The Technology Development of TMSR and Its Applications

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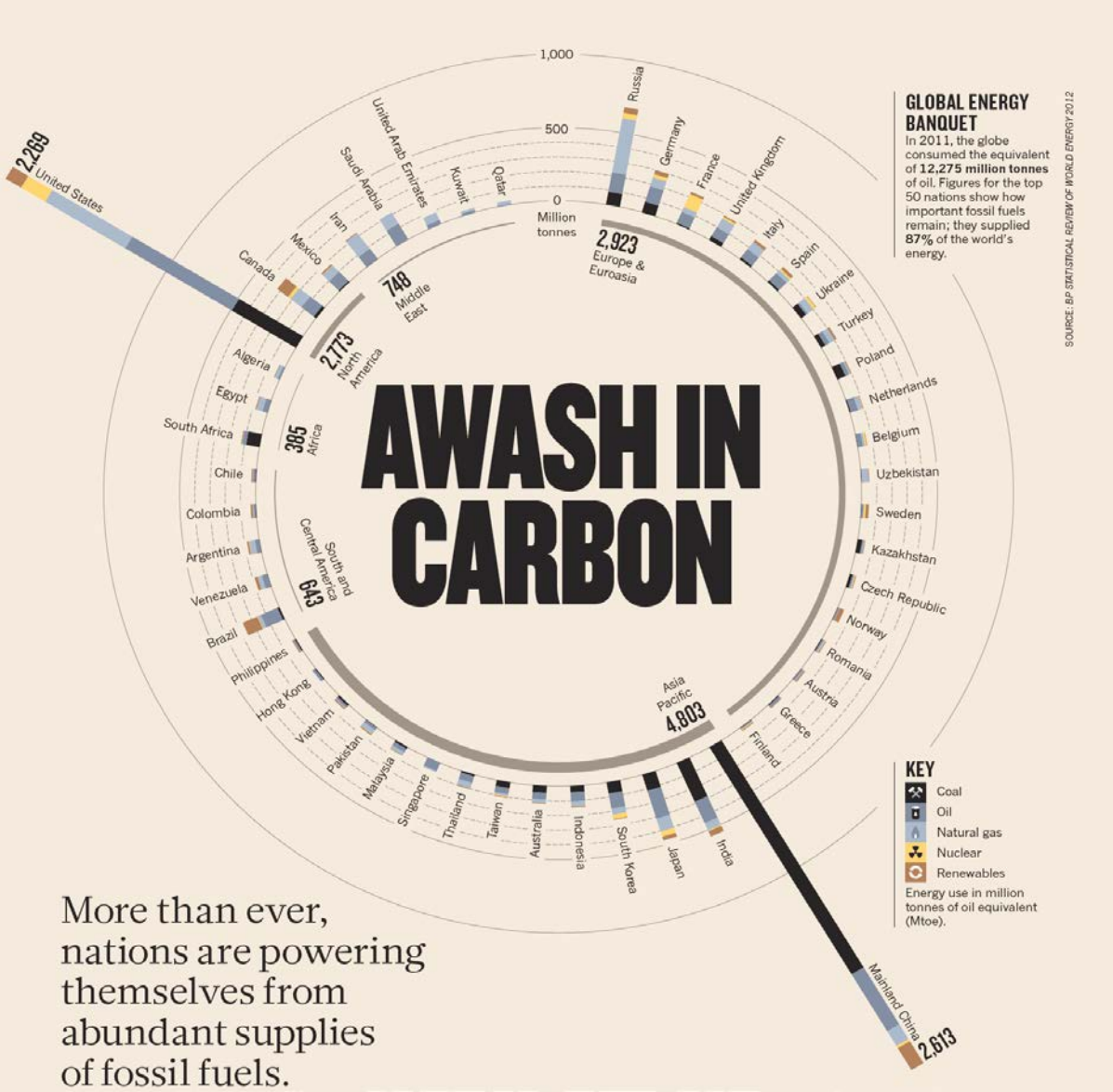
The Structure of the Global Energy Consumption



- The fossil energy accounted for 87% of global energy consumption.
- As the two largest energy consumers in the world, China's energy supply is dominated by coal , mainly oil and nature gas in US.

