Proceeding of the Korean Nuclear Society Spring Meeting
Cheju, Korea, May 2001

Cold Leg Large Break LOCA Analysis for KNGR using TRAC-M Code

Han Gon Kim, Jae Hoon Lee*, and Byung Sop Kim

Korea Electric Power Research Institute
103-16 Munji-dong, Yusung-gu
Taejon, Korea 305-380

(*) KEPCO Nuclear Fuel Co.
150, Deogjin-Dong, Yusung-gu
Taejon, Korea 305-353

Abstract

The KNGR is the evolutionary PWR which is enhanced the safety and economics drastically compared to existing PWRs. For this purpose, safety injection water is injected into the reactor vessel downcomer directly (Direct Vessel Injection, DVI). In cold leg LBLOCA, it is assumed that the water injected through broken cold leg is spilled out the break in current PWR, which the water is injected to the cold legs. By the adoption of DVI, it is not necessary to assume the spillage of the injection water. Due to this effectiveness, Low Pressure Safety Injection Pumps (LPSIPs) are removed in the KNGR.

According to the Phenomena Identification and Ranking Table (PIRT), ECC Bypass, Multi-dimensional flow, Steam jet impingement, and Condensation are important to LBLOCA. The general approach to verify the conservatism of the EM code is to use Best Estimate (BE) code, which simulates DVI related phenomena well. We can get the picture for the conservatism of EM code from the analysis results of a BE code. And we can understand the phenomenological behavior during LBLOCA in the KNGR. These are the main purpose of this paper.

In this analysis, TRAC-M code is used. The PCT is much lower than the acceptance criteria (=2,200°F). And cladding temperature behavior during late reflood phase is similar to those of the experimental results.

1. Introduction

The Korean Next Generation Reactor (KNGR) is the evolutionary PWR which is enhanced the safety and economics drastically compared to existing PWRs. The major principles to achieve enhanced safety and economics are as follows; redundancy, independence, simplification, and economics (effectiveness). KNGR Safety Injection System (SIS) has been designed according to these principles. For the redundancy, KNGR has four (4) mechanically identical SIS trains. For the independence, each train is physically separated, that is there is no cross-tie connection between trains. For the simplification, cross-tie connections are removed, the water source is unified into In-containment Refueling Water Storage Tank (IRWST) so the recirculation operation mode is removed. For the effectiveness, safety injection water is injected into the reactor vessel downcomer directly (Direct Vessel Injection, DVI).

In cold leg Large Break LOCA (LBLOCA), it is assumed that the water injected through broken cold leg is spilled out the break in current PWR, which the water is injected to the cold legs. By the adoption of DVI, it is not necessary to assume the spillage of the injection water. Due to this effectiveness, Low Pressure Safety Injection Pumps (LPSIPs) are removed in the KNGR.

The Standard Safety Analysis Report (SSAR) for the KNGR has been prepared and issued to the Korean Regulatory Authority to get the design certification. To verify KNGR SIS performance, LBLOCA analyses have been performed using CEFLASH-4A and COMPERC-II codes. These are Evaluation Model (EM) codes, which were developed according to 10CFR50 Appendix K rules. They are licensed codes and they have been used for the performance evaluation of many CE typed PWRs. There can be some technical issues to use above codes for the KNGR LBLOCA although the analysis results are acceptable. The Westinghouse-CE code packages might be developed for Cold Leg Injection (CLI) although App. K rules are not restricted to cold leg injection. Some different Thermal-Hydraulic (T/H) phenomena could be occurred due to DVI.

According to the Phenomena Identification and Ranking Table (PIRT) developed by the KAERI and the Seoul National University, following phenomena are important to LBLOCA;

- ECC Bypass (entrainment, de-entrainment, and sweepout)
- Multi-dimensional flow
- Steam jet impingement
- Condensation

The EM code is simple and conservative code. It does not need to simulate all the phenomena occurred during LBLOCA. This can not be changed although above phenomena by the adoption of DVI are stranger than those of CLI. Therefore, the question is that the EM code is still conservative when it is used for the DVI plant, that is KNGR.

The general approach to verify the conservatism of the EM code is to use Best Estimate (BE) code, which simulates DVI related phenomena well. We can get the picture for the conservatism of EM code from the analysis results of a BE code. And we can understand the phenomenological behavior during LBLOCA in the KNGR. These are the main purpose of this paper.

2. Model Description

The reactor vessel modeling is shown in Fig. 1. The reactor vessel is divided into 16 axial levels, 4 radial rings, and 6 azimuthal sectors. The sub-components in reactor vessel are modeled as follows;

- Lower plenum : levels 1 ~ 3
- Downcomer : levels 3 ~ 14 in ring 4
- Upper plenum : levels 9~11 in rings 1 ~ 3
- Active core : levels 4 ~ 8 in rings 1 ~ 3
- Upper head : levels 12 ~ 14 in rings 1 ~ 3 and levels 15 ~ 16
- Flow skirt : outer boundary of ring 3 in level 3
- Fuel alignment plate : top boundary of level 9 in rings 1 ~ 3

Some 1D components are connected to the 3D reactor vessel as follows;

