International Workshop on Advances in Design of Generation-IV Small and Medium Sized of Modular Reactors (SMRs)
Beijing, 3rd ~7th June2024

中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY
中核集团 CNNC

Development of SFR SMR Technology

Yang Yong
CIAE

2024/06/04 Beijing

CONTENTS

01 Main Features of SFR

02 Development of SFR

03 Development of International SFR SMR

04 Development of SFR and SMR In China

05 SMR challenge

01 Main Features of SFR

Main features of SFR

1、Characteristics and advantages of FR

□ Isotopes of natural uranium

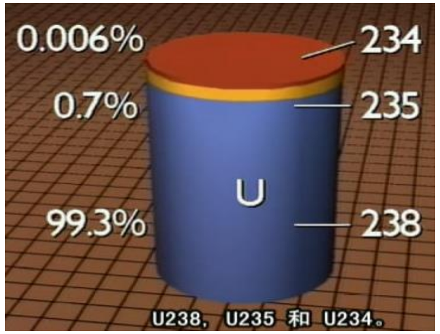
- ^{238}U，99.284%
- ^{235}U，0.711%
- ^{234}U，0.0054%

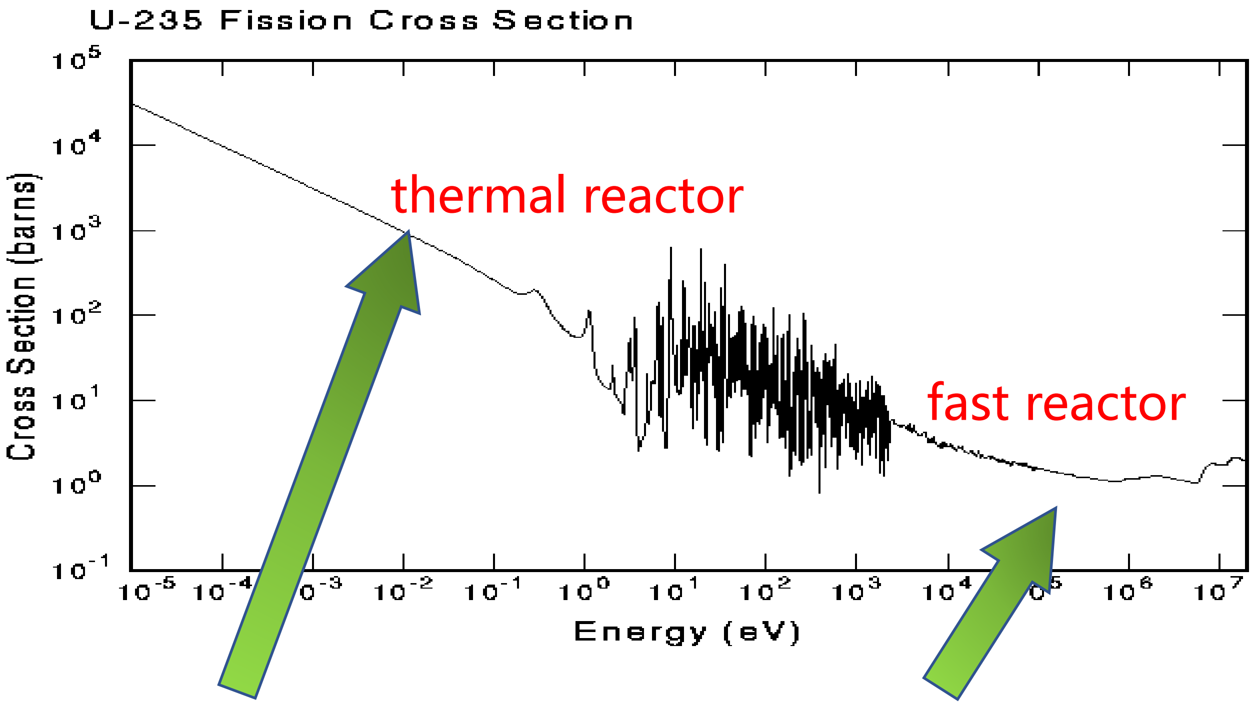
□ fissile nuclide

- ^{235}U，natural
- ^{239}Pu，artificial
- ^{233}U，artificial

□ fertile

- ^{238}U
- ^{232}Th





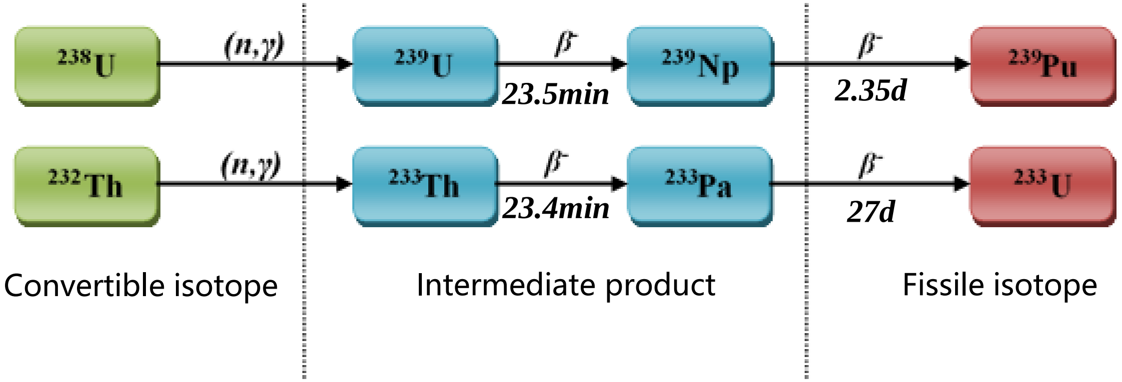
A reactor that chain fission used **thermal neutrons**, such as PWR

A reactor that chain fission used **fast neutrons**

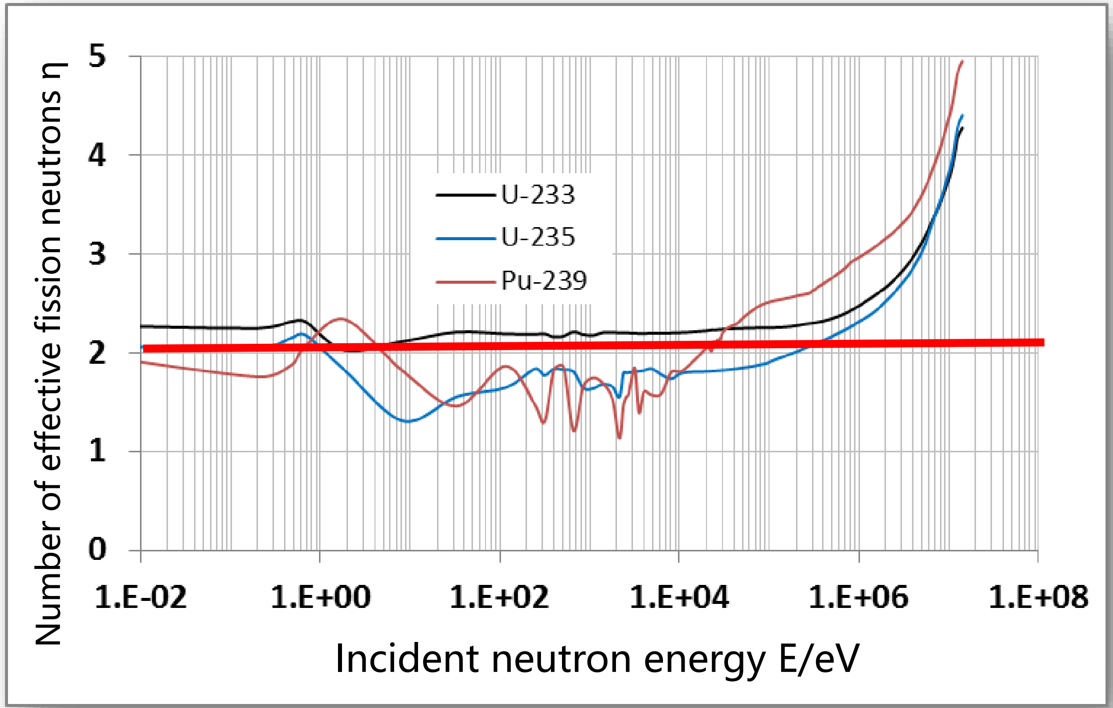
Main features of SFR

中国原子能科学研究院
中核集团 CNNC
CHINA INSTITUTE OF ATOMIC ENERGY

1、Characteristics and advantages of FR



FR can achieve breeding (Fast Breeder Reactor)



"The country which first develops a breeder reactor will have a great competitive advantage in atomic energy."

"Countries that master fast reactor technology may forever solve energy problems."

