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Safety Analysis of MicroURANUS LFR for Unprotected Loss of Flow and Unprotected Loss of Heat Sink

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1. Introduction

Nuclear energy is facing a new phase in many ways. In a broader direction, it has two aspects: high safety, competitive high economic feasibility due to the need for alternative energy sources. First, after the Fukushima accident, more reliable verification of the safety of large nuclear reactors such as existing PWRs was required from society and the public. To fill the demand, a nuclear reactor with a higher level of safety is needed, not the level of current nuclear power plants.

Next, the need for next-generation energy sources to reduce carbon emissions and ultimately achieve carbon neutrality by 2050 is on the rise. Thermal power systems, which currently use most of the electricity, structurally emit a large amount of carbon. In addition, transportation vehicles and machinery engines that use fossil fuels also emit a significant amount of carbon. To cope with climate change, it is serious to develop and enhance new energy sources that can replace thermal power generation and fossil fuels. However, renewable energy sources such as solar and wind power, although excellent in not emitting carbon, have many disadvantages from the perspective of power plants that need to supply electricity stably. Therefore, next-generation nuclear reactors are gaining attention as an energy technology that can overcome the supply instability of renewable energy and completely replace thermal power generation and fossil fuels.

For these two reasons, Gen-IV reactors are being developed in many countries, and various types of reactors are being studied [1]. The Gen-IV reactors have several representative types, including Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Supercritical Water-cooled Reactor (SCWR), Sodium-cooled Fast Reactor (SFR), and Very High Temperature Reactor (VHTR). Among them, liquid metal reactors such as LFR and SFR are also gaining attention due to their various advantages and operational experiences. Liquid metal reactors are also characterized by high thermal conductivity of the coolant and the possibility of operation at atmospheric pressure.

Among various liquid metal coolants, research on Lead/LBE (Lead-Bismuth Eutectic) based LFR, which has the advantage of not reacting with water, is being conducted around the world. In addition, LFR has been operating since the 20th century, and there are practical experiences [2].

Although LFR has many advantages, it does not have a lot of operational experience or successful cases. LFR is still in the development stage. Research on how lead-based coolant works in terms of safety in the nuclear reactor, and whether LFR is safe in various accident scenarios such as pump trips, is essential. Safety concerns from society are increasing, but these reactors have little safety research, and they are only at the conceptual design level.

There are several safety analysis cases for LFR. First, there are safety analysis cases using ELFR and the demonstrator ALFRED in Europe [3,4,5]. Accident scenarios are classified into design-based conditions (DBCs) and design-extended conditions (DECs), and safety is demonstrated through each analysis. Next, safety analysis has been performed in various places, such as ULOF and UTOP analysis based on the SVBR 75/100 conceptual design [6], safety analysis in the natural circulation-based SNCLFR-100 design [7], and safety analysis in China's M2LFR-1000 [8].

The UNIST in Korea is also conducting research on LFR. MicroURANUS is an LFR that aims to replace the propulsion power of ships with micro LFR, reduce the use of fossil fuels, and operate ships for a long time without replacing nuclear fuel. However, MicroURANUS is still at the conceptual design stage, and therefore safety analysis is essential.

2. Numerical Method

MicroURANUS is a small-scale LFR being developed at UNIST, with an output of 60MWth. It utilizes the properties of LBE coolant to operate at a lower temperature range of 270°C to 370°C, compared to the traditional lead coolant. The primary system has a pool-type design, and heat removal is achieved through 12 SG (steam generators). Detailed figures can be found in Table I.

To perform the analysis, the MARS-LBE code, which put LBE's properties in the MARS-KS code was used. To ensure a more conservative safety analysis, unprotected accidents were analyzed where the scram signal is signed but the reactor core, pump, and heat source continue to operate. Therefore, in the event of an accident, the core output is controlled solely by the inherent safety characteristics of MicroURANUS.

Table I: MicroURANUS design parameter

Power	60MWth
Core material	UO_2
Cladding material	15-15Ti
Coolant material	LBE
Core inlet temp.	270℃
Core outlet temp.	370℃
# of SG	12
Primary system pressure	1 bar
Second system pressure	58 bar
Feed water temperature	231℃
Coolant mass flow rate	4105kg/s

Additionally, MicroURANUS has four PRACS systems to remove decay heat in case of an accident, but for a more conservative safety analysis, it was assumed that only one PRACS system would operate in case of an accident. It was also assumed that the auxiliary feed water system, designed to operate before PRACS activation, would not operate in an accident. The schematic diagram and nodalization of MicroURANUS used in the safety analysis are shown in Fig. 1 and Fig. 2, respectively.

