Status and Perspective of TMSR in China

Hongjie XU,

TMSR Center of CAS, SINAP

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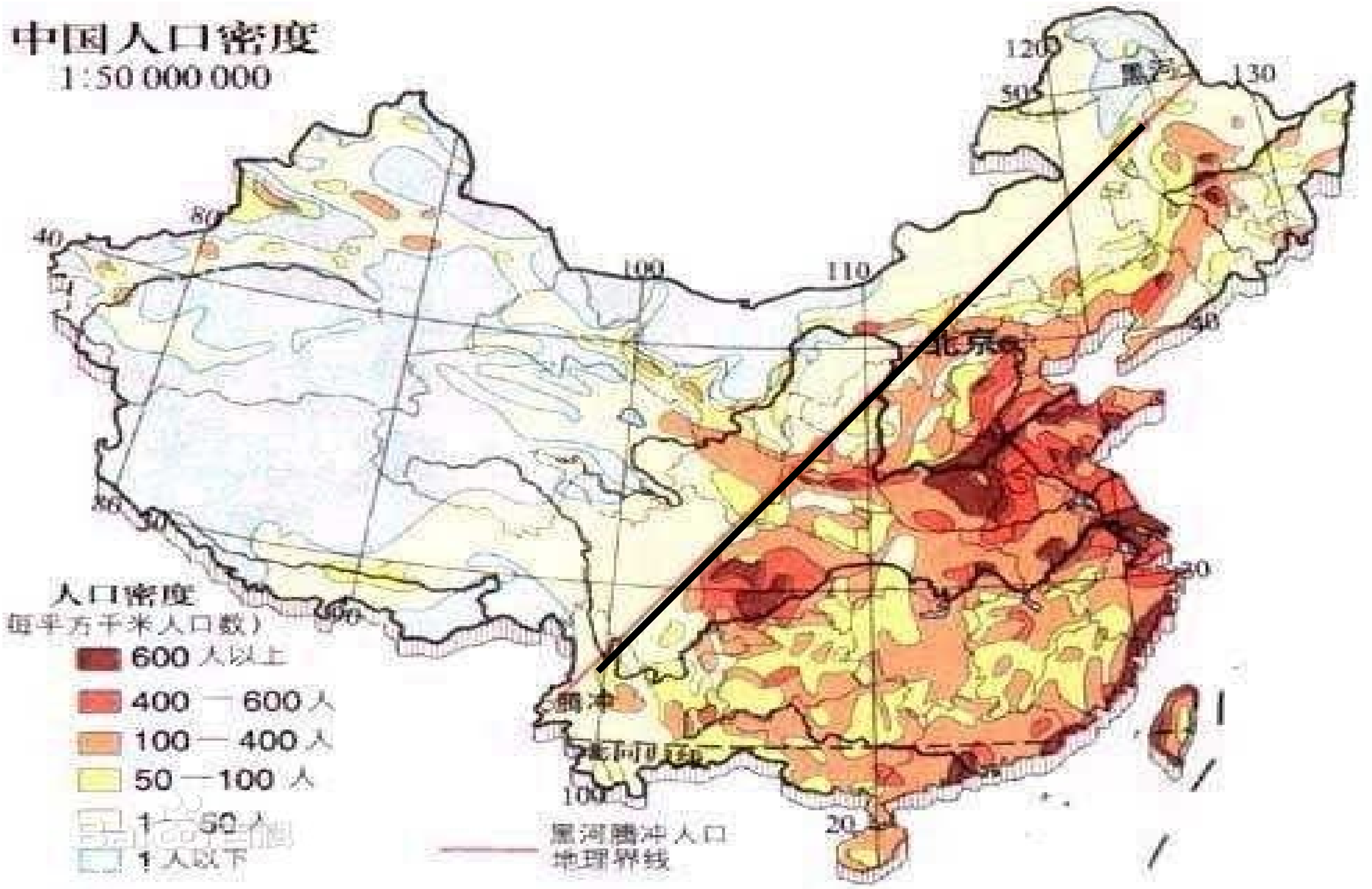
OUTLINE

Motivation of TMSR

Progress of TMSR

Perspective TMSR

TMSR-SF will be a energy solution for Northwest Area of 胡焕庸 line



SINAP | TMSR

Science AAAS

China-U.S. cooperation to adva...
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Science **353** (6299), 547-548. [...

A doubling to quadrupling of nuclear energy output is required in the next few decades, along with a large expansion of renewable energy---.

NUCLEAR ENERGY

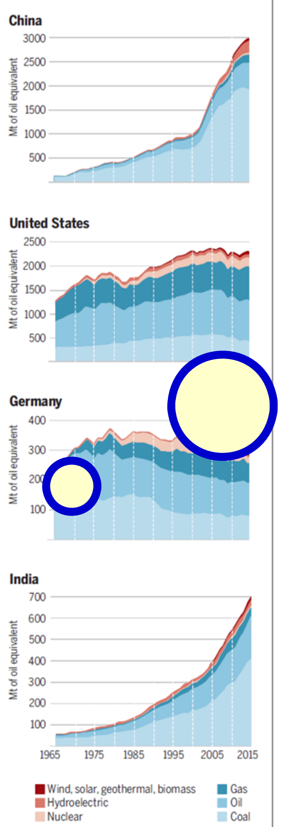
China-U.S. cooperation to advance nuclear power

Mass-manufacturing and coordinated approvals are key

By **Junji Cao**[1], **Armond Cohen**[2], **James Hansen**[3*], **Richard Lester**[4], **Per Peterson**[5], **Hongjie Xu**[6]

With China having the largest fossil fuel CO_2 emissions today and the United States being higher in per capita emissions (see related energy consumption in the first figure), these countries have a strong mutual interest in stabilizing climate and reducing air pollution. Yet even Germany, despite sizable subsidies of renewable energies, gets only a small fraction of energy from them (see the first figure). Historically the fastest growth of low-carbon power occurred during scale-up of national nuclear power programs (see the second figure). Some studies project that a doubling to quadrupling of nuclear energy output is required in the next few decades, along with a large expansion of renewable energy, in order to achieve deep cuts in fossil fuel use while meeting the growing global demand for affordable, reliable energy (*1*–*4*). In light of this large-scale energy and emissions picture, climate and nuclear energy experts from China and the United States convened (see Acknowledgments) to consider the potential of increased cooperation in developing advanced nuclear technologies.

Barriers to expansion of nuclear energy include high construction costs relative to coal and gas; a long time to build conventional large nuclear plants (about 4 to 7 years in Asia versus 1 or 2 years for coal-fired plants); and public concern about reactor safety, waste disposal, and potential for weapons use. Innovative nuclear technologies can help address some of these issues. A large reduction of cost and construction time, essential to accelerate deployment rates, likely requires mass manufacturing, analogous to ship and airplane construction. Such an approach lends itself to product-type licens-



Energy consumption in four nations. Data source (*6*). See supplementary materials.

[1]Key Lab of Aerosol Chemistry and Physics, SKLLQG, Institute of Earth Environment, Xi'an 710061, China. [2]Clean Air Task Force, Boston, MA 02108, USA. [3]Earth Institute, Columbia University, New York, NY 10025, USA. [4]Massachusetts Institute of Technology, Cambridge, MA 02139, USA. [5]University of California, Berkeley, CA 94720, USA. [6]Shanghai Institute of Applied Physics, Shanghai 21203, China. *Email: jimehansen@gmail.com

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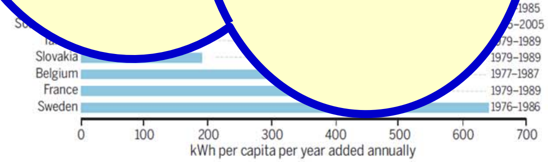
ing, which avoids the long delay and costs associated with case-by-case approval. Pa... sive safety features are available tha... low reactor shutdown and cooling w... external power or operator interv... Other innovative designs use fuel ... ficiently and produce less nuclea... can directly supply energy to i... processes that currently rely on fos... can be ordered in a range of scales ... variety of needs and geographies, a... reduce or eliminate cooling-water re... ments. Some of these developments c... be deployed on a large scale by 2030–20... a time when deep reductions in globa... carbon emissions will be needed, even ... much of the world's current nuclear fle... are approaching the end of useful life.

U.S.-China cooperation to accele... nuclear energy innovation has pote... to deliver benefits to both countries ... the world. Test sites at U.S. Departm... of Energy laboratories are needed to p... form experiments in existing test reacto... and to build a... ...te advanced designs. Chi... ...d for electricity, eve... ...its need to displac... ...g coal-fired capa... ...ket for nuclear ... drive down uni...

Innovati... ...ging in both countri... ...r development in the Un... ...es is entrepreneurially driven, in a departure from the traditional model in which nuclear innovation flowed outward from government. Technologies under development include small modular light-water, molten salt, gas-cooled, and liquid-metal-cooled reactors. China has recently made major investments in several nuclear innovation projects, including high-temperature gas reactors, thorium-fueled molten salt reactors, sodium-cooled fast reactors, and accelerator-driven subcritical systems.

Current China-U.S. cooperation includes collaboration between a U.S. company (TerraPower) and the China National Nuclear Corporation to demonstrate traveling-wave reactor technology, as well as the cooperation of Oak Ridge National Laboratory, U.S. universities, and the Shanghai Institute of Applied Physics to develop molten salt reactor technologies, including near-term options for fluoride salt–cooled, solid-fuel, high-temperature reactors. Molten salt technology, which has large potential but remains immature, provides a particularly large opportunity for U.S.-China cooperation.

Development of large floating nuclear plants—constructed in shipyards before being towed and anchored 10 to 20 km off-



Average annual increase of carbon-free electricity per capita during decade of peak scale-up. Energy data from (*6*) except California renewables data from (*7*). Population data from (*8*). See supplementary materials.

plant subsystems—such as a standards-based specification for reactor modules of all types that would address general safety criteria, fuel lifetime, transportability, and so on, as well as open-source codes for advanced reactors; (iii) joint programs to develop, demonstrate, and license advanced non–light-water reactors; (iv) agreement on a regulatory approach that encourages technical innovation in safety assurance, as opposed to detailed prescriptive specifications, also "stage gates" of approval rather than a single review that can require hundreds of millions of dollars in preparation. Jointly funded projects would be governed by the regulations of the host country.

However, obstacles to broader Sino-U.S. nuclear cooperation must be overcome. Obstacles and benefits are both illustrated by recent developments in light-water reac- projects may require participating commercial firms to decide on the intellectual property they are willing to transfer. Regulators in the two countries may choose to align safety standards, which would expand market opportunities for suppliers in both countries, or promulgate their own regulatory criteria, which might benefit their own suppliers by creating barriers to suppliers from the other country but limit their available market.

One barrier our U.S. authors recommend for review is U.S. policy requiring specific authorization for exports of civilian reactor technologies to China, in contrast to general authorization allowed for exports to Japan, South Korea, France, and the United Kingdom. The protracted review process makes cooperation between U.S. and Chinese industry difficult and slow

...or ...eration

...at the world ...sil fuel emis... ...stabilized. Fu... ...de climate and ...tries such as In... ...h—with the third ...ns and population ...ina's in 2021 (*6*)—has ... energy needs that are fos... ...dependent (see the first figure). ■

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ACKNOWLEDGMENTS

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/353/6299/547/suppl/DC1

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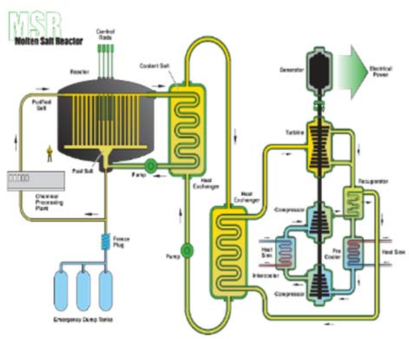
Overview of the Generation IV Systems

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
Supercritical-Water Reactor (SCWR)	Thermal, Fast	Open, Closed	1500	Electricity	Materials, Thermal-hydraulics
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 Production, Actinide Management	Fuel treatment, Materials, Reliability

Molten Salt Reactor

Suitable for generate electricity, comprehensive utilization and modular design



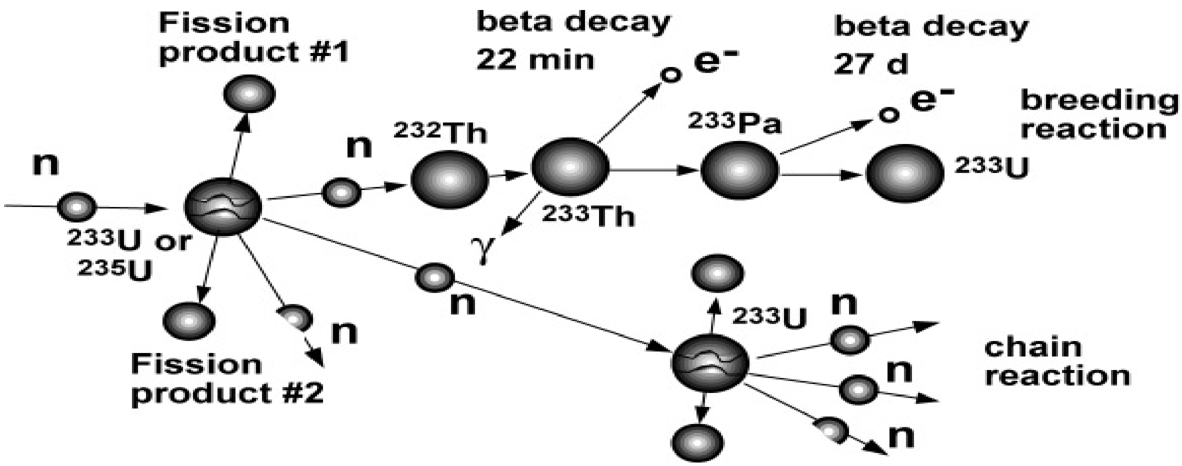
- **Th utilization :** Physical features applicable for Th fuel
- **Online refueling :** Refueling and reprocessing of fuel
- **Inherent safety :** Intrinsic safety features, can be built underground
- **Water-free cooling :** Applicable for inland arid area

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

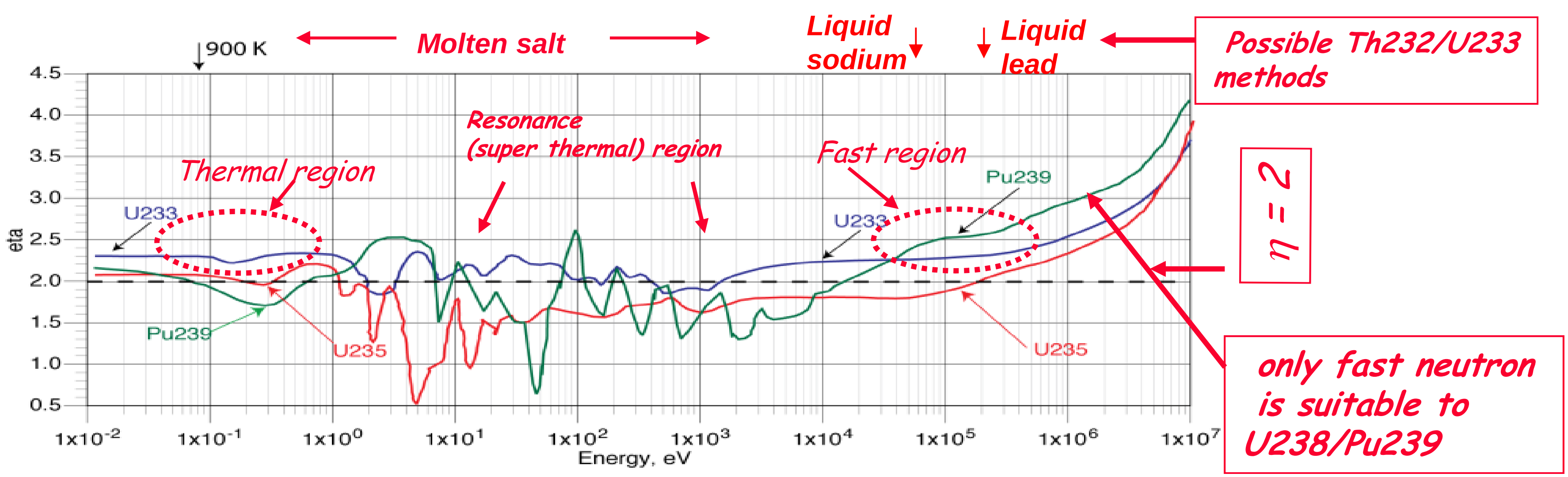
*@75 atm

Th232/U233 and U238/Pu239 fuel cycles



Mean released neutron number per fission η

$\eta = 2$ is the required condition for a sustain reactor



OUTLINE

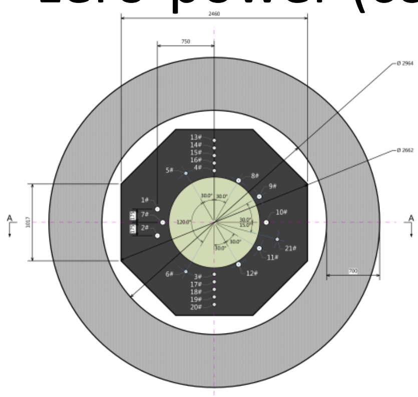
Motivation of TMSR

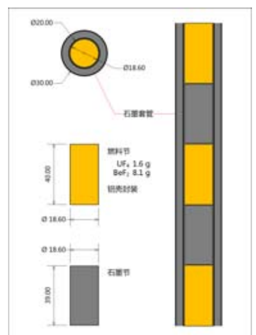
Progress of TMSR

Perspective TMSR

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 Project (Chinese Academy of Sciences)

