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Global Trend of Micro Nuclear Reactors

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1. Introduction

It is after the Fukushima nuclear accident occurred in 2011 that small nuclear reactors began to draw attention in earnest worldwide. The Fukushima nuclear accident raised anxiety about the safety of large nuclear power plants, which in turn led to the search for highly safe alternatives, and as a result, especially the development of micro nuclear reactors (MNRs). In this paper, a micro nuclear reactor is defined as a very small-scale nuclear power system that produces electricity output of less than 30 MWe or heat output of less than 100 MWth, which can specifically respond to off-grid energy demand. From this point of view, this paper investigates and analyzes the global trend of MNR developments. Chapter 2 reviews the historical development of MNRs by country. Chapter 3 investigates technological evolutions of MNRs by reactor type. In chapter 4, the conclusions summarized the research results and suggested the strategic direction for the development of Korea's micro reactors.

2. Historical Development

The United States has developed and used MNRs for national defense since the inception of nuclear technology. From 1954 to 1977, the United States Army developed and operated MNRs to operate military bases in remote locations through the Army Nuclear Power Program (ANPP). At that time, eight MNRs were constructed, of which five are of mobility. This included the first 10 MWe floating nuclear power plant (MH-1A) and the ML-1, a 0.3 MWe mobile MNR that could be transported by truck. More recently, the U.S. Army has been pushing for the introduction of very small mobile nuclear power plants. In 2018, the feasibility study was completed, and the project is underway. The mobile nuclear power plants are considered as an alternative to reduce energy supply vulnerabilities and operating costs during military operations. The development of the U.S. MNRs for the private sector was supported by the Department of Energy's DOE's Advanced Research Projects Agency-Energy (ARPA-E), established under the 2007 Act. Overall, ARPA-E focuses on high-potential, high-impact energy technologies that are too early for private sector investment. ARPA-E is currently launching a program to support technology development in subminiature sizes under 10 MWe. In the United States, it is expected that the first commercial MNRs will be deployed in the mid-2020s. Russia has been developing and operating MNRs for defense and civilian use since the late 1950s. Most of them are based on light water reactors and high temperature gas cooled reactors, and are designed to be used in remote civilian or military bases. In particular, Russia is leading the development of light-water reactor-based micro reactors worldwide. From 1961 to 1965, the mobile 2MWe light-water reactor type TES-3 was operated, and the world's smallest commercial reactor, 12MWe, has been in operation since 1976. As of 2019, four types of light water reactor-based micro reactors are being developed: ABV-6, UNITHERM, SHELF, and ELENA. Canada's initial nuclear reactor demonstrated 19.5 MWe of electrical output. In Canada, Automat Energy of Canada Limited (ECL) has developed several MNRs, including the Slowpoke Energy System 10 and Compact Nuclear Power Source, to power Canadian Arctic military facilities and remote communities in the north. In recent years, Canada is actively pursuing the development of MNRs. Canada's Ontario is pursuing the deployment of MNRs for remote mining in the north. In addition, the Canadian Nuclear Laboratories (CNL) is pursuing the construction of small or micro nuclear reactors on the Choke River site by 2026. Meanwhile, the Canadian Nuclear Safety Commission (CNSC) is conducting a Pre-Licensing Vendor Design Review (PVDR) service for small nuclear reactors (hereinafter referred to as the "Supplier Design Pre-Review"). As of October 2019, CNSC is conducting preliminary reviews of supplier designs for eight types with capacities ranging from 3 to 300 MWe. China has been developing MNRs mainly as a test reactor for 4th generation nuclear power plants. The HTR-10 of 10MWe class, which started operation in 2000, is being used for development as a 200MWe class high temperature gas cooled reactors to be developed by 2025. China has been developing HTR-10 and developing high temperature gas cooled reactor pebble-bed module (HTR-PM) of 210 MWe since 2001. China is developing and operating CEFR, a 20 MWe-class experimental expressway, and it is being used for the CFR600 highway reactor project, which is being developed for demonstration in the 2030s. The 2MWe thorium molten salt test reactor currently under construction is intended to commercialize the world's first thorium-based molten salt reactor around 2030. In addition, in May 2017, the world's first mobile mini-reactor "Hedian Bao" using lead-based alloy material as a coolant was developed. In Japan, a High Temperature Engineering Test Reactor (HTTR) is in operation, and light water reactor MRX and high-speed reactor 4S are being developed. Japan Atomic Energy Research Institute (JAERI) is operating the HTTR with a heat output capacity of 30 MWt. The first rated power was reached in December 2001 at a reactor outlet coolant temperature of 850 ˚C. In 2009, it operated at 950 ˚C for 50 days. Based on the experience of HTTR, JAERI is developing a large gas turbine high temperature gas cooled reactor (GTHTR) with output of up to 600 MWt per module and 275 MWe per module.