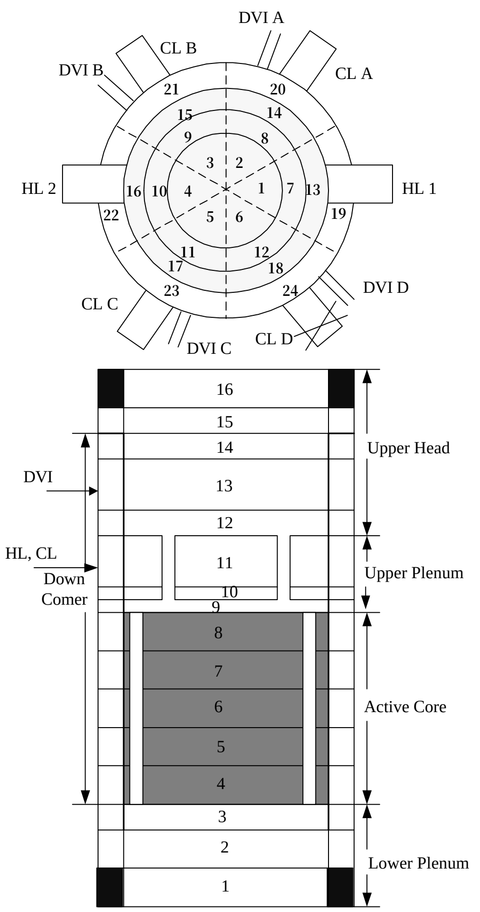
- 2 hot legs : level 11 in outer boundary of ring 3
- 4 cold legs : level 11 in outer boundary of ring 4
- 4 DVI line : level 13 in outer boundary of ring 4
- Core shroud and CEA guide tubes : one pipe for each sector of ring 3 between top of level 3 and top of level 8
- CEA guide tubes in upper plenum : one pipe for each sector of rings 1 ~ 3 between top of level 9 and top of level 11

The fuel rods heat structure is coupled with levels 4 ~ 8 in rings 1 ~ 3 of the reactor vessel. Reactor power is generated in the average fuel rod heat structures distributed evenly in the core. The axial power shape is top skewed as the most conservative shape. The peak power is occurred at 65% elevation. The hot rods to simulate maximum cladding temperature are inserted in each core sectors. Therefore, the total number of hot rods is 18.

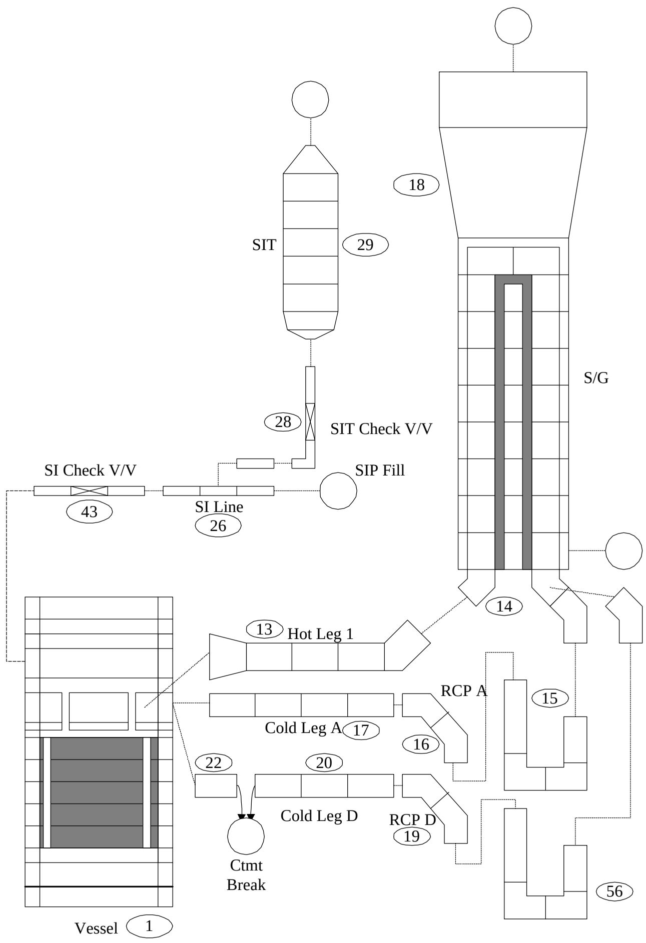
The 1D components in the loop are modeled as Fig. 2. Fig. 2 shows one of two RCS loop and one of four SIS. In this model, the fluidic device is not modeled in SIT. Instead, the SIT check valve area is adjusted to simulate the fluidic device. According to the fluidic device performance requirement derived from EM calculation is as follows;

- The flow switching is occurred at 45 sec after transient initiation
- The low flow is maintained up to 200 sec (in case of nominal SIT volume) or 150 sec (incase of minimum SIT volume).

To meet above requirement, SIT check valves are fully opened until 46 sec. The valve area is reduced to 0.1 of full area at 46 sec.



<Fig. 1> Vessel Model Diagram



<Fig. 2> RCS and SIS Loop Model Diagram

3. Calculation Results

3.a. Major Boundary / Initial Conditions

As described in Section 1, the main purpose of this paper is to verify the conservatism of EM calculation and to understand the thermal hydraulic differences between DVI and CLI. The uncertainty quantification is not the purpose of this analysis. Therefore, the base input deck has not been fully realized. Originally, the TRAC input deck has been generated based on the design data for EM calculation. For example, the system pressure loss is maximized, the fuel stored energy is maximized by minimum gap conductance and minimum fuel conductance, and so on.

Some system parameters and boundary/initial conditions are modified from conservative values to realistic values as shown in Table 1.

Table 1 Major realistic conditions for the base case

Parameters or Conditions	EM values	Base Case	Note
Power (MW)	4062.67	3983	EM value is 102% of licensed power.
SIT volume (m^3)	45.3	52.9	Min / Nom
SI temperature (K)	321.9	300	Max / Nom
SIP flowrate (kg/s)	65.8	74.3	Min / Nom
Single Failure	1 EDG failure	No Failure	Note 1
Decay Power	ANSI/ANS 1971 * 1.2	ANSI/ANS 1979	
Containment Pressure	Minimum	Nominal	Note 2

(Note 1) If one EDG fails to start, two SIPs are not running.