Ref: Nature 491, 29 Nov. 2012 p654

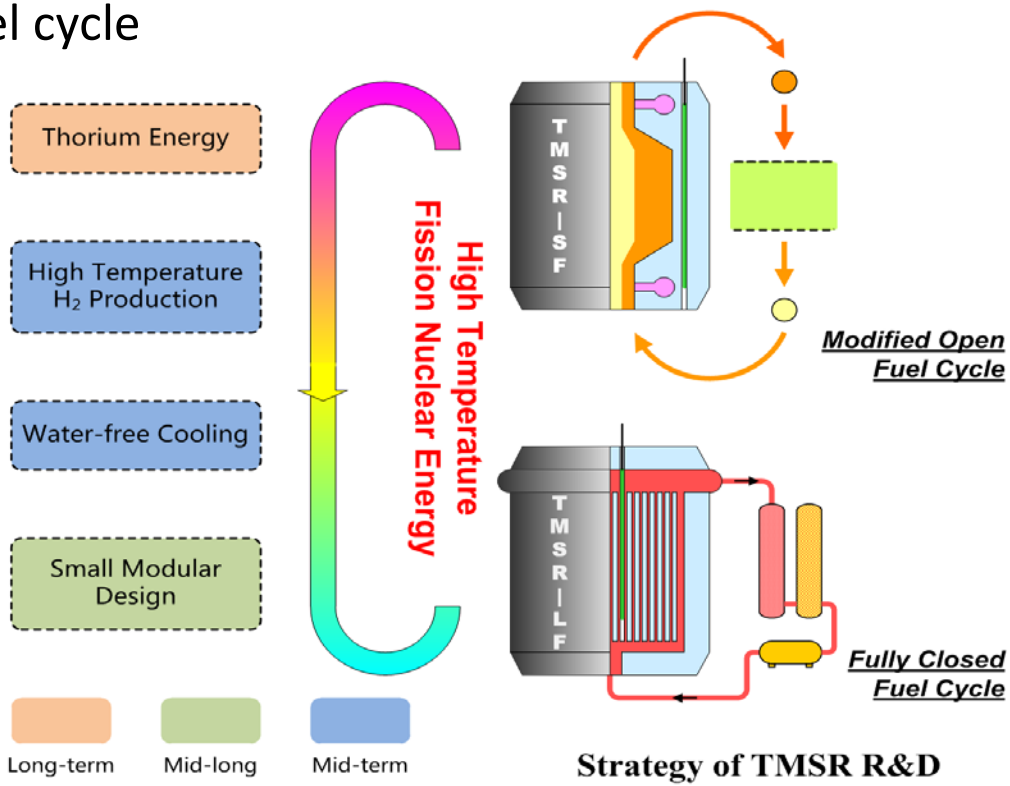
Challenge of Global Climate Change

- Facing with the challenge of global climate change, China will implement a series of policies and measures to develop clean energy, optimizing industrial structure, to build a low-carbon energy system, to develop green buildings and low carbon transportation, to establish national carbon emissions trading market, and constantly to promote the green low-carbon development and harmony between man and nature.

- China pledges to peak CO2 emissions by around 2030 and strive to achieve it as soon as possible, and by 2030, reduce CO2 per unit of GDP by 60-65% over the 2005 level, raise the share of non-fossil fuels in primary energy consumption to about 20% and increase forest stock by around 4.5 billion cubic meters over 2005. （The Paris Climate Accord）

Nuclear Energy Initiative: TMSRs

- **Thorium Molten Salt Reactor Energy System (TMSRs) is an Energy Initiative of Chinese Academy of Sciences, which started in 2011.**
- The mission of TMSRs is to research and develop TMSR-SF and TMSR-LF in the next 20 to 30 years
  - Use thorium fuel and close fuel cycle
  - Nuclear heat application



TMSR-SF, a solid fuel molten salt reactor or FHR

TMSR-LF, a liquid fuel molten salt reactor or MSR

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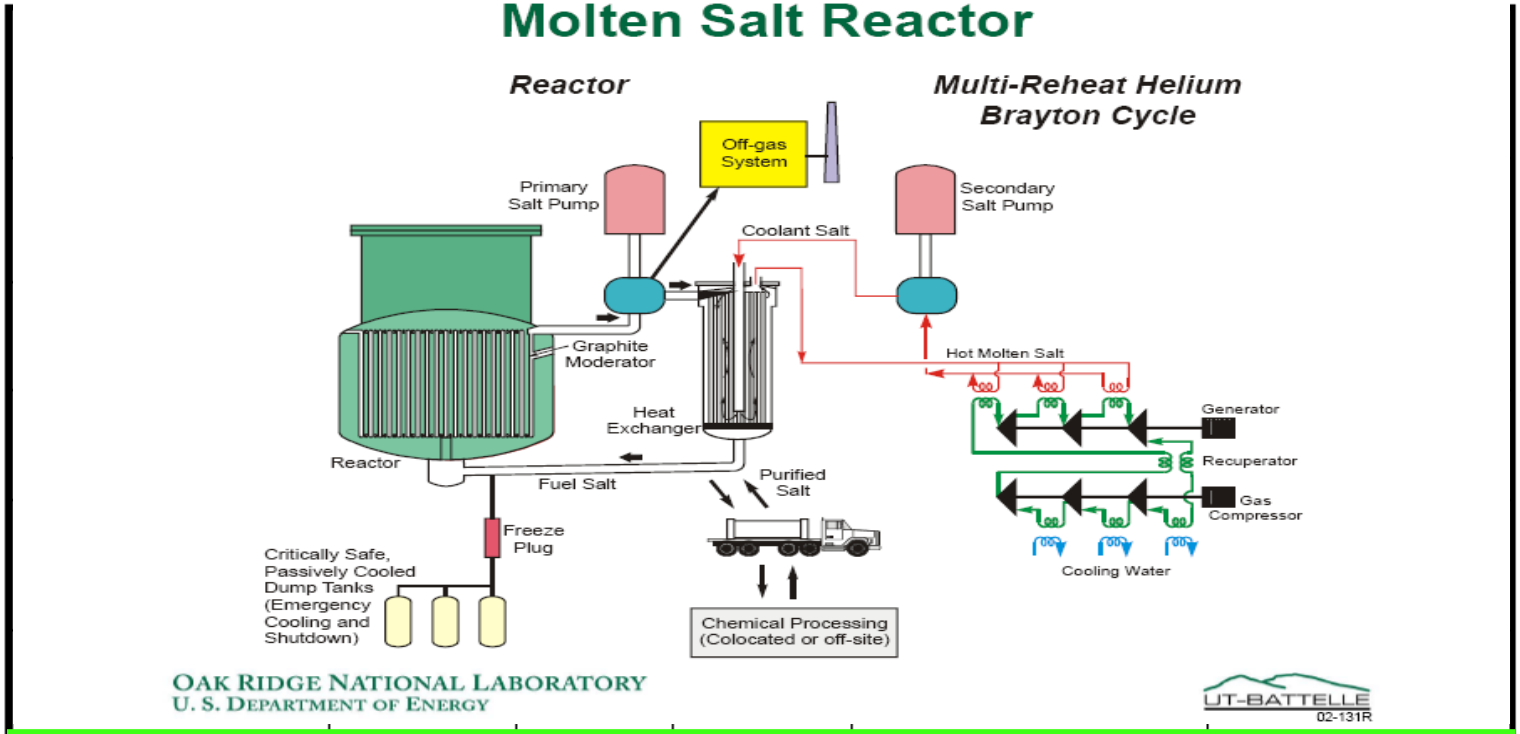
Why MSR: One of The Six Generation IV Systems



Molten Salt Reactor (MSR)	Epithermal	Closed	1000	Electricity, Hydrogen Production, Actinide Management	Fuel treatment, Materials, Reliability

