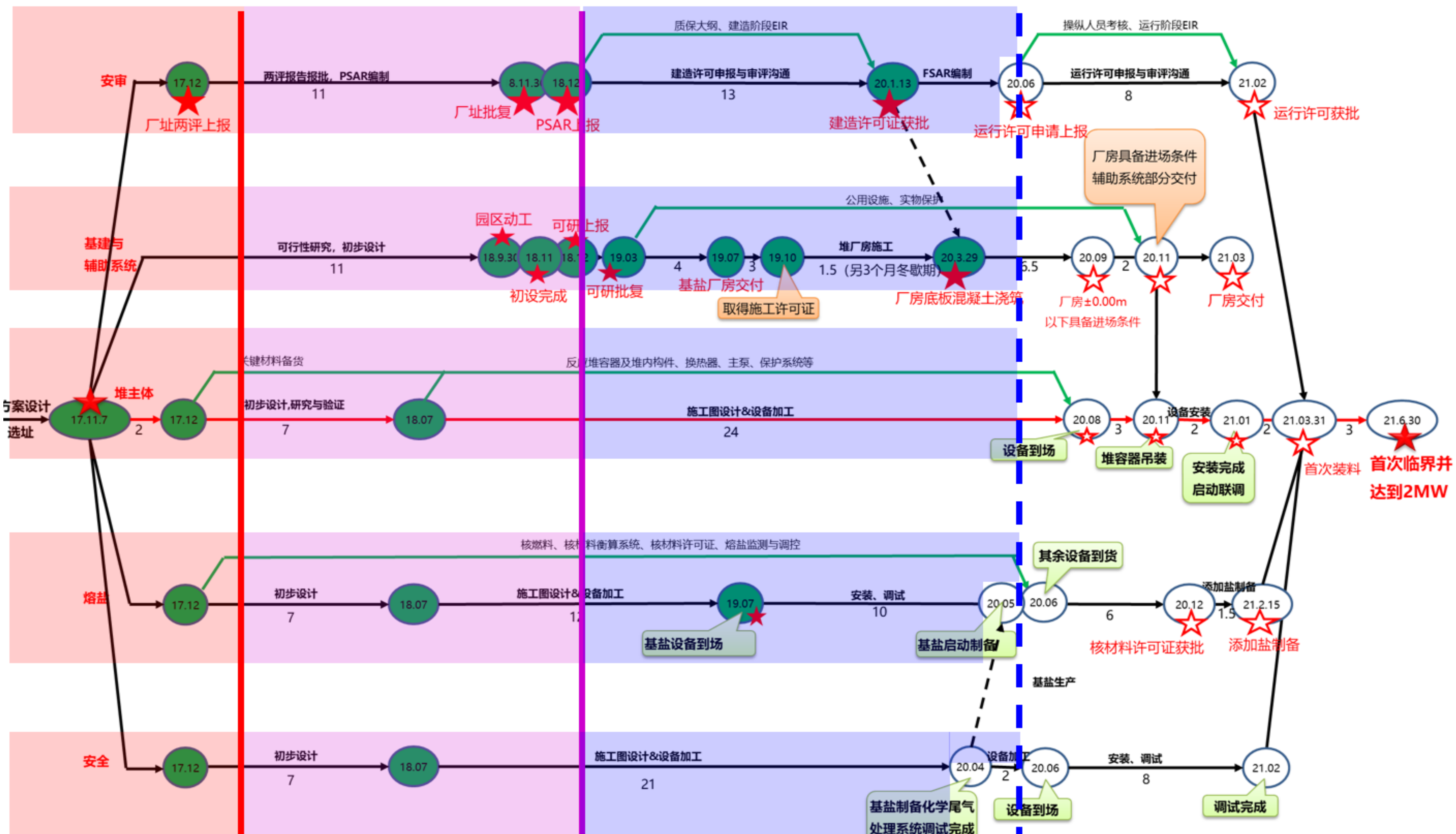
TMSR-LF1 Flow Schematic



TMSR Test Reactor

- 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.

