MULTI-PURPOSE APPLICATIONS OF SMALL MODULAR SODIUM-COOLED FAST REACTORS IN TWO-COMPONENT NUCLEAR POWER SYSTEM

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Abstract

At the 28th United Nations Climate Change Conference (COP28), a declaration was made to triple nuclear energy by 2050. The global installed capacity of nuclear energy is expected to continue growing rapidly, with a focus on the crucial issue of natural uranium in the development of nuclear power plants. Fast Reactors (FR) are critical in providing efficient, safe, and sustainable energy for long-term nuclear power development, developing a two-component nuclear system of pressurized water reactors (PWR) and FR will be critical globally in the future. Small Modular Sodium-cooled Fast Reactors (SMSFR) are expected to play a role in developing a two-component nuclear power system by acquiring and processing its' reactor fuel. This study aims to predict and analyze the future development prospects of SMSFR within the framework of the two-component nuclear power system and to explore the potential application and economic evaluation of SMSFR in power generation, hydrogen production, steam production, and isotope production simultaneously.

1. INTRODUCTION

The installed capacity of nuclear energy worldwide will continue to proliferate. The COP28 was a historic event for nuclear energy when it was formally specified as one of the solutions to climate change in the First Global Stocktake of progress toward meeting the goals of the Paris Agreement, and a declaration was signed to make efforts to triple nuclear energy by 2050. However, with the increase of nuclear power plants around the world, the demand for natural uranium has increased dramatically, which will be a crucial issue in developing nuclear power plants. Globally identified recoverable resources of uranium, which identified resources amounted to 7 917 500 tU, according to the "Red Book" [1]. A million-kilowatt PWR requires 10,000 tons of natural uranium during the 60-year lifespan's operation. If only the PWR were under construction, natural uranium would be expected to be used up at the end of this century, as a million-kilowatt PWR also produces about 170 tons of depleted uranium and 20 tons of spent nuclear fuel (SNF) per year. Fast reactors can provide efficient, safe and sustainable energy, supporting long-term nuclear power development and decreasing the burden of nuclear waste, simultaneously. Hence, developing the PWR and FR's two-component nuclear system will be critical worldwide.

Based on VVER and BN series reactor, Russia has developed a two-component nuclear system with a total installed capacity predicted to be up to 140 GW at the end of the 21st century [2]. BN-800 had been fully use MOX fuel at 2022.The Russian government has formulated the "PRORYV" plan for future nuclear energy development, supporting the development of fast reactors such as BN-1200 and BREST-OD-300.

France is an international leader in SNF processing, and the MOX fuel has already been used in PWR to build a closed nuclear fuel cycle. Japan Atomic Energy Agency (JAEA) formulated a roadmap for the fast reactor's development plan, which plans to develop fast reactor technology by the middle of this century in 2018.[3][4]. India has a unique energy and resource situation, scarce uranium resources, and abundant reserves of thorium resources. India has formulated a fast reactor technology development strategy that is different from other countries, namely the development of the thorium-uranium cycle, which can be called India's "three-step strategy for fast reactor development"

SMSFR has the advantages of high energy density, low reactor cooling system pressure, strong environmental adaptability, and lower radioactive waste generation, which will play a vital role in the SMR in the future. SMSFR could be developed through the development of a two-component nuclear power system, where SFR has more than 400 reactor years of experience, as shown in Fig. 1. The Argonne National Laboratory proposed a conceptual design scheme for the advanced small fast reactor AFR-100 with a capacity of 100MWe and explored the non-electric multi-purpose application of small SFR's hydrogen production. General Electric Company (GE) has developed an integrated sodium-cooled fast reactor PRISM with thermal power of 471MW; TerraPower is developing a 345MW SFR, Natrium, which innovatively integrates with molten salt energy storage devices to achieve a continuous 5.5 hour 500 MWe power supply during peak hours, to track changes in the daily load of the power grid. The first Natrium demonstration project is planned to be constructed in Wyoming, with a construction permit application submitted in 2024 and completion scheduled for 2028.