(Note 2) Minimum pressure is obtained by EM code and nominal pressure is obtained by RELAP / CONTEMPT.

1.0 DEGB (Double Ended Guillotine Break) in RCP discharge leg is assumed to occur at time 0. Concurrently with the break, all RCPs are stopped and the containment is isolated. Reactor trip is initiated by pressurizer low pressure trip signal. The reactor power, however, is decreased due to negative void coefficient prior to reactor trip. In KNGR, the safety injection signal is initiated by pressurizer low pressure or containment high pressure. In this analysis, however, pressurizer low pressure is credited only. SIP supplies full SI flow to the RCS with 40 sec time delay after SI signal.

3.b. Steady State Calculation

The KNGR LBLOCA calculation is initialized from a point at which the flows, temperatures, powers, and pressures are at their approximate steady-state values before the postulated break occurs. Once the RCS fluid temperature, flow pressures, loop pressure drops, and fuel rod parameters are in agreement with the desired input parameters and they show steady state conditions, a suitable initial condition has been achieved for the LBLOCA transient.

Table 2 Summary of the steady state calculation

Parameter	SS result	Design Data	Error (%)
Reactor Power (MWth)	3983	3983	0.0
Pressurizer pressure (MPa)	15.511	15.513	0.01
Cold leg temp (K)	564.0	563.6	0.07
Hot leg temp (K)	597.5	596.9	0.1
RCS flowrate (kg/s)	20952.4	20982.3	0.14
Core flowrate (kg/s)	20511	20352.6	0.77
Hot rod fuel center line temp (K)	2075	2085.2	0.44
Reactor vessel water volume (m^3)	159.62	163.13	2.19
Secondary system pressure (MPa)	68.0	68.94	0.06
Feedwater temp (K)	505.3	505.35	0.01

Error = | (SS result – Design Data)/(SS result) | $\times$ 100

Table 3 Sequence of Events for KNGR Cold Leg LBLOCA

Time (sec)	Events
0	Cold leg break (RCP discharge leg guillotine break, discharge coefficient = 1.0)
0	RCP trip, SG secondary isolation
7.5	Max. PCT during blowdown (1,070.6K)
13.0	SIT injection initiated
14.2	Min. PCT during blowdown (833.6K)
22	Peak SIT flow (1043.3kg/(sec.SIT))
25	Pressurizer empty
25	Reactor vessel lower plenum starts to refill
37	Core reflood begins
46	SIT flow turn down by fluidic device
49	SIP starts injection (SIP time delay : 40 sec)
200	Max. PCT during reflood (1,133.9K)
227	SIT starts to empty due to non-condensable gas in SIT starts to inject into SI line.
284	SIT empty (flow rate < 10 kg/(sec.SIT))
420	Water inventory in reactor vessel reaches its minimum value
500	Calculation is terminated

The comparison between the results of steady state calculation and the KNGR design data is given in Table 2. As shown in the table, the steady state results are matched with KNGR design data well. The largest error is shown in the reactor vessel water volume. The reason is the modeling of CEA guide tube bypass pipes. The model is focused to fit bypass flow area and flow rate. So, internal water volume in the guide tubes is not reflected exactly.

3.c. Transient Calculation

LBLOCA transient is simulated using restart files from steady state results and transient input. The cold leg break is modeled using "break" component. The "break" component simulates containment back-pressure with pressure-time table derived from RELAP/ CONTEMPT codes calculation. The cold leg guilotine break is occurred at time 0. At the same time, the off-site power is lost, so all RCPs start to coast down and the containment is isolated. The important events during transient are summarized in Table 3

Typically, the LBLOCA scenario is divided into three time periods, that is blowdown, refill, and reflood which are defined by the core and lower plenum liquid mass fraction behaviors. The blowdown period starts at the time break occurs and ends following the start SIT injection at the time the lower plenum begins to refill. Unlike, EM calculation, the time of end of blowdown is not clearly defined in BE calculation. During blowdown, some water injected from SIT is penetrated into lower plenum. Clear definition of end of blowdown, however, is not so important to describe LBLOCA senario. The refill period ends when the mixture level in the vessel lower plenum approaches the core inlet and remain full thereafter and conditions are established for continuously reflooding the core with coolant. The reflood period ends when the entire core is quenched, that is, all fuel rod cladding temperature are at or slightly above the coolant saturation temperature. The reflood period can be divided into two sub periods, that is, early reflood and late reflood, again. The criterion to divide these sub periods is the time that SIT is empty. In KNGR, there is fluidic device in SIT, so the time SIT is empty is 200sec.

<u>Blowdown : 0 ~ 23 sec</u>

At time 0, RCP discharge leg is broken. The off site power is assumed to fail concurrently with the break, so the RCPs starts coast down and it is assumed that SG secondary side is isolated at same time. At the pump side break, two phase critical flow is established from the start of blowdown. The reason why the subcooled critical flow is not established at pump side break is that the flow is limited by RCP. On the other hand, subcooled critical flow is established during 3 ~ 4 sec after break through vessel side break. (Fig. 3) Due to these break flow, reactor vessel and RCS are depressurized rapidly. (Fig. 4)

2 sec after break, reactor core is almost vaporized. At time time, two phase mixture flow in

