Progress of TMSR in China

-Thorium Molten Salt Reactor Energy System (TMSR)

June 14, 2018. Tokyo , Japan

Hongjie XU

TMSR Center of CAS/ SINAP

OUTLINE

What is TMSR

Motivation for TMSR

Progress of TMSR

Perspective on TMSR

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Motivation for TMSR

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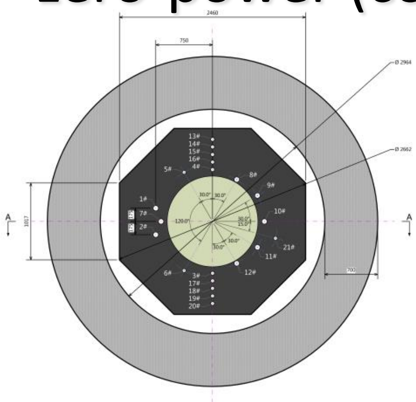
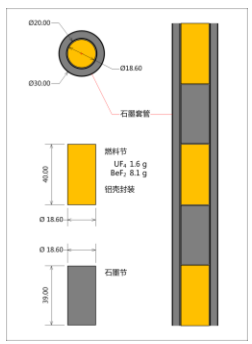
Early Efforts for MSR in China

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)

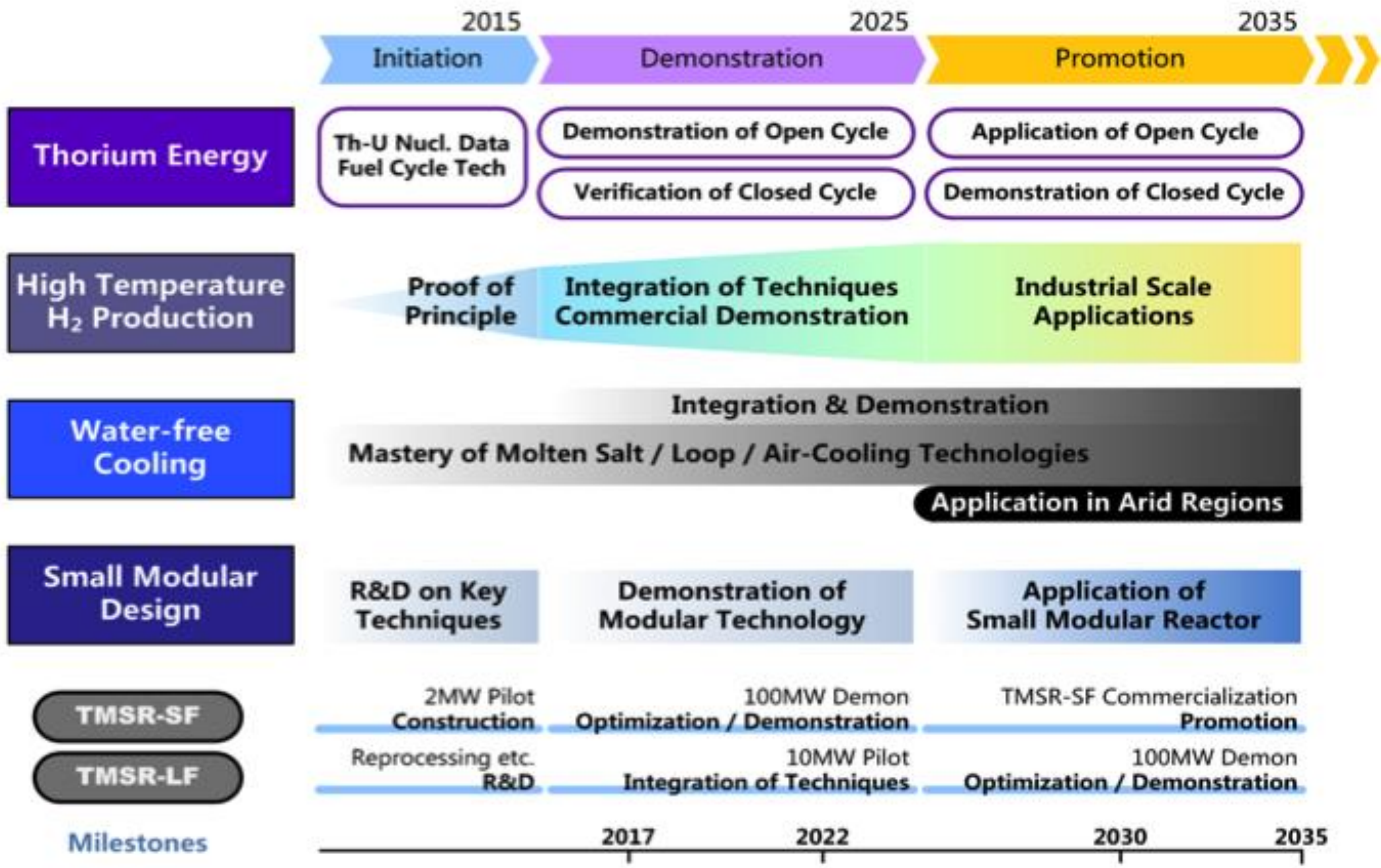
中文名称：钍基熔盐堆核能系统

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 Schedules



TMSR Development Plan

R&D、Design、Licensing → Demonstration → Commercial

Simulator (2018)

Key technology and component development, Simulator (mock-up) (TMSR-SF0)

Test Reactor (2020)

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

10MWth Solid-fuel test reactor (TMSR-SF1)

Demonstration Reactor (2030)

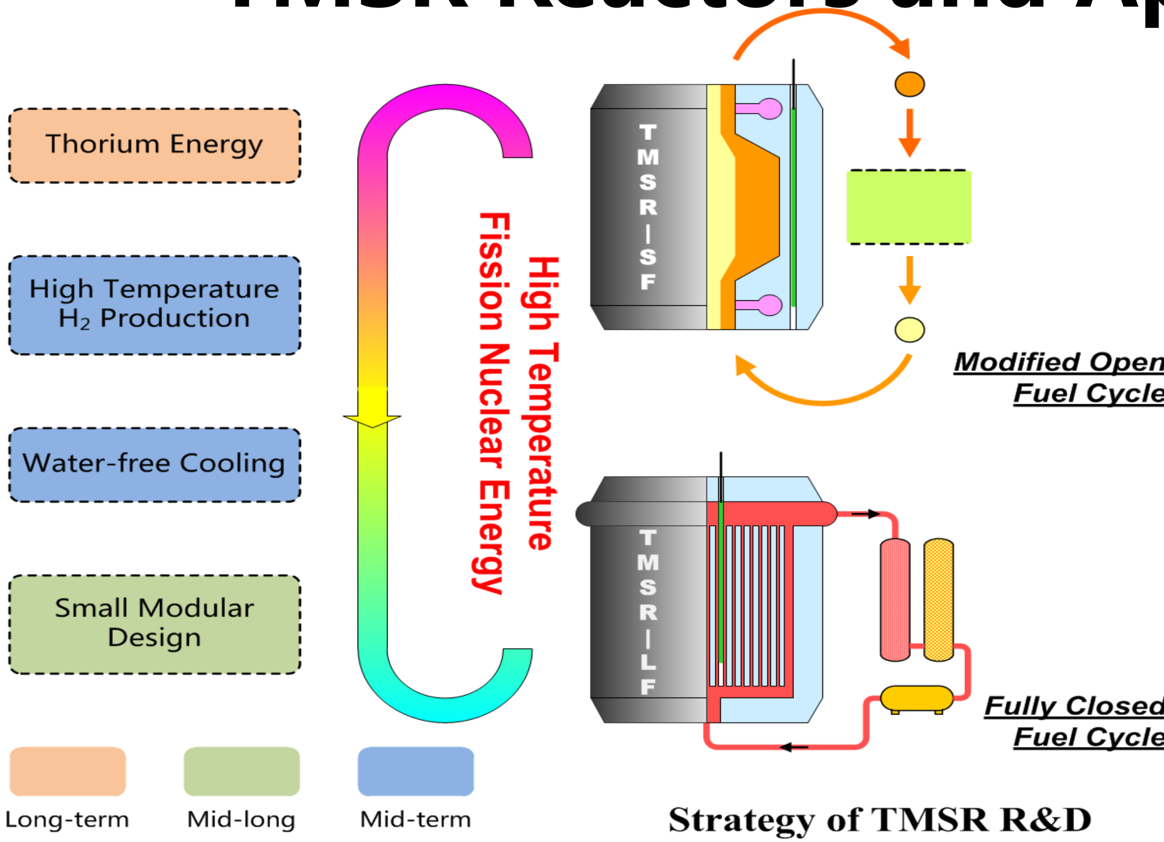
168MWe liquid-fuel demonstration reactor (TMSR-LF2)

168MWe solid-fuel demonstration reactor (TMSR-SF2)

Commercial 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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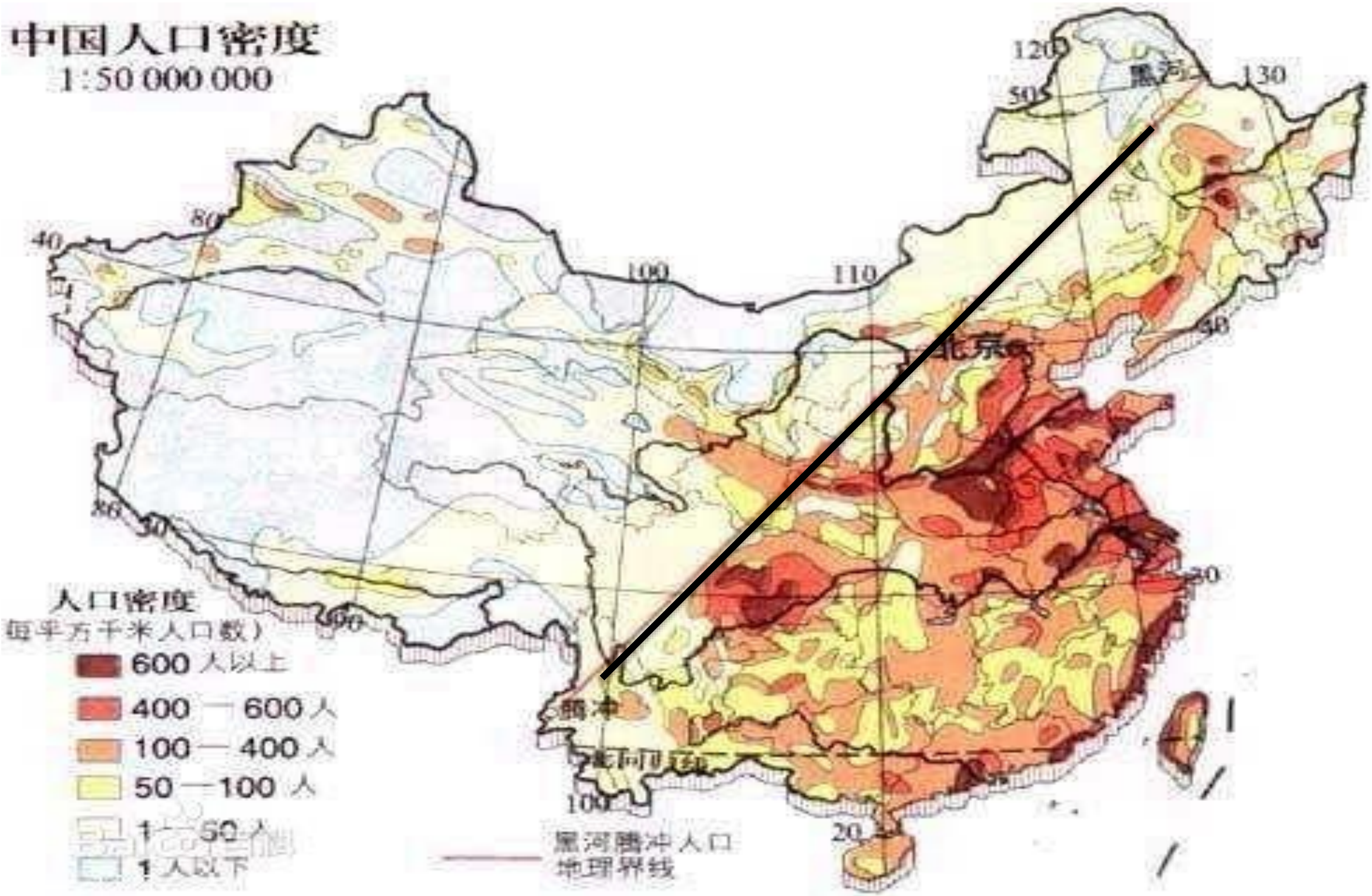
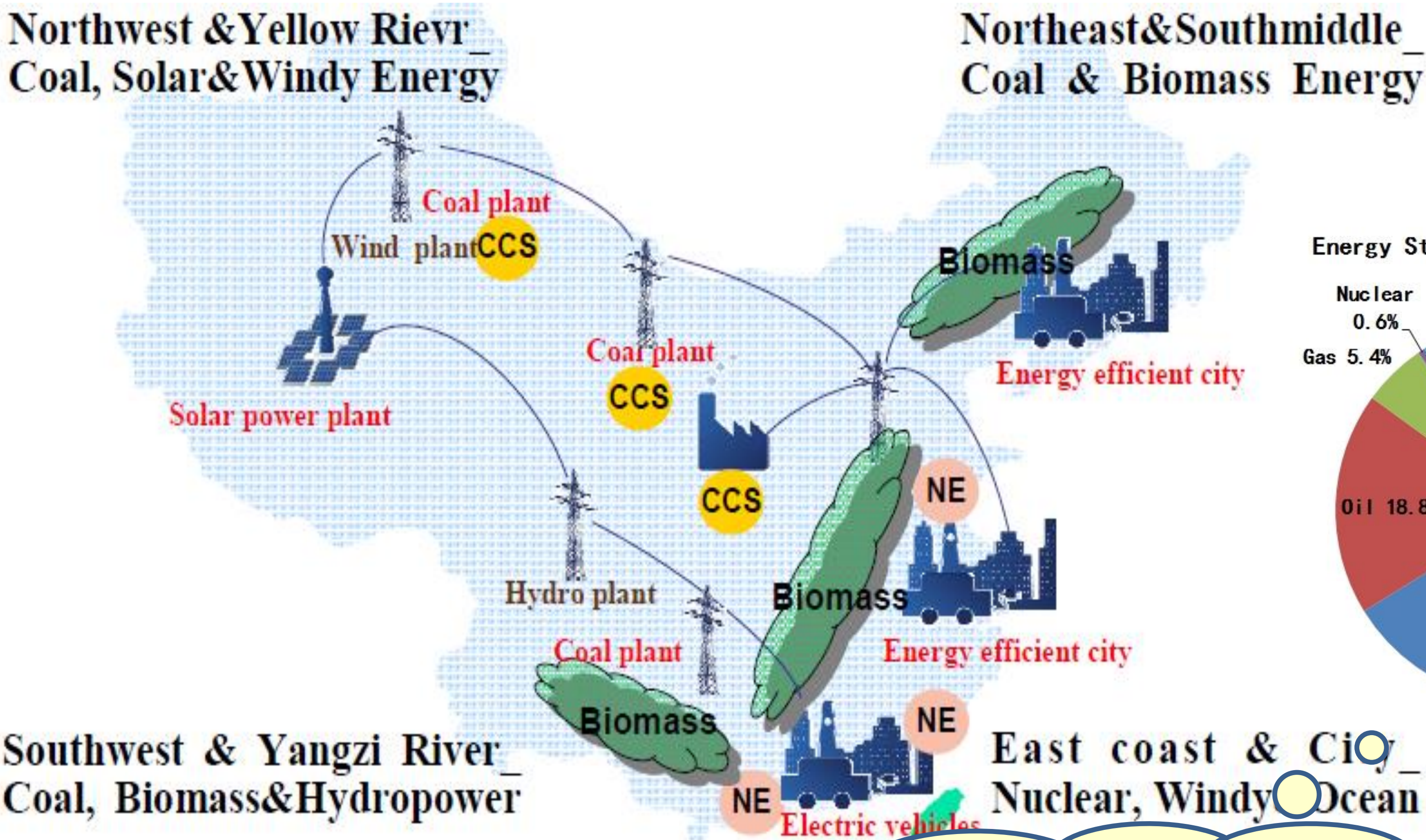
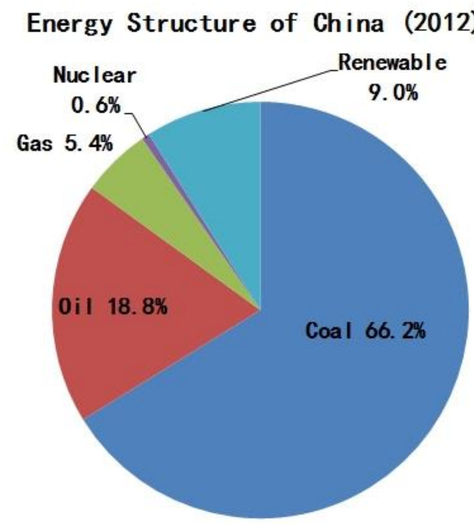
胡焕庸（ Hu Huangyong) line



Coal dominates primary energy consumption of China



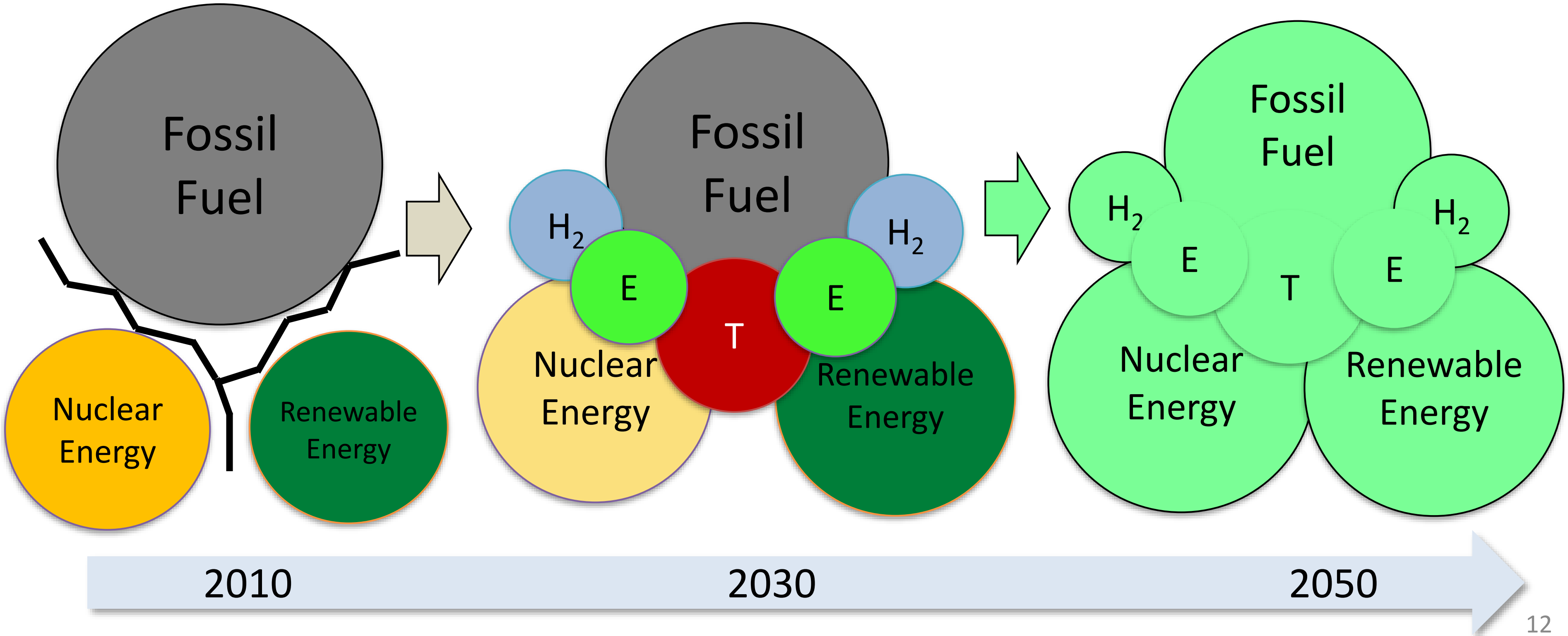


>620 coal-fired power plants

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

TMSR Clean Energy System

- Molten salt reactor 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.



