Benchmark Analysis of EBR-II SHRT45R using MARS-LMR

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Abstract. KAERI has joined the International Atomic Energy Agency (IAEA) coordinated research project (CRP) on Benchmark Analysis of an EBR-II Shutdown Heat Removal Test (SHRT). The major goal for joining this program is to validate MARS-LMR, which is a newly developed safety analysis code for PGSFR. One of benchmark tests is a SHRT-45R, which is an unprotected loss of flow test in the EBR-II. Thus, sodium natural circulation and reactivity feedbacks are major phenomena of interest. The EBR-II SHRT45R is analyzed using MARS-LMR. Overall prediction of the EBR-II SHRT45R by MARS-LMR shows good agreement with experimental results. Except the results of the XX10, the temperature and flow in the XX09 agreed well with the experiments. In addition, sensitivity tests are carried out for a decay heat model, reactivity feedback model, inter-subassembly heat transfer, internal heat structures and so on. The decay heat model of ANS-94 shows better results of fission power, however, the fission power is still over-estimated in the long-term transient region by the reactivity feedbacks. The inter-subassembly heat transfer is the most influential parameter, especially for the non-fueled XX10, which has a low flow and power subassembly. In addition, the appropriate internal heat structure model can be an influential parameter. This study can give the validation data for the MARS-LMR and better understanding of the EBR-II SHRT-45R.

Key Words: MARS-LMR, EBR-II, unprotected loss of flow (ULOF), validation

1. Introduction

In 1974, a thermal hydraulic testing program at the EBR-II conducted to support the continued safe and reliable operation of the EBR-II was primarily directed toward understanding the detailed response of the EBR-II to a wide variety of accident conditions and utilizing this knowledge to validate general-purpose thermal-hydraulic-neutronic system analysis codes for application to new plant designs. Based on early experimental works, the shutdown heat removal test (SHRT) program was developed by the Department of Energy (DOE) in US. Major goals for the SHRT program are demonstrations of passive removal of decay heat by natural circulation of primary sodium coolant, passive reactor shutdown following a loss of forced circulation, passive reactor shutdown following a loss of heat sink, and the generation of test data for validating computer codes used in the design, licensing, and operation of LMRs. The International Atomic Energy Agency (IAEA) launched a program, the "Benchmark analysis of an EBR-II shutdown heat removal tests," as a part of an IAEA coordinated research project (CRP) in 2012, which is technically supported by ANL [1-2]. The program has major three tasks: a system analysis of the SHRT-17 test and SHRT-45R, and neutronic analysis of the SHRT45R [3]. Korea Atomic Energy Research Institute (KAERI) has currently designed a prototype Gen-IV sodium-cooled fast reactor (PGSFR), whose safety analysis code is the MARS-LMR. To validate the MARS-LMR code, KAERI has participated in this IAEA-CRP. The reactivity feedback and thermal hydraulic characteristics in the MARS-LMR were validated with EBR-II SHRT-45R test data. Moreover, sensitivity tests for some parameters were conducted to get a better prediction and understanding of physical phenomena during the EBR-II SHRT-45 test.

2. Benchmark Calculation of EBR-II SHRT-45R

2.1.EBR-II SHRT-45R

The EBR-II plant is experimental reactor, which is illustrated in FIG.1. Two primary pumps draw a sodium flow from the cold pool to their outlet pipe, which is bifurcated into two inlet plenums, high-pressure and low-pressure plenums, which are controlled by a throttle valve on the top of the pipe connected to the low-pressure inlet plenum. Hot sodium from a core outlet flows into an upper plenum and mixes before going through the single Z-shaped pipe, referred to as a Z-pipe, and into the single intermediate heat exchanger (IHX). Then, the cooled sodium through the IHX flows back into the primary pool before entering the primary sodium pumps again. Therefore, EBR-II has only a single primary pool and the upper plenum is connected to the Z-pipe. The sodium in the intermediate loop travelled from the IHX to the steam generator, where its heat was transferred to the balance-of-plant (BOP).