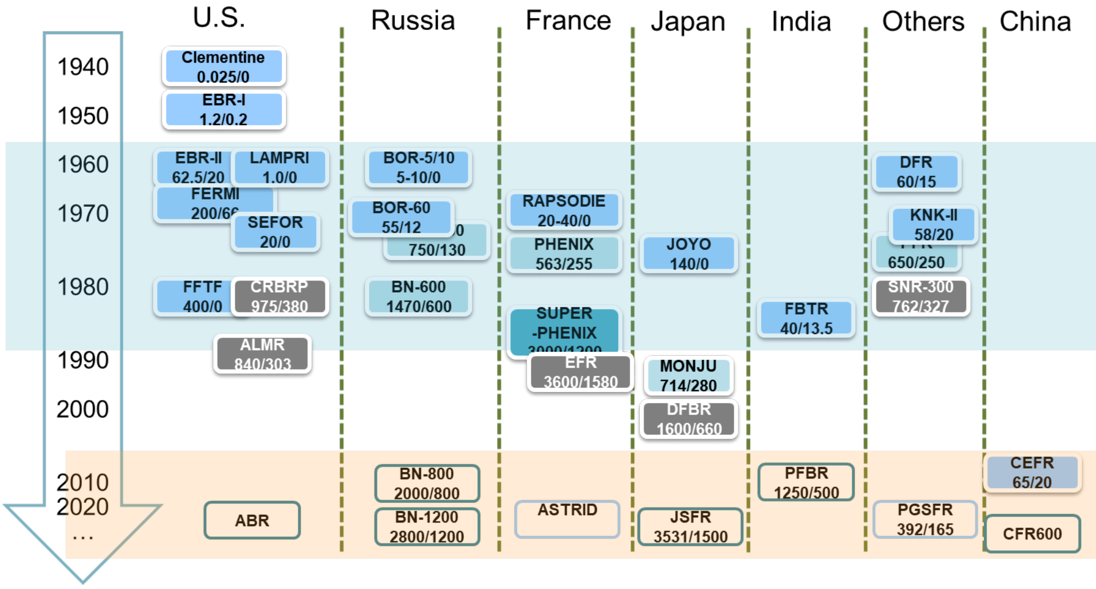

FIG. 1. Development of fast reactor worldwide

The SMSFR holds significant potential for various applications, such as high-quality industrial steam production, hydrogen production, seawater desalination, isotope production, and advanced reactor materials. This study analysis the method and economics of the SMSFR multi-purpose application in electricity production, hydrogen production, and steam production.

2. SMSFR DEVELOPMENT IN TWO-COMPONENT NUCLEAR POWER SYSTEM

A two-component nuclear power system includes PWR and FR, FR could generate energy and breeding fuel at the same time, and a centralized closed nuclear fuel cycle that permits reprocessing spent fuel, repeated fuel recycling, and conditioning and isolation of wastes.[5]

After natural uranium extraction, through the enrichment and manufactured into PWR’s fuel. After entering the PWR and generating the electricity, it becomes the SNF. The SNF is reprocessing a nuclear reprocessing plant and turning it into a fast reactor’s MOX fuel. After entering the fast reactor power plant, it generates power and proliferates into new fuel, turning the U-238 into the Pu-239. Simultaneously, the breeding fuel can be made into a PWR’s MOX fuel, which could be used by PWR, as shown in Fig. 2.

The two-component nuclear power system could break the limitation of PWR’s installed capacity due to the lack of natural uranium. The two-component nuclear energy system based on fast reactors can maximize the advantages of nuclear energy, break resource ceilings and long-life radioactive waste limitations, and achieve large-scale, sustainable, green, and environmentally friendly development of nuclear energy.

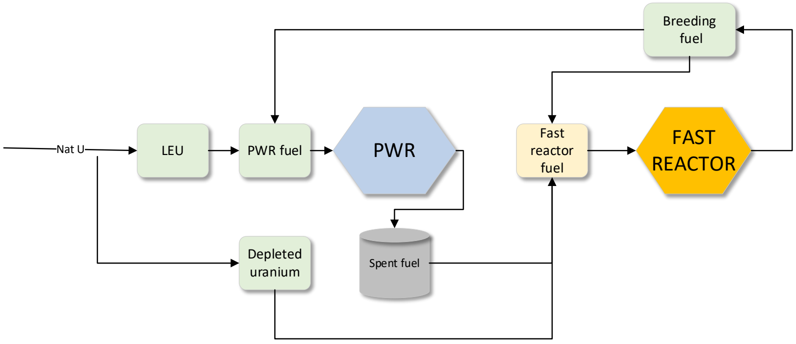

FIG. 2. Two-component system of fast reactor and PWR

The SMSFR or the other kind of SMR can utilize fuel from the two-component nuclear power system, and the SNF of SMSFR(or other kind of SMR) can be sent to a two-component nuclear power system for burning and recycling, as illustrated in Fig. 3.

