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RELAP5 Analysis of the Loss-of-RHR Accident during the Mid-Loop Operation of Yonggwang Nuclear Units 3/4

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ABSTRACT

A loss of the residual heat removal (RHR) accident during mid-loop operation of Yong-gwang Nuclear Units 3/4 was analyzed using the RELAP5/ MOD3.1.2 code. In this work the following assumptions are used; (i) initially the reactor coolant system (RCS) above the hot leg center line is filled with nitrogen gas, (ii) two 3/4-inch diameter vent valves on the reactor vessel head and the top of pressurizer in the reactor coolant system are always open, and a level indicator is connected to the RHR suction line, (iii) the two steam generators are in wet layup status and the steam generator atmospheric dump valve assemblies are removed so that the secondary side pressure remains at nearly atmospheric condition throughout the accident, and (iv) the loss of RHR is presumed to occur at 48 hours after reactor shutdown. Findings from the RELAP5 calculations are (i) the core boiling begins at ~5 min, (ii) the peak RCS pressure is ~ 3.0 bar, which implies a possibility of temporary seal break, (iii) ~94 % of the decay heat is removed by reflux condensation in the steam generator U-tubes in spite of the presence of noncondensable gas, (iv) the core uncovery time is evaluated to be 7.2 hours. Significant mass errors were observed in the calculations.

I. INTRODUCTION

The loss of the RHR function during midloop operations has been of increasing concern for years. It can be caused by loss of electric power, inadvertent closure of isolation valves, air ingestion to the RHR suction piping, and others. Several incidents have been reported and some of them resulted in core boiling. Although the incidents did not lead to core damage, they showed the potential for a rapid core uncovery under shutdown condition.

The important thermal-hydraulic phenomena following a loss of the RHR during mid-loop operation were well identified by Naff, et al. (1992). So far, the best estimate system codes have not been fully assessed against such accidents characterized by low pressure, low flow transients under the presence of noncondensable gases. However, it has been shown that, using the RELAP5 code (Carlson, 1990), the accidents can be analysed with reasonable accuracy (Nakamura et al., 1992; Hassan and Raja, 1993; Hassan and Baberjee, 1994).

In this work, a plant specific calculation for Yonggwang Nuclear Units 3/4 (YGN 3/4) was performed using the RELAP5/MOD3.1.2 code. Primary objectives of the work are to improve the understanding of system behaviors during the accident and to investigate the steam generator cooling capability. Timings of primary coolant boiling, pressurization, and core uncovery are also analyzed since they are crucial in terms of recovery procedure. In addition, the mass errors of RELAP5 are discussed.

II. PLANT CONFIGURATION AND CODE INPUT MODELS

YGN 3/4 is a two-loop, 2815 MWt, PWR plant. The RCS contains two primary coolant loops, each of which has a hot leg, a steam generator (SG), two reactor coolant pumps, and two cold legs. In post shutdown periods, the reactor coolant is taken from the two hot legs, cooled by RHR heat exchangers, and then returned to the four cold legs. Initial plant configurations for this calculation are listed below.

- The RCS is operated under midloop condition, that is, the RCS water level is at the height of hot leg center line. The upper part of the RCS is filled with nitrogen gas.
- Coolant temperatures at the cold and hot legs are 323 K and 333 K, respectively.
- The SG secondary sides are in filled with water at 333 K, of which the water level covers the top of U-tubes.
- Two 3/4-inch dia. vents at the top of reactor vessel head and the pressurizer are open.
- A level indicator is connected to the RHR suction line (taken from the bottom of hot leg A). The end of level indicator is open to containment at the height of the pressurizer top.
- Atmospheric dump valve (ADV) assemblies of the SGs are removed, which provides a vent area of 0.158 m^2 to each SG.
- The loss of the RHR is assumed to occur at 48 hours after reactor trip (Q_{decay}=11.6 MW).

Such a configuration can exist shortly after shutdown before refueling or maintenance operations begin.

The RELAP5 input model is illustrated in Fig. 1. The plant was nodalized in detail enough to capture important thermal-hydraulic phenomena and design characteristics of YGN 3/4. However, since the environmental heat losses were known to be a small fraction of the decay heat, all the structures except for the fuel rods and U-tubes were not modelled. It should be noted that no choking option is used for all junctions because RELAP5 predicts unrealistically low sound speed when noncondensable gases are present.