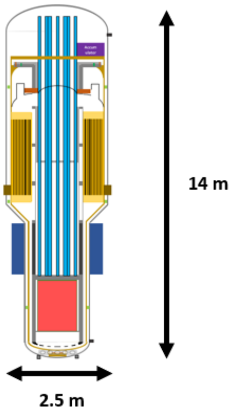

Fig. 1. Schematic diagram of MicroURANUS

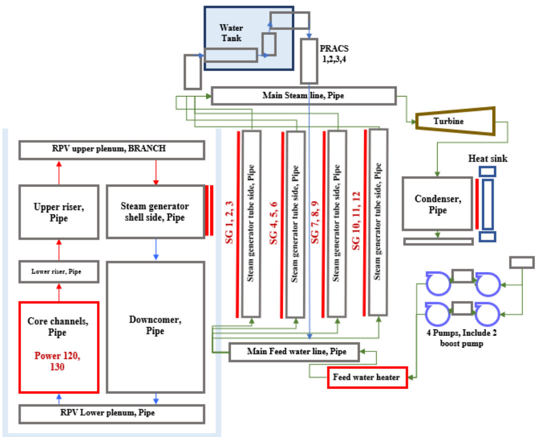

Fig. 2. MARS-LBE nodalization of MicroURANUS

When analyzing accidents, a criterion for determining the point at which safety is threatened is needed. Three safety criteria were classified based on the properties of three materials. First, nuclear fuel must remain in a solid state, so a criterion of 2673℃ or below was established based on safety analyses of LFRs that use UO_2. Second, the cladding, which uses 15-15Ti, must also remain in a solid state, so a criterion of 1407℃ or below, the melting point, was established. Finally, to maintain LBE in a liquid state, a criterion of 127℃ or higher, above the melting point, but below 1670℃, the boiling point, was established [9]. The analysis of unprotected accidents focused on loss of flow and loss of heat sink. Although the loss of coolant accidents may occur due to damage to SG or other reasons, it was not calculated as MicroURANUS operates at atmospheric pressure in the primary system.

3. Numerical Results

It is analyzed that the unprotected loss of flow (ULOF) accident occurs when the flow in the primary system is lost due to the failure of the pumps. In this situation, only natural circulation can remove the heat generated in the core. The mass flow rate is conserved at around 50% due to the natural circulation caused by the height difference between the thermal centers. The accident starts at 3 seconds from the steady-state condition. Negative reactivity is inserted due to the Doppler effect and coolant density effect, resulting in a slight decrease in power. From the reactivity graph, the total reactivity which has a negative value drops significantly and returns to zero. The power does not decrease to the level of decay heat, because the heat sink is operating properly and removing the heat. If the heat sink had not been operating, the primary system temperature would have continued to rise, and the power could have decreased to the level of decay heat due to the high negative reactivity. The peak coolant temperature, peak cladding temperature, and maximum fuel temperature were found to be 468.0℃, 539.5℃, and 1259.6℃, respectively. All three values are below the safety criterion. The graph of the calculation is shown in Fig. 3.

Next, an analysis was performed for unprotected loss of heat sink (ULOHS). Unlike ULOF, this accident refers to a situation where the transfer of heat from the coolant through the steam generator (SG) is lost due to a failure in the secondary system. The coolant pump operates normally, so the mass flow rate in the primary system is maintained at a certain level or above. However, a phenomenon occurs where the mass flow rate gradually decreases, because the coolant temperature becomes more similar between the hot and cold pools due to the loss of heat sink, and the natural circulation decreases accordingly. Negative reactivity is inserted due to the Doppler effect and coolant density effect, and the resulting power decrease is greater than in the case of ULOF. In the reactivity graph, it can be seen that the total reactivity, which is a negative value, approaches zero as time passes. Due to the loss of heat sink, it became impossible to balance the heat transfer, and it can be confirmed that the power decreases closer to the decay heat level unlike in the case of ULOF. The peak coolant temperature was 857.6℃, the peak cladding temperature was 861.9℃, and the maximum fuel temperature was 1202.9℃, all of which were below the safety criterion. Compared to ULOF, it had a higher coolant and cladding temperature and a lower maximum fuel temperature, which is because the ULOHS accident has a slower rise in coolant temperature but ultimately results in a higher temperature due to the loss of heat sink. The calculation graph is shown in Fig. 4.

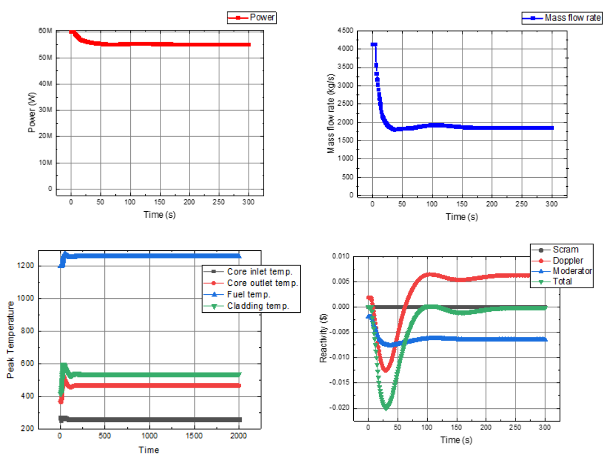

Fig. 3. ULOF safety analysis result (Power, Mass flow rate, Temperature, Reactivity)

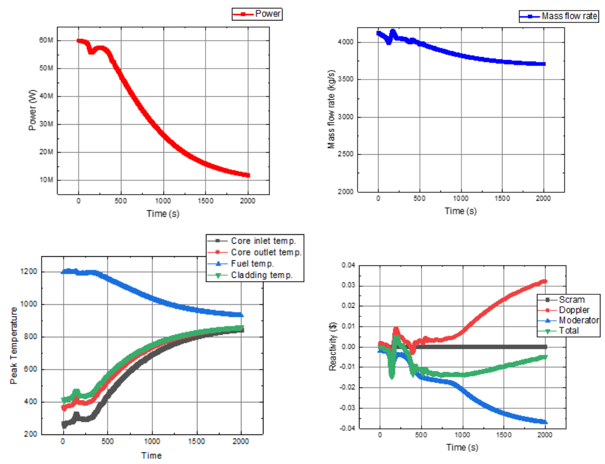

Fig. 4. ULOHS safety analysis result (Power, Mass flow rate, Temperature, Reactivity)

4. Conclusion

Based on the MicroURANUS conceptual design being developed at UNIST, a safety analysis was performed. Peak temperatures that do not exceed the safety criterion were observed for both unprotected loss of flow (ULOF) and unprotected loss of heat sink (ULOHS), demonstrating the safety of the design extended conditions. However, additional issues such as shaking due to the LBE coolant mass, and polonium emitting exist for the liquid fuel reactor (LFR), and further research is needed to demonstrate its safety in these areas.

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