The SHRT-45R is a test for unprotected loss of flow test to demonstrate the effectiveness of EBR-II's passive feedbacks. During the test, the plant protection system was disabled to prevent the initiation of a scram. Starting from full power and flow, both the primary and intermediate loop coolant pumps were simultaneously tripped to simulate an unprotected loss of flow accident. As the SHRT-45 test continued, the reactor power decreased due to reactivity feedback. Table I summarizes the initial conditions of the SHRT-45R test. When the primary pumps trip, the core flow will follow the pump coastdown by when a natural circulation is developed due to a temperature difference in the core.

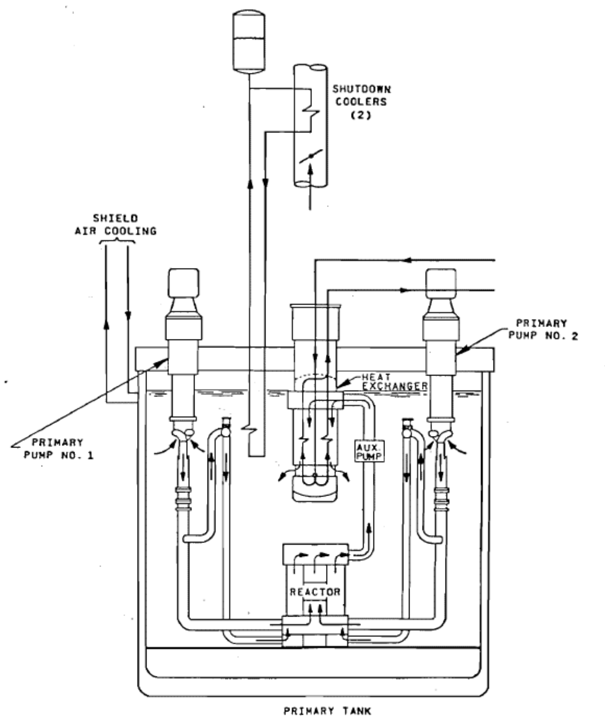

FIG 1. EBR-II plant illustration [3]

TABLE I: EBR-II SHRT-45 TEST INITIAL CONDITONS

Parameters [Unit]	**values and conditions**
Initial core power [MW]	60
Initial core flow [kg/s]	481.01
Initial intermediate flow [kg/s]	303.47
Initial core inlet temperature [K]	616.92
Initial intermediate temperature [K]	562.09
Control rods	Insertion disabled
Primary pumps	Coastdown

2.2.MARS-LMR Code

MARS-LMR is a liquid metal cooled reactor (LMR) version of MARS (Multi-dimensional Analysis for Reactor Safety) code, which is developed by KAERI for multi-dimensional and multi-purpose realistic thermal-hydraulic system analysis of light water reactor transient [4]. The plant can be modeled with various hydraulic and heat structure components, such as pipe, pump, valve, and so on, provided in MARS. However, there were no models related to LMR in the MARS. Therefore, sodium properties were embedded using a soft sphere model, which is based on Monte Carlo calculation for particles interacting with pair potentials [5]. And liquid metal heat transfer models for fuel bundle, various heat exchangers, and pressure drop model for fuel bundle were appropriately added [5]. The neutron physics in MARS-LMR is basically based on a point kinetics model. In addition, to consider reactivity feedback by structure expansion, a fuel axial expansion, core radial expansion, control rod drive-line/reactor vessel (CRDL/RV) expansion reactivity feedback models were individually added in MARS-LMR [6-8].