III. RESULTS AND DISCUSSIONS

For initial steady-state calculation, the RHR system is modelled using time-dependent volumes and junctions. Nitrogen gas at 333 K and 100 % relative humidity is present in all volumes above the centerline of the hot legs and cold legs. After several hundred seconds of the null transient calculation, a steady state is obtained. The calculation results showed oscillations of the void fraction and mass flowrate in the upper plenum of reactor vessel, hot legs and cold legs. The oscillations did not damp out and maintained certain amplitudes. Thus, the results at 1000 s were adopted as initial conditions of the transient. The transient begins by eliminating the RHR system model in the code input. A maximum time step of 1 msec was used for the transient calculation.

Primary-Side Behaviors

Because of the loss of the RHR function, the primary coolant temperature gradually increases and then local boiling begins at ~370 s. However, since the mass flow at the core strongly oscillates, bulk boiling occurs later. Figure 2 shows the water temperature behaviors in the downcomer, core inlet, and core exit. The temperature differences in the three volumes tend toward zero by oscillation-induced mixing and steam condensation in the downcomer region where the steam flows from the bypass paths.

As can be seen in Fig. 3, the RCS pressurization begins at ~400 s and the primary-side pressure seems to reach a quasi steady state after ~ 6,000 s by the energy balance between the decay heat and the heat removal through the SGs and three RCS vents. The first pressure peak marked "A" in Fig. 3 is related to water temperature behavior in the secondary side, which will be discussed later. The second and third pressure peaks result from rapid changes of the discharge flow through the level indicator, which is also shown in Fig. 3.

When the RCS pressure increases enough to overcome the hydrostatic head of the water in the level indicator, single-phase water begins to flow out from the bottom of hot leg A at ~3,640 s. The discharge flow remains nearly around 2.4 kg/s until 6800 s and then decreases rapidly. This is due to ingestion of steam into the RHR suction line. Meanwhile, each of the two top vent flows is about 0.023 kg/s at maximum because of large flow resistance and pure vapor discharge.

In Fig. 4, void fractions in the hot legs are illustrated. Until ~ 1,500 s the void fractions decrease in a oscillatory manner. This means the increase of the upper plenum water level by core boiling. In case of the hot leg B, void fraction does not change significantly after ~ 2,000 s. However, in the hot leg A, void fraction rapidly increases after 5,000 s, which is caused by water discharge through the level indicator. When the void fraction in the hot leg A becomes close to 1.0 at ~6,800 s, the discharge flow drastically decreases due to two-phase mixture or pure vapor discharge. Thereafter the void fraction decreases again and, in turn, the discharge flow increases. This process occurs again at ~ 9,200 s.

Figure 5 shows the noncondensable gas behaviors in the pressurizer and the steam generator U-tubes. The role of small vent is clearly shown; the noncondensable gas in the pressurizer is completely eliminated at ~ 6,800 s.

In Fig. 6, the collapsed water levels in the downcomer and upper plenum of the reactor vessel are compared, where the reference elevation is the bottom of active core. It is shown that the water levels are under manometric head balance between the inside and outside of the core support barrel. Temporal imbalances are concerned with the pressure peak B and C.

Heat Removal by the Steam Generators

The reflux cooling can be established when the core boiling sufficiently pressurizes the RCS to compress the nitrogen gas in the upper region of the RCS to expose a tube condensing surface to the steam flow. Figure 7 shows volumetric vapor generation rate (in other words, condensation rate) in the first volume of the SG U-tubes. Approximately 95 % of the condensation is predicted to occur in the first volume. After 6,000 s, the condensation rate becomes smaller in the SG A than in the SG B. This asymmetry is believed to be due to discharge flow through the level indicator connected to the hot leg A. In Fig. 8, the integrated heat removal by the SGs is compared with total core heat generation. It can be seen that, after ~ 5000 s, the energy balance is in a nearly equilibrium state.

