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An Analysis of the Loss of Residual Heat Removal System Event for Pressurized Water Reactor at Reduced Inventory Operation

Kee Soo Han and Jin Ho Song
Korea Atomic Energy Research Institute
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가압경수로의 저수위 운전시 잔열제거계통 상실사고에 대한 분석

한기수 · 송진호
한국원자력연구소
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Abstract

The loss of Residual Heat Removal System (RHRS) event during reduced inventory operation for the Korean Standard Nuclear Power Plants (KSNPPs) is simulated by RELAP5/MOD3 and RELAP5/MOD3.1. Two cases are considered : Base case for an intact Reactor Coolant System (RCS) with no vent and a vent case for an open system. Comparative simulations of base case are performed by RELAP5/MOD3 and RELAP5/MOD3. 1 computer codes.

The results of two simulations are generally in good qualitative and quantitative agreement. However, since the results of RELAP5/MOD3 simulation reveals the deficiency of RELAP5/MOD3 wall heat model, the RELAP5/MOD3.1 computer code is used for the simulation of the vent case.

The analysis results of base case show that two steam generators are insufficient to remove decay heat at one day after shutdown, where the RCS is closed. The RCS pressure increased continuously and reached the RCS temporary boundaries design pressure of 0.24 MPa around 4,000 seconds. In the vent case with a flow capacity equivalent to three times the capacity of Pressurizer Safety Valve (PSV), it is shown that the RCS pressure does not reach 0.24 MPa and core uncovery does not occur until 10,000 seconds.

The detailed discussions on the results of this study suggest the feasibility of RELAP5/MOD3.1 as an analysis tool for the simulation of the loss of RHRS event at reduced inventory operation. The results of this study also provide insight for the determination of proper vent capacity.

요 약

표준원전을 대상으로하여 저수위 운전시의 잔열제거제통상실사고를 RELAP5 /MOD3 및 RELAP5 /MOD3.1 전산프로그램을 이용하여 분석하였다. 증기발생기가 이용가능할 때 원자로냉각재계통에 배기 경로가 없는 경우와 배기경로가 있는 경우에 대하여 분석을 수행하였다.

배기경로가 없는 경우에 대해 RELAP5 /MOD3 전산프로그램과 RELAP5 /MOD3.1 전산프로그램으로 비교 분석을 수행하였다. 분석결과 두 전산프로그램의 계산결과는 정성적인 면 뿐 아니라 정량적인

면도 비교적 잘 일치하였다. 그러나 계산결과로부터 RELAP5 /MOD3의 경우에는 벽 열전달모델의 결함이 발견되어 배기경로가 있는 경우에 대해서는 RELAP5 /MOD3.1 전산프로그램을 이용하여 분석을 수행하였다.

분석결과 원자로정지후 하루가 지났을때 배기경로가 없는 경우에는 두개의 증기발생기로도 잔열이 충분히 제거되지 않아 원자로계통의 압력이 지속적으로 증가하여 사고 개시 후 4,000초 정도에 원자로계통의 임시밀봉재의 설계압력인 0.24 MPa에 도달하였다. 가압기 안전밸브 용량의 세배정도 크기의 배기경로가 있는 경우에는 10,000 초가 지나도 원자로냉각재계통의 압력이 0.24 MPa에 도달하지 않았으며 노심노출이 초래되지 않았다.

분석결과의 상세한 검토를 통해서 저수위 운전시 잔열제거능력 상실사고가 발생하였을 경우 RELAP5 /MOD3.1을 이용한 사고해석 방법론의 타당성을 제안하였으며 또한 적절한 배기용량을 산정하기 위한 자료를 제공하였다.

1. Introduction

Loss of residual heat removal during non-power operation and consequences of such a loss have been of increasing concern for years. The report of Diablo Canyon, NUREG-1269[1], stated that operating a plant with a reduced reactor coolant system inventory was a particularly sensitive condition and identified many generic weaknesses in RHRS. After the loss of vital alternating current power and RHRS during shutdown at Vogtle Unit 1 on March 20, 1990[2], attention has been increased on the need to evaluate system performance following such an event in Pressurized Water Reactors (PWRs).

During shutdown, with the reactor coolant system at reduced pressure and temperature, inventory reductions are achieved through an introduction of nitrogen into the system. If the RHRS fails under such conditions, the steam generators may be able to be used as an alternate means of residual heat removal provided RCS integrity can be ensured. Moreover, once boiling initiates, RCS pressure increases due to the presence of noncondensable gases in the system. As a consequence, there is a need to assess the RCS pressure response since the success of this strategy depends on whether the peak pressure is sufficient to cause failure of any of the RCS temporary boundaries used during plant refueling outages. If there is insufficient time to close an open RCS and boiling initiates, a source of coolant makeup is needed to prevent core uncovery and fuel damage.

References 3, 4, 5, and 6 employed RELAP5/MOD3[7] as an analysis tool to analyze the loss of RHRS event for various plant configurations. In Reference 3 a loss of RHRS during midloop operations was simulated for a typical four-loop PWR. Two cases are considered : One for an intact reactor coolant system with no vent and the other for an open system with a vent in the pressurizer. The results of simulation showed that reflux condensation which occurred in the steam generator U-tubes prevented complete core uncovery and the total heat removed by the steam generator was one-third of that produced by the core. References 4 and 5 analyzed cases to assess the capability of steam generators for decay heat removal. The RELAP5/MOD3 model was used to assess the consequences of a loss of RHRS event for the H. B. Robinson plant which is a three-loop Westinghouse PWR with a thermal power rating of 2,300 MWt with U-tube steam generator. Depending on the time after shutdown and initial RCS water level four cases are considered : One day after shutdown, one week after shutdown, RCS water level at the top of hot leg, and RCS water level at the elevation of reactor vessel flange. The transient was simulated well after the boiling in the steam generator secondary side was initiated. However, the secondary system behavior showed rather unrealistic behavior.

Also the vent case was not investigated in these studies.

The objective of the present study is to simulate the loss of RHRS event during reduced inventory operation for the Korean Standard Nuclear Power Plants (KSNPPs), which are 2,815 MWt two-loop PWR jointly designed by ABB-CE and Korea Atomic Energy Research Institute (KAERI). Another objective of this study is to assess the feasibility of the use of RELAP5/MOD3 and RELAP5/MOD3.1 codes as an analysis tool. Two cases are considered : One for an intact reactor coolant system with no vent and the other for an open system with a vent in the pressurizer. The pressurizer vent flow capacity selected is equivalent to three times the flow capacity of pressurizer safety valve, which is selected to enable comparison with available literature[3].

2. Method of Analysis

2.1. Computer Codes and Nodalization

The computer codes used in this analysis are RELAP5/MOD3 (Version 7j) code which was executed on an Apollo DN-10000 workstation and RELAP5/MOD3.1 code executed on a HP-UX workstation. The nodalization used for the modeling of KSNPP is provided in Figure 1. The nodalization has 169 volumes and 184 junctions. The two primary coolant loops are explicitly represented in the model as Loop A and Loop B. Each loop consists of a hot leg, U-tube steam generator (SG), two suction legs (loop seals), two reactor coolant pumps, and two discharge legs (cold legs). The pressurizer is attached to Loop A. Heat structures are modeled to represent the metals in the pipings and reactor vessel.