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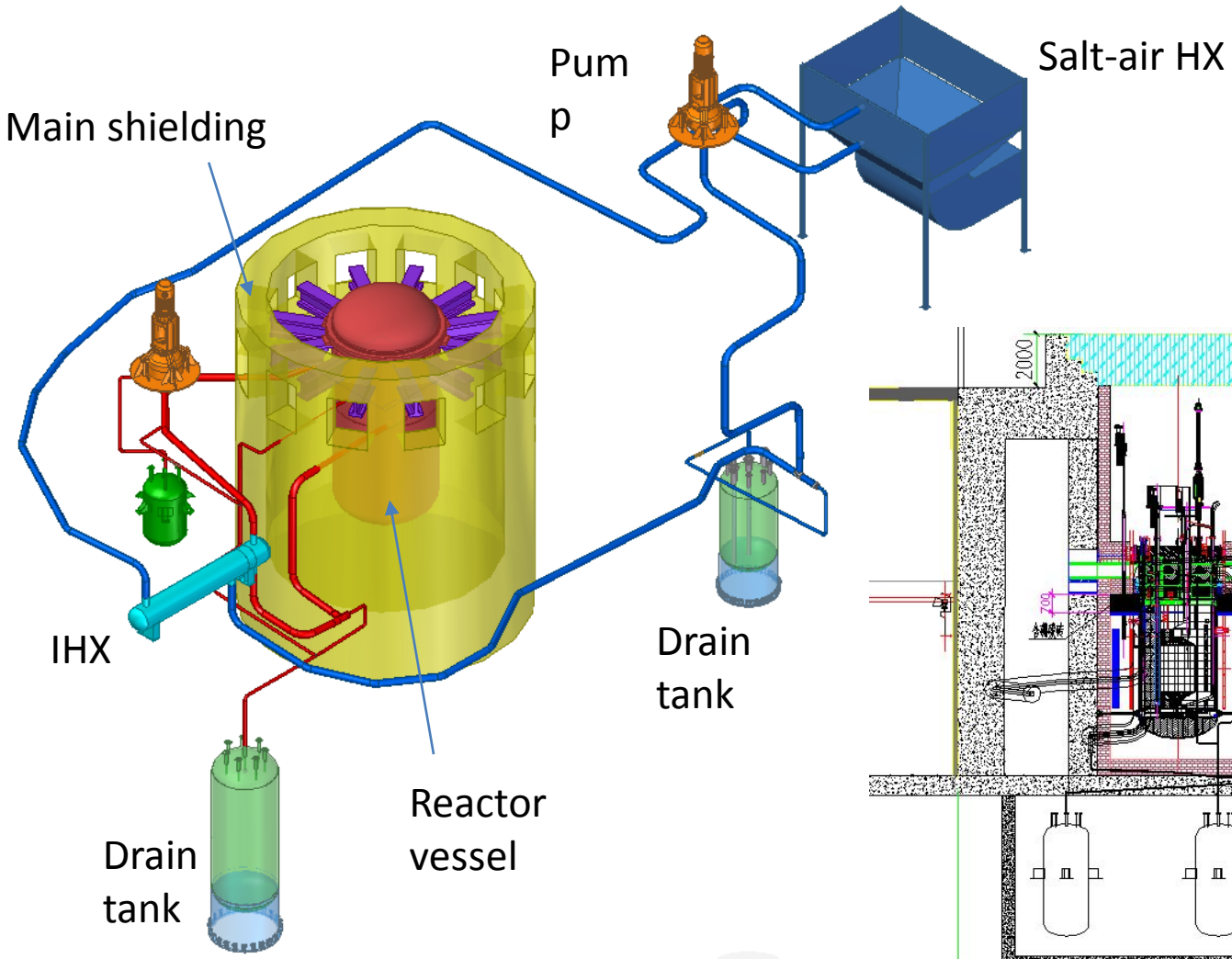
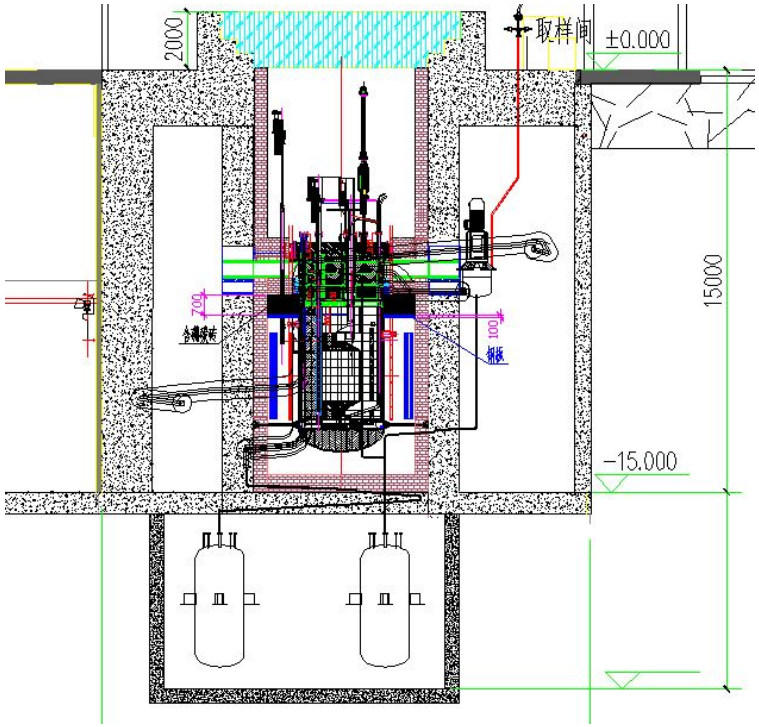
R&D for Thorium Molten Salt Reactor Energy System in China

The Main Tasks

- **Production and Purification of Molten Salt, Molten Salt Test Loops, Separation of ^{7}Li**
- **Research of Thermal Hydraulics, Materials** (Hastalloy-N, Graphite, Carbon-based structure materials)**, Radiation-Chemistry, Th/U Fuel Technology, and Safety Technology.**
- **Development of Pump and Heat Exchanger, Power Conversion Unit, Nuclear Hydrogen Production.**
- **Build of a 10 MW Solid-Fuel (TMSR-SF) and a 2MW Liquid-Fuel (TMSR-LF) experimental reactors + demo. of Th-U Cycle around the year 2020.**
- **Set up the non-electric application experimental facilities.**

