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Analysis of the Vent Path Through the Pressurizer Manway Under the Loss of Residual Heat Removal(RHR) System During Mid-Loop Operation in PWR

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가압경수로 부분충수 운전중 잔열제거(RHR)계통 상실시 가압기 통로를 통한 배출유로 특성 분석

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Abstract

The present study is to understand the physical phenomena anticipated during the accident with RHR loss under mid-loop operation in a PWR and, at the same time, to examine the prediction capability of RELAP5/MOD3.1 on such an accident, by simulating an integral test relevant to this accident, for reliable analysis in an actual PWR. The selected experiment, i.g. BETHSY Test 6.9a, represents the configuration with the pressurizer manway open and steam generators unavailable during the accident. Accordingly, the results of this work are sure to contribute to understanding both the key events as well as the sensitive parameters, anticipated in the accident, for validity of the actual analysis.

In the simulation result, overall behavior as well as major phenomena observed in the experiment have been predicted reasonably by RELAP5/MOD3.1, however, the problem associated with enormous computing time due to small time step size has been encountered. Besides, the code prediction of higher swollen level in the pressure vessel has given rise to overestimation of both pressurizer level and RCS pressure. Subsequently, overprediction of the break flow through the manway has led to earlier core uncovery than that in the experiment by about 400 seconds.

As a whole, it is demonstrated from both the experiment and the analysis that gravity feed has not been sufficient to recover the core level and thus additional forced feed has been necessary in this configuration.

요 약

본 연구는 가압경수로의 부분충수 운전중 잔열제거기능 상실사고 해석시 신뢰성을 확보하기 위해 RELAP5/MOD3.1 코드로 관련 대형실험을 모의계산하여, 사고시 예상되는 주요 물리적 현상의 파악

과 코드의 예측능력을 평가하는 것이다. 대상 실험으로 선택된 BETHSY Test 6.9a는 이 사고중 증기발생기가 작동하지 않고, 가압기 Manway를 개방한 상태(Configuration)를 모의한 실험이다. 이 연구결과는 실제 원전 사고시 예상되는 중요 현상 뿐 아니라, 이에 영향을 미치는 민감한 인자를 파악하여 사고 해석결과의 유효성을 판단하는 데 상당히 기여할 것으로 기대한다.

연구결과 RELAP5/MOD3.1 코드는 대체적으로 계통의 과도기 거동은 타당하게 예측하고 있지만, 모의계산에서 Time-Step이 아주 짧아 막대한 시간이 소요된다는 문제점이 발견되었다. 그 외에도 노심 팽창수위(swollen level)를 과대평가하여 가압기의 수위 및 계통의 압력을 높게 계산하였다. 이로 인해 가압기를 통한 방출량도 과대계산하여 노심노출을 약 400초 빨리 예측하였다.

실험과 코드 예측결과를 종합할 때 가압기 Manway 만의 개방으로는 계통압력이 상승하고, 중력주입 냉각수로는 노심수위 회복에 불충분하며, 결국 강제주입에 의해서 노심수위가 회복될 수 있음이 입증되었다.

1. Introduction

For a pressurized water reactor(PWR), the plant should be in a special operation mode, called mid-loop operation where the reactor coolant system is partially filled for inspections or maintenances of such components as steam generator U-tubes, valves, or reactor coolant pump(RCP) seals during plant overhauls. During mid-loop operation, RHR(Residual Heat Removal) system is the only way of core decay heat removal when steam generators are not available due to a maintenance reason. Loss of RHR system is possible due to several reasons, for example, loss of AC power or ingestion of air into the RHR suction line, etc. Such events, without a special action, could eventually lead to core damage following core boiling and uncovery.

For this reason, loss of RHR system during nonpower operation and the consequences of such accidents had been of increasing concern for years. The Diablo Canyon event in April 10 1987(NUREG-1269), and ensuing work by both the USNRC staff and industry organizations had provided additional insight. Yet the problems continued and the identified problems had not been understood by GL (Generic Letter) 88-12 responders. Thus USNRC issued GL 88-17 which stated that deficiencies existed in procedures, hardware, and training in the areas of (1) prevention of accident initiation, (2) mitigation of accidents before they potentially progress to core damage, and (3) control of radioactive material if a core damage accident should occur. GL 88-17 recommended to conduct analyses to supplement existing information and develop a basis for procedures, instrumentation installation and response, and equipment/NSSS interactions and response. It also placed emphasis upon obtaining a complete understanding of NSSS behavior under nonpower operation.