China-U.S. cooperation to adva
Junji Cao, Armond Cohen, Jame
Peterson and Hongjie Xu (Augu
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

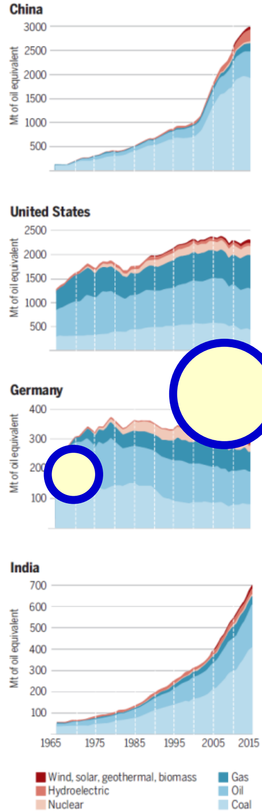
China-U.S. cooperation to advance nuclear power

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.

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 m... ficiently and produce less nuclea... can directly supply energy to in... 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 2030–205... 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 r... drive down unit...

Innovati... ging in both countri... develop-ment in the Unit... 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-

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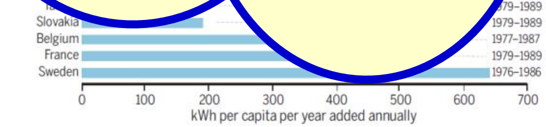
... for ... ration

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



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

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ACKNOWLEDGMENTS

Our essay draws upon discussions at the Workshop on Advanced Nuclear Energy to Address Climate Change and Air Pollution, 17 to 20 December 2015, Wanning, Hainan, China. The Chinese Academy of Sciences funded local workshop costs. Travel costs of a majority of non-Chinese participants were paid by the U.S. nonprofit Climate Science, Awareness and Solutions, Inc., with funding from Gary L. Russell. P.P.'s research group receives funding from the U.S. Department of Energy and the Shanghai Institute of Applied Physics to work on advanced molten salt reactor technologies.

SUPPLEMENTARY MATERIALS

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

10.1126/science.aaf7131

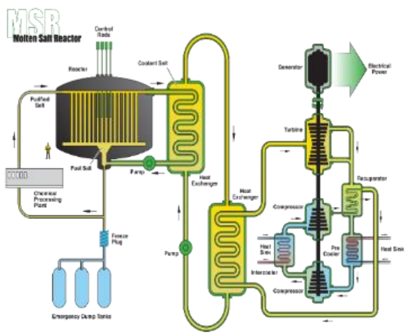
Overview of the Generation IV Systems

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

http://www.gen-4.org/Technology/systems/index.htm

Molten Salt Reactor

Suitable for generate electricity, comprehensive utilization and modular design

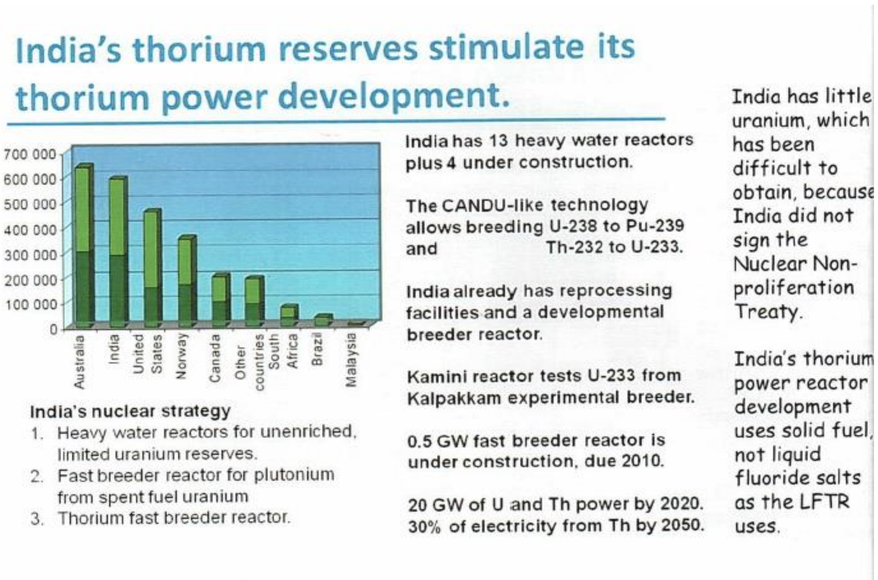


- **Th utilization:** Physical features applicable for Th fuel
- **Online refueling:** Refueling and reprocessing of fuel
- **Inherent safety:** Intrinsic safety features, can be built underground
- **Water-free cooling:** Applicable for inland arid area

Excellent properties of MSR coolant

	Outlet temperature (℃)	Pressure (atm)	Heat Capacity (kJ/m^3℃)	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



India's thorium reserves stimulate its thorium power development.

India's nuclear strategy
1. Heavy water reactors for unenriched, limited uranium reserves.
2. Fast breeder reactor for plutonium from spent fuel uranium
3. Thorium fast breeder reactor.

India has 13 heavy water reactors plus 4 under construction.

The CANDU-like technology allows breeding U-238 to Pu-239 and Th-232 to U-233.

India already has reprocessing facilities and a developmental breeder reactor.

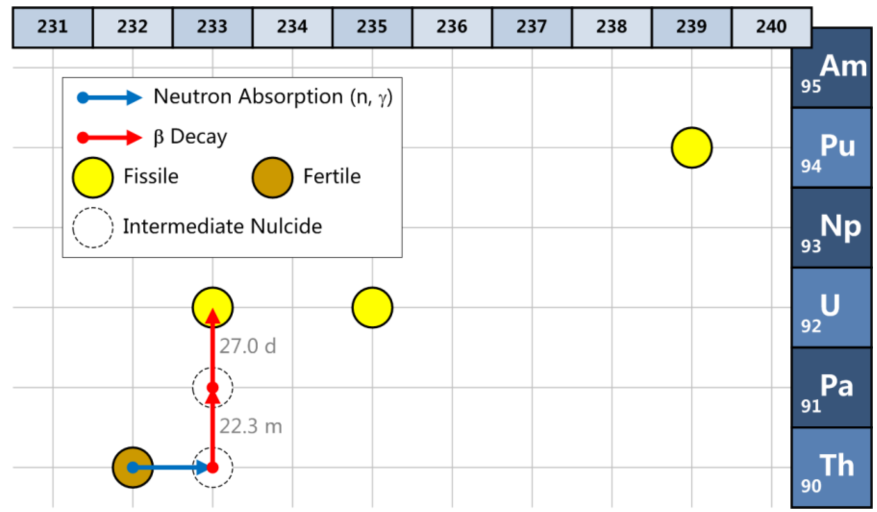
Kamini reactor tests U-233 from Kalpakkam experimental breeder.

0.5 GW fast breeder reactor is under construction, due 2010.

20 GW of U and Th power by 2020. 30% of electricity from Th by 2050.

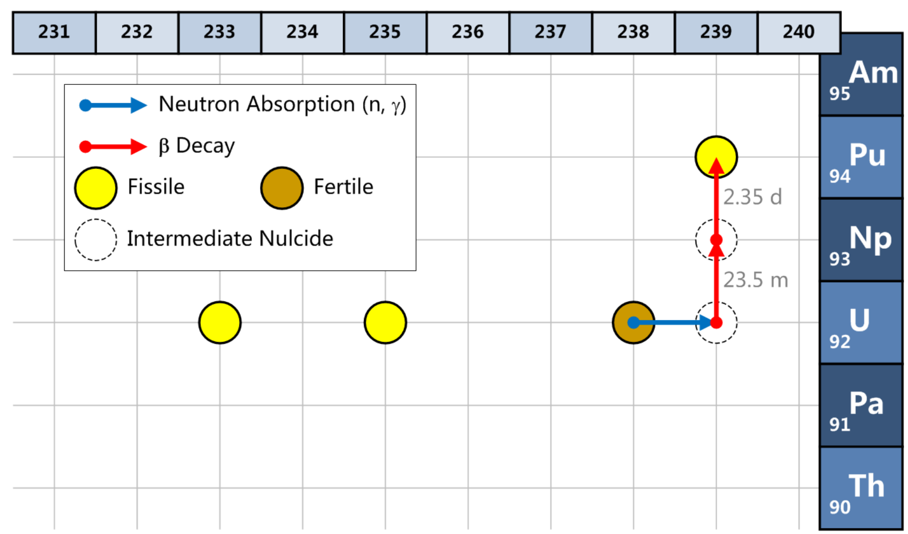
India has little uranium, which has been difficult to obtain, because India did not sign the Nuclear Non-proliferation Treaty.

India's thorium power reactor development uses solid fuel, not liquid fluoride salts as the LFTR uses.

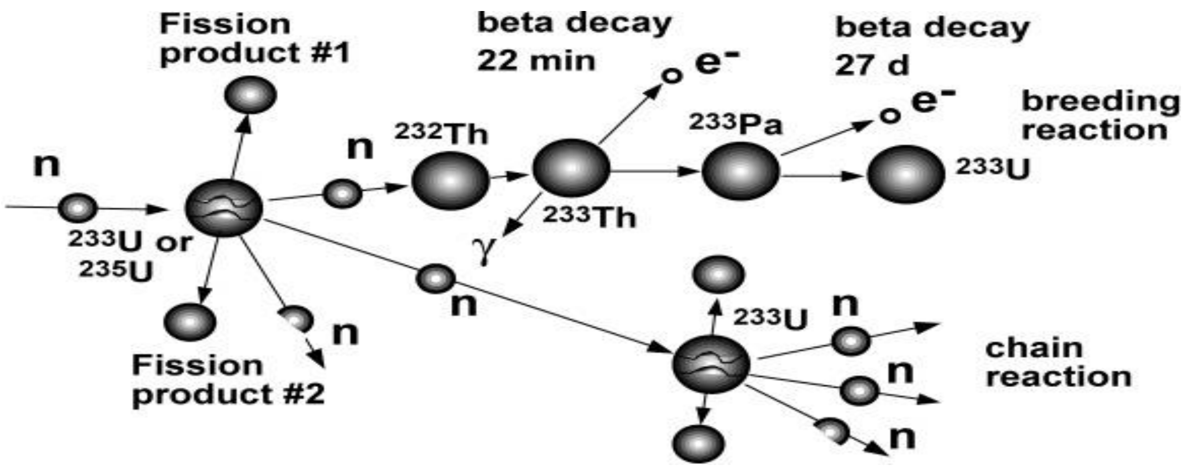


CONCLUSION –C.Rubia

Unlike other energy sources, China's reserves of Thorium, may ensure the major domestic energetic supply for many centuries to come. For instance the whole China's today electricity (3.2 Trillion kWh/year) could be produced during ≈20'000 years by well optimized Th reactors and 8,9 million ton of Th, a by-product of the China's REE basic reserves.

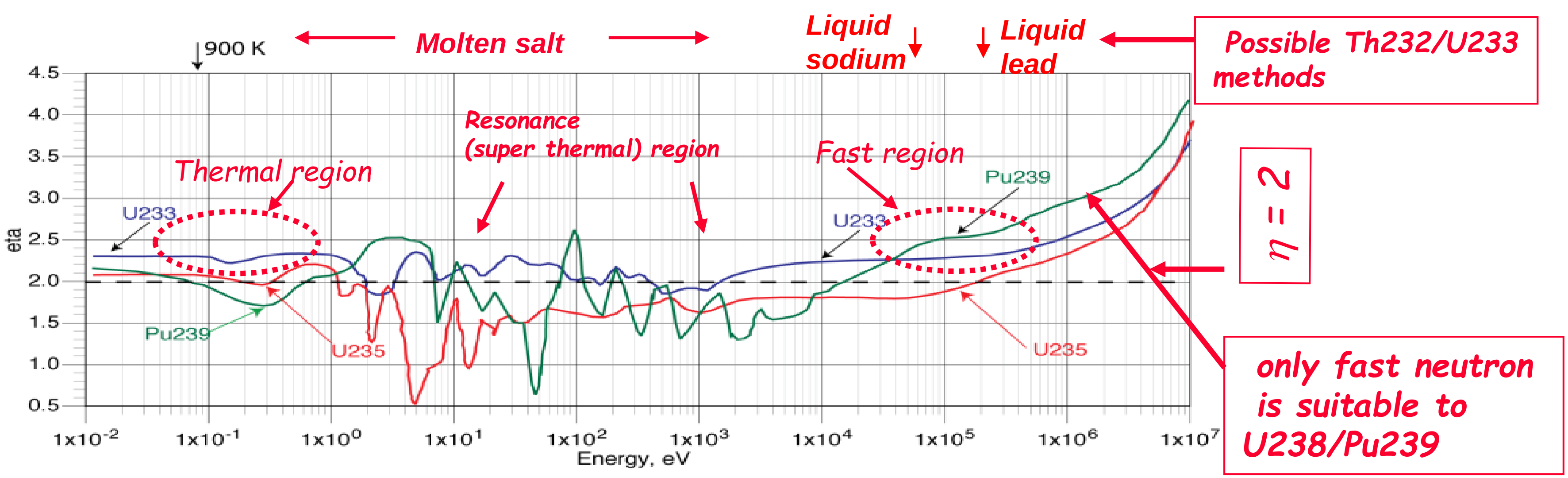


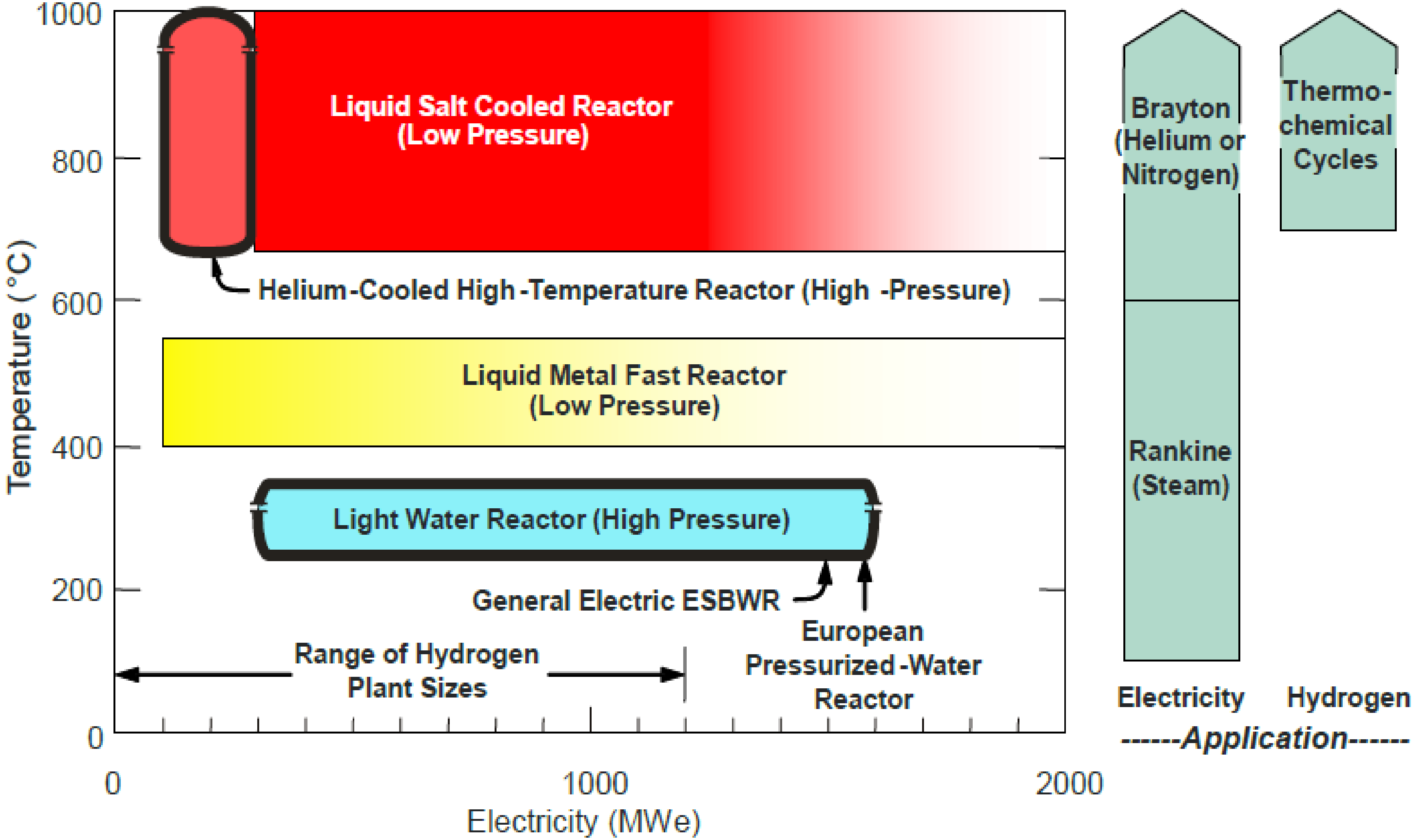
Th232/U233 and U238/Pu239 fuel cycles



Mean released neutron number per fission η

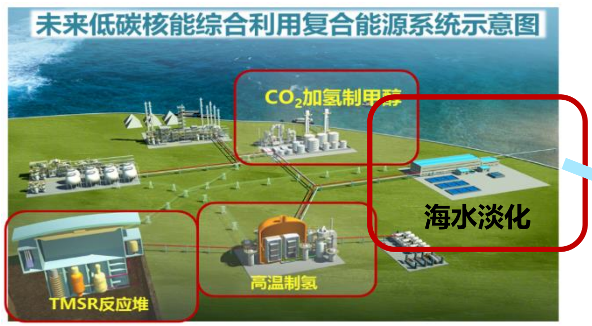
η ***= 2 is the required condition for a sustain reactor***

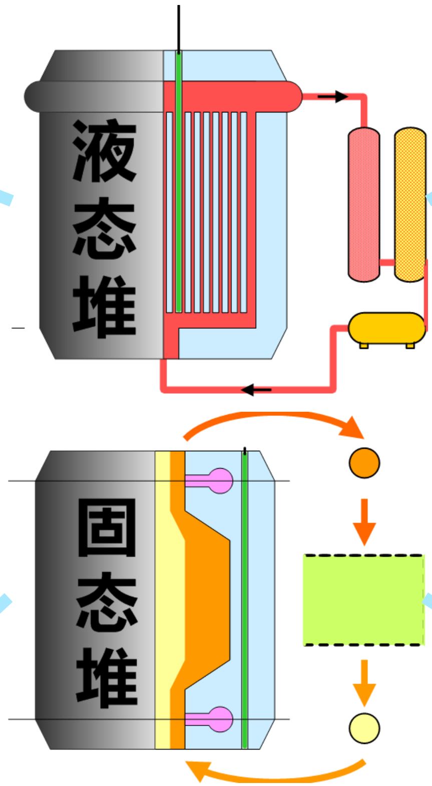


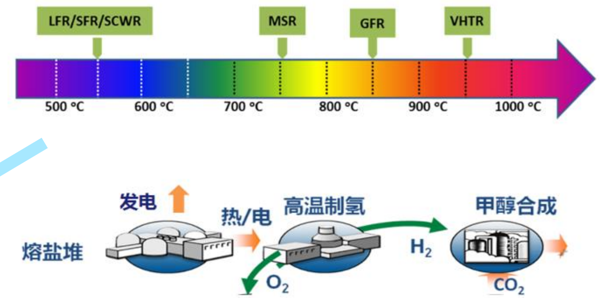

1000
800
600
400
200
0
Temperature (°C)
Liquid Salt Cooled Reactor
(Low Pressure)
Helium-Cooled High-Temperature Reactor (High -Pressure)
Liquid Metal Fast Reactor
(Low Pressure)
Light Water Reactor (High Pressure)
General Electric ESBWR
European
Pressurized-Water
Reactor
Range of Hydrogen
Plant Sizes
0
1000
2000
Electricity (MWe)
Brayton
(Helium or
Nitrogen)
Rankine
(Steam)
Thermo-
chemical
Cycles
Electricity
Hydrogen
------Application------