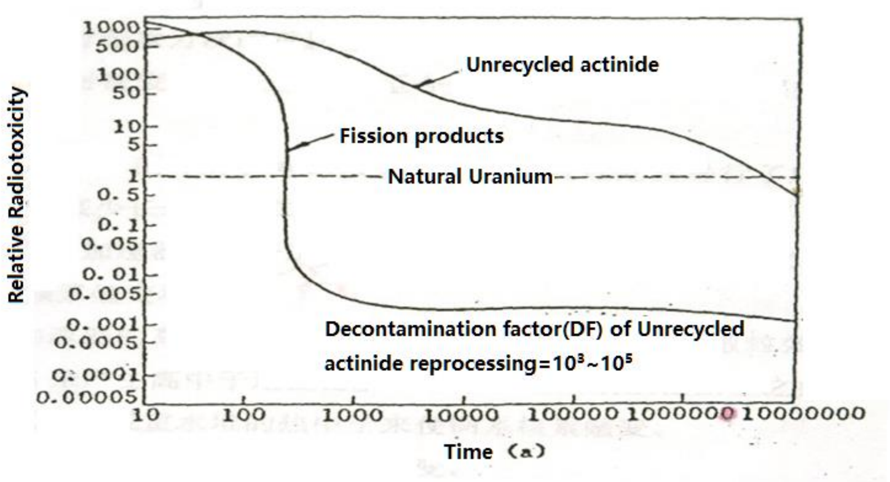
—— Enrico Fermi

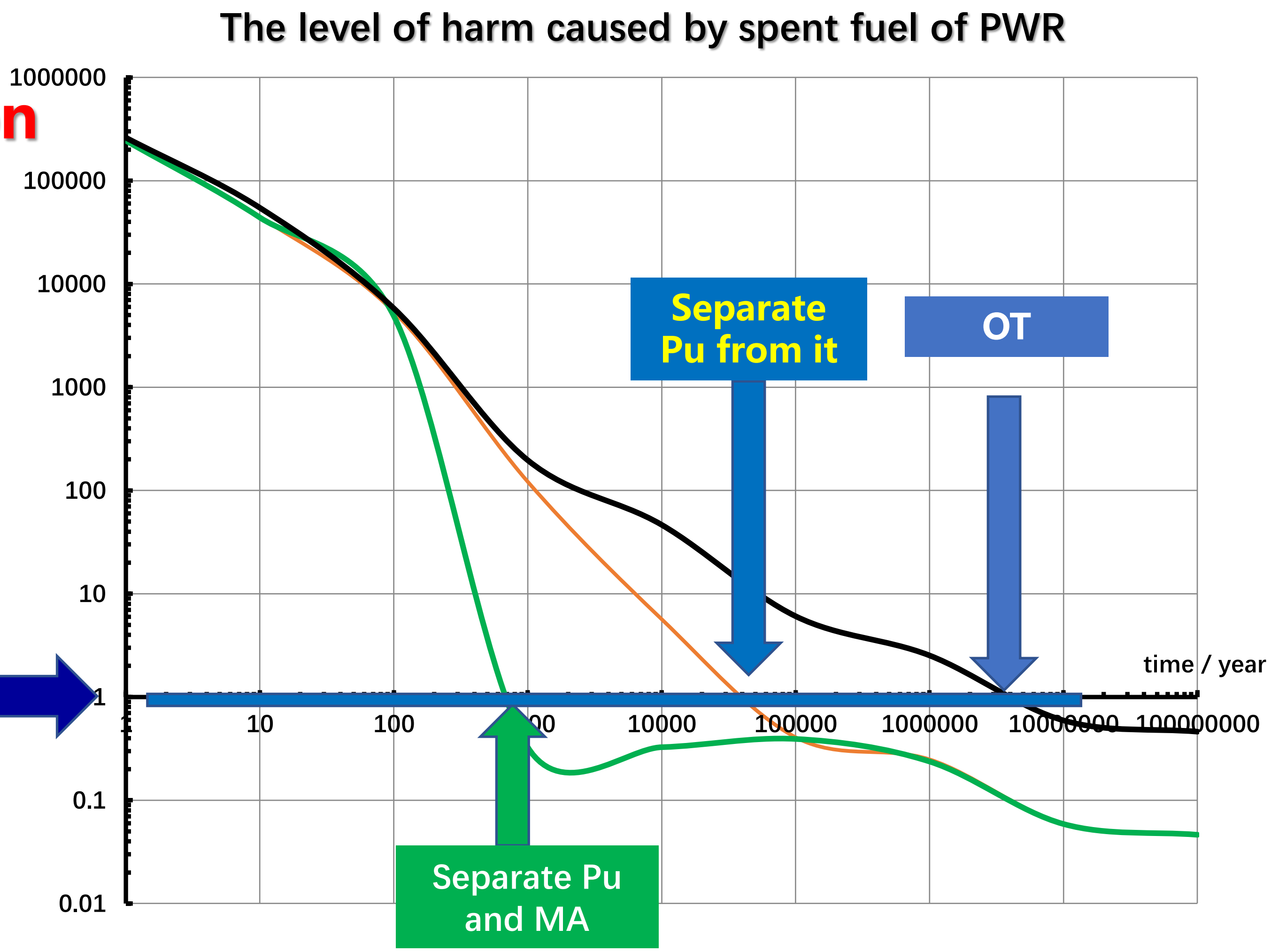
Main features of SFR

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY

1、Characteristics and advantages of FR

FR can achieve transmutation



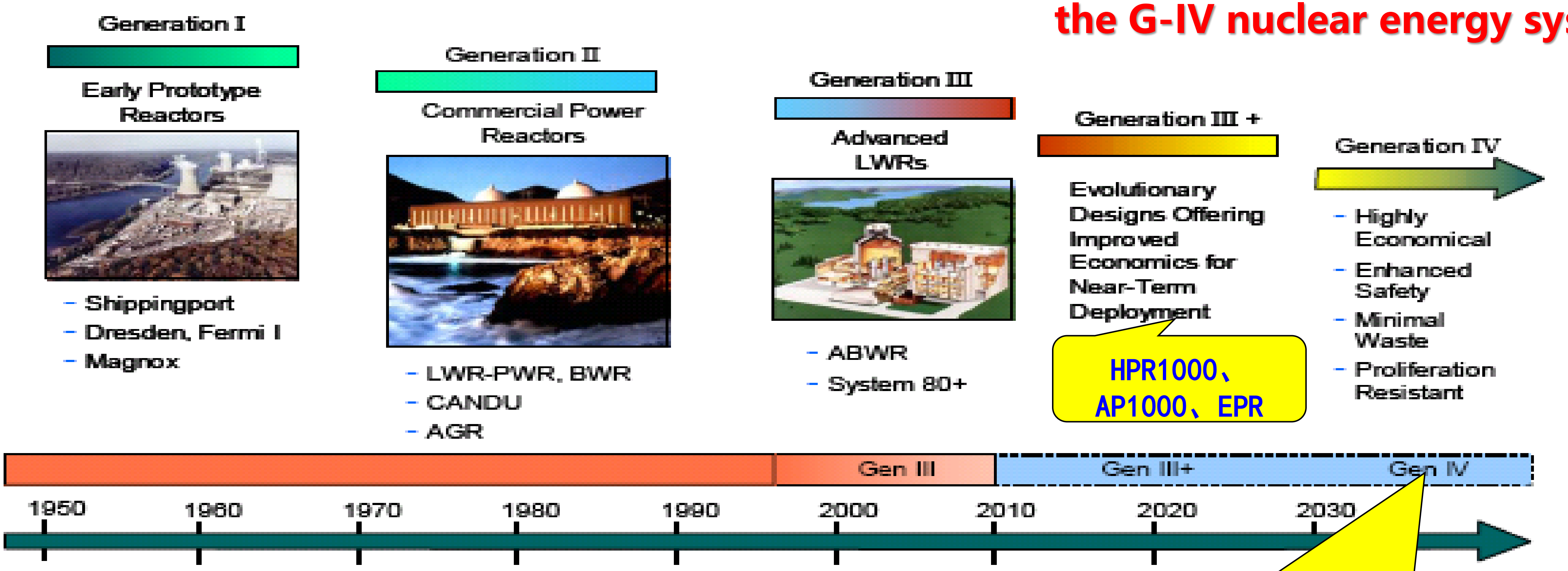


a 1 GWe fast reactor can burn down at least 5 equivalent power pressurized water reactors to produce minor actinide .

Main features of SFR

1、Characteristics and advantages of FR

Fast Reactor—The main type of the G-IV nuclear energy system



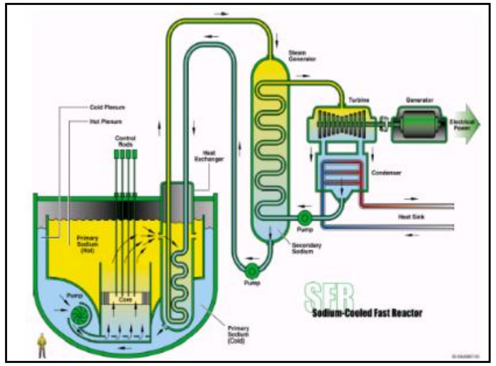
Fast reactor is a key type of G-IV nuclear energy systems

Main features of SFR

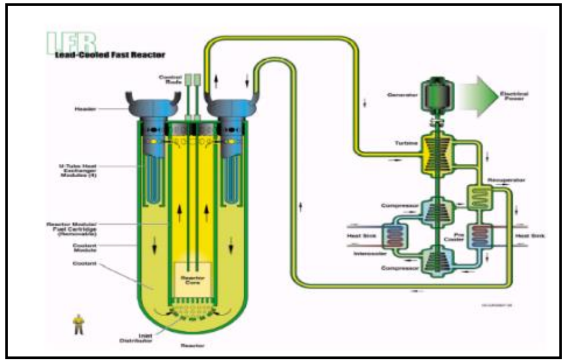
中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY

1、Characteristics and advantages of FR

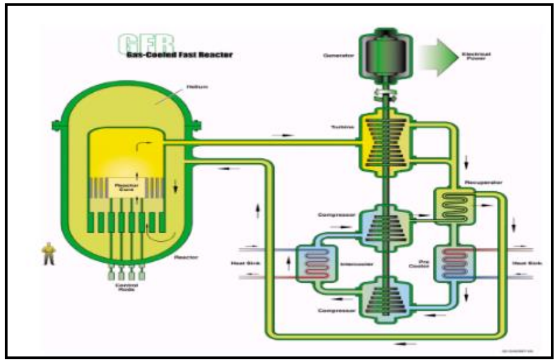
Six types of reactors for G-IV nuclear systems



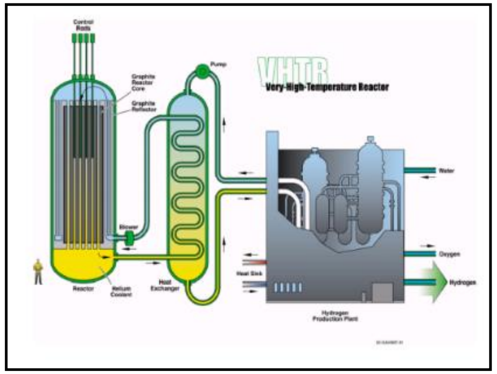
Sodium Fast reactor



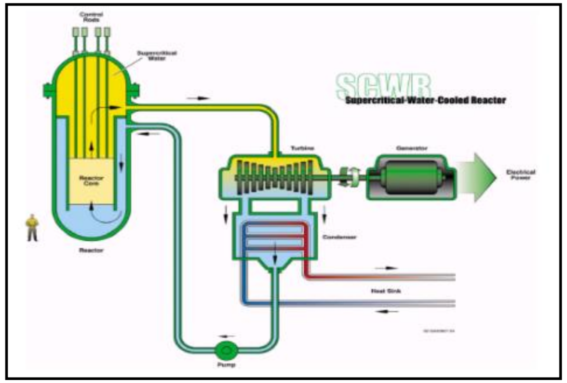
Lead Fast Reactor



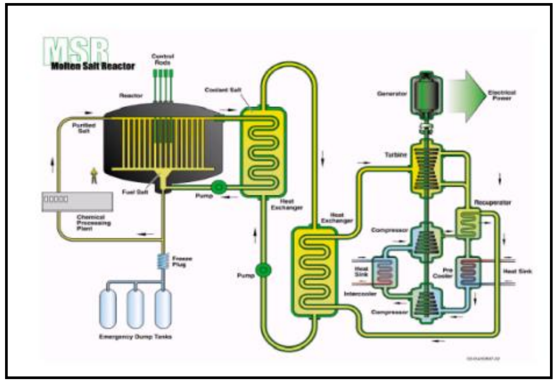
Gas Fast Reactor



Very High Temperature Reactor



Supercritical Water Reactor



Molten Salt Reactor

Main features of SFR

2、Design characteristics of SFR

Liquid sodium is a coolant that is very suitable for FR

- High heat carrying capacity, suitable for high power density FR cores
- Perfect compatibility with stainless steel
- Low ability to absorb and slow down neutrons
- Although it can be activated, the half-life is short
- A very wide temperatures range of liquid, and high boiling points, which can be designed as high-temperature reactors to achieve high thermal electric conversion efficiency

Main features of SFR

2、Design characteristics of SFR

Thermophysical properties	Na	NaK (K:77.8%)	Pb	PbBi (Pb:44.5%)	Li	Hg	He (atmospheric pressure)
Melting point (atmospheric pressure)/℃	97.83	-12.6	327.5	~125	180.2	-38.87	
Boiling point (atmospheric pressure)/ ℃	881.4	~785	1744.8	~1670	1342	356.65	
density（400℃）/ g/cm^3	0.8562	0.7857	10.6	10.24	0.495	13.113(200℃)	0.073×10^{-3}
Specific heat capacity（400℃）/ cal/g·℃	0.3054	0.21	0.035	0.035	1.004	3.28(200℃)	1.243
Thermal conductivity（400℃）/ kcal/m·h℃	62.08	22.53	13.67	10.8	42.07	8.9(200℃)	0.24
Volume thermal expansion coefficient/ l/℃	2.418×10^{-4}	2.77×10^{-4}					

2、Design characteristics of SFR

□ Characteristics of SFR

Characteristic	Relationship with Safety
Low cover gas pressure	The consequences of pressure loss in the primary circuit system are not serious
Sodium has excellent heat transfer performance	Natural convection can remove out decay heat
No chemical reaction occurs between the cladding and coolant	No zirconium water reaction
The coolant temperature in the heat pipe is more than 200 ℃ lower than the boiling point	Excessive undercooling
Sodium halogen reaction	Iodine escaping from damaged fuel is still trapped in the coolant
Sodium air combustion releases energy	There is a possibility of sodium leakage in the coolant system, and sodium fire monitoring and corresponding sodium fire treatment measures must be in place
Sodium water reaction	Steam generator leakage can lead to energy release
The coolant temperature rises above 150 ℃ through the core	High thermal stress at the end of the coolant system
Positive sodium void coefficient (large sodium cooled fast reactor)	After coolant vaporization, a positive sodium void coefficient can cause core overheating
Increased reactivity of fuel compaction	Any accident that causes the fuel center in the core will cause a positive reacitvity

Main features of SFR

2、Design characteristics of SFR

□ Inherent safety of SFR

a) Negative reactivity feedback coefficient can introduce negative reactivity in the event of an accident or core heating, reduce reactor power, and prevent core melting;

b) The sodium loading capacity of the pool design provide a huge initiate thermal capacity during the severe accident;

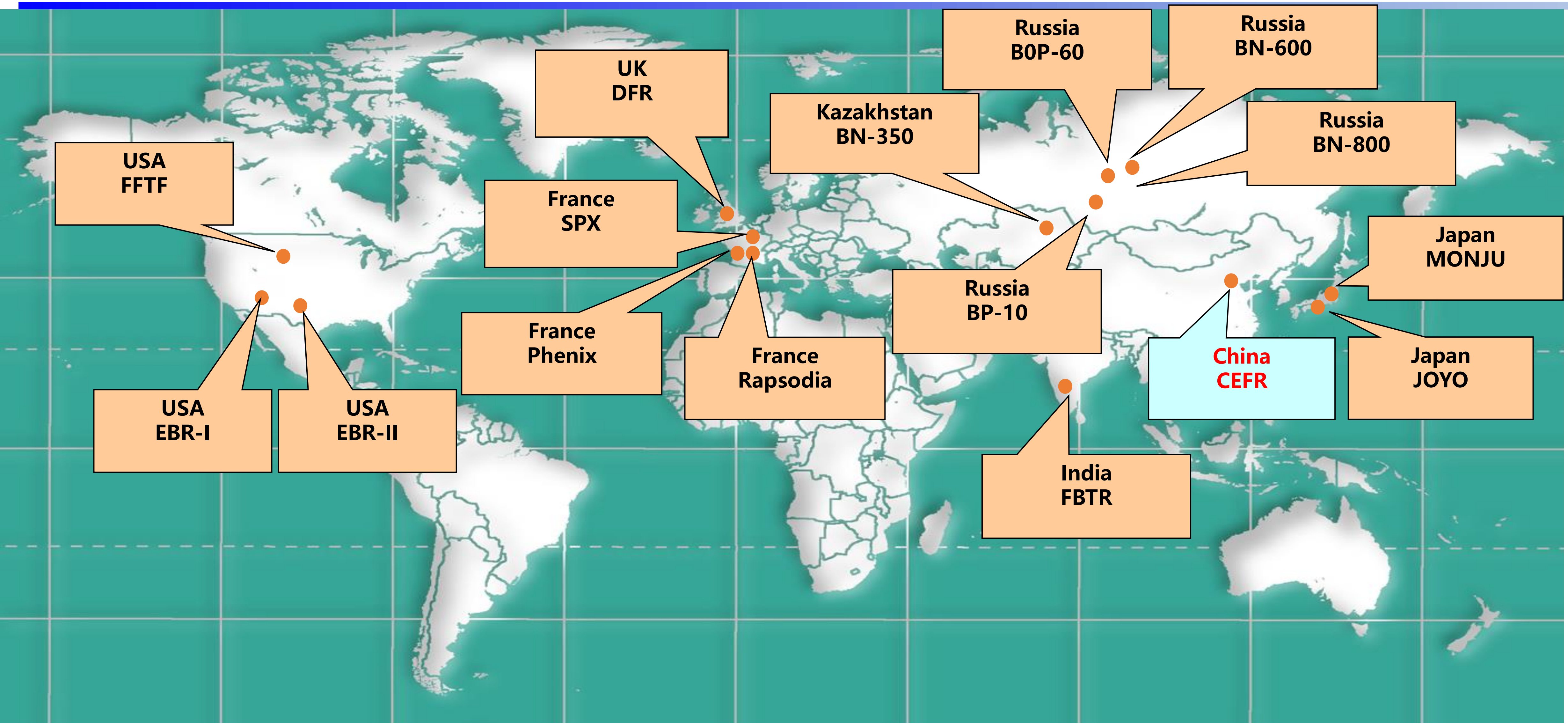
c) Low coolant pressure,;

d) Radioactive containment boundaries, due to the strong chemical activity of sodium, can easily react with fission products such as I-131 and remain in the coolant, thereby reducing the release of radioactivity into the environment;

e) Passive decay heat removal utilizes natural circulation and air convection.