2.2. Cases Analyzed

Two cases are considered : One for an intact reactor coolant system with no vent where the both steam generators are in wet layup condition. In the second case a small vent in the pressurizer is provided. The analytical vent area is equivalent to three times of the flow capacity of pressurizer safety valve.

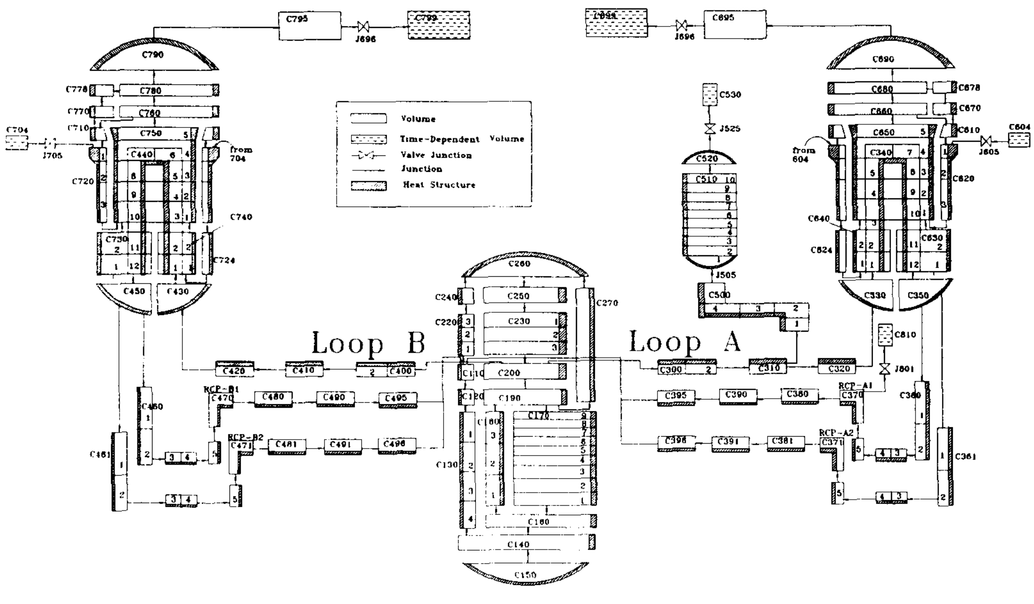

Fig. 1. RELAP5 Nodalization of KSNPP for Loss-of-RHR Event

2.3. Initialization and Transient Run

Since manometric balance is a major hydrodynamic phenomenon during loss of RHRS event, correct system K-factors should be used for the analysis. To confirm and verify the system K-factors a 100% power steady state condition was simulated. After setting up steady state base deck for 100% power condition a modification to establish reduced inventory operation has been performed.

The initial conditions used in this analysis are provided in Table 1. The RCS is at mid-loop conditions with a water temperature of 50°C (323.15K) and an initial liquid level at the hot leg centerline elevation. Nitrogen at 50°C (323.15K) and 100% relative humidity by using ε bt=004 option is assumed to represent the mid-loop condition. Since the core full power is 2815 MWt, the decay heat power level corresponding to one day after shutdown is assumed to be 0.63% of full power or 17.7346 MWt. To establish steady state initial conditions at mid-loop level a 300 seconds simulation is performed with no decay heat. After 300 seconds the decay heat input corresponding one day after shutdown is turned on in the core and a loss of RHRS is assumed simultaneously.

Another point to mention is on the selection of specific options to minimize potential numerical problems. By couple of parametric studies it is found that no choking option for all junctions, no water packing and vertical stratification options for all primary and secondary volumes are recommendable. The no choking option is selected because RELAP5/MOD3 and RELAP5/MOD3.1 codes predicted unrealistically low sound velocities when noncondensables are present.

The time steps are carefully selected to minimize numerical divergence. A small scale nodalization is utilized to optimize the time step. The time steps between 0.05 second and 0.0025 second are used in this study. For these time steps, the calculation of base case requires over 44.34 hours of CPU time on HP-UX workstation for a transient of 10,300 seconds.

3. Results and Discussion

3.1. Base Case

3.1.1. Major Analysis Results

The loss of RHRS event is simulated when the RCS is at mid-loop level with no primary vent. Both steam generators are in wet layup condition, which are available for decay heat removal. Since previous analysis results[3,4,5] showed a little anomalous behavior, comparative simulations by RELAP5/MOD3 and RELAP5/MOD3.1 are performed in this study. The results of RELAP5/MOD3 simulation are found to be generally in good qualitative and quantitative agreement with those predicted by RELAP5/MOD3.1. Therefore, the results of RELAP5/MOD3.1 simu-

Table 1. Initial Conditions for the Base Case

Parameters	Values of Base Case
Primary Pressure	0.101325 MPa
Hot-Leg Temperature	323.15 K
Cold-Leg Temperature	323.15 K
Liquid Level	Center Line of Hot/Cold Legs
Secondary Pressure	0.101325 MPa
Secondary Temperature	323.15 K
SG Liquid Volume per SG	138.2457 m^3
SG Vent Area per SG Vent Set Pressure (*)	0.01924 m^2 (2 ADVs) 0.101325 MPa
Decay Heat Power (One Day after Shutdown)	17.7346 MWt (2815 MWt×0.63%)
RCS Nitrogen Humidity	100%
Number of Available SGs	2
Aux. Feed Water Supply	No
RCS Vent Path	No

*) SG vent area is assumed to be equivalent to the area of two atmospheric dump valves (ADVs). Set pressure is arbitrarily selected to be equal to atmospheric pressure.

lation are mainly discussed in this section. The detailed comparison between two results is provided in the next subsection. Table 2 provides the major sequence of event simulated by RELAP5/MOD3.1.

Figures 2 presents the pressure transients of cold leg and hot leg when the RHRS is lost at one day after shutdown. The pressure in the hot leg has the same trend as cold leg and is slightly higher than that of cold leg. In the present study RCS pressures are not stabilized even after the secondary side boiling, which are quite different from those presented in References 4 and 5. However, as can be shown in Figures C-6 and C-7 of Reference 4, the secondary system behavior reported in Reference 4 is somewhat unrealistic. Therefore, the reasons for the difference in pressure behavior are judged to be due to difference in boundary conditions for the steam generator secondary side configuration including venting capacity. The hot leg pressure reaches 0.24 MPa (20 psig) which is design pressure of RCS temporary boundaries around 4,000 seconds, even though both steam generators are available for secondary heat removal. Since this case will impact the integrity of temporary RCS boundaries such as thimble tube seals, timely addition of cold feed flow to the RCS or opening of RCS vent path is recommended to mitigate the loss of RHRS consequence.

