한국에너지공학회지(2003), 제12권 제2호
Energy Engg. J(2003), Vol. 12, No. 2, pp. 101~108

Development of an Entrainment Model for the Steam Line Break Mass and Energy Release Analysis

Young-Chan Park and Yoo Kim

Department of Mechanical Engineering, Chungnam National University, 220 Gung-Dong,
Yuseong-Gu, Daejeon 305-764, Republic of Korea
E-mail : k2pyc@kepri.re.kr, yookim@cnu.ac.kr

Abstract — The purpose of this study is to develop an entrainment model of the Pressurized Water Reactor (PWR) U-tube Steam Generator (SG) for Main Steam Line Break (MSLB) analyses. Generally, the temperature of the inside containment vessel at MSLB is decreased by introducing the liquid entrainment effect. This effect makes a profit on the aspect of integrity evaluation for Equipment Environmental Qualification (EEQ) in the containment. However, the target plant, Kori unit 1 does not have the entrainment data. Therefore, this study has been performed. RETRAN-3D and LOFTRAN computer programs are used for the model development. There are several parameters that are used for the initial benchmark, such as Combustion Engineerings (CE) experimental data and the RETRAN-3D model which describes the test leg. A sensitivity study is then performed with this model in which the model parameters are varied until the calculated results provide reasonable agreement with the measured results for the entire test set. Finally, a multiplication factor has been obtained from the 95/95 values of the calculated (best-estimate) quality data relative to the measured quality data. With this new methodology, an additional temperature margin of about 40℃ can be obtained. So, the new methodology is found to have an explicit advantage to EQ analyses.

1. Introduction

The entrainment methodology for the analysis of Main Steam Line Break (MSLB) accident consists of running LOFTRAN and RETRAN-3D models in an iterative manner[1][2]. The LOFTRAN model is able to describe the entire Nuclear Steam Supply System (NSSS) thermal hydraulics which was developed by Westinghouse. RETRAN-3D is also able to describe NSSS thermal hydraulics which was developed by Electric Power Research Institute (EPRI). The steam releases are put into either a Containment integrity calculation or an Environmental Qualification (EQ) calculation[3][4][5]. The LOFTRAN model requires the input of the time dependent break quality, since LOFTRAN does not have the capability to perform this calculation. The RETRAN-3D model only represents the Primary and Secondary sides of the broken loop Steam Generator (SG) and calculates the time dependent break quality. The output from the LOFTRAN calculation provides thermal-hydraulic boundary conditions to the RETRAN-3D model, and the time dependent quality calculated by RETRAN-3D is put back into the LOFTRAN model. The applicability criteria are defined as those physical and operational parameters of the steam generator design that must be in reasonable agreement with those of the test facility and the capability of covering the corresponding range which the benchmark tests were run.

This model development is based on the RETRAN-3D program code manuals. The initial benchmark methodology and results are described in the main contents.

This study contains a description of the methodology and assumptions. The methodology and analyses of the results that were performed to develop the model are described. Also, the applicability criteria and model requirements are contained.

2. Methodology and Assumptions

The methodology is to develop a specific set of RETRAN-3D model input parameters that result in reasonable agreement with the test results. The comparisons between the RETRAN-3D computed results and the test measurements provide a set of benchmark. These comparisons are used to establish the uncertainty and bias between the calculated and measured results.

When the model is applied to the analyses of a MSLB for a U-tube steam generator that has the appropriate geometric properties of the test facility U-tube steam generator, the uncertainty and bias can be used with reasonable assurances that the calculated results are within the upper bound one side tolerance limit at the 95% probability with a 95% confidence level (95/95) of the measured results.

2-1. Development of Methodology

The methodology consists of developing a geometric model of the test facility SG based on the available information along with an assumed set of thermal-hydraulic models and their respective model parameters. A sensitivity study is then performed with this model in which the model parameters are varied until the calculated results provide reasonable agreement with the measured results for the entire test set that has been selected. Finally, the uncertainties are developed to yield the 95/95 limit associated with this model.

