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Global Trend of Molten Salt Reactors

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1. Introduction

In order to meet the sustainable development, it is necessary to develop nuclear technology without the risk of radiation accidents. Current nuclear technology on the basis light water reactors can provide very high reliability of energy supply with very little carbon emission, but it faces political and social opposition due to the risk of radiation accidents. The Fukushima nuclear accident happened in Japan on 11 March 2011 amplified the grave concerns about the danger of radiation accidents. In order for nuclear power to contribute to the sustainable development, therefore it is necessary to develop new technologies that can radically solve the serious accidents in both operating nuclear reactors and managing spent nuclear fuel. Molten salt reactors (henthforth MSR) have been evaluated to be able to meet such expectations. In particular, the Fukushima nuclear accident highlighted the safety which is a great advantage of MSRs. As a result, the development MSRs with high safety has been being increasing worldwide. Against this backdrop, this study aims to examine the trends of MSR development worldwide which will be useful in establishing the strategies for research and development of MSRS in Korea. This paper consists of the following: Chapter 2 examines the characteristics of molten salts. Chapter 3 investigates and analyzes the trends of MSR development worldwide. In chapter 4, the conclusion summarizes the research results and presents the strategic direction for the development of MSRs in Korea

2. Technological Characteristics of MSRs

The molten salt reactor (MSR) is a nuclear fission reactor that simultaneously uses nuclear fuel salt, a mixture of coolant and nuclear fuel, as fuel and coolant for the reactor by dissolving nuclear fuel in molten (base) salt that maintains a stable liquid state at an very high temperature and atmospheric pressure.

First, during the operation of MSRs, the nuclear fuel and the coolant are integrated into a liquid mixture (melted salt) and the nuclear fuel is always cooled. Therefore, there is no possibility of serious accidents, like the Fukushima accident, in which nuclear reactors melt down due to the loss of coolant.

Second, the need for a control rod is greatly reduced since the MSRs continuously removes the fission products generated and charges the nuclear fuel during their operation. Accordingly, human errors linked to the control rods can be reduced. Third, the MSRs can easily remove residual heat when they are shut down. Since the MSRs continuously remove fission products generated during their operation, residual heat is generated very little when the reactors stop operating. Fourth, the MSRs with fast neutrons using chlorine base salt can carry much less risk of radiation accidents due to spent nuclear fuel because they do not discharge highly radioacitve materials with long half-life, and weaken the toxicity of fission products. Fifth, in these fast MSRs using chlorine salt as sensitive nuclear materials are used as fuels and burned 100%, during the entire life of the reactor operation, so the risk of nuclear proliferation dramatically decreases. Sixth, MSR offers high energy productivity because they produce high energy conversion efficiency and high temperature heat. Last, MSRs could be economical to produce electricity and heat because of its very high safety, simple structure, high thermal efficiency, and very little waste management burden. Overall, it is expected that the cost of electricity production with molten salt will be only 1/2 of that of light reactors.

3. Historical Evolution of MSRs

Globally, MSRs began to be developed in the United States in the early 1950s. The Oak Ridge National Laboratory (ORNL) in the US developed and operated three experimental MSRs with thermal neutrons such as ARE, PWAR-1, MSRE from the early 1950s to the end of the 1960s. By 1954, the ORNL developed the first MSR, named ARE that was the 2.5MWh-class experimental reactor for the US Air Force. The ARE ran for nine days. In 1957, another MSR, or PWAR-1 of Pratt & Whitney Aircraft Company (PWAC) was developed and operated for weeks at zero power at an oak facility. By 1965, ORNL had developed the 7.5MWth-class MSRE for power generation and operated for about 20,000 hours for four years. From 1970, a molten salt furnace using fast neutrons was developed. By 1976 ORNL had designed a Molten Salt Breeder (MSBR) with an output of 2,250 MWth. However, the MSBR project was suspended as the US government preferred fast breeder reactors, more specifically. the liquid metal fast breeder (LMFBR). In the 21st century, especially after the Fukushima nuclear accident, the development of MSRs with high nuclear safety resumed in earnest. In 2011, Liquid Fluoride Thorium Reactor (LFTR) with an electrical output of 20-50 MWe using the thorium fuel cycle began to be developed to power military bases. Transatomic Power developed a Waste-Annihilating Molten Salt Reactor (WAMSR) capable of burning spent nuclear fuel dischared from the light water reactors and operated it from 2011 to 2018. Molten Chloride Salt Reactors using fast neutrons began to attract attention when Terra Power, founded in 2015 by Microsoft founder Bill Gates, began development. Terra Power founded in 2015 by Bill Gates and Southern Company is developing a Molten Chloride Salt Reactors using fast neutrons, named Molten Chloride Fast Reactor (MCFR) under government subsidies.