Table 2. Major Sequence of Event for Base Case (RELAP5/MOD3.1)

Time (second)	Major Events
300	Loss-of-RHR is initiated
about 620	Incipient boiling in the core
about 1100	Saturation of reactor vessel upper plenum liquid
about 1530	Water clearing in the cold legs
about 1690	Incipient reflux condensation in both SGs
about 7660	Saturation of SG [B] evaporator & riser regions
about 8040	Saturation of SG [A] evaporator & riser regions

Figure 3 illustrates the liquid temperatures of the primary and secondary side of SGs. The steam generator temperatures increase linearly before the boiling starts in the secondary side (see temperature transients of components 650 and 750). Since the steam generated in the core cannot penetrate the U-tubes due to noncondensable gases accumulated in the U-tube, the temperatures of SG outlet plenum (components 350 and 450, not shown) are lower than those of SG inlet plenum (components 330 and 430).

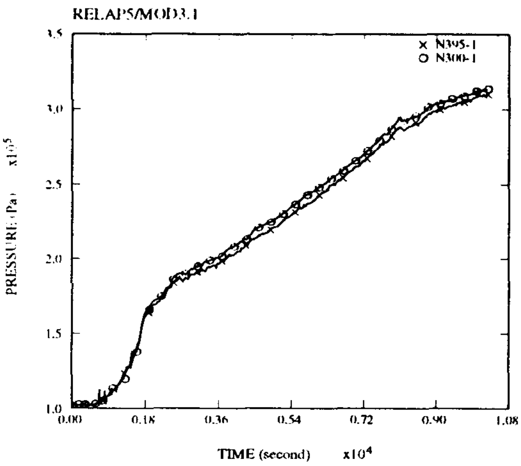

Fig. 2. Primary Pressures

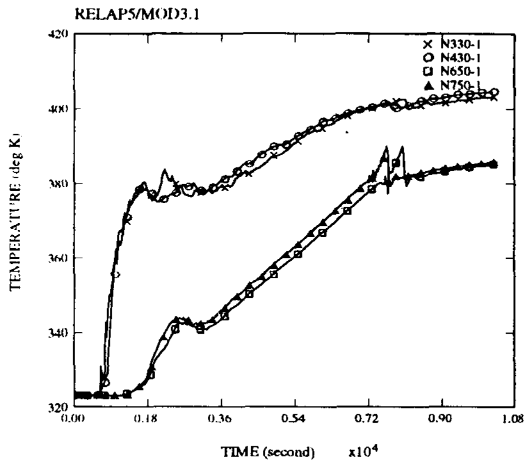

Fig. 3. Temperatures of Primary and Secondary Sides of SGs

Figure 4 shows cold leg liquid void fraction. It indicates that the cold water in the cold leg flows into the reactor vessel completely around 1,530 seconds. Figure 5 shows hot leg liquid void fraction. Saturation of reactor vessel upper plenum liquid occurs at about 1,100 seconds as can be seen in Table 2, after that the temperature increase slows down. The liquid void fraction increases before saturation due to thermal expansion and is maintained around 0.75 after the boiling starts in the core. After the onset of boiling the steam generated in the core pushes water in the reactor vessel and hot leg to the steam generator inlet plenum. This increases liquid void fraction in the steam generator inlet plenum as shown in Figure 6.

Figures 7b presents the vapor void fractions in the first two volumes of the steam generator U-tubes of the Loop A. Following the initiation of bulk boiling in the vessel, a condensing surface is formed once the steam has compressed the nitrogen in the RCS to a volume less than that of the steam generator active tube region. As a result, the primary heat transfer rate starts to increase as can be seen in Figure 9b and secondary side is heated up as shown in Figure 3. The condensation in the steam generator occurs primarily in the first U-tube volume above the tube sheet, with some condensation also occurring in the next active U-tube volume.

3.1.2. Comparison between the Results by RELAP5/MOD3 and RELAP5/MOD3.1

The most noticeable distinction between two predictions is whether the symmetric thermal-hydraulic behavior in the primary side and secondary system is predicted or not. The results by RELAP5/MOD3.1 predict symmetric thermal-hydraulic behavior. However, those by RELAP5/MOD3 do not predict symmetric behavior, which is irreconcilable with physical reality. Followings are discussions and explanations on the major differences in two predictions.

Void fraction in the inlet portion of U-tube primary

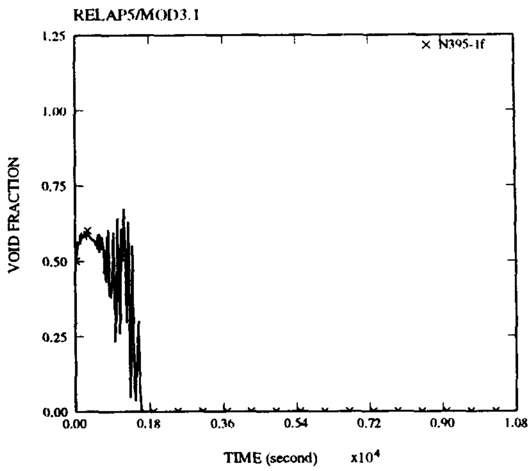

Fig. 4. Cold Leg Liquid Void Fraction [A]

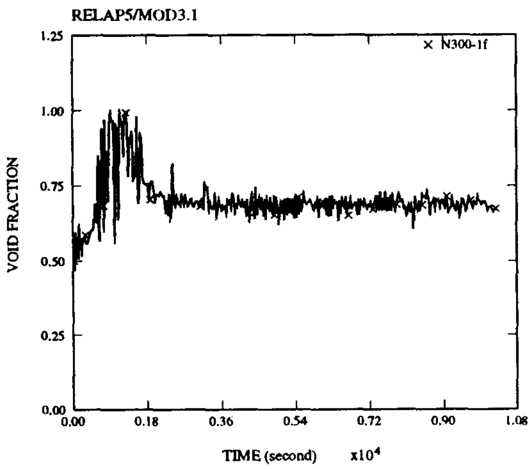

Fig. 5. Hot Leg Liquid Void Fraction [A]

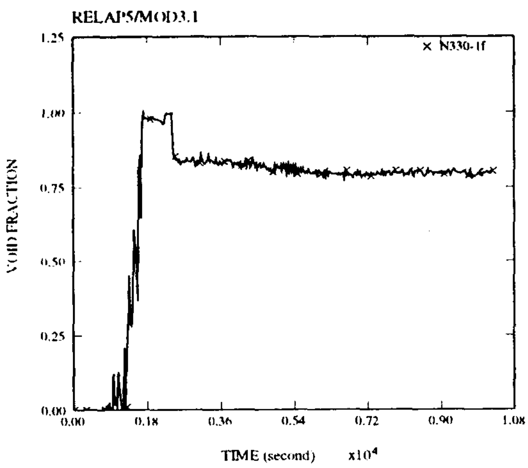

Fig. 6. SG Inlet Plenum Liquid Void Fraction [A]