As a part of the methodology, the actual volumes used for the regions inside the vessel that contain water (155 and 156 as shown in Fig. 1) for each of the tests were adjusted so that the total calculated initial water and steam masses matched the test conditions. The steam mass was matched by changing the volume of 156, and the water mass, by changing the volume of 155, respectively. As a part of this methodology, the total vessel volume is checked for reasonability and consistency.

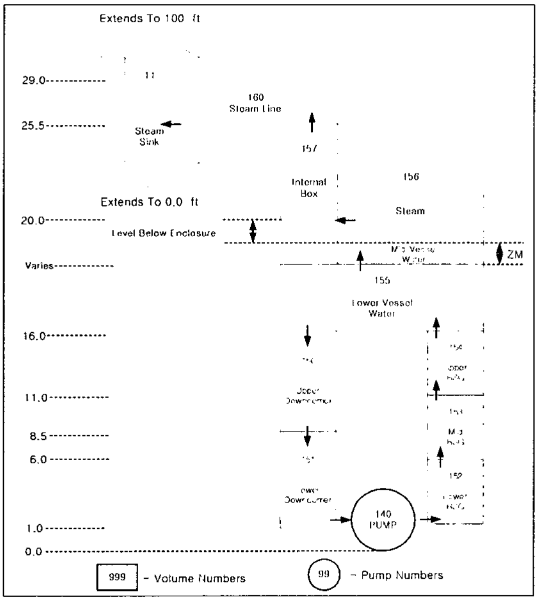

Fig. 1. CE test rig RETRAN-3D nodding diagram.

The control system models and the minor edits are used to edit the necessary data required to process the output for comparisons to the reported measurements. The minor edits facilitate the calculations required to obtain the results. It should be noted that this RETRAN-3D model is normally used in conjunction with another Nuclear Steam supply system computer code such as LOFTRAN that requires the input of the MSLB quality vs. time data. The RETRAN-3D and the other system transient models used in that application are specific to the plant that is being modeled. The RETRAN-3D model must incorporate the principle features of the benchmark model, and the SG design must conform to the applicability criteria. The methodology for this application consists of running the other model that provides boundary conditions to the RETRAN-3D model. After the RETRAN-3D model has been run, the quality vs. time output data are then used as an input boundary condition to the other model. This iterative process is continued until a converged set of cases is completed. Then, the final run is made with the other model in which the entrainment model uncertainties are applied to the quality vs. time RETRAN-3D output before input to the other model. The RETRAN-3D nodalization of the CE test rig is shown in Fig. 1.

2-2. Assumptions

The following assumptions have been made for the entrainment model development. The break opens and closes instantaneously. Instantaneous closure is achieved by terminating the transient closing time. The average quality of the break flow is obtained as follows;

The ratio of the total energy loss divided by the total mass loss yields the average enthalpy of the break flow (<h>). The average pressure <p> is taken as the average of the initial and final pressures. The saturated liquid and steam enthalpies at the average pressure ($<h_f>$ and $<h_g>$) are then used to calculate the average quality from the following equation;

$<x>=[<h>-<h_f>]/[<h_g>-<h_f>]$.

For these calculations, the water properties of American Society of Mechanical Engineers (ASME) steam table are used. A numerical verification of the use of this procedure for CE Test 109 is as follows;

$<p>=(7.067+2.302)/2=4.685$ MPa
$<h_f>=1134.34$ kJ/kg
$<h_g>=2796.49$ kJ/kg
$<h>=(2.44*10^6-1.28*10^6)/522.5=2220.96$ kJ/kg
$<x>=(2220.96-1134.34)/(2796.49-1134.34)$
$=0.653(66\%)$

When this procedure is used for the calculation, the average calculated pressure is used, not the measured pressure.

The following problem control options are assumed.