PRA result has shown that CDF(Core Damage Frequency) of the loss of RHR system during mid-loop operation is never lower than that of normal operation. [1] Since there is no guidelines established against such accident in Korea, Korea Institute of Nuclear Safety(KINS) imposes action items referring to those in GL 88-17 to the KEPCO(Korean Utility). It was known that KEPCO had already shown many achievements in procedures, hardware, and training but weak point associated with the analytical bases was pointed out by KINS. The major problem encountered is considered that a required analytical methodology under such low pressure as nearly atmosphere with noncondensable gas like nitrogen or/and air, has not been well established in Korea yet. Therefore it is desirable that an analytical methodology under such an accident should be developed soon and used for accident management as well as safety assessment of Korean nuclear plants during mid-loop operation.

Considering current situation, the present study is particularly important since it would provide an analysis methodology using an existing code, RELAP5/MOD3 and at the same time, sensitive parameters prevailing the transient would be identified, which have not been studied much within Korea. The most important aspect of the study will be understanding of physical phenomena which may occur during the accident for reliable analysis and assessing the predictability of the code against such an accident so as to apply it to an actual plant. Majority of previous studies presented in the literatures[2, 3, 4, 5] has focused on this point but vent path analysis with such a large opening as pressurizer manway has not been found often so far. Therefore essential parts of interests must be on vapor flow behaviors through various available paths which has been understood less important in previous analysis, release characteristics through the opening, liquid hold-up in the pressurizer, core uncovery time, system pressurization, liquid entrainment, condensation, and finally effectiveness of recovery actions, namely, gravity feed as well as forced feed incorporated with confirmation of adequate flow path for make-up water.

2. BETHSY Test 6.9a

BETHSY is a scaled-down integral test facility of a three-loop 900 MWe Framatome PWR, designed to study accident management. [5] With reference to the reactor, the volumetric scaling factor is 1/100. Since flow patterns in the primary coolant system (PCS) are often gravity-dominant under most of accident conditions, the elevations and heights of all the components are preserved. The PCS shown in Fig. 1 consists of the pressure vessel containing core, an external downcomer, three identical loops each equipped with a reactor coolant pump(RCP), and a steam generator(SG). The reactor core is composed of 428 full-length electrically heated rods and 29 guide thimbles. It is powered with 3 MW electric heat supply, which corresponds to the decay heat level in the BETHSY scale. All the bypass flow paths in PWRs except "cold to hot leg" path, are properly modeled. Each SG contains 34 inverted U-tubes of the same radial dimensions and height stepping as those of the reference SG, thus providing a scaled heat transfer area between the primary and the secondary sides. The PCS is designed to be operated at pressure of 17.2 MPa and temperature of 673 K. The SG also can be operated at pressure up to 8 MPa.

BETHSY test 6. 9a simulates the loss of RHR system during mid-loop operation with pressurizer manway opened. While the primary side water level remains within the elevation span of the hot leg, the secondary sides have already been drained and are full of air. For the transient, the pressurizer manway is opened and at the same time, core power is increased to 141 kW assuming the coolant temperature already reached saturation point at the beginning of the experiment. The main purpose was to investigate whether the opening of pressurizer manway

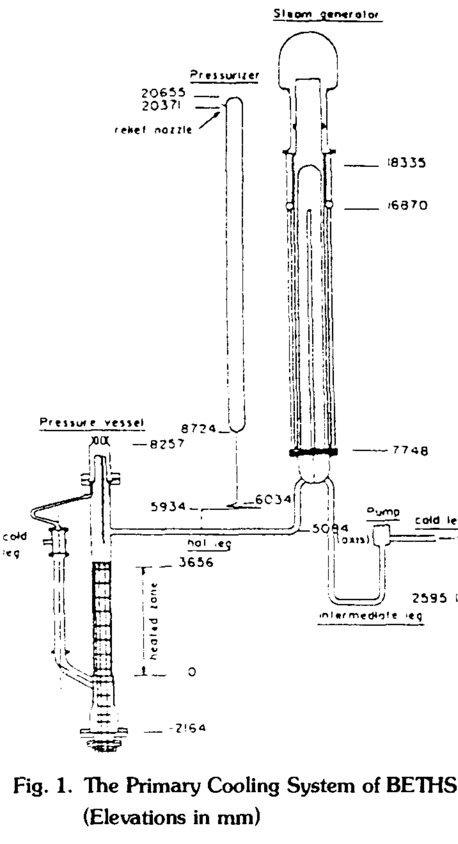


Fig. 1. The Primary Cooling System of BETHSY (Elevations in mm)

was capable of removing the vapor generated in the core. Another point was general understandings of the physical phenomena under such low pressure and low power condition. The physical phenomena concerned are liquid entrainment in the hot leg and in the upper plenum due to the steam flowing upward from the core, liquid entrainment and hold-up in the pressurizer, condensation effect, system pressurization, effectiveness of forced feed as well as gravity feed, and make-up water flow path.