Solution of Low Carbon New Energy

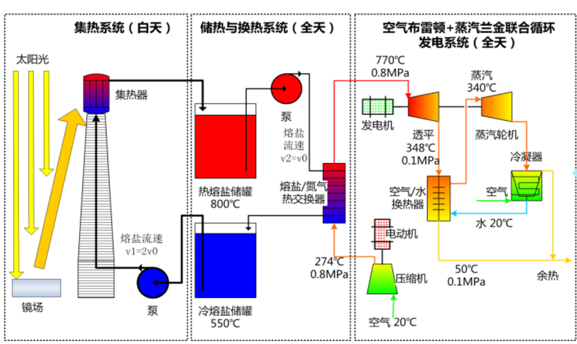
High temperature TMSR+ hybrid-energy utilization

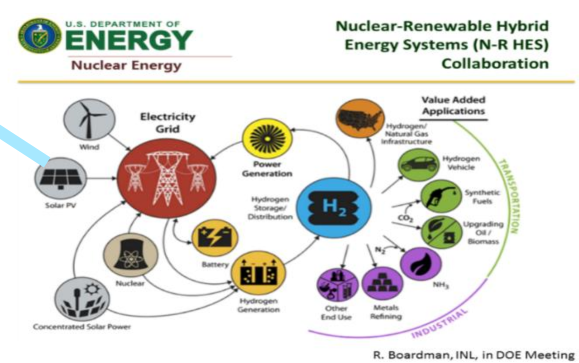






CAS-TMSR

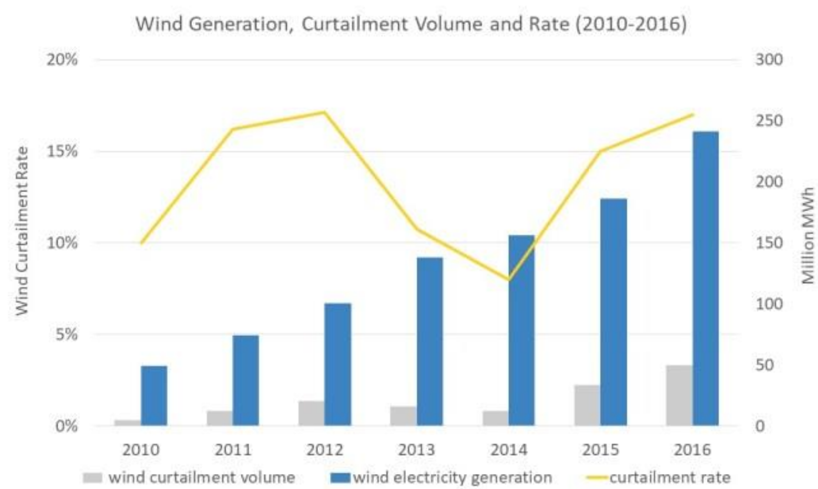




DOE-INL

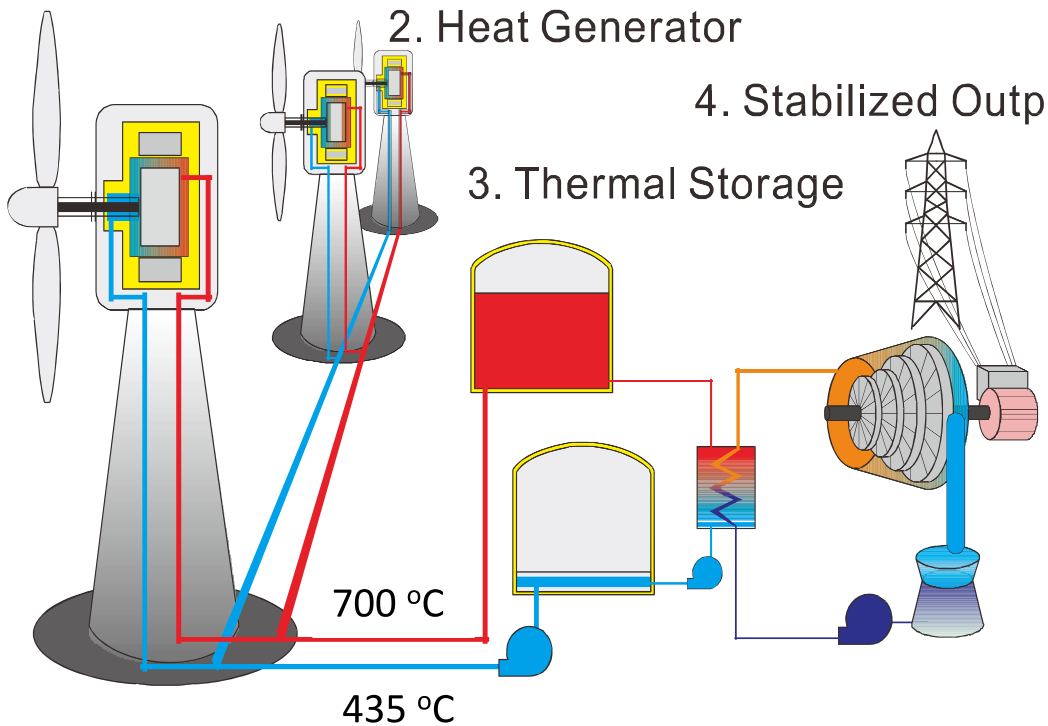
Wind abandoned in China

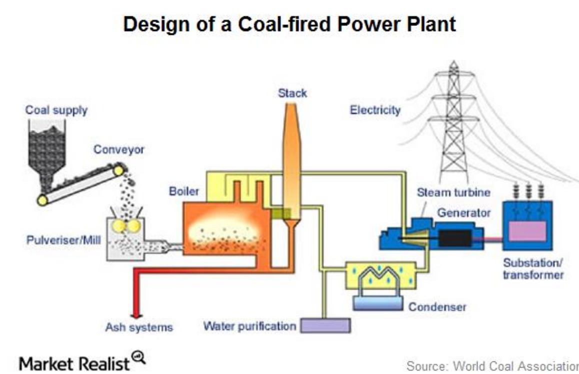
- Much of the electricity produced by vast wind farms goes unused, with grids unable to accommodate fluctuating sources of power and amid rising overcapacity in the country's total power generation.
- From 2010 to 2016, 150.4 million megawatt hours, or as much as 16 percent of overall wind generation,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

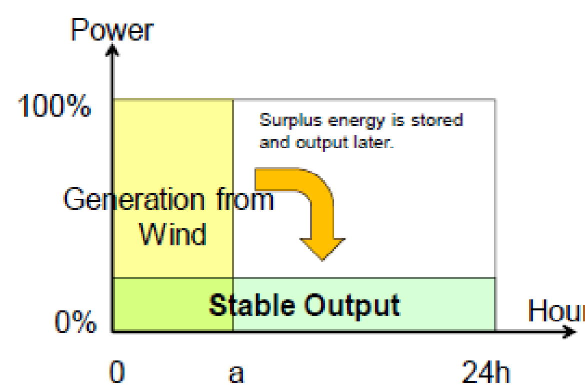


Wind Thermal Power System

1. Intermittent Input







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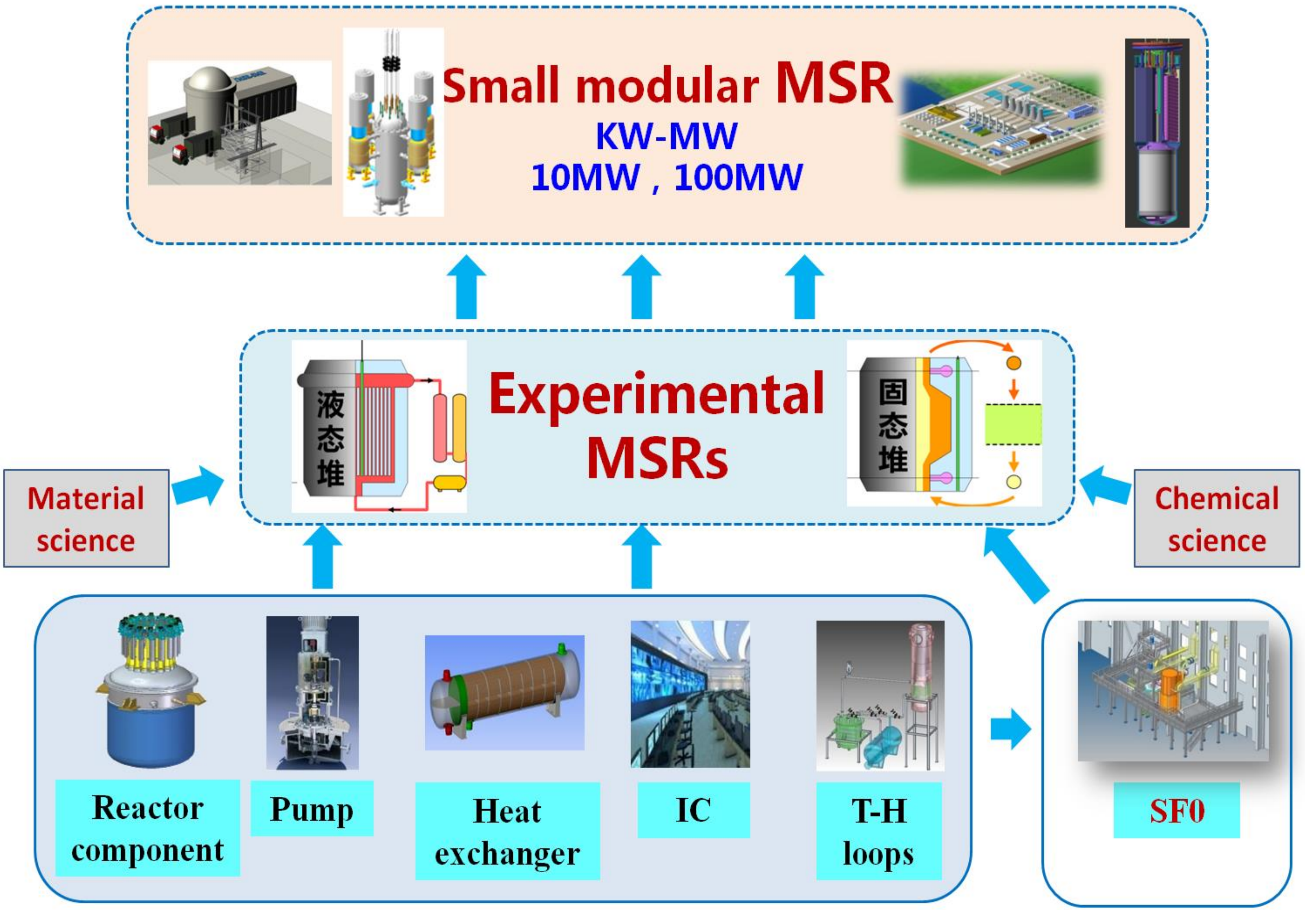
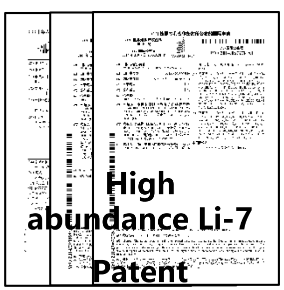
Roadmap of Technologies R&D



^{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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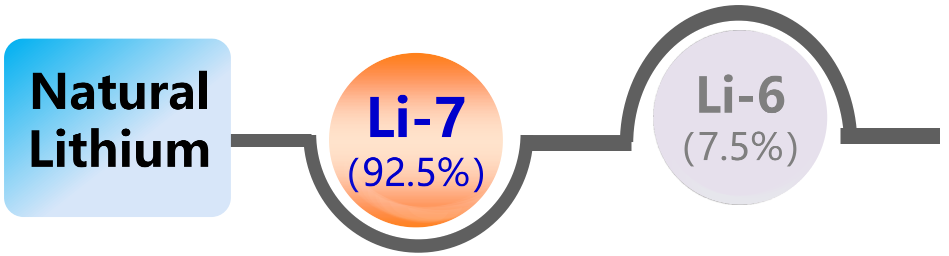


- **PWR pH control (abundence≥99.9%)**
- **MSR coolant (abundence≥99.99%)**

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**

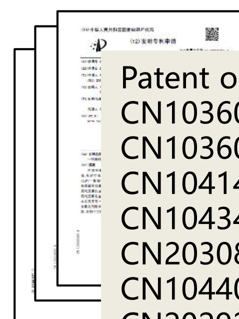
- Synthesis technology of nuclear grade FLiBe with boron equivalent < 2 ppm
- Purification technology of high purity FLiNaK with total oxygen < 100 ppm
- High purity FLiNaK batch production of 10 tons per year
- Capability of fluoride salt physical properties measurement

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 (6 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

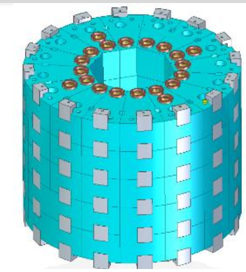
Chinese Patent CN103966476 A (under review)


Component（head）

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

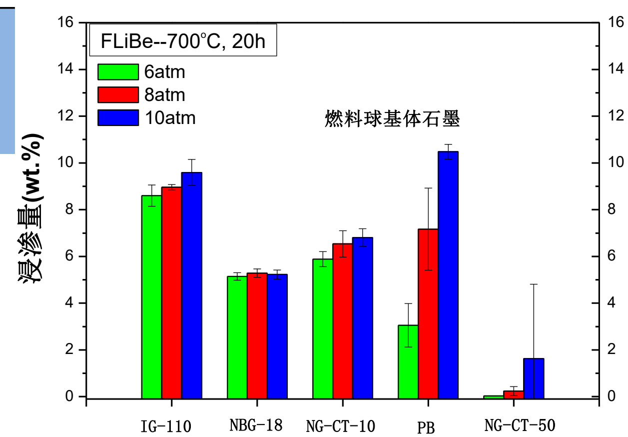


Graphite Core

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

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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

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

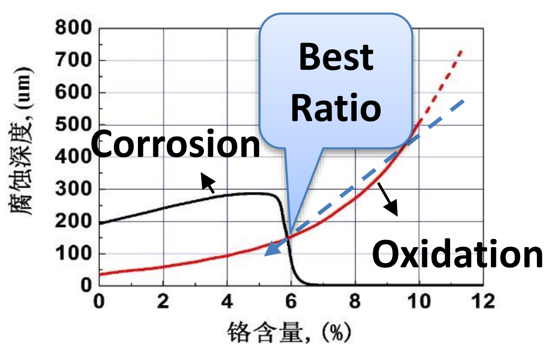
Investigating Corrosion Mechanism

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

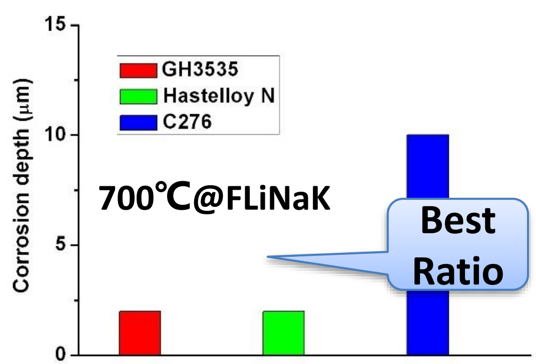
Developing Corrosion Control Technology

- 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;

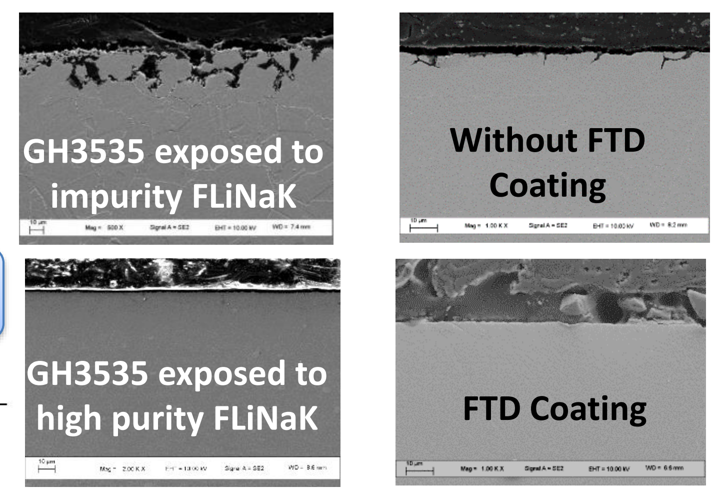
Solving the corrosion control in fluoride salt (GH3535 static corrosion rate < 2μm/y) ！



Composition Optimization of Alloy (Cr)



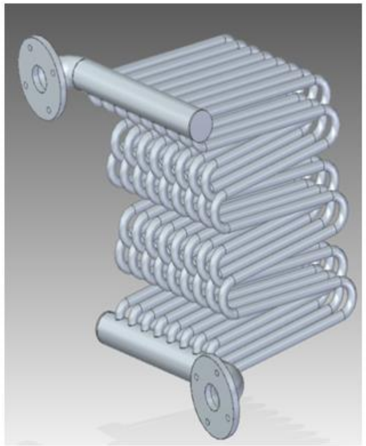
Corrosion Depth (μm/y)



