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Evaluation of a Loss of Residual Heat Removal Event during Mid-Loop Operation

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Abstract

The potential for the RELAP5/ MOD3.2 was assessed for the loss-of-RHR event during the mid-loop operation and the predictability of major thermal-hydraulic phenomena was also evaluated for the long term transient. The analysis results of the typical two cases(cold leg opening case and pressurizer opening case) were compared with experimental data which was conducted at ROSA-IV/LSTF in Japan. As a result, it was shown that the code was capable of simulating the thermal-hydraulic transport process with appropriate time step during the reduced inventory operation with the loss-of-RHR system.

I. Introduction

The Residual Heat Removal (RHR) system is used to operate with the reactor inventory reduced to mid-level of the primary loop (mid-loop operation) for a maintenance of components such as steam generator (SG) during a plant outage in pressurized water reactor (PWR). Recently, the loss-of-RHR was of great concern, since there have occurred many events associated with it and the potential for the significant risk has been identified. The major causes of these events were found to be a loss of vital ac power, inadvertent closure of isolation valve in the RHR suction line, and the loss of RHR flow due to air ingestion into the RHR pump. Some of these events resulted in boiling of the reactor vessel inventory and eventually the possibility to uncover the core if the loss of RHR conditions should continue for a long time period [1,2]

In order to understand thermal hydraulic process following the loss-of-RHR event, several experiments and analyses have been performed. In analytic approach, the predictability of the major thermal hydraulic phenomena was mainly evaluated using the best-estimate transient analysis codes such as RELAP5. However, there were many difficulties in calculating the transient [3,4], especially in consumption of very long calculational time and occurrence of a severe flow oscillation, due to system cofiguration of reduced inventory under low pressure and existence of noncondensable gas. Recently, the USNRC developed the modified RELAP5/ MOD3.2 version, which incoporates new models and improvements into the MOD3.1 version to resolve the deficiencies in the code with respect to the analysis of the loss-of-RHR event. In particular, in calculating process of the noncondensable gases, several improvements were made in the numerics of the code to handle the appearance, transport and disappearance of noncondensable gases in hydrodynamic control volumes. The objective of the present analysis is to assess the potential of the RELAP5/MOD3.2 in predicting the system behavior following the loss-of-RHR event during the mid-loop operation, and evaluate the major thermal hydraulic phenomena for a long term transient. To do this, the calculated results are compared and evaluated with the experiment which was conducted at the ROSA-IV/LSTF in Japan.

II. Experimental Facility and Conditions

The Large Scale Test Facility (LSTF) of the Rig of Safety Assessment-IV (ROSA-IV) program is a 1/48 volumetrically scaled model of a Westinghouse type 3423 MWt four loop PWR. The facility includes a pressure vessel, two symmetric primary loops and steam generators (SG), pressurizer and ECCS including RHR system [5]. The core power can be controlled by electrically heated rods and simulate decay heat up to 14 % of the 1/48-scaled nominal PWR core power. The facility has the same major component elevation as the reference PWR. The hot and cold legs were sized to conserve the volume scaling and the ratio of the length to square root of the pipe diameter. In measurement systems, more than 2000 instruments were installed to measure transient parameters.

In experiment for the simulation of loss-of-RHR event during mid-loop operation, four different cases were performed with different location of the opening on the RCS pressure boundary to simulate typical plant geometry during maintenance [6]; cold leg opening (CLO case) to simulate the plant geometry during the maintenance of the reactor coolant pump, hot leg opening (HLO case) to represent an open manway on the SG inlet plenum, pressurizer opening (PRO case) to simulate an open manway on the pressurizer and no-opening (NOO case) for the closed RCS condition. The areas of the opening were equivalent to 5 %, 10 % and 33.5 % cold leg breaks for each experiment. The initial liquid level in the primary loop was set approximately to the centerline of the horizontal legs to simulate a mid-loop operation. The SG secondary sides were either filled to the normal level with water or empty. The core power was 0.6 % (430 kW) of the scaled moninal PWR power and was kept at this value throughout the experiments, to simulate the decay power at approximately one day after the reactor shutdown. The primary coolant temperature was controlled using the RHR system typically at 334 K and 313 K in the hot and cold legs, respectively. The initial pressure was atmospheric in both primary and secondary systems with the relief valves on the pressurizer and SGs latched open. The upper portion of the primary and secondary loops above the water level was filled with air. The experiment was initiated by isolating the RHR system from the primary loop and closing the pressurizer relief valves at the same time. The SG relief valves were left open and no operator action was taken unless the core temperature exceeded 700 K, at which the ECCS was initiated or the core power was turned off.