The transient of the experiment divided into 4 phases according to the major phenomena. Phase I is from 0 seconds to about 3000 seconds, when the primary side is pressurized till two-phase mixture discharges through the pressurizer manway. The two-phase level in the primary side quickly rises and it reaches the pressurizer and the vertical parts of the hot legs near the steam generator inlet nozzles. Steam paths are formed through both the upper head-downcomer bypass to the cold legs and the pressurizer manway. Phase II is the period between 3000 seconds and 6000 seconds, during which the two-phase level is located below the hot legs and thus all steam produced in the core flows into the pressurizer manway through the surge line. Core uncovery occurs during this phase. Phase III corresponds to the period between 6000 seconds and 7000 seconds and gravity feed is started for recovery of the core level. During this period, pressure difference in the loops arise from condensation due to cold water injected in the cold leg. The final phase IV begins around 7000 seconds and the test terminates at 12000 seconds. In this final period the core is rapidly recovered and the two-phase level reaches the hot legs, which enables liquid entrainment to move towards the pressurizer again.

3. Modelling of the Experiment Using RELAP5/MOD3.1

RELAP5 [8] nodalization of the BETHSY facility is shown in Fig. 2. The PCS including all three loops, is modelled with 209 volumes and 214 junctions while the secondary sides of the steam generators are modeled as "time dependent volume" filled with

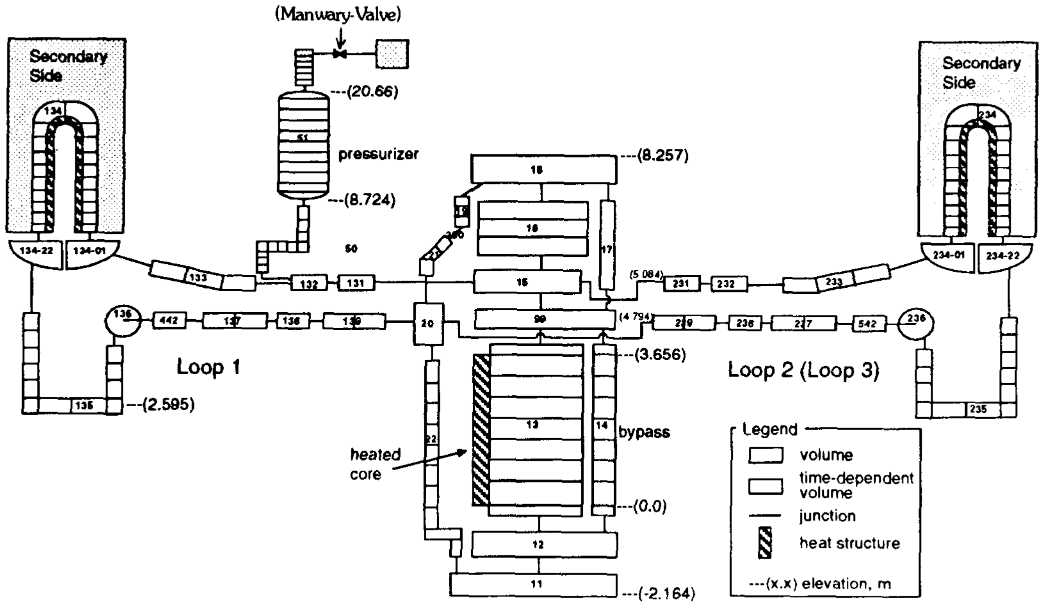


Fig. 2. RELAP5 Nodalizations for BETHSY test 6.9a

air of 105°C. Surge line is connected to hot leg using single junction. The core is modelled as a pipe component with eight volumes and the fuel rods are modeled by heat structures producing 0.5% of the normal power. Each of upper plenum and upper head to downcomer bypass is modeled by a pipe component with three volumes. Inlet and outlet of the pressure vessel are modeled by branch component with several junctions and primary side of the steam generator is modeled as a pipe component with twenty-two volumes. Also, pressurizer and surge line are modeled by pipe components nodalized with ten volumes [7]. Trace heating power, 21 kW, which was adapted to obtain the desired fluid temperature conditions in the Test 6.9a to compensate heat loss from heat structures of the RCS to atmosphere.