2.3.Modeling of EBR-II

All modeling information is obtained by Ref. [3]. FIG. 2 shows the nodalization of MARS-LMR for the EBR-II SHRT-45R test. The sodium cold pool is modeled with 6 volumes in volume number 300. The first and third volumes in the pool are connected to the inlets of the primary pumps and the outlet of the IHX shell-side, respectively. The two primary pumps are modeled with component nos. 305 and 335. The high-pressure pipes connected to the primary pumps are modeled with component nos. 310 and 340. And low-pressure pipes bifurcated from the high-pressure pipes are modeled with 320, 330, 350, and 360 components. The high- and low-pressure inlet plenums are modeled with 370 and 390 components, respectively. The boundary conditions are applied to the tube-side of the IHX of component nos. 770 and 600. All flows in the core subassemblies are mixed in the upper plenum of component 450, which is connected to Z-pipe of component 460. The IHX shell- and tube-sides are modeled with components 520 and 780, respectively. During the EBR-II SHRT-45R test, leakages in various locations are detected. However, in the model of MARS-LMR, all leakages are simplified to two leakages, which are from the high-pressure inlet plenum with component no. 372 and from the upper plenum with component no. 457. The outlets of the leakage flows from the high-pressure inlet plenum and the upper plenum are connected to the fifth and fourth volumes in the pool component, respectively.

The subassemblies in the core are modeled with ten flow channels. Two flow channels of the outer reflector and uranium blanket subassemblies are connected to the low-pressure inlet plenum. In addition, eight flow channels are connected to the high-pressure inlet plenum. The steel subassembly has a 7 pin stainless rod bundle, and the reflector has a hexagonal duct with 6 slots. The control rod subassembly has a lower fuel 61 pin bundle and upper B_4C 7 poison pin bundles. The instrumented subassemblies have a thimble region for the measurement wiring. There is sodium coolant flow in the thimble region, and therefore the thimble region in XX09 and XX10 are independently modeled, as shown in FIG. 2. The local temperatures and flow rates are measured in the instrumented subassemblies of XX09 and XX10, respectively. The XX09 has a 59 fuel pin bundle and the remaining two pins are installed for flow-meters, as shown in FIG. 3. The XX10 has a 19 steel rod bundle, and a flow meter is installed in one of them. As shown in FIG. 3, the locations of measurements are considered in the modeling of the experimental subassemblies.

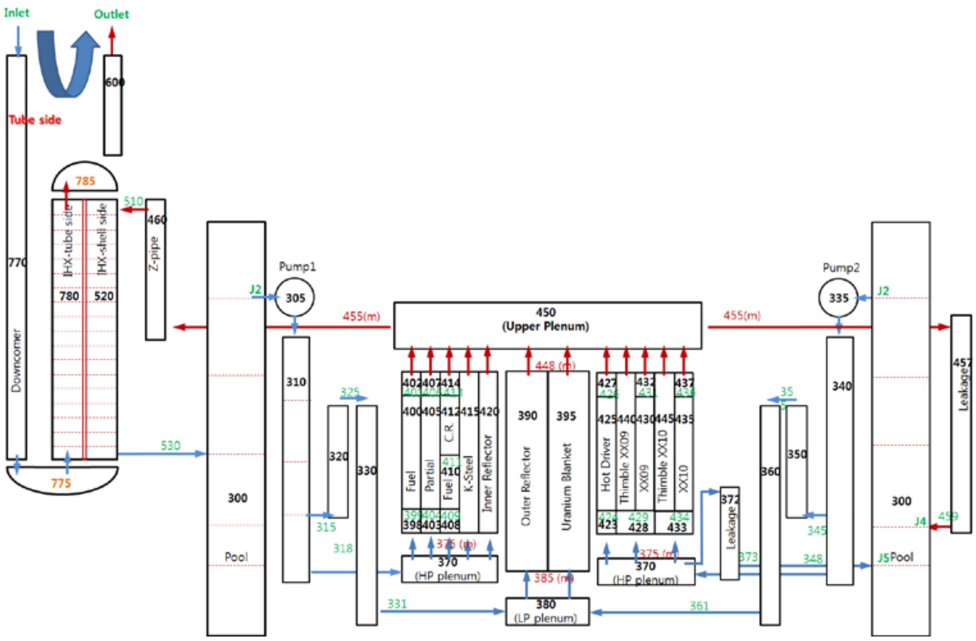

FIG 2. Nodalization of EBR-II for MARS-LMR.