Water temperature behaviors in the secondary side volumes 740, 750-01, 750-02, and 750-03 (see Fig. 1) are shown in Fig. 9. The temperature in volume 740 increases at first, because the volume directly contact to the first volume of U-tube inside. However, the temperature increase in the upper volumes 750-02 and 750-03 is negligible until ~ 4,400 s. This means there are neither heat transfer through the upper part of U-tubes nor bulk motion of the secondary water. During this period, an internal circulation is formed from volume 740, 750-01, 720-02, 724, and back to 740. At ~4,400 s, the water temperature in volume 740 gets to a saturation temperature and a local boiling occurs. The resulting buoyancy force causes a change of circulation mode from the internal circulation to bulk manometric oscillations. As the manometric oscillation occurs, the water in the SG downcomer, evaporator, and riser regions is mixed, which results in temporal water temperature decrease in volume 740. As a result, the heat removal by the SGs increases during that period. This causes the pressure peak A in Fig. 3. If the secondary water level was higher than the separator can deck elevation, bulk natural circulation would occur from the beginning of the transient.

Evaluation of Core Uncovery Time

It is necessary to find out the timing of core uncovery, which is expected to occur several hours later. However, because of high computational cost, the calculation was stopped at 9,700 s. Instead, the core uncovery time was estimated from the present calculation results and an extrapolation method with some assumptions.

To estimate the core uncovery time, it is essential to know the discharge flow through the vents. Therefore, we need to know, first of all, whether the RCS pressure that governs the discharge flows will increase further or not. If the pressure increases, the effective heat transfer area in the U-tubes and the temperature difference between the primary and secondary side will also increase, which means an increase of SGs heat removal. This implies the pressure will not increase further in the calculation. Therefore, the discharge flows also will not increase over the maximum value shown in Fig. 4. So it is conservatively assumed the maximum discharge in Fig. 4 will continue until the core uncovery.

Next, it is needed to know the RCS mass inventory (M_{final}) at the time of core uncovery (T_{final}). In this work the core uncovery means the two-phase mixture level in the core is 0.3 m above the top of active core. The following assumptions are used to estimate M_{final}: (i) 4 crossover legs are completely filled with water, (ii) 30 % of the hot leg volumes are filled with water, (iii)The reactor core and downcomer levels are in manometric head balance (see Fig. 6), (iv) The core region is filled with two-phase mixture and the downcomer region with saturated liquid. A drift flux model is used to obtain a quasi-steady state void profile of the core region at T_{final} and, then, the water inventory is calculated. The water level (or inventory) in the downcomer region is obtained from the manometric head balance with the core region.

Using the above assumptions, M_{final} can be estimated. Then, T_{final} is represented as

$$T_{final} = T_{initial} + (M_{final} - M_{initial}) / \sum_{i=1,3} W_{i,max}$$

where the subscript "initial" indicates the time when the code calculation is stopped, and $W_{i,max}$ is the maximum vent flow. The core uncovery time is evaluated to be 7.2 hours after the loss of the RHR.

Limitations of the RELAP5 Code

Significant mass errors were observed in the RELAP5 calculations. With a (maximum) time step of 1 msec, 5500 kg of the RCS water corresponding to 5.2 % of the initial RCS inventory disappeared by 9700 s. When a time step of 2.5 ms was used, the mass error increased up to 50 % of the initial inventory. The volumes with the largest mass error were the upflow sides of U-tubes. For instance, in case of the first volume of the SG A U-tube, the void fraction was predicted to be close to 1.0 throughout the whole transient. However, Figure 7 shows the volumetric condensation up to ~ 1.5 kg/m^3s in that volume. It seems that, due to the mass error, the condensate disappears as soon as it forms. Significant mass errors also have been observed before in low pressure transient calculations (G.W. Johnsen, 1995). The cause of mass error was not understood. So far it was found that, to reduce the mass error, a fine nodalization is required for the region where the large mass error is detected.

A practical limitation of RELAP5 is very long computation times. As shown in Table I, the ratio of CPU time to problem time is ~50 when the mass error is maintained within ~ 5 % of the initial RCS inventory.

IV. CONCLUSIONS

The loss-of-RHR accident during mid-loop operation of Yong-gwang Nuclear Units 3/4 was analyzed using the RELAP5 code. In this work, it was assumed that the two top vents and the level indicator are open throughout the transient, the SGs are in wet layup status, and the SG ADV assemblies are removed so that the secondary pressure remains at atmospheric condition. The loss of RHR is presumed to occur at 48 hours after reactor shutdown.

Overall findings from the calculation are summarized as follows:

- The core boiling begins at ~5 min after the loss of RHR function.
- The peak RCS pressure is ~3.0 bar, which implies a possibility of temporary seal break.
- ~94 % of the decay heat is removed by reflux condensation in the steam generator U-tubes in spite of the presence of noncondensable gas
- The core uncovery time is evaluated to be 7.2 hours with a conservative approach.