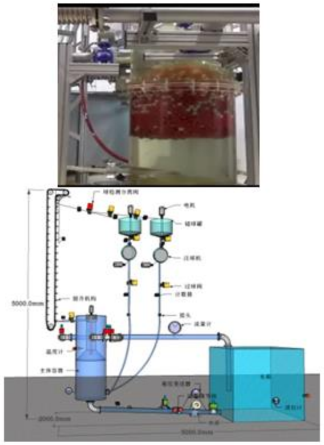
R&D of Components


Salt pump


Freezing valve

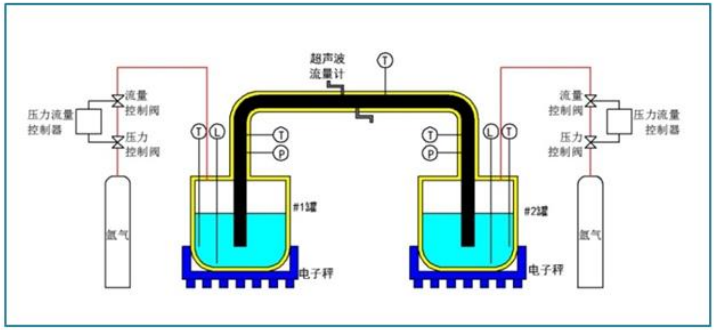

Heat exchanger


Control rod test facility


Fuel sphere Loading facility


Graphite structure test facility

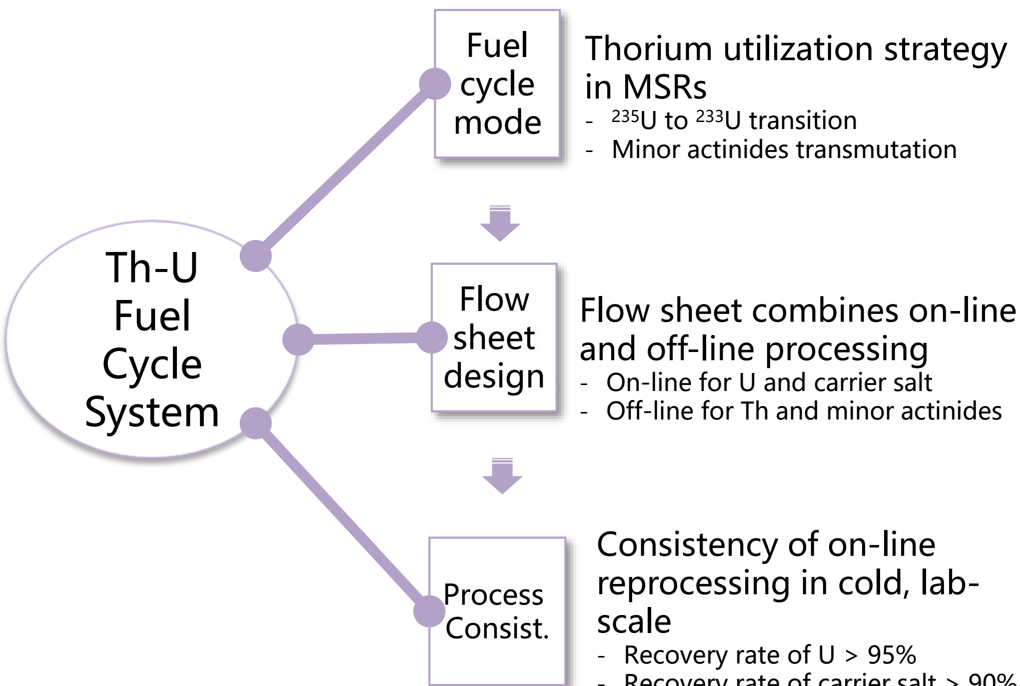

Pressure meter film

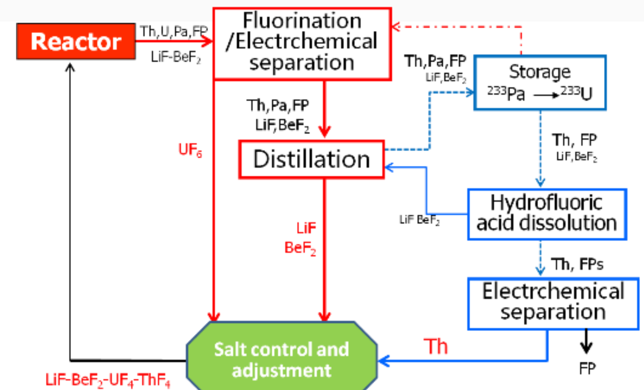


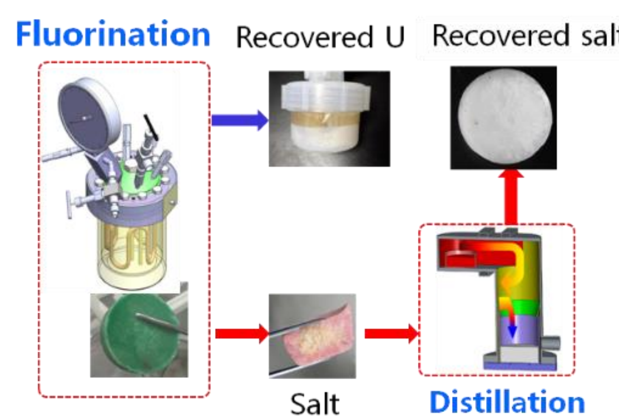
Ultrasonic flowmeter benchmark platform

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**







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

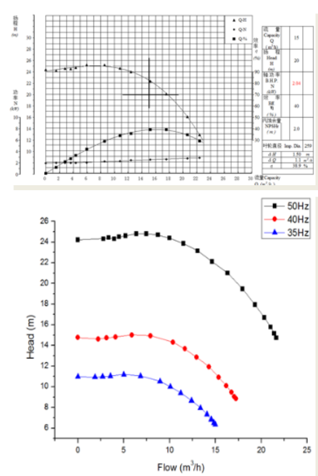
Fluoride Salt Loops

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

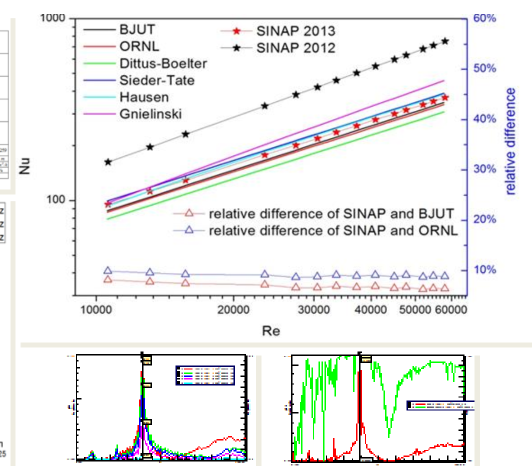
- Design and analysis methods for high-temperature fluoride salt loops
- Prototypes for pump, valve, heat exchanger, etc.
- Experience of loading and unloading of fluoride salts
- Experience of high-temperature fluoride salt loops operation and maintenance


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

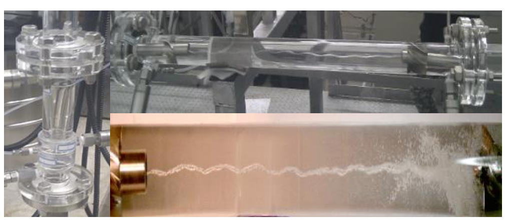
- Developing safety analysis methods and codes
- Developing safety design criteria and completing safety system design
- Established a salt natural circulation test loop for safety code validation
- Participating in the development of ANSI/ANS-20.1 and 20.2

- 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,
		  	

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

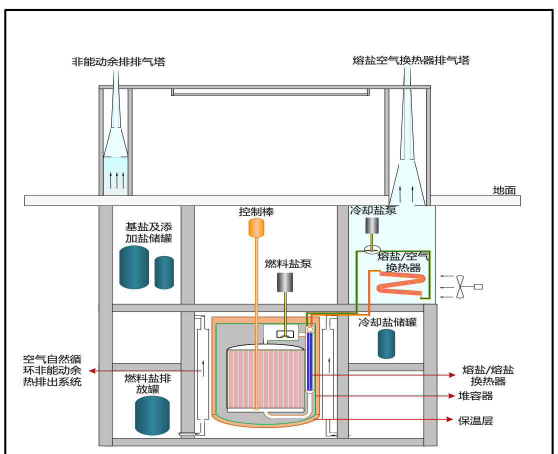
TMSR-Molten Salt for Heat Transfer and Storage

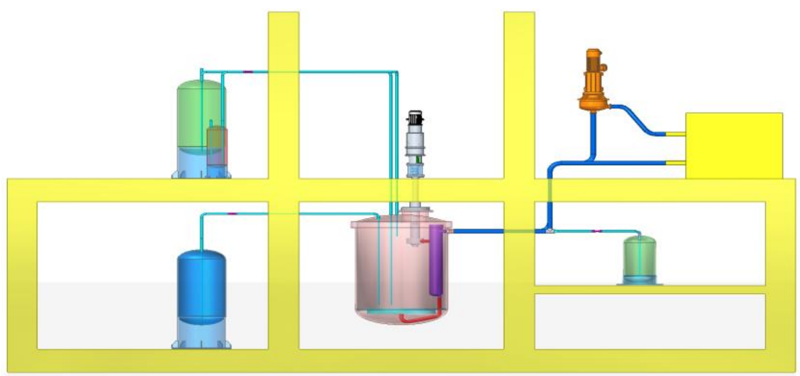
System	Molten Point ℃	Decomposed Point /℃	Density g/cm^3	Viscosity $10^6 m^2/s$	Heat Capacity kJ/m^3℃	Thermal Conductivity W/m·K
$NaNO_3$-KNO_3 (60-40wt.%) @400^{o}C	221	600	1.8	1.58	2850	0.62
Hitec ($NaNO_3$-KNO_3-$NaNO_2$) (7-53-40wt%) @400^{o}C	142	535	1.86	1.61	2900	0.4
$LiNO_3$-$NaNO_3$-KNO_3 (29.56-17.73-52.72wt%) @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

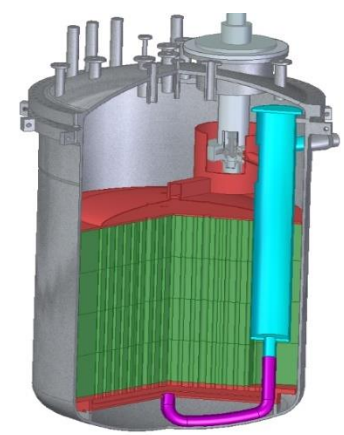
2MW TMSR-LF1

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

Power	2MW
Temperature	630 ℃ / 650 ℃
Type	Integrated design
Fuels	$LiF\text{-}BeF_2\text{-}UF_4\text{-}ThF_4$
Residual heat removal	Passive air natural circlation system

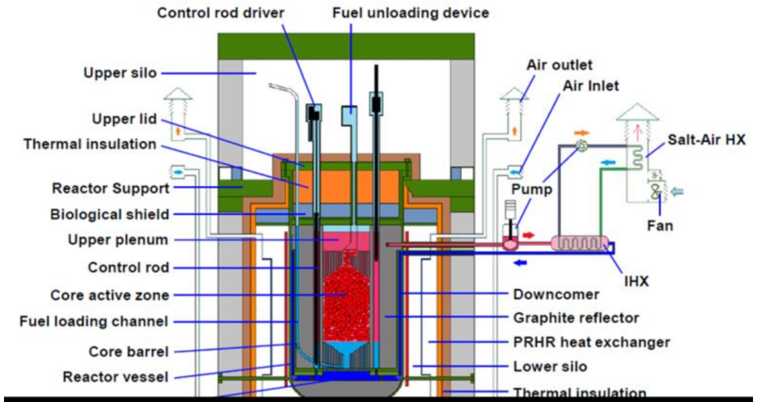






10MW TMSR-SF1

- **Demonstrate concept and safety of solid-fueled MSR**
- **Develop and integrate key technologies and components**
- **platform for future reactors**

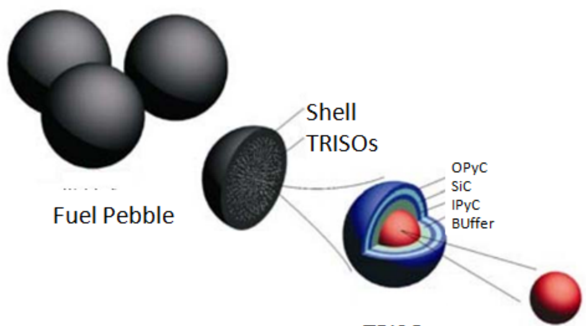


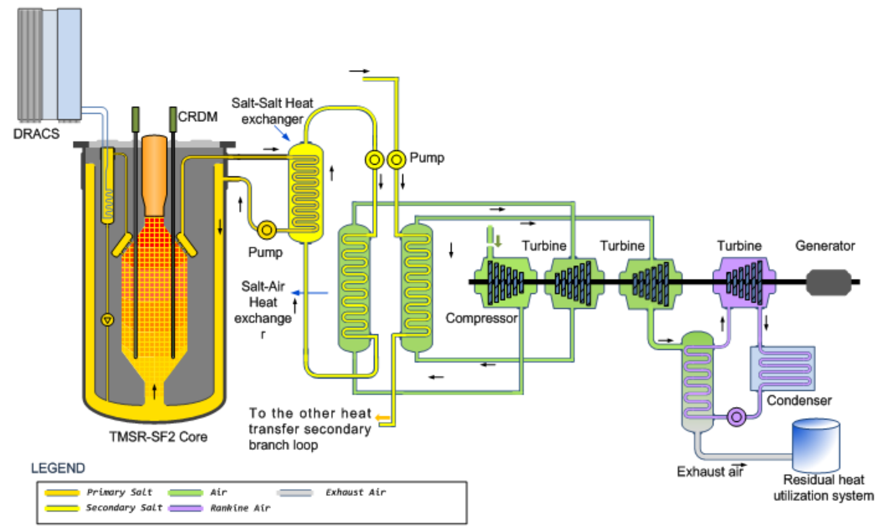
[redacted]

- Reactor power: $10MW_{th}$
- Coolant temperature: Inlet 600°C, outlet 650°C.
- Fuel element: TRISO fuel, 6cm sphere.
- Core: Graphite core, conventional pebble bed arrangement.
- With passive residual heat removal.
- Temperature limitations: Fuel, <1400°C; coolant outlet, <750°C.
- Reactor vessel pressure limitations: <5atm.

100MWe level Pebble-bed TMSR

- **a 168MWe solid-fueled (Pebble Bed) Fluoride-cooled High-temperature Reactor (PB-FHR).**



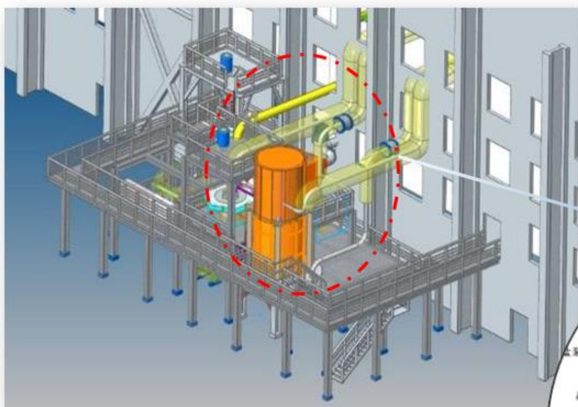


Electrical capacity (MW(e))	168
Thermal capacity (MW(th))	400
Coolant/moderator	Flibe/Graphite
Core inlet/outlet temperatures (°C)	600 /700
Fuel type/assembly array	Pebble / Floating bed
Fuel enrichment (%)	19.75%

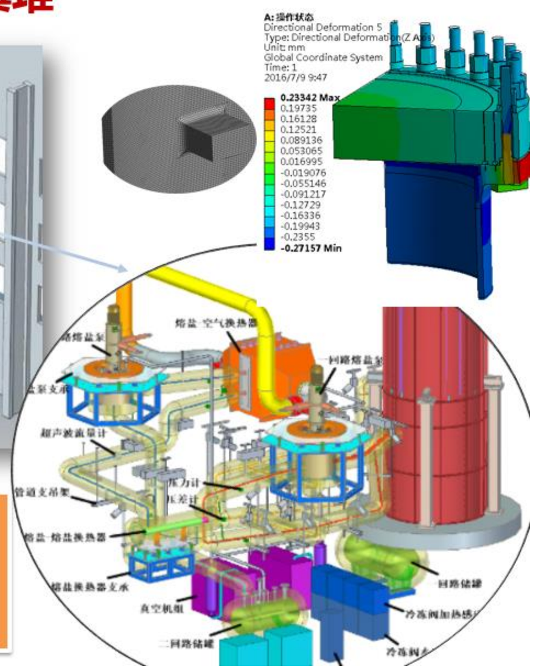
- **Inherent safety:**
  near-ambient pressure,
  low excess reactivity,
  large margin of fuel temperature.
- **Free-water cooling:**
  suitable for a variety of areas.
- **Mature technology:**
  fuel pebbles in HTR,
  fluoride salts in MSR,
  turbine technology in gas turbine.

TMSR-SF0

TMSR缩比仿真堆



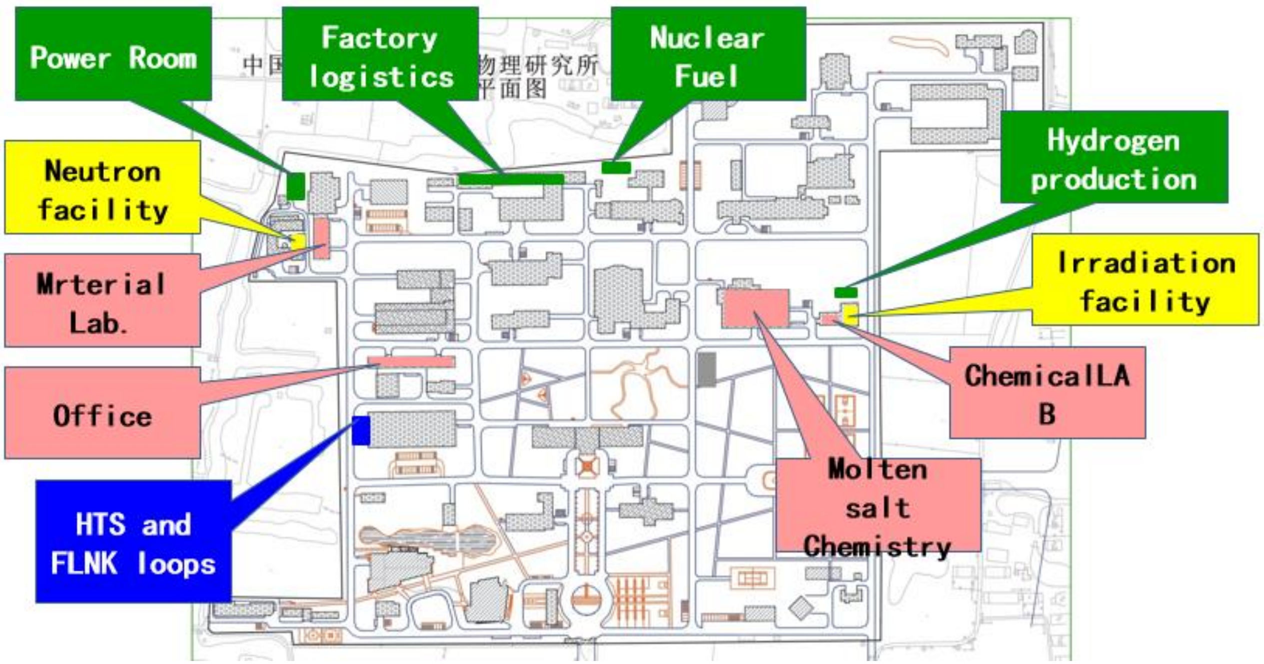
- ◆ 2016-7月中旬完成初步工程设计评审，形成109份设计报告；
- ◆ 2016-8月缩比仿真堆由设计阶段转入采购、加工制造阶段