side : Figures 7a and 7b represent the vapor void fraction in the first two volumes of the SG U-tubes. In Figure 7a, the void fractions in the steam generator U-tube in the loop with pressurizer (Loop A) stay around 1.0 and condensation does not occur. This is due to deficiencies in the wall heat model of RELAP5/MOD3 under noncondensable conditions. Since the pressurizer is filled with noncondensable gas, the wall temperatures of the pressurizer metal are initialized with higher temperature than the vapor temperature due to incorrect wall heat initialization scheme employed in the RELAP5/MOD3. Therefore, soon after the initiation of transient the noncondensable gas and steam in the pressurizer are heated by wall heat and expanded, which result in steam flow from the pressurizer to hot leg. Since the noncondensable gas has same velocity as steam, the noncondensable gas contained in the pressurizer flows into hot leg together with steam. After core starts to boil, the steam generated in the core flows into the hot leg and the steam generator. This results in more noncondensable accumulation in the pressurizer side U-tube (Loop A, see Table 3 for the distribution of non-condensable in the RCS). Since saturation temperature to start condensation becomes lower as the amount of noncondensable increases, the condensation does not occur in the pressurizer side steam generator as can be seen in Figure 7a. However, in RELAP5/MOD3. 1 analysis, since wall heat structures are initialized with the same temperature as that of steam and noncondensable, this kind of anomalous behavior does not occur as shown in Figure 7b, which shows reflux condensation in the first U-tube node in the loop with pressurizer (Loop A).

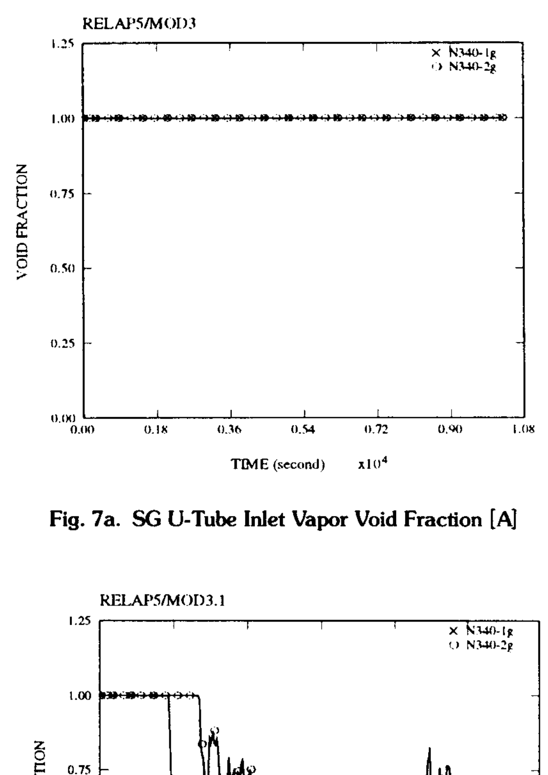

Fig. 7a. SG U-Tube Inlet Vapor Void Fraction [A]

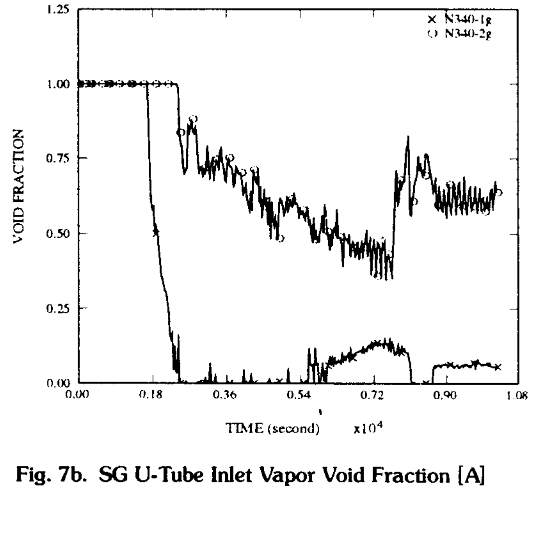

Fig. 7b. SG U-Tube Inlet Vapor Void Fraction [A]

Junction flow rate from SG inlet plenum to SG U-tube inlet : Figures 8a, 8b, 8c, and 8d illustrate the establishment of junction mass flowrates of liquid (330-1f) and vapor (330-1g) from the SG inlet plenum to SG U-tube inlet. For RELAP5/MOD3.1 analysis, the junction liquid mass flow rates show rather oscillatory behavior around zero flow rate and the steam flow is in the upward direction. After the sudden increase of steam flow into the U-tube inlet, the reflux condensation seems to be started (see Figures 7b and 8b). In RELAP5/MOD3 case, the steam flow in the loop with pressurizer (Loop A) is greater than that of other loop (Loop B, not shown) and no liquid flow occurs in the loop with pressurizer. The RELAP5/MOD3.1 case shows symmetric behavior between loops (see distribution of nitrogen of Table 4).

Integrated SG U-tube heat flux : Figures 9a and 9b show integrated heat flux along the SG U-tubes.

Table 3. Distribution of Nitrogen in the RCS for Base Case (RELAP5/MOD3)

Primary Side Components	Mass of Nitrogen (kg)			
	t=0 second	t=300 seconds	t=3300 seconds	t=10300 seconds
RV IA Nitrogen Mass	12.0622	11.5235	1.87515	1.886665
(RV-RV IA) Nitrogen Mass	42.3284	39.7552	0.0	0.137875
HL Piping [A] (300, 310, 320)	2.20336	2.16778	0.0	0.0
SG Inlet Plenum [A] (330)	7.5657	7.692	0.0024	0.00167
SG U-Tubes [A] (340-01~06)	16.5878	17.5322	27.8909	21.7773
SG U-Tubes [A] (340-07~12)	16.5878	17.3877	31.2759	37.681
SG Outlet Plenum [A] (350)	7.3937	7.2613	14.048	18.025
CL Piping [A1] (360, 370, 380, 390, 395)	3.27142	3.61221	10.35016	8.50103
CL Piping [A2] (361, 371, 381, 391, 396)	3.27142	3.61221	10.33631	8.395282
Loop [A] Nitrogen Mass	56.8812	59.6654	93.90367	94.381282
Loop [B] Nitrogen Mass	56.8812	59.3394	78.51765	71.421027
PZR/Surge Line (500, 510, 520)	48.9805	46.7395	36.447395	30.4301035
Total Nitrogen Mass	217.134	217.023	210.74386	198.25695

RV=Reactor Vessel, IA=Inlet Annulus, CL=Cold Leg, HL=Hot Leg,
PZR=Pressurizer, SG=Steam Generator

Table 4. Distribution of Nitrogen in the RCS for Base Case (RELAP5/MOD3.1)

Primary Side Components	Mass of Nitrogen (kg)			
	t=0 second	t=300 seconds	t=3300 seconds	t=10300 seconds
RV IA Nitrogen Mass	12.0622	11.7178	7.63565	0.0
(RV-RV IA) Nitrogen Mass	42.3284	41.2578	0.0	0.0
HL Piping [A] (300, 310, 320)	2.20336	2.14033	0.0	0.0
SG Inlet Plenum [A] (330)	7.5657	7.5304	0.0	0.0
SG U-Tubes [A] (340-01~06)	16.5878	16.5222	18.6003	15.5064
SG U-Tubes [A] (340-07~12)	16.5878	16.5293	26.6922	35.7723
SG Outlet Plenum [A] (350)	7.3937	7.3883	6.1577	9.1954
CL Piping [A1] (360, 370, 380, 390, 395)	3.27142	3.60458	11.85447	9.95018
CL Piping [A2] (361, 371, 381, 391, 396)	3.27142	3.60458	12.07598	9.04345
Loop [A] Nitrogen Mass	56.8812	57.31969	75.38065	79.46773
Loop [B] Nitrogen Mass	56.8812	57.2525	77.57518	80.17489
PZR/Surge Line (500, 510, 520)	48.9805	49.57104	56.14428	56.18281
Total Nitrogen Mass	217.134	217.1188	216.73576	215.82543