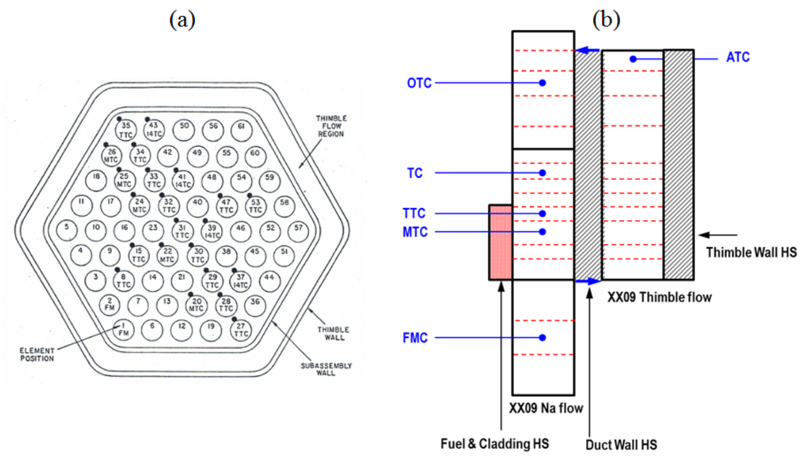

FIG 3. Model of XX09 subassembly: (a) radial measurement location, (b) axial measurement location with modeling.

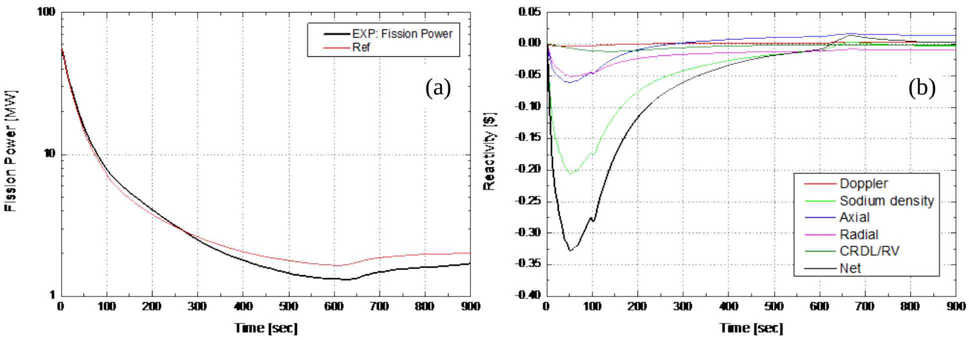

FIG 4. Blind test results of MARS-LMR for SHRT-45R: (a) fission power, (b) reactivity feedbacks.

2.4.Blind Results of SHRT-45R

As a first phase, the experimental results are not shared in this CRP. Therefore, a blind analysis is conducted with shared information [3]. The fission power and reactivity feedbacks are shown in FIG. 4. The power is initially under-estimated and over-estimated in the long term. The major reactivity feedback is density reactivity feedback and maximum net reactivity was approximately -0.325$ at 50 seconds. Although the results are not presented, the flow rates in the core is well predicted during the transient, particularly the natural circulation region, except for that in the XX10. The flow rate in the XX09 follows the measured data well. However, there is sudden reduction of the flow rate, which is unpredictable. Even the temperature behavior in the XX09 has no related trend for this flow reduction. The flow rate in the XX10 is under-predicted. FIG. 5 represents typical results of temperature in the instrumented subassemblies. Coolant regions in the XX09 and XX10 are modeled with single radial volume in MARS-LMR. Thus, the MARS-LMR results represent the average temperatures. Therefore, all data measured at different radial locations are averaged and represent with a solid line, as shown in FIG. 5. Additionally, the dotted line in FIG. 5 indicates the minimum and maximum values among the measured data. The peak