02 Development of SFR

Development of SFR

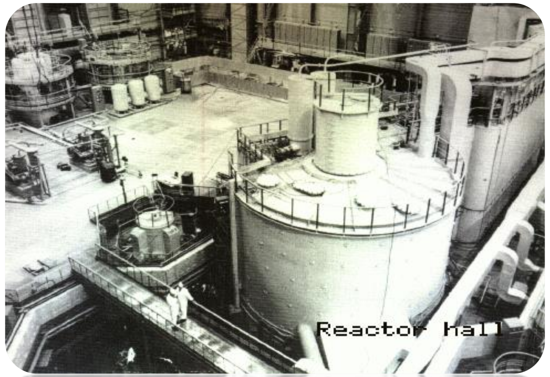


Development of SFR

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY

1、Russia

BR-10 → BOR-60 → BN-350 → BN-600 → BN-800 → BN-1200



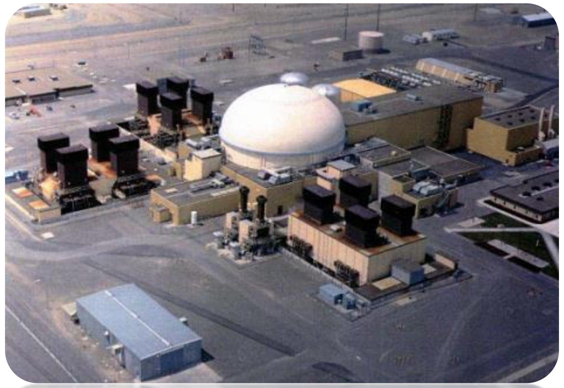
Development of SFR

2、USA

Clementine → EBR-I → LAMPRE → EBR-II → Fermi → SE-FOR → FFTF → CRBRP → IFR (ALMR)

GIF GNEP

ABR



Development of SFR

3、France

Rapsodie → Phenix → Super-Phenix → **ASTRID**

Development of SFR

中国原子能科学研究院
中核集团 CNNC
CHINA INSTITUTE OF ATOMIC ENERGY

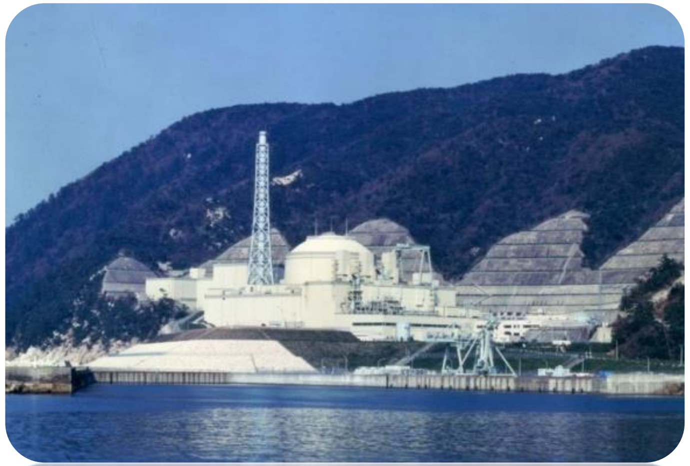
4、Japan

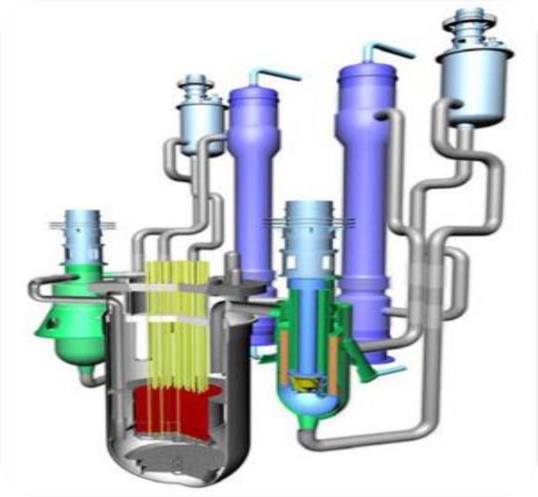
JOYO

MONJU

DFBR
(Canceled)

JSFR

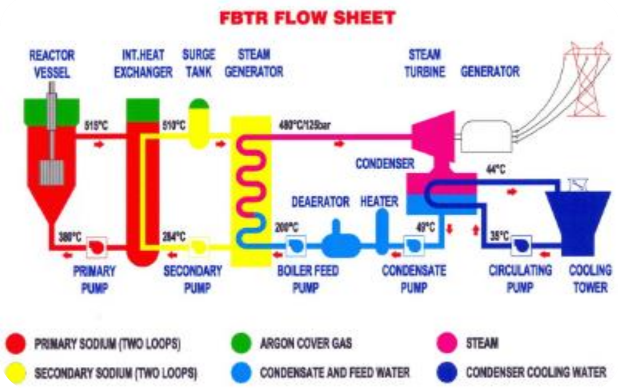




Development of SFR

5、India

FBTR → PFBR → CFBR → Thorium uranium cycle



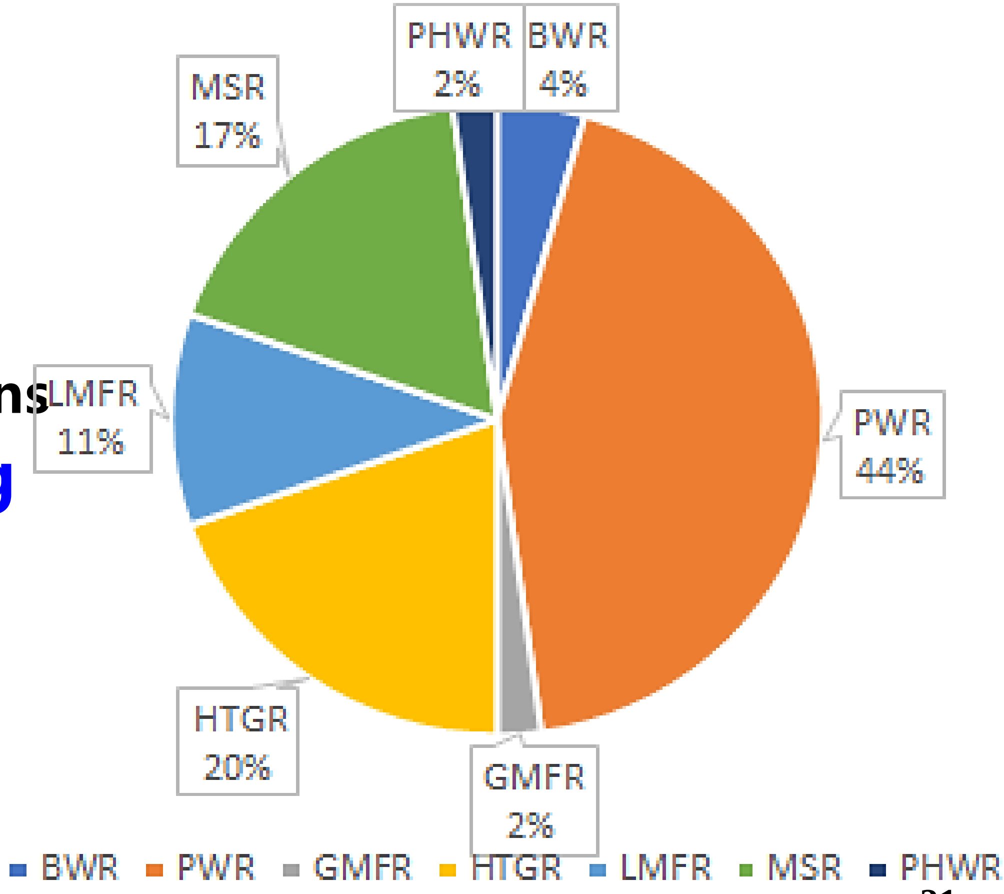
03 Development of International SFR SMR

Development of International SFR SMR

中国原子能科学研究院 中核集团 CNNC CHINA INSTITUTE OF ATOMIC ENERGY

1、Technological advantages for SFR developing into SMR

- Fast reactors are the preferred type of small special reactors
  - Compact reactor core
  - Modular design and construction
  - Simplified design with high safety
  - Long refueling cycle and strong scalability
  - Diverse operating modes and wide applications
- main reactor type still being PWR, taking into account BWR HWR、MSR、HTGR、LMFR、GFR



Development of International SFR SMR

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY 中核集团 CNNC

1、Technological advantages for SFR developing into SMR

G-IV Characteristics

- High thermal inertness
- High Underheating
- Low pressure of the primary circuit
- Passive residual heat removal
- U238 breeding
- Nuclear Waste Transmutation

Advantages and disadvantages of sodium as a coolant

+	−
High coolant temperature allow to use None-water electric generation system	High melting point: 98 ℃
Small size of reactor core	High fuel erichment
Small reactivity lost of burnup	High neutron flux
Easy conduct the decay heat	Long time and high temperature requirement of steel
Perfect compatibility with steel	

With over 400 years of operational experience, SFR is closest to the commercial G-IV nuclear energy system!

Development of International SFR SMR

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY
中核集团 CNNC

2、development of SFR SMR

Small SFR already built in the world

strictly speaking is a experimental reactor

Reactor name	Rapsodie	KNK-II	FBTR	PEC	JOYO	DFR	BOR60	EBR-II	FERMI	BR10	CEFR
Country	France	Germany	India	Italy	Japan	Britain	Russia	USA	USA	Russia	China
First critical	1967	1972	1985	Never	1977	1959	1968	1961	1963	1958	2010
Thermal power /MW	40	58	40	120	140	60	55	62.5	200	8	65
electric power /MW	0	20	13	0	0	15	12	20	61	0	23.4
Fuel type	MOX	MOX	PuC-UC	MOX	MOX	U-Mo	MOX	U-Zr	U-10Mo	UN	UO2
Inner zone enrichment (%)	30 (Pu)	88–95	55	28.5	30	75	56–90	67	25.6	90	64.4

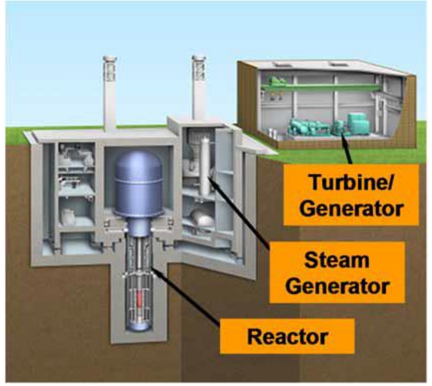
Small SFR being designed or built in the world

