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A Loss-of-RHR Event under the Various Plant Configurations in Low Power or Shutdown Conditions

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Abstract

A present study addresses a loss-of-RHR event as an initiating event under specific low power or shutdown conditions. Two typical plant configurations, cold leg opening case with water-filled steam generators and pressurizer opening case with emptied steam generators, were evaluated using the RELAP5/ MOD3.2 code. The calculation was compared with the experiment conducted at ROSA-IV/LSTF in Japan. As a result, the code was capable of simulating the system transient behavior following the event. Especially, thermal hydraulic transport processes including non-condensable gas behavior were reasonably predicted with an appropriate time step and CPU time. However, there were some code deficiencies such as too large system mass errors and severe flow oscillations in core region.

I. Introduction

Recently, the loss-of-RHR (Residual Heat Removal) event at low power or shutdown conditions is of great concern, since there have occurred many associated events and the potential for the significant risk has been identified. Some of these events resulted in boiling of the reactor coolant and eventually the possibility to uncover the core and to cause the core damage if the loss of RHR conditions should continue for a long time period [1]. In order to analyze the events initiated under the low power or shutdown conditions, the plant operating states and the physical configurations such as RCS boundary opening and emptied SG should be considered as well as the initiating events. The plant states may include a RCS heatup process, a low power and cooldown with SGs, a pressurized RHR cooldown with normal inventory, reduced inventory, or water-filled refuelling cavity. Time after reactor shutdown is also included in the operating conditions to establish the decay heat rate. The initiating events to be addressed under the operating states are obtained from the operational experiences. A loss-of-RHR such as failure of its pump, a loss-of-inventory such as a coolant overdraining, and a loss-of-offsite power can be included in this event catagory [2].

With respect to the analysis of the initiating events, some studies [3, 4] were performed to evaluate the predictability of the analysis codes. However, there have been many difficulties in calculating the transient behavior, especially in consumption of very long calculational time and occurrence of severe flow oscillations. The problems were usually caused by a small driving force under low pressure and low flow conditions and an existence of non-condensable gas. Recently, the USNRC developed the modified version, RELAP5/MOD3.2, which incorporates new models and improvements to resolve the deficiencies in the code with respect to the transient analysis at the low pressure and flow conditions. In addition, the numerical schemes to handle the transport of non-condensable gases in hydrodynamic volumes were significantly upgraded. The present study addresses a loss-of-RHR event as an initiating event under specific low power or shutdown conditions. In particular, it aims to assess the new code version in predicting the transient behavior during the depressurized RHR cooling with reduced inventory, and to evaluate the major thermal hydraulic phenomena for a long term transient. To do this, the calculated results are compared and evaluated with the experiments which were conducted at the ROSA-IV/LSTF in Japan.

II. Experimental Setup and Calculational Models

1. Experimental Setup: 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 3,423 MWt four loop pressurized water reactor. The facility includes a reactor pressure vessel, two symmetric primary loops and SGs, pressurizer and ECCS including RHR system. The pressure reactor vessel contains a core with full length fuel of 1,104-rods simulating rod bundle, a cylindrical downcomer surrounding the core, upper and lower plena, and a upper head. The core bypass region is not simulated. Also, more than 2,000 instruments were installed to measure transient parameters including fluid density. The detailed system description such as scaled dimension and geometry configurations, and detailed measurement systems such as the installed locations and estimated accuracy were described in reference [5].

In experiment for the simulation of loss-of-RHR event during the depressurized RHR cooling with reduced inventory, 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 case to simulate the plant geometry during the maintenance of the reactor coolant pump, hot leg opening case to represent an open manway on the SG inlet plenum and a nozzle dam installed between the opening and the reactor vessel, pressurizer opening case to simulate an open manway on the pressurizer, and no-opening case for the closed RCS condition.

2. Calculational Models: The RELAP5 is well recognized best-estimate system transient analysis code, based on a non-homogeneous and non-equilibrium model for one dimensional two phase flow system. In this study, the unmodified released code version of the RELAP5/MOD3.2 is used on a main frame computer, DEC workstation 5000/240 with UNIX operating system. The modeling is based on 179 hydrodynamic volumes connected by 199 junctions and 202 heat structures. The two loops of the LSTF system are represented by an intact-loop and a broken-loop in an almost symmetrical way. The secondary sides of two SGs are also simulated using an identical schematization. Both SG U-tubes are modeled with 12 volumes. In particular, fine noding scheme was used at the inlet portion of the U-tube, which is to accurately simulate the steam migration and condensation phenomena. The core is modeled as two types of noding schemes; single channel core with 12 hydraulic volumes and heat structures and two channel core connected by crossflow junctions. This arrangement is adopted to assess the multi-dimensional effect such as natural circulation flow in the core region.