4. Transient Result

Initially most of the primary coolant is saturated, however, cold legs are filled with about 10°C subcooled liquid. The transient is started by opening the pressurizer manway and ramped increase of core power to 141 kW. Table 1 shows comparison of calculated initial conditions with those of the experiment. The major event is given in table 2.

As the pressurizer manway is opened, large amount of swollen liquid of the core instantaneously moves into both pressurizer and guide tubes through upper plenum. Accordingly, sudden jump of void fraction in the hot leg has been calculated as observed in the experiment on Fig. 3. Around 1200 seconds, however, rapid liquid build-up in the hot leg is observed in the calculation while the void fraction varies within a certain band up to 1600 seconds in the experiment. This occurrence corresponds to that of surge line differential pressure(DP) increase(Fig. 4) as well as upper plenum pressure increase (Fig. 5) since the code condensation model is likely to be excessively sensitive to the pressure change.

The initial swelling also leads to a drastic increase of pressurizer DP at early transient and then this DP

Table 1. Initial Condition of BETHSY Test 6.9a

Parameter	Experiment	1
Core power, kW	4.1	4.1
Upper plenum pressure, bar	1.15	1.15
PRZ. pressure, bar	1.18	1.15
PCS inventory, kg	1083±15	1082.5
Cold leg temp.,K	365.2±2	367.8
Hot leg temp.,K	376.0±2	378.8
Hot leg void fract.	0.5±0.03	0.5±0.05
Cold leg void fract.	0.0±0.03	0.0

Table 2. Chronology of Major Event

Parameter	Experiment	1
Core power=141kW(±3), s	15	15
Pressurizer mass at maximum, s	1702	1875
Pressure peak of upper plenum, s	1986(1.58 bar)	2140(1.64bar)
Increase in cladding temperature, s	4970	4510
Gravity fed injection(Tc=523K), s	6045	5282
Core mixture level minimum, s	6462	5380
Force fed injection(Tc=673 K), s	7100	5758
Core reflooded, s	8025	7400
Mixture level reaches hot leg, s	9446	8140
Nominal cold leg level, s	10160	10120