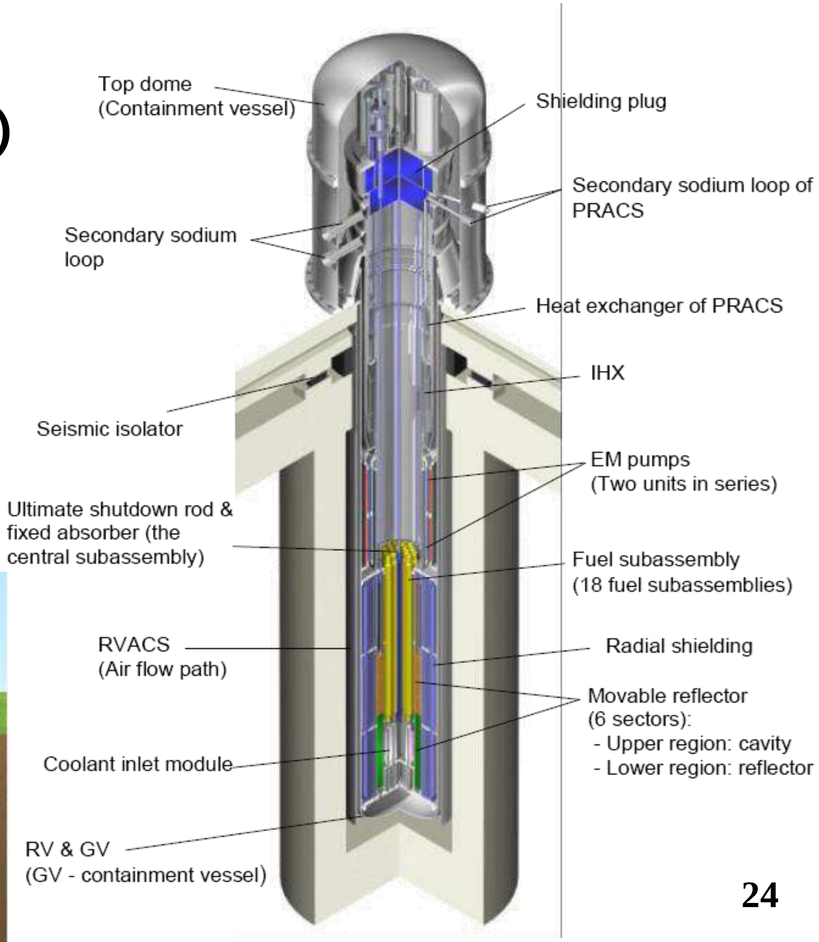
Reactor name	4S	PGSFR	SMFR	PRISM	AFR-100	MBIR	BN GT-300
Country	Japan	Korea	USA	USA	USA	Russia	Russia
current state	conceptual design	preliminary design	conceptual design	detailed design	conceptual design	Construction and installation	conceptual design
Thermal power/MW	135或30	450	125	840	250	150	715
electric power /MW	50或10	150	50	311	100	60	300
Fuel type	U-Zr(metal)	U-Zr or U-TRU-Zr	U-Zr(metal)	Pu-Zr(meta)	U-Zr(metal)	MOX	MOX

3、4S Reactor

■ Japan 4S（Super-Safe，Small，Simple）Reactor

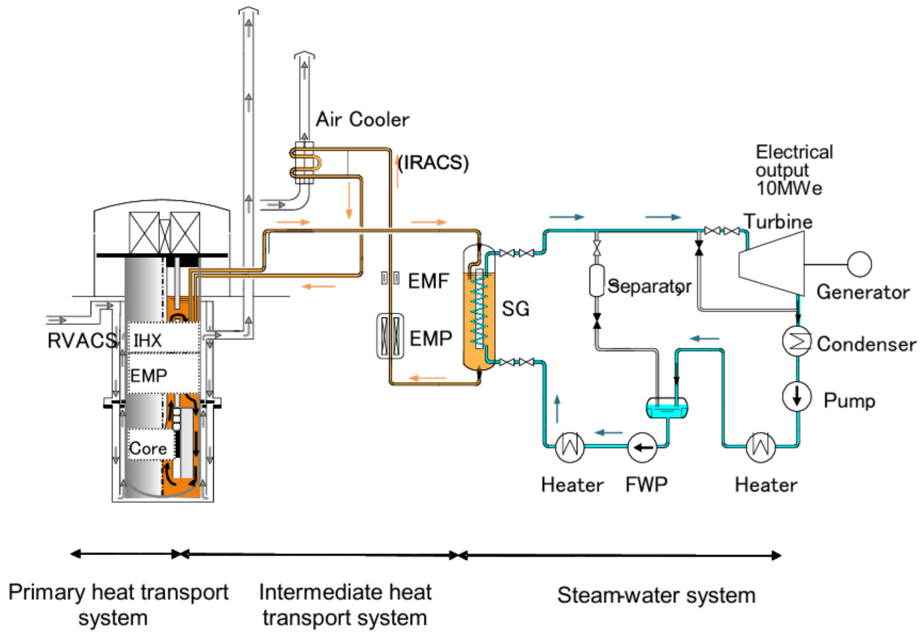
- ◻ Sodium cooled pool type fast reactor
- ◻ Power level
  - Two designs：10MWe（30MWt）/50MWe（135MWt)
- ◻ main features
  - Passive safety (passive residual heat removal)
  - Long refueling cycle (30 years)
  - Can operate in underground sealed spaces
  - Negative reactivity feedback temperature coefficient
  - Metal fuels have high thermal conductivity
- ◻ Multipurpose applications
  - Electricity supply in remote areas
  - Desalination of seawater
  - Steam supply (oil sand extraction)
  - Nuclear hydrogen production





中国原子能科学研究院 中核集团 CNNC CHINA INSTITUTE OF ATOMIC ENERGY

3、4S Reactor



Simplified schematic diagram of the 4S plant of 10 MW(e)

ATTRIBUTES	DESIGN PARTICULARS	
Power	30MWt/10MWe	135MWt/50MWe
Load factor/availability (targets)	>95 %	
Fuel material	Metal fuel(U-Zr alloy) based on enriched uranium	
Reactivity control system	Axially movable reflectors/Fixed absorber	
Reflector type	Cylindrical type; divided into 6 sectors	
Primary shutdown system	Axially movable reflectors of 6 sectors	
Back-up shutdown system	A single ultimate shutdown rod	
Inherent shutdown system	Inherent characteristics based on reactivity feedbacks	
Type of primary pump	Two EM pumps in series	
Reactor vessel diameter	Approximately 3.5 m	Approximately 3.6 m
Shutdown heat removal system(1)	Reactor vessel auxiliary cooling system(RVACS)	
Shutdown heat removal system(2)	Intermediate reactor auxiliary cooling system(IRACS)	Primary reactor auxiliary cooling system(PRACS)
Boundary for primary sodium	Double boundary: reactor vessel(RV) and guard vessel(GV)	
Secondary cooling system	One sodium loop: heat transport from intermediate heat exchanger(IHX) to steam generator(SG)	
Type of secondary pump	EM pump	
Number of steam generators(SGs)	1	

4、PRISM

- USA PRISM（Power Reactor Innovative Small Module） SFR

PRISMMain features

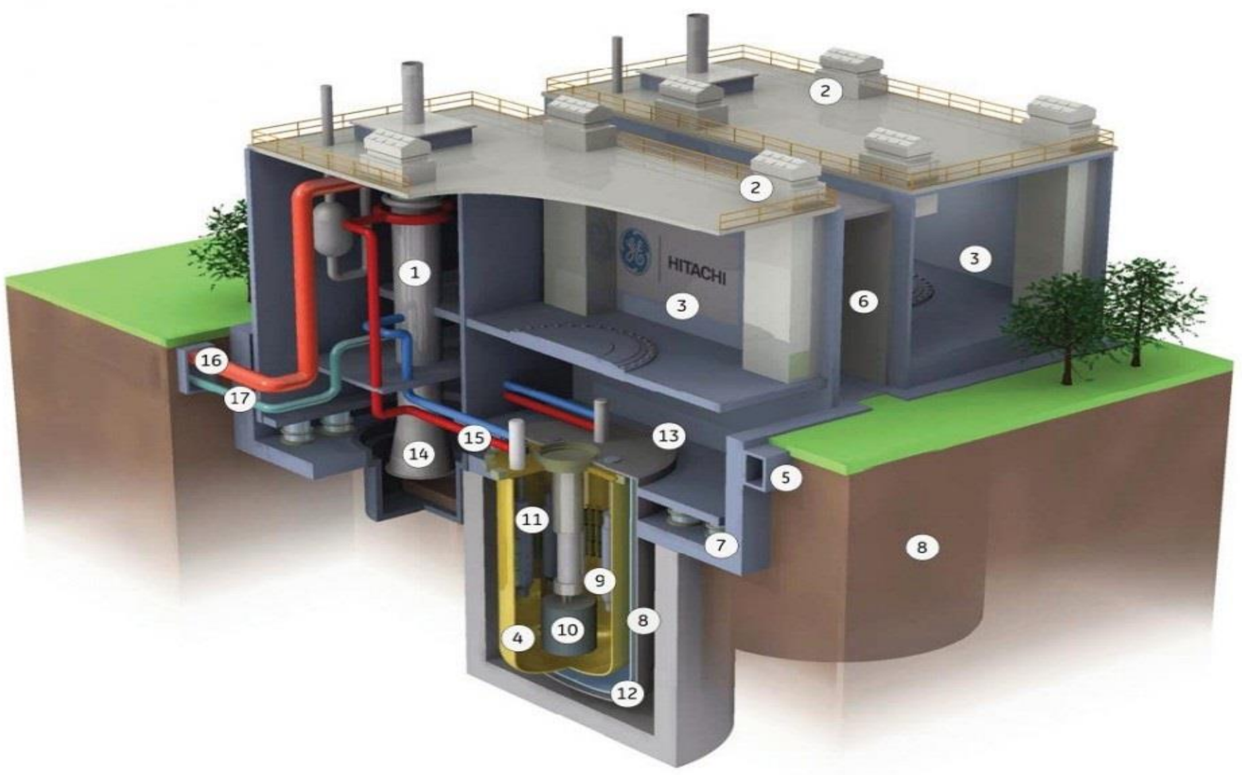
① Integrated modular design
② Passive safety
③ Underground design of reactor
④ All power systems are electromagnetic pumps

PRISM Main design parameters:	
Electrical capacity:	311 MW(e)
Thermal capacity:	840 MW(th)
Coolant:	Sodium （Liquid metal sodium）
Primary circulation:	Forced circulation
System pressure:	Low pressure operation
Core outlet temperature:	485°C
Thermodynamic cycle:	Indirect Rankine cycle
Fuel material:	U–Pu–Zr
Fuel enrichment:	26% Pu,10% Zr
Fuel cycle:	18 months
Emergency safety systems:	Passive Residual heat
Reactivity control:	Rod insertion
Design status:	Detailed design

Development of International SFR SMR

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY
中核集团 CNNC

4、PRISM



PRISM: Power Reactor Innovative Small Module

PRISM module unit layout:

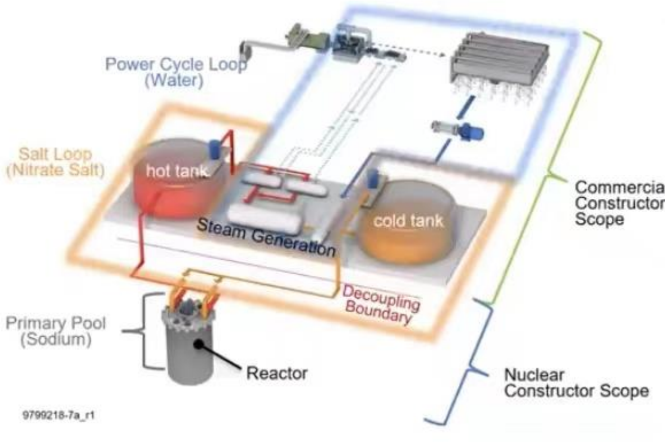
① SG module
② Auxiliary cooling system for reactor pressure vessel
③ Refueling room
④ Sheathing container
⑤ Reactor protection system module
⑥ Electrical equipment module
⑦ Isolation bearings
⑧ Reactor modules (2), each 311MWe
⑨ Main electromagnetic pump (4 per module)
⑩ reactor core
⑪ Intermediate heat exchanger (2)
⑫ Lowering the containment vessel
⑬ Upper level factory building
⑭ Sodium storage tank
⑮ Intermediate heat transfer system
⑯ Steam outlet pipeline to steam turbine
⑰ Water supply and return pipeline

5、Natrium Reactor

Terra Energy in the United States represented the Natrium fast reactor, that supported by the Advanced Reactor Program (ARDP) of the Department of Energy (DOE). A 500MW molten salt energy storage power system based on sodium cooled fast reactors will be built in Wyoming, USA by 2030, achieving advanced technology demonstration.