Two typical cases of the physical configurations of the plant are analyzed in this study; the cold leg opening (CLO) case with water-filled SGs and pressurizer manway opening (PRO) case with emptied SGs. The opening sizes are equivalent to 5 % and 33.5 % of cold leg cross area for CLO case and PRO case, respectively. The openings are located at centerline of the cold legs and at the top of the pressurizer, respectively. The detailed modeling scheme used in the study can be found in reference [7].

III. Calculational Results and Discussion

1. Initial and Boundary Conditions

The initial steady-state conditions were obtained from new transient run up to 1,000 seconds.

Table 1 shows the considered operating states and comparison of initial conditions between the experiment and the calculation. The major calculated parameters of the primary and secondary sides agreed well with the measured values. The transient calculation was initiated by decreasing linearly the RHR flow from the initial value to zero for 20 seconds and by opening either the cold leg opening valve or the pressurizer opening valve. The pressurizer relief and safety valves were closed at the same time. The calculation was attempted up to over 4 hours for the CLO case and 2.5 hours for the PRO case until an operator takes an action to stop the experiment.

2. Calculational Results for Cold leg Opening Case

• Pressure Response: Figure 1 shows the pressure behavior in hot and cold legs after the loss-of-RHR event occurred at 1,000 seconds during depressurized RHR cooling with reduced inventory. The coolant in core began to boil and the pressure in the hot leg increased rapidly at about 1,600 seconds. The calculation agreed well with the experiment in the early phase. At 2,100 seconds, the pressurization rate reduced immediately. This was because a steam flow through guide tubes was established at this time. However, the calculated pressurization rate was still lower than the experiment. Such a low pressurization rate resulted in delaying an occurrence of loop seal clearing (LSC). Actually in the experiment, the steam condensation on SG U-tubes wall did not occurred before the LSC, while in the calculation, a significant amount of steam was condensed at the inlet part of the SG U-tubes. At 3,740 seconds, when the calculated pressure reached 0.138 MPa which is almost the same value as in the experiment, the LSC occurred in crossover legs. The pressure dropped immediately to a little higher value than in the cold leg pressure.

Just after the LSC, the gas flow path was formed through the loops and the steam penetrated the SG U-tubes and began to condense on the entire U-tubes wall. The condensate from the SG U-tube started to accumulate in crossover legs from about 6,400 seconds. Such a liquid accumulation resulted in preventing again the gas flow from the hot leg toward the cold leg. Thus, the pressure reincreased gradually and the second LSC was caused at 9,420 seconds. The calculation shows the pressure was increased a little fast by more accumulation of the condensate than in the experiment.

Table 1. Operating States and Initial Conditions

Items	Major Conditions	
• Plant Operating States	- Depressurized RHR cooling with reduced inventory	
• Time after Shutdown	- One day, 0.6% of full power (430 kW)	
• RCS Opening	- Cold leg open(CLO), Pressurizer manway open(PRO)	
• Initiating Event	- Loss of RHR event	
Major Parameters	Experiment; CLO/PRO	RELAP5; CLO/PRO
• 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 loops (m)	middle of loop	middle of loop
- hot leg void		0.41 / 0.30
- cold leg void		0.51 / 0.21
• Secondary pressure (MPa)	0.1013 / 0.1013	0.1013 / 0.1013
• Secondary fluid temp. (K)	317 / 317	317.0 / 317.0
• Water level in SG (m)	10 / empty	10.08 / empty
• Initial coolant inventory (kg)	-	2590 / 2686
• RHR flowrate (kg/s)	-	3.2 / 3.0
• Noncondensable gas	air / air	air / air

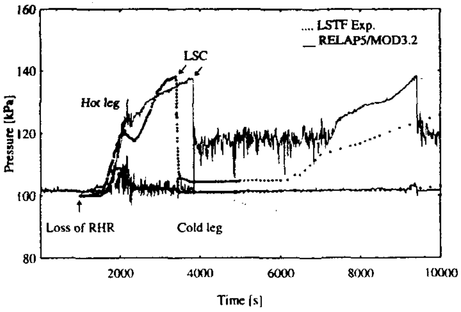

Fig.1 Pressures at Hot and Cold Legs in Intact Loop in CLO Case

• Thermal Response: Following the loss-of-RHR flow, coolant in the core became stagnated and the coolant temperature immediately increased. After the temperature reached saturation value, it remained constant. In the experiment, due to the decreased inventory in the reactor vessel, the top part of the core was uncovered for a very short time period and eventually the first core heat up was caused locally just on a few fuel rods. After the LSC, the core water level was recovered by the inflow of the water from the loops and the fuel rods were quenched. With the continuous steaming in the core and steam condensation on SG U-tubes, the reactor coolant was redistributed gradually to the leg sides. Thus the second core heat up was initiated from 11,920 seconds. The maximum fuel surface temperature exceeded 830 K. In the calculation, the first core heat up did not occurred because the core was modeled simple nodes such as an averaged volume. As shown in Fig. 2, the calculated core heat up at the middle of the core (below 3.05 m) was initiated earlier by about 1,300 seconds than in the experiment, but the heat up rate well agreed with the experiment. The earlier heat up timing was due to the underprediction of the coolant inventory in the reactor vessel.

