**Development status of commercial**

**small modular reactors and its**

**experience to China**

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**Abstract**

The safety and economy of a nuclear reactor are closely related to the sustainable development of nuclear energy, and people pay more attention to it. Authorities and investors favor small nuclear power reactors due to their enormous potential for small size, safety, and economy. This study summarized the technical route, government support, investor interest, investigated the present situation and the development trend of small nuclear power reactors in Russia and the United States. The benefits of developing small nuclear power reactors include reducing greenhouse gas emissions, job creation, advances in space exploration, and improvements in the competitiveness of nuclear energy exports. The challenges include reducing the initial investment and the financial risk, establishing new international licensing standards, etc. Due to the massive demand, the Chinese government supports the development of commercial small modular reactors (SMR) actively. Based on the comprehensive evaluation of the safety and economy of all kinds of commercial SMR, at present, developing a small modular lead-bismuth-cooled fast reactor is a better choice in China.

## INTRODUCTION

A recent International Atomic Energy Agency （IAEA）study shows the world's installed nuclear power generating capacity is projected to grow up to 363 GW(e)~715GW(e)by 2050 [1]. The construction of large nuclear power plants plays a key role, but SMR are also indispensable. The energy sector and investors favor SMR because of their small size, safety, and economy. The SMR have a strong appeal to some countries and regions with insufficient funds, poor infrastructure, and weak technical capabilities. At the same time, because of the relative decline in total investment and the diversification of investment parties, SMR are also the focus of attention to some developed countries, whose operating nuclear power plants are starting to close due to aging and which have invested heavily in the construction of new large nuclear power plants hardly [2].

The world's first small commercial reactor has been working well since it was built in the Arctic in 1976[3]. At present, there are more than 70 conceptual designs of SMR based on commercial development [4]. As the main research and development (R&D) countries, Russia and the U.S. have different technology choices. Russia prefers the research and development of small liquid metal cooled reactors, such as lead-cooled fast reactor (LFR), lead-bismuth-cooled fast reactor (LBFR), sodium-cooled fast reactor (SFR); simultaneously, the U.S. develops heat pipe reactors (HPR), high-temperature gas-cooled reactors (HTR), and liquid metal cooled reactors. In short, liquid metal cooled reactors are an important choice of nuclear power technology in Russia and the U.S.

After more than 30 years, China's nuclear power plant construction has made remarkable achievements. The installed capacity currently under construction ranks first in the world [5]. According to the Energy technology innovation plan of action (2016- 2030) issued by the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA), China has made long-term plans for the development of advanced small modular reactors (ASMR) while vigorously developing large nuclear power [6].

**List of abbreviations**

ADS Accelerator Driven Sub-critical System

ANL Argonne National Laboratory

ASMR Advanced Small Modular Reactor

BW Babcock & Wilcox Enterprises, Inc.

BWR Boiling-water Reactor

CAS Chinese Academy of Science

CIAE China Institute of Atomic Energy

CNG China General Nuclear Power Corporation

CNNC China National Nuclear Corporation

DoE Department of Energy

ENNET Enlightenment New Nuclear Energy Technology Corporation Limited

FHR Fluoride Salt-cooled, High Temperature Reactor

FNR Fast Neutron Reactor

GEH GE Hitachi Nuclear Energy

GIF Generation IV International Forum

HPR Heat Pipe Reactor

HTGR High Temperature Gas-cooled Reactor

HTR High-temperature Gas-cooled Reactor

IAEA International Atomic Energy Agency

IBWR Integrated Boiling Water Reactor

INEST Institute of Nuclear Energy Safety

INET Institute of Nuclear Energy and New Energy Technology

IPWR Integrated Pressurized Water Reactor

LBFR Lead-bismuth-cooled Fast Reactor

LFR Lead-cooled Fast Reactor

LWR Light Water Reactor

MSR Molten Salt Reactor

NDRC National Development and Reform Commission

NEA National Energy Administration

NIKIET Research and Design Institute of Energy Engineering

NPIC Nuclear Power Institute of China

NRC Nuclear Regulatory Commission

OKBM OKB Mechanical Engineering

PWR Pressurized Water Reactor

R&D Research and Development

RRC KI Russian Research Centre "Kurchatov Institute"

SFR Sodium-cooled Fast Reactor

SINAP Shanghai Institute of Applied Physics

SMR Small Modular Reactors

SNERDI Shanghai Nuclear Engineering Research & Design Institute

SNN Societea Nationala Nuclearelectrica

SNPTC State Nuclear Power Technology Corporation Limited

SPIC State Power Investment Corporation Limited

UC Berkeley University of California, Berkeley

1. Commercial SMR in Russia

Russia's nuclear energy strategy is to have nuclear reactors of different capacity units, and the purpose of developing small commercial reactors is to provide safe and reliable energy for remote areas and inaccessible areas [7]. It can also be used for icebreakers, merchant ships, floating nuclear power plants, desalination, thermal energy supply, and nuclear energy export. There are 17 types of commercial SMR in Russia, mainly divided into the water-cooled reactor and liquid-metal cooled reactor. See Table 1 for details.