RV=Reactor Vessel, IA=Inlet Annulus, CL=Cold Leg, HL=Hot Leg,
PZR=Pressurizer, SG=Steam Generator

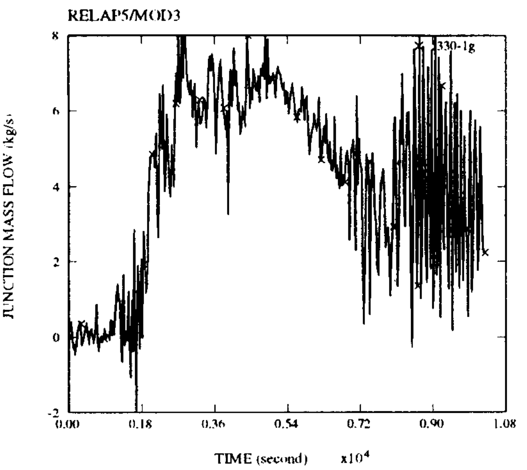

Fig. 8a. Mass Flow (SG_IP→SG_U-Tube)

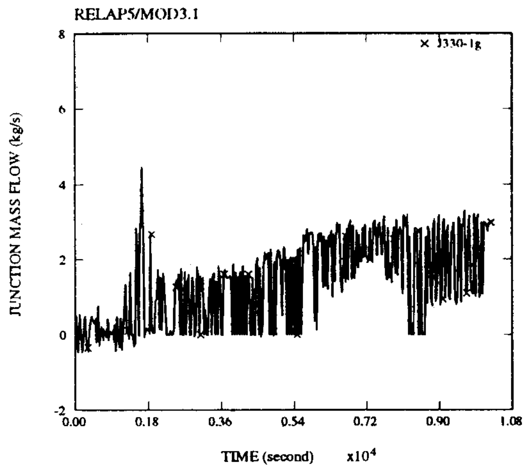

Fig. 8b. Mass Flow (SG_IP→SG_U-Tube)

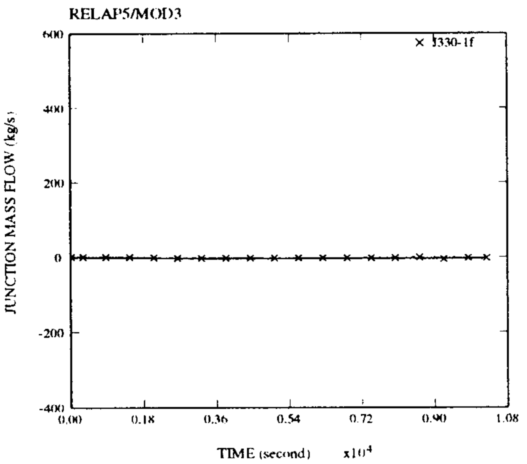

Fig. 8c. Mass Flow (SG_IP→SG_U-Tube)

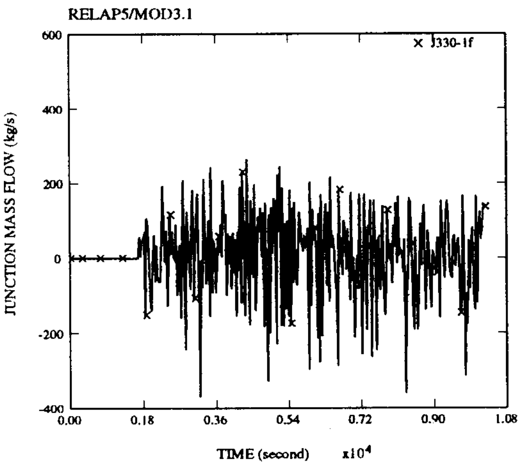

Fig. 8d. Mass Flow (SG_IP→SG_U-Tube)

Even though the void fractions are quite different between both SGs and the condensation does not occur in the SG U-tube in the loop with pressurizer (Loop A), the magnitude and trend of heat transfer are quite similar in the RELAP5/MOD3 analysis. As expected, symmetric heat transfer is predicted by RELAP5/MOD3. 1 analysis (not shown).

Steam generator secondary side : Since the spaces just above the components of 650-5 and 750-5 in Figure 1 contain the nitrogen, the slight addition of nitrogen into the interface node makes that the saturated temperature is the same as the liquid temperature in the RELAP5/MOD3.1 analysis. However, initial water temperatures in the RELAP5/MOD3 code increase due to the incorrect wall heat model and the subsequent water volume expansion prevents the slight addition of nitrogen. Therefore, the saturated water temperatures are always greater than the liquid temperature for the initial duration of the transient. However, since this difference is limited to the inter-

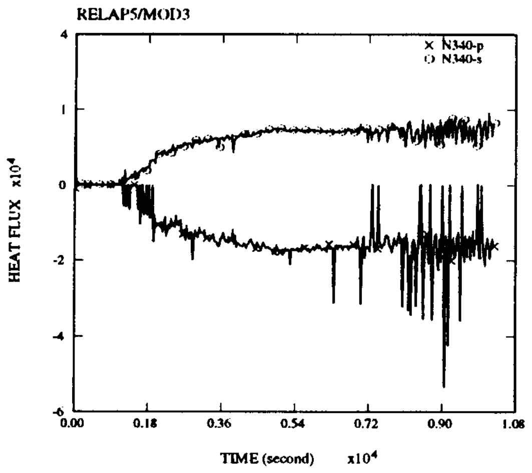

Fig. 9a. Integrated SG U-Tube Heat Flux [A]

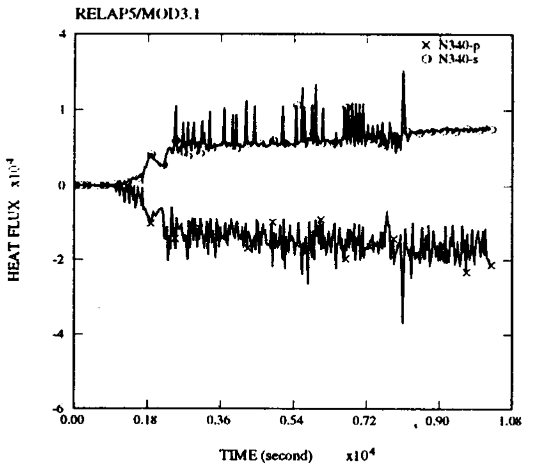

Fig. 9b. Integrated SG U-Tube Heat Flux [A]

face region, the impact is judged to be minimal on the overall behavior.