• Non-condensable Gas Behavior: Initially, total mass of non-condensable gas of about 5.25 kg existed in primary system. Due to the increasing of steam partial pressure, the air inside reactor vessel was completely pushed out at about 2,000 seconds and total air mass rapidly reduced. However, the air inside U-tubes temporally increased before the LSC, because the air migration into SG U-tubes was simultaneously accompanied with the steam transport. When the LSC occurred, the air in primary system rapidly decreased, especially inside U-tube, since direct steam flow path was formed from hot leg to cold leg. In overall, the noncondensable gas behavior was reasonably predicted.

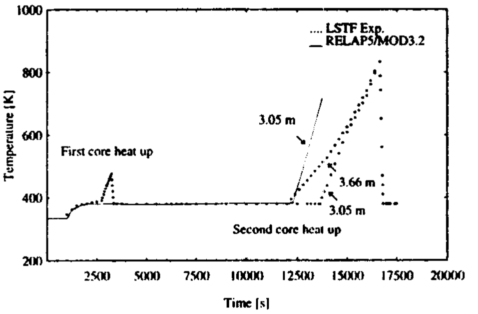

Fig. 2 Fuel Cladding Temperatures in CLO Case

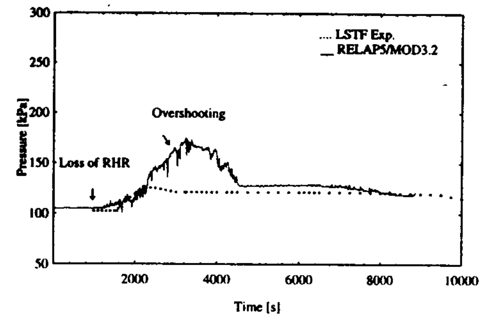

Fig. 3 Pressures in Reactor Vessel Upper Plenum in PRO Case

3. Calculational Results for Pressurizer Manway Opening Case

• Pressure Responses: Since the initial conditions in PRO case were nearly identical to the CLO case, the calculated transient had almost the same behavior until boiling in the core was initiated. Figure 3 shows the pressure behavior in reactor vessel upper plenum. A starting time of pressure increase and pressurization rate agreed well with the experiment but the pressure overshut the experiment a little. This difference was caused by an excessive vaporization in core region, which resulted in excessively moving the core coolant toward the hot legs. Due to the overpredicted water level in hot legs, the steam flow toward pressurizer opening was blocked. Thus, the calculated pressure continued increasing for a longer time than in the experiment. When the steam flow path from the upper plenum to the pressurizer opening was formed by the high differencial pressure, the pressure stopped increasing and decreased. After the steam flow was stabilized, the pressure remained nearly constant. The calculation agreed well with the experiment.

• Thermal Responses and Loop Behavior: Figure 4 shows fuel cladding temperatures at the top part of the core. Following the loss-of-RHR, the calculated liquid temperatures increased rapidly in the early phase and, after reaching saturation value, it remained constant. The calculation agreed well with the experiment. As the coolant was continuously discharged through the pressurizer opening, the core coolant inventory decreased slowly. Such an inventory reduction caused a core uncovery and a core heat up. The calculated heat up was initiated earlier by 3,000 seconds than in the experiment. It was because, as described above, the underprediction of the coolant inventory in the reactor vessel. Due to the excessive voiding in the core, the water level in pressurizer also increased rapidly. As shown in Fig. 5, even though the collapsed water level in the pressurizer started to increase a little later by 600 seconds, it was quite overpredicted. Even after the surge line was completely emptied from about 4,000 seconds, the calculated water level remained a high value. Such large water hold up in the pressurizer may come from an overprediction of interfacial drag between two phases. The calculation also showed that the relative velocities in the pressurizer were predicted very high.

- Non-condensable gas behavior: The air in primary system decreased rapidly just after the steam flow toward pressurizer opening was formed at about 3,400 seconds. Because the SG U-tubes were completely filled with an air, the rapid change of the air fraction in U-tubes did not occurred. It implies that the effect of non-condensable gas was not important in the PRO case because the steam condensation phenomena was not dominant during all the transient.