中文名称：钍基熔盐堆核能系统

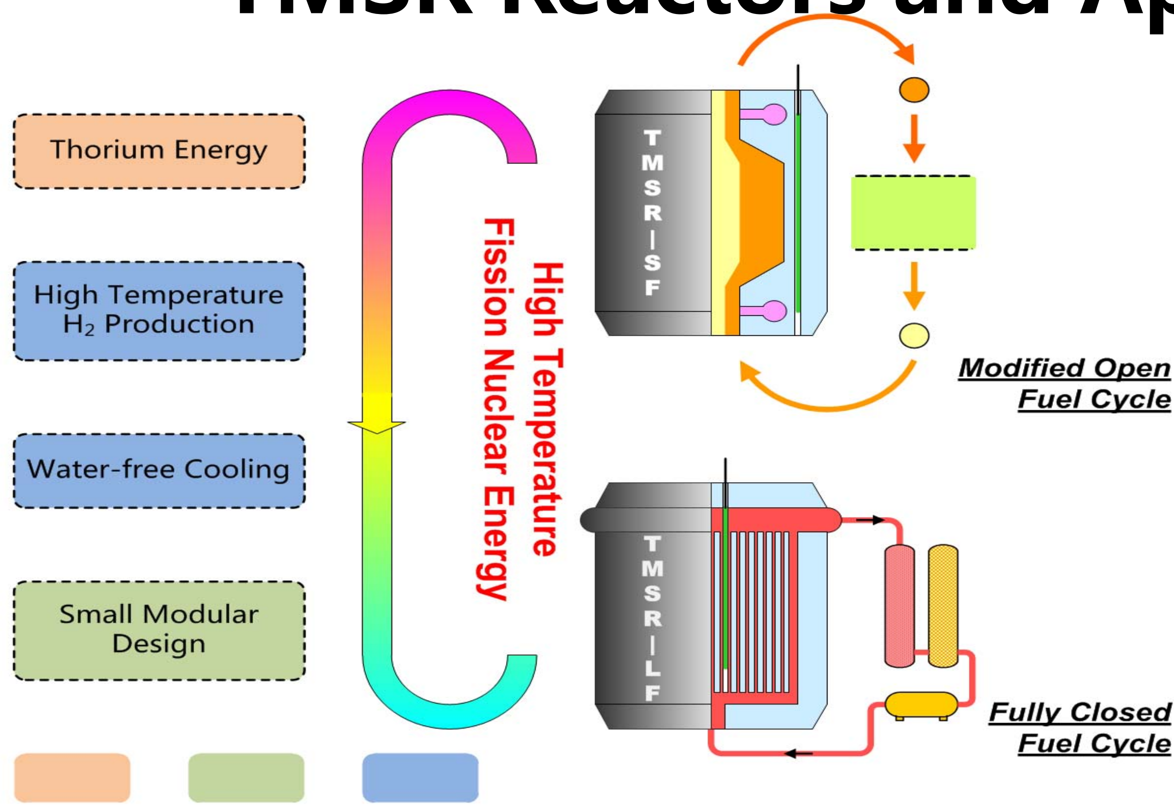
英文名称：Thorium Molten Salt Reactor

Nuclear Energy System

Abbr. ：TMSR

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

TMSR Reactors and Applications



Strategy of TMSR R&D

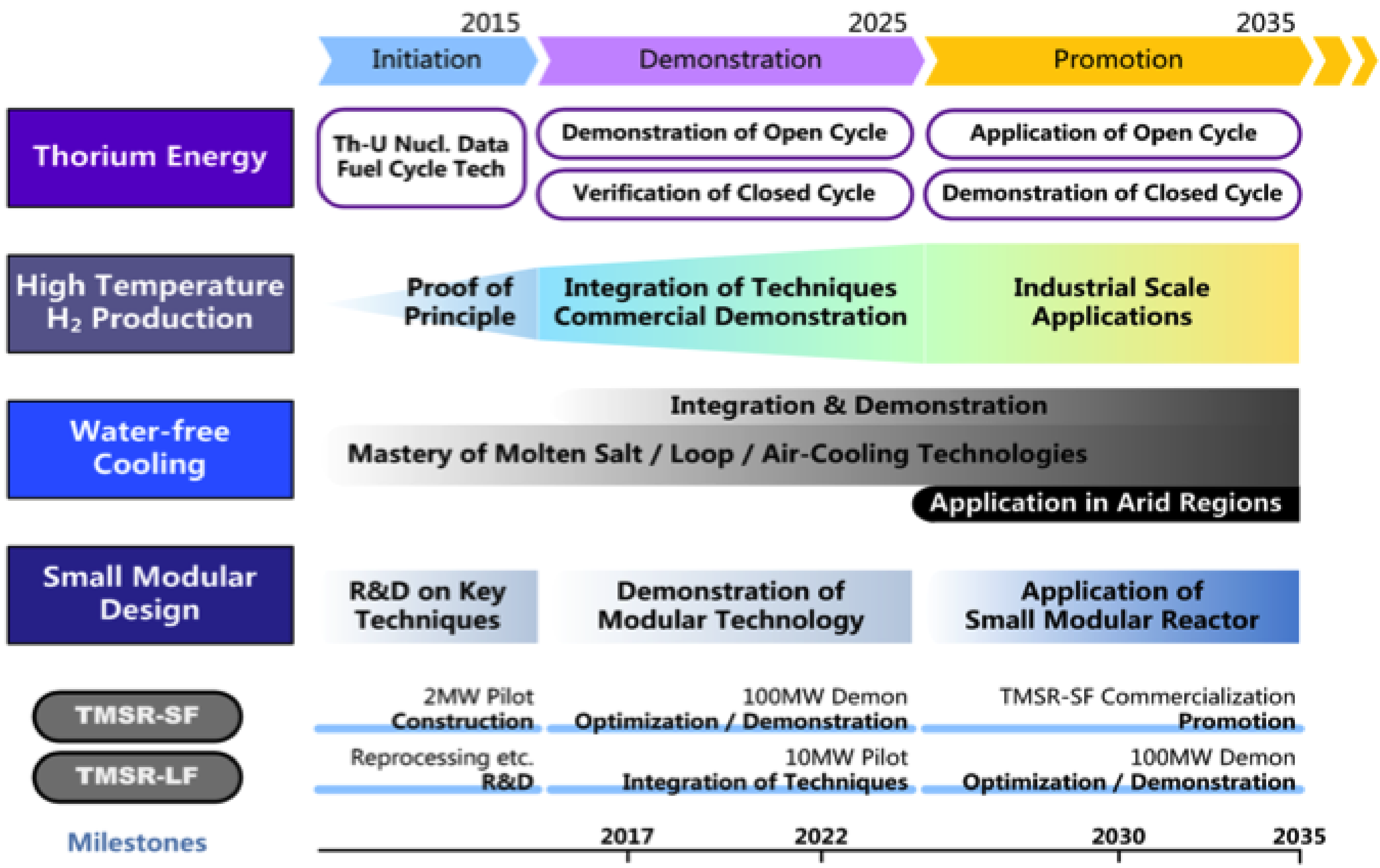
Th Energy :
Long-Term Supply of Nuclear Fuel

MSR :
Elevated Safety
Efficiency
Nonproliferation

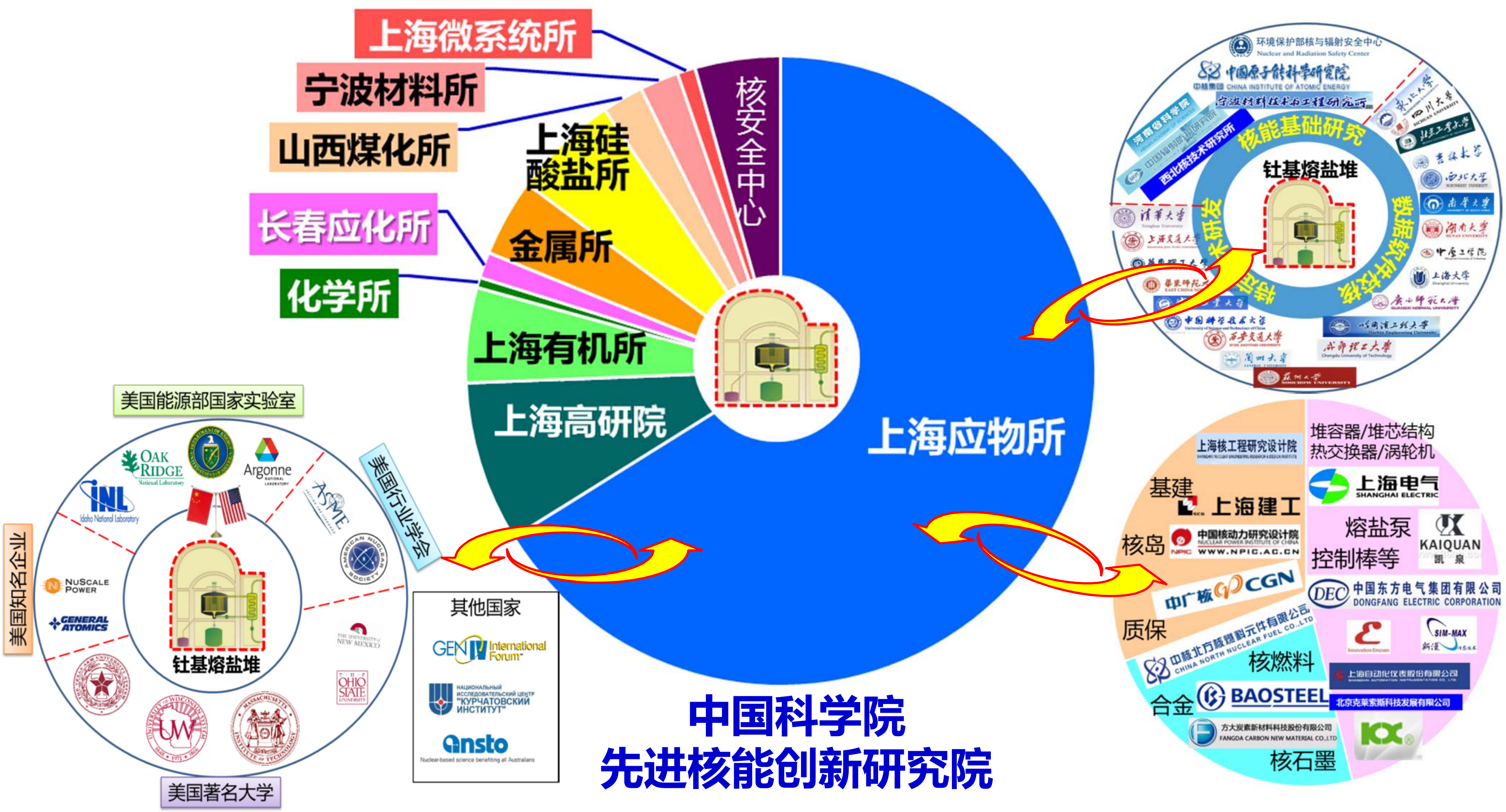
TMSR-SF(Solid-Fuel): Optimized for high-temperature based hybrid nuclear energy application.

TMSR-LF(Liquid-Fuel): Optimized for utilization of Th with Pyroprocess.

TMSR Schedules



International and Domestic Collaborations



TEAMS: Staffs ~600; Graduate students ~200

TMSR Technologies R&D

- **Fuel fabrication and spent fuel management:** Unrealized online fuel salt reprocessing, technology of pyroprocessing.
- **Corrosion and penetration of materials (molten salt, graphite and alloy):** Improved safety protection requirements, R&D of the first experimental TMSR-SF and material.
- **Reactor design(experimental reactor, demonstration reactor and small modular reactor), equipment development, system integration and validation:** Based on the international science and technology level and industrial manufacturing capacity.
- **Design, safety analysis and technical standards of reactor:** Lack of knowledge accumulation results in the restricting compared to international technology level, control and blockade of western technology leads to the increased pressure of domestic industrial manufacturing capacity.
- **High temperature application and hydrogen production:** Development of high temperature nuclear heat comprehensive utilization technology suitable for the molten salt reactor.

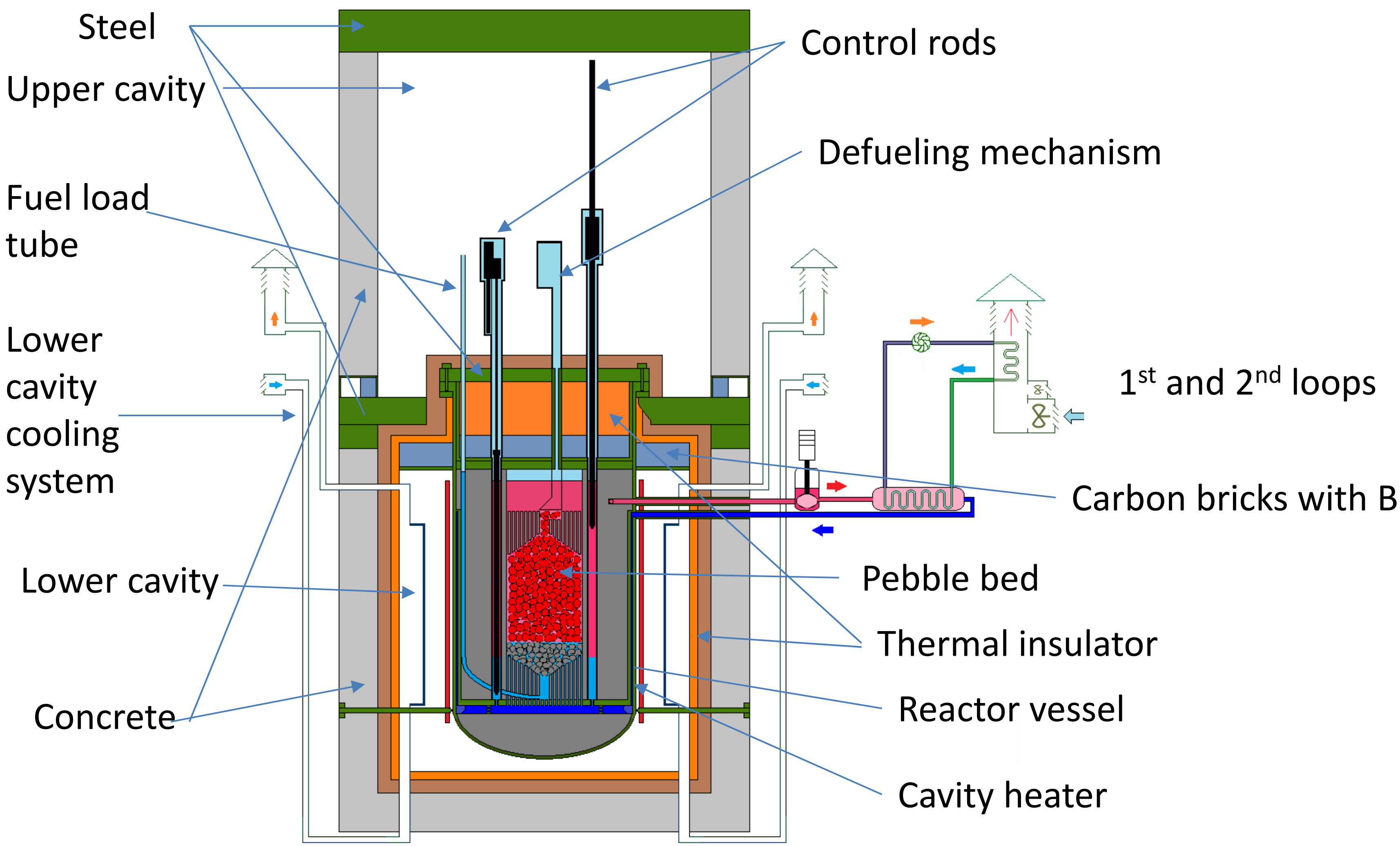
TMSR Test Reactors

- 10 MW solid fuel molten salt test reactor (TMSR-SF1)
  - Preliminary engineering design, in cooperation with Nuclear Power Institute of China (NPIC) and Shanghai Nuclear Engineering Research & Design Institute (SNERDI);
  - Material, component and instrumentation development;
  - Simulate reactor for design verification and research.
- 2 MW liquid fuel molten salt test reactor (TMSR-LF1)
  - Conceptual design modified to better match the requirements of thorium fuel cycle research and MSR online pyro processing scheme verification.