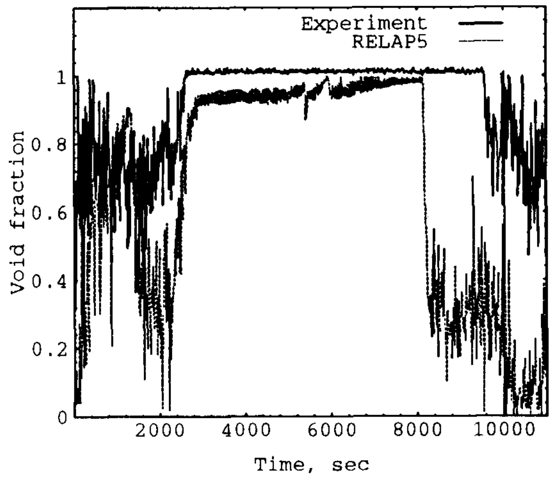


Fig. 3. Hot Leg Void Fraction

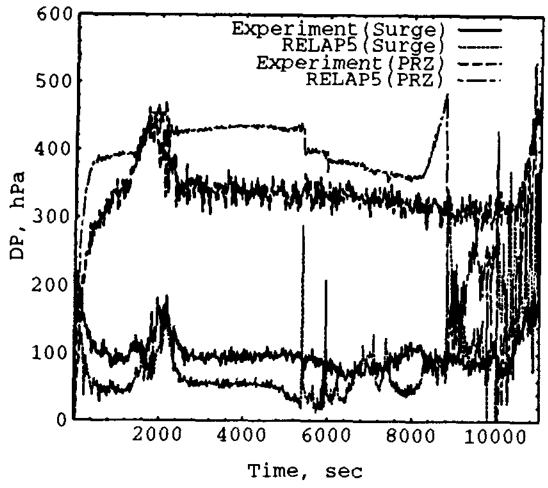


Fig. 4. The DPs at the Pressurizer and the Surge Line

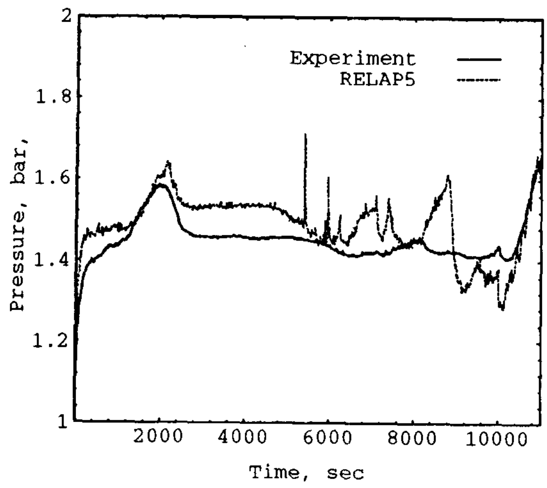


Fig. 5. The Upper Plenum Pressure

gradually increases as shown in Fig. 4, which indicates majority of liquid hold-up in the pressurizer occurs at the beginning. In the experiment the DP also goes up quickly but almost linearly. This comparison makes it possible to deduce that early level swelling be overestimated in the code and it affects rest of the transient. This result seems to come from combined effects of both overestimations of interfacial heat/momentum transfers in swelling and one dimensional nature of RELAP5 simulation which does not account for multi-dimensional mixing of coolant within the core. Fig. 6 and Fig. 7 represent the comparisons of calculated DP across the core and the guide tubes with those of measurements, respectively. It is clear that the liquid entrainment from the core has been overpredicted from the beginning because the initial DP difference is maintained until the end of phase Ⅱ. It causes DP of the core to drop to a 400 hPa in the calculation compared to a 500 hPa in the experiment. The overestimation of the liquid entrainment carried into both guide tubes and the pressurizer through the hot leg gives the differences of DP to that extent between calculation and experiment in the guide tube and in the loop DP(Fig. 7, 8). It also affects on RCS pressurization so that the code overpredicts the upper plenum pressure, resulting in

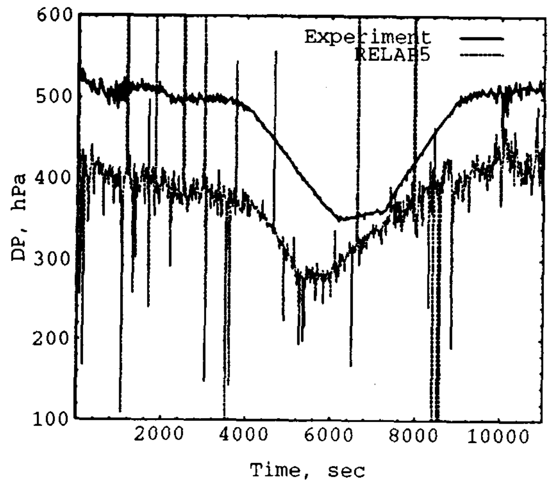


Fig. 6. The Core DP

over-estimations of both the flowrate at the manway (Fig. 9) and mixture flow(Fig. 10) through the upper head to downcomer bypass.

As liquid builds up in the pressurizer above a certain level, vapor can not easily penetrate so that relatively small amount of vapor can pass the pressurizer. In Fig. 9 slight reduction of the manway flow after 1000 seconds in the experiment could be explained by this. On the other hand, the calculation shows the reduction of the flowrate after 1300 seconds probably due to the higher upper plenum pressure in the calculation than that in the experiment. As long as mixture level in the core sustains above a cold leg, continuous insurge of the liquid entrainment from the core gives rise to the liquid level increase in pressurizer and the level eventually reaches the manway around 1600 seconds. Then two-phase mixture is discharged and the manway flow is drastically increased until the liquid level drops below the manway. Also, system inventory as shown in Fig. 12 is rapidly diminished by two-phase discharge.