Table 1. commercial SMR in Russia

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Design | Designers | Type | Output  MW(th)/MW(e) | Status |
| ELENA | RRC KI | PWR | 3.3/0.068 | Conceptual Design |
| KARAT-45 | NIKIET | BWR | 180/45-50 | Conceptual Design |
| KARAT-100 | NIKIET | BWR | 360/100 | Conceptual Design |
| RITM-200 | OKBM | IPWR | 175/50×2 | Under Construction |
| RUTA-70 | NIKIET | IPWR(Pool) | 70/NA | Conceptual Design |
| UNITHERM | NIKIET | PWR | 30/6.6 | Conceptual Design |
| VK-300 | NIKIET | IBWR | 750/250 | Detailed Design |
| ABV-6E | OKBM | PWR | 38/6-9 | Final Design |
| KLT-40S | OKBM | PWR | 150/35 | In Operation |
| RITM-200M | OKBM | IPWR | 170/50×2 | Under Construction |
| SHELF | NIKIET | IPWR | 28.4/6.6 | Licensing Stage |
| MHR-T | OKBM | HTR | 600/205.5×4 | Conceptual Design |
| MHR-100 | OKBM | HTR | 215/25-87 | Conceptual Design |
| BREST-300 | NIKIET | LFR | 700/300 | Under Construction |
| SVBR-100 | AKME-Engineering | LFR | 280/100 | Shelved |
| GT-MHR | OKBM/General Atomics | HTR | 600/285 | Preliminary Design |
| VBER-300 | OKBM | PWR | 917/325 | Licensing Stage |

1. Commercial SMR in the U.S.

Due to the good development prospect of commercial SMR, the U.S. considers them to be the key to the competition in the future nuclear energy market [8]. The U.S. DoE and private investors have invested over $1 billion in the R&D of commercial SMR since 2012 [3]. There are 22 types of reactors developed in the U.S. 73% are advanced nuclear energy systems defined by the GIF. See Table 2 for details.

Table 2. commercial SMR in THE U.S.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Design | Designers | Type | Output  MW(th)/MW(e) | Status |
| mPower | BW | IPWR | 575/195×2 | Shelved |
| Nuscale | Nuscale Power | IPWR | 160/50×12 | Under Construction |
| SMR-160 | Holtec  International | PWR | 525/160 | Near term deployment |
| Xe-100 | X-energy | Modular HTR | 200/75 | Near term deployment |
| EM2 | General Atomics | Modular HTR,FNR | 500/240 | Conceptual Design |
| SUPERSTAR | ANL | LFR(Pool） | 300/120 | Conceptual Design |
| W-SMR | Westinghouse | IPWR | 800/225 | Conceptual Design |
| LFTR | Flibe Energy | MSR | 600/250 | Conceptual Design |
| MK1 PB-FHR | UC Berkeley | MSR | 236/100 | Conceptual Design |
| MCSFR | Elysium Industries | MSR/FNR | 100/50 | Near term deployment |
| eVinci | Westinghouse | HPR/FNR | 0.6-40/0.2-15 | Near term deployment |
| W-LFR | Westinghouse | LFR(Pool） | NA/300 | Near term deployment |
| ThorCon TMSR | Martingale | MSR | 557/250 | Detailed Design |
| Holos Quad | HolosGen | HTR | NA/3-13 | Conceptual Design |
| Gen4 module | Gen4 Energy | Lead-bismuth FNR | 70/25 | Conceptual Design |
| Aurora | Oklo | HPR/FNR | NA/1.5 | Conceptual Design |
| Nuscale mico | Nuscale | HPR/FNR | NA/1-10 | Conceptual Design |
| SC-HTGR | FRAMATOME | Prismatic block HTGR | 625/272 | Near term deployment |
| MMR | UltraSafe Nuclear | HTR | 15/5 | Preliminary Design |
| BWRX-300 | GEH | BWR | 840/300 | Pre-licensing |
| KP-FHR | KAIROS Power,LLC. | FHR | 320/140 | Conceptual Design |
| StarCore | StarCore Nuclear | HTGR | 35-150/14-60 | Pre-Conceptual Design |