TMSR-SF System Layout





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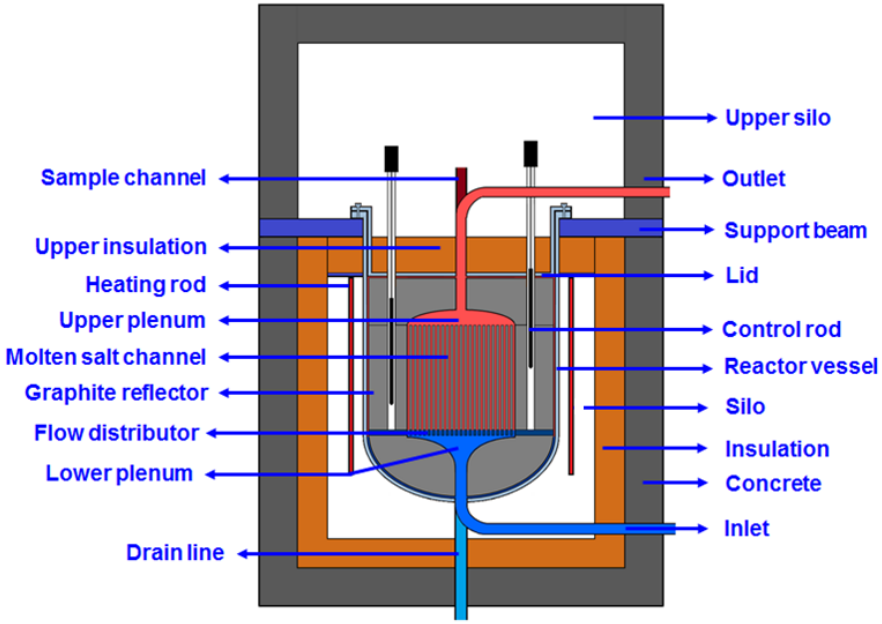
TMSR-LF Reactor Design

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

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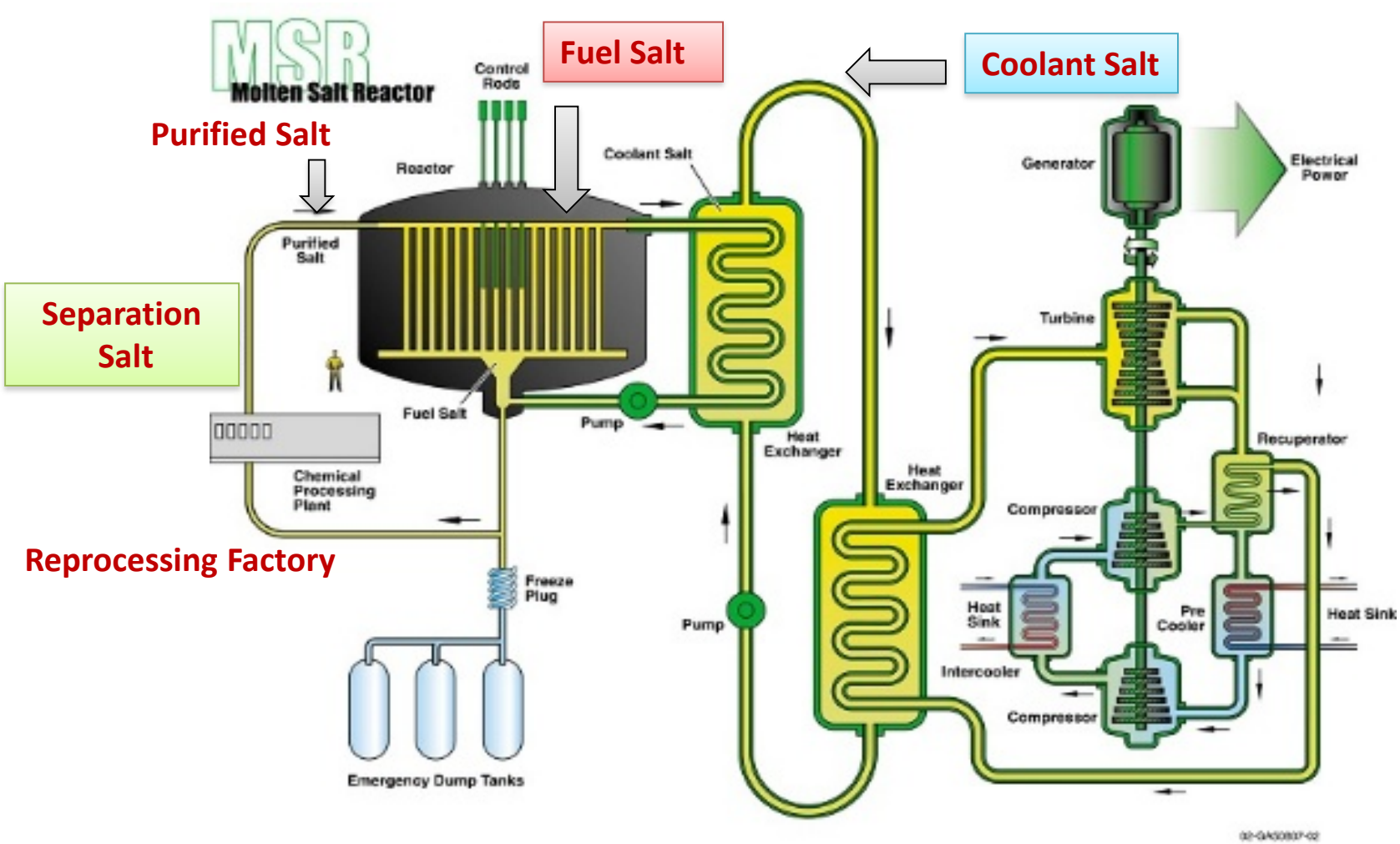
The Role of Molten Salt in TMSRs