Basic design features of TMSR-SF1

- Reactor power: $10MW_{th;}$
- Coolant temperature: Inlet 600°C, outlet 650°C;
- Fuel element: TRISO fuel, 6cm ball, HTR-PM type;
- Core: conventional pebble bed;
- Passive residual heat removal by cavity cooling;
- Materials: N-alloy, fine grain graphite, C-C;
- Temperature limitations: Fuel, <1400°C; coolant outlet, <700°C;
- Reactor vessel pressure limitations: <5atm.

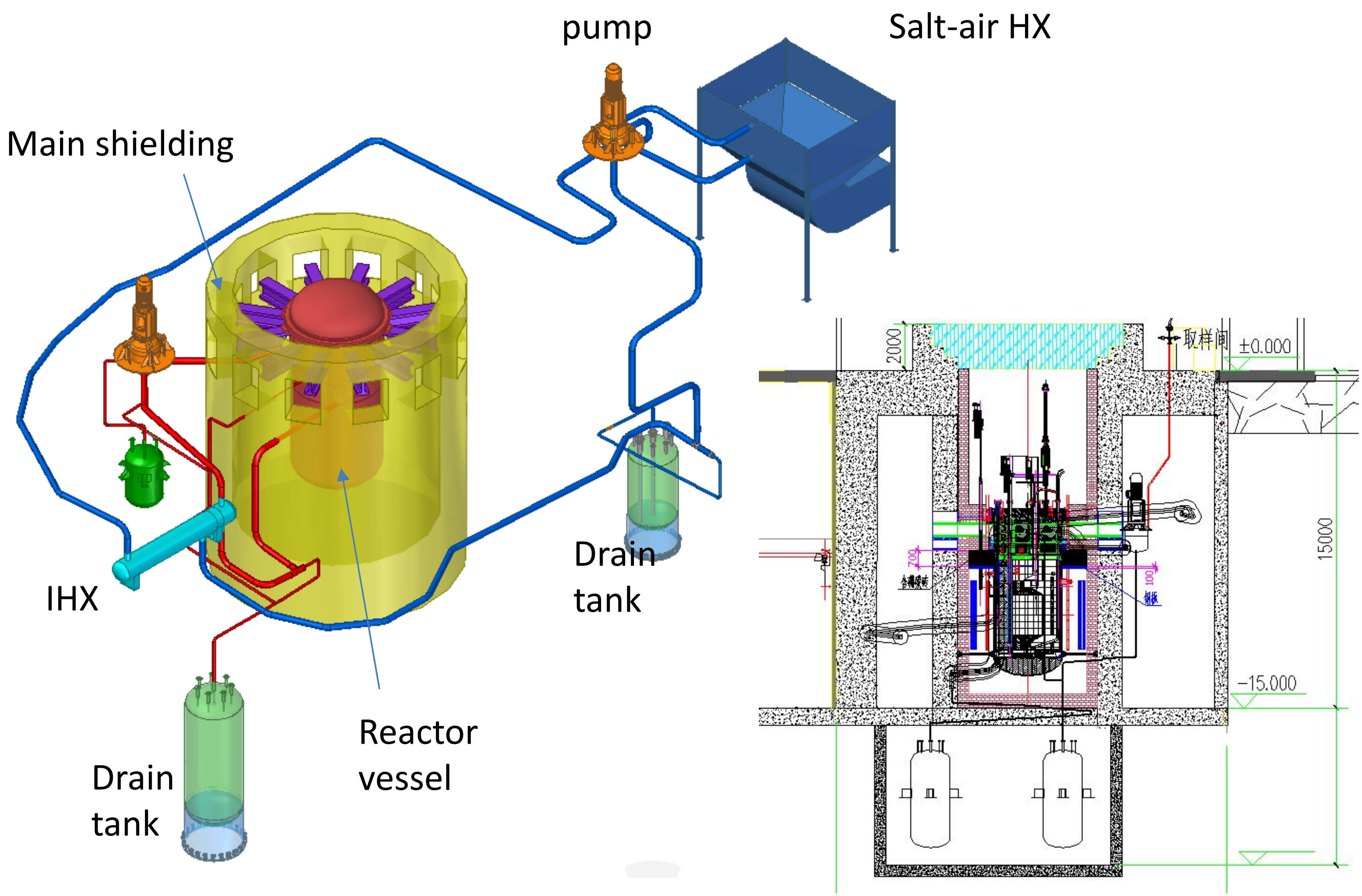
TMSR-SF1 Schematic layout



Main design parameters of SF1

Power	10 MWt
Lifetime	20 year
Operation time	100 EFPD for single batch of fuel
Average power density	4.0 MW/m^3
Fuel element / abundant / ^{235}Uload	6cm ball / 17.0% /15.6 kg
Coolant（1st loop，2nd loop）	FLiBe（99.99%Li7），FLiNaK
Structure material	N alloy，graphite
Reactor coolant inlet temperature	600 ℃
Reactor coolant outlet temperature	650℃
Vessel temperature / pressure designed	700°C / 0.5MPa (abs.)
Vessel upper cover temperature designed	<350℃
1st /2nd loop coolant flow rate	84 kg/s / 150kg/s
Cover gas / pressure	Ar / 0.15MPa (abs.)

TMSR-SF1 system layout



TMSR-SF1 simulate reactor (TMSR-SF0)

Purpose

- SF1 design verification: passive heat removal capability, integrate and separate hydraulics, thermal insulation and temperature control…;
- SF1 design research: simulation research of various SF1 events, including LOFC transient;
- Benchmark: T-H and safty analyzing codes…
- Training: reactor operation…

Basic feature

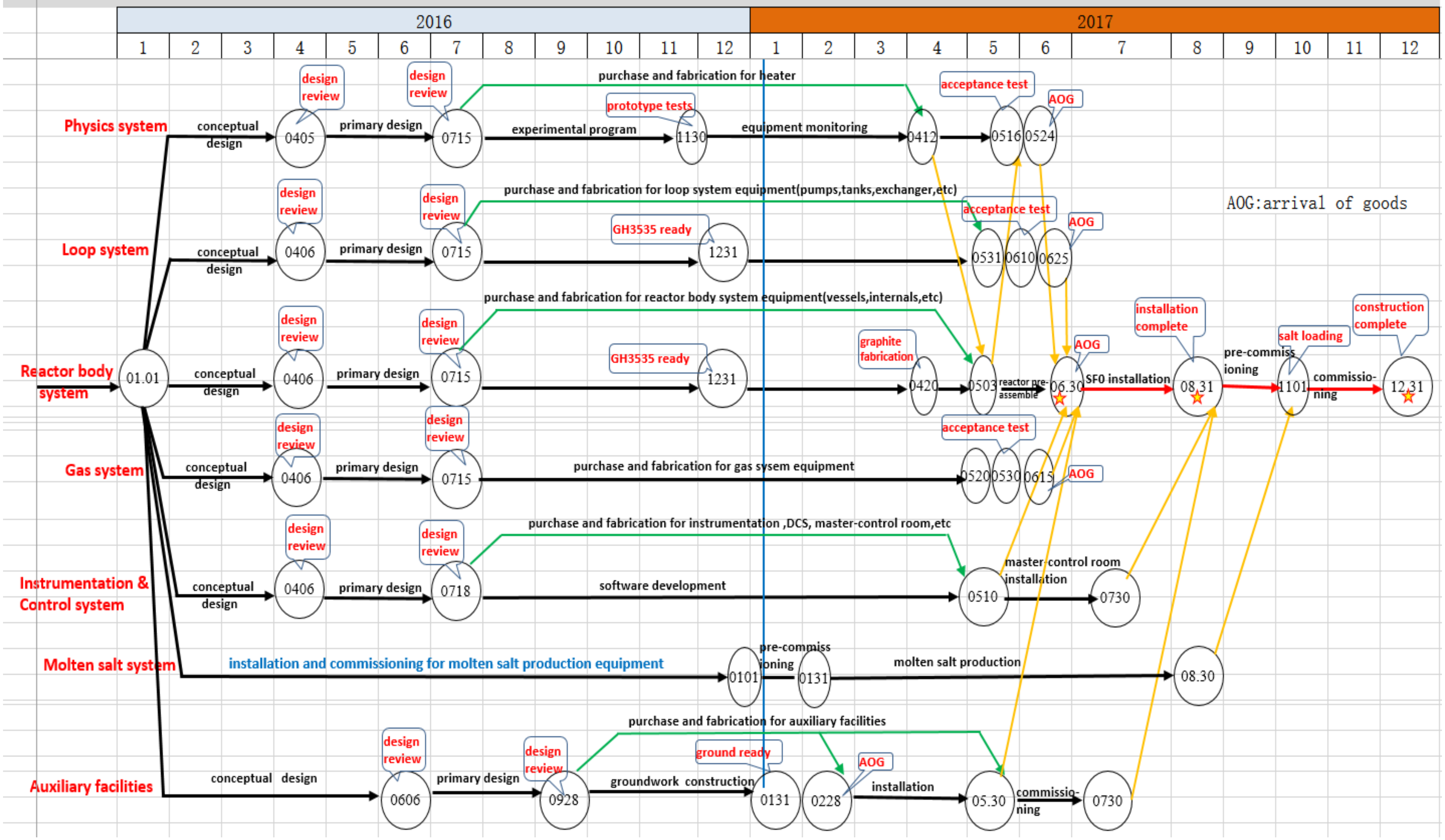
- Size scaling: ~1/3 of TMSR-SF1;
- Core power: 400kW by electric heating;
- Coolant: FLiNaK;
- Scaling analysis for important experiments.

SF0 design parameters vs. SF1

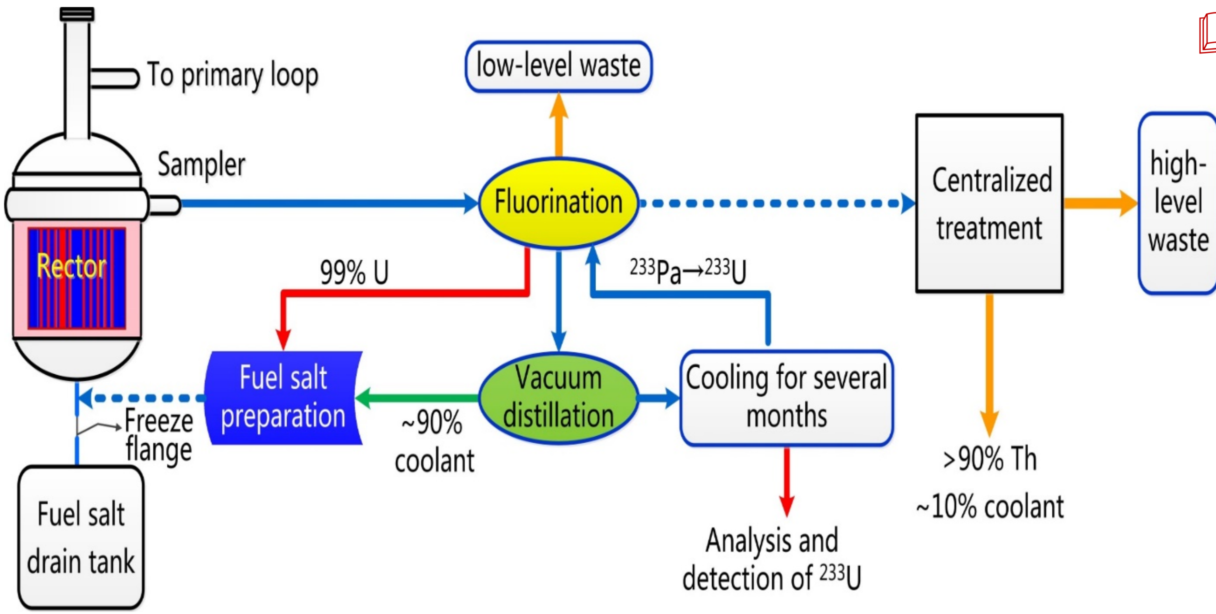
	TMSR-SF1	TMSR-SF0
Core heat power	10MW	400kW
1st loop coolant temperature	600/650°C	600/650°C*
1st loop coolant flow rate	84kg/s	10kg/s*
1st loop coolant	FLiBe	FLiNaK
1st loop pressure loss	0.2MPa @ 84kg/s	0.2MPa @ 10kg/s
Passive decay heat removal ability	200kW	12.8kW
Core height	3000mm	1200mm
Core diameter	2850mm	880mm
Active heating region: diameter	1350mm	500mm
height	1800mm	600mm
Main Vessel diameter	3050mm	1020mm
MainVessel height	7840mm	3120mm

* For different operation mode.

Plan of project schedule for Molten salt cooled reactor test facility (TMSR-SF0)



Overview of TMSR-LF1 conceptual design



- Design considerations
  - Investigation on operation stability and safety
  - Test of online refueling and continuous gas removing
  - Testing of online pyro-processing of fuel salt
  - Operation with Th-U mixed fuel
  - Experiment of Th-U conversion

- Efficiency of online gas removal is about 70%
- Fuel salt batch reprocessing: 10 L per course
- Thorium inventory ~ 50 kg; CR (Th-U) ~ 0.1

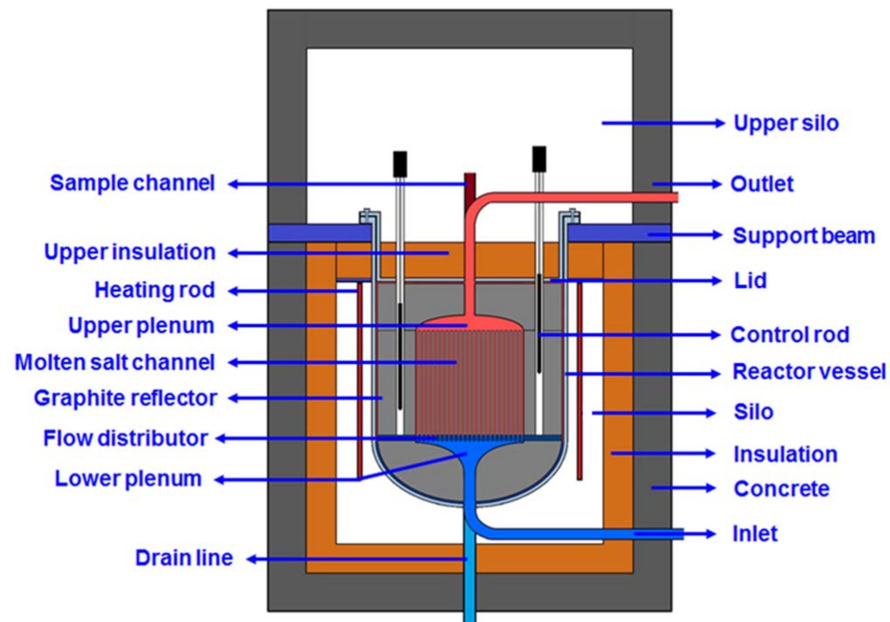
- Validation of key techniques of reprocessing flowsheet, fluorination and vacuum distillation
- Validation of Th-U conversion and online refueling

TMSR-LF1 reactor design

Core design constrains and principles

- U-235 enrichment ＜ 20%
- Li-7 abundance: 99.95%
- Appropriate amount of Th (verification for Th-U fuel cycle)
- Low excess reactivity
- Negative temperature feedback
- Simple core structure, easy for system integration, control and maintenance
- Uncertainty of physical parameter, engineering feasibility and practical ability of post-processing technology.