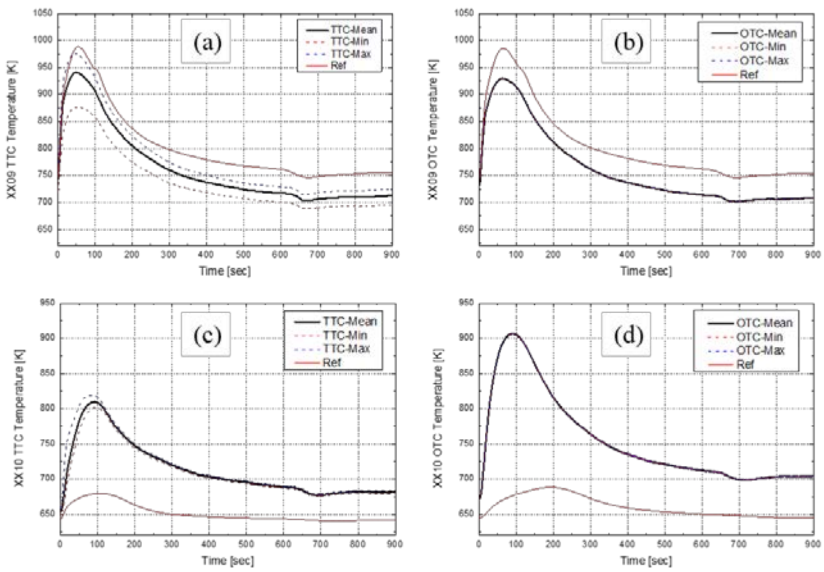

FIG 5. Temperatures in the XX09 and XX10 during SHRT-45R: (a) XX09-TTC, (b) XX09-OTC, (c) XX10-TTC, and (d) XX10-OTC.

temperatures in the XX09 are slightly over-predicted in MARS-LMR. In addition, the temperatures in the XX10 during the transient show very low values. With the exception of the results in the XX10, MARS-LMR reasonably predicted the trend in the EBR-II SHRT-45R test.

3. Sensitivity Test

3.1. Decay Heat Model

The ANS-94 model is used as a decay heat model in the blind test. MARS-LMR has three options for decay heat models: ANS-73, ANS-79, and ANS-94. ANS-73, -79 and -94 specify the proposed 1973, 1979, and 1994 ANS Standard data, respectively. For all decay heat models based on U^{235}, ANS-79 additionally considers isotopes of U^{238} and Pu^{239}, and ANS-94 considers U^{238}, Pu^{239}, and Pu^{241}. The decay heat depends on the concentration of isotopes of U^{235}, U^{238}, Pu^{239}, and Pu^{241} etc. However, the decay heat for the Pu^{239} and Pu^{241} is lower than U^{235} and U^{238} [9]. Therefore, the ANS-94 model generally predicts a lower decay heat than ANS-73 and ANS-79. The three decay heat models available in MARS-LMR are compared in FIG. 6. The ANS-79 and ANS-94 predict the highest and lowest decay heats, respectively. However, when the ANS-94 model is used, the fission power is still under-estimated. To match the initial fission power, the ANS-94 model is modified with a correction factor of 0.88, because the initial decay heat is over-estimated by 12%. Maeda and Aoyama measured the decay heat in JOYO Mk-II spent fuel subassemblies and compared the calculation results with ORIGEN2 [10]. Their results showed that the ratio of calculated and experimental values were between 0.89 – 0.94. Therefore, 12% for the correction factor is comparable to the measurement uncertainties.

3.2. Reactivity Feedback Model

For unprotected accident such as SHRT-45R, the reactivity feedbacks have important role to govern the reactor power. Therefore, accuracy of the reactivity feedback model is very important for transient analysis in an unprotected event. Sensitivity tests for each reactivity feedback model was conducted. The influences of reactivity feedbacks of the Doppler and CRDL/RV expansion are negligible, as shown in FIG. 4. The most sensitive reactivity feedback is the density reactivity, which has an influence on the initial region of the transient due to initial sodium temperature variation. The radial expansion uniformly affects the transient. However, its sensitivity is the lowest among the effective three reactivity feedback

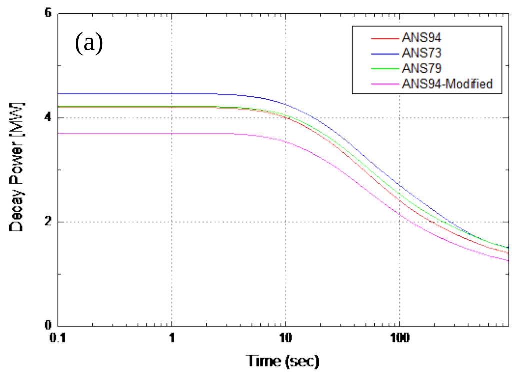

FIG 6. Comparison of decay heat models in MARS-LMR.

