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Historical Development and Current Application of Micro Modular Reactors and Path Forward

Jin Sun Choi, Jeong Ik Lee
Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

Micro modular reactors (MMRs) are advanced nuclear reactors that have a power capacity of up to 30 MW_e per unit.[1] The development of Micro Modular Reactors (MMRs) is critical in pursuing sustainable and accessible power at the isolated and remote region. Compared to fossil fuels such as gasoline, MMR technology using uranium has a high energy density and can produce abundant energy with long refueling time.

MMRs, with their small size, stability, and high output, possess the potential to provide energy solutions in remote areas without access to power grids. Currently, research is underway to meet the output and temperature requirements for each application field. MMR is currently being studied in various fields such as nuclear power generation and mobile energy supply. Furthermore, the defense industry is also interested in applying MMR technology.

Table 1. Design constraints on power and temperature requirements for the various targeted market [1].

Field	Requirement	
Target Market	Power (MW_{th})	Temperature (°C)
Industrial Manufacturing	20–40	600-1600
Paper, food, and biofuels	6-50	150-300
Shipping	6-25	Mostly or only electricity
Microgrid	0.15-100	Mostly or only electricity
District heating	15-100	50-100
Desalination	15-75	Mostly or only electricity
Remote communities	0.3-25	Co-generation: 50-100
Military application	0.3-5	Mostly or only electricity

This paper explores how MMRs have evolved from the past to the present, providing electricity and thermal energy tailored to environmental needs, extending to advanced industrial applications in remote regions. The historical development of MMRs is first discussed, and this will be followed by presenting the potential directions for future implementation, emphasizing their adaptability to environmental contexts and emerging needs.

2. Historical development of MMR

The development of MMR began in the 1950s, in an Army Nuclear Energy Program (ANPP) as a joint venture between the U.S. Department of Defense (DoD) and the Atomic Energy Commission (AEC) to meet defense requirements. In early 1950s, the Atomic Reactor Experiment (ARE), the first nuclear reactor experiment for aerial propulsion conducted in the United States, was used to evaluate the efficiency, safety, and practicality of nuclear fuel. Early experiments, which were of great interest in the development of nuclear technology at that time, played an important role in the safety assessment of current nuclear energy technology.

At the end of 1950, the Stationary Medium Power Reactor-1 (SM-1), developed by the U.S. Army, was used for military purposes to generate nuclear power for inter-operational use. In early 1960, the first commercial reactor in the United States had a larger output than the SM-1, so Portable Medium Power reactor-2A (PM-2A) was deployed in fishing boats or bases to supply electricity. Since then, the SM-1A, which had better stability, performance, and technical characteristics, was further developed to improve design, lower operating costs, and increase efficiency.

Developed by the U.S. Navy in the mid-1960s, the PM-3A is the first mobile nuclear power plant with a modular design and was designed to reduce fuel charging and replacement for ships. Thereafter, the Mobile Low Power Reactor (ML-1) was developed to be used in a wider range of remote and military areas than the PM-3A. It increased energy conversion efficiency by introducing a cooling system using high-temperature gas. In 1970s, the Mobile High Power Reactor (MH-1A) had higher efficiency and superior mobility than ML-1, enabling a timely energy supply for military operations. The output power and reactor type developed in the past are listed in Table 2.

Table 2. Characteristics of past MMR Technology[2–6].

	Output (MW_e)	Reactor Type	Power Cycle	Fuel Type
ARE	1-3	MSR	Brayton	NaF, UF_4, ZrF_4
SM-1	10	PWR	Rankine	UO_2
PM-2A	1.6	PWR	Brayton	U-235 contained in 90% enriched flat MTR type
SM-1A	20	PWR	Rankine	UO_2

PM-3A	1.5	PBR	Rankine	U-235 enrichment Of 93 percent.
ML-1	0.3	PWR	Brayton	UO_2
MH-1A	10	PWR	Rankine	LEU

3. Recent development of MMR

In the 2000s, as global energy demand increased, small modular reactor (SMR) technology emerged due to economic and environmental factors, and the development of small nuclear reactors became important. After the Fukushima nuclear accident in Japan in 2011, uncertainties in the nuclear utilization development environment increased worldwide, and ultra-small nuclear reactors with high safety and low investment risk attracted attention again. Accordingly, from the 2010s to the present, MMR technology, which has excellent mobility on a smaller scale than SMR, has been developed and applied in various ways around the world.

As Table. 3, MMR technology is being developed using a variety of reactor types. Of these reactors, the two most commonly used for MMR applications today are the High Temperature Gas Cooled Reactor (HTGR) and the Heat Pipe. HTGRs and heat pipes can operate at higher temperatures than conventional reactors, allowing them to produce electricity, heat, and hydrogen. These reactors can be built in a variety of sizes and shapes, allowing them to be designed to fit your requirements and have the potential to be utilized in many applications.

Table 3. Characteristics of current MMR Technology [7–10].