Reactor layout



- Reactor core
- Heat transfer system
- Pyroprocessing
- Radioactive gas removal system
- Safety system
- Auxiliary components

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

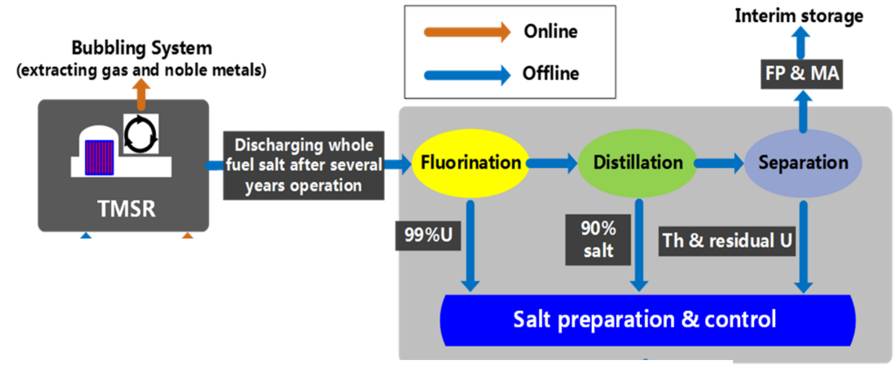
Step 2: step1 + fuel reload

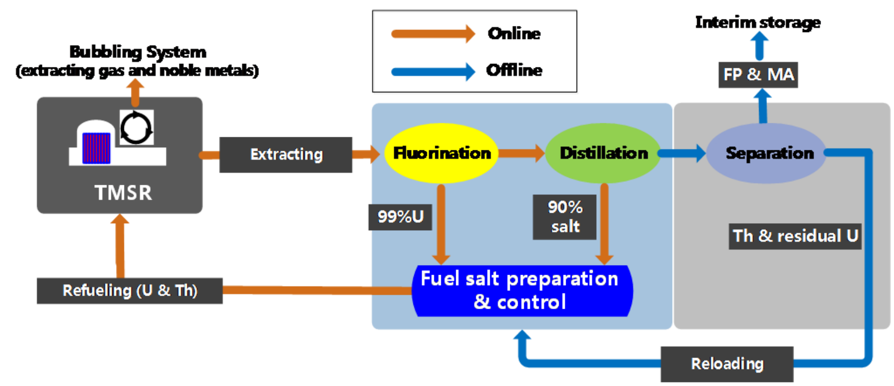
- Reloading of U and Th to realize thorium fuel cycle

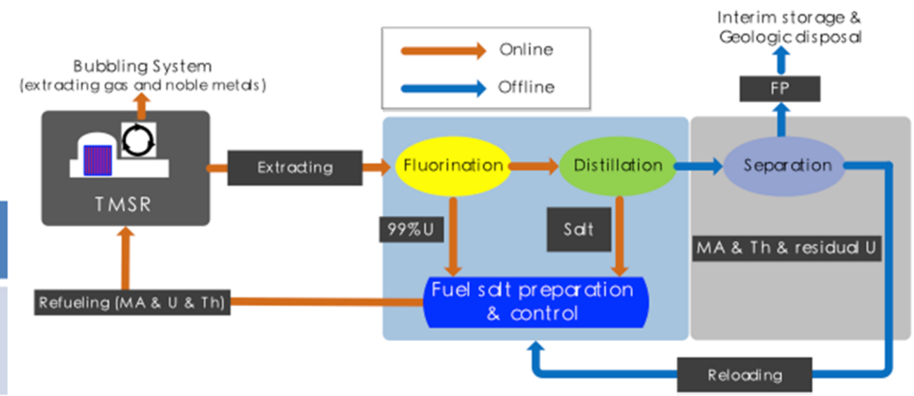
Step 3: step 2 + continuous process

- 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







Thorium-Uranium Fuel Cycle-Progress

- 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

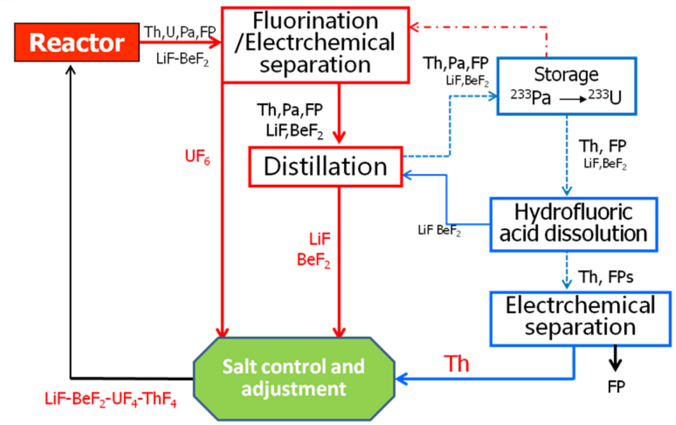
Flow sheet combines on-line and off-line processing

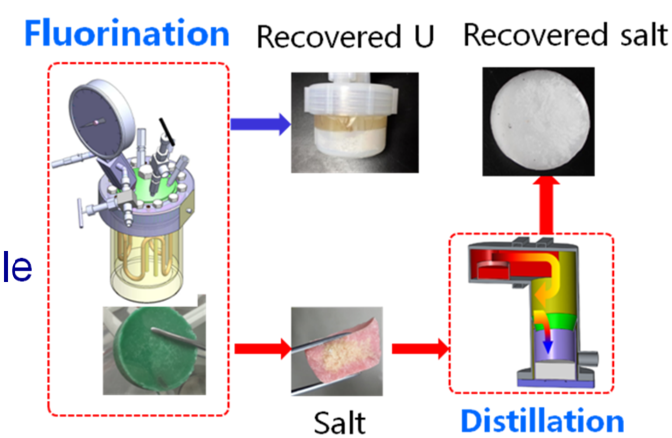
- On-line for U and carrier salt
- Off-line for Th and minor actinides

Process Consist.

Consistency of on-line reprocessing in cold, lab-scale

- Recovery rate of U > 95%
- Recovery rate of carrier salt > 90%





Pyro-processing Techniques

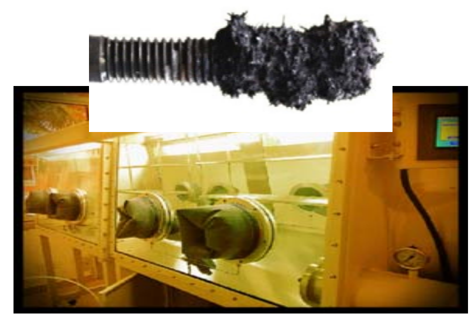
- Fluorination and distillation of fluoride salts in cold experiments
- Developing fluorides electrochemical separation techniques

- **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

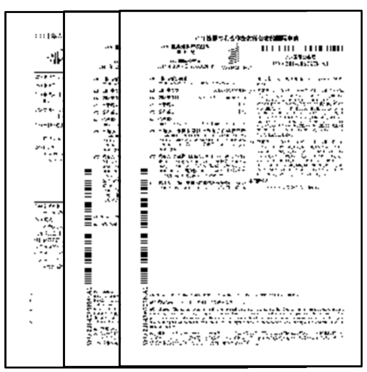


Electrochemical experimental set-up

^{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 99.999 % purity of thorium was achieved in batches.



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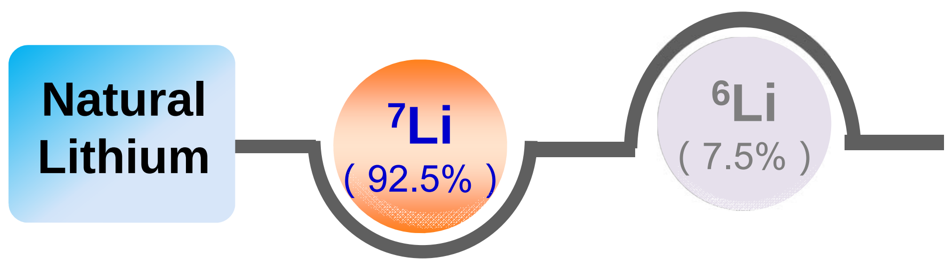


- PWR pH control (abundance ≥ 99.9 %)
- MSR coolant (abundance ≥ 99.99 %)

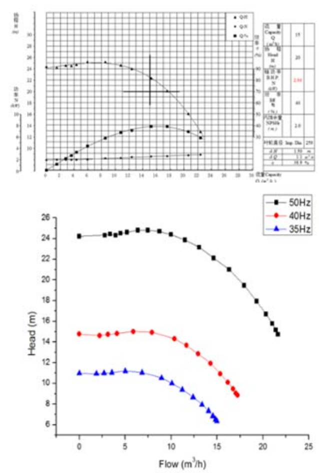
Fluoride Salt Loops

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

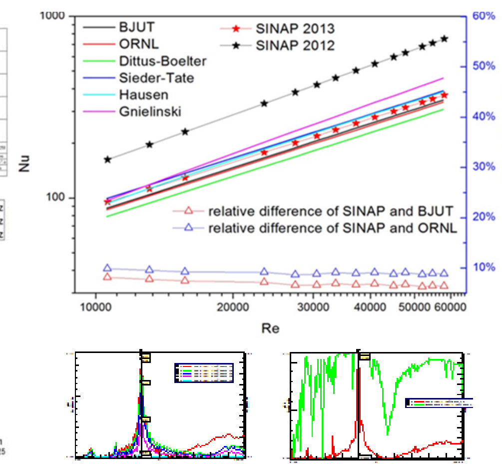
- Design and analysis methods for high-temperature fluoride salt loops
- Prototypes for pump, valve, heat exchanger, etc.
- Experience of loading and unloading of fluoride salts
- Experience of high-temperature fluoride salt loops operation and maintenance


High-temperature fluoride salt experimental loop


Prototypes of equipment



Hydraulic test of molten salt pump



Thermal hydraulic & mechanical test of loop

Nuclear Safety and Licensing

- Developing safety analysis methods and codes
- Developing safety design criteria and completing safety system design
- Established a salt natural circulation test loop 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

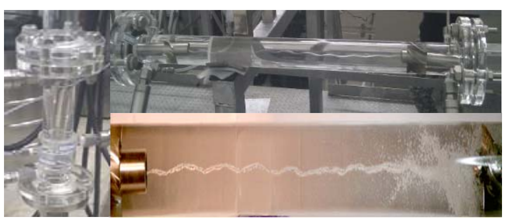
FSAR → Fuel Loading Permit

FSAR Rev. → Operation Permit

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,



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

- Smelling 6 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)

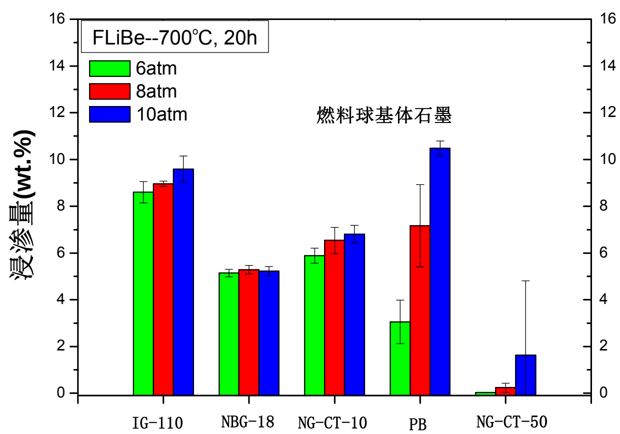
Production of Nuclear Grade Graphite

- 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

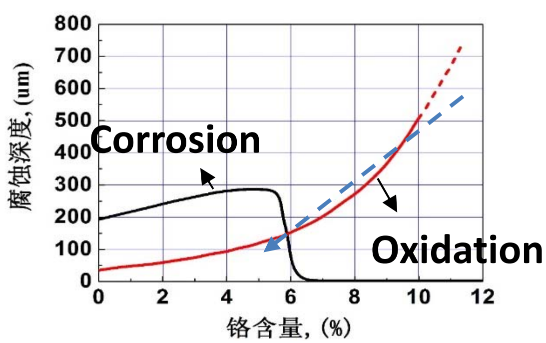
- Control the structural material corrosion by alloy composition optimization, salt purification and surface treatment

Investigating Corrosion Mechanism

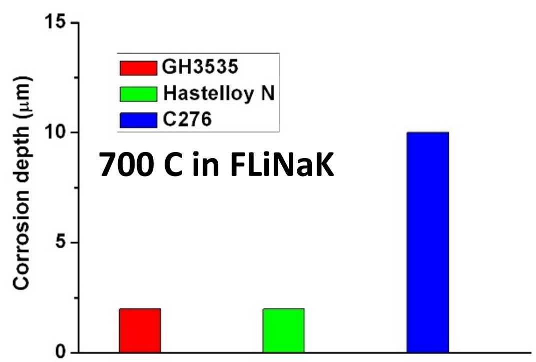
- Salt impurities
- Elements diffusion
- Mass transfer

Developing Corrosion Control Technologies

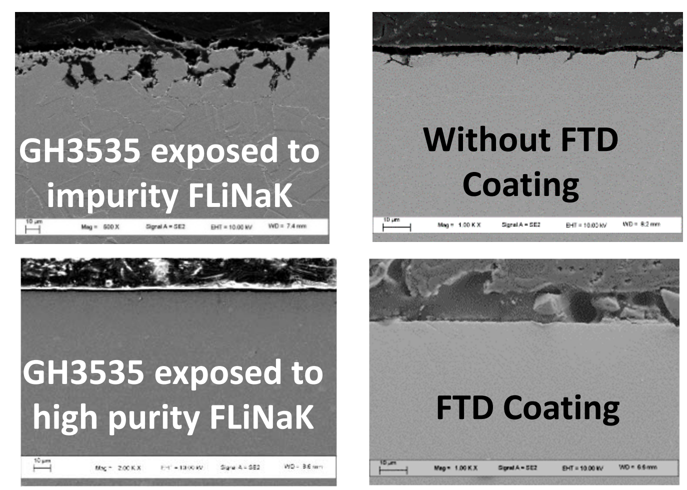
- Optimize the composition of alloy, diffusion of Cr
- Improve purification technology, minimize impurities
- Fluoride salt thermal diffusion coating



Composition Optimization (Cr)



Corrosion Depth (µm/y)