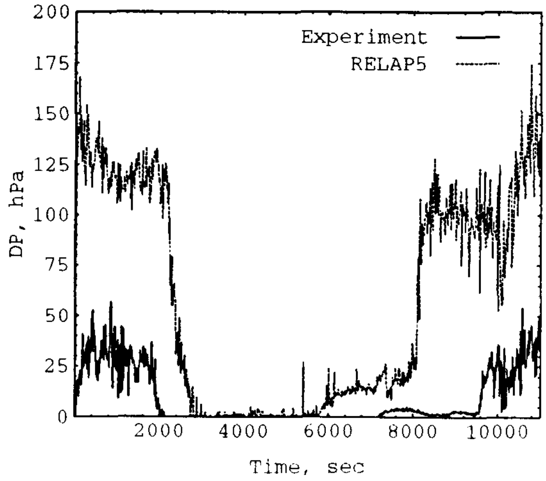


Fig. 7. The Guide Tube DP

The mixture discharge through the pressurizer manway swept out the liquid entrainment in the hot leg by larger steam being produced due to system depressurization, which in turn increases liquid carry-over in the upper plenum to the hot leg, and consequently the system inventory and the two-phase level in the pressure vessel rapidly fall down. After the two-phase discharge, there is a difference of about 100kg of the system inventory between the calculated and experimental data until safety injection, mainly due to overestimation of the mixture discharge flow through the manway. Remaining liquid in pressurizer augments the differential pressure of pressurizer(Fig. 4) in conjunction with the upper plenum pressure. The difference of void fraction in the hot leg after two-phase discharge after around 2400 seconds may be understood by examining the entrainment model in the code under stratified flow (Fig. 11).

Thus liquid always remains in the hot leg as long as the level maintains below h_b, which corresponds to void fraction of 0.85−0.9 under the present conditions, whereas all liquid is swept out during this period in the experiment.

Even after the two-phase level in the pressure ves-

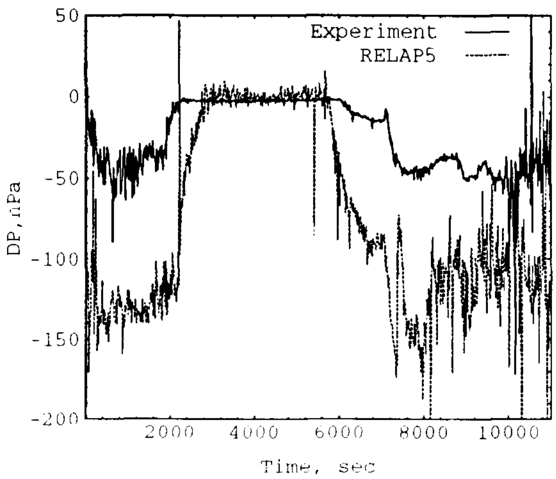


Fig. 8. The Loop 1 DP(Cold leg P-Hot Leg P)

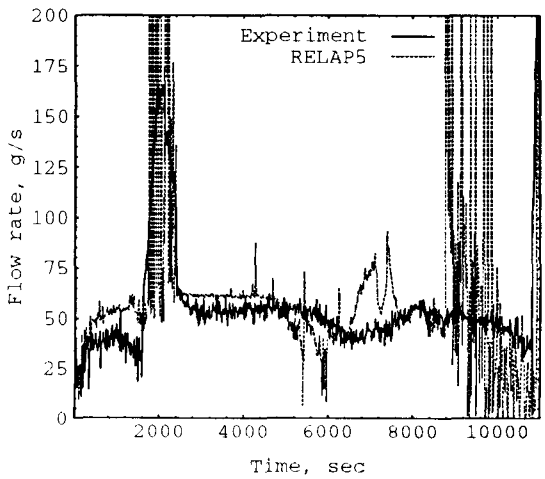


Fig. 9. The Mass Flow Through the PRZ Manway

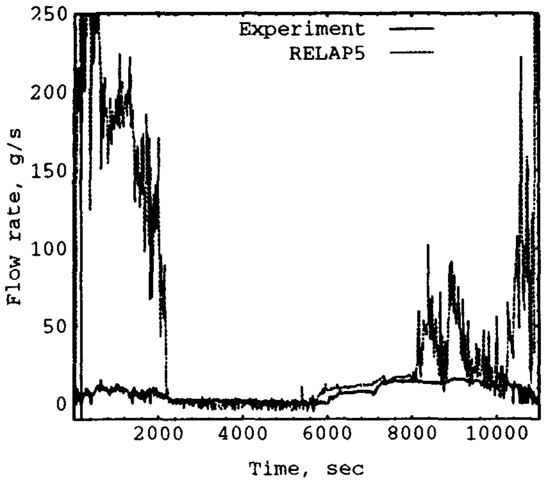
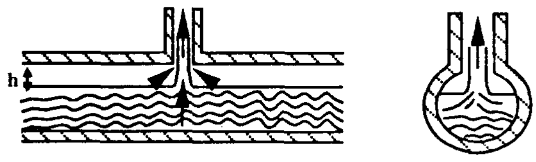