- Dynamic Slip (ISFLAG=1)
- No steady-state initialization (JSST=1)
- No temperature transport delay (ITRNS=0)
- The numerical solution technique for three- and four-equation options (NUMRCS=2)
- Arithmetic average junction flows for volume flow calculation (JFLAG=0)
- Thermodynamic equilibrium (NEWEQS=0)
- No general transport option (IGNTR=0)
- Block elimination solution scheme (NSOL34=0)

Since steady-state initialization is not used, a short (10 sec) null transient is run at the beginning of each case. The steam sink (atmosphere) is an infinite time dependent volume with a constant pressure. The initial fluid in the upper portions of the vessel is assumed to be stagnant.

However, the fluid in the lower section, the downcomer, and the riser is initially flowing at 3.08 kg/sec. Estimation of the several physical dimensions of the test components is necessary due to the lack of a complete detailed description of the test facility. In these cases, engineering judgment was used.

The pipes that correspond to the downcomer and riser have the same internal diameters as the nominal pipe sizes. Bubble rise is neglected in all regions except Volume 156 that initially contains water and steam. The initial water level in that volume is assumed to be 0.3048 m for all cases. The pressure is initially assumed to be uniform throughout the test assembly and equal to the initial test pressure.

Saturated fluid conditions are assumed throughout the test facility. The initial enthalpy (H) is set to 0.0 (flag) in all volumes. The initial qualities are input as 1.0 (flag) in all volumes that contain water only (150-155), 0.0 (flag) for the two-phase volume (156), and 1.0 in all the other volumes that contain steam only (157 and 160). Slip is neglected in the single phase regions; i.e. the downcomer and steam line, thus, IFRJ=-99 in all junctions except 156 and 157 (see Fig. 1) where it is 0. The combination of Extended Henry (subcooled) and Moody (saturated) choked flow option is selected for all junctions by setting JCHOKE=0. For all junctions except the break (170), the contraction coefficient (CONCO) is set to 1.0. The break junction contraction coefficient is set to 0.55 for the small break tests (Tests 114-119) and 0.32 for the large break tests (Tests 109-112) based on a reasonable match between the measured and calculated pressure traces. The break junction area is set to the physical break area for each test. The JVERT=0 option is assumed for all junctions except the junction (157) from the mixture level volume (156) to the internal box (157) where it is set to 2. The compressible single stream flow option is assumed by setting MVMIX=0 for all junctions except in the steam line where MVMIX=3 (omit momentum flux terms). The Baroczy two-phase multiplier with Fanning friction is assumed by setting JTPMJ=0 for all junctions. Horizontal junctions are assumed by setting ANGLJ=0.0 for all junctions. Enthalpy transport is not used by setting IHQCOR=0 for all junctions. Form loss coefficients are calculated initially by RETRAN-3D (JCALCI =3). Thus, only losses due to area changes are included with the assumption that these losses are from sharp edges. The parameters based on the nominal condition are assumed for the pump. The Westinghouse 5200 specific speed homologous curves are assumed (NPC=2). All of the volume flow lengths (FLOWL) and equivalent hydraulic diameters (DIAMV) are input as 0.0 to obtain the default values based on the volume (V) and flow area (FLOWA) parameters. The volume wall relative roughness for all volumes (EOVRD) is assumed to be 0.0.

The junction flow areas are set to the smaller of the two connecting volume flow areas and these areas are reference values for the irrecoverable loss coefficients. The junction reverse loss coefficients (FJUNR) are assumed to be equal to the forward coefficients which were obtained by setting them to 0.0. The junctions are assumed to be at the top and bottom of the connecting volumes. The inertia for all junctions is based on the total length/area (L/A) between the geometric centers of the connecting volumes. The inertia is initially calculated by RETRAN-3D (JCALCI =3). The assumption is made that all regions of the test facility are homogeneous except one that initially contains water and steam (156). In that region, the following assumptions are made regarding the bubble rise model 0.8 of ALPH and 4.0 of VBUB are used which are empirically determined from sensitivity studies. The Wilson bubble rise model is not used (IWILSN =0). The initial water level is 0.3048 m. The pump is assumed to be running throughout the test. The metal components of the test facility are not included in the model, since the time duration of the test is short. The time step control option (NCHK on card 030010) is set to 0 and the maximum time step (DELTM on 030010) is set to 0.01 second. The control system time step is set to 0.005 second.