Comparison of Hydrogen Production by Different Water Electrolysis Technology

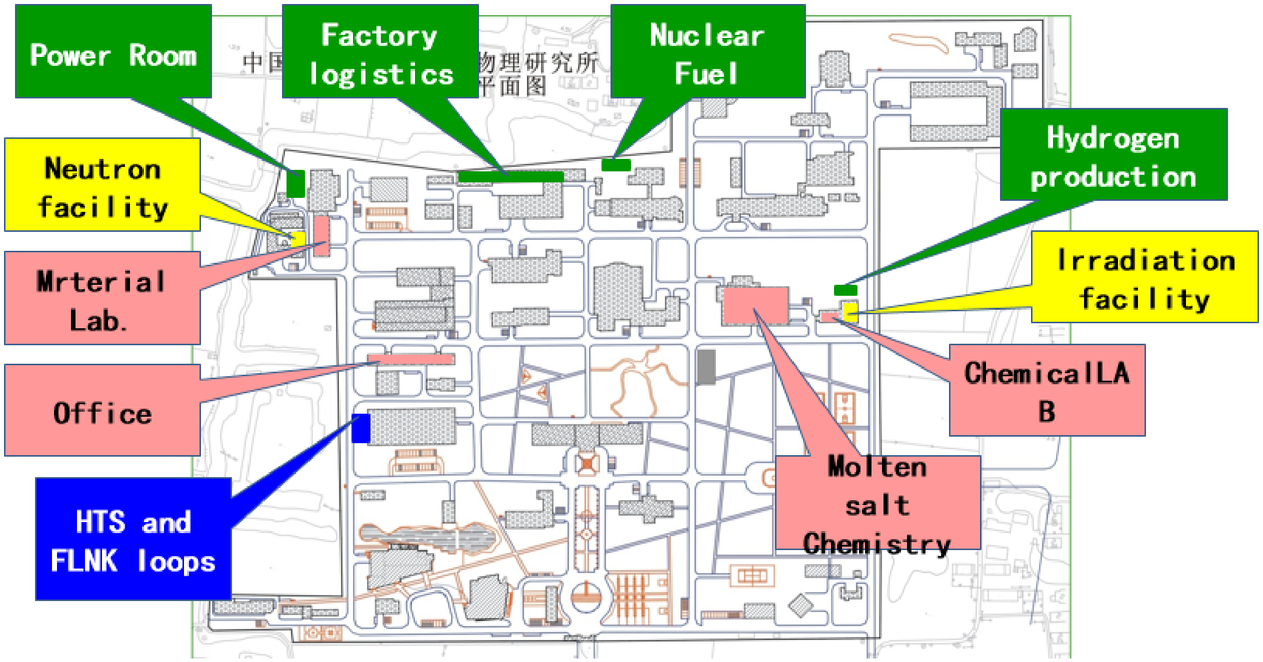
- The energy consumption of SINAP-Hydrogen-System is quite lower than most commercial products;

Company and Institute	Product	Technology	Energy Consumption kWh/Nm^3
SINAP, CN	**Lab-Scale**	**SOEC(HTSE)**	**~ 3.4**
INL, USA	Lab-Scale	SOEC(HTSE)	~ 3.2
Hydrogenic, CA	HySTAT	AEC	4.9
	HyLYZER	PEM	6.7
Proton, USA	Hydrogen-C	PEM	6.2
PERIC, Hebei, CN	ZDQ	AEC	<4.6
DaLu, Tianjin, CN	FDC5	AEC	<4.9
JingLi, Suzhou, CN	DQ-2	AEC	<5

TMSR-Molten Salt for Heat Transfer and Storage

System	Molten Point ℃	Decomposed Point /℃	Density g/cm^3	Viscosity $10^6 m^2/s$	Heat Capacity $kJ/m^{3o}C$	Thermal Conductivity W/m·K
$NaNO_3$-KNO_3 (60-40wt.%) @400^{o}C	221	600	1.8	1.58	2850	0.62
Hitec ($NaNO_3$-KNO_3-$NaNO_2$) (7-53-40wt%) @400^{o}C	142	535	1.86	1.61	2900	0.4
$LiNO_3$-$NaNO_3$-KNO_3 (29.56-17.73-52.72wt%) @400^{o}C	120	540	1.85	1.73	2920	0.48
$LiNO_3$-$NaNO_3$-KNO_3-$Ca(NO_3)_2$ （17.22-12.74-45.45-24.59 wt%）	90	500	2.17	2.76	3500	0.40
Li_2CO_3-Na_2CO_3-K_2CO_3 32.12-33.36-34.52wt%) @600^{o}C	397	800	2.01	5.5	3237	0.49
KCl-$MgCl_2$（66-37mol%）@600^{o}C	426	1450	1.61	0.86	1470	1.1
LiF-NaF-KF （46.5-11.5-42mol%）@600^{o}C	458	1570	2.05	2.32	3745	0.71
ZrF_4-KF（42-58mol%）@600^{o}C	420	1400	2.846	0.21	2988	0.32
LiF-BeF_2（67-33mol%）@600^{o}C	459	1430	2.16	3.96	5173	1.0

Fundamental Research Base at Jiading



Super Computer

Hot Cells

Material Testing Labs

Salt Properties Labs

β Irradiation Facility

OUTLINE

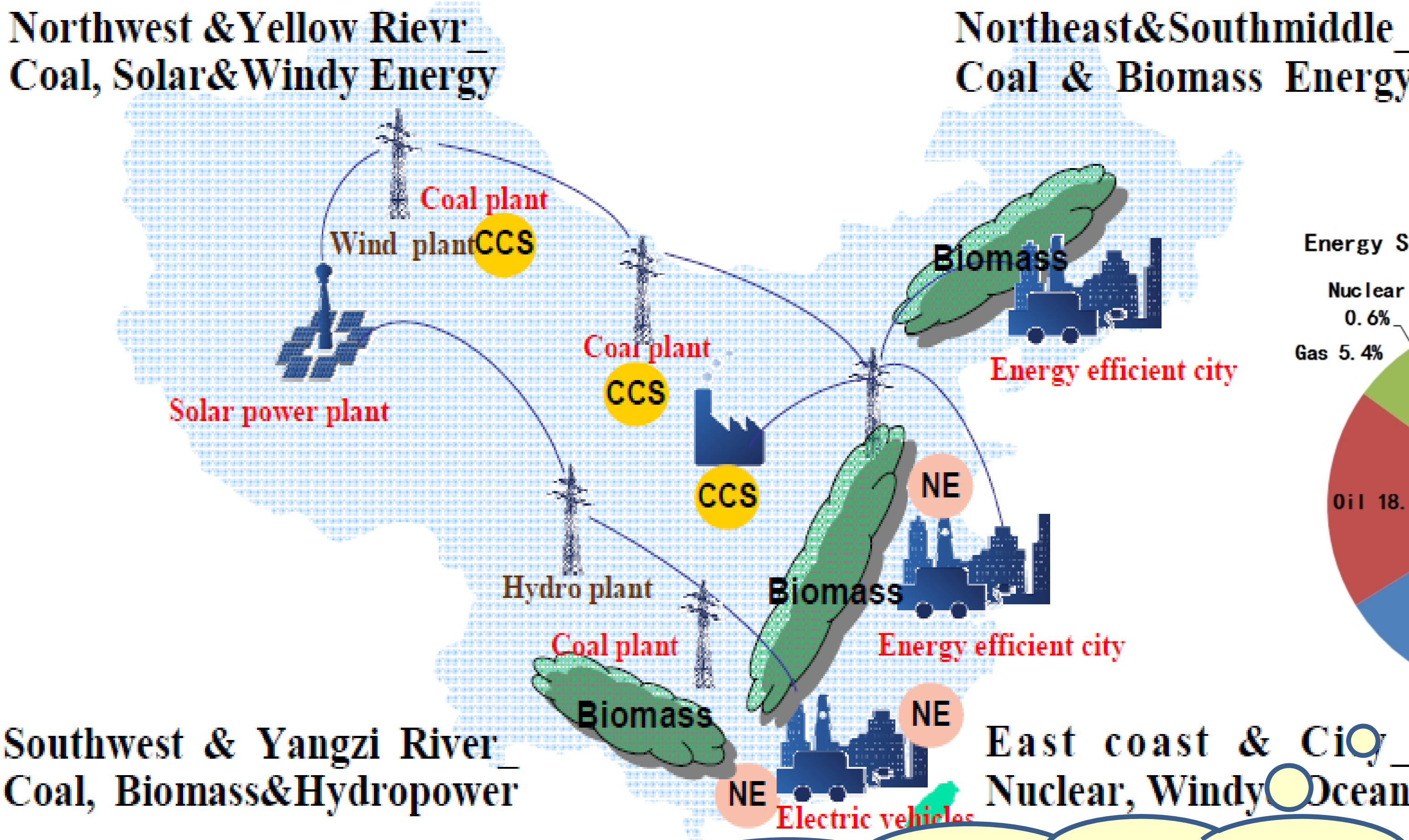
Motivation of TMSR

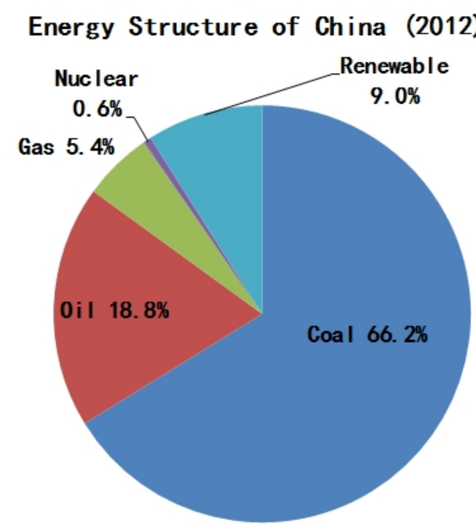
Progress of TMSR

Perspective TMSR

To allocate site for test reactor

Coal dominates primary energy consumption of China





>620 coal-fired power plants

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

To realize near term aims

100MW liquid-fueled demonstration TMSR

Th-U fuel cycle demonstration

Long-term (～2030)

100MW solid-fueled demonstration TMSR

10MW liquid-fueled experimental TMSR

Commercial FHR demonstration

Mid-term (～2025)

10MW solid-fueled experimental TMSR(TMSR-SF1)

2MW liquid-fueled experimental TMSR(TMSR-LF1) +Th-U cycle experimental verification

Technologies
Design
Integration

Near-term (～ 2020)

Technology transfer to other application

- To realize industrial level application for the technology we have hed in Lab-scale 。
  - CSP (salt purification, system design and operation , equipment production and so on)
  - Heat storage based on molten salt
  - R&D of molten salt battery
  - FTD

To prepare for mid-term project

100MW liquid-fueled demonstration TMSR

Th-U fuel cycle demonstration

Long-term (～2030)

100MW solid-fueled demonstration TMSR

10MW liquid-fueled experimental TMSR

Commercial FHR demonstration

Mid-term (～2025)

10MW solid-fueled experimental TMSR(TMSR-SF1)

2MW liquid-fueled experimental TMSR(TMSR-LF1) +Th-U cycle experimental verification

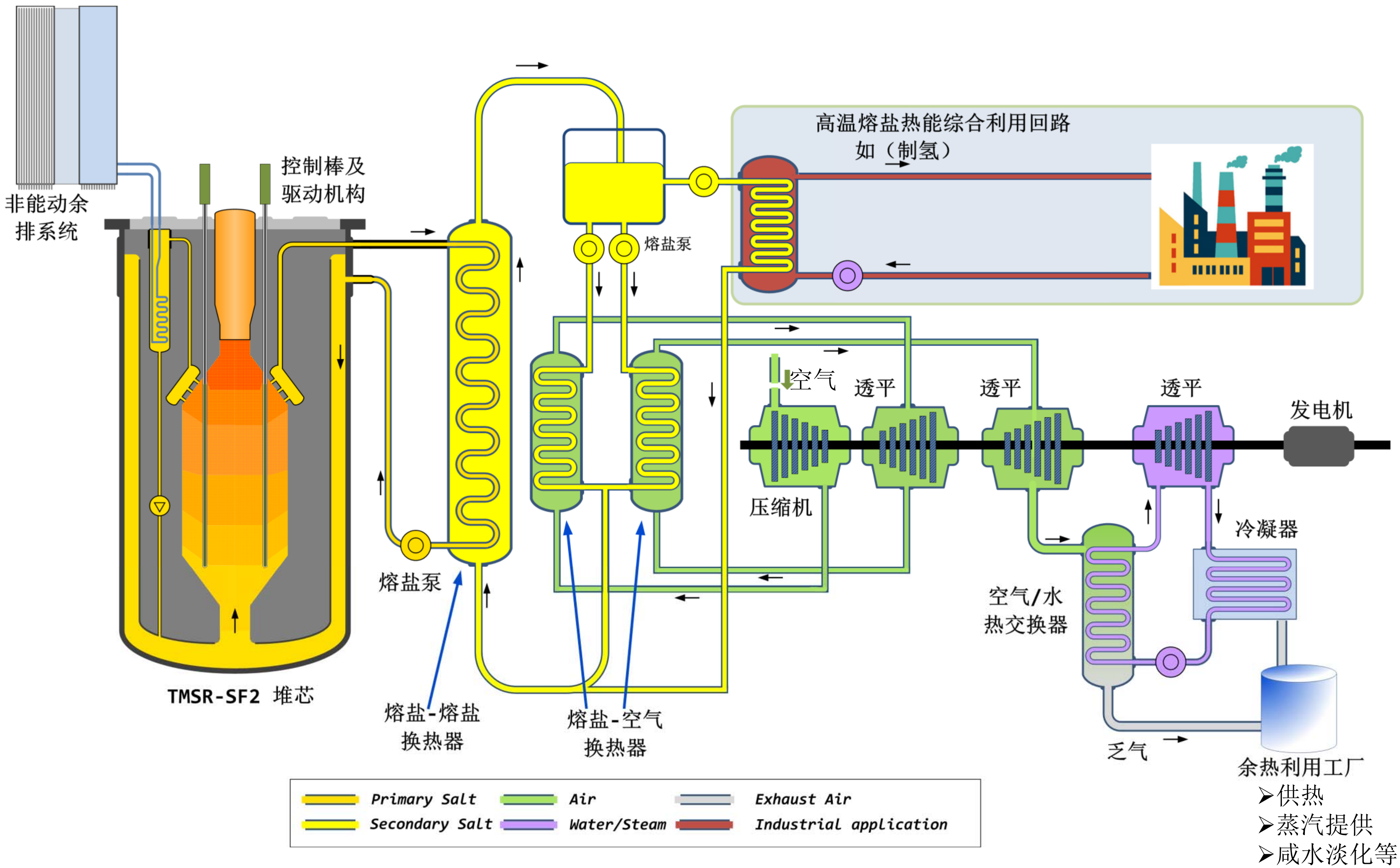
Technologies
Design
Integration

Near-term (～ 2020)

Mid-term project will focus on TMSR-SF/LF-SMR with TMSR fuel salt batch pyro-process demo-facility

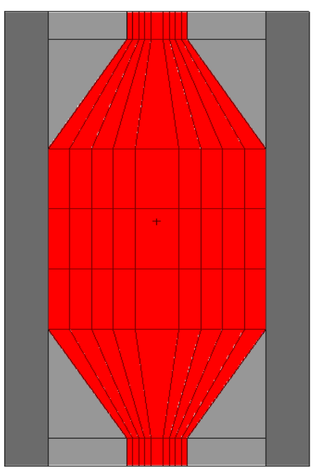
- Conceptual design of two TMSR-SF/LF-SMR
- Conceptual deisgn of batch pyro-process demo-facility
- Conceptual deisgn of Nuclear Hybrid Energy System

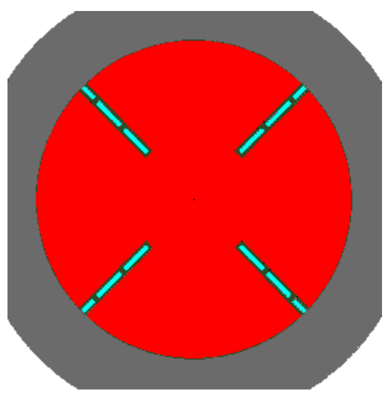
总体方案示意图

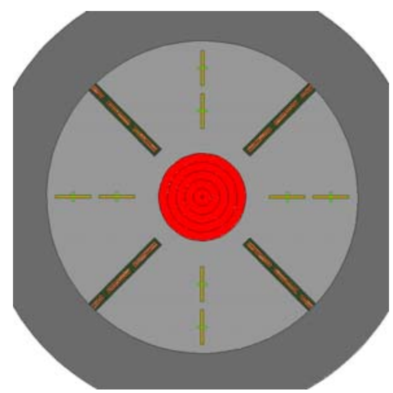

非能动余
排系统
控制棒及
驱动机构
熔盐泵
高温熔盐热能综合利用回路
如（制氢）
空气
透平
透平
透平
发电机
压缩机
冷凝器
空气/水
热交换器
熔盐泵
TMSR-SF2 堆芯
熔盐-熔盐
换热器
熔盐-空气
换热器
乏气
余热利用工厂
➢供热
➢蒸汽提供
➢咸水淡化等
Primary Salt
Secondary Salt
Air
Water/Steam
Exhaust Air
Industrial application