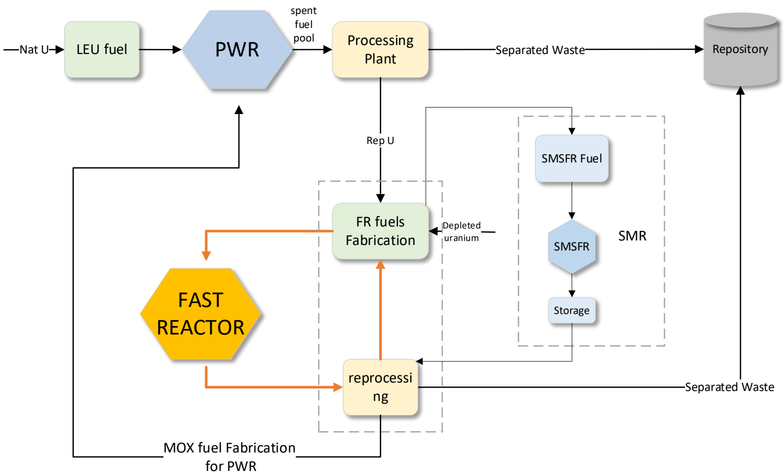

FIG. 3. Two-Component Nuclear Power System with SMSFR.

3. MULTI-PURPOSE APPLICATIONS OF SMSFR

Electricity production could not be the primary use of the SMSFR. However, according to the design of BN-1200, the investment rate is about $3,200/kW[6], which is comparable to VVER and shows the economic viability of SFRs. As for SMSFR, with its lower investment and shorter construction period, the SMSFR could offer a more comparative investment compared with PWRs.From the energy efficiency perspective, electricity generation is only one form of SMSFRs, but its multi-purpose use can significantly enhance energy efficiency and provide broad prospects.Advanced nuclear energy systems represented by SMSFR can provide petrochemical users with industrial steam with nearly zero carbon emissions and stable output, an essential option for the petrochemical industry to replace clean energy. Actively advancing the integration of nuclear energy with high-energy-consuming industries will further underscore the zero-carbon benefits of nuclear energy.

3.1. **Hydrogen production**

According to the source used in hydrogen production, hydrogen production methods can be classified into fossil fuel hydrogen production, industrial by-product hydrogen production, biomass hydrogen production, and water-splitting hydrogen production. Currently, 96% of hydrogen in the world comes from fossil fuels, and only 4% comes from water splitting. In 2023, the Nine Mile Point PWR nuclear power plant in the United States successfully demonstrated nuclear electrolysis for hydrogen production. This project generates electricity for the hydrogen production plant directly from the nuclear reactor. Hydrogen energy, known for its abundant resources, zero combustion pollution, and high calorific value, is increasingly used in batteries, transportation, and aerospace, making it a key component of future energy systems. It will be crucial for achieving global carbon peaking and carbon neutrality.

Argonne National Laboratory focused on hydrogen production using the small sodium-cooled fast reactor AFR-100.[2] Owing to the outlet temperature of the reactor core being lower (530°C), it is not possible to reach a high-temperature steam electrolysis temperature (600°C). Therefore, the electrical power of the reactor is used to overheat the steam from 500°C to above 600°C, and the power plant's power is used for high-temperature steam electrolysis simultaneously. It is expected that hydrogen production will be 0.768 kg/s[3]. This study provides a new solution for the medium-temperature hydrogen production process.

The IAEA developed hydrogen production through SMSFR using HEEP software. Results indicate that the most suitable hydrogen production methods for SMSFR are the copper-chlorine cycle and conventional electrolysis, considering the reactor's outlet temperature and the goal of zero-carbon emission. Economic analysis shows hydrogen production via water electrolysis using SMSFR with MOX fuel costs $3.78 per kg.

TABLE 1. Hydrogen Production through SMSFR

Details of Nuclear Power Plant	Value	Details of Hydrogen Plant	Value
Thermal rating (MWth/unit)	860	H2 generation per unit (kg/yr)	1.26×10^{8}
Heat for H2 plant (MWth/unit)	0	Heat consumption (MWth/unit)	0
Electricity rating (MWe/unit)	360	Electricity required (MWe/unit)	720
Number of units	2	Number of units	1
Initial fuel load (kg/unit)	17310	Overnight Capital cost(USD/unit)	$4.23E\times10^{8}$
Annual fuel feed (kg/unit)	5770	Energy usage cost# (USD)	0
Overnight Capital cost(USD/unit)	2.48×10^{9}	Other O&M cost(% of capital cost)	4
Capital cost fraction- electricity generating infrastructure (%)	10	Decommissioning cost (% of capital cost)	10
Fuel cost (USD/kg)	1850		
O&M cost (% of capital cost)	1.66		
Decommissioning cost (% of capital cost)	2.8		

3.2. Steam production

Compared to advanced reactors like PWR and HTGR, the SMSFR offers higher steam outlet temperature and pressure, producing high-quality steam for industrial use. Therefore, it is reasonable to predict that SMSFR could be built near industrial companies to supply high-quality steam. SMSFR can meet thermal users' high, medium, and low-pressure steam requirements without additional heat sources.