4. Trends of MSR Development by Country

The United States has been leading the development of MSRs worldwide. The US created the concept of MSRs and led global MSR research from the mid-1950s to the mid-1970s worldwide. In 1954, it developed an Aircraft Reactor Experiment (ARE) with an output of 2.5 MWth for aircraft propulsion and operated it for about 9 days. The MSRE (Molten-Salt Reactor Experiment) for power generation, was developed as an experimental reactor with an output of 7.5MWt and operated for about 20,000 hours for 4 years from 1965. The United States then promoted the design and development of MSBR using high-speed neutrons in the early 1970s. However, the MSBRprogram was suspended as the U.S. government preferred the liquidmetal high-speed proliferation path (LMFBR). In the 21st century, Transatomic Power developed a Waste-Annihilating Molten Salt Reactor (WAMSR) capable of burning spent nuclear fuel dischared from the light water reactors and operated it from 2011 to 2018. Terra Power and Southern Company are developing a molten chloride fast reactor (MCFR). Recently, Idaho National Laboratory designed a moltensalt furnace with an expected output of 1000 MWe. The UK developed MSRs from 1964 to 1974. Atomic Energy Research Establishment (AERE) in the UK studied a Molten Salt Fast Reactor (MSFR) with an electrical output of 2.5GWe using fast neutrons. In the 2010s, the development of MSRs resumed again in the UK. UK Moltex Energy is developing three innovative MSRs. SSR-W, SSR-U and SSR-Th are designed to use plutonium, uranium and thorium as fuel respectively.

The Kurchatov Institute in Russia began the research of MSRs in the late 1970s while paying attention to thermo-chemcal, corrosive and radiative properties of MSR materials. After the Chernobyl accident in 1986, R&D on MSRs was also reduced along with the overall downturn of the nuclear industry. In 2020, Rosatom announced a plan to build a 10MWth MSR by 2031.

In 2011, China started the development of a thorium molten salt furnace (TMSR-SF) using solid fuel and aims to operate it by 2024. China is also developing a liquid-fueled thorium molten salt furnace (TMSR-LF). By 2020, two 12 MW class TMSR-LF1 prototypes have been built at Wuwei. In September 2021, it succeeded in operating TMSR-LF1, the world's first experimental MSR using thorium. After that, the TMSR-LF1 being operated by 2024, a larger 100-MW-class TMSR-LF is planned to be operated by 2035 for demonstration. In 2021, Canada's Terrestrial Energy is developing an Integrated Molten-Salt Reactor (IMSR) with a power output of 400 MWt (190 MWe) using denatured uranium(U-235) and graphite moderator. In 2017, the IMSR completed the first phase of 'Pre-Licensing Vendor Design Review' by the Canadian Nuclear Safety Commission. Denmark which adopted a policy to ban nuclear power generation in 1985 is developing two designs of MSRs. Copenhagen Atomics is developing a Copenhagen Atomics Waste Burner (CAWB) using fluorine salt and thermal neutrons. Denmark's Seaborg Technologies is developing a Compact Molten Salt Reactor (CMSR) with a thermal output of 100 MWth. Germany, which leads anti-nuclear power policy worldwide, is also developing a MSR. German Institute for Solid State Nuclear Physics (GISSNP) is developing a lead cooling MSR using fast neutrons. Since 2015, Indonesia which has frequent earthquakes is earnestly pushing for the development of two MSRs by importing ThorCon MSR (TMSR) in the US. TMSR-500 is expected to be built in the early 2030s. Indonesia began to develop TMSRs with a scale of less than 50 MWe for power generation or marine propulsion. India is developing MSR as an alternative to the thorium-based nuclear program in the country. India announced the design of MSR in 2015. The Fuji Molten Salt Reactor (FMSR) under development in Japan is a 100 to 200 MWe LFTR and is expected to take 20 years to commercialize. France's CNRS conducted a study on the industrial feasibility of molten salt fast reactor (SAMOFAR) named EVOL(Evaluation and viability of liquid fuel fast reactor system) and published final report in 2014.

5. Conclusions

This paper analyzed the global evolution and national trends of MSR development in 11 countries. MSRs are expected to be among the safest, most non-proliferation and economical energy providers which will be used in the near future. Hence MSRs are being developed in Denmark and Germany, which have a policy to ban nuclear power generation, and Indonesia which has frequent earthquakes. Since the 1950s, the MSRs have been developed but not reached commercialization until 2021. In terms of policy, the US and the UK preferred fast breeding options to MSRs. However technical challenge linked to material corrosion has become a critical barrier to the further development of MSRs. However, after the Fukushima nuclear accident, safety was emphasized more than economics. And the corrosion problem are getting to find potential answers. This changing circumstance has renewed the interests in MSRs. As of 2021, 25 institutions and companies in many countries are developing MSRs. however, their progress mostly remain in the pre-commercialization stage. By country, the United States is leading the development of MSR while the UK, Russia, China, Denmark, Canada, and Indonesia working on the MSR projects. Bearing this understanding in mind, this study proposes strategic directions for the R&D of molten chloride salt reactors in Korea. First, R&D should be focused on solving techical uncertainty. Second, R&D should produce international patents for key technologies for exploiting and dominating global markets. Third, technical challenges should be efficiently overcome through international cooperations.

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