总体参数

参数	值
反应堆功率	384 MWth，163MWe（匹配电机）
设计寿命，换料	60年，流动球床，不停堆在线燃料管理
维护周期	>=10年
负荷因子	95%
热电效率	42.5%
堆芯进出口温度	600/700 ℃
燃料	3cm燃料球（TRISO颗粒燃料）
冷却剂	FLiBe熔盐，99.995%的Li-7
材料	镍基合金/石墨/SiC复合材料







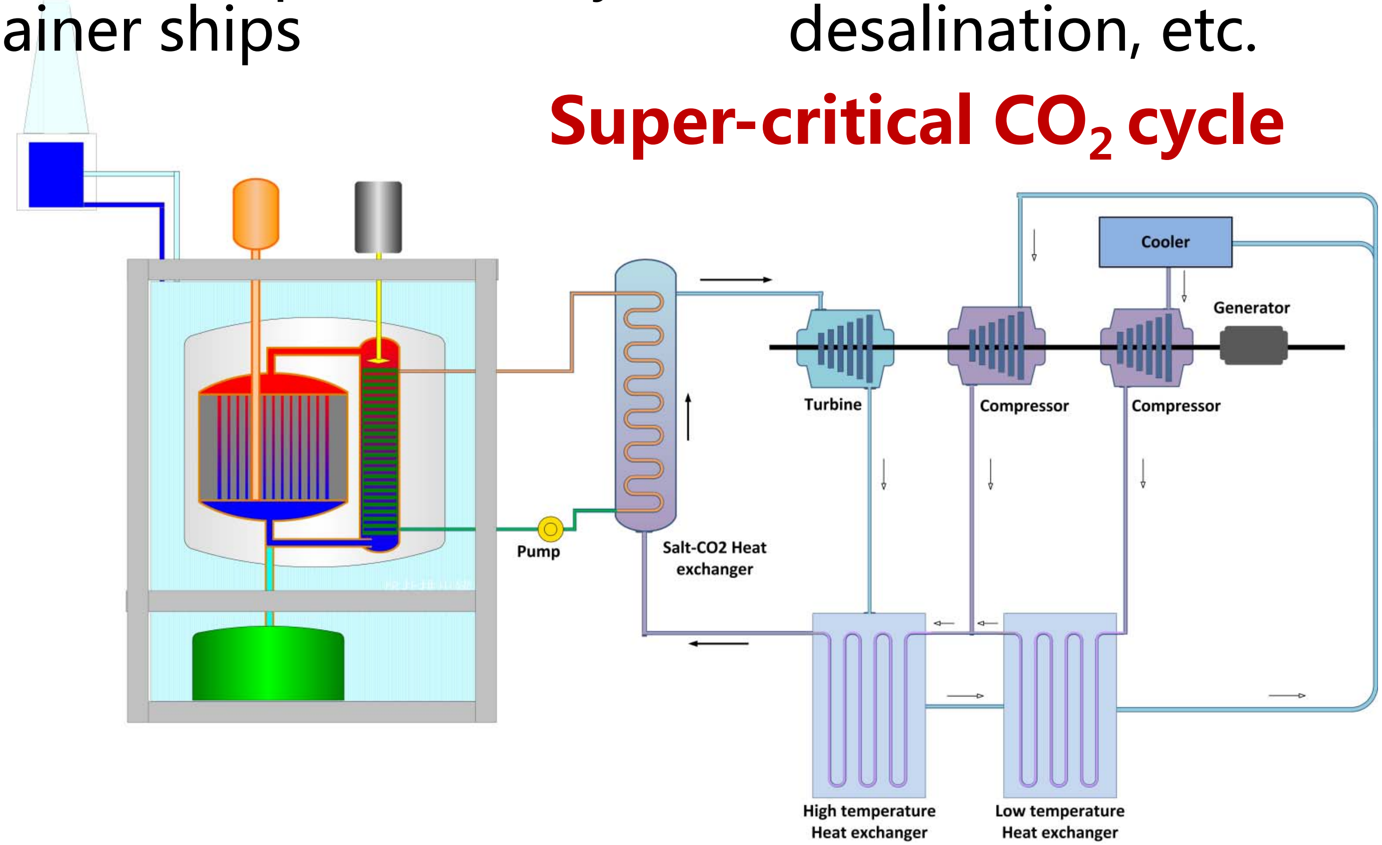
主要物理参数

参数	值
功率密度（活性区）	18.6 MW/m^3
堆芯直径/等效高度	2.5 m / 4.2 m
反射层直径/高度	3.5 m / 6.5 m
平均卸料燃耗	170000 MWd/tHM
燃料球总数	87.4 万
燃料类型及富集度	UCO，19.75%
第一 / 二套停堆系统	12根 / 8 根控制棒
温度反应性系数	-5.90 pcm/K
一回路冷却剂质量流量	1588 kg/s
非能动余热排出系统能力	2% FP
堆内覆盖气体最大压力	<0.5 Mpa
堆容器外径	<3.78 m

168MWe Small modular liquid-fueled Molten Salt Reactor

- Small electricity generation unit
- Modular transportation by container ships
- Thorium utilization demonstration
- Can be used for Seawater desalination, etc.

Super-critical CO_2 cycle



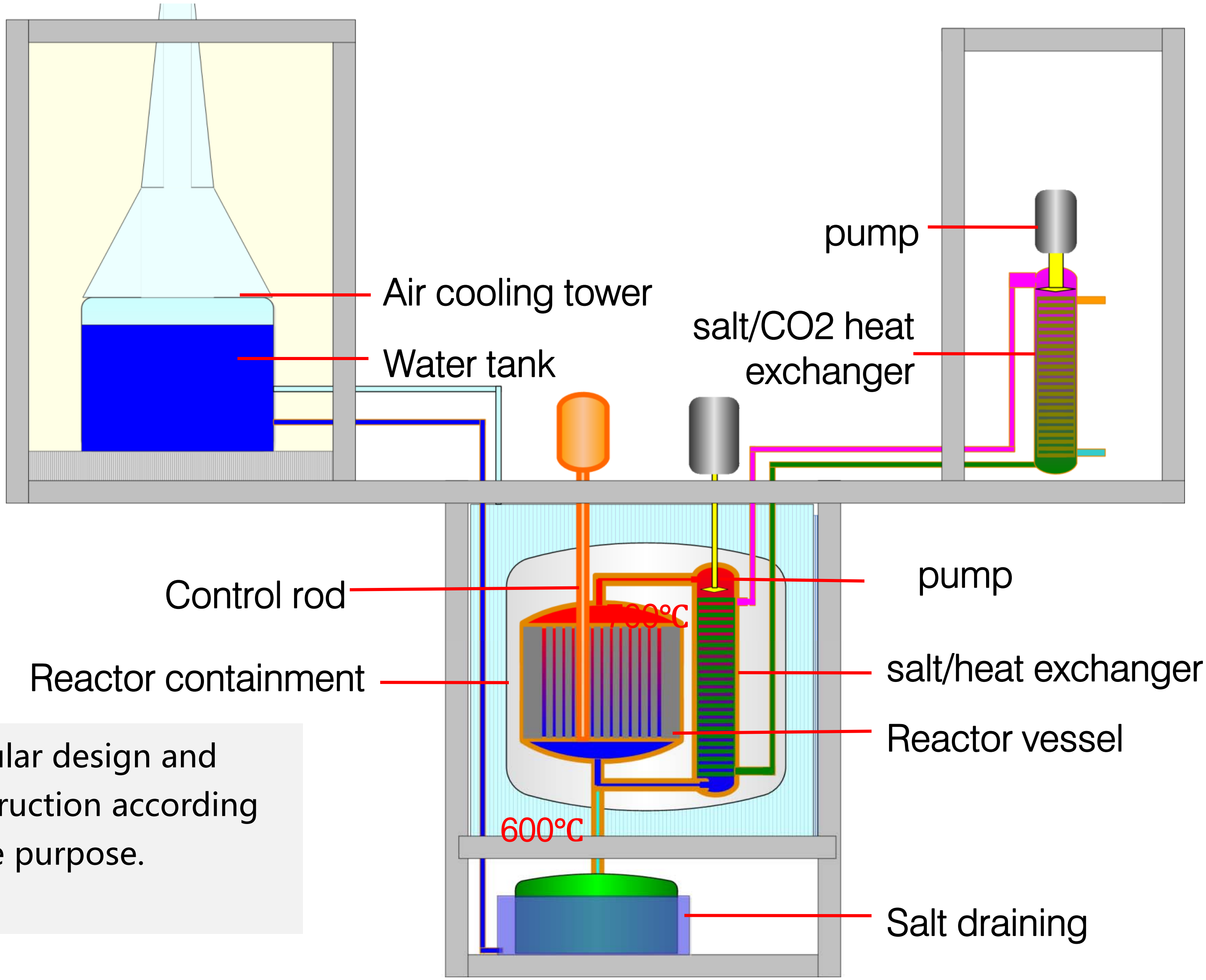
Overall design features

Power of one unit	373MWth / 168 MWe
In / Out temperature	600 / 700 ℃
Power generation cycle	Super CO2 cycle
Fuel salts	LiF-BeF2-UF4-ThF4 (19.75% U-235) LiF-BeF2-PuF3-ThF4
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
Reactor body modules	Reactor body will be changed per 6-8 years
Fuel	Fuel will be purified per 6-8 years with dry-processing
Residual Heat removal	Whole passive residual heat removal system

Main features

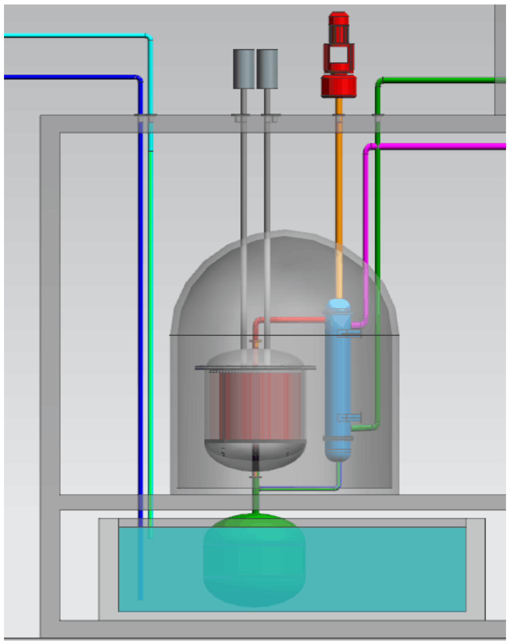
- Equivalent burnup is 330 MWd/kgU which has fuel utilization 2-3 times larger than that of PWR(convert to uranium mine), and waste is one order of magnitude lower than PWR.
- Thorium-derived energy is more than 30%.
- Online fueling without shutdown and can be operated for 8 years.
- Ambient pressure and high safety, small equipment and high economy.
- Complete passive heat removal system can fulfill the demande of long-term safety.
- Modular design with simple structure and fast construction period. (a new reactor can be completed in 2-3 years)

Schematic of reactor island



Modular design and construction according to the purpose.

Nuclear island parameter

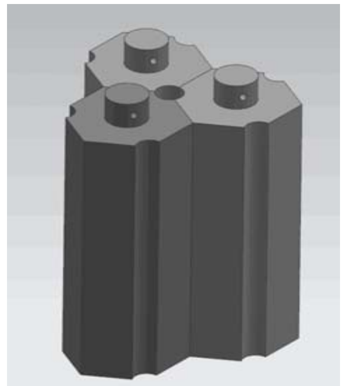


Design Parameters	value
The shape of graphite component	Hexagonal prism
Length of side	26cm
Diameter of molten salt channel	8.63cm

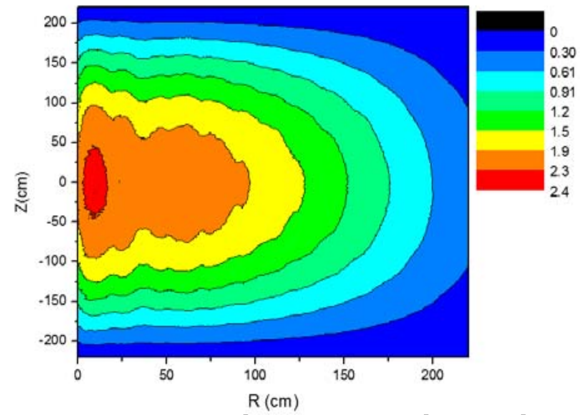
Design Parameters	value
Electric power	168MWe
Thermal power	373MWth
Core diameter / height	4.8m/5.0m
Primary vessel diameter / height	5.2m/6.0m
Uranium enrichment	19.75%
The final loaded U / Th ratio	1:1
Initially loaded uranium	2100kg
Initially loaded thorium	15700kg
Adding mass of uranium per day	1.08kg
Burnup	330GWd/TU
The number of control rods	6

Neutron properties

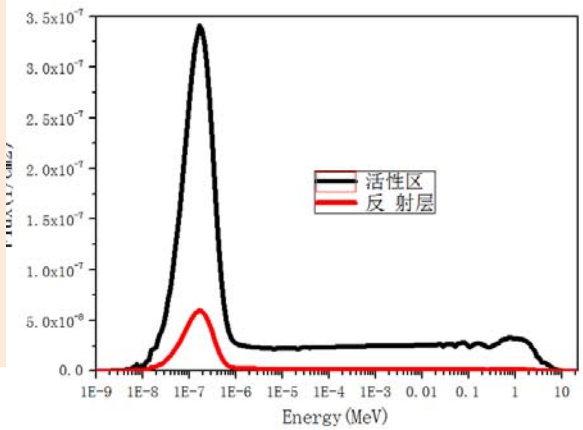
- Thorium-derived energy greater than 20%.
- Approximately equivalent burnup 300MWd/kg U
- Graphite life: Meet the 8-year refueling requirements



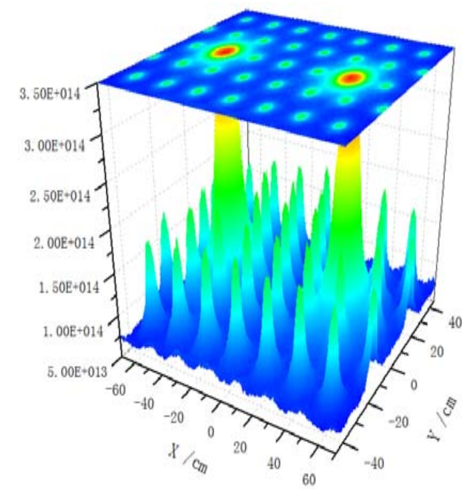
Fuel assembly



Power density distribution

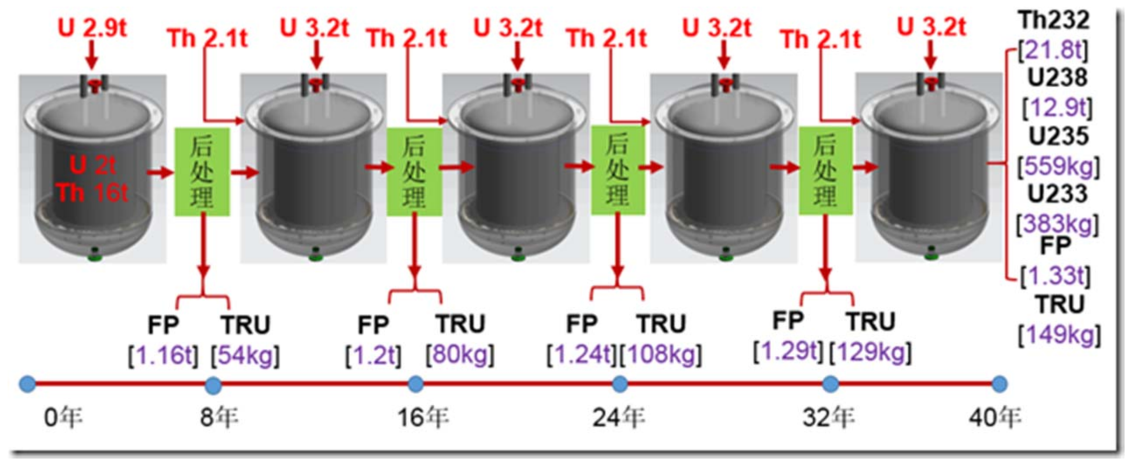


Spectrum

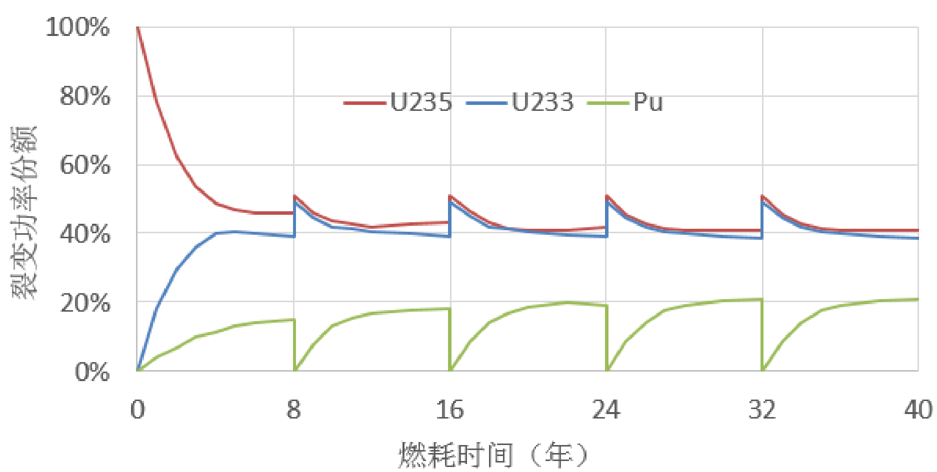


Fast neutron flux distribution in core.