Natrium Main parameters of the reactor

parameter	data
Thermal power	840 MWt
electric power	345 MWe
Energy storage power generation	500 MWe*5.5 h
Primary side sodium inlet and outlet temperature	360 ℃/499 ℃
Primary sodium flow rate	5.4 m^3/s
Heat exchanger type	Sodium nitrate heat exchanger
Triple circuit steam	superheated steam



Natrium Main System Diagram

5、Natrium Reactor

Natrium

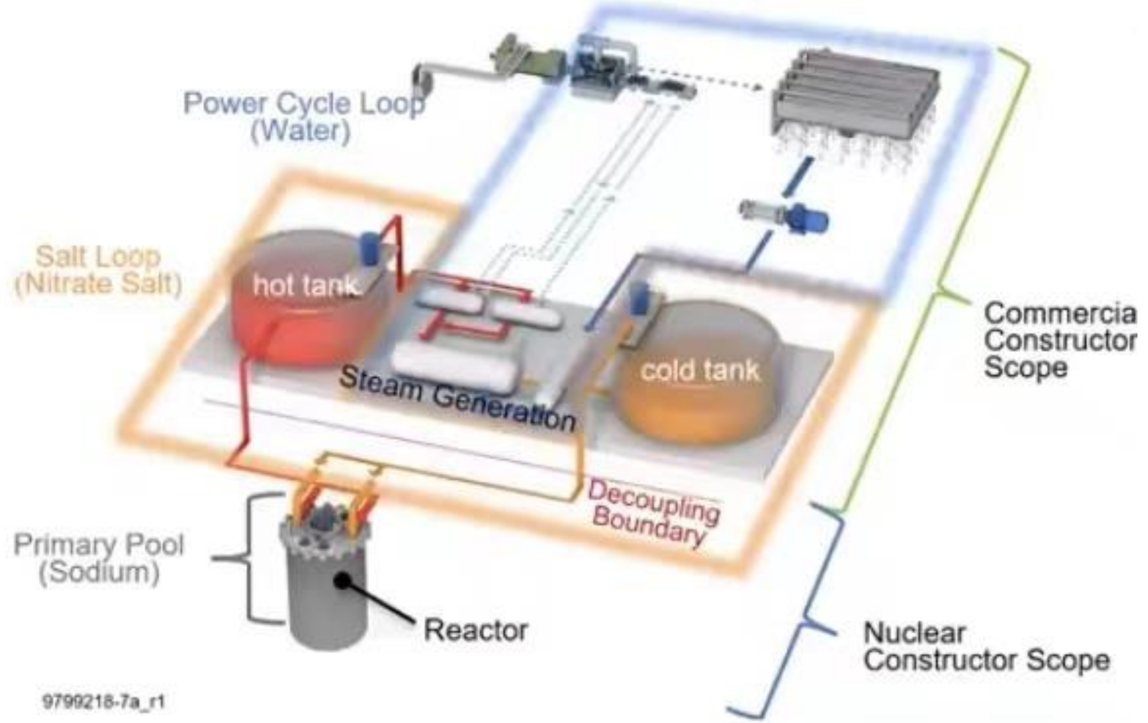
↓

Sodium cooled fast reactor

+

Nitrate molten salt heat transfer and storage system

Terra Power Natrium



advantage:

- **Strong peak shaving ability, complementary to intermittent energy sources for peak shaving and valley filling**
- **Eliminate sodium water reaction and improve safety**
- **Using conventional island system equipment for thermal power to reduce costs**

6、Marvel Reactor

The Microreactor Applications Research Validation and Evaluation (MARVEL) project will be installed and operated at INL's Transient Reactor Testing (TREAT) facility. MARVEL is a 100 kW thermal reactor inspired by existing TRIGA fuel design and technology, which has high safety and can be designed, manufactured, and started within approximately 2-3 years.

The reactor will be a sodium potassium natural circulation cooled reactor with temperature of 500-550 ℃ Four Stirling engines that generate electricity through main cooling and intermediate cooling pumps convert thermal energy into~20 kW of electricity. The system is expected to run for approximately 2 years.

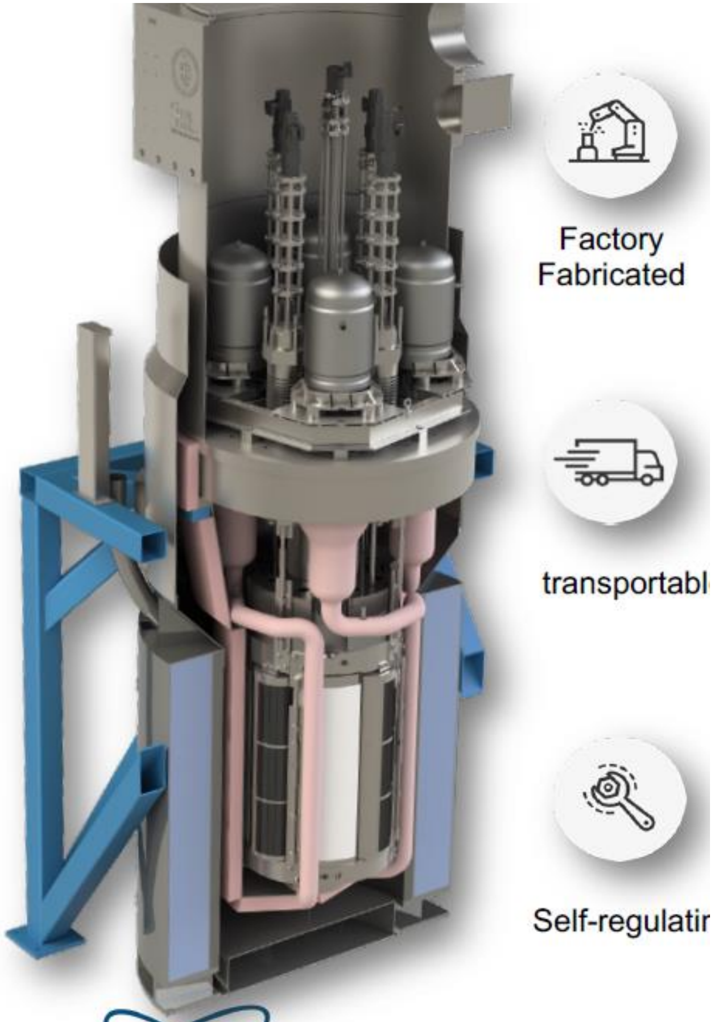
6、Marvel Reactor

MARVEL - Test Microreactor

Microreactor Application Research, Validation and EvaLuation Project

Key Design Features	
Thermal Power	100 KW_{th} (85 kW_{th} nominal)
Electrical Power	20 kW_e (QB80 Stirling Engines)
Heat Extraction	40 kW_{th} (450°C), 60kW_{th} (60°C)
Weight	~11 metric ton (12 US ton)
Primary Coolant	Sodium-Potassium eutectic
Intermediate Coolant	Molten Lead
Coolant Driver	Natural Convection, single phase
Fuel	HALE(UZrH), 304SS clad, end caps
Moderator	Hydrogen
Neutron Reflector	Graphite, Beryllium (S200), Beryllium oxide
Reactivity Control	Radial Control Drums, Central Absorber
Primary Coolant Boundary	SS316H

Innovation- MARVEL used an inherently safe research reactor fuel and design a high-temperature advanced reactor



MRP Microreactor Program

7、Aurora Reactor

■ USA Oklo Aurora Powerhouse

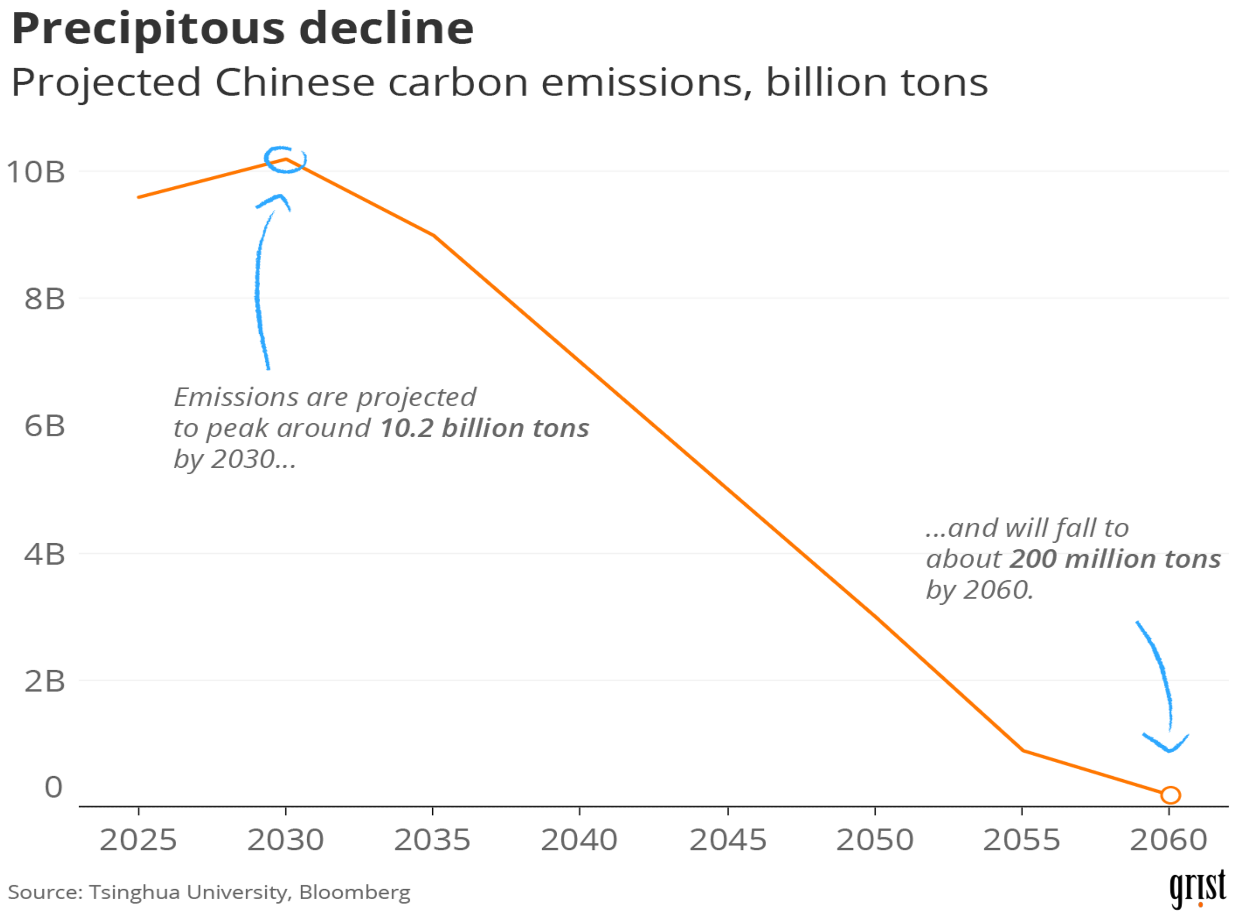
Plant Characteristic	Description
Reactor Type	**Compact fast reactor** that builds on the Experimental Breeder Reactor-II and space reactor legacy. Heat is transported using **heat pipes** that function as thermal superconductors.
Containment Type	**Underground**. Reactor contained in several layers, including a robust cask-like module.
Power Level	4 MWt(~ 1.5 MWe)
Fuel	**Metallic** uranium-zirconium. High Assay Low Enriched Uranium (**HALEU**)
Balance of Plant	**Supercritical CO_2** Power Conversion System

04 Development of SFR and SMR In China

Development of SFR and SMR In China

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY 中核集团 CNNC

1. Needs and strategy

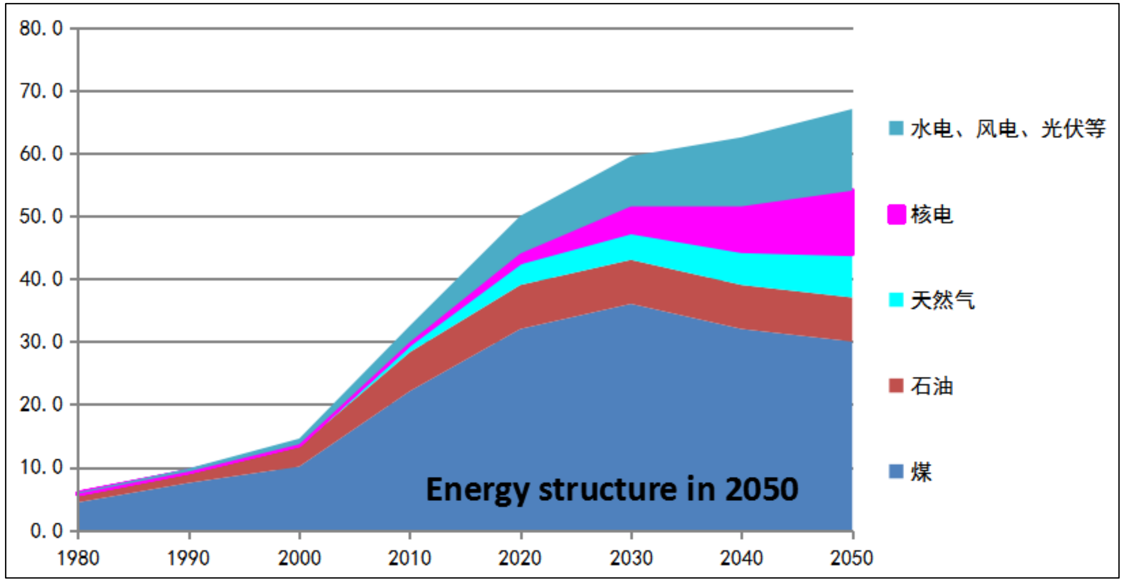


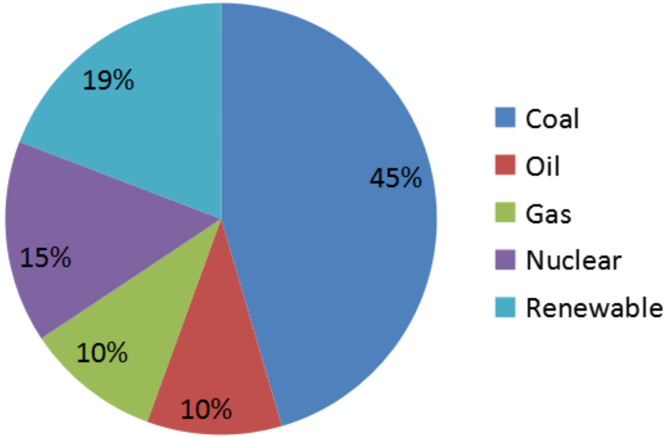
- China promised in Paris Climit conference, “Non-fossil Energy in China will account for about 20% of Primary Energy consumption”.It is expected that nuclear power will have more greater development by 2030.
- Chinese President Xi Jinping promised at the UN general conference in Sept 2020,"China will improve its country's independent contributions and adopt more powerful policies and measures to make carbon dioxide emissions peak by 2030 and become carbon neutral by 2060."
- **Nuclear energy is an important approach for China to carry out the international commitment of reducing carbon emission**

