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Development of a plant dynamics analytical model using flow network for the MONJU ex-vessel fuel storage system

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ABSTRACT

If a station blackout (SBO) occurs in a fast breeder reactor, heat removal by natural circulation is expected, because the height between the heat source and the sink was considered in the plant design to provide the potential for natural circulation. Therefore, many studies about heat removal by natural convection have been reported to date. In these studies, it was determined that the thermal hydraulics for natural circulation depend on the plant structure, cooling system, and component positions, unlike in the case of forced circulation. Thus, the heat removal ability by natural circulation differs in each system and each plant.

For the fast breeder reactor (FBR) "MONJU" during normal operation, the ex-vessel fuel storage system (EVSS), which uses a natural circulation flow inside the ex-vessel fuel storage tank (EVST), and the EVST sodium cooling system rely on forced convection with an electromagnetic pump. The decay heat can be removed by air coolers and blowers. If an SBO occurs in this EVSS, all pumps and blowers would be stopped. However, the plant dynamics of the EVSS in the time after all the pumps and the blowers were tripped has not yet been evaluated.

Therefore, in this study, a plant dynamics analysis model was developed using a flow network to calculate the entire dynamics of the EVSS in the event of an SBO. The Super-COPD program, which has been validated for models of the reactor and the main cooling system using several tests including the plant trip test and the natural circulation test, was used. A model of the EVSS was developed by considering the design information, and the modeling technique was based on specific analytical models for the reactor and the main cooling system, because there was no sufficient data to confirm the behavior of the sodium temperature and flow in this EVSS. For the model to simulate natural circulation, the heat capacity of the coolant plenum of the EVST, geometrical information such as the height of the components, and the heat transfer characteristics of the cooling coils were considered.

Based on a comparison to experimental data, it was confirmed that the calculated the behavior of the sodium temperature and flow of the EVST sodium cooling system in an SBO is accurate. The thermal center of the heat transfer area of only the helical coils decreased to approximately 21% in comparison with that under normal operation, and the flow rate in the EVST decreased by approximately 20%. The natural convection force depends on the differences in the densities and the thermal centers of the heat transfer areas between each component. The calculation results based on the theory were almost equivalent to the analysis results. It is estimated that the developed model correctly considered the heat transfer characteristics of each component and can accurately calculate the natural convection force.

From these results, it is concluded that the developed model for the EVSS is effective for calculating the temperature and flow behavior of the entire system under natural circulation conditions like those expected during an SBO. In the future, these models will be validated using a 3D fluid dynamics analysis and additional test results.

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1. Introduction

The Fukushima Daüchi Nuclear Power Plant was severely damaged by the Tsunami after the earthquake on 11 March, 2011. Following the Tsunami, the power supply to all safety systems was cut off, and the plant lost all cooling capabilities, which ultimately led to a meltdown of the reactor core. Because this long-term station

Abbreviations: SBO, station blackout; B-DBA, beyond design basis accident; FBR, fast breeder reactor; DRACS, direct reactor auxiliary cooling system; EVSS, ex-vessel fuel storage system; EVST, ex-vessel fuel storage tank.

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blackout (SBO) was assumed as a beyond design basis accident (B-DBA) in the safety design guidelines for commercial nuclear power plants, to take safety measures against this SBO accident is an urgent need for existing plants.

The assumptions for an SBO in the basic design phase were quite similar to those for the fast breeder reactor (FBR) "MONJU." A long-term SBO was not included in the DBA for MONJU, either; however, the capability for the removal of decay heat by natural circulation was considered in the detailed design phase. Natural convection is generated by the density difference in the coolant, and if the elevation of the heat sink is higher than that of the heat source, natural circulation occurs efficiently. However, the actual cooling conditions change as a function of the quantity of decay heat from the fuel subassemblies. Further, the heat transfer characteristics behave dynamically under low flow rate conditions and the thermal center displacement of the heat exchanger. To evaluate the cooling capability, the heat transfer and pressure loss characteristics of each part of the plant must be appropriately considered. Therefore, many studies regarding heat removal by natural convection have been reported to date.