2-3. Calculation of Multiplication Factor

The results from RETRAN-3D are compared to the measured data shown in Table 1. This table only contains the comparisons of the key parameters that relate to the quality. Note that the values of h_f and h_g have been obtained from the average water pressure properties for both DATA and CALC, and that the average measured qualities have been recomputed instead of using the values reported in Table 1.

Table 1. Average quality calculated vs. measured.

AVERAGE QUALITY (%)				
RUN	Mes	Cal	Mes/Cal	Mes-Cal
117	58.9	100	0.589	−41.1
118	69.5	100	0.695	−30.5
119	77.1	100	0.771	−22.9
114	21.7	21.4	1.014	0.3
115	25.7	26.7	0.963	−1.0
116	41.3	36.4	1.135	4.9
109	65.3	68.2	0.957	−2.9
110	25.8	21.6	1.194	3.9
111	36.5	31	1.177	4.2
112	48.1	43.6	1.103	4.2
Average Value			0.9598	−7.9
Standard deviation			0.1999	16.191

*Notes.
Mes : Measured value, Cal : Calculated value.

The 95/95 value of the calculated (best-estimate) quality relative to the measured quality may be obtained from either one of the following two formulas. That is, add 39.23%(7.900+2.911*16.191; Eq. 1) to the calculated value. or multiply the calculated value by 1.5417(0.9598+2.911*0.1999; Eq. 2). The former value is calculated using statistical method as dividing measured by calculated value, the latter is calculated using statistical method as subtracting measured for calculated value. In this paper, the latter method was used. Per Fig. 9, two methods give the similar results. The factor 2.911 is the 95/95 one-sided tolerance

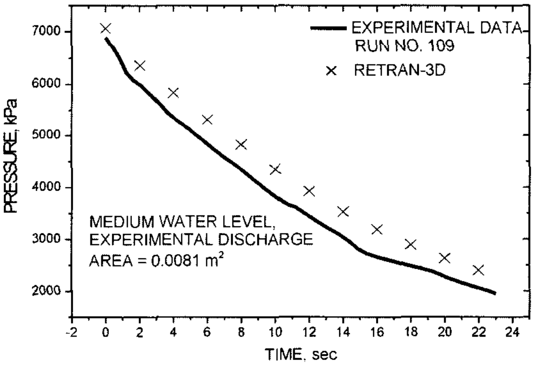

Fig. 2. Pressure responses for run 109.

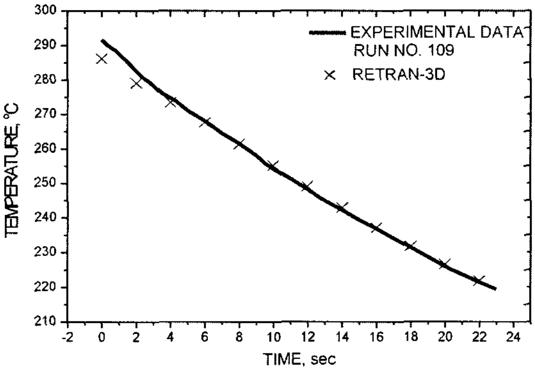

Fig. 3. Temperature responses for run 109.