1. Trends of Commercial SMR in Russia and the U.S.
   1. **Advanced nuclear energy systems of SMR on the rise**

The main commercial SMR currently being developed in Russia are based on pressurized water reactor technology, while the lead-bismuth technology is based on a nuclear submarine and sodium-cooled fast reactor technology in the 1980s. It is expected to complete the deployment of pilot projects for a series of pressurized water reactor type commercial SMR (for barge-mounted nuclear power plants) and lead-bismuth fast neutron reactors in the next decade, and other concept type advanced reactors such as high-temperature gas-cooled reactors are also in progress [7]. To be a leader in the next generation of nuclear technologies, the U.S. DoE has launched a series of support programs to support the development of advanced commercial SMR, which aimed to address various non-light water SMR technology challenges. The R&D trends of commercial SMR in Russia and the U.S. are shown in Figure 1.

*FIG.1.The number of different types of commercial SMR designs in Russia and the U.S*.

* 1. **Nuclear energy export competition focus on advanced SMR**

According to the estimation of nuclear power installed capacity in various regions of the world from 2030 to 2050 by the IAEA, Central Asia, and East Asia will have the fastest growth of nuclear power, followed by Eastern Europe, Northern Europe, Western Europe, and Southern Europe, which will become the target markets and competition areas for nuclear power exporting countries [1]. See Figure 2.

Advanced nuclear energy systems of SMR are a critical area of competition in the nuclear energy market in these regions for five reasons: First, some landlocked countries are not rich in water resources, so it is not feasible to build large-scale pressurized water reactor nuclear power plants. Second, some underdeveloped regions cannot afford large nuclear power plants' high investment. Third, SMR can be flexibly matched to local grid capacity. Fourth, nuclear power plants built with advanced SMR can provide multi-purpose needs, such as cogeneration of heat and power, hydrogen production, seawater desalination, etc. Fifth, SMR present a lower proliferation risk than large reactors. Therefore, it is feasible to develop advanced SMR in these areas. Because of this, Russia and the U.S., and other countries have vigorously invested in the R&D of advanced SMR and promoted their application [9] [10].

*FIG.2.The estimation of nuclear power installed capacity in various regions of the world from 2030 to 2050*

* 1. **Breaking regulatory bottlenecks**

Benjamin et al. evaluated the regulatory fees structure of SMR in the U.S. by establishing an economic analysis model and concluded that regulatory fees as a potential obstacle to the economic feasibility of SMR [11]. The U.S. NRC developed a licensing process based on 40 years of experience building and operating pressurized water reactors. For SMR of any type to be economically competitive with large LWR, the regulatory process must accommodate these new systems. Otherwise, the value such as modularity, factorization, reduced risk factors, and increased margins of expected safety cannot be captured and measured. [12]. Therefore, adjusting the supervision cost structure, establishing the thermal-hydraulic design standard of SMR, developing the safety analysis software under the laws and regulations, and verifying the modularity test is the current research focus of SMR prerequisite for the commercialization of SMR [13].

* 1. **Develop specific economic models to improve evaluation accuracy**

Because of a misleading interpretation of economies of scale, SMR are considered economically uncompetitive [14] [15]. Economies of scale in nuclear power refer to the state where the enterprise obtains the best economic benefits by increasing the unit capacity and power output. Economies of scale apply when comparing the benefits of reactors of very similar designs. The design differences between SMR and large reactors are enormous. It is not accurate to use the principle of economies of scale to determine that the capital cost of SMR is higher than that of large reactors [15]. Suppose the economic evaluation model fully considers the following aspects:

* Modular equipment components (production, transportation, and installation) [16]
* A wholly controlled work environment
* The standardization of components
* Overall design simplification
* Shortened construction time

In that case, nuclear power plant modular integration (organized by several of the identical small reactors integrated power plant), the production of the multiplier effect, more products, such as electricity, heat, and hydrogen, less workforce output, the process of operation, learning effects, etc., only then may obtain the appropriate SMR economic and financial competitiveness evaluation [14].

In 2007, the IAEA launched a three-year study on methodologies and applications for the economic assessment of SMR. Participants will jointly develop a systematic approach that can assess the economics of building SMR projects, the economics of factory manufacturing, and supply chain localization in the context of differences in the level of technical readiness [17].