CPM of TMSR-LF1 Project



TMSR-LF1 Licensing

- Site Selection Work Completed, Site Assessment Report was approved by NNSA in December, 2018.


中华人民共和国生态环境部

关于2MWt液态燃料钍基熔盐实验堆环境影响报告书（选址阶段）的批复


国家核安全局文件

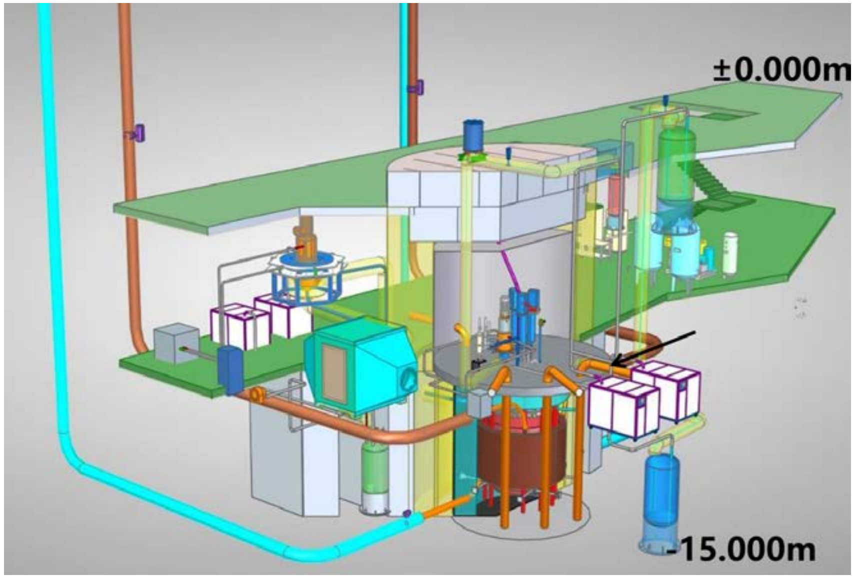
关于颁发2MWt液态燃料钍基熔盐实验堆场址选择审查意见书的通知

- PSAR has been reviewed, and construction License has been approved by NNSA in January, 2020.