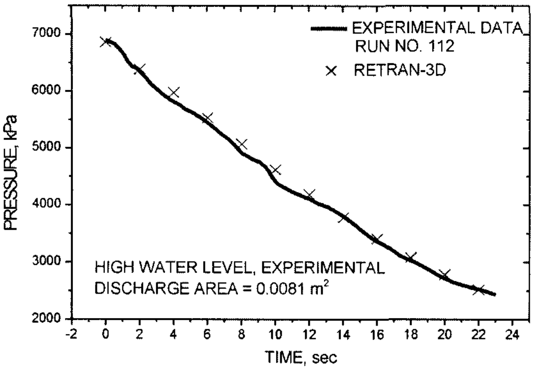

Fig. 4. Pressure responses for run 112.

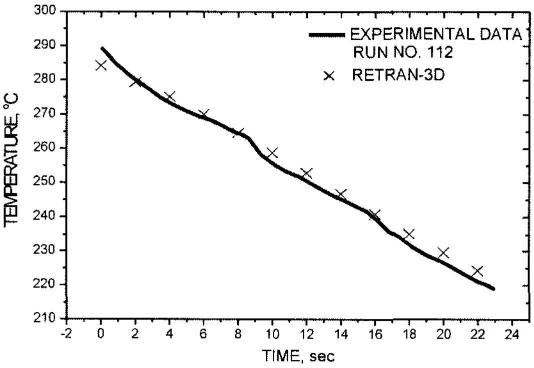

Fig. 5. Temperature responses for run 112.

limit for a sample size of 10[6]. The comparisons of the time-dependent pressure and temperature responses between the calculations and measurements for runs 109 and 112 are shown in Figs. 2 through 5. These comparisons show very good agreement.

2-4. Development of Interface Programs

The LOFTRAN code model is a representation of the entire NSSS that calculates the mass and energy releases. The LOFTRAN model requires the input of the time dependent break quality, since LOFTRAN does not have the capability to perform this calculation. The RETRAN-3D model only represents the primary and secondary sides of the broken loop Steam Generator and calculates the time dependent break quality. The output from the LOFTRAN provides thermal-hydraulic boundary conditions to the RETRAN-3D model, and the RETRAN-3D calculated time dependent quality is put back into the LOFTRAN model. This iterative process is continued until a converged set of LOFTRAN and RETRAN-3D cases has been completed. Then, the final run is made with the LOFTRAN model in which the entrainment model uncertainties are included. The following programs have been developed to facilitate the data transfer between LOFTRAN and RETRAN-3D.

An interface program is developed to prepare the portion of the RETRAN-3D input requirement from the output file generated by LOFTRAN. This portion of the input consists of the fill junction data associated with the time dependent broken loop primary and secondary side flows, enthalpies, and pressures. A portion of the LOFTRAN output contains the minor edits that are controlled by the NAMELIST parameter IPRINT(Printer option).

The interface program requires interactive specification of the IPRINT parameters that correspond to the following six variables: Broken loop hot leg flow (the Broken loop cold leg flow is assumed to be equal to this flow), the enthalpy of the water entering into the broken loop SG hot side inlet plenum, the pressurizer pressure, the broken loop SG total feedwater flow and enthalpy, and the broken loop SG secondary side pressure.

An interface program is developed to break up the output file generated by RETRAN-3D into its five major components. One of these components contains the minor edits. The interface program requires the minor edit which is the RETRAN-3D SG quality of the break flow. This minor edit is specified on the 0200YY cards of RETRAN-3D input deck.

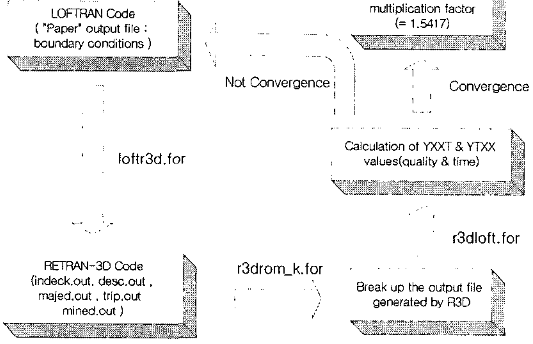

Fig. 6. Interface program system to calculate the entrainment.