In addition, significant mass errors were observed. The cause of mass error was not understood. So far it was found that, to reduce the mass error, a fine nodalization is necessary for the region where the mass error is large. The RELAP5 computation times were very long, which may limit practical applications on these accidents.

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Table I. Comparison of the computation times

Time step (s)[a]	Problem time (h)	CPU time (h)[b]
0.001	2.7	134.5
0.0025	2.7	55.1

[a]Maximum time step, [b]executed on Cray-YMP

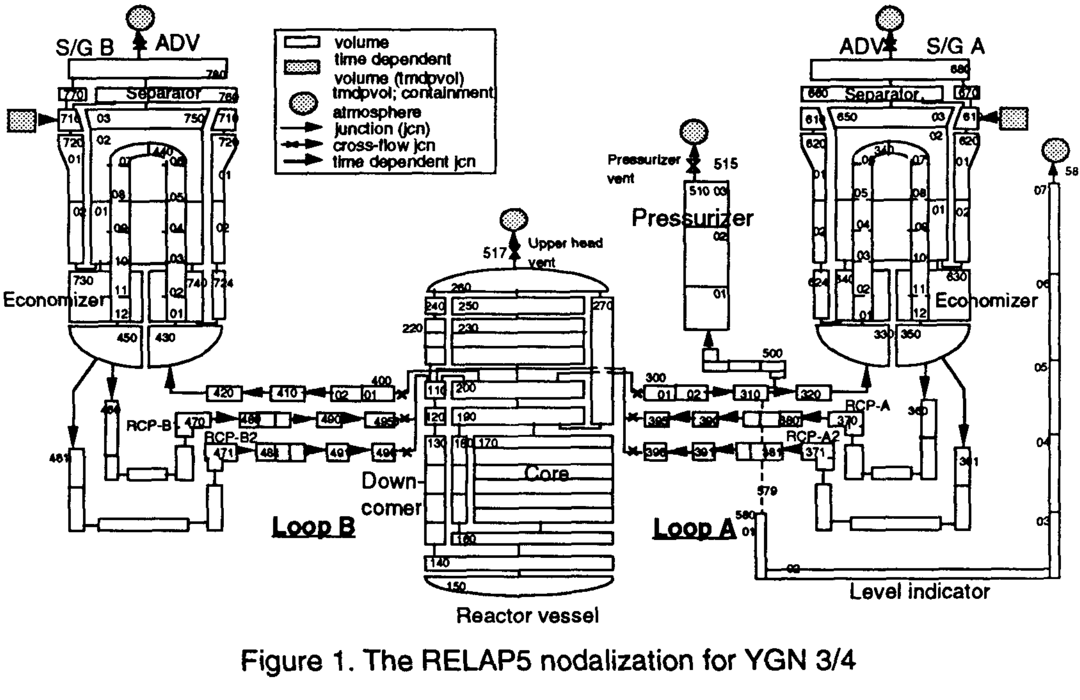

Figure 1. The RELAP5 nodalization for YGN 3/4