Thorium resource utilization



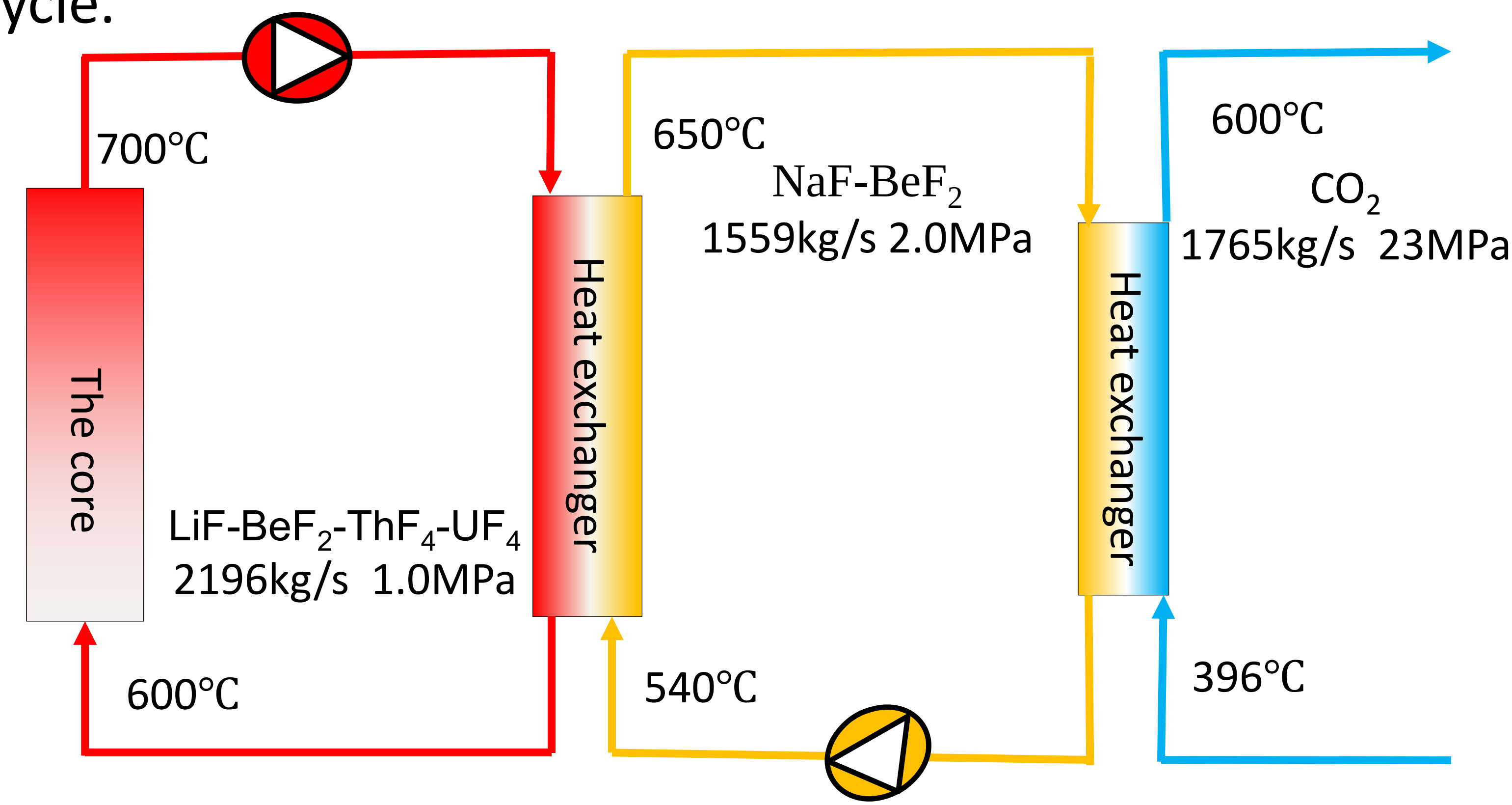
- 19.75% Enrichment of U .
- **Loaded with a large amount of thorium initially**
  Th full conversion, incineration in all life ;
- **Online refueling**
  Reduce the residual reactivity, improve fuel efficiency;



- **Offline batch processing**
  Recovery of U, Th and carrier salts ; Low spent fuel disposal ;
- **Thorium fission contribution 30~40%.**
- **The equivalent fuel efficiency increased 1.5 to 2 times**
- **Spent radioactivity is 5-10 times lower**

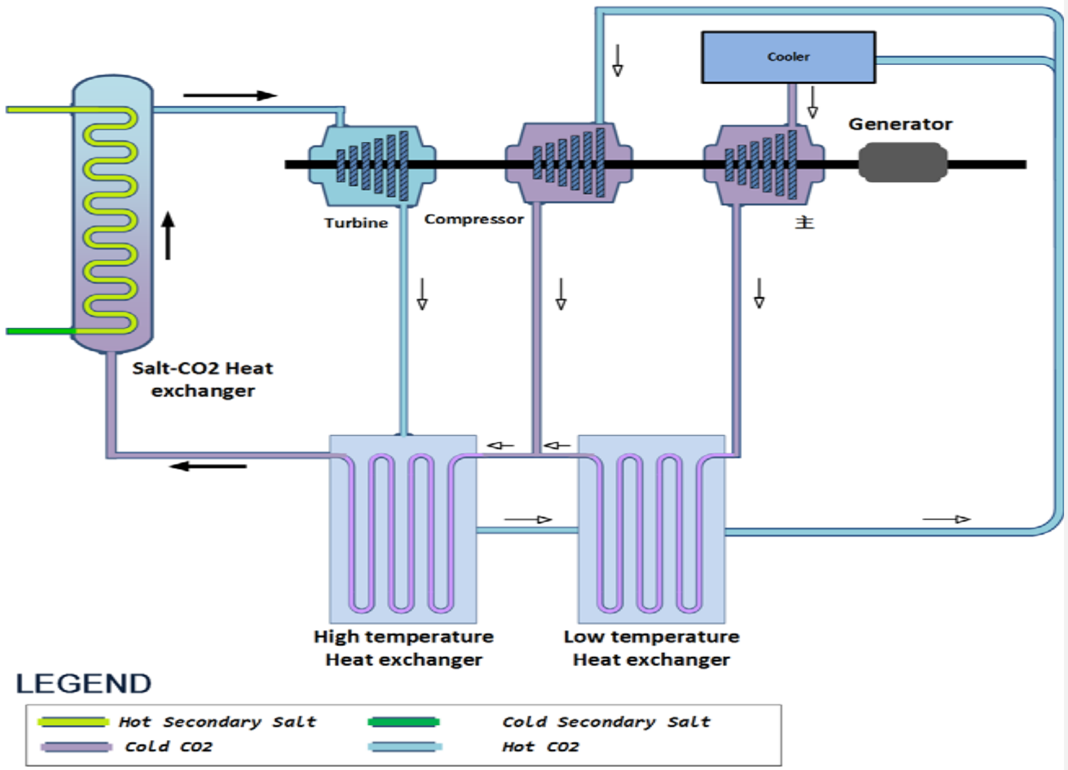
Thermal - hydraulic flow chart

- Three-loop design, each loop consists of a circuit ；
- The first loop is the fuel salt loop; the second loop is the radioactive isolation loop; the third loop is the power generation loop, using supercritical carbon dioxide Brayton cycle.



Energy cycle flow chart

Super-critical CO_2 energy cycle system



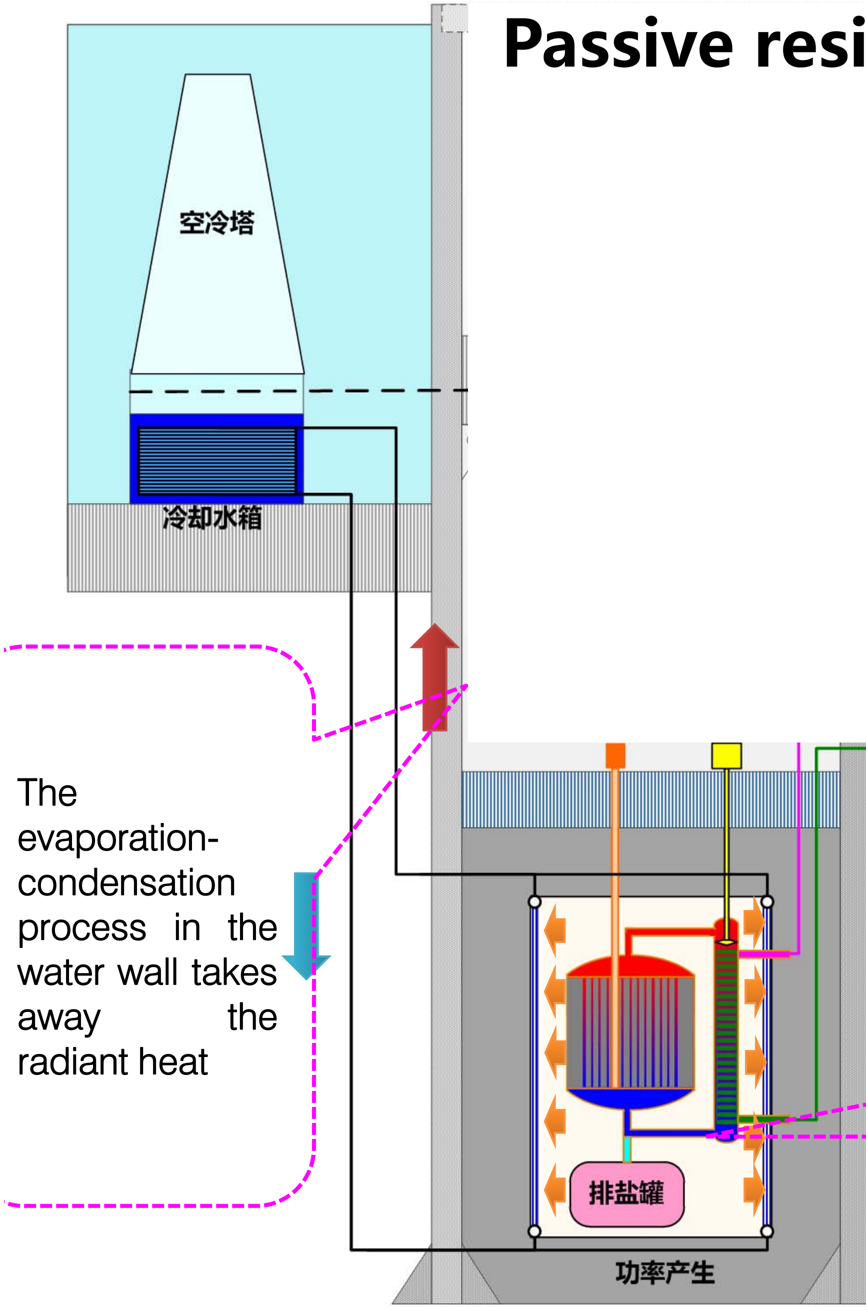
Technical features:

1. The volume is small, about 1/100 of the steam Rankine cycle.

2. Power generation efficiency is high, about 40-50%.

3.At present the technology is at laboratory stage, and the overseas has 10MW level experimental device. China has some pre-research projects, some for military purposes.