3.1.3. Distribution of Noncondensable Gases During Transient

Fundamental assumptions employed in the RELAP5 noncondensable models are as follows : 1) The temperature of noncondensable is same as that of steam, 2) Total pressure is determined by addition of partial pressures of steam and noncondensable, 3) Vapor specific energy is mass weighted sum of the steam specific internal energy and the noncondensable specific internal energy, and 4) Noncondensable gas has same velocity and temperature as steam.

As can be seen in Tables 3 and 4, the nitrogen is displaced from the reactor vessel and hot leg piping and accumulates in the steam generator active tubes, outlet plenum, and cold leg piping. The total nitrogen mass is slightly disturbed during the transient simulation. For RELAP5/MOD3.1 analysis, the magnitude of error is order of 1%, while it is order of 8.7% for RELAP5/MOD3 analysis. Base case results by RELAP5/MOD3.1 show that nitrogen distribution prediction is symmetric, which is quite improved compared with the results by RELAP5/MOD3 shown in Table 3.

3.1.4. Discussions

By comparative simulation of base case by RELAP5/MOD3 and RELAP5/MOD3.1 some deficiencies are found in the analysis results of RELAP5/MOD3 simulation. The deficiencies found are : 1) Unrealistically high temperatures in heat structure geometry of hydrodynamic volumes containing noncondensable gas after RELAP5/MOD3 input processing than those of initial input (about 20 to 50K). 2) Asymmetric heat transfer mode of the steam generator U-tubes in the Loops A and B. By use of RELAP5/MOD3.1 above mentioned deficiencies disappear.

3.2. RCS Vent Case : Small Vent with Two Steam Generators Available

3.2.1. Major Analysis Results

Since the results of base case simulation indicate that RELAP5/MOD3.1 is more reliable than RELAP5/MOD3, only RELAP5/MOD3.1 computer code is used for the simulation of the RCS vent case. Table 5 provides the major sequence of event for vent case. The vent path is assumed to be available after the event initiation.

The reactor vessel upper head pressure increases continuously during the transient, which reaches 0.22 MPa around 10,000 seconds (see Figure 10), which is below RCS temporary boundaries design pressure of 0.24 MPa. The core starts bulk boiling around 1,460 seconds and the void fraction in the top node of the core (component 170−9) reaches 0.55 and is maintained at constant value during the transient (not shown). The cold legs are completely drained around 1,500 seconds, which is quite similar to the no vent case.

The core liquid flow rate oscillates around zero during the transient and steam generated in the core flows out of the core as shown in Figures 11a and 11b. In reality, this phenomena is governed by multidimensional natural circulation phenomena as well discussed in Reference 6. However, this oscillatory flow rate predicted by RELAP5/MOD3.1 seems to reflect the natural circulation effect.

The hot legs are filled with water due to thermal expansion during 950-1,300 seconds (see Figure 12). After the initiation of bulk boiling in the core

Table 5. Major Sequence of Event for Vent Case (RELAP5/MOD3.1)

Time (second)	Major Events
300	Loss-of-RHR is initiated, small vent path provided
about 620	Incipient boiling in the core
about 920	Saturation of reactor vessel upper plenum liquid
about 1500	Water clearing in the cold legs
about 1750	Incipient reflux condensation in SG of Loop A
about 2890	Incipient reflux condensation in SG of Loop B
about 6380	Saturation of SG [B] evaporator & riser regions
about 9580	Saturation of SG [A] evaporator & riser regions

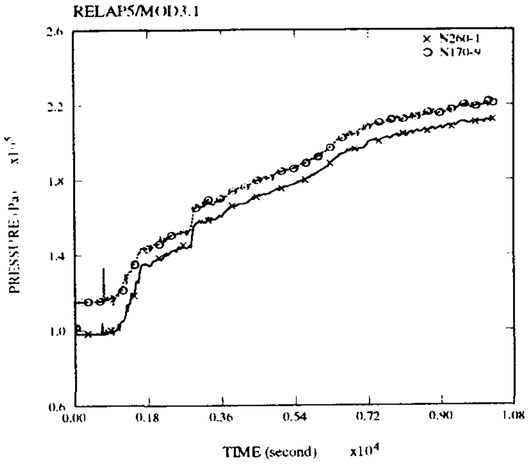

Fig. 10. Reactor Vessel Pressures

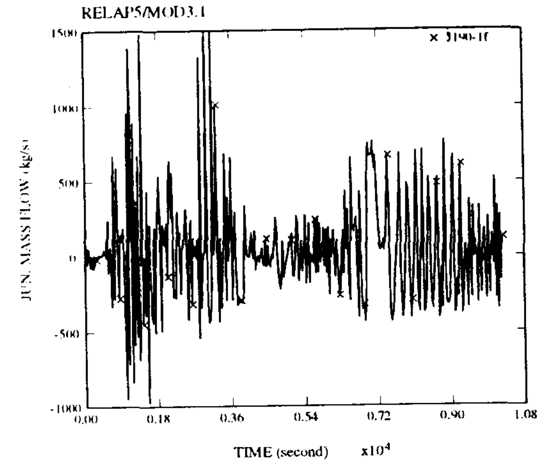

Fig. 11a. Liquid Mass Flow (Core→RV UP)

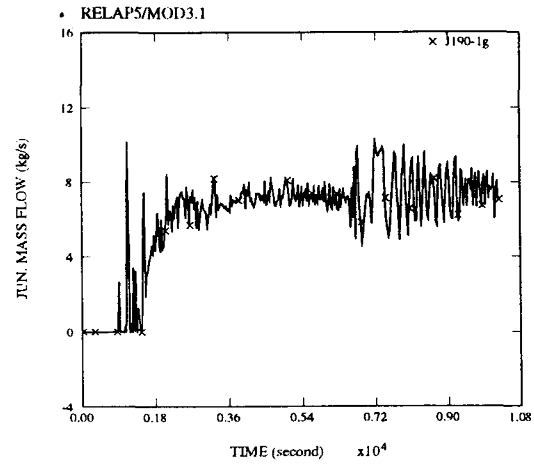

Fig. 11b. Vapor Mass Flow (Core→RV UP)

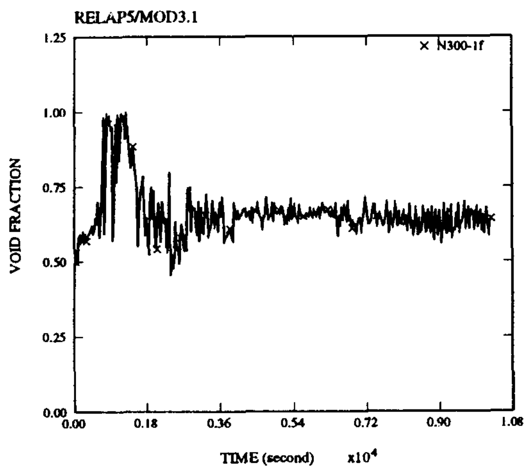

Fig. 12. Hot Leg Liquid Void Fraction [A]