1. Commercial SMR in China
   1. **Strong market demand and active support from the government**

Due to the strong market demand for SMR in China, such as cogeneration of heat and power, hydrogen generation, seawater desalination, and power supply, the market potential for commercial promotion is great. Therefore, while developing large commercial nuclear power plants, China also pays attention to the R&D and utilization of SMR.

For example, Coal-fired cogeneration is the main heat source for urban heating in northern China. The annual consumption of heating coal is about 400 million tons of standard coal [18]. The key factor for the deterioration of air quality in winter in northern China is the emission of pollutants caused by heating [19]. At the end of 2017, 10 ministries and commissions issued the Clean Winter Heating Plan in Northern China (2017-2021), which proposed to study and explore nuclear energy heating, promote active nuclear power units to provide heating to neighboring areas, and safely develop low-temperature swimming pool heating demonstration, etc. [18]. The SMR heating projects under construction in northern China include the Xudapu Pool Heating Reaction Demonstration Project, the Baishan Nuclear Energy Heating Project, and the Jiamusi Comprehensive Smart Nuclear Energy Heating Demonstration Project.

* 1. **SMR promotes the implementation of the "Go Global" nuclear power strategy**

In October 2013, the NEA published the Service Nuclear Power Enterprise Scientific Development Coordination Work Mechanism Plan and put forward the "Go Global" strategy of nuclear power [20]. Since then, Chinese nuclear power companies have been awarded project opportunities in the United Kingdom, Romania, Pakistan, Argentina, and other countries. However, large nuclear power units have a huge investment, long construction period, and high risks. For example, in Romania's nuclear power project with a total investment of 7.2 billion Euros [21], the CGN has been promoting the project for ten years, and the SNN canceled the agreement unilaterally in 2020. There are two possible reasons for this result: On the one hand, it may come from the conflict of political interests; on the other hand, it is related to the long construction cycle of large-scale nuclear power plants. The advantages of commercial SMR can better cope with the international nuclear power market's economic risks. Therefore, the development of small commercial reactors is the key to China's nuclear power "Go Global" strategy.

* 1. **Active R&D of SMR**

Currently, the CNNC and other enterprises and public institutions engaged in SMR R&D have launched or plan to launch more than 20 kinds of commercial SMR, as shown in Table 3. Analysis of the advantages and disadvantages of commercializing major advanced SMR is shown in Table 4.

Table 3. Commercial SMR in China

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Design | Designers | Type | Output  MW(th) /MW(e) | Status |
| ACP100 | NPIC, CNNC | IPWR | 385/125 | Under Construction |
| ACP100S/25S | NPIC ,CNNC | IPWR | NA/25-100 | Under Construction |
| CAP200 | SNERDI,SPIC | PWR (Compact) | 660/150-200 | Detailed Design |
| DHR400 | CIAE,CNNC | PWR (Pool) | 400/NA | Under Construction |
| CNP300 | SNERDI,SPIC | PWR (Loop) | 1000/300-340 | In Operation |
| SNCLFR-100 | CAS | LFR(Pool) | 100/NA | Conceptual Design |
| BOC600 | SNERDI,SPIC | PWR (Compact) | NA/NA | Conceptual Design |
| ACPR50S | CGN | PWR (Compact) | 200/60 | Under Construction |
| HTR-PM | INET, Tsinghua University | Pb- HTR(Modular) | 250/210 | Under Construction |
| ACPR100 | CGN | IPWR | 340/NA | Conceptual Design |
| HAPPY200 | SPIC | PWR (Pool) | 200/NA | Under Construction |
| NHR200 | INET, Tsinghua University | PWR (Compact) | 200/NA | Under Construction |
| CAP150 | SNPTC | PWR(Modular) | NA/NA | Conceptual Design |
| HeDian Bank | INEST,CAS | LFR | NA/NA | Conceptual Design |
| smTMSR-400 | SINAP,CAS | MSR | 400/168 | Pre-Conceptual Design |
| M1-V | CIAE,CNNC | LFR | NA/1 | Conceptual Design |
| NTO-L Minor | CIAE,CNNC | LFR | 20/≥3 | Conceptual Design |
| HHP25 | SPIC | PWR (distributed) | 100/25 | Conceptual Design |
| BLESS | SPIC | LFR(Pool) | 300/NA | Conceptual Design |
| HeMei1 | SPIC | IPWR | 200/NA | Preliminary Design |
| HeHai5 | SPIC | IPWR | NA/NA | Conceptual Design |
| Blue-ray hot well | ENNET | PWR (Pool) | NA/400 | Conceptual Design |