III. Analysis Code and Modeling

The RELAP5/MOD3.2 version [7], in which several new models and improvements have been incorporated, is used to evaluate system behavior following the loss-of-RHR event during a mid-loop operation. The main computer used in the calculation is a DEC station 5000/240 with UNIX operating system. The nodalization to simulate the LSTF facility consist of 174 volumes connected by 193 junctions and 202 heat structures. The core was modeled as two types of nodes; single channel core with 12 volumes as a base case and two channel core with 12 volumes each for sensitivity study on the multi-dimensional effect. The SG U-tube was modeled as fine nodes at the inlet portion of the U-tube to simulate accurately the steam migration and condensation phenomena. The RHR system was modeled by time dependent volumes and junctions connected to the hot and cold legs in both loops. Two cases (CLO and PRO) are analyzed to assess the code; the cold leg and pressurizer opening were modeled by trip valves. The opening sizes were equivalent to a 5 % and 33.5 % cold leg break for CLO and PRO case, respectively and the openings were located at centerline of the cold legs and at the top of the pressurizer. In the noncondensable model of the RELAP5, the steam/noncondensable mixture is assumed to be in thermal equilibrium and the saturation properties of the liquid and steam are assumed to be a function of the partial pressure of the steam. These assumptions intend to force the phasic temperatures and the saturation temperature to the same value. It causes a reduced driving potential for the interface mass and heat transfer models. Consequently, low interfacial heat transfer regimes, such as the vertical stratification flow regime, may give heat transfer coefficients that are too low for stable calculation as evidenced by oscillatory behavior. When this occurs, the RELAP user's guide [7] recommends that the vertical stratification model (VSM) should be turned off on a volume basis. According to this guideline, the VSM option was turned off at the volumes in the core in this calculation.

IV. Results and Discussion

IV.1. Initial Conditions

Table 1 represents the comparison of initial conditions between the experiment and the calculation. The major calculated parameters of the primary and secondary sides agree well with the measured values. The transient calculation is initiated by isolating the RHR system and opening the cold leg break valve at 1000 seconds. The calculation was attempted up to 17000 seconds for the CLO case and 9000 seconds for the PRO case when the operator actuated to stop the experiment. The calculated results are compared with experimental data which were obtained in open literatures [3,6].

IV.2. Analysis Results

(1) Pressure Response for CLO case; Figure 1 shows the pressure behavior in hot and cold legs in intact loop after the loss-of-RHR system occurred at 1000 seconds. At about 1500 seconds, the liquid in core started to boil and vaporized, and the generated steam migrated from the core toward the hot legs through the core upper plenum. The pressure in the hot legs increased rapidly at about 1600 seconds in experiment, while it was delayed in the experiment by 400 seconds. This is due to multi-dimensional effect and flow oscillation between the core and the downcomer (Fig. 7). Eventually at about 4400 seconds, when the calculated pressure reached a maximum of 0.14 MPa which is almost the same value as the experiment, the loop seal clearing (LSC) occurred in the crossover leg and the pressure dropped immediately to higher value than the cold leg pressure. The delayed LSC, compared to the experiment which occurred at about 3400 seconds, was due to the lower pressurization rate before the LSC by the excessive condensation in the SG U-tubes (Fig.4). Also in the calculation, the LSC occurred partially on both the broken and the intact loops, while it occurred completely in the broken loop and partially in the intact loop in the experiment. This is associated with underestimation of the interfacial drag. The partial LSC kept the small amount of liquid remained in the crossover leg and the condensate from the SG U-tubes wall was accumulated and blocked the gas flow towards the cold legs. Thus, the pressure in the hot leg again increased and the second partial LSC occurred at about 6000 seconds at the maximum pressure difference between both legs. These pressurization and LSC were repeated for a long time period.

(2) Thermal Response for CLO case; Figure 2 represents liquid temperatures at inlet, mid section and outlet of the reactor core. After the loss of residual heat removal function, the coolant in primary loops became stagnated and the liquid temperature in the core increased monotonously. The maximum liquid temperature was located first at upper part of the core, however, because of the cosine shape of power distribution, the temperature at the mid-height of the core become the highest. At the mid section core, the calculation data agree well with the experiment. Figure 3 represents liquid temperatures in the hot and cold legs. It also increased with some delay following the increasing of fluid temperature in the core. After saturation of the upper plenum at

about 1500 seconds, the liquid temperatures in the hot legs increased stepwise to the steam temperature in the experiment, while the calculation shows the gradual increase. The experimental data compared in this figure were measured at the ceiling of the horizontal pipe, which means steam temperature. Reference 3 stated that the temperature measured on the bottom wall indicated gradual increase (not shown) as those calculated by the code. After the LSC, the hot and cold legs were voided completely and the calculated steam temperature remained saturation value (not shown). Figure 4 shows the liquid temperatures at the bottom of the SG secondary side. The calculation data show that the SG liquid temperatures began to increase earlier than the experiment. It implies that the the core decay heat was transferred to the SG secondary side before the LSC. In the experiment, after the LSC, steam entered the SG U-tubes and began to condense on the U-tubes wall. This indicated that the steam migrated to and reached SG U-tubes earlier than in the experiment, resulting in the excessive condensation, and the code overestimated the SG side liquid temperatures. It also implies that the effect of noncondensable gas was underestimated due to the assumption of a thermal equilibrium homogeneous mixture, even vertically stratified non-equilibrium flow in the gas phase.