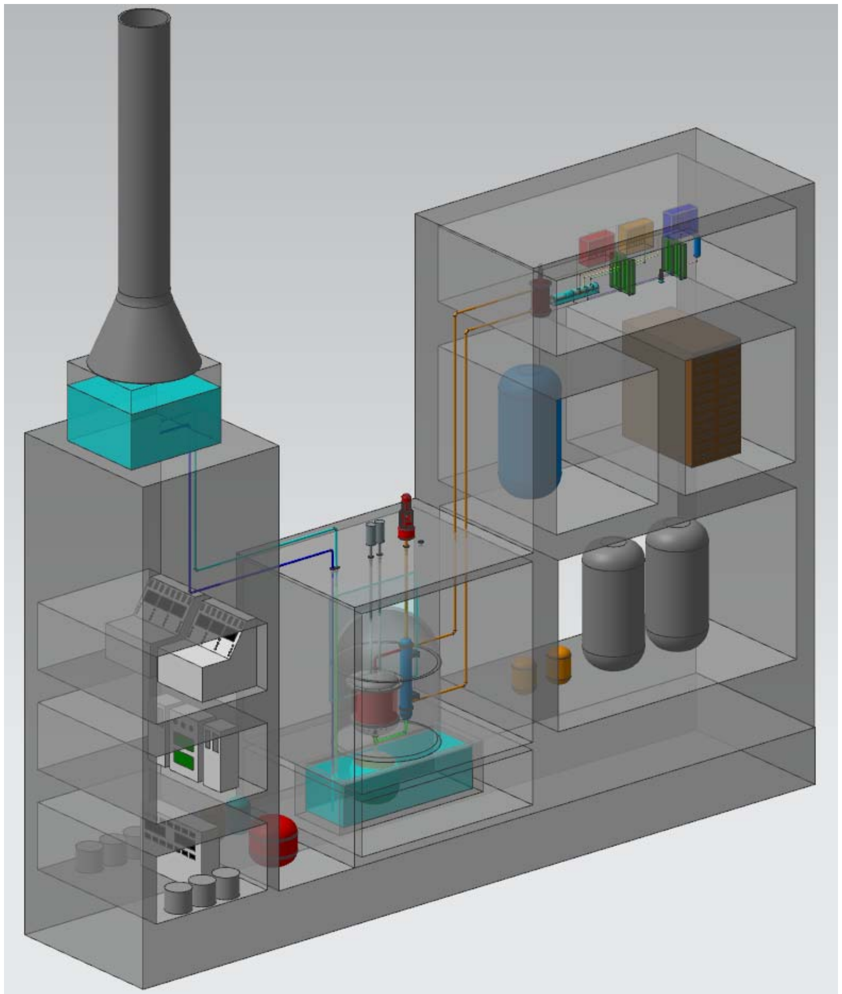
Passive residual heat removal system

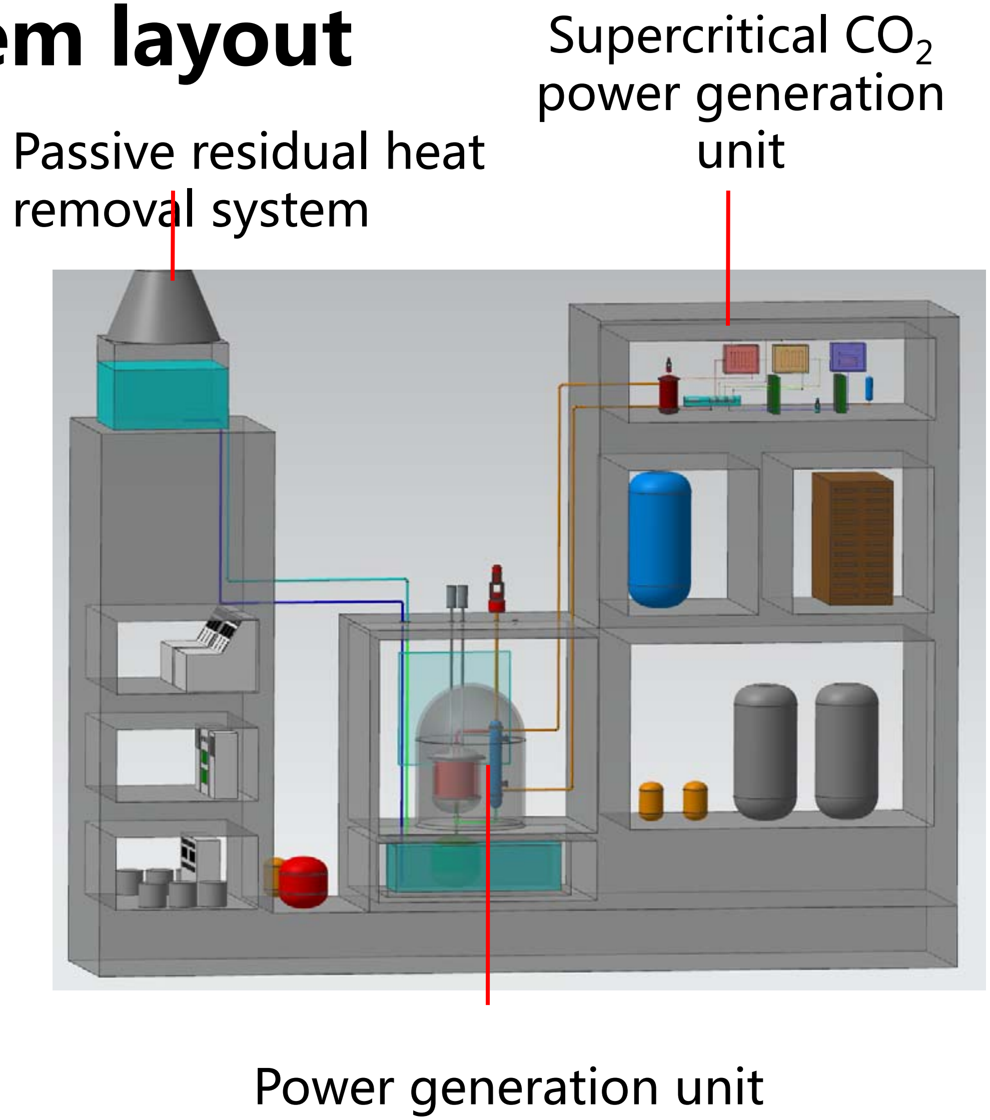


- **2 category of safety systems to ensure long-term passive safety of reactors**
  - Water - cooled wall passive heat removal system.
  - Emergency exhaust molten salt tanks.
- **3 sets of independent non-dynamic residual system.**
  - 2 sets in use and 1 for backup
  - Single set of power: 1% of reactor rated power .
- **Water cooling wall cooling scheme**
  - Cooling water tank (three-loop natural circulation)
  - Direct air cooling (two-loop natural circulation)

The reactor primary circuit removal residual heat through radiation to the water wall.

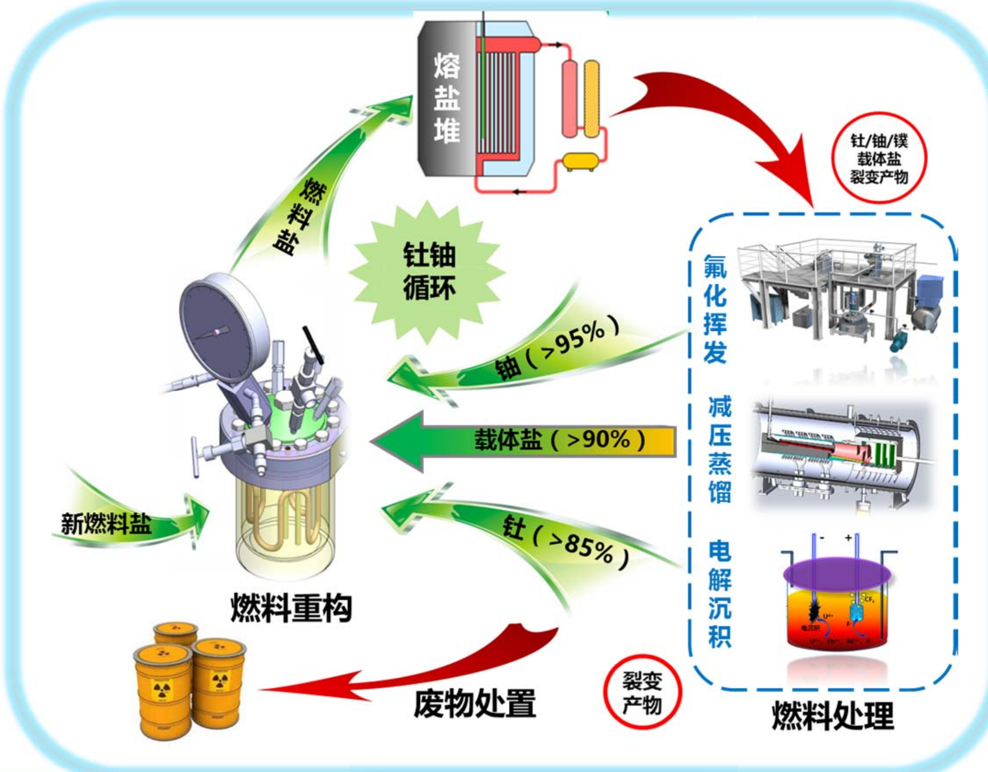
Three - dimensional map of Single - pile system layout



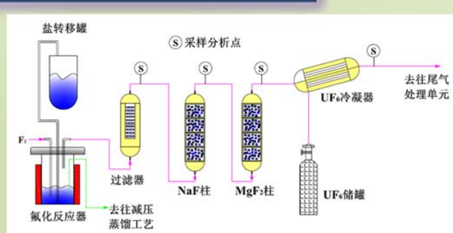


TMSR Fuel Salt Batch Pyroprocessing Demo-Facility

Purpose	Demo of TMSR fuel salt batch pyroprocessing and Th utilization
Process	Fluorination, Distillation, Electrochemical separation
Capacity	$5m^3$/batch，$20m^3$/year
Recovery	U>95%; Th>85%
Th fisson fraction	>25%
Fuel utilizition	~5%
Th/U conversion	~0.8

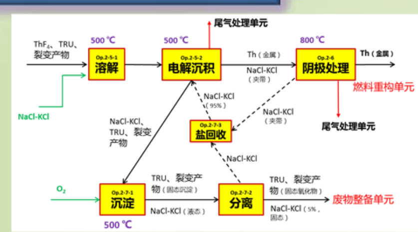


U separation



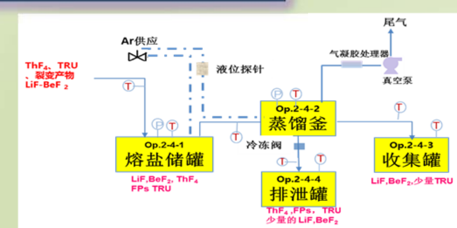
Capacity：$5m^3$/batch
Recovery: 95~99%
Fluorination

Th separtion

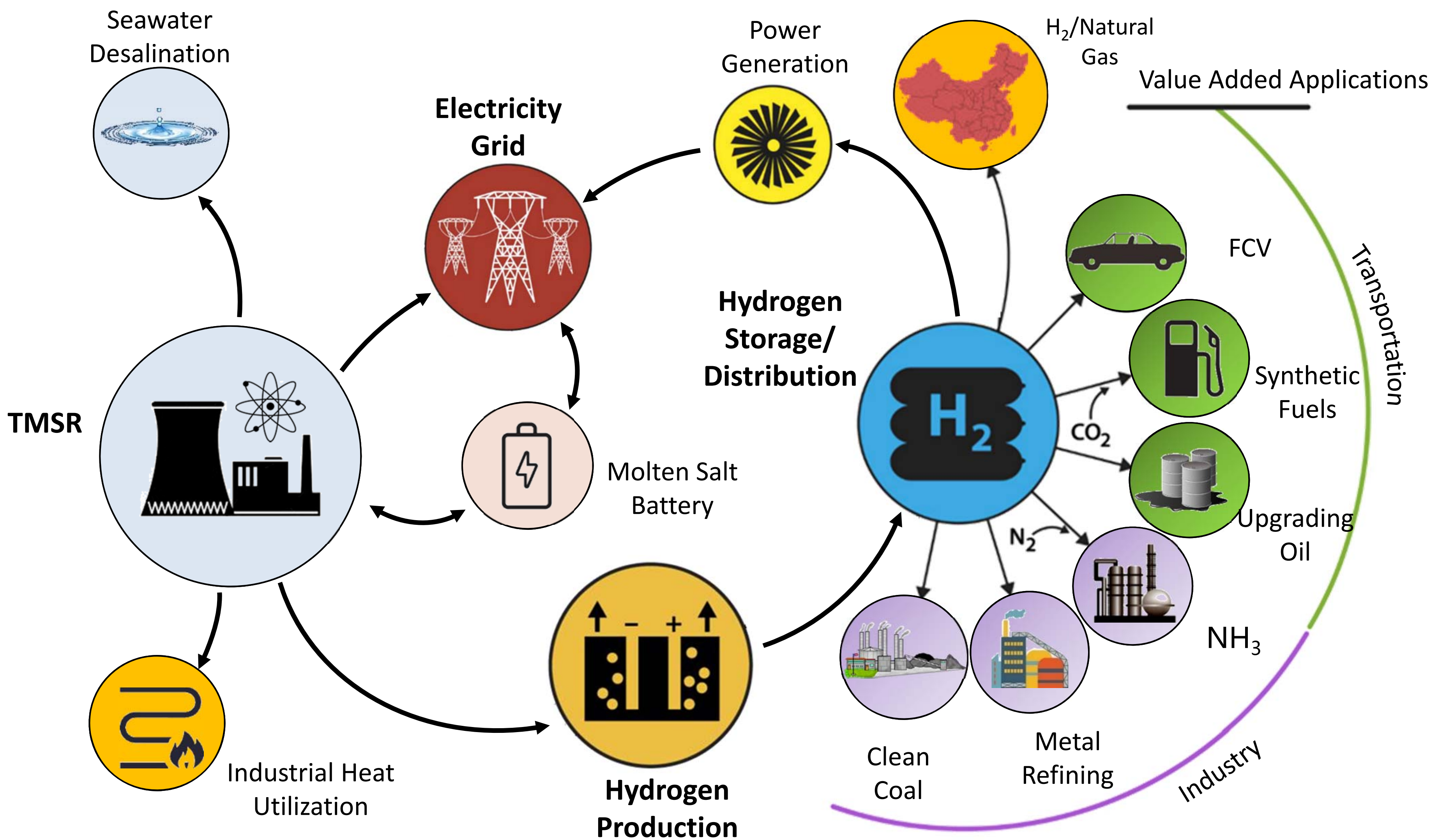


Capacity：200kg/batch
Recovery: 5~90%
Electrochemical separation

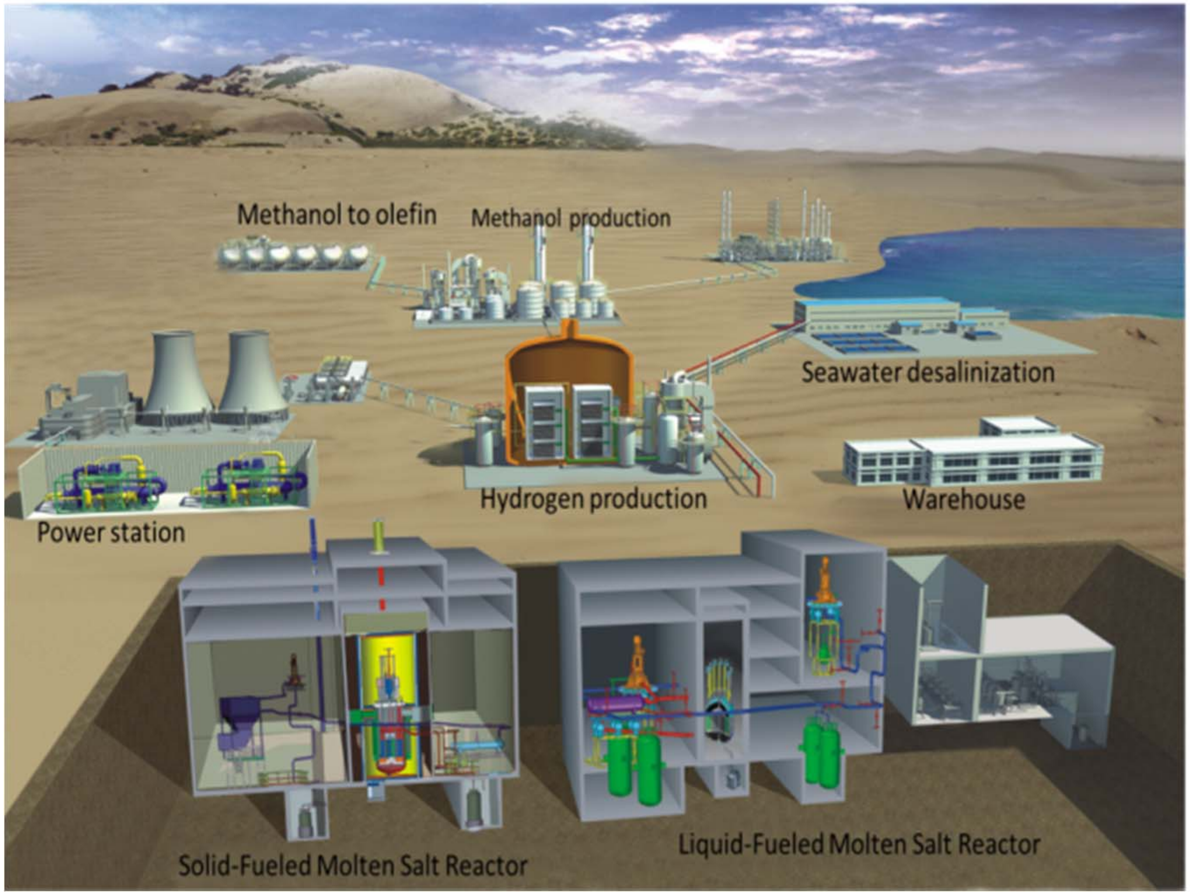
Salt clean-up



Capacity，20L/h
Recovery: 90~95%
Distillation


Seawater Desalination
Electricity Grid
Power Generation
H_2/Natural Gas
Value Added Applications
FCV
Transportation
Synthetic Fuels
CO_2
Hydrogen Storage/ Distribution
H_2
TMSR
Molten Salt Battery
Upgrading Oil
N_2
NH_3
Industrial Heat Utilization
Hydrogen Production
Clean Coal
Metal Refining
Industry

Nuclear Hybrid Energy System



ANES have Great Potential for Development in China

MIT
Technology
Review

Fail-Safe Nuclear Power

Cheaper and cleaner nuclear plants could finally become reality—but not in the United States, where the technology was invented more than 50 years ago.

by Richard Martin   August 2, 2016

Cheaper and cleaner nuclear plants （注：MSR） could finally become reality—but not in the United States, where the technology was invented more than 50 years ago.

The dream of American scientists at Oak Ridge, a half-century ago, is taking shape here (注：上海), thousands of miles away.


Thanks for
your
attention!