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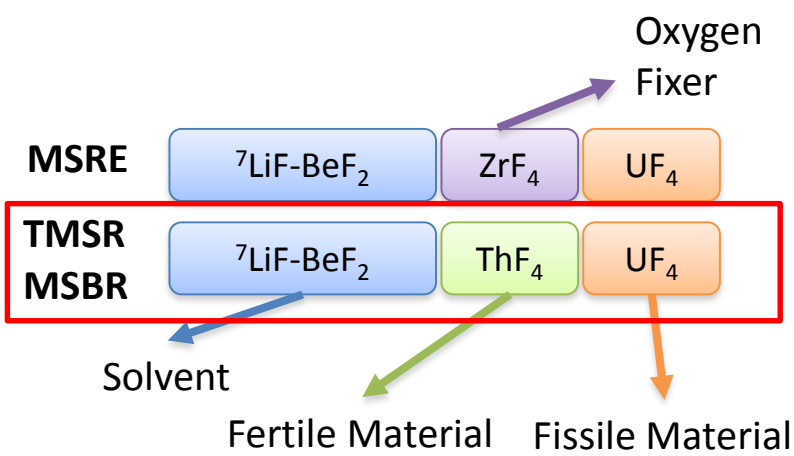
The R&D of Molten Salt in TMSRs

Requirements of Molten Salt for TMSRs

- Thermodynamically stable up to high temperatures;
- Stable to radiation (no radiolytic decomposition);
- Low vapor pressure at the operating temperature of the reactor;
- Compatible with nickel-based structural materials;
- Wide range of solubility for fuel and fission products;
- Compatible with the clean-up technology;

Research of Fuel Salt Chemistry in TMSRs



- ✧ Optimize composition to safety margins and properties;
- ✧ Oxygen measurement and control;
- ✧ Redox measurement and control
- ✧ Fuel fabrication & purification
- ✧ Understanding of the fission product chemistry and in particular
- ✧ Behavior of Cs, I and Te
- ✧ Optimize and demonstrate the clean-up technology
- ✧ Fission product removal techniques
- ✧ Salts recovery techniques

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The R&D of Molten Salt in TMSRs

Fuel and its Separation

- Fuel is prepared by dissolving ThF_4 and UF_4 in ^7LiF-BeF_2;
- Molten salt is resistant to strong radiation, reusable and making short cooling period spent fuel process;
- Fuel and fission product can be separated by choosing suitable system based on solubility.

Easy dissolution of High-Z fuel in carrier salt

Easy separation of Fuel and FP

Carrier salt

^7LiF-BeF_2

Fuel salt

^7LiF-BeF_2-ThF_4-UF_4

(71.6–16–12–0.4 mol%)

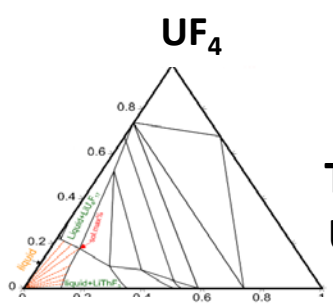
ThF_4
UF_4

TMSR

- Separate U — Fluoride volatility method
- Separate FLiBe — Vacuum distillation
- Separate Th and FP — Molten salt electrochemistry

Dry reprocessing

Quaternary phase diagram



$(LiF)_{0.28}(BeF_2)_{0.68}$ ThF_4

Solubility:

ThF_4 = 10.16%

UF_4 = 17.91%

Applications：

fuel preparation and spent fuel reprocessing

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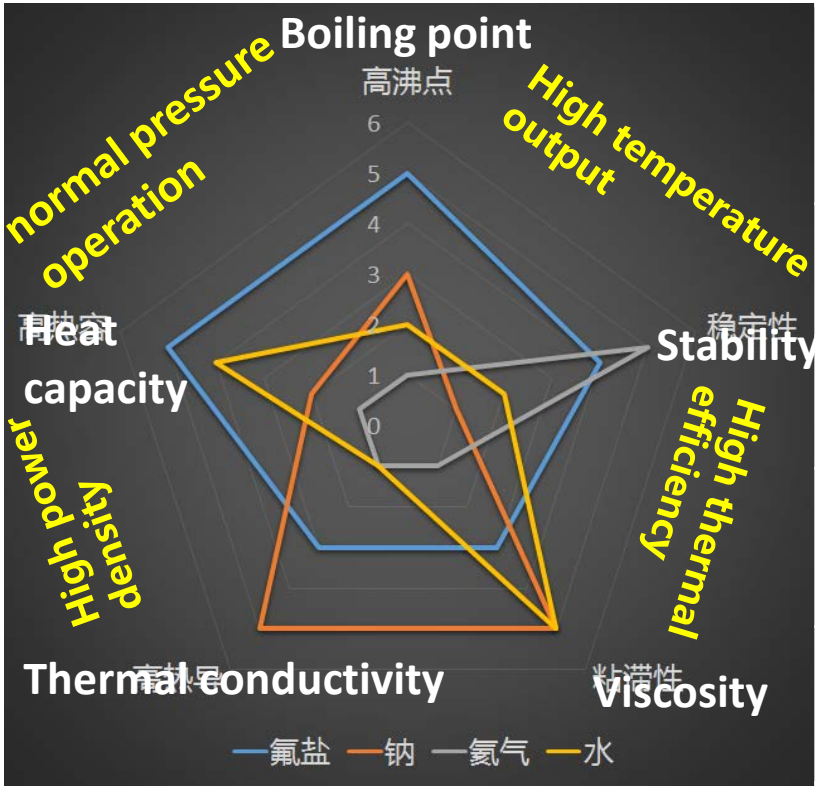
The R&D of Molten Salt in TMSRs

Coolant

Advantages of Using Molten Salt as Coolant



Coolant (Reactor)	Physical properties				
	T_m (°C)	T_b (°C)	Cv (KJ/m³°C)	λ (W/m°C)	v (10^6 m²/s)
FLiBe（MSR）	459	1430	4670	1	2.9
Sodium（SFR）	97.8	883	1040	62	0.1
Helium /75atm（GFR）	—	—	20	0.29	11
Water /150atm（PWR）	0	320	4040	0.56	0.1

Fluoride salt & Sodium & Helium & H_2O

Water-free cooling; High temperature output; Normal pressure operation; High power density; High thermal stability