Development of SFR and SMR In China

1. Needs and strategy

- Some studies show that the nuclear power will reach to 120~150GW by 2030, and over 300GWe by 2050.
- Nuclear energy policy
  - **The nuclear energy development must be sure of safe and with high efficiency.**
  - **PWR is the main type of thermal reactor.**
  - **The strategy is developing with the route: thermal reactor, fast reactor and fusion.**
  - **Fuel cycle will be developed with nuclear power stations at the same time.**

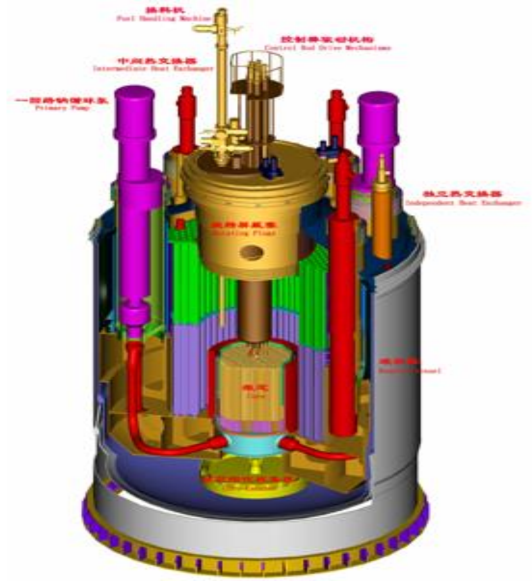


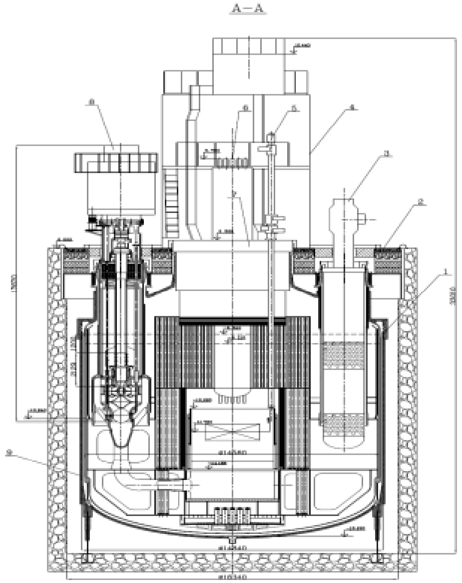


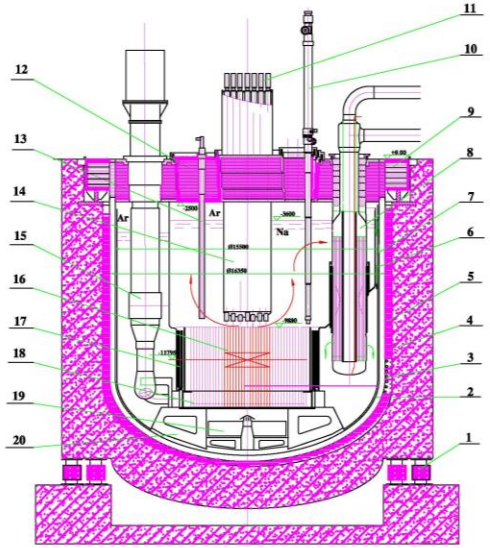
Development of SFR and SMR In China

中核集团 CNNC 中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY

1. Needs and strategy







CEFR — 2011
- Power: 20MWe
- Fuel: UO_2
- Experimental reactor

CFR600 — 2023
- Power: 640MWMWe
- Fuel: UO_2/MOX
- Demonstration reactor

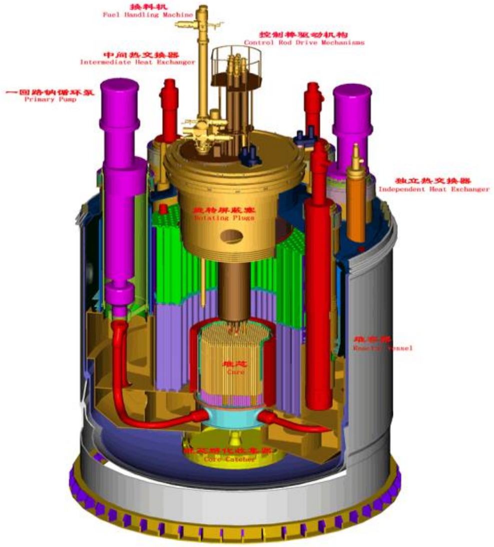
CFR1000 — 2030～2035
- Power: 1200MWe
- Fuel: MOX
- Commercial Reactor

CiFR1000 — After 2035
- Power: 1200MWe
- Fuel: Metal fuel
- Commercial Reactor

2. CEFR

CEFR（China Experimental Fast Reactor）：

The power of CEFR is 65MWt and 20MWe. It is a pool-type sodium-cooled fast reactor. First critical on July 21, 2010. And CEFR reached the full power on December 18, 2014.



Schematic diagram of the CEFR rector vessel

Aerial view of CEFR

2. CEFR

Main parameters of CEFR

Parameter	Unit	Value	Parameter	Unit	Value
Thermal Power	MW	65	Primary Circuit		
Electric Power, net	MW	20	Number of Loops		2
Reactor Core			Quantity of Sodium	t	260
Height	cm	45.0	Flow Rate, total	t/h	1328.4
Diameter Equivalent	cm	60.0	Number of IHX per Loop		2
Fuel		MOX (first loading is UO_2)	Secondary Circuit		
Linear Power max.	W/cm	430	Number of Loop		2
Neutron Flux	$n/cm^2 \cdot s$	3.7×10^{15}	Quantity of Sodium	t	48.2
Bum-up, first load max.	MWd/t	60000	Flow Rate	t/h	986.4
Inlet/outlet Temp. of the Core	℃	360/530	Tertiary Circuit		
Diameter of Main Vessel(outside)	m	8.010	Steam Temperature	℃	480
Design Life	A	30	Steam Pressure	MPa	14

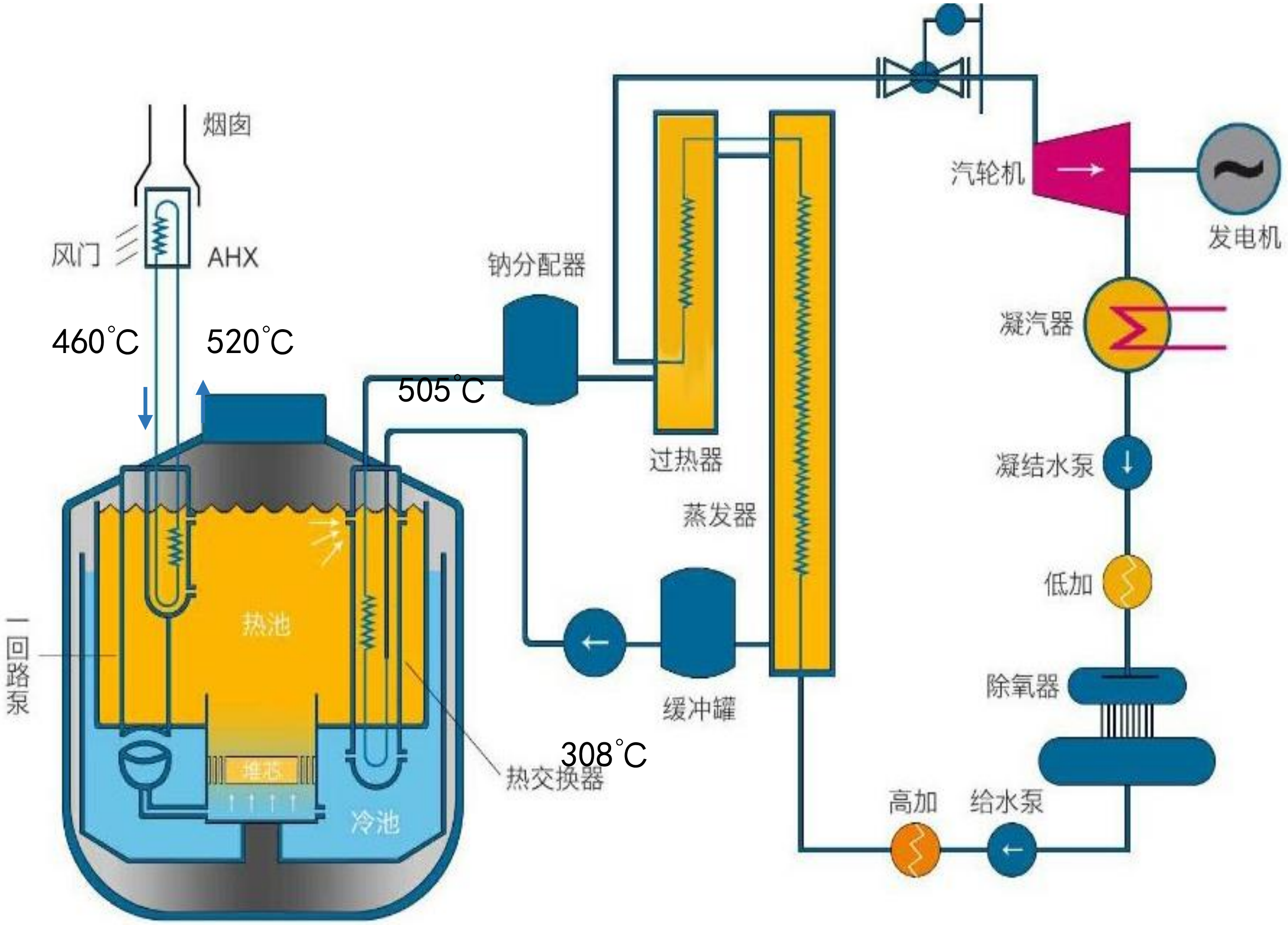
Development of SFR and SMR In China

中国原子能科学研究院
中核集团 CNNC
CHINA INSTITUTE OF ATOMIC ENERGY

3. CFR600

Main parameters of CFR600

Parameters	Value
Thermal Power, MW	1500
Electrical Power, MW	600
Efficiency	>40%
Design load factor	80%
Fuel	UO_2/MOX
Loop Number	2
IHX number per circuit	2
CDF, per year	$<10^{-6}$
Frequency of large radio active release, per year	$<10^{-7}$



The goal of CFR600 is to demostrated an industrial scale closed fuel cycle system .

4. CFR1000

The preliminary site of CFR1000 is planed to locate in Putian City, Fujian Province. A total of six units are planned, with two units in the first phase.

Main parameters of CFR1000

Parameters	Value
Thermal Power, MW	2800
Electrical Power, MW	≥1200
Efficiency	≥40%
Fuel	MOX
Loop Number	4

The goal of CFR1000 is to improve SFR' s economy , that will not more than 1.2 times of PWR.