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

	SF1	SF0
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

Fundamental Research Base at Jiading

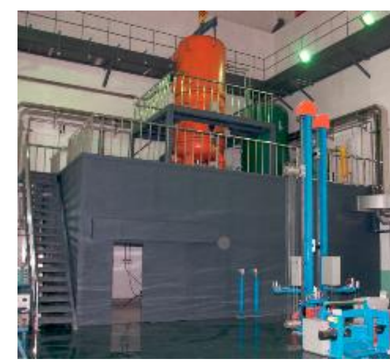


Super Computer

Hot Cells

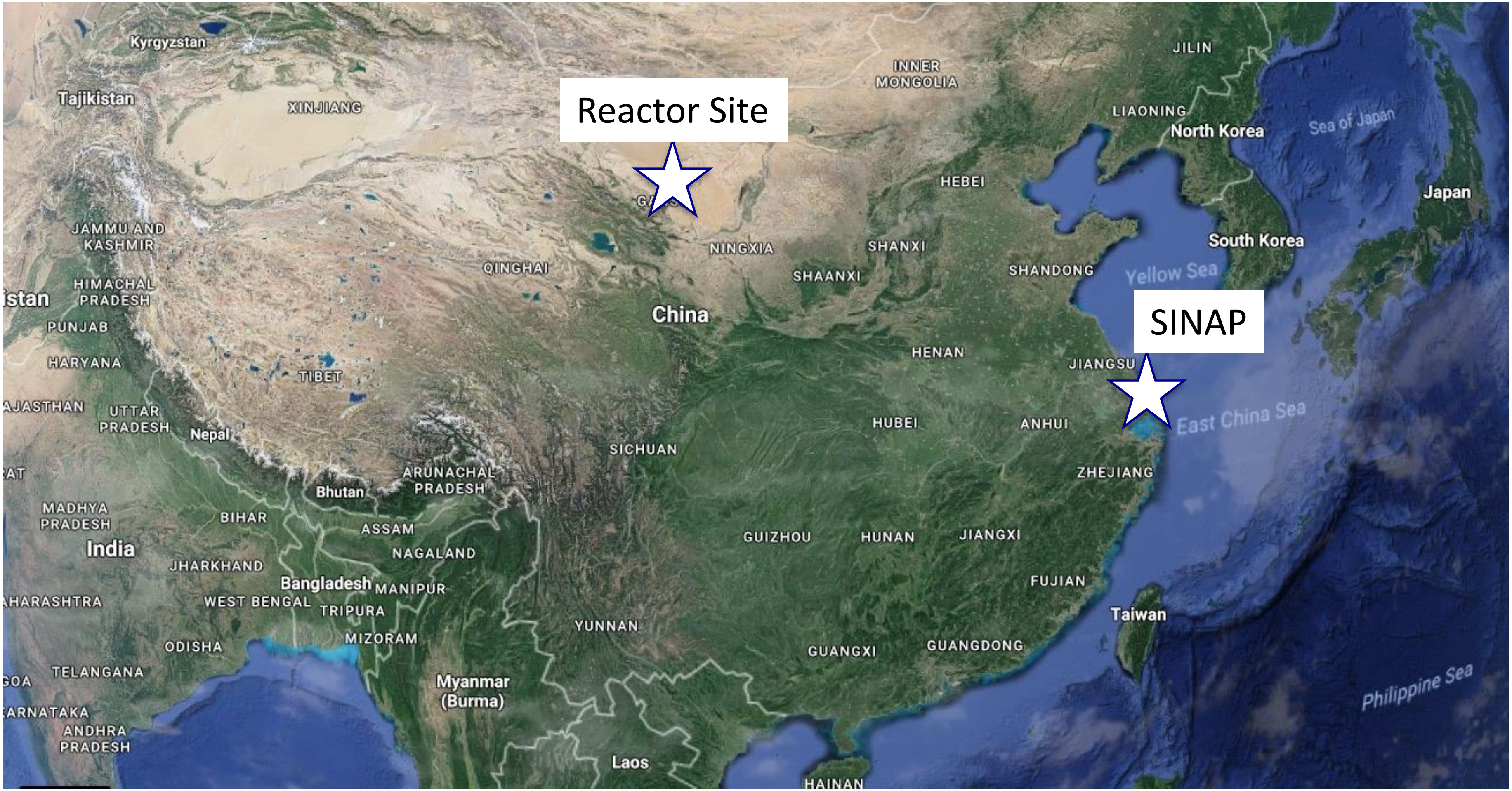
Material Testing Labs

Salt Properties Labs



β Irradiation Facility

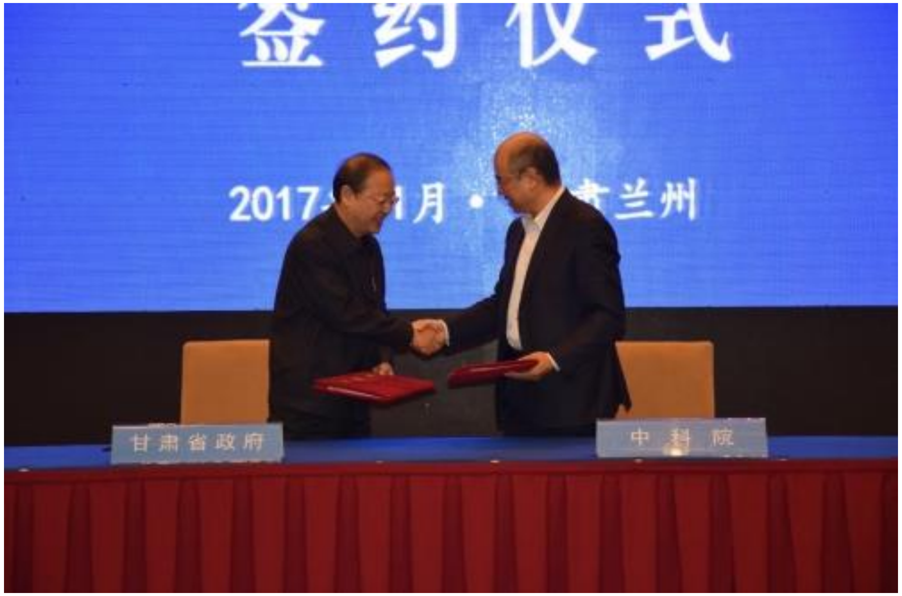
New Candidate Site of TMSR test reactor



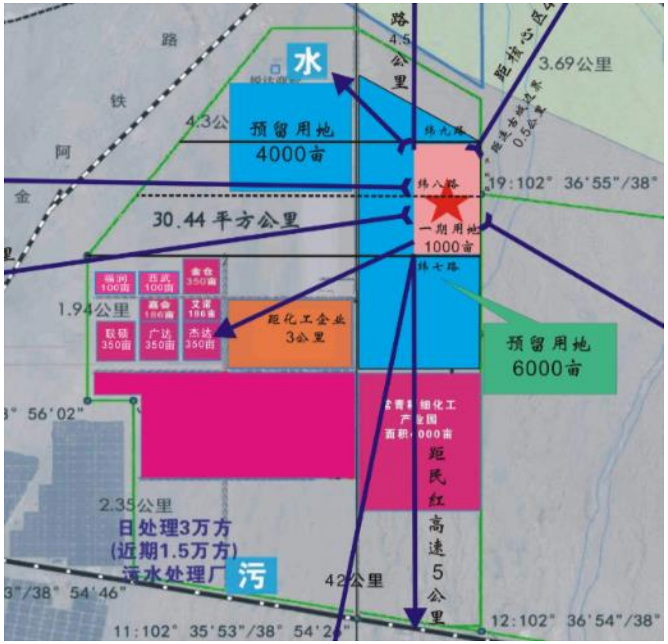
- The candidate site is located in Wuwei (武威）, Gansu Province, about 2000 Km from Shanghai, the annual precipitation is 128 mm and the annual average temperature is 8.3 °C.

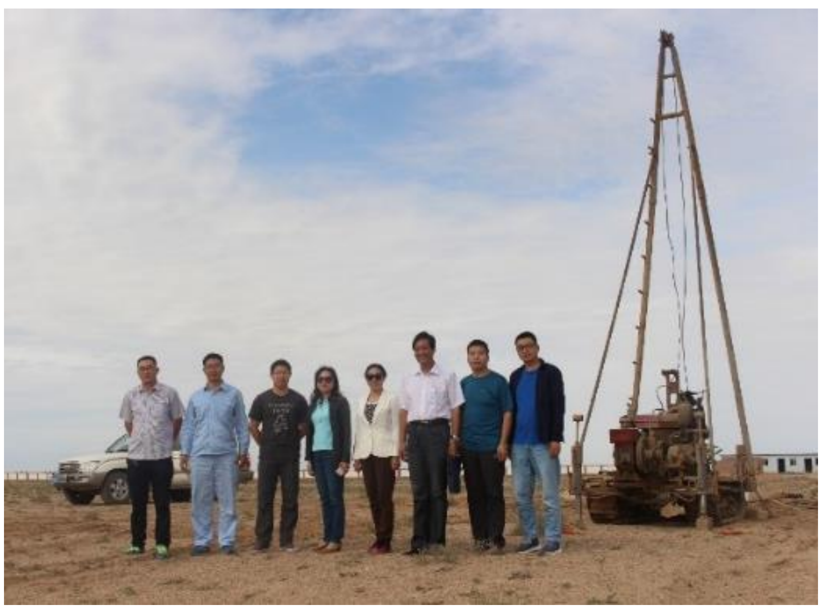
CAS and Gansu Collaboration

- Nov. 8, 2017, CAS and Gansu Signed collaboration agreement



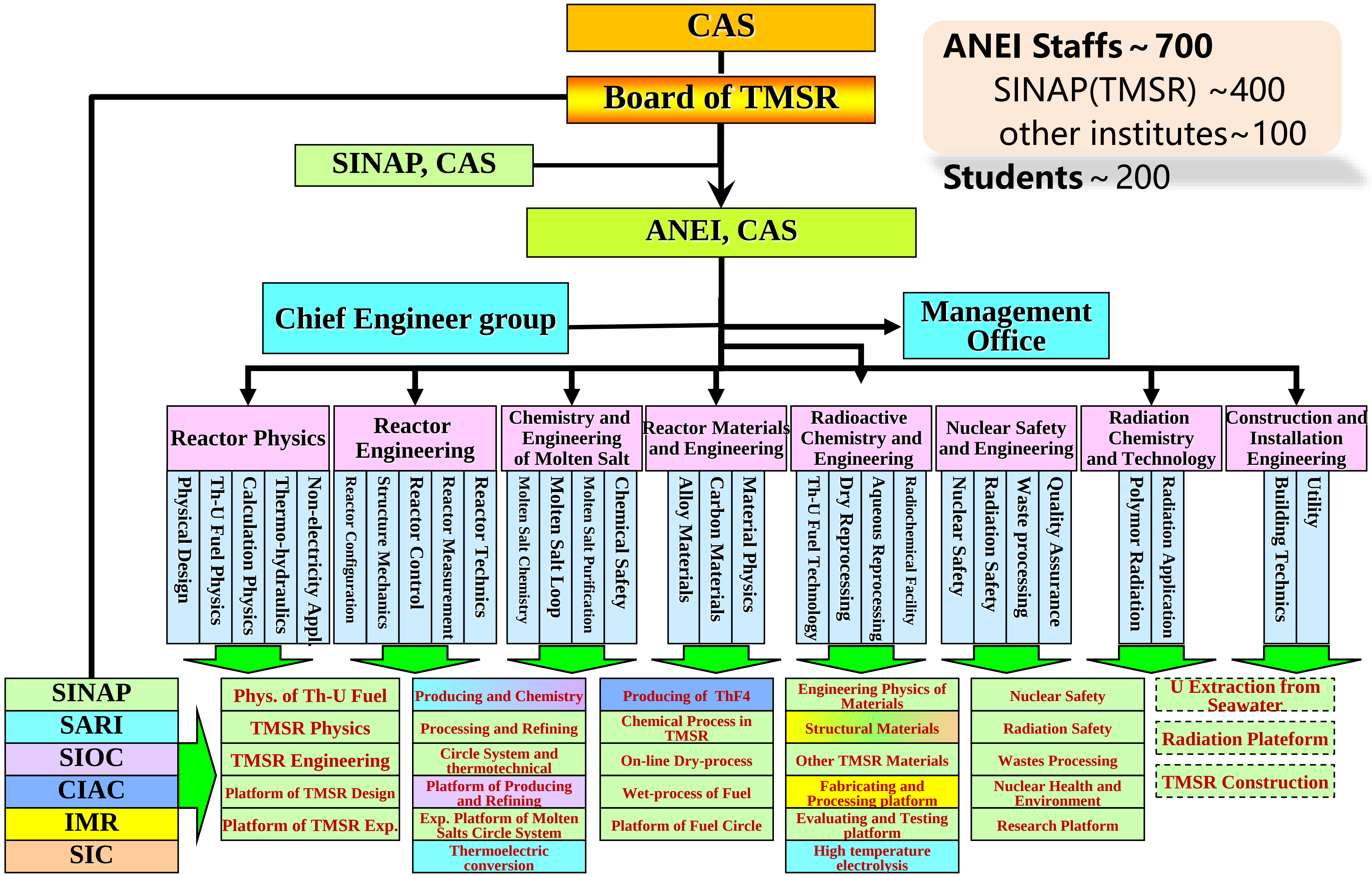
Survey of the Candidate Site



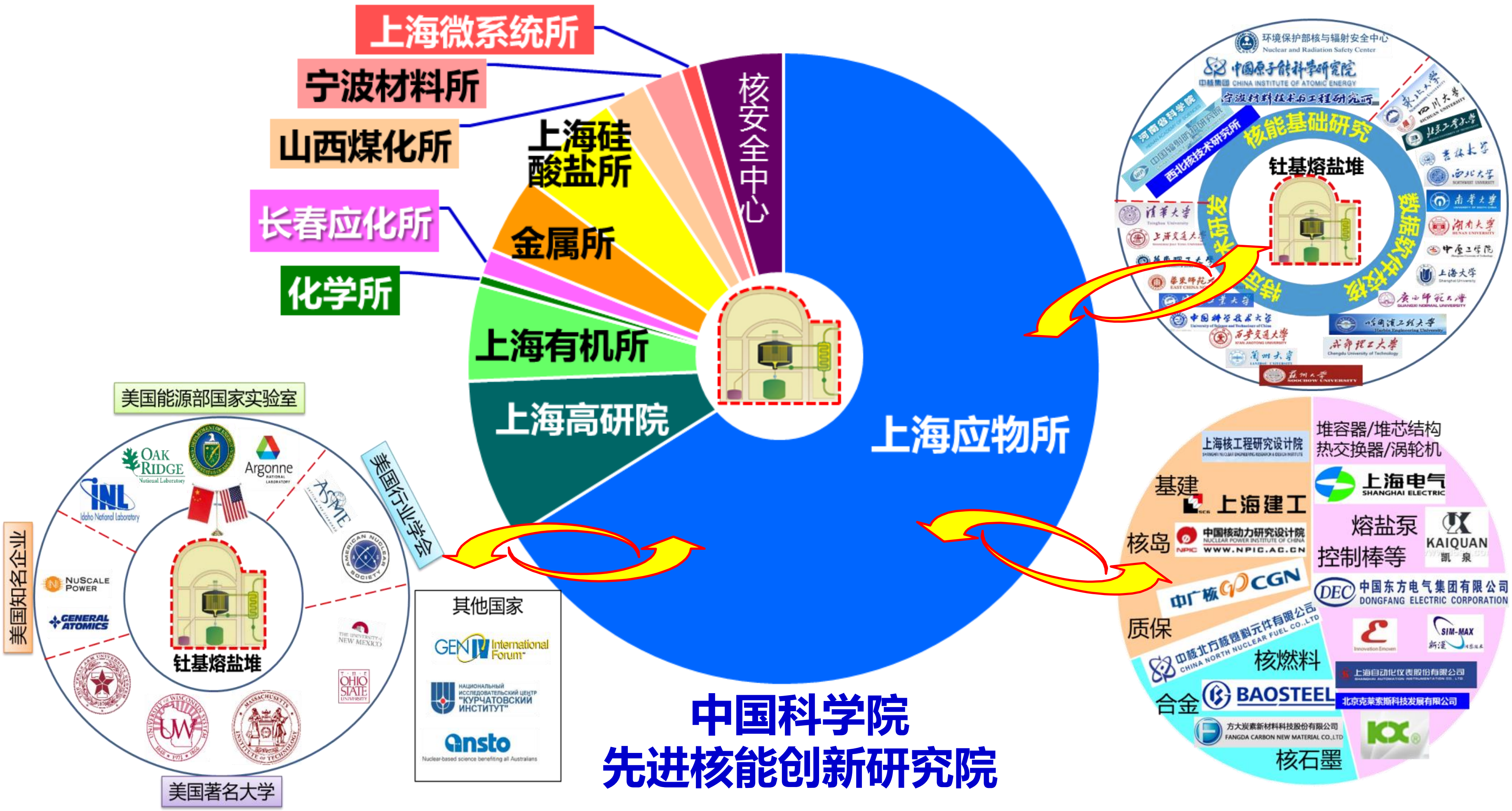


- Onsite survey completed in August
- Application for the site permit to be submitted to government this year.

TMSR Organization



International and Domestic Collaborations



TEAMS: Staffs ～600; Graduate students ～200

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.

OUTLINE

What is TMSR

Motivation for TMSR

Progress of TMSR

Perspective on TMSR

OUTLINE

What is TMSR

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Perspective on TMSR

International situation

2016年美国版反应堆发展路线图

--Public-Private Partnerships for Reactor Development

第二代

- PWR
- BWR

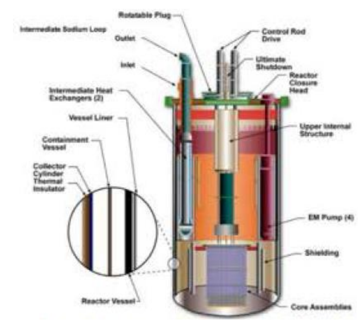
第三代

- AP1000
- ESBWR

小型模块堆

- NuScale
- B&W mPower
- Holtec SMR-160
- Westinghouse SMR

第四代



- Sodium Fast Reactor
- High Temp. Gas Reactor
- Lead Fast Reactor
- Gas Fast Reactor
- Molten Salt Reactor

GEN II → GEN III + → SMR → GEN IV Advanced Reactor

Accelerating the Development and Deployment of Advanced Reactors

VISION

By 2050,advanced reactors will provide a significant and growing component of the nuclear energy mix both domestically and globally, due to their advantages in terms of improved safety, cost, performance, sustainability, and reduced proliferation risks.

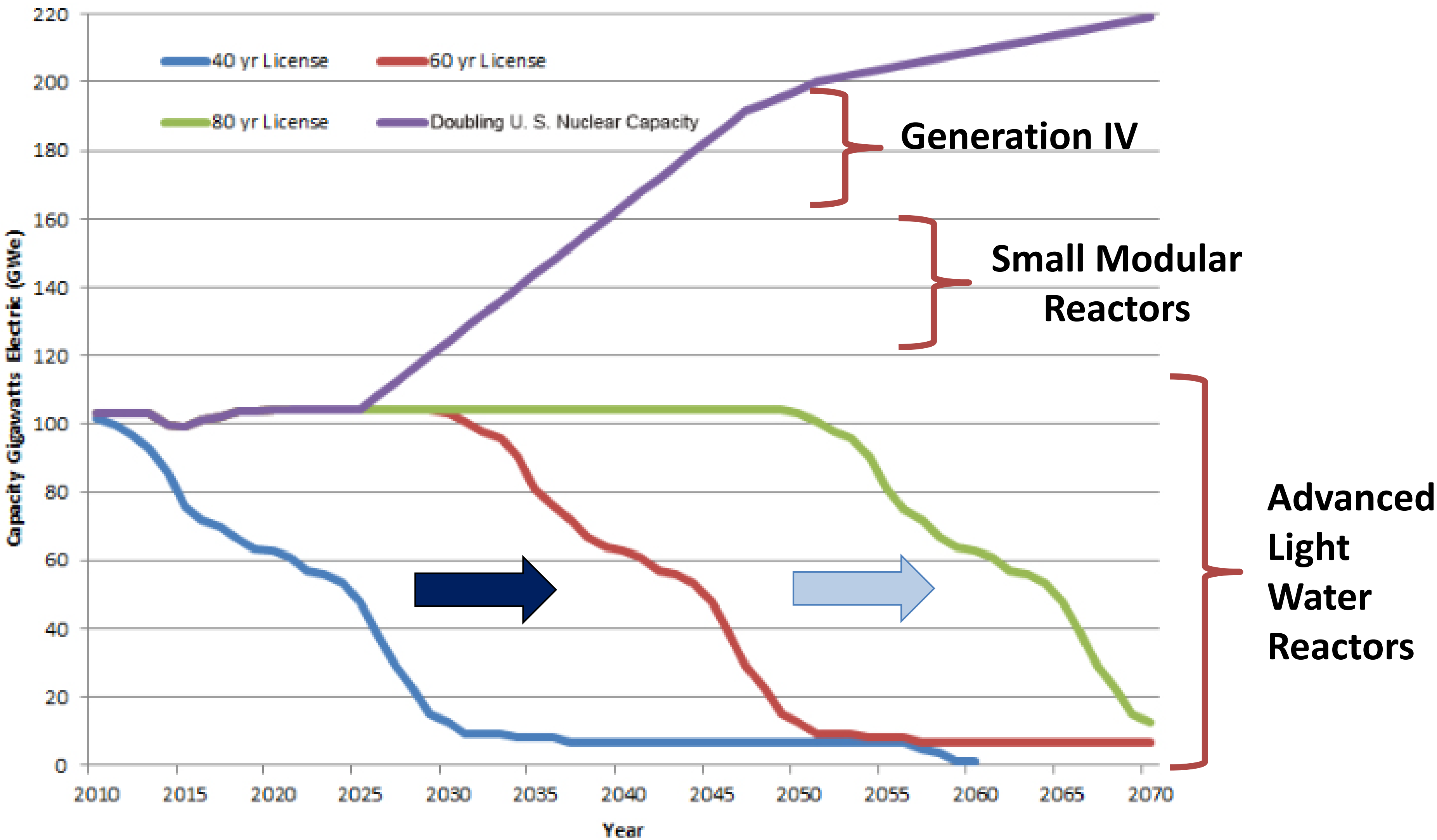
GOAL

By the early 2030s, at least two non-light water advanced reactor concepts would have reached technical maturity, demonstrated safety and economic benefits, and completed licensing reviews by the U.S. Nuclear Regulatory Commission (NRC), sufficient to allow construction to go forward.