Note：Measurement conditions : Li_2BeF_4@700°C，Na@550°C, He@750°C，H_2O@300°C

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The R&D of Molten Salt in TMSRs

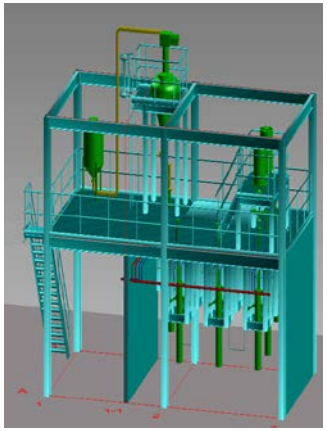
Preparation of Fluoride Salt

Laboratory research

(500g/batch)

Bench scale production

(5Kg/batch)



Pilot scale production

(10t/year)

★

Demo scale production (100t/year)

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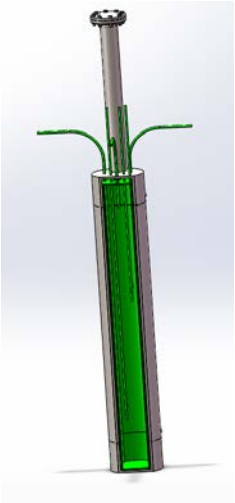
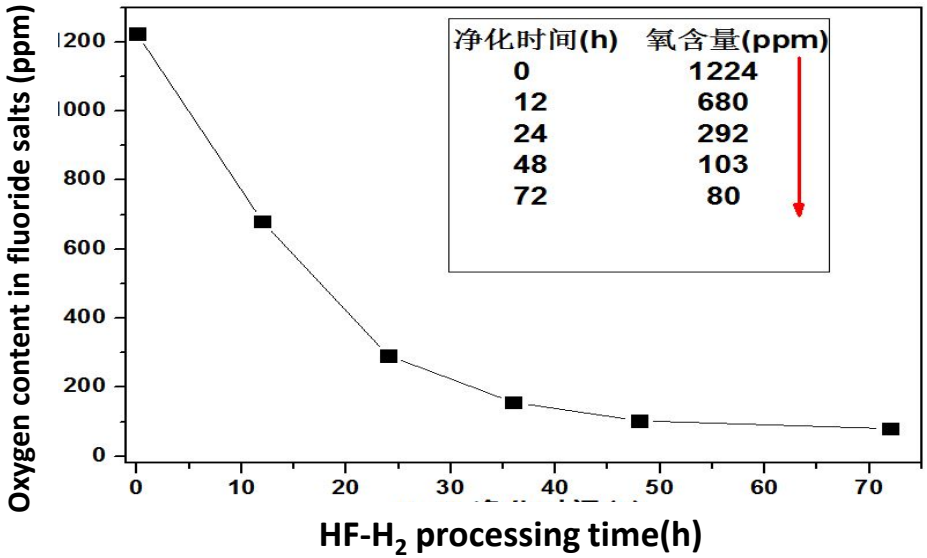
The R&D of Molten Salt in TMSRs

Preparation of Fluoride Salt

HF-H_2 process was employed as the purified method for production of fluoride salt

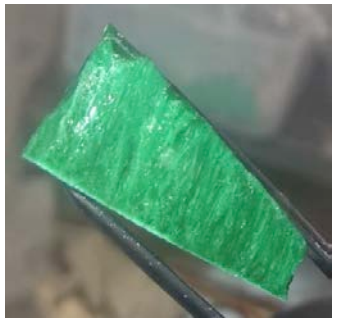


Bubble tower for HF-H_2 process



FLiNaK

FLiBe



FLiBe-ThU

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Material Corrosion and Control

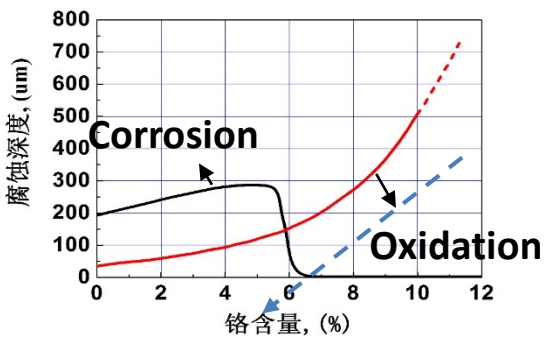
- Control the structural material corrosion by alloy composition optimization, salt purification and surface treatment

Investigating Corrosion Mechanism

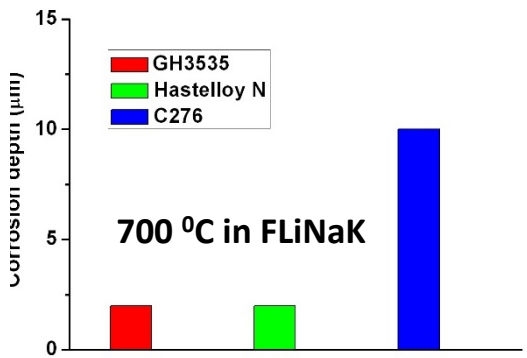
- Salt impurities
- Elements diffusion
- Mass transfer

Developing Corrosion Control Technologies

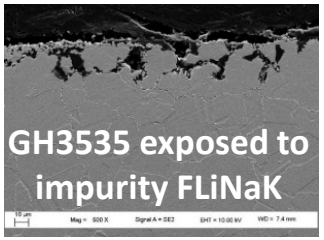
- Optimize the composition of alloy, diffusion of Cr
- Improve purification technology, minimize impurities
- Fluoride salt thermal diffusion coating

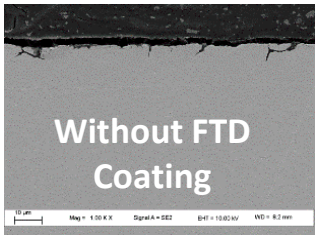


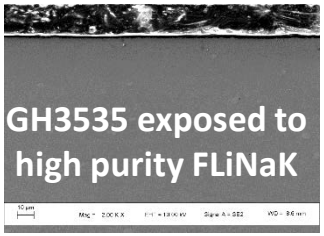
Composition Optimization (Cr)