In some particular conditions, when the project steam supply requirements are enormous or there is economic competition with traditional heat sources, the economic issue of the independent steam supply of fast reactors can be considered. A coupled steam supply scheme between fast reactors and PWRs can determine the overall economic efficiency of nuclear power supply projects. A hybrid steam supply scheme using both fast reactors and PWRs can improve the overall economic efficiency of nuclear power projects. In this setup, the heat from PWRs can generate medium and low-pressure steam, while the main steam from fast reactors can produce high and medium-pressure steam and further superheat it to meet user requirements.Table 2 compares steam quality, indicating that the steam produced by SMSFRs, with a temperature of 455℃ and pressure of 10MPa, is competitive with that from PWRs and HTGRs.

TABLE 2. Comparison of Steam Quality in Steam Production

	PWR	HTGR	SMSFR
Thermal power（MWt）	3180	1500	850
SG outlet pressure（MPa）	6.73	14.3	14
SG outlet temperature（℃）	283.18	541	485
SG outlet flow rate（t/h）	6381.72	2142.72	1200
Flow of steam（t/h）	4000	1600	900
Steam pressure（MPa）	5.4	10	10
Steam temperature（℃）	268.8	510	455

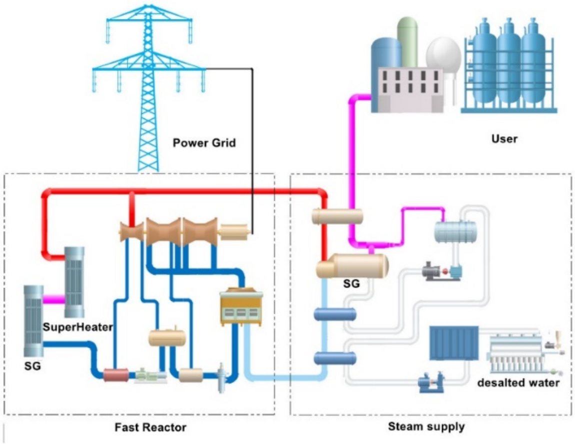

FIGURE 4: Steam Production through SMSFR

3.3. Isotope production

The isotope production technology using SMSFR can generate isotopes such as ^{14}C, ^{60}Co, and ^{63}Ni. Medical isotopes, in particular, have high value, profit margins, and broad market prospects. Moreover, advanced isotope production supports the development of related upstream and downstream industries in China, including the energy, processing and manufacturing, chemical, and scientific research sectors. This promotes the growth of supporting industries and scientific innovation worldwide, effectively enhancing the modernization of the isotope and supply chains.

Fast reactors such as SMSFR have been shown to produce isotopes like ^{63}Ni and ^{60}Co. ^{63}Ni is used in nuclear batteries, is widely employed in aerospace and medical equipment, and has a market demand worth billions annually. Fast reactors are the only reactors capable of producing high specific activity ^{63}Ni that meets nuclear battery requirements. Similarly, ^{60}Co is used as an industrial or medical source, with a market demand of billions of dollars. The mass production of ^{60}Co using SMSFR offers lower costs and significant economic benefits.

The production of actinide isotopes such as ^{252}Cf and ^{238}Pu will be economically significant. ^{252}Cf is primarily used for reactor start-up neutron assemblies and is expensive. ^{238}Pu is used primarily for nuclear batteries in aerospace applications.

4. CONCLUSION

The SMSFR holds significant potential for various applications, such as high-quality industrial steam production, hydrogen production, isotope production, and advanced reactor materials. This paper analyzes the method and economics of the SMSFR multi-purpose application in electricity production, hydrogen production, and steam production.

The main conclusion is as follows:

1. Economic analysis shows that water electrolysis via SMSFR with MOX fuel costs \$3.78 per kg.

2. Compared to advanced reactors like PWR and HTGR, the SMSFR's higher steam temperature and pressure make it ideal for industrial use. SMSFRs can supply high-quality steam directly to industrial companies, meeting various pressure requirements without additional heat sources.

3. A combined steam supply from fast reactors and PWRs can enhance efficiency for large-scale projects or economic competition with traditional heat sources. SMSFR-produced steam, at 455°C and 10MPa, is competitive with steam from PWRs and HTGRs.

4. The SMSFR can produce valuable isotopes like 14C, 60Co, and 63Ni, which have high market demand and profit margins, particularly in medicine, enhancing the modernization of the isotope supply chain. Fast reactors uniquely produce high-specific-activity 63Ni for nuclear batteries and cost-effective 60Co for industrial and medical uses. Additionally, producing actinide isotopes like ^{252}Cf and ^{238}Pu for reactor start-up and aerospace applications presents significant economic opportunities.

The main challenge of the development of SMSFR is the economic challenges from other renewable energy, like solar, and wind power. However, with the lower investment and shorter construction period, the SMSFR could offer a more comparative investment compared with other powers. Its multi-purpose use can significantly enhance energy efficiency and provide broad prospects.

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