Another interface program was developed to prepare the quality and time data input cards utilized in the LOFTRAN model. This contains the time dependent quality of the break flow. In addition, this program utilizes the uncertainty factors as specified by the user to generate the quality data. The user has an option to check the convergence of the resulting quality vs. time data against the data from a prior case.

It is essential that the two models have the same initial conditions. In general, the RETRAN-3D model initial conditions are forced to be the same as the LOFTRAN model initial conditions. The following procedures are used for that purpose.

The initial SG liquid inventory has been assumed that the RETRAN-3D model is adjusted by changing the circulation flow rate and the level in the downcomer. The initial primary side pressure is assumed by adjusting the RETRAN-3D model, changing the pressure in the pressure forced volume (cold leg) to match the LOFTRAN model initial pressurizer pressure. The initial primary side flow is assumed by adjusting the RETRAN-3D model, setting the hot leg forced flow to match the LOFTRAN model flow in the broken loop. The initial primary side average temperature is assumed by adjusting the RETRAN-3D model, setting the hot leg temperature matching the LOFTRAN hot leg temperature based on the enthalpies. The initial secondary side temperature is assumed by adjusting the RETRAN-3D model, forcing the steam generator pressure to match the LOFTRAN model temperature. The initial feedwater and steam flows are assumed by adjusting the RETRAN-3D model, matching the LOFTRAN model with those flows.

It should be noted that in cases where the RETRAN-3D model cannot be initialized with the above guidelines, biases or multipliers may be used to compensate for the LOFTRAN and RETRAN-3D model differences. As an example, if the initial feedwater flow for LOFTRAN is 485.34 kg/sec and 473.75 kg/sec for RETRAN-3D, then a bias of 11.59 kg/sec can be applied to the RETRAN-3D 1302XX cards that are based on the LOFTRAN output before they are input to the corresponding RETRAN-3D case.

2-5. Delta 60 SG Model for RETRAN-3D Code

Kori Unit 1 (Kori1) is 2-loop pressurizer water reactor designed by Westinghouse. To model the SG (Model-Delta60), the operation and design data were used. The SG was modeled as 8 nodes in the primary side and 9 nodes in the secondary. The SG nodes for the secondary side were divided into downcomer, heater, riser, primary separator, upper downcomer/dome, and dry region. Also, the tube region of SG in the primary side were divided into 8 nodes. To analyze the entrainment, detailed node modeling was assumed. Upper downcomer/dome region was applied to the bubble riser model. The nodding diagram is shown in Fig. 7[7].

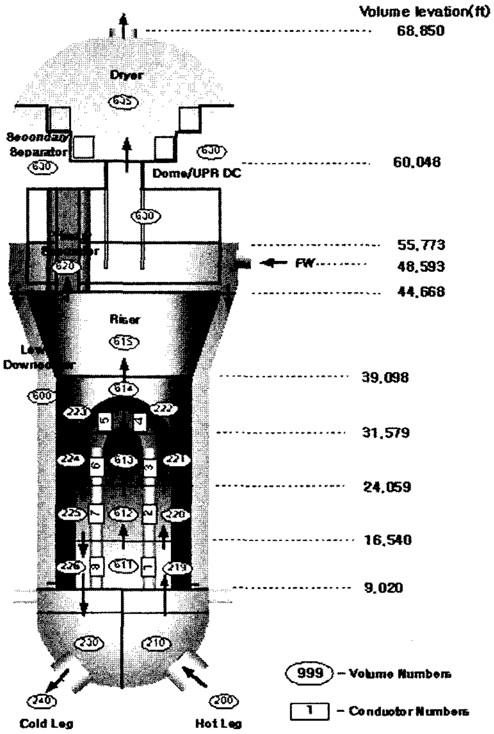

Fig. 7. Delta 60 SG RETRAN-3D nodding diagram.