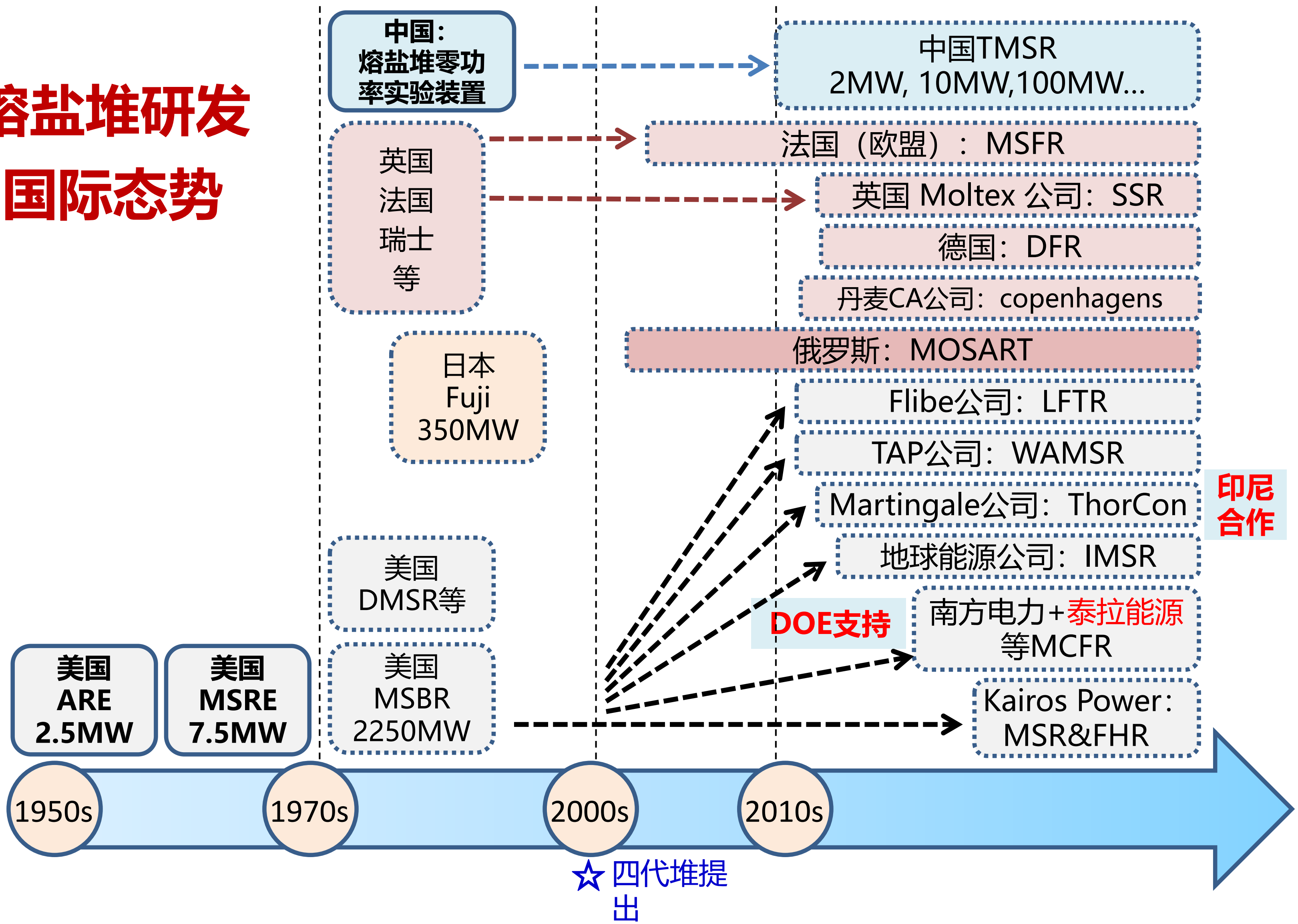
U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Nuclear Power Capacity needed to meet U.S. Clean Power Goals



熔盐堆研发国际态势


中国：
熔盐堆零功率实验装置
中国TMSR
2MW, 10MW,100MW...
英国
法国
瑞士
等
法国（欧盟）：MSFR
英国 Moltex 公司：SSR
德国：DFR
丹麦CA公司：copenhagens
日本
Fuji
350MW
俄罗斯：MOSART
Flibe公司：LFTR
TAP公司：WAMSR
Martingale公司：ThorCon
印尼
合作
地球能源公司：IMSR
美国
DMSR等
DOE支持
南方电力+泰拉能源
等MCFR
美国
ARE
2.5MW
美国
MSRE
7.5MW
美国
MSBR
2250MW
Kairos Power：
MSR&FHR
1950s
1970s
2000s
2010s
☆ 四代堆提出

OUTLINE

What is TMSR

Motivation for TMSR

Progress of TMSR

Perspective on TMSR

---Chinese Proposal

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 2020
- To complete the construction of TMSR-LF-SMR demo-facility by 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.

TMSR Roadmap

Combination of batch-scale pyro process treatment and on-line fission production removing, 80% energy contribution from Th-based fuel, basically achieve U-Th cycle

2040s JIUQUAN+WUWEI

Build batch-scale pyro process demonstration facility, 40% energy contribution from Th-based fuel

2040 JIUQUAN

Build 100MWe small module TMSR, 20% energy contribution from Th-based fuel

2030 WUWEI

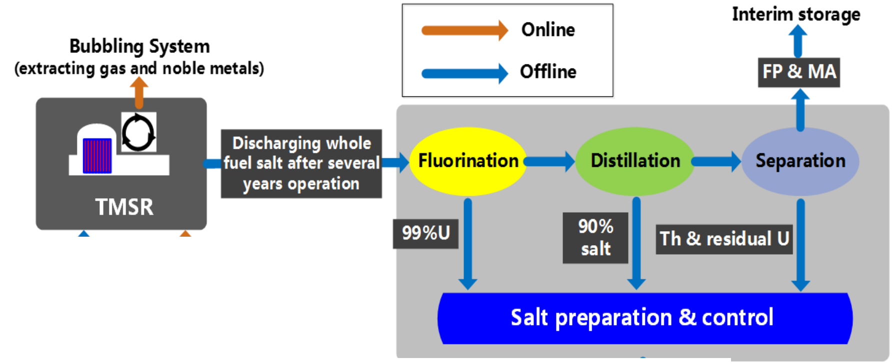
Build 2MWt TMSR-LF1 and Low Carbon Clean Energy Demonstration System

2020 WUWEI

A 3-step Strategy for Th-U Fuel Cycle

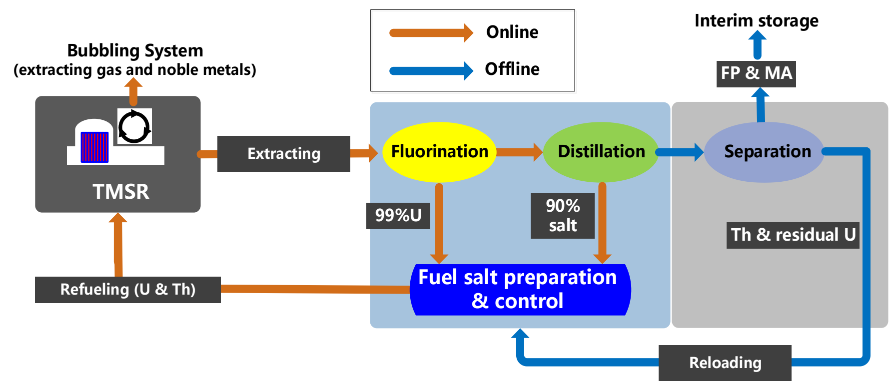
Step 1: batch process

- 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



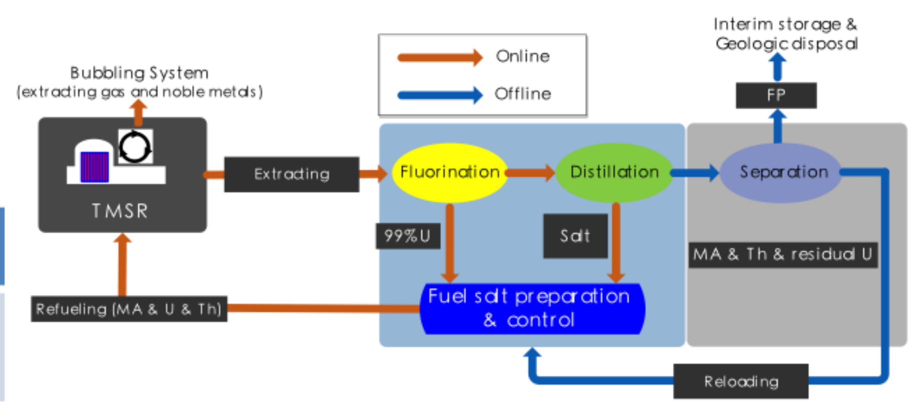
Step 2: step1 + fuel reload

- Reloading of U and Th to realize thorium fuel cycle



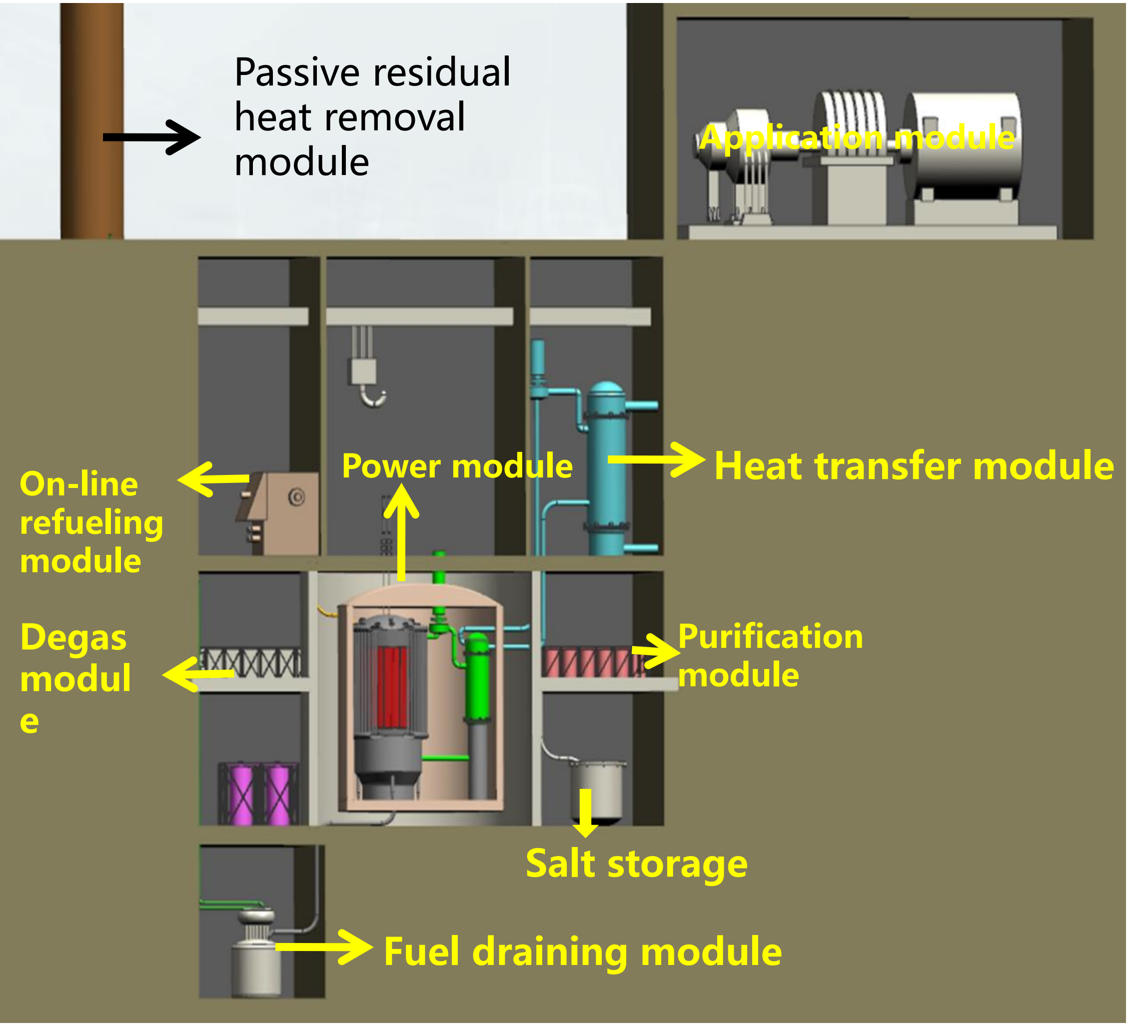
Step 3: step 2 + continuous process

- 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-LF Small Modular Demo-Reactor

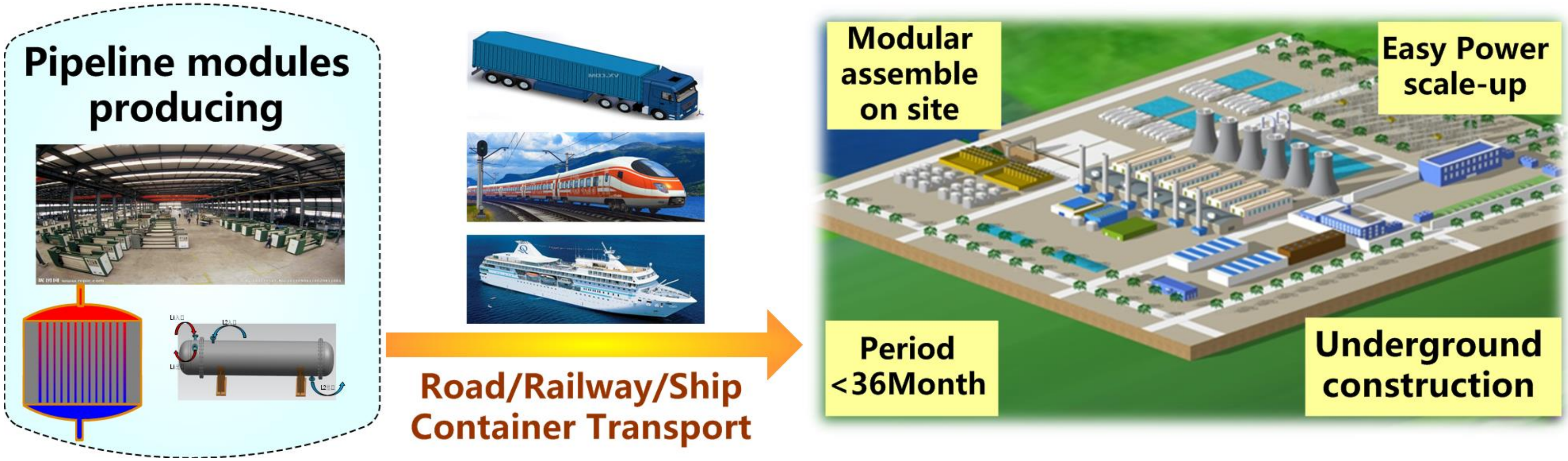


- **Key modules**: power、heat transfer、fueling draining、Passive residual heat removal、on-line refueling
- **Application modules:** generator、hydrogen production、Changed、etc. (Changed with goals)

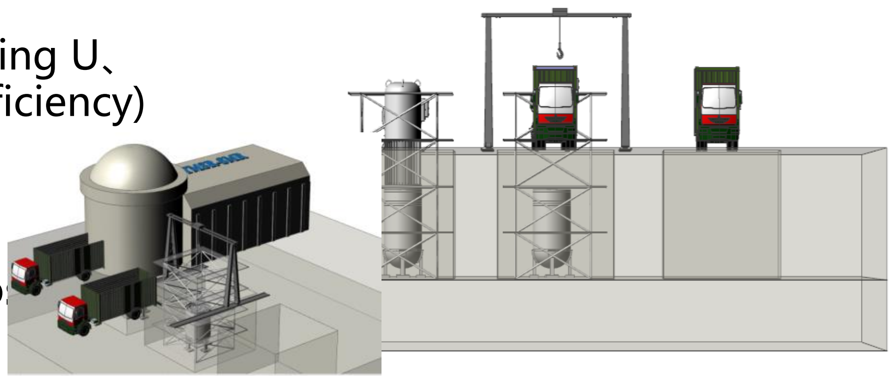
Power	168MWe
Temperature	600 ℃ / 700 ℃
Efficiency	40%-50%
Th power	>=20%
Main vessel	5.2m×6.0m (D×H)
Safety	Passive residual heat removal system
Economics	Cheaper than coal

TMSR-LF Small Modular Demo-Reactor

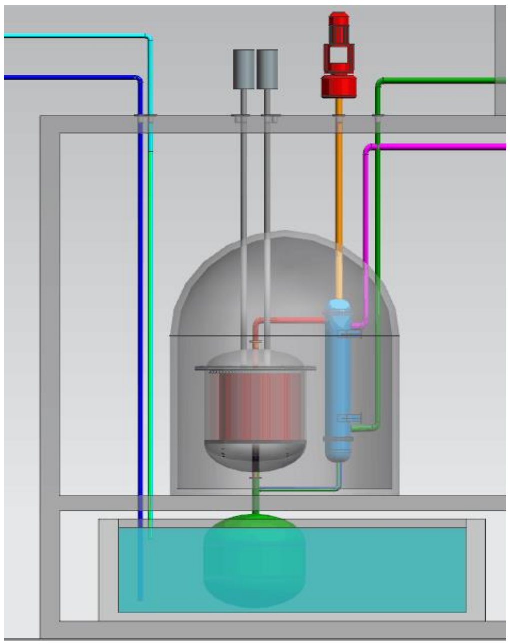
Modular construction and operation



- **Power module life： 8 y** (Material life)
- **Fuel salt dry-process time： 8 y** (extracting U、Th，removal fission products,improve fuel efficiency)
- **Other modules：changed easily**
- **On-line fueling without shut down**
- **Multi-building one by one (decrease co**



Nuclear island parameter

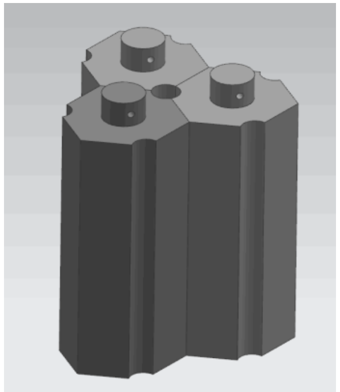


Design Parameters	value
The shape of graphite component	Hexagonal prism
Length of side	26cm
Diameter of molten salt channel	8.63cm

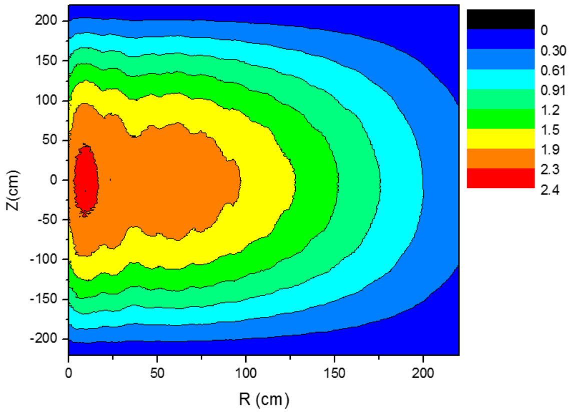
Design Parameters	value
Electric power	168MWe
Thermal power	373MWth
Core diameter / height	4.8m/5.0m
Primary vessel diameter / height	5.2m/6.0m
Uranium enrichment	19.75%
The final loaded U / Th ratio	1:1
Initially loaded uranium	2100kg
Initially loaded thorium	15700kg
Adding mass of uranium per day	1.08kg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

Neutron properties

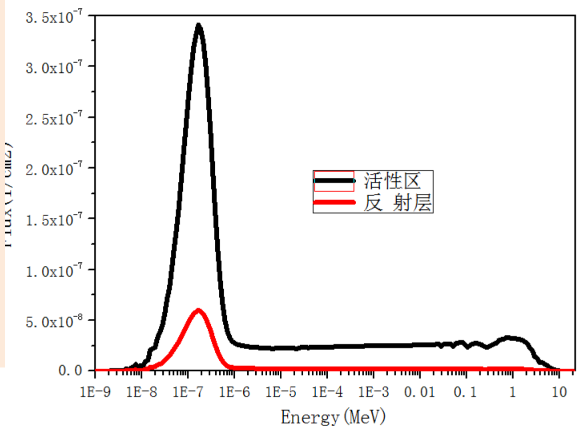
- Thorium-derived energy greater than 20%.
- Approximately equivalent burnup 300MWd/kg U
- Graphite life: Meet the 8-year refueling requirements