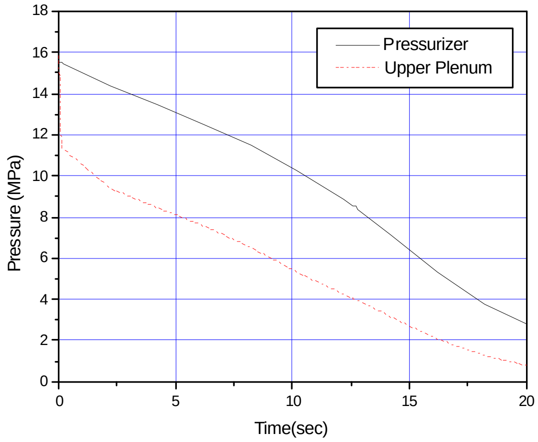
the core is stagnant due to the pressure loss balance between the flow paths through hot leg and through lower plenum. (Fig. 5) This flow stagnation is maintained upto 5 sec. During this period, fuel cladding temperature is rapidly increased due to very low heat transfer. (Fig. 6) But the reactor power starts to decrease due to insertion of negative reactivity by vaporization and it reaches decay heat power level at 8 sec after break. (Fig. 7) The reactor vessel is fully vaporized at 10 sec. At the early stage of break, steam is vented through upper plenum and hot legs as shown in the Fig. 5(Slightly positive core exit flow). During this period, cladding temperature is increased due to very poor heat transfer and reaches its maximum value, 1070.6K at 6 sec. (Fig. 6) From 7.5 sec after break, steam path is changed from upper plenum – hot legs to lower plenum – downcomer due to lower plenum vaporization. After this time, the fuel is cooled down rapidly by inventory discharge from reactor vessel upper head via reactor core and lower plenum to downcomer as shown in Figs. 5 and 6. This cooldown is proceeded until the water in the upper head is exhausted and after that point, 14 sec after break, the fuel is reheated. (Fig. 6) After this time, the fuel is adiabatically heated until the core is refilled with safety injection water.

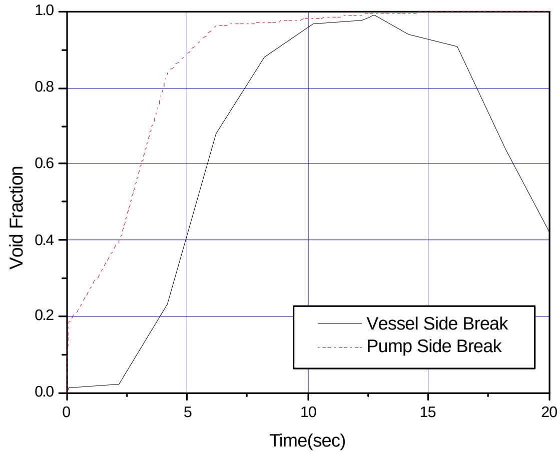
At 13.0 sec, the borated water in SIT is started to inject into safety injection line because RCS pressure became less than SIT pressure. (Fig. 8) At early phase of injection, the injected water can not penetrate into the lower plenum because of very high steam flow from lower plenum to the break. The injected water is oscillated near cold leg level and most of the injected water is discharged through the break. The downcomer penetration starts at 23 sec.

During the blowdown, the pressurizer is empty at time 25sec and the system pressure reaches its minimum value at 36 sec. The safety injection signal is actuated at 9 sec by the pressurizer pressure. The SIP will be operated with 40 sec time delay.

Refill : 23 ~ 27 sec

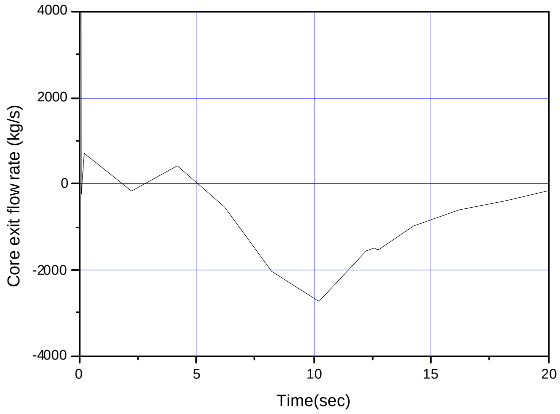
Actually, it is hard to divide end-of-blowdown and refill period clearly. From 25 sec after break, some ECC penetration is occurred in part of downcomer. However, the lower plenum is refilled clearly from 25 sec.(Fig. 9) As shown in the Fig. 9, lower plenum is not fully dried during blowdown period. It is well matched with the observation through UPTF test. During this phase, there is little discharge flow through the break but only small amount of steam is discharged. The coolant starts to flow into the core at 26 sec. (Fig. 10)

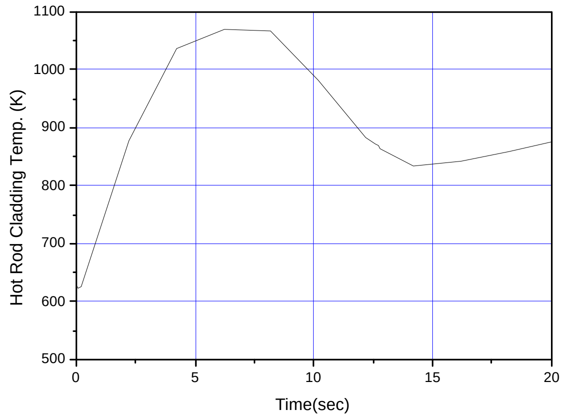




<Fig. 3> Void fraction of the break flow at blowdown period

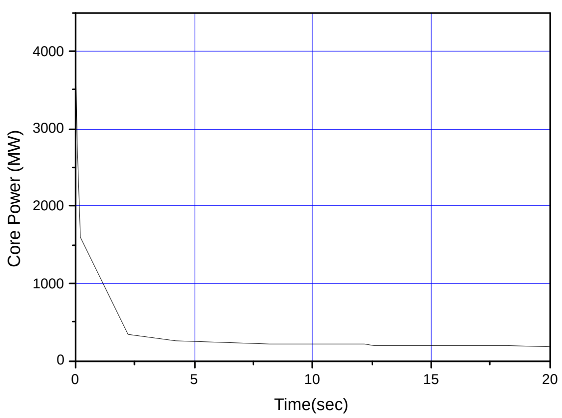
<Fig. 4> The pressure behavior during blowdown