Fig. 10. The Upper Head Bypass Flow Rate

sel drops below the axis of the hot leg after around 2400 seconds, the difference of pressurizer DP between the experimental and the calculated values is repeated after two-phase discharge. Larger liquid hold-up after the mixture discharge in the code is presumably related with overestimation of interfacial friction between vapor and liquid phase in such a large diameter as pressurizer. The change of CCFL options in the code have not showed any distinct improvement. Thus pressurizer DP is prone to decrease in the experiment between 2000 seconds and 5500 seconds, however, it slowly increases in the calculation because a small quantity of liquid entrained in the hot leg continued into the pressurizer through the surge line due to larger interfacial momentum transfer. During this period, most of steam produced in the core is discharged through the pressurizer manway and there is no flow through the upper head to downcomer bypass line after the core level is placed below the hot leg so that the cold leg pressure exhibits the same value as that of upper plenum(Fig. 8). The RCS pressure keeps almost constant until the top of core is uncovered. The core uncovery time is estimated about 4510 seconds in the calculation while it takes about 4970 seconds in the experiment. This difference results from the overprediction of both the pressurizer manway flow rate and liquid hold-up in the pressurizer as shown in Fig. 4 and Fig. 9.

As the system pressure decreases due to core uncovery, so the rod temperature increases. In the calculation, gravity fed safety injection is triggered and water is injected into the cold leg of loop 1 when the rod temperature reached 250°C at around 5282 seconds. This injection occurs about 700 seconds earlier in the calculation because the higher upper plenum pressure has caused more coolant to be discharged through the opening. The system pressure continues decrease as cold water is injected into the cold leg. Rapid depressurization due to the steam condensation caused to fall down the liquid hold-up in the pressurizer into the hot leg. This generates unrealistic pressure peaks between 5400 seconds and 6200 seconds(Fig. 5). While about 50g/s of the cold water is injected by gravity fed for 1000 second in the experiment, about 30g/s of water is injected for 500 seconds in the calculation due to higher system pressure. But gravity injection is not sufficient to recover the core level in either results.

After all, forced fed safety injection is actuated with increasing flowrate around 5800 seconds and the core begins to be reflooded from 6000 seconds. The flowrate through pressurizer manway increases because more steam is produced in the core as the core is recovered(Fig. 6, 9). The system pressure as shown in Fig. 6 greatly fluctuated due to steam condensation by forced fed injection from 6000 seconds



$X = R^{3.25(1-R)^2}$ X : Flow quality of the offtake

$R = h/h_b$ R : Non-dimensional distance

$h_b = \frac{W_k^{0.4}}{(g\rho_k \Delta\rho)^{0.2}}$ h_b : Inception height

Fig. 11. Horizontal Stratification Entrainment Model

to 7600 seconds. The initiation of safety injection causes loop DP to increase again(Fig. 8) because of condensation in the cold leg, which enables the mixture to flow through the upper plenum to downcomer bypass as the core level recovers, in Fig. 10. The RELAP5 always overestimates the condensation as well as the bypass flow.

Fig. 9 shows the temperature of upper part of rod. In the calculation, the peak rod temperature reached 742 K at 6665 seconds, but it reached 712 K at 7480 seconds in the experiment. The core seems to be completely recovered around 7600 seconds. The void fraction in the hot leg rapidly decreases as the two-phase level reaches bottom of the hot leg and is maintained in lower value in the calculation around 8150 seconds(Fig. 3). From this time to about 8800 seconds, the mixture level of the pressurizer which has been decreased due to condensation rapidly rises due to liquid entrainment increase in the hot leg and the upper plenum is repressurized.

Once more, two-phase discharge occurs at the pressurizer manway and the system pressure and inventory suddenly drops as previously mentioned. Two-phase mixture flow is also possible through the upper head to downcomer bypass. In the experiment, the two-phase level reached the axis of the hot leg at around 9500 seconds and discharge of the mixture through the manway continues as liquid entrainment flowing toward the pressurizer.

Increased safety injection filled the cold leg around 10000 seconds and upper head bypass flowrate becomes negligible by 10500 seconds (Fig. 4, 9, 10). Thereafter, the system pressure increases by injection flow. The experiment has been carried out for 12420 seconds, however, the simulation for the transient is terminated at 11000 seconds because of ealier evolution.