3. Technological Evolutions

Many MNRs are being developed at various stages worldwide. It can be broadly classified into evolutionary (progressive) innovative technologies derived from large-scale nuclear power plants of the 3rd generation and fundamental innovative technologies of the novel 4th generation concepts. Of the many MNRs under development, very few are actually in operation or under construction, but most are in the stage of design development. The MNRs of the 3rd generation concept belongs to the light water reactor (LWR). Designs already in operation or closest to deployment are based on Russian technology and have already been adopted by the military. As of 2019, one product is operating and six products are under development worldwide. Russia's EGP-6 has been in commercial operation at the Bilibino nuclear power plant since 1976. As of 2019, there are 6 LWR-type MNRs under development including VKT12 (Russia), ABV-6 (Russia), UNITHERM (Russia), SHELF (Russia), ELENA (Russia) and MRX (Japan). MNRs of the 4th generation concept are not light water reactors. Six products of MNRs that are under development are high temperature gas cooled reactors (HTGRs). HTTR (Japan) and HTR-10 (China) are in operation, but both are experimental reactors. Except for them, MMR-5 (USA), Holos (USA), U-battery (UK), Starcore (Canada), MTSPNR (Russia) and MHR-100 (Russia) are in the stage of basic or conceptual design. Seven products of MNRs are fast breed reactors (FBRs) which are now under conceptual design. They are three MNRs (Gen4, SSTAR, Oklo) in the USA, two MNRs (4S, Rapid) in Japan, and ANGSTREM (Russia) and Sealer (Sweden) in Russia and Sweden, respectively. China Atomic Energy Institute has been operating CEFR since May 2010. But it is a test reactor. Three molten salt MNRs are being developed. The United States and China are jointly developing one. And Canada and Russia are developing one each. In addition to the concept of the 4th generation type, MNRs using heat pipes have recently been developed. Heat pipes have rarely been used in commercial reactors. The heat pipe-based micro reactor is expected to be the safest and most reliable reactor by securing passive inherent safety. Two products are being developed in the U.S., such as eVinch and NuScale Micro.

4. Conclusions

This paper investigated and analyzed the trend of MNRs development worldwide. The MNRs of commercial purpose are currently being developed in the United States, Russia, the United Kingdom and Canada. Historically, MNRs was developed primarily for military or civilian use to provide independent energy systems in remote areas. The United States and Russia have been leading the development, while Canada, China and Japan are following. In recent years, the UK is pursuing MNRs development. In the technological evolution of MNRs, light water reactors has been the most common. It had been developed in the United States and Russia since the late 1950s. Russia led this type of MNRs. Russia is still operating three LWR-type MNRs at the Bilibino power plant, which has been operational since the mid-1970s. Now Russia is developing four other models. Besides the LWR type, the development of high temperature gas cooled MNR was very active. It was developed in Russia in the 1970s. Recently and in the early 2000s it was developed and in operation in China and Japan for testing purposes. The fast-breed and the molten-salt type are being developed in the United States, Japan, Russia, Sweden, and Canada. Both types are mostly in the conceptual design stage. In addition, recently, MNRs that introduce the concept of heat pipes to nuclear technology have been developed. They pursue passive intrinsic safety as their greatest advantage. As for a further study, a strategic planning should be explored for the development of MNRs in Korea in both terms of technical challenges and socio-economic opportunities from a perspective of sustainable development.

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