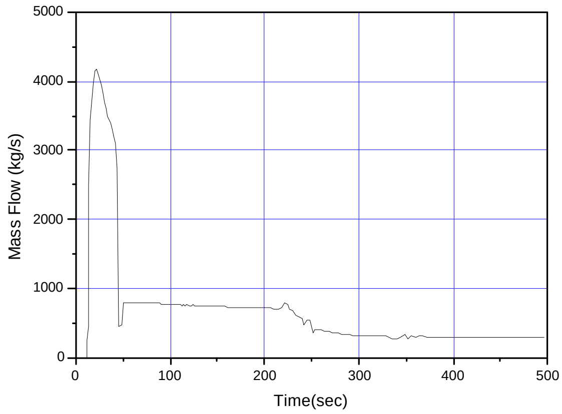




<Fig. 5> Core exit flow rate during blowdown

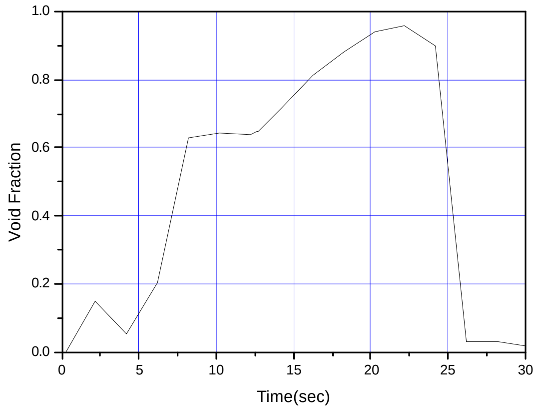
<Fig. 6> Hot rod cladding temperature during blowdown



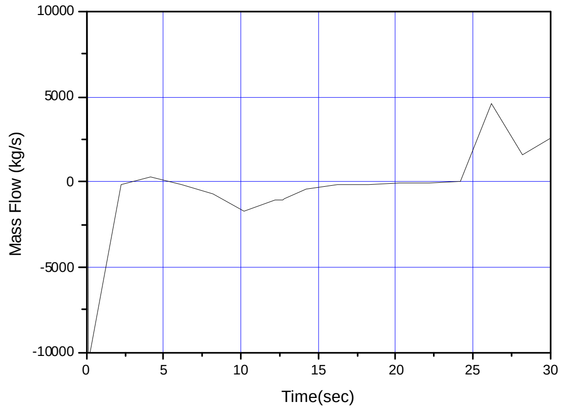


<Fig. 7> Core power level

<Fig. 8> Total SI flow rate



<Fig. 9> Lower Plenum void fraction



<Fig. 10> Core inlet liquid mass flow rate

<u>Early Reflood (SIT injection period) : 27 ~ 250 sec</u>

During SIT injects water into the downcomer, sufficient water for core cooling is supplied though some of the injected water is bypassed through the break. The downcomer is rapidly filled with water and the additional water is discharged through the break.

The maximum SIS flow rates are reached during the blowdown period at 22 sec.(Fig. 8) Soon after, the SIT flow rates begin to decrease. The fluidic device in each SIT becomes active at 46 sec and prolongs SIT injection period upto 250 sec. As shown in Fig. 8, the flow rate from SIT starts to decrease from 220sec. The reason of this phenomenon is that the nitrogen gas in the SIT starts to discharge with water at near end of SIT empty. It is unclear that this is physically possible phenomenon.

At this period, very effective core cooling is progressed until very strong steam binding in SGs is occurred at 40 sec. (Fig. 11) At early reflood phase, highly subcooled water supplied by SIT enters the core to suppress the rise in the fuel cladding temperatures. The core is fill with water rapidly because the vessel is almost dried so there is no resistance to protect water flow and SIT water flow rate is large. (Fig. 12) However, the core water level is not be maintained due to the strong steam binding. As shown in the Fig. 12, core water is pushed back to lower plenum due to the vapor force generated in the steam generators between 40~50 sec.

After strong steam binding, the core is filled with water again, and well known bottom-up reflood is progressed. Figs. 13 ~ 18 show the cladding temperature behavior for hot rods inserted in Ring 1 of the core. The elevations in those figures indicate relative axial position from active fuel bottom (=2.534m). The total active fuel length is 3.81m. Therefore, “2m” means slightly above of the actuve fuel center and “3.81m” means active fuel top. As shown in those figures, reflood peak occurs near the elevation “2.95m”, which 77.4% elevation from active fuel bottom. For all hot rods, reflood peak occurs at 200 sec and the cladding temperature is decreased as time goes by.