国家核安全局文件

关于颁发2MWt液态燃料钍基熔盐实验堆建造许可证的通知

Reactor Body of TMSR-LF1 is under the ground



Construction of TMSR-LF1 building

FCD of on Mar. 29th, 2020

Finish +/-00 Floor on 30 Jun. 30th, 2020

Manufacture of TMSR-LF1 Main Components

上部筒体组件

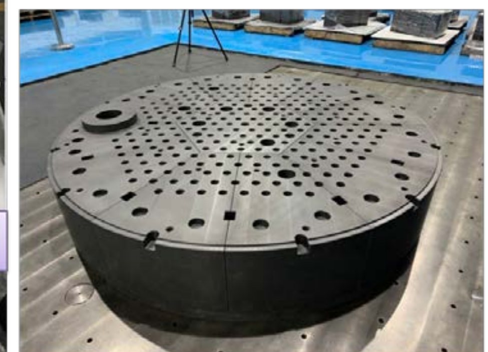
下筒体组件

顶盖组件：已完成泵通道套管焊接

Reactor Vessel

堆芯石墨组件：六边形中心石墨砖

堆芯石墨组件：散形石墨砖



已开展进行 堆芯石墨组件 第一层石墨砖 预组装前期准备和预组装操作培训。

Graphite Core

OUTLINE

What is TMSR

Motivation for TMSR

Progress of TMSR

Perspective on TMSR

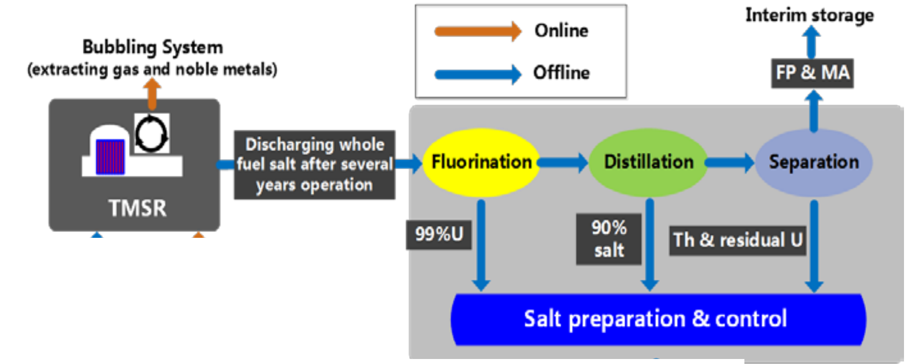
Chinese Proposal for TMSR Roadmap

- Base on the technologies have had in Lab-scale during last a few years, TMSR team propose the roadmap as following:
- To complete the construction of test reactor TMSR-LF1 by 2021
- To complete the construction of smTMSR-Research facility (~2030).
- To complete the construct of TMSR fuel salt batch pyro-process demo-facility .
- To realize Th-U Fuel Cycle usage based on the 3-step strategy by the early 2040s.

A 3-step Strategy for Th-U Fuel Cycle

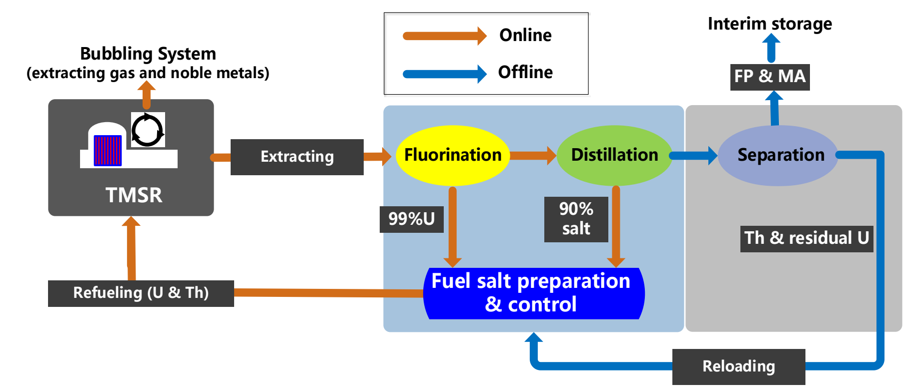
Step 1: batch process

- Fuel: LEU+Th
- Online refueling and removing of gaseous FP
- Discharge all fuel salt after 5-8 years
- Extract U , Th and salt
- FP and MA for temporary storage