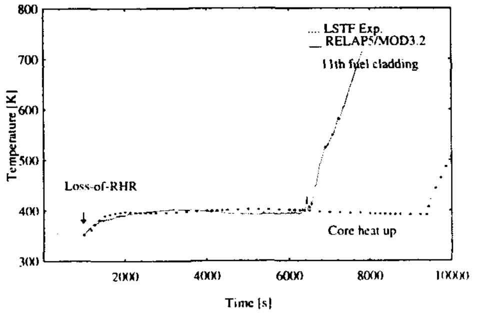

Fig. 4 Fuel Cladding Temperatures in PRO Case

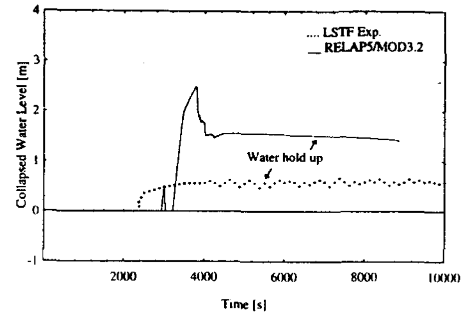

Fig. 5 Collapsed Water Levels in Pressurizer

4. Discussion on the Calculational Results

The transient calculations were successfully performed with appropriate time steps and CPU time without any failure. The similar CPU time was required for both CLO and PRO cases. However, the code predicted too large system mass errors during the transient. In general, the mass error is caused by several reasons such as the truncation errors in the linearization procedures, the use of incorrect properties in the numerical scheme and the first appearance of non-condensable gas in a volume. In order to mitigate the mass error in RELAP5/MOD3 code, if the excessive mass error is detected, the time step is repeated at a reduced interval. In calculation, the mass error in primary system was estimated about 80 ~ 90 kg, that was nearly 4 % of initial coolant inventory for the transient of 3 hours. Figure 6 shows the estimated mass errors behavior with the transient time. The mass errors were rapidly generated for the phase of coolant boiling and it gradually rised thereafter. Since the large mass error could significantly reduce the reliability of the calculational data, these mass errors should be reduced to the negligible value.

The nodalization scheme in the core was known to have influence on thermal hydraulic behavior during the transient. As shown in Fig. 7, which represents the mass flow rate at mid-core junction in two channel core model, the natural circulation flow was formed for about 700 seconds following the loss-of-RHR event. However, severe flow oscillations also occurred thereafter, which did not occurred in the experiment. In single channel core model, there was no natural circulation flow but more severe flow oscillations occurred. These flow oscillations were caused by void oscillations in the core region. In spite of the unrealistic flow behavior, the two channel nodalization gave a little more stable flow and more coolant mixing in the reactor vessel than the single channel model. It implies that the multi-dimensional flow characteristic in the core region was compensated by the two channel core nodalization.

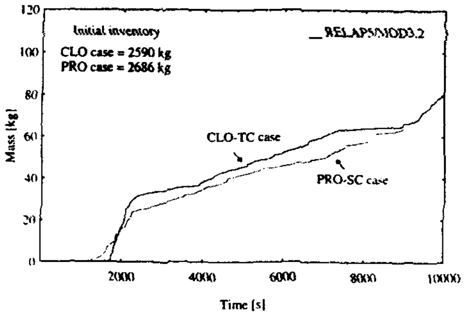

Fig. 6 The Estimated Mass Errors

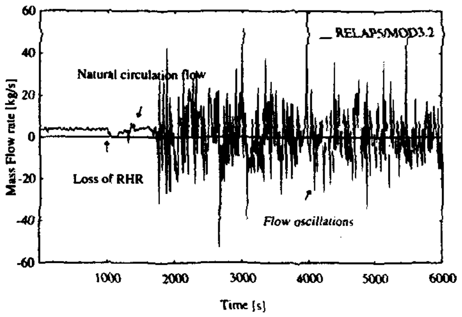

Fig. 7 The Flow Rate at Mid-Core Junction for CLO Case

IV. Summary and Conclusions

A loss-of-RHR event as an initiating event under specific low power or shutdown conditions was evaluated by using RELAP5/MOD3.2 code. The calculations were compared with two cases of experiments, cold leg opening (CLO) case with water-filled SGs and pressurizer manway opening (PRO) case with emptied SGs, which were conducted at ROSA-IV/LSTF in Japan.

- The code reasonably predicted thermal hydraulic transport processes including non-condensable gas behavior with appropriate time steps and CPU time. However, there were some code deficiencies such as an estimation of too large system mass errors and severe flow oscillations in the core region. These deficiencies should be improved to apply the code to the real plant.
- For the two typical geometry configurations, the code predicted well the major phenomena during the long term transient, such as the coolant boiling off in the core, system pressurization, the occurrence of loop seal clearing (LSC), the migration of the non-condensable gas, liquid hold up in pressurizer, core uncovery and so on. However, the occurrence of the LSC was delayed a little in CLO case, and the maximum pressure was overpredicted in PRO case. Also, the calculated core heat up was initiated much earlier than in the experiment for the both cases.

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