As shown in cladding temperature behavior in Figs. 13 ~ 18, the upper part of the fuel has not been quenched yet after 500 sec from the break. According to CCTF (Cylindrical Core Test Facility) test results, C2-SH1, performed during International 2D/3D program, the upper part of the fuel is quenched near 600 sec after reflood. The temperature behaviors for each elevation of the test are similar to those of the KNGR. [2]

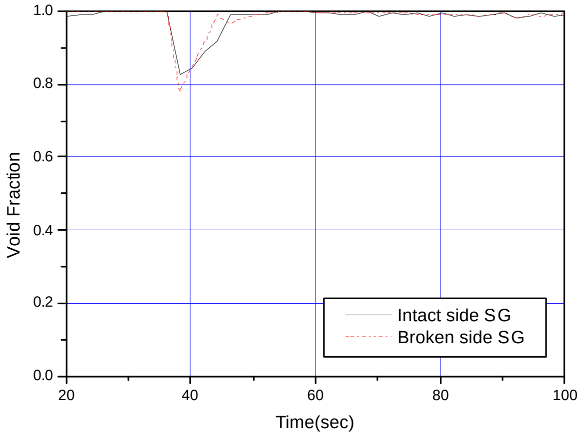
The lower plenum void fraction is given in Fig. 19. As shown in the figure, the lower plenum is vaporized due to steam binding for a while, but subcooled water is filled in the lower plenum during reflood period. Only subcooled boiling, i.e. void fraction is less than 0.05, is observed in the lower plenum. Also, as shown in Fig. 20, the lower plenum maintains subcooling margin for the whole reflood period.

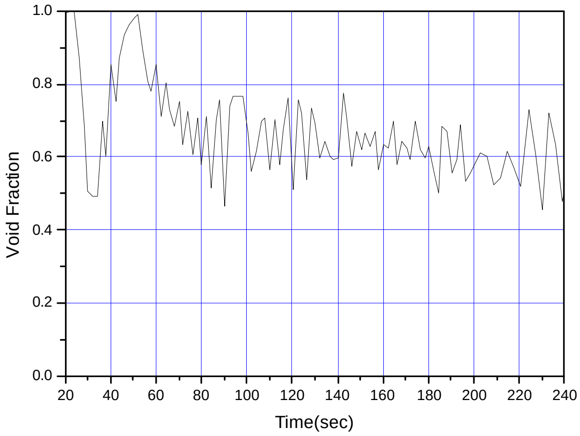
The collapsed liquid levels for core and downcomer are given in Fig. 21. During fluidic device is acutating, the downcomer liquid level is maintained above the cold leg nozzle bottom. When collapsed level for the downcomer is calculated, the water in levels 2 ~ 14 are considered. Therefore, during the time period 100~ 250 sec, the reason that downcomer liquid level is higher than the cold leg nozzle bottom is the water in upper downcomer. During same time period, the core water level is maintained at 4m, 38.5% of the core elevation. As shown in the figure, sufficient water to fill downcomer upto cold leg nozzle bottom is supplied by fluidic device and SIPs. Therefore ECC bypass is not the concern in this time period no matter how much injected water is discharged through the break.

During this period, the steam flow vented through both hot legs is about 50 kg/s and about 100kg/s of water is entrained by steam flow. (Fig. 22) Therefore, the carry over ratio could be 2.0. The entrained water droplets will pass through SG U-tubes and additional steam is generated by heat addition through SG secondary water. This steam binding reduces the core reflooding rate. Due to this steam binding, the cold leg steam flow including pump side break is increased to 100kg/sec as shown in Fig. 23. That is, 50kg/sec of the steam is generated into SG U-tubes.

<u>Late Reflood (SIP injection period) : 250 ~ 500 sec</u>

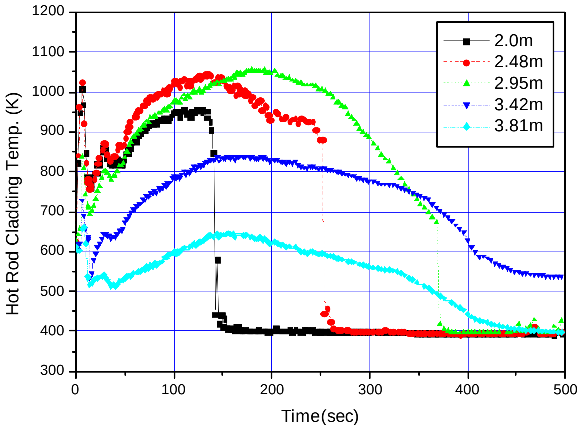
Core cooling is progressed by safety injection pumps (SIPs) only after SIT is empty. Before this period, the system maintains quasi steady state condition. Downcomer and core maintaim constant water level (Fig. 21) although they show some oscillatory behavior and hot and cold legs steam flows also show fairly constant behavior. (Figs. 22 and 23) After SIT is empty, however, the major boundary condition to maintain quasi steady state is changed, that is injected SI flow rate is decreased from 730 kg/s to 290 kg/s. Due to this change, the system converges to another steady state condition for about 100 sec.