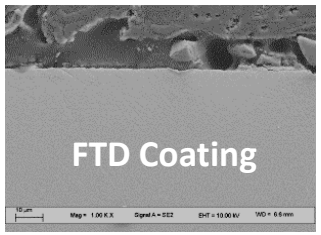


Corrosion Depth (μm/y)









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Development of Molten Salt Equipment

Molten Salt Pump

Chemical pump

Engineering pre-prototype

Parameters

Temperature：550~700℃

Flow rate：300m^3/h

Lift：～20m

Rotary speed：1480r/min

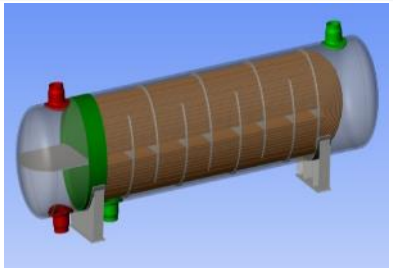
Valve

Principle prototype

Engineering pre-prototype

Heat Exchanger

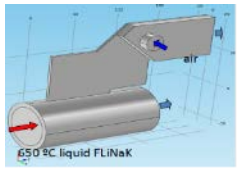
Salt – Air exchanger



Salt- salt exchanger

Meter

NaK Pressure meter

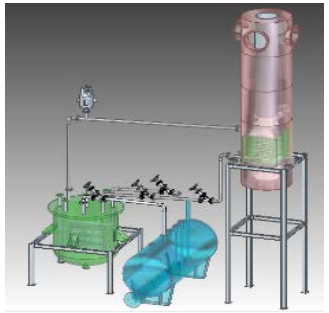


High T ultrasonic flow meter

Molten Salt Loops

HTS loop

High-temperature FLiNaK loop



Natural circulation loop

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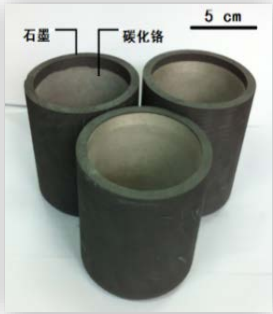
Nuclear Safety

- 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

Other Application of Molten Salt

Demo for salt utilization in heat treatment of steel wire.



High purity graphite for long life use with oxidation resistance layer

Tower CSP

Wind Electricity

Electricity Generation

Hydrogen Production

Heating

High temperature molten salt for energy storage system

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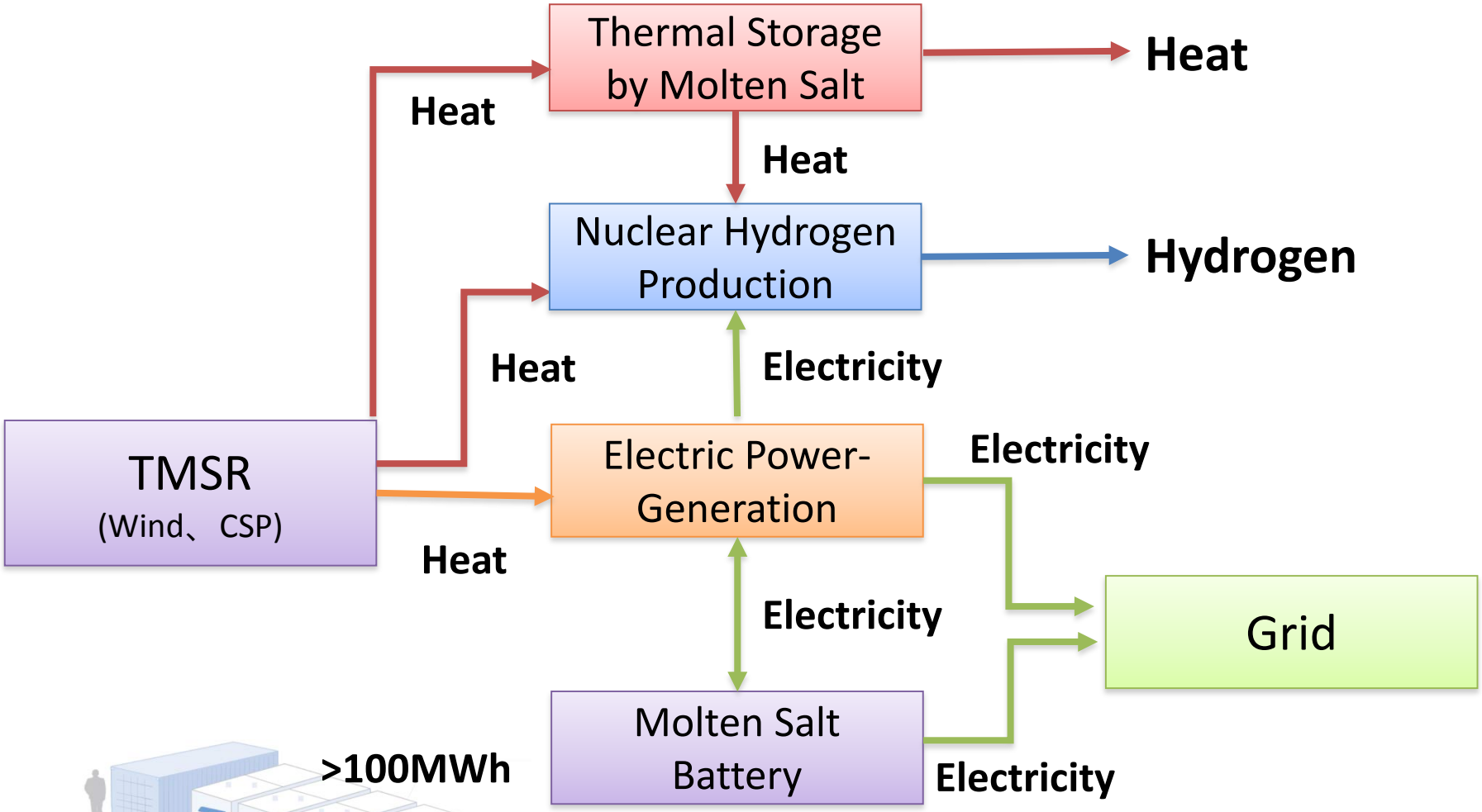
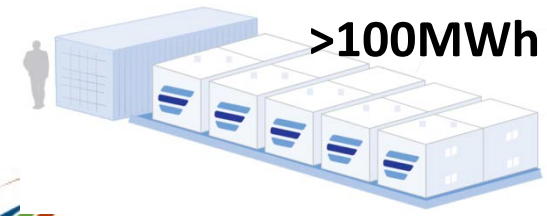
Other Application of Molten Salt