Table 4. The advantages and disadvantages of commercial SMR

|  |  |  |
| --- | --- | --- |
| Type | Advantages | Disadvantages |
| Advanced PWR | Experience in construction and operation;  Passive safety design;  Low initial investment and construction costs. | Inefficient in Nuclear fuel;  Rigorous construction site selection. |
| HTR | Closed fuel cycle;  The coolant is chemically inert;  Inherent safety performance;  Cogeneration of heat and power, high-temperature heat and hydrogen production [22]. | Because SiC coating is difficult to be damaged and high burnup consumption, the fuel coating particles used in the high-temperature reactor are only applicable to the once-through fuel cycle at present [23].  The core may heat up rapidly after losing forced cooling due to low thermal inertia;  Control and regulation of fast neutron dose;  Solution of air oxidation problem of nuclear grade graphite [24]. |
| LFR/LBFR | Closed fuel cycle;  Lead (Lead-Bismuth) coolant can operate at low pressure, is chemically stable, and does not react exothermally with water and air.  The economic efficiency of reactor neutrons enables the reactor system to have higher nuclear waste transmutation and nuclear fuel multiplication capacity;  Lead-based materials have strong heat carrying capacity and natural circulation capacity;  Lead-cooled reactors are experienced in construction and operation[25];  Lead (Lead-Bismuth) cooled reactors have more economic advantages than sodium-cooled reactors [26]. | Corrosion of lead at high temperature and flow rate;  The weight of the coolant poses a challenge to the equipment structure;  The opacity of lead makes monitoring difficult;  The reprocessing of nuclear fuel has not yet been resolved [27]. |
| SFR | Closed fuel cycle;  Thermophysical advantage of sodium;  Sodium-cooled reactor technology is relatively mature [28]. | The control and prevention of sodium water reaction is the most important problem;  Development and validation of passive safety systems [28] [29]. |
| MSR | Closed fuel cycle;  Liquid salt provides a negative temperature and void reactivity coefficient.  The extreme negative temperature coefficient of reactivity;  Thorium fuel is more abundant and cheaper than uranium fuel;  Thorium fuel rod manufacturing and spent fuel disposal costs are low [25]. | The thorium fuel operation database has not been established yet, and the lack of empirical data increases the uncertainty risk. |

* 1. **Establish a database of lead-based nuclear reactors and promote engineering research**

The conceptual design of lead-based reactors in China began in 1986. After more than 30 years of R&D of lead-based reactors, a large amount of empirical data has been accumulated, which has laid a good foundation for the development of commercial lead-based reactors, which is conducive to the control of R&D time and the reduction of research and development cost, to improve the competitiveness.

Through long-term research on lead-based reactors, the CIAE under the CNNC has established a particular nuclear database for lead-bismuth fast reactor transmutation. It has continued developing the VENUS , VENUS Ⅱ, and VENUS Ⅲ lead-bismuth experimental reactor. VENUS Ⅲ for the first time critical in 2019, which means that China's lead-bismuth cooled reactor research will enter the stage of engineering. The Future Advanced Fission Energy - ADS project of the Chinese Academy of Sciences has carried out systematic research on lead-based reactors. Three engineering technology experimental platforms have been established to carry out a series of engineering verification experiments.

1. Conclusion

In China, with the development of the social economy, the energy demand is growing, and the existing energy structure does not meet the requirements of climate change targets. To accelerate the formation of a green development mode and lifestyle and build an ecological civilization and a beautiful China, China has set a goal of achieving carbon neutrality by 2060. In the coming decades, the country will not have to sacrifice economic growth and prosperity to achieve the ambitious goal of carbon neutrality. The development of nuclear energy is an important option, so the development of large nuclear power plants will be accompanied by the development of small reactors.

The paper combed the relevant articles of Russia and the U.S., analyzed the status and trend of SMR, and concluded that the advanced SMR will be mainstream in the future. Nuclear power will be a more diversified investment subject. Nuclear energy international trade will be more heated competition, for SMR regulation reform and fees framework adjustment will further enhance the competitiveness of its economy.

The Chinese government strongly supports the construction of SMR to meet the growing energy demand and reduce carbon emissions and the key to realizing China's nuclear power "Go Global" strategy.

Based on the technical experience feedback of the development of commercial SMR in Russia and the U.S., combined with the long-term research foundation of lead-based reactors in China, and the comprehensive analysis of safety and economy, the small modular lead (lead-bismuth) fast reactor has a good prospect as the first stage of commercial promotion. Therefore, the development of a small modular lead (lead-bismuth) fast reactor in China is a favored choice.

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