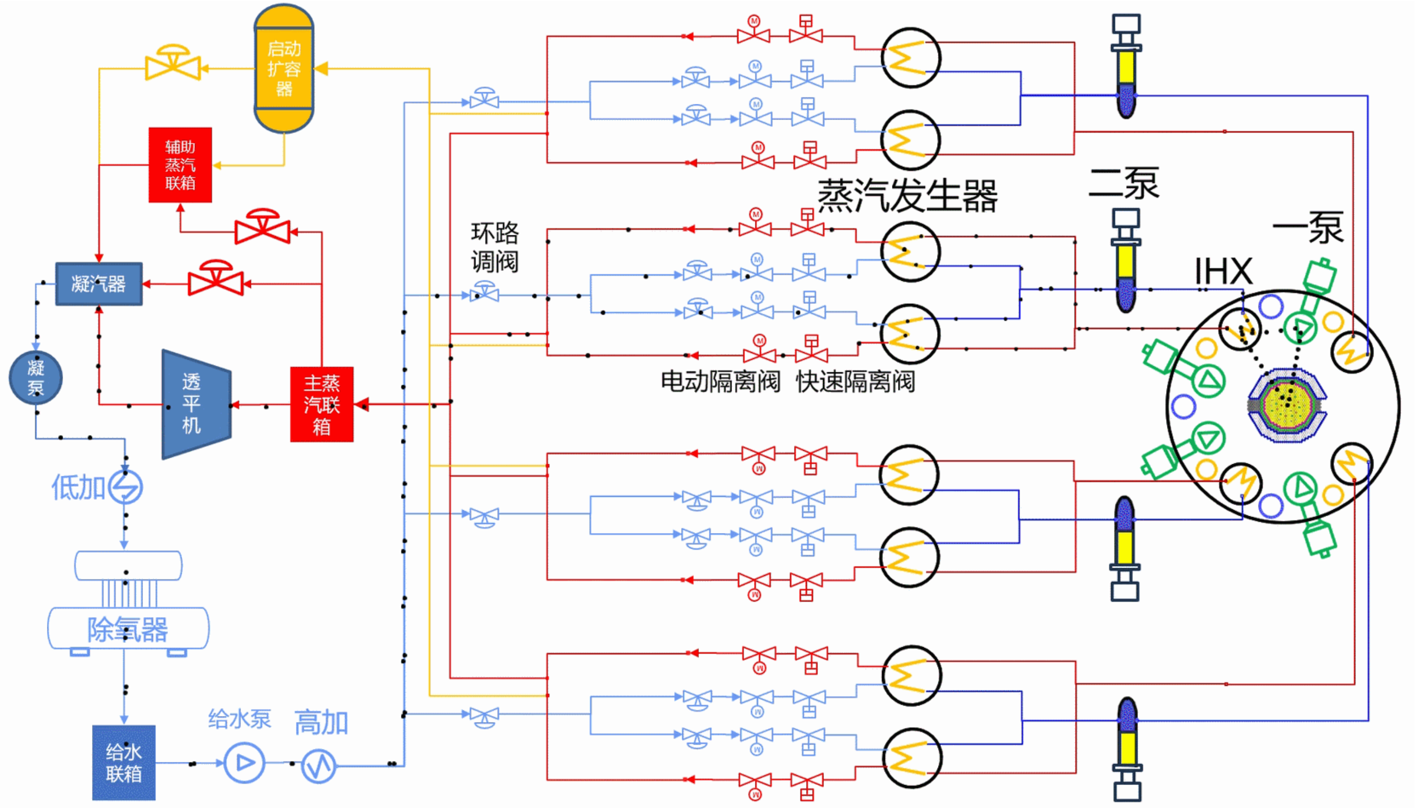
Development of SFR and SMR In China

中国原子能科学研究院
中核集团 CNNC CHINA INSTITUTE OF ATOMIC ENERGY

4. CFR1000

□ Heat transfer system

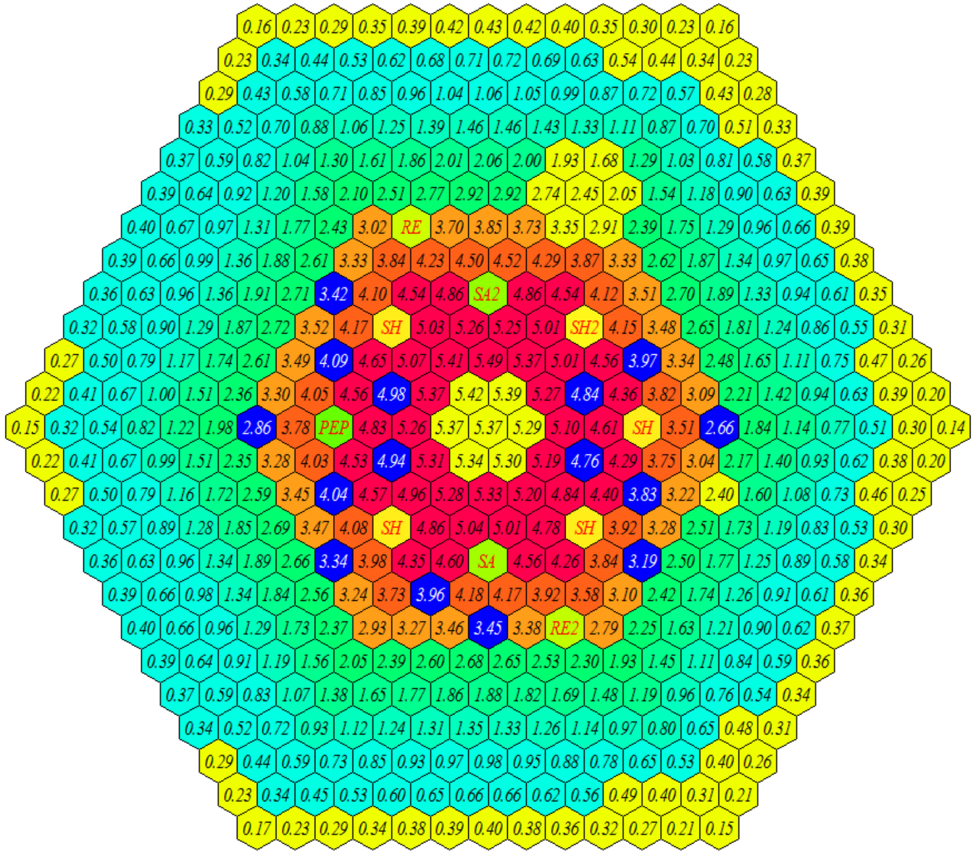
- Pool-type SFR
- Four loops
- Four IHXs
- Eight SGs
- Inlet/outlet Temp. of the Core：358/535 ℃



Flow chart of heat transfer system of CFR1000

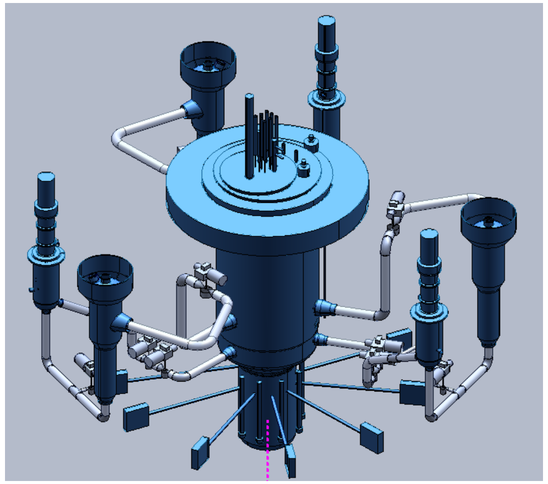
Development of SFR and SMR In China

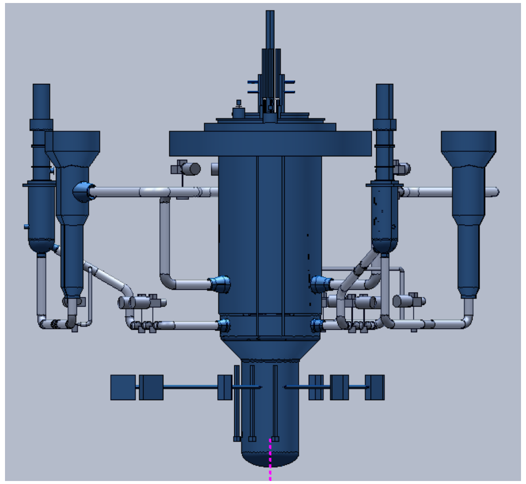
5. New generation test reactor



neutronflux ,× 10^{15} n/cm^{2}s

- Loop-type reactor
- 2 independent irradiation loops
- 14 irradiation positions inside the reactor
- 8+8 irradiation positions inside the reactor
- The neutron flux： 5.0E15 n/cm^{2}s





6. SFR SMR technology in China

Compact structure, system safety, high efficiency, good economy

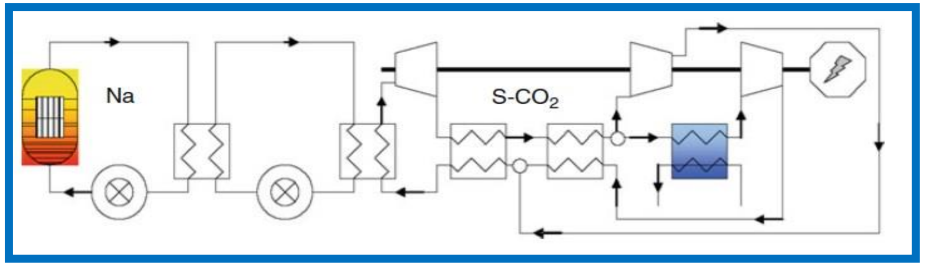
safety of sodium

sodium fire

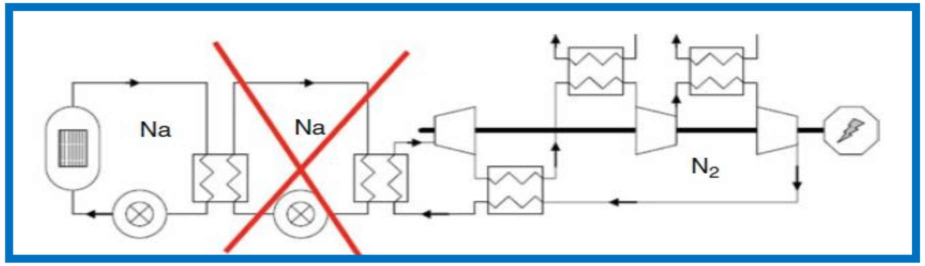
sodium-water reaction

intermediate circuit

new type of circulation

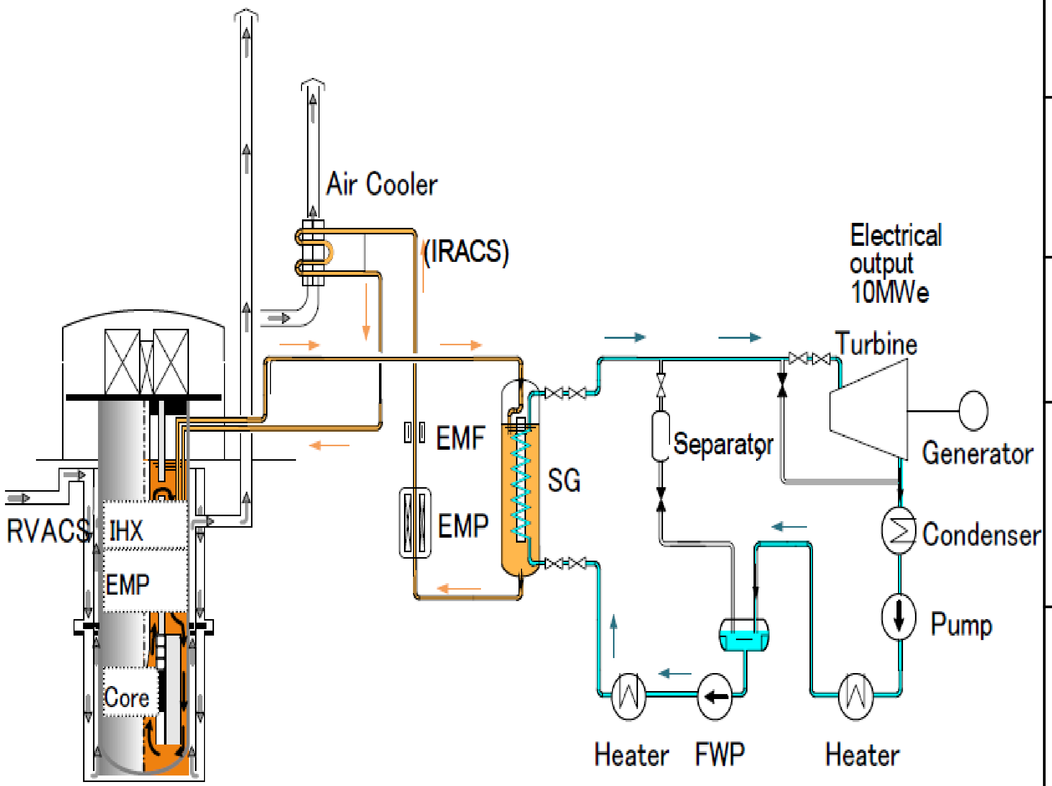


alternative media



6. SFR SMR technology in China

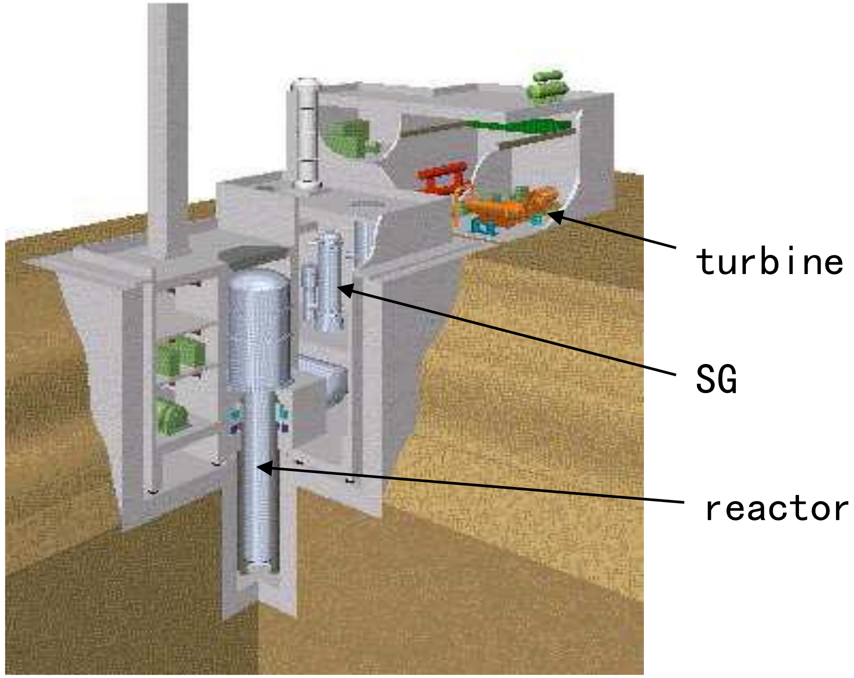
□ Small SFR design



Technology Option	Purpose
Metal fuel	Hard spectrum, high multiplication ratio, long refueling cycle or even full life without refueling
Integrated reactor vessel	Easy to manufacture and transport, beneficial for preventing nuclear proliferation, beneficial for export and commercial promotion
Supercritical CO_2 Bretton cycle	Simple structure, low manufacturing cost, compact system, avoiding sodium-water reaction
Pool-type primary circuit	High thermal inertness, strong natural circulation ability, good radioactive containment in accidents, and avoiding radioactive sodium leakage through pipelines during operation
Passive safety systems	Negative sodium viod reactivity coefficient, gravitational detachment of the reflector layer, passive safety rods, air cooling of the reactor vessel, and residual heat removal through the natural circulation of the primary circuit