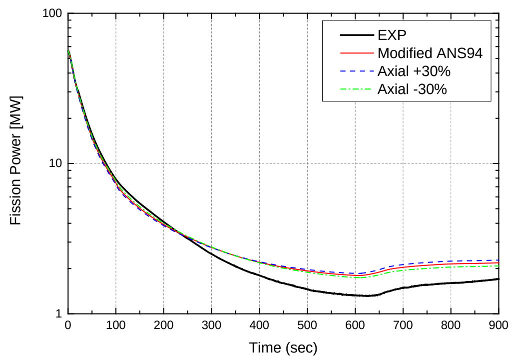

FIG 7. Sensitivity result for the axial expansion reactivity feedback of MARS-LMR.

models. The fuel axial expansion has the opposite trends for the initial and long term regions (FIG. 7), because the axial expansion reactivity initially becomes negative but is changed to positive in the long term region owing to the lower fuel temperatures as shown in FIG. 5. Chang and Mohr reported that the EBR-II has a bowing effect of the positive reactivity [11]. Therefore, without considering additional positive reactivity feedback model, the power can be under-estimated. Finally, the fuel axial expansion reactivity feedback is modified with 70% of the blind test case, however, the fission power is still over-estimated in a long-term transient after about 200 seconds.

3.3.Additional Heat Structure

In the blind test, most of the heat structures in the EBR-II including reactor shield, inner shield in the fuel subassemblies, duct, IHX housing, and Z-pipe are appropriately modeled However, there is no information for some components. For example, a mixer installed before measuring the location of the OTC and the handling part for the subassemblies in the upper plenum have no information. Modeling of structures in the reactor are very important during thermal transient since the thermal mass of structures govern the change rate of temperatures in a system. In order to check the effect of the heat structures in the upper plenum, sensitivity tests with the reference case (A1) were conducted. The test cases of D1 - D3 are defined with SS316 handling parts of all subassemblies with diameters of 2 cm, 3cm, and 4cm, respectively. As shown in FIG. 8, the inlet temperature of the IHX shell-side has higher sensitivity for different mass of the heat structures.

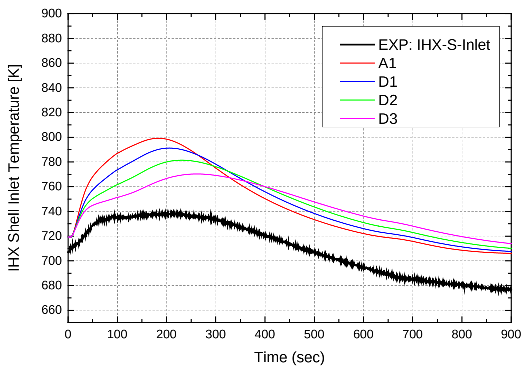

FIG 8. Effect of heat structure of the internal structure in the upper plenum.