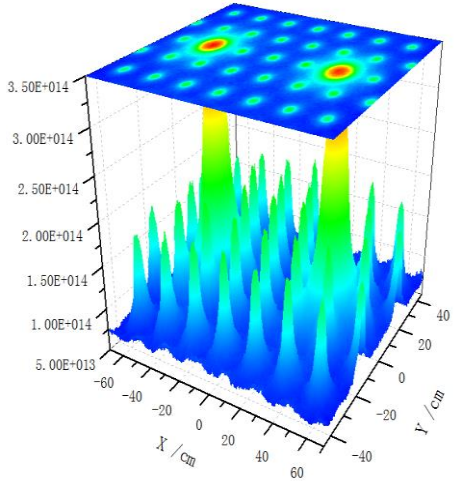
Fuel assembly



Power density distribution

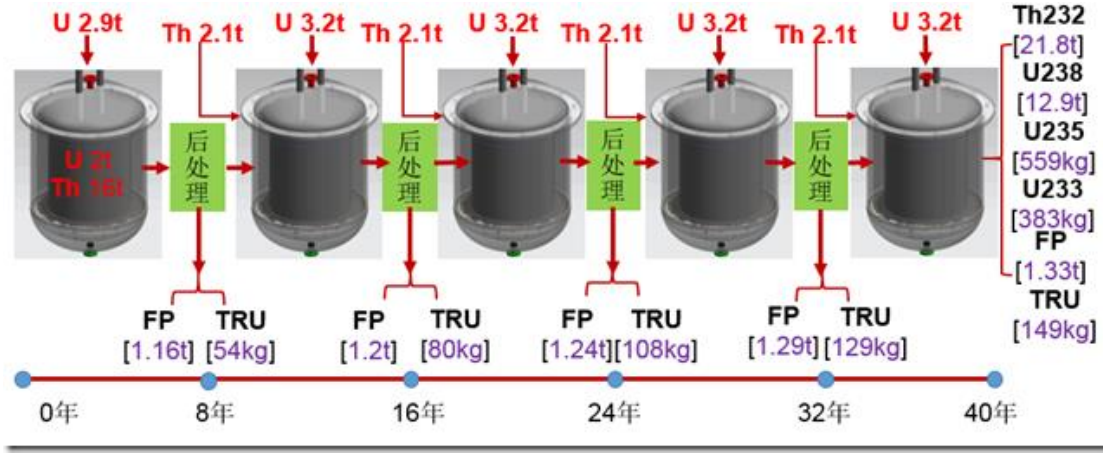


Spectrum

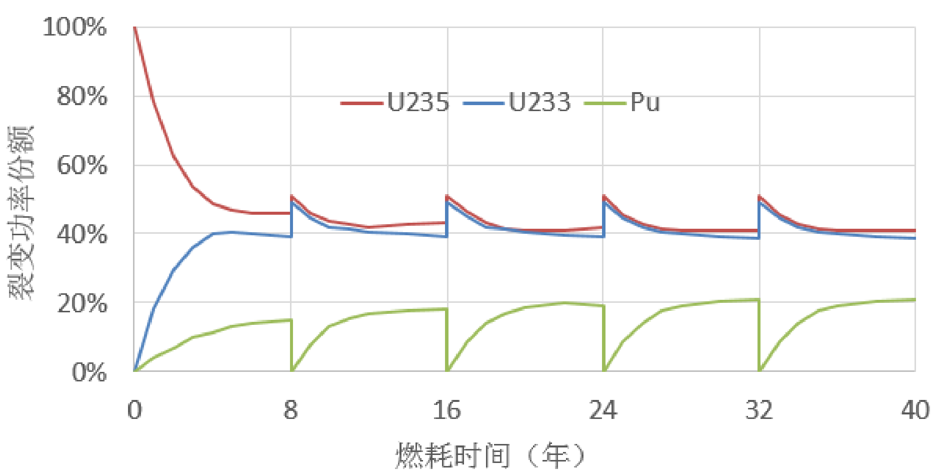


Fast neutron flux distribution in core.

Thorium resource utilization

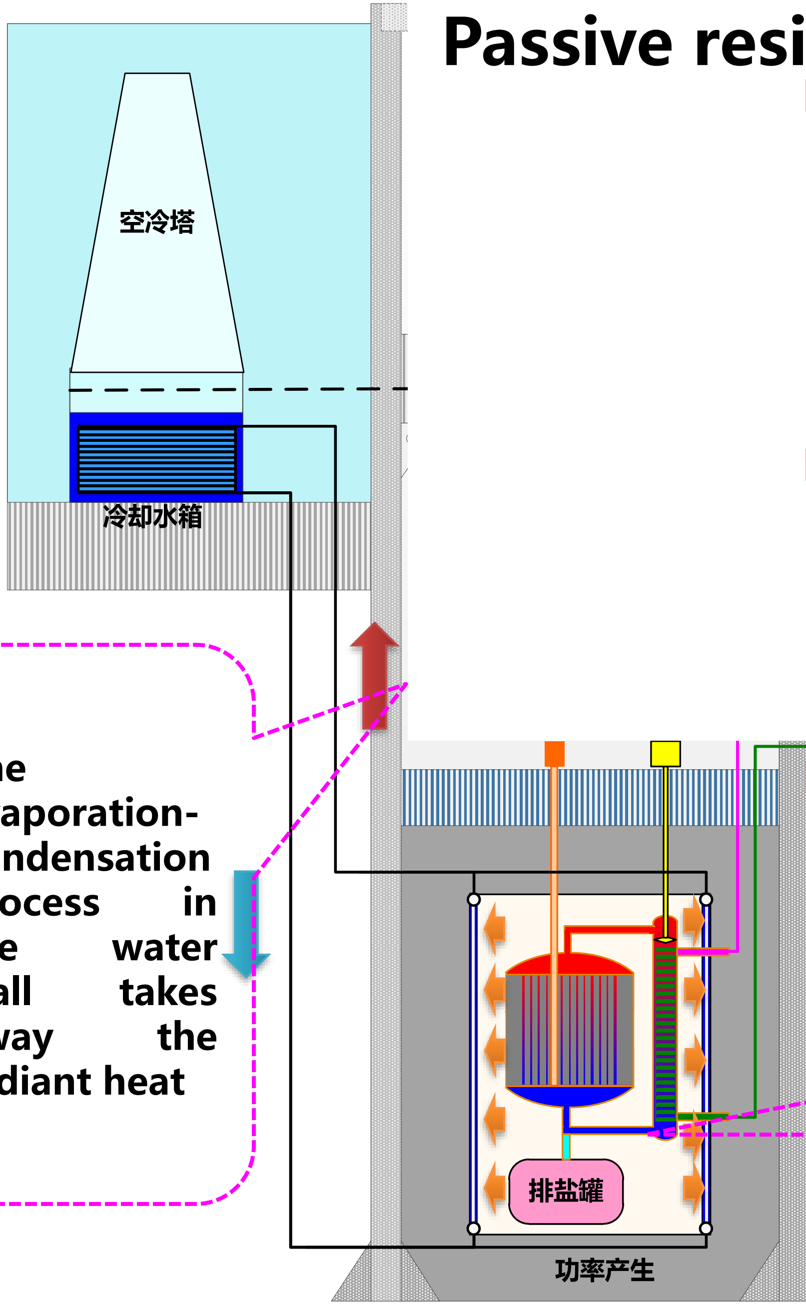


- **19.75% Enrichment of U .**
- **Loaded with a large amount of thorium initially**
  Th full conversion, incineration in all life;
- **Online refueling**
  Reduce the residual reactivity, improve fuel efficiency;



- **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**

Passive residual heat removal system

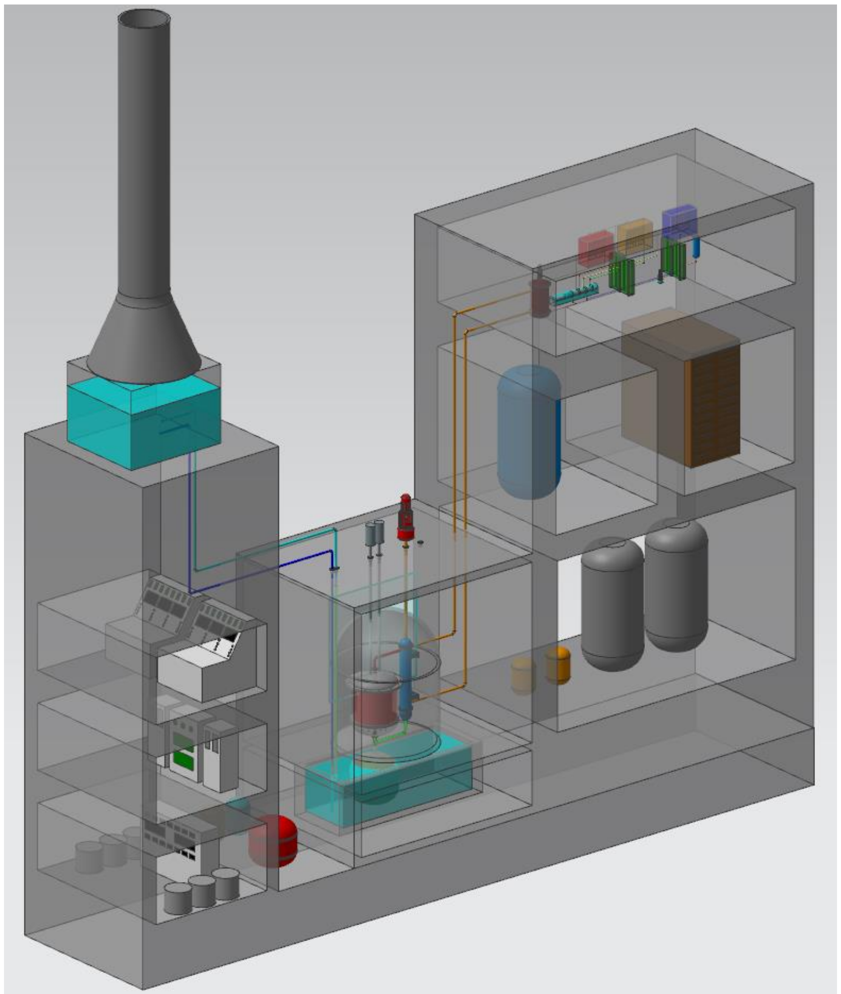


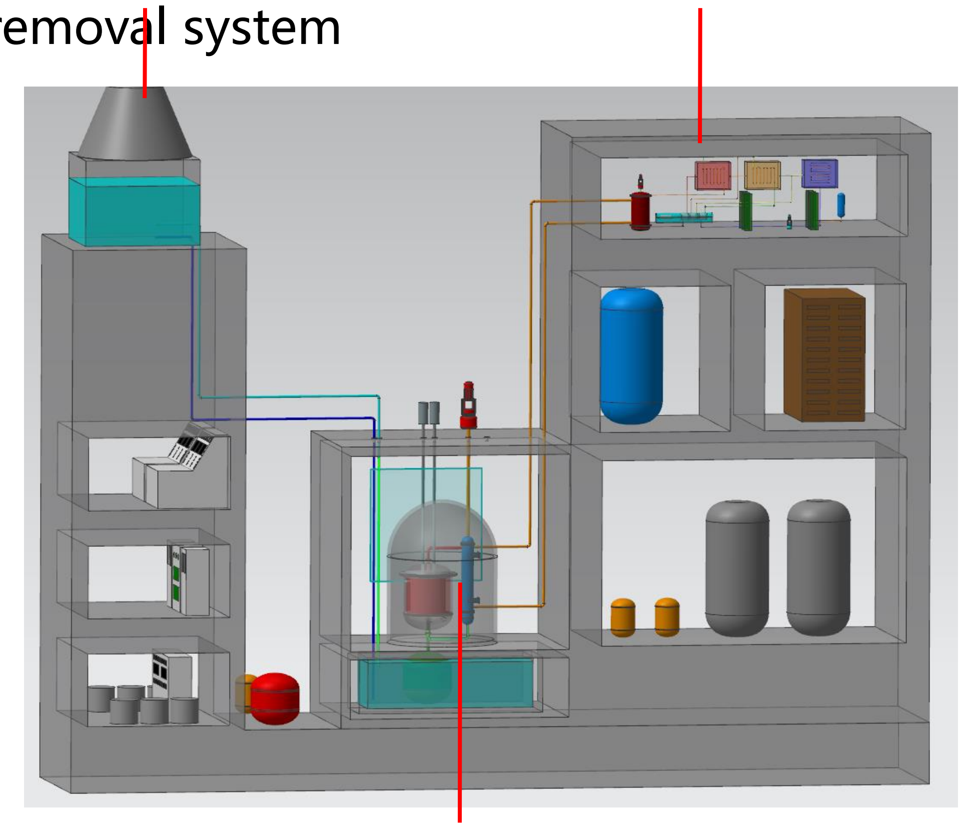
The evaporation-condensation process in the water wall takes away the radiant heat

- **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.

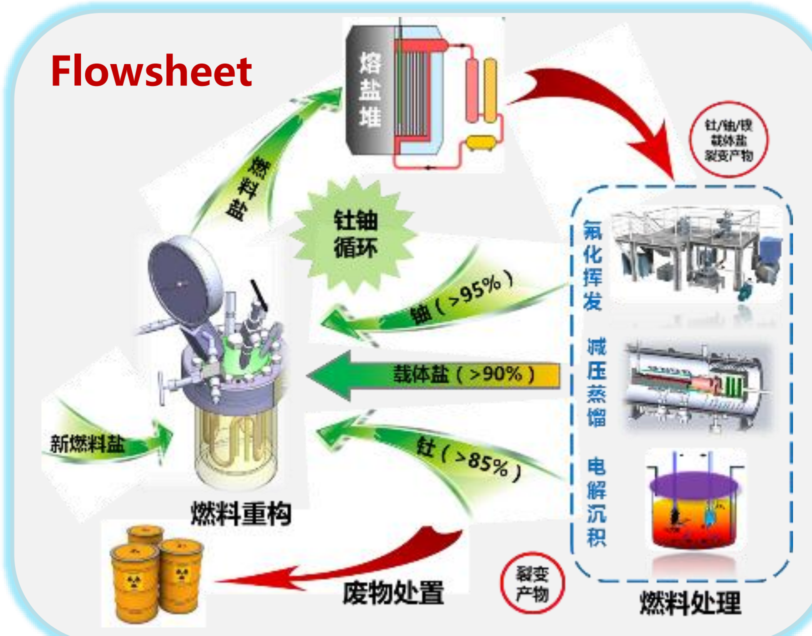
Three - dimensional map of Single - pile system layout





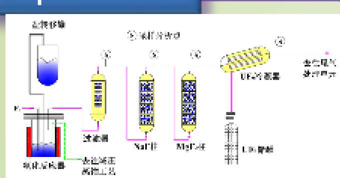
Facility for dry process of Th-U fuel cycle

Goal	Large scale Th utilization
Technologies	Fluorination, Electroysis, Distillation
Capability	5m3/batch， 20m3/year
Efficiency	U>95%; Th>85%
Waste	10 times lower than current technologies