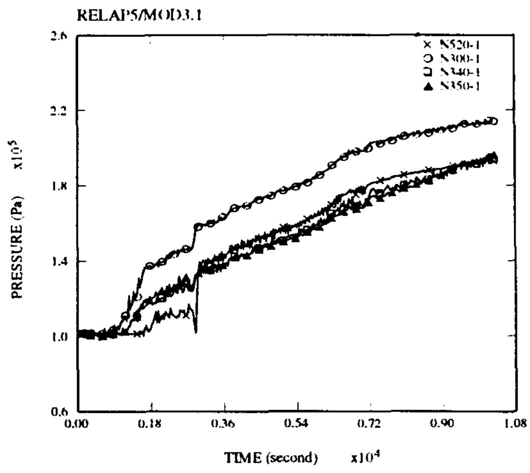

Fig. 13a. RCS Pressures [A]

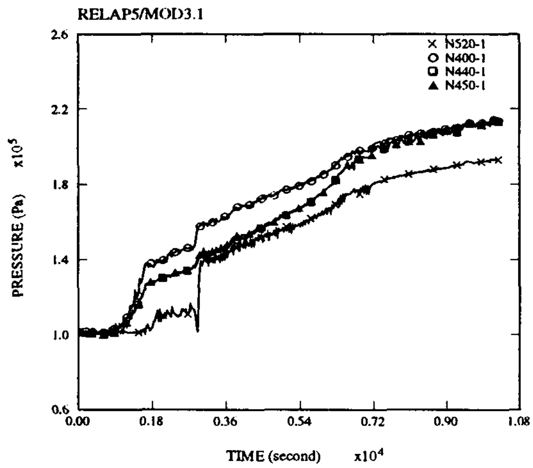

Fig. 13b. RCS Pressures [B]

around 1,460 seconds since the bubbles generated in the core push the water in the hot leg to the steam generator side, the hot leg void fraction in the Loop A increases to 0.7 and is maintained constant around that value during the transient. In the loop without pressurizer (Loop B) the void fraction increases to 0.7 till 6,330 seconds and then shows oscillatory behavior around 0.5 (not shown).

Figures 13a and 13b show the pressure transients of hot leg, pressurizer, SG U-tube inlet, and SG outlet plenum in the Loop A and Loop B, respectively. The pressure in the hot leg node (component 300-1 and 400-1) adjacent to the reactor vessel shows symmetric behavior. The pressurizer pressure is lower than the hot leg pressure due to steam flow through the vent path. The pressure of the SG outlet plenum (component 450-1) in the loop without pressurizer (Loop B) is maintained above pressurizer pressure. However, in the loop with pressurizer (Loop A) SG outlet plenum (component 350-1) pressure approaches pressurizer pressure. The cold leg pressure is almost same as hot leg pressure due to bypass flow path (alignment key) between reactor vessel upper plenum and cold leg. Therefore, the pressure difference between the U-tube and cold leg is balanced by water column between loop seal and SG outlet plenum. The void fraction in the SG outlet plenum is closely related to this. Since the SG U-tube pressure approaches cold leg pressure in the loop without pressurizer (Loop B), the SG outlet plenum is completely voided after 5,800 seconds as shown in Figure 14b. On the other hand, the void fraction in the loop with pressurizer (Loop A) is maintained around 0.4 as shown in Figure 14a.

The heat transfer in the steam generators is indicated by Figures 15a and 15b. The heat transfer in the SG of Loop B (Figure 15b) is more active due to

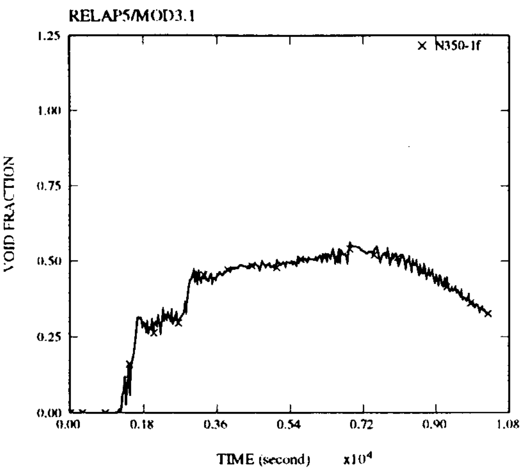

Fig. 14a. SG Outlet Plenum Liquid Void Fraction [A]

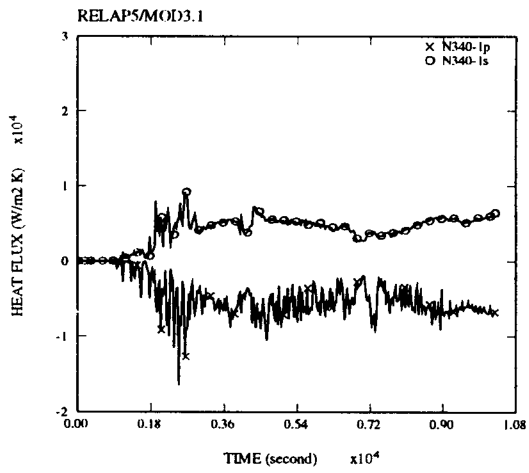

Fig. 15a. SG U-Tube Inlet Heat Flux [A]

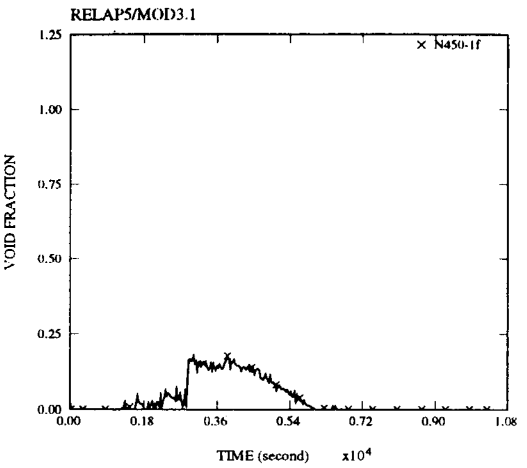

Fig. 14b. SG Outlet Plenum Liquid Void Fraction [B]

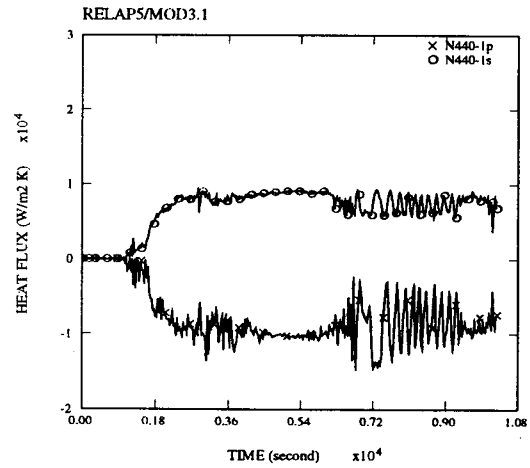

Fig. 15b. SG U-Tube Inlet Heat Flux [B]

higher pressure (see Figures 13a and 13b) and bigger steam flow in the SG U-tube. Figure 16 indicates that heat transfer of SG U-tube is moving to adjacent node with certain time delay. However, the magnitude of heat flux is lower than that of the first volume of SG U-tube and the condensation does not occur in this volume (not shown).