(3) Pressure and Thermal Responses to PRO case; Since the initial conditions in PRO case were nearly identical to the CLO case, the calculated transients were almost the same until boiling in the core initiated. With increasing in the primary pressure due to the boiling, the liquid level in the pressurizer increases rapidly because the manway at the top of pressurizer was opened. Figure 5 and 6 show the comparison of the temperature in the hot leg and the collapsed water level in the pressurizer with the experiment data, respectively. The liquid temperature was predicted well, but the water level started to increase later than the experiment and rapidly increased and dropped due to gravity. In experiment, the liquid flow into the pressurizer occurred only for a short time period when the primary pressure increased and the water level remained constantly. These differences were caused by the continuous increase of the pressure in the core because the hot leg was filled with liquid at the begining of transient. These calculation data were obtained from the base calculation. The further study will be necessary to assess in detail the predictability of the code.

IV.3. Discussion

(1) Consumption of CPU Time; There have been many difficulties in getting convergence of transient calculation following the loss-of-RHR event during mid-loop operation. In particular, it was difficult for the code to calculate the transport process of the mixture phase involving noncondensable gas. When the noncondensable gases enter a volume which was filled with steam, the extremely small size of time step was required and the long CPU time was consumed. For example, the calculation performed by H. Nakamura et. al. [3] using the RELAP5/MOD3 v5m5 code on FACOM M-780/20 scalar computer, took CPU time of 37.2 hours to simulate the transient of 3831 seconds. Also, the calculation performed by S. Banerjee et. al. [4] took over 60 hours of CPU time for the same transient of 3040 seconds, even using the CRAY-YMP supercomputer. In present calculation using the modified RELAP5/MOD3.2 version on a DEC station 5000/240, it just took the CPU time of about 6 hours to simulate the transient of 3500 seconds, which is nearly 10 times fast. In addition, the running was successfully performed without any failure during the calculation. Therefore, it indicated that the RELAP5/MOD3.2 version was quite improved, especially in the numerics to handle the transport process of noncondensable gases in hydrodynamic volumes. Consequently, it shows that the new version is capable of simulating the thermal hydraulic process including noncondensable gases during the reduced inventory operation with loss-of-RHR.

(2) Effect of Core Nodalization; The nodalization scheme in core was known to have influence on the calculation time and thermal hydraulic behaviour [3]. In particular, two channel core nodalization could reduce the flow oscillation, which was not observed in the experiment. In addition, it could provide somehow the resolution of the problems resulted from one-dimensional nature of the RELAP5 code, especially for the initial core coolant heat-up calculation after loss-of-RHR. Figure 7 shows the the calculated liquid temperatures in upper plenum for the two types of core nodalization. The single core node showed the delay of boiling start, while the two channel core well predicted the onset of boiling. It implies the natural circulation due to multi-dimensional effect inside the reactor vessel was compensated by the two channel nodalization.

V. Conclusions

The potential for the RELAP5/ MOD3.2 was assessed for the loss-of-RHR event during the mid-loop operation, and the predictability of major thermal-hydraulic phenomena was also evaluated for the long term transient. The calculations were compared with two cases of experiments which were conducted at ROSA-IV/LSTF in Japan.

1) The RELAP5/MOD3.2 was quite improved, especially in numerics to handle the transport of the noncondensable gases. Consequently, it was shown that the code was capable of simulating the thermal-hydraulic transport process with appropriate time step during the reduced inventory operation with the loss-of-RHR system.

2) For the typical two cases, the cold leg opening case to simulate the geometry during the maintenance of the RCP and the pressurizer opening case to simulate an open manway on the top of the pressurizer, the code predicted well the major phenomena during the transient, such as the boiling in the core, system pressurization, LSC, coolant enterance into pressurizer and so on. Also, thermal behavior in the core could be well predicted by two channel nodalization.

3) However, in CLO case, the heat transfer to the SG secondary side was overestimated due to the excessive condensation on the SG U-tubes wall from larger amount of steam migration toward the SG U-tubes. Thus, the onset of the LSC was delayed and the LSC occurred partially as compared to the experiment.