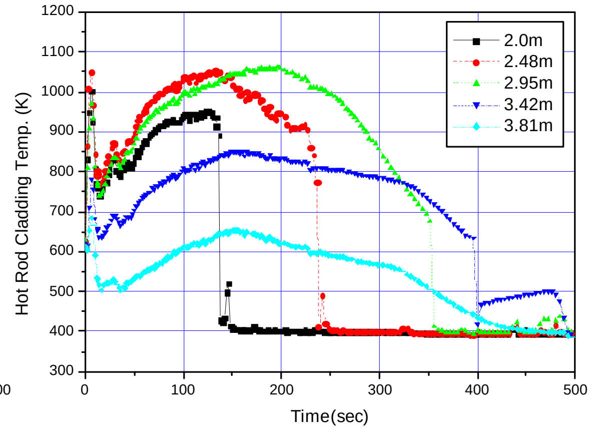


<Fig. 11> Void fraction in SG inlet U-tube

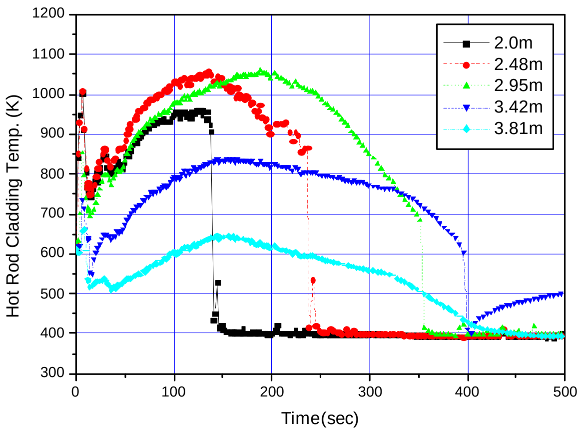
<Fig. 12> Average core void fraction



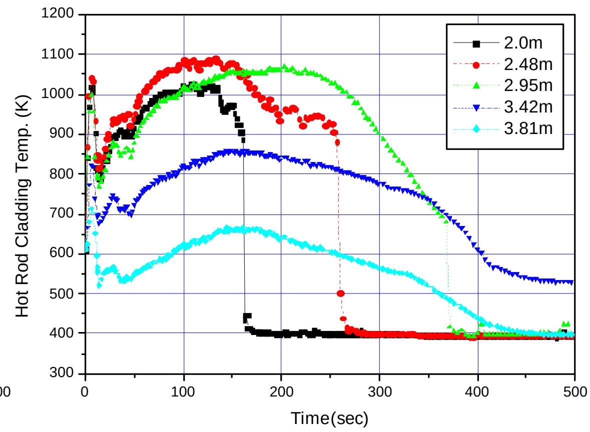
<Fig. 13> Hot rod cladding temp. (r=1, θ=1)



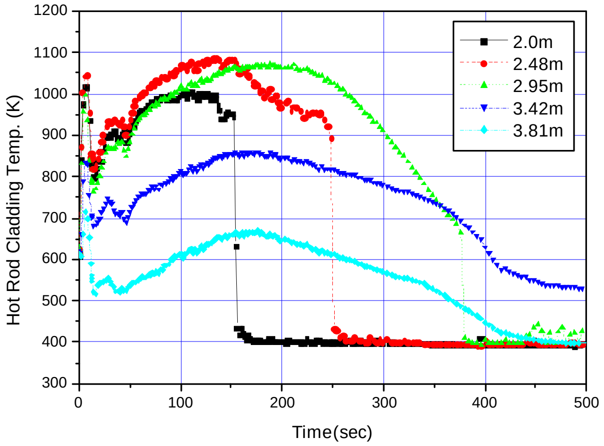
<Fig. 14> Hot rod cladding temp. (r=1, θ=2)

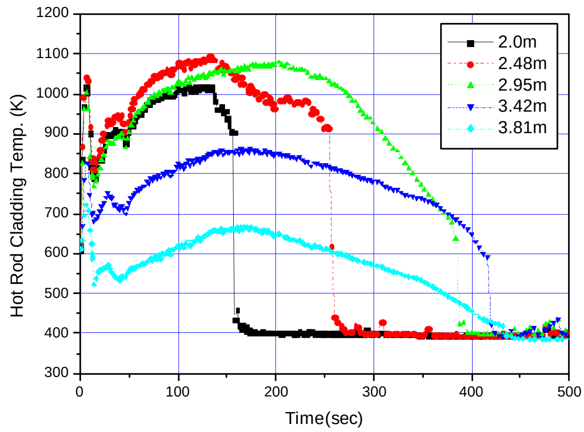


<Fig. 15> Hot rod cladding temp. (r=1, θ=3)

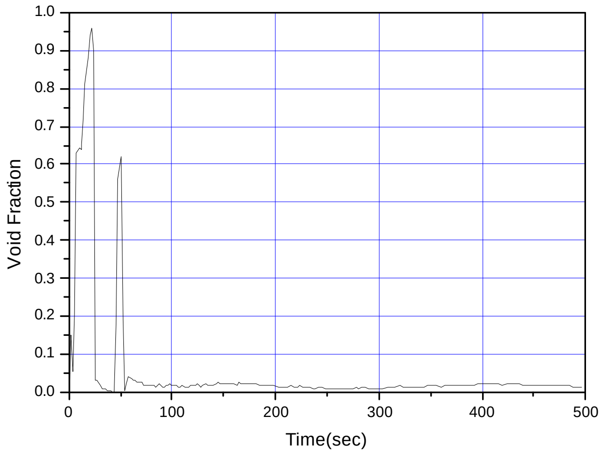


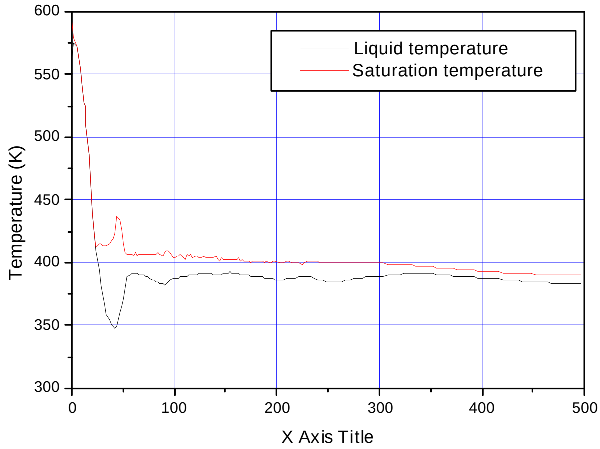
<Fig. 16> Hot rod cladding temp. (r=1, θ=4)