The primary and secondary side temperatures of the SG U-tubes of both SGs show asymmetric behavior (not shown). The temperatures of the Loop B increase more fast due to more active heat transfer and reach early saturation condition. After boiling the temperatures of Loop B are maintained constant. However, the temperatures of Loop A increase linearly until reaching the saturation temperature. The vent flows from the secondary side occur around 9,580 seconds in the SG of Loop A and around 6,380 seconds in the SG of Loop B (see Table 5).

The pressurizer pressure behavior in Figure 13a (see pressure of component 520-1) is closely related

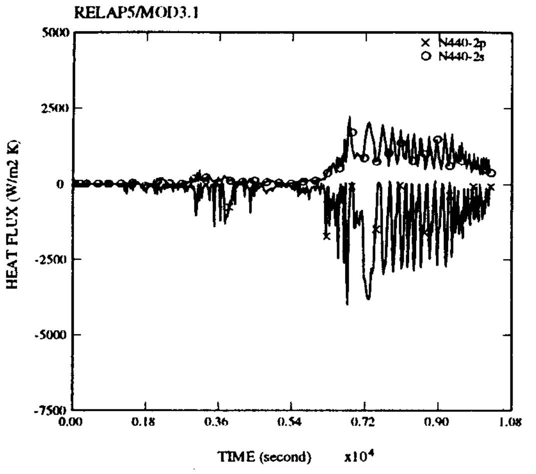

Fig. 16. SG U-Tube Inlet Heat Flux [B]

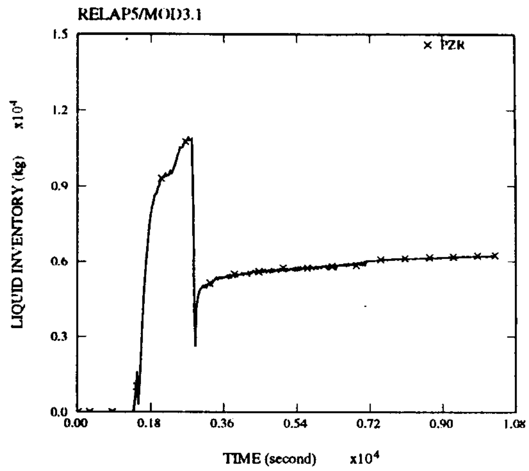

Fig. 17. Pressurizer Liquid Inventory

Table 6. Distribution of Nitrogen in the RCS for Vent Case (RELAP5/MOD3.1)

Primary Side Components	Mass of Nitrogen (kg)			
	t=0 second	t=300 seconds	t=3300 seconds	t=10300 seconds
RV IA Nitrogen Mass	12.0622	11.6348	13.52596	9.78492
(RV-RV IA) Nitrogen Mass	42.3284	40.9125	1.304878	5.187767
HL Piping [A] (300, 310, 320)	2.20336	2.11533	0.0	0.0
SG Inlet Plenum [A] (330)	7.5657	7.489	0.077	0.0
SG U-Tubes [A] (340-01~06)	16.5878	16.4219	17.3555	9.99541
SG U-Tubes [A] (340-07~12)	16.5878	16.4279	21.2212	24.081
SG Outlet Plenum [A] (350)	7.3937	7.3433	5.313	9.9345
CL Piping [A1] (360, 370, 380, 390, 395)	3.27142	3.49194	9.08422	9.78239
CL Piping [A2] (361, 371, 381, 391, 396)	3.27142	3.49194	9.07482	9.8344
Loop [A] Nitrogen Mass	56.8812	56.78131	62.12574	63.6277
Loop [B] Nitrogen Mass	56.8812	56.93027	65.24639	64.90636
PZR/Surge Line (500, 510, 520)	48.9805	49.06602	0.0016	0.0045358
Total Nitrogen Mass	217.133	215.3249	142.20457	143.51128

RV=Reactor Vessel, IA=Inlet Annulus, CL=Cold Leg, HL=Hot Leg,
PZR=Pressurizer, SG=Steam Generator

to the pressurizer liquid inventory which is shown in Figure 17. Since a vent path is provided in the pressurizer, the steam flow generated in the core after the boiling pushes the two-phase mixture in the reactor vessel upper plenum and hot leg into the pressurizer, which results in the pressurizer pressure increase. During this time period, in the SG U-tube of Loop A, noncondensable gas is compressed enough to enable primary to secondary heat transfer by reflux condensation (see Table 6). After the initiation of condensation in the SG U-tube of Loop A, the SG U-tube pressure drops quickly (see pressure of component 340-1 in Figure 13a), which disturbs the manometric balance of the water column between the pressurizer and SG U-tube of Loop A. Therefore, the water inventory in the pressurizer is drained down to the hot leg during about 60 seconds (see Figure 17) and the pressure rapidly decreases (see pressure of component 520-1 in Figure 13a). During this duration, the hot leg pressure does not decrease due to the drain flow into the hot leg and steam generated in the core (see pressure of component 300-1 in Figure 13a). Since enough steam is generated in the core, the pressurizer pressure rapidly increases again until choking condition is met at the vent path. After choking condition is met, the pressure increase rate slows down as shown in Figure 13a and the pressurizer liquid inventory reaches new steady state condition as shown in Figure 17.

3.2.2. Distribution of Noncondensable Gases During Transient

As can be seen in Table 6, the nitrogen is displaced from the reactor vessel and hot leg piping and accumulates in the steam generator active tubes, outlet plenum, and cold leg piping, which is similar to the base case. As expected, the noncondensable gas in the pressurizer is vented out to the atmosphere by the steam flow.

4. Summary and Conclusion

In the present study the loss of RHRS event during reduced inventory operation for the Korean Standard Nuclear Power Plants (KSNPPs) is simulated by RELAP5/MOD3 and RELAP5/MOD3.1. Two cases are considered : Base case for an intact reactor coolant system with no vent and the other for an open system with a vent in the pressurizer.

By comparative simulation of base case by RELAP5/MOD3 and RELAP5/MOD3.1 some deficiencies are found in the analysis results of RELAP5/MOD3 simulation. The deficiencies found are : 1) Unrealistically higher (about 20 to 50 K) temperatures than those of initial input in heat structure geometry of hydrodynamic volumes containing noncondensable gas after RELAP5/MOD3 input processing. 2) Asymmetric heat transfer mode of the steam generator U-tubes in the Loops A and B. By use of RELAP5/MOD3. 1 the above mentioned deficiencies disappear.

In the base case where the RCS is closed, it is found that both steam generators are insufficient to remove decay heat at one day after shutdown for the KSNPPs. The RCS pressure increases continuously and reaches the RCS temporary boundaries design pressure of 0.24 MPa around 4,000 seconds. In the case where small vent path is provided in the pressurizer and both steam generators are available for primary to secondary heat removal, the reactor vessel upper head pressure does not reach 0.24 MPa and core uncovery does not occur until 10,000 seconds.

The detailed discussions on the results of this study suggest the feasibility of RELAP5/MOD3.1 as an analysis tool for the simulation of the loss of RHRS event at reduced inventory operation. The results of this study also provide insight for the determination of proper vent capacity.

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