References

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Table 1. Comparison of Initial Conditions

Parameters	Experiment; CLO/PRO	RELAP5; CLO/PRO
• Core power (kW)	430 / 430	430 / 430
• Hot leg temperature (K)	334 / 337	334.1 / 337.1
• Cold leg temperature (K)	318 / 320	318.0 / 320.0
• Primary pressure (MPa)	0.1013 / 0.1013	0.1013 / 0.1013
• Water level at loop (m)	middle of loop	middle of loop
- hot leg void	0.46 / -	0.48 / 0.91
- cold leg void	0.37 / -	0.54 / 0.82
• Secondary pressure (MPa)	0.1013 / 0.1013	0.1013 / 0.1013
• Secondary fluid temperature (K)	317 / 317	317.0 / 316.4
• Water level in SG (m)	10 / empty	10.4 / empty
• Noncondensible gas	air / air	air / air

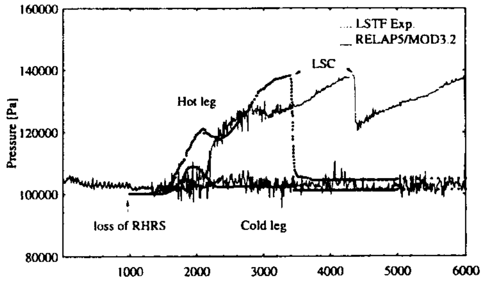

Fig. 1 Comparison of Pressures at Hot leg and Cold leg in Intact Loop

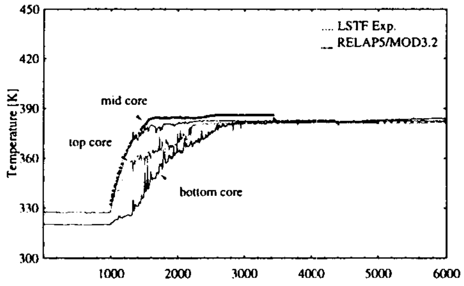

Fig. 2 Comparison of Core Fluid Temperatures

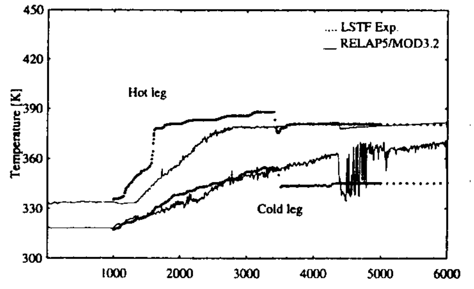

Fig. 3 Comparison of Liquid Temperatures at Hot and Cold legs in Intact Loop

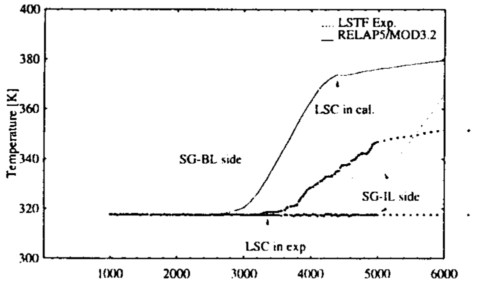

Fig. 4 Comparison of SG Liquid Temperatures

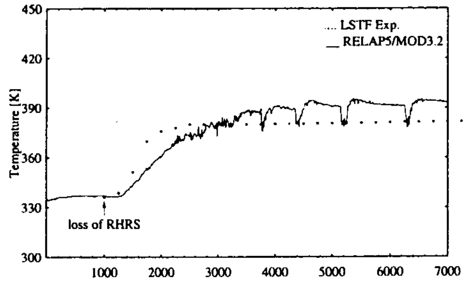

Fig. 5 Comparison of Hot Leg Temperature in Intact Loop

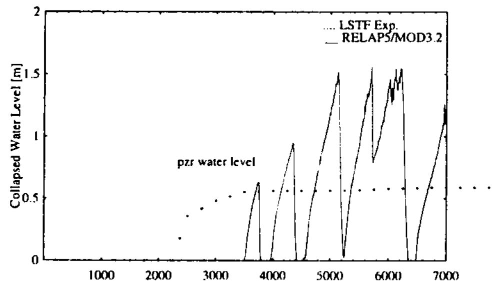

Fig. 6 Comparison of Pressurizer Water Levels

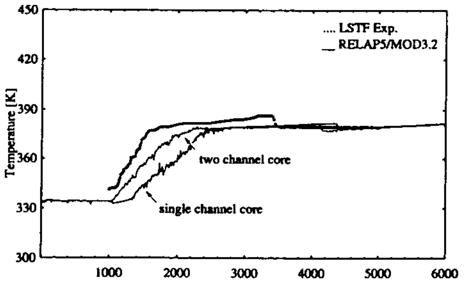

Fig. 7 Comparison of Fluid Temperatures at Core Upper Plenum