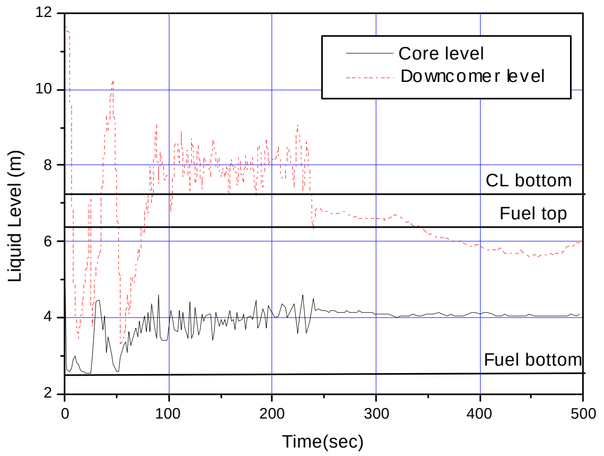


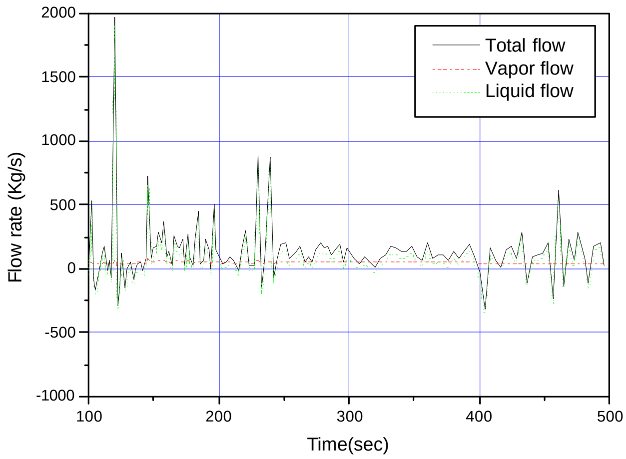
<Fig. 17> Hot rod cladding temp. (r=1, θ=5) <Fig. 18> Hot rod cladding temp. (r=1, θ=6)



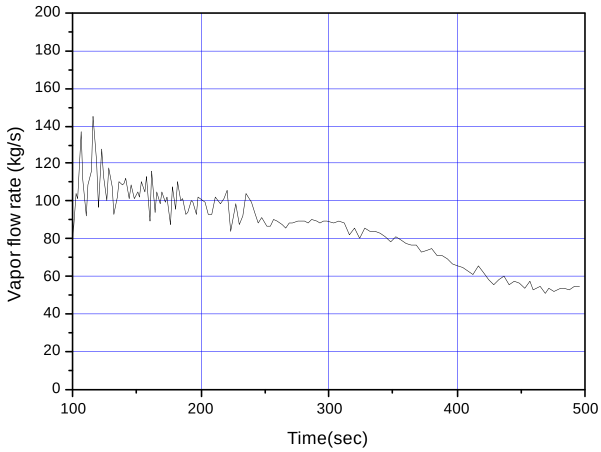


<Fig. 19> Lower plenum void fraction <Fig. 20> Lower plenum liquid and sat. temp.





<Fig. 21> Collapsed liquid level for core and DC <Fig. 22> Hot leg flow rate



<Fig. 23> Total cold leg steam flow

As shown in Figs. 21~23, steam flow rates are reduced. For example, total cold leg steam flow rates are reduced from 90 kg/s to 60 kg/s. Downcomer water level is reduced from 6.5m to 5.5m. However, the core water level is unchanged during this transient time period.

The reason why the core water level is unchanged although the downcomer water level is decreased is as follows:

- Due to decreased SI flow, the effective steam flow area in upper downcomer is increased and therefore steam venting is easier than previous situation.
- More effective steam venting reduces difference pressure between upper plenum and downcomer with same elevation.
- Reduced differential pressure makes to maintain the core water level with constant level although the downcomer water level is decreased.

The reason why the downcomer water level is decreased when SI flow rate is reduced is as follows:

- Due to the reduced SI flow, steam condensation in the downcomer is reduced. Almost steam flowing into the downcomer from cold legs is condensed in the downcomer. Therefore, before 250sec, there is no steam discharge through the vessel side break.
- However, when SI flow is reduced, the condensation rate is reduced, much steam flows in the downcomer and discharges through the break. This increasing steam flow rate sweeps out the water in the downcomer to the break.

From 450 sec, the system maintains quasi steady state again. The downcomer water level starts to increase (Fig. 21), the cold leg steam flow rate is fairly reduced, and the core exit steam temperature is reduced to saturation level (Fig. 23). From this time, there are no initiating events to make the system behavior worse although the upper most part of the fuel is not quenched yet and therefore the calculation is ended.

4. Conclusions

We performed LBLOCA analysis using best estimate code, TRAC-M for KNGR. The purpose of this calculation is to understand the major phenomena during the transient because DVI could make some different phenomena compared to CLI. As shown in the results, the PCT is much lower than the acceptance criteria (=2,200°F). And cladding temperature behavior during late reflood phase is similar to those of the experimental results. During late reflood phase, some of the injected water is bypassed through the break, therefore, the downcomer water level is decreased for some time. However, the core water level is maintained and the core cooling is still progressed.

In this paper, we performed base case calculation. To identify sensitivity of the various parameter, many sensitivity analyses should be performed.

References

1. Korean Next Generation Reactor Standard Safety Analysis Report, Vol. 5, KEPCO, Feb. 1999.
2. P. S. Damerall and J. W. Simons, "2D/3D Program Work Summary Report," NUREG/IA-0126, US NRC, June 1993.
3. P. S. Damerall and J. W. Simons, "Reactor Safety Issues Resolved by the 2D/3D Program," NUREG/IA-0127, US NRC, July 1993.
4. R. G. Steinke et al., " TRAC-PF1/Mod2 Volume II User's Guide," NUREG/CR-5673, Los Alamos National Lab., July 1993.
5. Design Parameter Lists for Plant Safety, Performance and Containment Analyses for KNGR (Rev. 00), KEPCO/KOPEC, Feb. 1999.