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°C	221	600	1.8	1.58	2850	0.62
Hitec ($NaNO_3$-KNO_3-$NaNO_2$) (7-53-40wt%) @400°C	142	535	1.86	1.61	2900	0.4
$LiNO_3$-$NaNO_3$-KNO_3 (29.56-17.73-52.72wt%) @400°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°C	397	800	2.01	5.5	3237	0.49
KCl-$MgCl_2$ (66-37mol%) @600°C	426	1450	1.61	0.86	1470	1.1
LiF-NaF-KF (46.5-11.5-42mol%) @600°C	458	1570	2.05	2.32	3745	0.71
ZrF_4-KF (42-58mol%) @600°C	420	1400	2.846	0.21	2988	0.32
LiF-BeF_2 (67-33mol%) @600°C	459	1430	2.16	3.96	5173	1.0

Energy Conversion and Storage System in TMSRs





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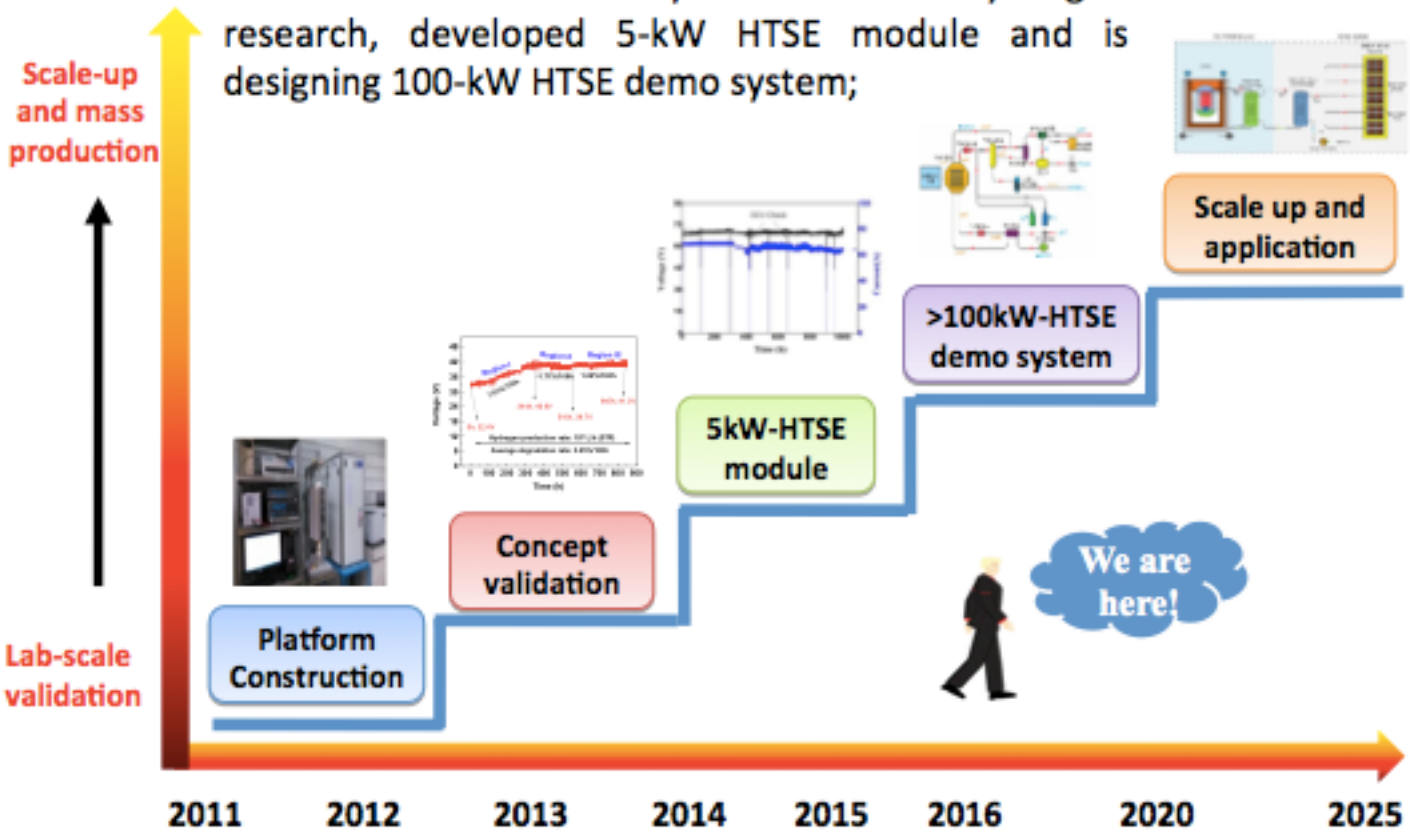
Research of Nuclear Hydrogen

Blueprint of Nuclear Hydrogen in SINAP

- SINAP built laboratory for nuclear hydrogen research, developed 5-kW HTSE module and is designing 100-kW HTSE demo system;



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Research of Nuclear Hydrogen

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

Recent Progress of TMSR Test Reactors

- 10 MW solid fuel molten salt test reactor (TMSR-SF)
  - 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-LF)
  - Conceptual design modified to better match the requirements of thorium fuel cycle research and MSR online pyro processing scheme verification.

Summary

- Energy Initiative of Chinese Academy of Sciences，Thorium Molten Salt Reactor Energy System (TMSRs)

- Progress of R&D for Production of Molten Salt, Molten Salt Test Loops and Pump and Heat Exchanger

- Nuclear Hydrogen Production and Energy Conversion and Storage System in TMSRs in the future.

Thank you for your attention

vapor pressure measured at 900°C；others measured at 700°C； Neutron capture relative to graphite