	Output (MW_e)	Reactor Type	Power Cycle	Fuel Type
MoveluX (Japan)	3	Heat Pipe	Brayton	Uranium/ Hexagonal
UNITHERM (Russia)	6.6	PWR	Rankine	U-Zr metal ceramic
AMR (South Africa)	3	HTGR	Brayton	TRISO / LBE / SiC tubes
U-Battery (U.K.)	4	HTGR	Brayton	HALEU
Aurora (U.S.)	1.5-50	LMFR	Brayton	HALEU
MARVEL (U.S.)	0.015-0.027	LMFR	Brayton	HALEU
BANR (U.S)	17	HTGR	Brayton	TRISO

While MMR technology was initially focused on military applications in the past, it is now being utilized in various fields such as nuclear power generation, mobile energy supply, and green hydrogen production. It contributes not only to military field but also to providing power to remote areas and addressing environmental issues. As research and development progress worldwide, this technology, surpassing the proposed application areas, demonstrates extensive potential for utilization.

The United States, Canada, and Russia are developing small-scale nuclear power plants using MMR technology. As shown in Fig. 1, Oklo Inc. in the United States are developing a reactor to produce electricity and supplying energy with environmentally friendly and safe nuclear energy solutions. These small-scale power plants enhance safety and environmental suitability and can operate for decades without refueling, ensuring sustainability and efficiency.

Accordingly, the Defense Advanced Research Projects Agency (DARPA) of the United States actively explores the deployment of MMRs through the Portable Electric Power (PELE) project for mobile energy supply. This initiative aims to ensure timely energy supply even in remote areas.

Table 4. Characteristics of PELE project [11].

Output (MW_e)	1-5
Reactor Type	-
Power Cycle	-
Fuel Type	HALEU
Purpose	Military Operation Energy Supply

For the PELE project, the U.S. Department of Defense selected BWX Technologies (BWXT), which supplies nuclear reactors for submarines and aircraft carriers. The MMR developed by BWXT is transportable to BANR and a modular, factory-built system is being developed. The BANR will provide flexible options for energy output, including electricity and steam for process heating through cogeneration, while minimizing greenhouse gas emissions.

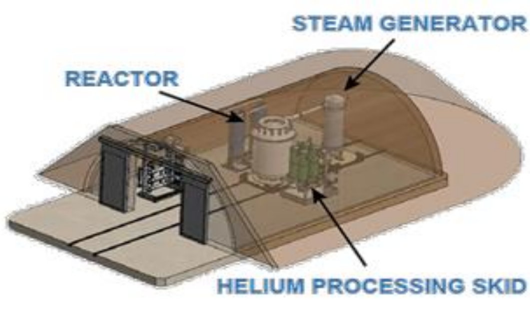

Fig 1. BWXT Advanced Nuclear Reactor(BANR) [12].

Furthermore, by enhancing the efficiency and sustainability of hydrogen production, MMR can be a decarbonized clean energy source. In Canada, Hyundai Engineering, SK E&C, and Ultra Safe Nuclear Corporation (USNC) are fostering a hydrogen economy using USNC MMR technology. As shown in Fig. 2, combining MMR with Solid Oxide Electrolysis Cells (SOEC) technology improves the efficiency of hydrogen production.

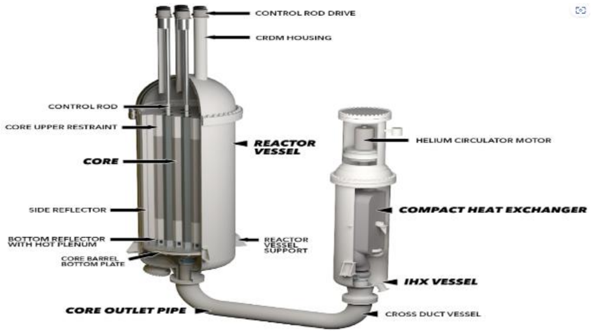

Fig 2. Combining MMR with SOEC [13].

Table 5. Characteristics of MMR (USNC) [14].

Output (MW_e)	5-10
Reactor Type	HTGR
Power Cycle	Brayton
Fuel Type	TRISO
Purpose	Hydrogen Production

In the defense sector, apart from providing 50-200 kW of energy per hour, it enables flexible installation of battery modules under vehicles or in designated spaces, thereby securing additional room. Additionally, it enhances survivability against Improvised Explosive Devices (IEDs) or anti-tank mines.

Fig 3. Battery Platform for Electric Military Vehicle (GM) [15].

As the demand for data-centric technologies and AI data centers increases, the importance of stable power supply to data centers is also emphasized. The application of MMRs enables reliable electrical energy supply to data centers, contributing to intensive energy needs in IT infrastructure and the global data economy.

Table 6. The power demand and consumption of a data center measuring 5000 square meters [16].

	Power Draw
Computing	588kW
Lighting	10kW
UPS and distribution losses	72kW
Cooling power draw for computing and UPS losses	429kW
Building switchgear / MV transformer / Other losses	28kW
TOTAL	1,127kW

5. Discussion / Summary

Developed countries are developing MMR technology for reasons of affordability, reliability, and efficiency in construction and operation. Most of the next generation of reactors will use high temperatures. Nuclear policy trends in the United States are moving toward relaxing containment building requirements for TRISO. While the core volume is large, the overall system volume can be small. For this reason, HTGRs using TRISO fuel may be the best fit.

While initially developed for military purposes, as the economic viability and stable energy supply increase, MMR technology will continue to be developed. If the proposed ultra-small reactor utilizing MMR technology is developed and commercialized, it is expected to significantly contribute to energy self-sufficiency and flexibility in the defense sector and ensure stable power supply for data centers in the near future. However, efforts to address its shortcomings are also necessary, and reducing the license uncertainty will be imperative for the further development of the MMR system.

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