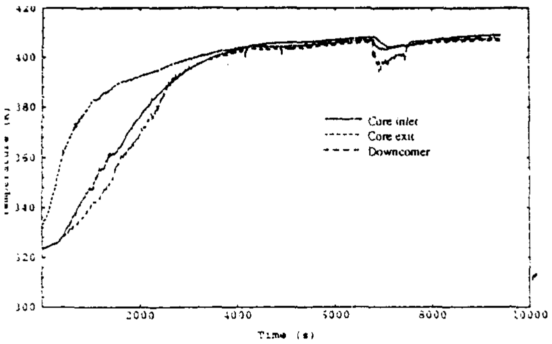

Fig. 2 Coolant temperature behaviors

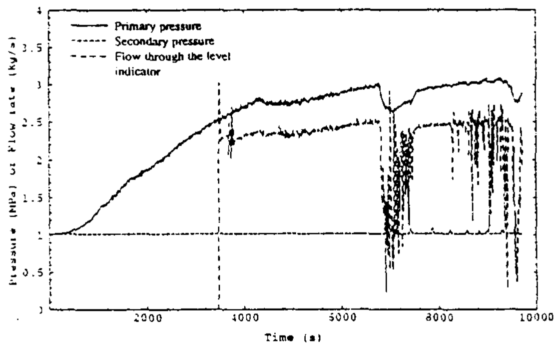

Fig. 3 System pressure and flow through the level indicator

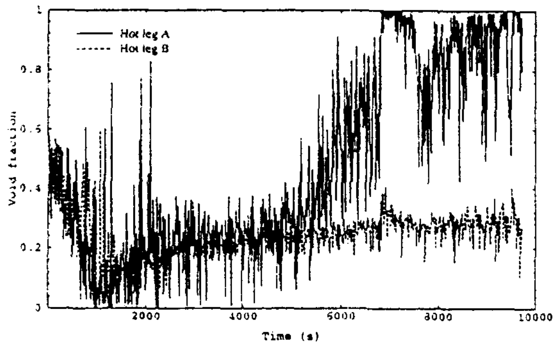

Fig. 4 Void fractions in the hot legs

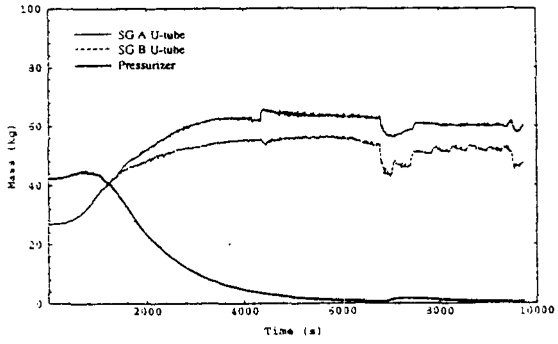

Fig. 5 Nitrogen gas mass behaviors

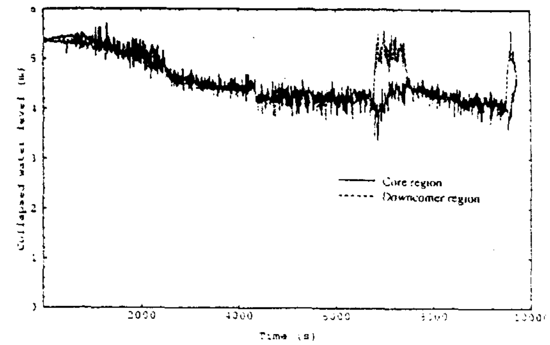

Fig. 6 Collapsed water levels

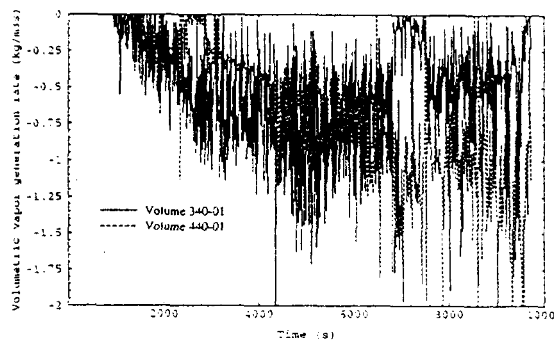

Fig. 7 Vapor generation rates in volume 340-01 and 440-01

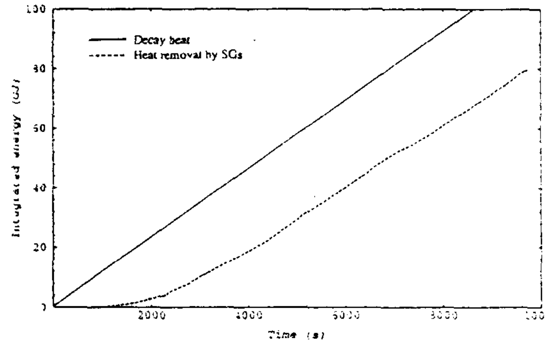

Fig. 8 Comparison of the integrated energy

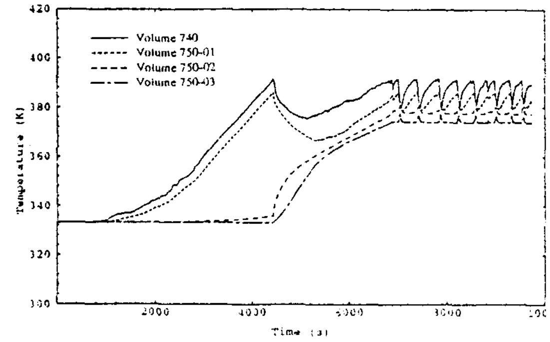

Fig. 9 Secondary-side water temerature behaviors