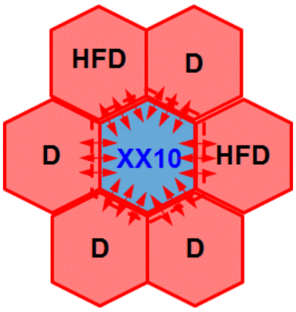

FIG 9. Subassembly configuration surrounding of the XX10

3.4.Inter-subassembly Heat Transfer

The prediction of MARS-LMR for the temperatures and the flow rate in the XX10 was poor. The XX10 is a non-fueled subassembly, which means generated heat is not high comparing that in a fuel. Therefore, surrounding subassembly can be an additional heat source. As shown in FIG. 9, the XX10 is surrounded by the fuel subassemblies. To study the effect of heat transfer between subassemblies, the conduction heat transfer model is applied between ducts of subassemblies. It is assumed that all surrounded subassemblies are fuel drivers and the sodium gap between ducts is stagnant. Because of a difficulty in defining the appropriate heat transfer area, four kinds of cases are selected based on the heat transfer area. Case A1 – case A4 are defined as 100%, 50%, 25%, and 12.5%, respectively. Fig. 10 shows all four case results with the measured data and reference case. When the inter-subassembly heat transfer model is applied, a remarkable improvement for the temperatures in the XX10 is observed. Because of the heat transfer from the surrounding subassemblies increases the sodium temperature in the XX10. In addition, the flow rate in the XX10 is enhanced due to a buoyancy effect. However, the flow rate in the XX10 is still under-estimated, which means that predicted sodium temperatures in the XX10 can be under-estimated. As the heat transfer area is decreased, the peak temperatures in the XX10 are decreased. According to the sensitivity test, the heat transfer area of 12.5% shows the most closed result. This result indicates that the inter-subassembly heat transfer model is an important parameter for the thermal hydraulic behavior in the EBR-II SHRT-45R test, especially for a low-power subassembly like a non-fueled one.

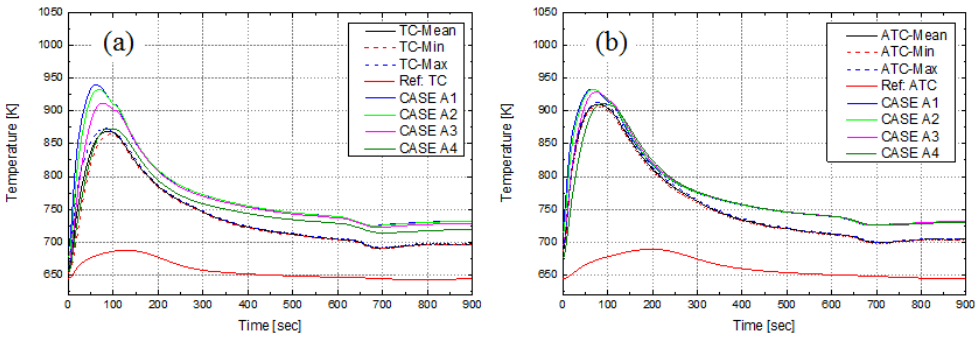

FIG 10. Effect of inter-subassembly heat transfer in the XX10: (a) XX10-TC and (b) XX10-ATC.

4. Summary

To validate the Korea-SFR safety analysis code, MARS-LMR, the EBR-II SHRT-45R test was analyzed as part of the IAEA CRP program. The EBR-II SHRT-45 is an unprotected loss of flow test. Therefore, major concerns are a transition from the force flow to natural circulation and interaction between neutronic and thermal-hydraulic characteristics. Using only the initially provided information, the blind analysis was conducted using the MARS-LMR. The overall results of the blind test agree well with the experiments. However, it is difficult to predict the flow and temperature in the non-fueled instrumented subassembly, XX10. In this study, uncertain but influential parameters were selected, and their sensitivity tests were conducted. Based on the sensitivity test, the following conclusions were derived.

- The decay heat model of ANS94 shows the lowest value compared to ANS73 and ANS79. For better initial decay heat, correction factor of 0.88 is applied.

- The density reactivity feedback is a dominant reactivity component during EBR-II SHRT45R. The fission power in the long-term is over-predicted by the reactivity feedback. Thus, a study about the additional reactivity feedback models is necessary for the better prediction of the core power during the EBR-II SHRT-45R.

- Sensitivity test for the internal structures in the upper plenum shows that heat structure modeling can influence on the temperature variation during transient.

- Inter-subassembly heat transfer is the most important parameter for coolant temperature in a low power subassembly like a non-fueled subassembly. In addition, when the flow is governed by natural circulation, the inter-subassembly heat transfer must influence on the coolant flow.

5. Acknowledgments

This work was supported by the Nuclear Research & Development Program of the National Research Foundation (NRF) grant funded by the Korean government MSIP (Ministry Science, ICT and Future Planning).

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