The experimental fast reactor JOYO, which has a cooling-type system similar to that of MONJU, was subjected to a natural circulation test from 1981 to 1986. The feasibility of decay heat removal by natural convection was demonstrated, even when the plant was tripped from the rated power operation. After this test, the JOYO flow network model was validated using the test results. In this validation, it was confirmed that flow redistribution and heat transfer coefficient degradation occurred due to the Péclet number reduction (Swada et al., 1990). In MONJU, natural circulation tests for the primary and secondary heat transport systems were separately performed by simulating the heat released from the primary pump instead of the decay heat. Heat removal through natural convection was demonstrated on the basis of the results of both tests. The plant dynamic analysis program Super-COPD validated using these test results was shown to be able to simulate the entire plant dynamics with good accuracy (Yamada and Ohira, 2010). From the evaluation using the mainly MONJU test data, it was concluded that the heat transfer coefficient for the shell side of the heat exchanger for sodium was significantly degraded when the Peclet number was low (Mochizuki and Takano, 2009). Moreover, at other international locations, natural circulation tests were performed at FBR plants, and the capability of natural circulation was confirmed (Beaver et al., 1982; Vasile et al., 1985; Schubert, 1985; Singer et al., 1985; RNG Revue Generale Nucleaire, 2009; Favet et al., 1990; Webster, 1982; Tenchine, 2010). In addition, the heat removal capability by natural convection in a pool-type reactor was discussed. It was reported that the direct reactor auxiliary cooling system (DRACS) of the pool-type reactor did not contribute to the initiation of natural circulation of primary sodium through the core. It was determined that the plant should be designed considering the position of the components and only after analyzing the thermal–hydraulic behavior in various possible initial situations, due to the risk of freezing of the sodium inside the sodium–air heat exchanger tube in the air cooler, which is the ultimate heat sink, during onset of natural convection (Tenchine, 2010). Thus, unlike in the case of forced circulation, the thermal hydraulics of natural circulation were observed to depend on the plant structure, cooling system, and component position.

MONJU has an ex-vessel fuel storage system (EVSS) which consists mainly of an ex-vessel fuel storage tank (EVST) and an EVST sodium cooling system. EVST uses natural circulation of sodium for decay heat removal. Natural circulation in the EVST is generated by the decay heat from the spent fuel assemblies and the heat extraction of the cooling coils installed in the EVST. The EVST sodium cooling system consists of three independent loops. In each loop, sodium is circulated by electromagnetic pumps and the heat is removed by an air cooler with blowers. The ultimate heat sink is the atmosphere. The equipment layout considers the elevation of the heat exchanger and air cooler stack for effective natural convection. If an SBO occurs in the EVSS, the situation which all pumps and blowers stopped would continue. However, the plant dynamics of this situation has not yet been evaluated. Therefore, it is necessary that some tests or simulations be performed to confirm the feasibility of heat removal by natural convection in the EVSS.

In this study, a plant dynamics analytical model was developed using a flow network to calculate the entire system dynamics of the EVSS in an SBO. The Super-COPD program was used as the plant dynamics analysis program for the model development, because it was previously validated for models of the reactor core and the main cooling system, including natural circulation conditions, using the plant trip test, and was shown to simulate results that were in good agreement with the test results.

Since there have been few tests performed to evaluate the natural circulation heat removal capability of an EVSS, no sufficient data is available to confirm the temperature and flow behavior, and the characteristics of each component have not been exactly clarified. Hence, models for the EVSS that consider the design information and use modeling techniques based on the specific analytical models for the core and main cooling system should be developed. The purpose of developing this model was to evaluate the plant behavior under natural circulation conditions. Therefore, the heat capacity of the coolant plenum of the EVST, geometrical information such as the height and elevation of the components, and the heat transfer characteristics of the heat exchangers were considered.

2. Outline of the ex-vessel fuel storage system

2.1. Ex-vessel fuel storage system

The outline of the fuel handling and storage systems is shown in Fig. 1. The EVSS belongs to one of these systems. The EVSS consists of the EVST, the EVST sodium cooling system, the EVST primary and secondary auxiliary sodium systems, the EVST primary and secondary argon cover gas systems, and the gate valve gas replacement system.

The EVSS is used for the transit storage of new core elements and spent core elements and for the reduction storage of spent fuel subassembly. The EVST is shown in Fig. 2. It is a vertical and cylindrical tank that has an outer vessel to mitigate sodium leakage and can store approximately 250 core elements. While maintained in the EVST, the core elements are enclosed in transfer pots that are placed circularly in six concentric layers, as shown in Figs. 2 and 3.

The decay heat from the spent fuel subassemblies in the EVST is removed by the EVST sodium cooling system, whose coolant is the secondary sodium. The cooling system is shown in Fig. 4. This cooling system consists of three independent loops with 330 kW of cooling capacity in each loop. Two loops are used during normal operations because the designed decay heat capacity of EVST is up to 660 kW. Two of the operating loops are changed according to maintenance policy of the cooling system. The heat from the pots transfers directly to the primary sodium of the EVST. The heat of the primary sodium is removed by the cooling coils in each loop. Helical-type cooling coils are installed around the side wall of the EVST. There are approximately two circles of helical coils for every loop. The elevations of the vertical centers of the helical parts, which are different for each loop, are located in the order C loop, B loop, and A loop from the lower end. The decay heat is finally removed by the blower in the air cooler of each loop. The primary sodium circulation in the EVST occurs via natural convection created by the heat from the spent fuel assemblies and the heat extraction of the cooling coils. The secondary sodium circulation in the EVST sodium cooling system is powered by electromagnetic pumps.

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