2-6. Applications and Results

This methodology has been applied to the Kori unit 1. An iterative manner (by using the RETRAN-3D and LOFTRAN codes) was used to calculate the quality data for the Delta 60 SG. Boundary conditions (B.Cs) used as input at the RETRAN-3D are generated by LOFTRAN. And, B.Cs calculated from LOFTRAN is used in RETRAN-3D program as input conditions. An iteration is stopped when quality data get converged. If

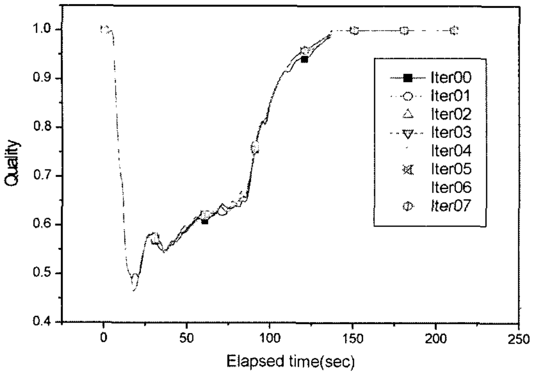

Fig. 8. Quality calculation by RETRAN-3D.

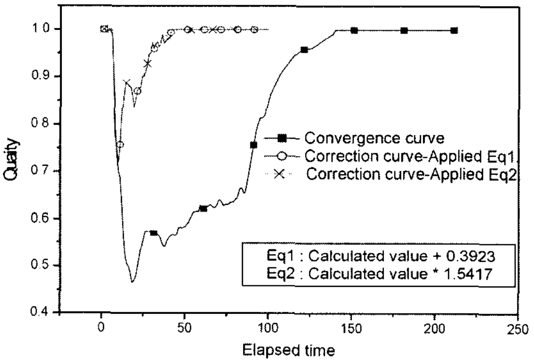

Fig. 9. Result by using the multiplication factor.

the quality data do not change any more per iteration, multiplication factor determined in this process is applied to quality data. These quality values become the final data. The following figures show the iteration process and the result using the multiplication factor. After all, Differences between those two values in Fig. 9 come from the RETRAN-3D's modeling.

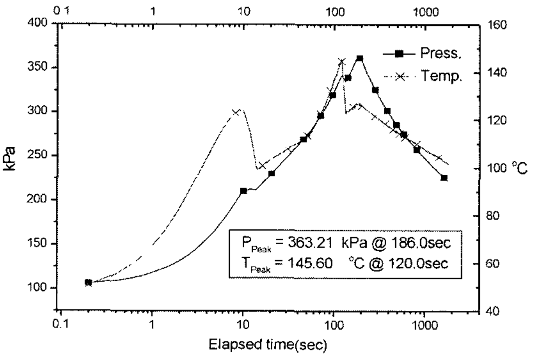

Fig. 10. Inside containment P/T result using the entrainment data.

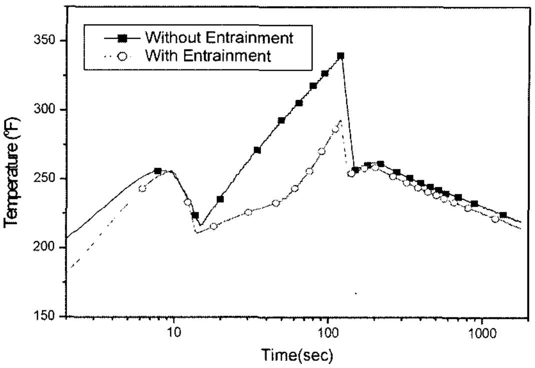

Fig. 11. Temperature profile change according to the entrainment assumption.

Table 2. Comparisons of entrainment effects.