6. SFR SMR technology in China

Small SFR design



Schematic diagram of a small SFR

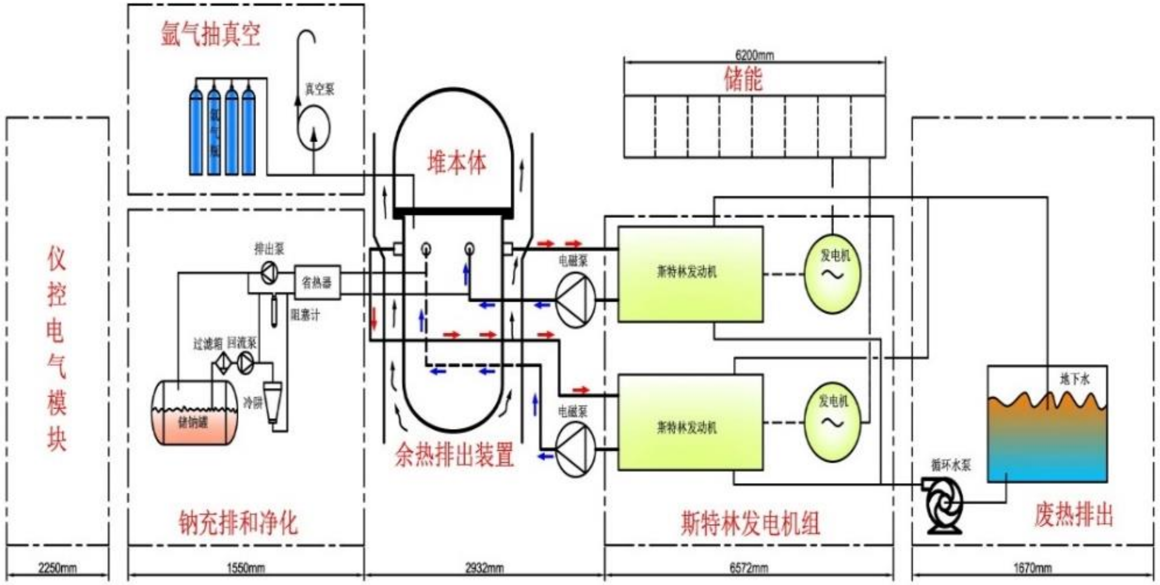
Small SFR Application Scenarios

- Power and heat supply for polar regions, islands, etc.
- Desalination of sea wate
- Heat or hydrogen production for some special industy
- Power supply for sparsely populated areas with low grid capacity

7. Micro SFR power supply

□Overall technical solution

- Small loop-type SFR
- Stirling power
- Sodium - Helium - Water/air



Flow chart of Min SFR

Attribute	Technical solution
Primary circuit	Pool-type
Fuel	UO_2
Coolant	Sodium
Primary pump	Electromagnetic pump
Power conversion system	High power Stirling machine
Decay heat removal	Passive system, air cooling

Technical solution of Min SFR

7. Micro SFR power supply

□R&D Progress

- The key equipments of mini SFR, including the reactor vessel, control rod drive mechanism, and primary circuit electromagnetic pump, have practical application experience.
- The Stirling power conversion system has experience in application on model equipment and is currently conducting related technical research on coupling with sodium coolant system.
- The design, assembly, construction, and comprehensive performance testing verification of the mini SFR principle-level non-nuclear integrated testing device have been completed.

05 SMR challenge

User’s requirement

□operation requirement

- SMR should not be only one small NPP， it need a innovated technology to realize “plug and pay” mode.

□loog life requirement

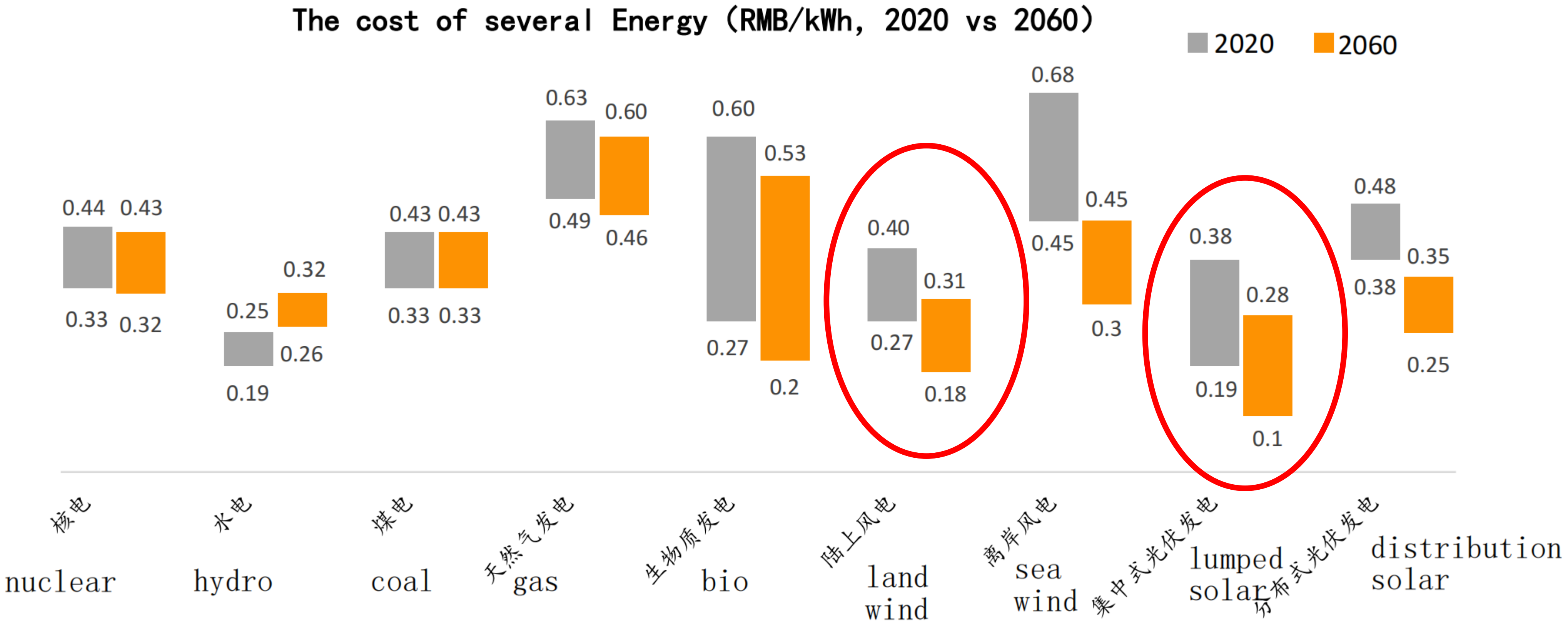
- fuel and material should adopt the high temperature and long time.
- The reliability and maintenance-free time of the equipment need to be greatly improved

Economics Challenges from Other Renewalbe Energy

	Desulphuration Coal	Solar	Wind	Nuclear
Average investment (CNY/kW)	3700	8460	7760	12000~14000
Cost of electricity generation (CNY/kWh)	0.33	0.5-0.7	0.43	0.31
Benchmark Price (CNY/kWh)	0.26-0.45	0.65-0.85	0.4-0.57	0.43
Annual Operation Hours	4219	1205	1949	7089

- Current On-grid Price: Nuclear(Gen-II & II+) ≈Coal power plant < Hydro < Solar/Wind
- The Gen-III nuclear plants have a lifetime up to 60 years and availability over 90%, so that the cost will be around 16000 RMB/kW, competitive to the coal power if environment cost is included.
- Solar and wind energy is expected that the cost could reduce significantly.
- what' s the investment of SMR?

Economics Challenges from Other Renewalbe Energy



数据:BCG、中国石油经济技术研究院

source: Energy Outlook 2060

Economics Challenges of SMR

Economy of scale (OECD-NEA, 2011)

$$\mathrm{Cost}(P_1) = \mathrm{Cost}(P_0)\left(\frac{P_1}{P_0}\right)^n$$

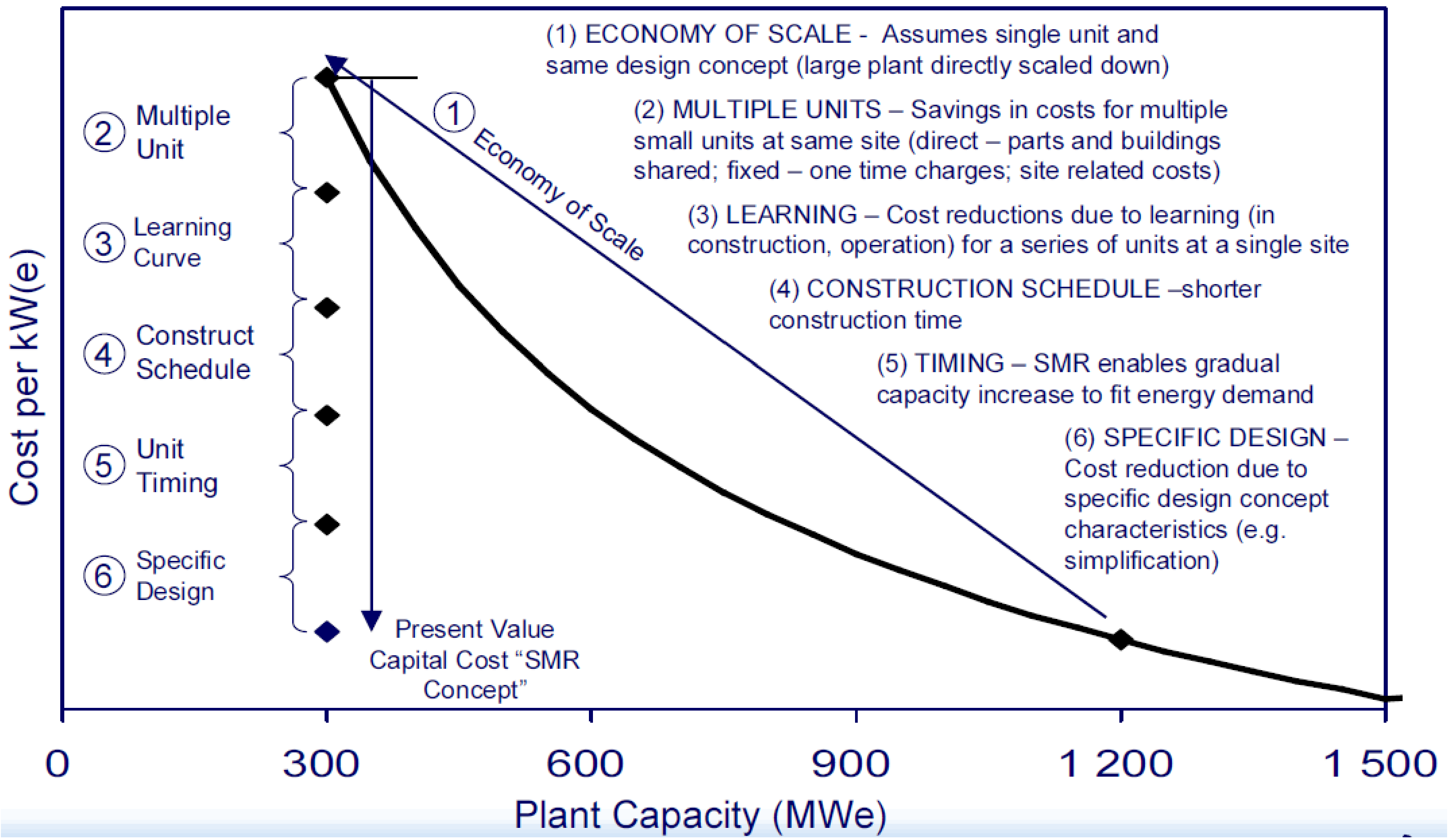
Cost (P_0) = Cost of power plant of unit capacity P_0,
Cost (P_1) = Cost of power plant for unit capacity P_1,
n = Scaling factor, n=0.4-0.7.

W (e), MW	1200	300	150	50
C_x/C_{1200} x 1200/x [$/kW(e)]	1	1.97*	2.77	4.75
C_x/C_{1200} [$]	1	0.49	0.35	0.2

* n = 0.51 (OECD-NEA, 2011)

Economics Challenges of SMR

Present Value Capital Cost (PVCC) Model – Westinghouse, USA



中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY

Thank you for your attention!