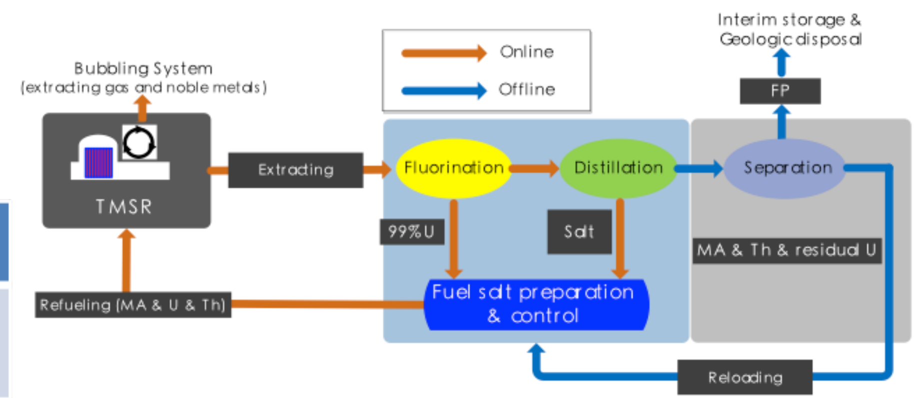
Step 2: step1 + fuel reload

- Reloading of U and Th to realize thorium fuel cycle



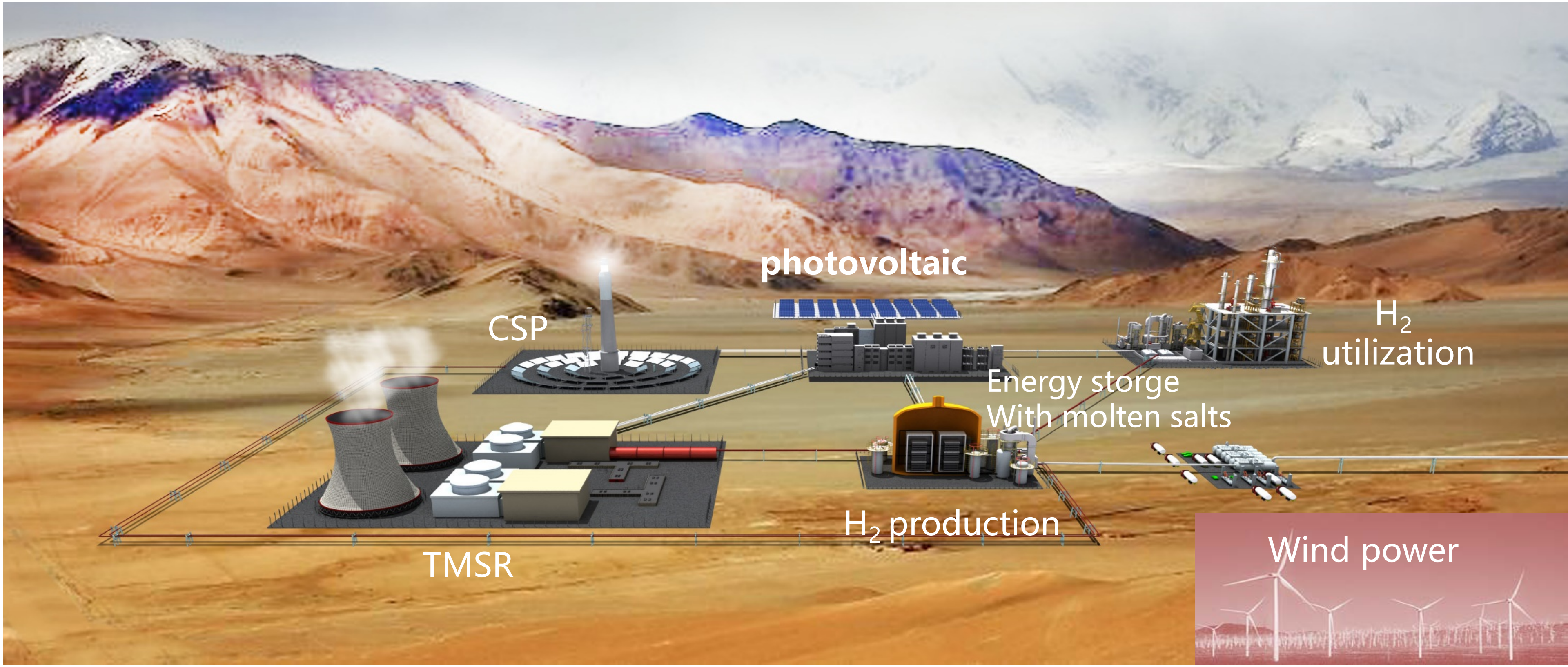
Step 3: step 2 + continuous process

- Continuous process to recycle salt, U and Th
- FP and MA partly separation



	Step 1	Step 2	Step 3
Th fission fraction (%)	~ 20	~ 40	~ 80

TMSR Innovative Hybrid-energy Park



Thanks for your attention!