Case no.		P_{peak} (kPa)		T_{peak} (°C)	
		kPa	Elapsed time (sec)	°C	Elapsed time (sec)
1	Wo/E	54.67	206	339.80	119
	W/E	53.56	204	297.88	118
2	Wo/E	55.94	248	338.80	123
	W/E	54.49	248	294.47	115
3	Wo/E	56.36	362	336.70	124
	W/E	55.06	360	292.55	117
4	Wo/E	53.30	488	331.40	127
	W/E	51.69	470	288.39	124

*Notes.
1 : 102% power, 0.13 m^2 full-DER, CSS failure.
2 : 70% power, 0.13 m^2 full-DER, CSS failure.
3 : 30% power, 0.13 m^2 full-DER, CSS failure.
4 : 0% power, 0.13 m^2 full-DER, CSS failure.
- Wo/E : Without entrainment.
- W/E : With entrainment.
- DER : Double Ended Rupture.
- CSS : Containment Spray System.

To analyze the pressure and temperature(P/T) at the inside containment, CONTEMPT L/T-028 code was used. The containment design pressure of Kori unit 1 is 397.82 kPa.

In aspect of temperature, the entrainment affected the temperature decrease of the inside containment. The temperature have decreased by about 40~50°C.

3. Applicability Criteria

The applicability criteria are defined as the physical and operational parameters of the steam generator design that must be in reasonable agreement with those of the CE test facility and the capability of covering the corresponding range which the benchmarked tests were run. These same criteria have been accepted by the USNRC for application of this methodology to MSLB analyses for the Kewaunee Nuclear Power Plant. The two key physical parameters that influence the entrainment phenomenon are the ratio of the break area to the vessel volume (A_{break}/V_{vessel}) and the ratio of the break area to the vessel free surface area ($A_{break}/A_{free\ surface}$). The ratio A_{break}/V_{vessel} is important in that it impacts the depressurization profile of the vessel (vessel pressure vs. time) and hence directly impacts the internal forces that provide the primary mechanisms that drive the fluid toward the break. This ratio also influences the flooding phenomenon that takes place in the upper regions of the vessel during blowdown phase that experiences appreciable entrainment. The flooding phenomenon greatly affects the level of entrainment and is not influenced significantly by the geometric details in that region. In a blowdown of a typical U-tube SG during a main steam line break, the flooding of the upper vessel region is an expected phenomenon. The ratio $A_{break}/A_{free\ surface}$ is important in that it impacts the availability of water to separate from the predominate liquid mixture regions and enter the predominate vapor mixture regions and to rise upward and ultimately flow out of the break.

4. Conclusions

To generate the quality data of delta 60 SG for Kori unit 1, the methodology using the LOFTRAN and RETRAN-3D code has been developed. The purpose of this new methodology is to decrease a temperature of the inside containment following MSLB.

As a result of application to Kori Unit 1, the temperature and pressure have decreased by about 40~50°C and 20.68~27.58 kPa, respectively. For several MSLB cases analyzed to calculate the M/E release and the containment P/T, the effect of entrainment in the steam flow is confirmed to make the temperature reduction of the inside containment.

References

1. Heberle, G.H.: "LOFTRAN-Code Description and Users Manual," WCAP-7878, Rev.5, Westinghouse Co., Nov. (1989).
2. Agee, L.J.: "RETRAN-3D A Program for Transient Thermal-Hydraulic Analysis of Complex Fluid Flow Systems", NP-7450, Research Project 889-10 Computer Code Manuals, December 1997, Prepared by Computer Simulation & Analysis, Inc. Prepared for Electric Power Research Institute.
3. SAS 12.2: "Mass and Energy Release to containment Following a Steamline Rupture".
4. SAS 19.0: LOFTRAN Base Deck, Revision 4, January (1997).
5. WCAP-8860: "Mass and Energy Releases Following a Steam line Rupture," September (1976).
6. Owen, D.B.: "Factors for One-sided tolerance limits and for values sampling plans", SCR-607, March (1963).
7. "Final Safety Analysis Report for Kori Unit 1," KEPCO (1997).