U seperation

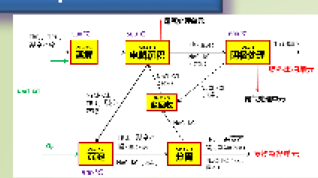
Fluorination



产品收率95~99%
总β和γ去污系数10^7

Th seperation

Electroysis



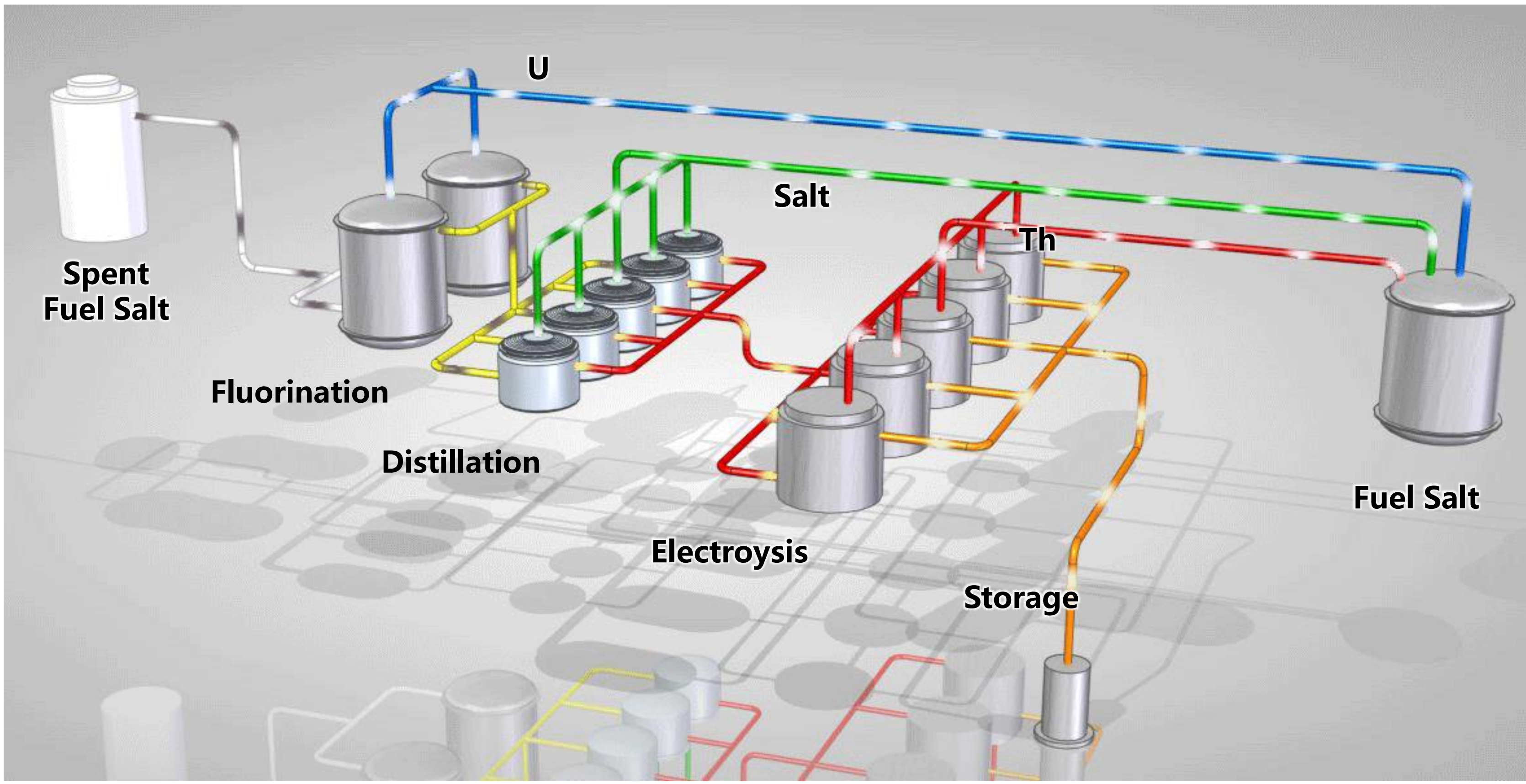
产品收率85~90%
总β和γ去污系数10^2

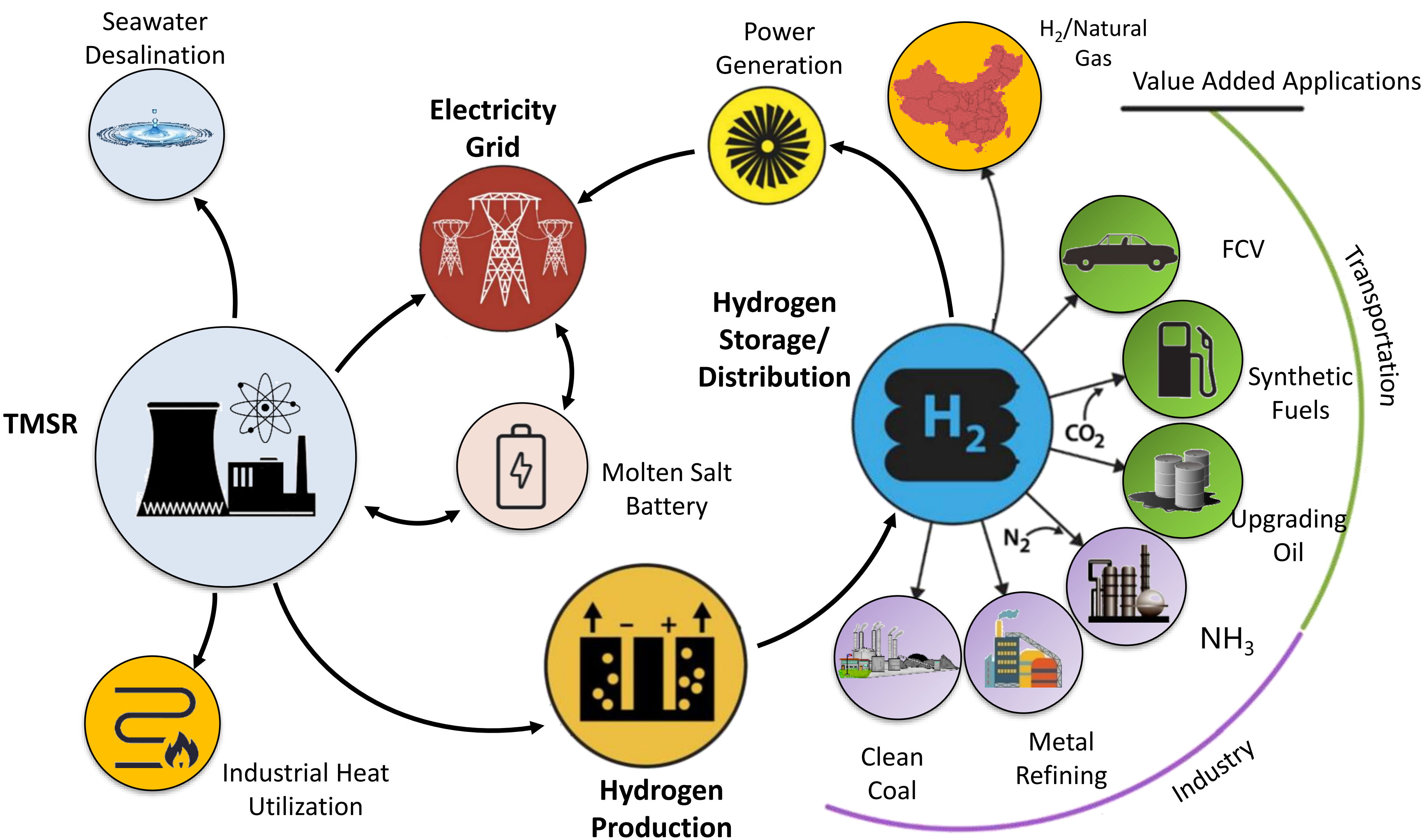
Salt seperation

Distillation

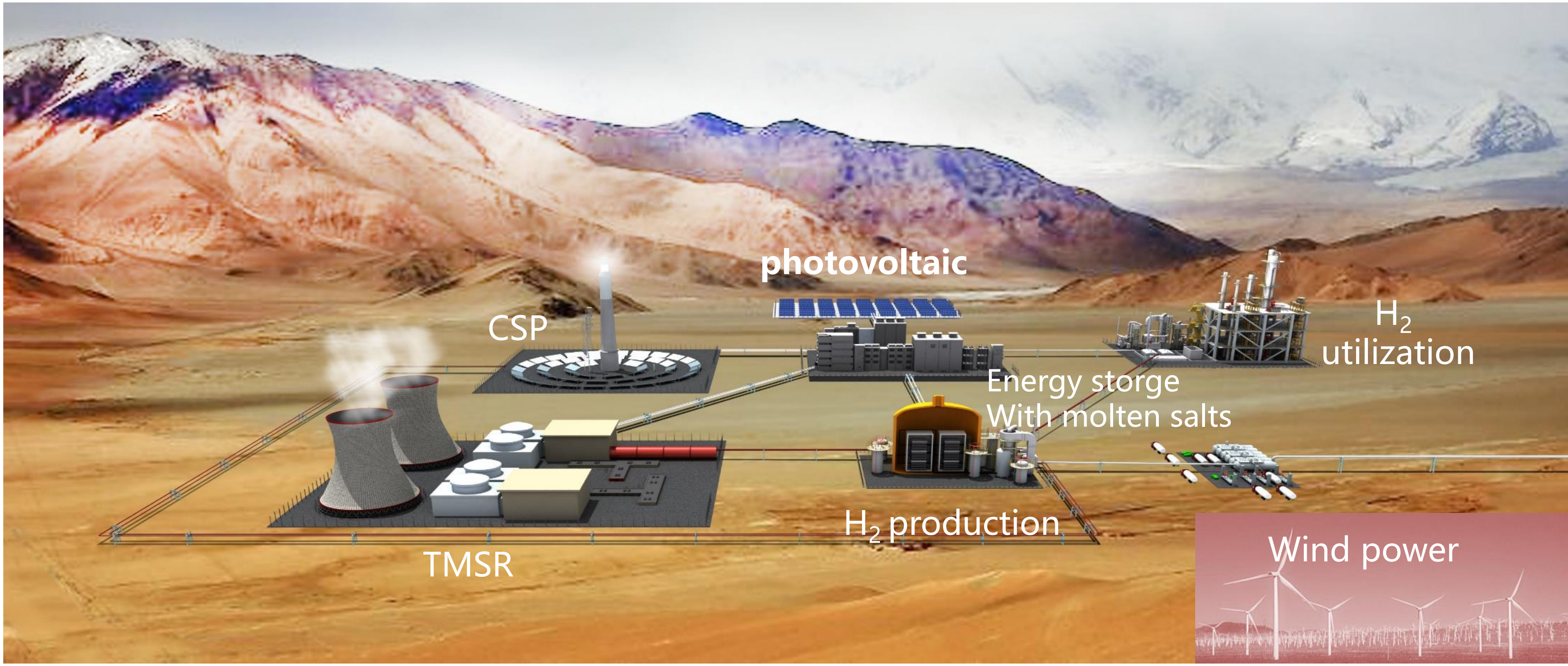
产品收率90~95%
总β和γ去污系数10^4

Batch pyroprocess Facility




Seawater Desalination
Electricity Grid
Power Generation
H2/Natural Gas
Value Added Applications
FCV
Transportation
Hydrogen Storage/ Distribution
TMSR
Molten Salt Battery
Synthetic Fuels
CO2
Upgrading Oil
N2
NH3
Industrial Heat Utilization
Hydrogen Production
Clean Coal
Metal Refining
Industry

TMSR Innovative Hybrid-energy Park

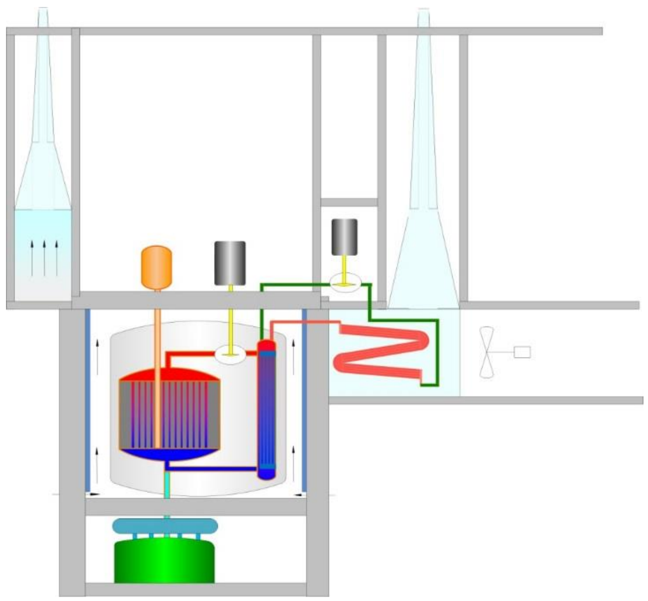


Objectives

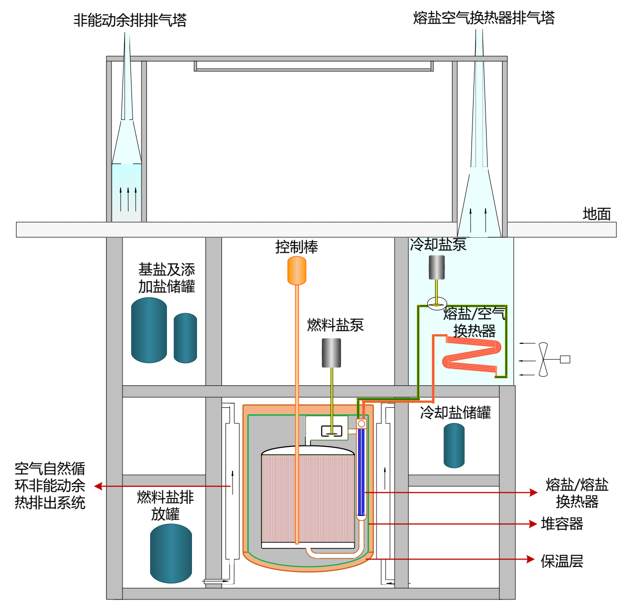
- **By 2020, finish construction of 2MW liquid-fueled Thorium Molten Salt Reactor, and achieve full power operation.**

- Platform of design and technologies R&D for small modular MSR
- Experimental facility for Th-U fuel cycle, dry-processing
- Nuclear section for Low-carbon innovative energy demonstration system.

Compact Loop Design VS Integrated Design



Compact Loop Design



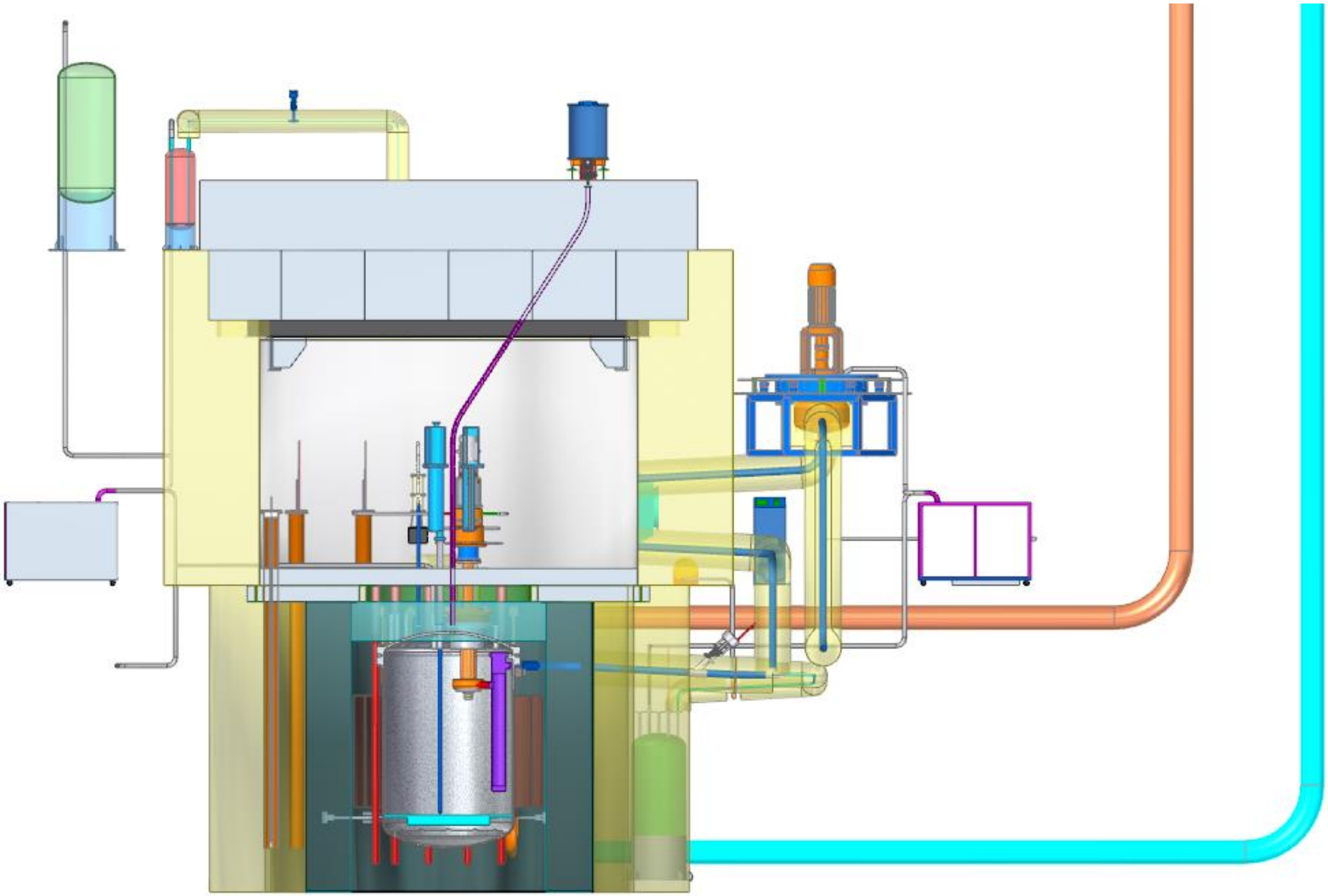
Integrated Design

- Good to maintain radioactivity.
- save cost.
- Future trend for small modular reactor.

General Description

- **Fuel**: $LiF-BeF_2-ZrF_4-UF_4$ $(+ThF_4)$,
- **Structural Materials**: UNS N1003 alloy, superfine particle graphite
- **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.

3D Graph of Engineering Design



Main Parameters

Reator type	Liquid-fueled molten salt reactor
Power	2 MW
Life	10 years
EFPD	300 days
Max EFPD / year	60 days
Inlet/outlet Temperature (fuel salt loop)	630℃ / 650℃
Inlet/outlet Temperature (coolant salt loop)	560℃ / 580℃
Fuel salt	$LiF-BeF_2-ZrF_4-UF_4$ ($+ThF_4$)
U-235 Enrichment	19.75wt%
Coolant salt	$LiF-BeF_2$

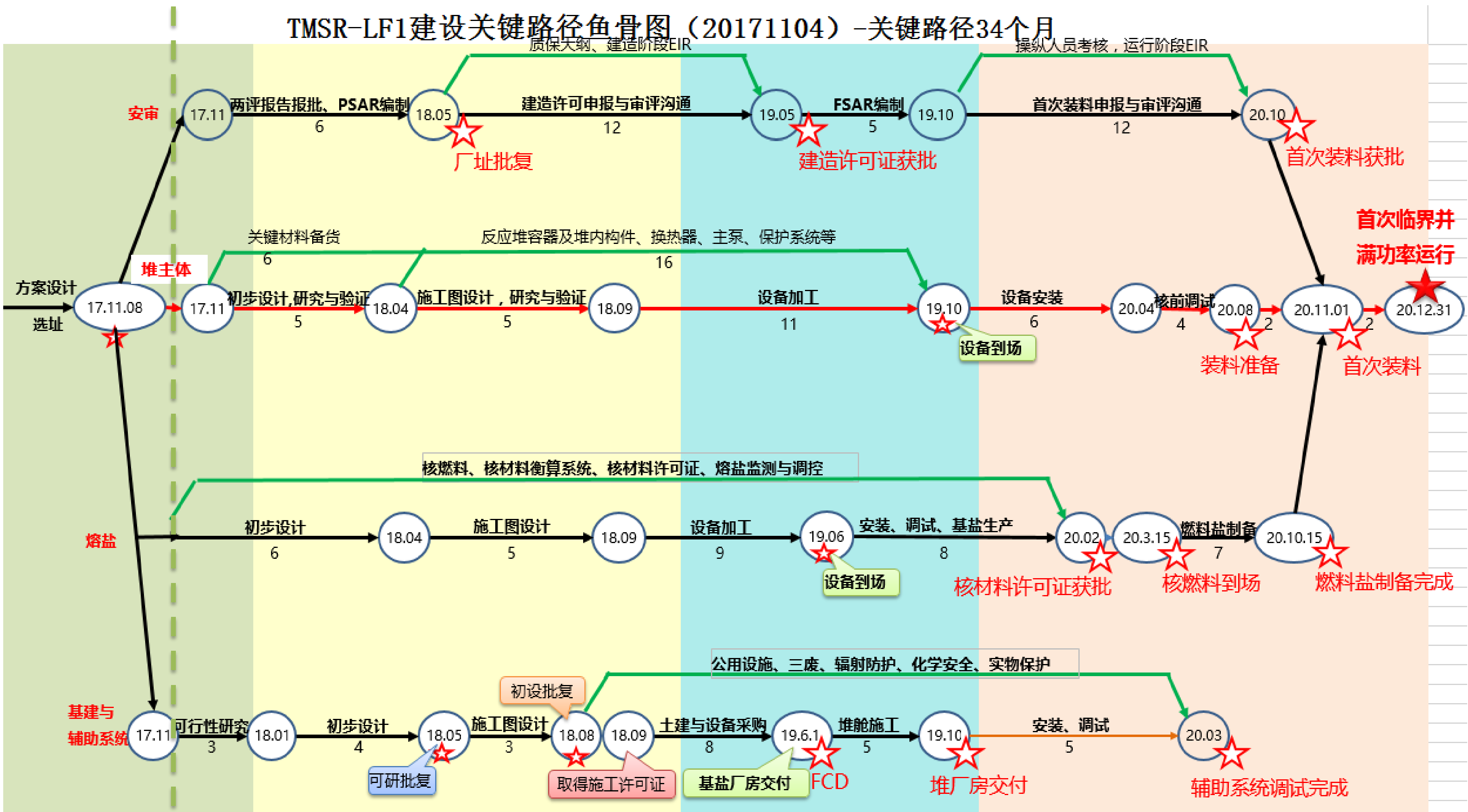
TMSR-LF1 Design

Fuel Loading / discharging	Ar gas + capsule
Reactivity Control	Control rods
Mass flow rate (fuel salt)	~50 kg/s
Mass flow rate (coolant salt)	~42 kg/s
Residual heat removal	1. Loop 2. Air natural circulation Passive residual heat removal system
Alloy	UNS N1003
Graphite	Superfine particle graphite
Cover gas	Argon, 0.05 MPa

千里之行

始于足下！

A thousand journey is started by taking the first step.


TMSR-LF1建设关键路径鱼骨图（20171104）-关键路径34个月
质保大纲、建造阶段EIR
操纵人员考核，运行阶段EIR
安审
17.11
两评报告报批、PSAR编制
6
18.05
建造许可申报与审评沟通
12
19.05
FSAR编制
5
19.10
首次装料申报与审评沟通
12
20.10
厂址批复
建造许可证获批
首次装料获批
首次临界并
满功率运行
关键材料备货
6
反应堆容器及堆内构件、换热器、主泵、保护系统等
16
方案设计
选址
17.11.08
堆主体
17.11
初步设计,研究与验证
5
18.04
施工图设计，研究与验证
5
18.09
设备加工
11
19.10
设备安装
6
20.04
核前调试
4
20.08
2
20.11.01
2
20.12.31
设备到场
装料准备
首次装料
核燃料、核材料衡算系统、核材料许可证、熔盐监测与调控
熔盐
初步设计
6
18.04
施工图设计
5
18.09
设备加工
9
19.06
安装、调试、基盐生产
8
20.02
20.3.15
燃料盐制备
7
20.10.15
设备到场
核材料许可证获批
核燃料到场
燃料盐制备完成
公用设施、三废、辐射防护、化学安全、实物保护
初设批复
基建与
辅助系统
17.11
可行性研究
3
18.01
初步设计
4
18.05
施工图设计
3
18.08
18.09
土建与设备采购
8
19.6.1
堆舱施工
5
19.10
安装、调试
5
20.03
可研批复
取得施工许可证
基盐厂房交付
FCD
堆厂房交付
辅助系统调试完成

Thanks for your attention!