A main problem encountered in this analysis was that RELAP5/MOD3.1 requires extremely small time step sizes because of the complex nature of the phenomena as well as numerical scheme which adapts semi-implicit method. Also, system mass error was accumulated 7.5% of the total mass at the end of the calculation. For this reason, there exist the definite limit in time step size even for slow transient. The shortest time step size has been only 0.6ms. The calculation of the whole transient has required over 120 hours of CPU time on the CRAY-YMP for 3 hours of simulation.

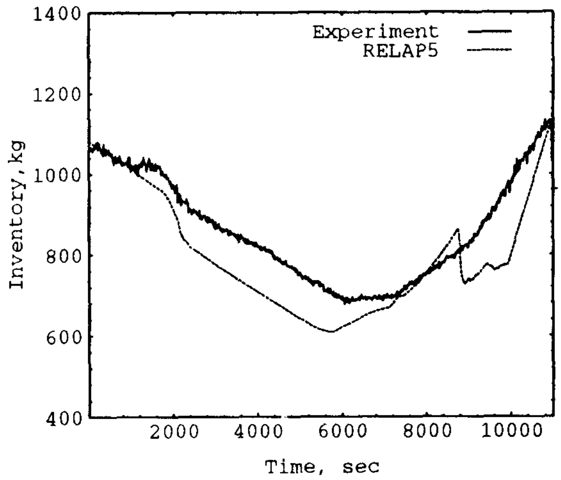


Fig. 12. The Primary Mass Inventory

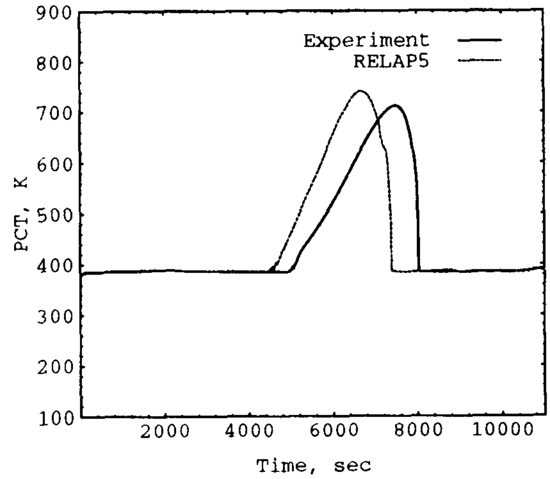


Fig. 13. The Heater rod Surface Temperature

5. Conclusions

The RELAP5/MOD3.1 has been used to simulate

BETHSY test 6.9a, 'the loss of residual heat removal system during mid-loop operation', conducted in the BETHSY facility at CEN-Grenoble of CEA, France. From this study following conclusions have been obtained:

1. The modelling of both core bypass channel and upper head to downcomer bypass is the most sensitive in overall RCS behavior. The initial swelling in the pressure vessel and DP between upper head and downcomer has significantly affected on the break flow through the pressurizer manway. The overestimation of interfacial friction appears to be obvious because the RELAP5/MOD3.1 has overpredicted both the pressurizer DP and the upper plenum pressure so that the larger break flow through the manway, which has brought earlier core uncovery by about 400 seconds.
2. The use of CCFL option in the code input has not improved the results distinctively in the present analysis.
3. The liquid holdup in the pressurizer might be possible and so the RCS pressure might be higher than that estimated without this effect in the actual accident analysis.
4. In contrast with the experimental observations, the condensation model in RELAP5/MOD3.1 is extremely sensitive to pressure change. Unrealistic behaviors of pressure spikes reveals the fact. The spikes seem to come from falling of the liquid holdup in the pressurizer, following slight depressurization attributing to excessive condensation near the safety injection points.
5. It is demonstrated that gravity feed has not been sufficient to recover the core level under this configuration. Therefore one should evaluate the procedure whether it is prepared in such a way in an actual plant. This fact suggests that forced feed may have to be in operable condition when only the pressurizer manway is open as a large opening during this accident.
6. Generally, overall transient as well as main events has been predicted reasonably by RELAP5/MOD3.1 but it has been computationally exhaustive because it required extremely small time step sizes. For this reasons, RELAP5/MOD3.1 could be applied to the accident analysis of an actual plant, however, it is not an efficient way.
7. For the reliable accident management, other options of large openings should be studied in order to understand the system behaviors completely under various configurations during the accident and at the same time, an efficient method of the analysis should be investigated.

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