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A Study on Effect of Capture Volume in a Cavity on Direct Containment Heating Phenomena

C.Y. Chung and M.H. Kim
Pohang University of Science and Technology
San31 Hyoja-dong, Nam-gu, Pohang, Kyungbuk 790-784, Korea

H.Y. Lee
Samsung Engineering and Construction Co. LTD.
Power Plant Civil & Arch.Team

P.S. Kim
Korea Electric Power Cooperation
84-4 Bugu-ri, Bug-myeon, Ulchin-gun, Kyungbuk 767-890, Korea

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Abstract

Direct Containment Heating, DCH, is supposed to occur during a core melt-down accident if the primary system pressure is still high at the time of vessel breach in a Nuclear Power Plant (NPP). In this case, DCH is considered to be one of very important severe phenomena during postulated severe accident scenario because of the fast heat transfer rate to atmosphere and the sharp pressure increase in a containment. To reduce the effect of this DCH phenomena, the capture volume was designed at Ulchin NPP units 3 and 4. But, the effect of this has not been studied extensively. This work consists of experimental and numerical analyses of the effects of capture volume in the cavity on DCH phenomena. The experimental model is a 1/30 scaled-down model of Ulchin NPP units 3 and 4. We used three types of capture volumes to investigate the effect of size. Numerical analysis using CONTAIN 1.2 is performed with the correlation for the dispersed fraction of molten corium from the cavity into the containment derived from the experimental data to examine the effect of capture volume on DCH phenomena in full scale of Ulchin NPP units 3 and 4.

1. Introduction

High Pressure Melt Ejection, HPME, is one of very severe accidents postulated during a severe accident scenario in a NPP. It is supposed to occur if the pressure in the primary system is still high when the reactor vessel breaches. Steam ejects molten corium from the reactor vessel that is then dispersed as debris into the containment through the cavity. Then, the debris is rapidly transferred with enormous energy to the atmosphere in the containment and the energy transferred to the air increases the pressure and temperature in the containment inrease by the energy transferred from the debris to air. Finally, this threatens the safety of the containment. This phenomena is called DCH (Direct Containment Heating) DCH [1].

DCH phenomena play an important role in assessment of NPP safety. Therefore, it is necessary to find an effective way to reduce DCH. It has been suggested up to now that the optimization of cavity geometry can be achieved by reducing the dispersed fraction from the cavity to the containment. This study is focused on cavity geometry-capture volume. We investigate the effect of capture volume by performing experimental investigation with a 1/30 scaled-down model of Ulchin NPP units 3 and 4. The new correlation was developed to estimate the fraction of the dispersed debris to the containment based on our experimental results. When we performed a numerical analysis of the pressure and temperature response, we apply the new correlation was applied to investigate the effect of capture volume on DCH phenomena in the full scale model of Ulchin NPP units 3and 4.

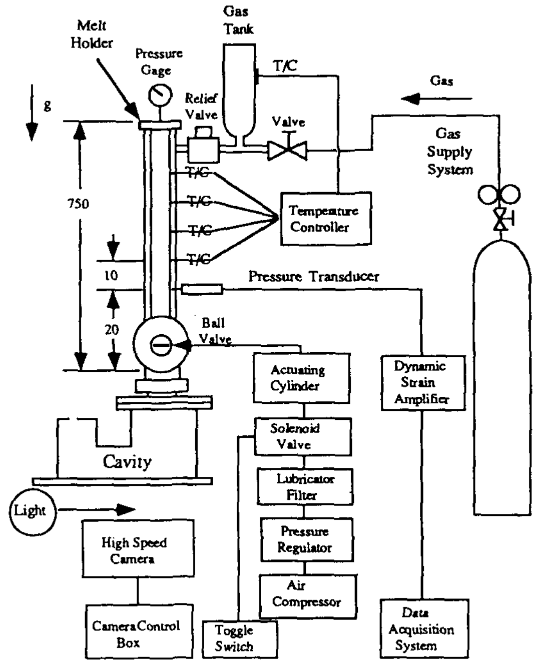

Fig. 1. Schematic Diagram of Experimental Facility

2. Experiments

Figure 1 and 2 show the experimental facility[2, 3, 4] and the cavity with capture volume used in the experiment. They are 1/30 linear scaled-down model of Ulchin NPP units 3 and 4. Nitrogen is used as the simulant of steam in the primary system. Water is used as the simulant of the molten corium. The water in the melt holder is ejected by the pressurized gas in the gas tank when the ball value is opened by the solenoid value and the compressed air. An electric balance is used to measure the dispersed fraction of water from the cavity to the atmosphere after the experiment. Pressure is measured continuously by a pressure transducer and amplifier.

The total volume of the fuel assembly of Ulchin NPP units 3 and 4 is calculated to be $12.8m^3$ [5]. We get the reference value of the capture volume, 000474 m^3, which is a 1/30 linear scaled-down value. The capture volumes used at the experiments are 1.8, 3.6 and 5.4 times as large as this reference value. The capture volume is located in the lower part

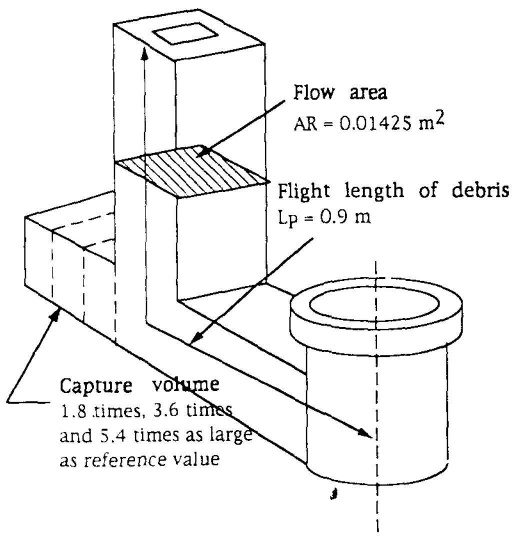

Fig. 2. Cavity Models Used in Experiment

toward the exit wall of the cavity in order to collect the molten corium climbing along the exit wall of the cavity. This is based on the previous analysis of flow motion from the films taken using a high speed camera [3].

Figure 3 shows the experimental results. The dispersed fraction of the molten corium injected from the cavity decreases with increasing the size of the capture volume. Therefore, the capture volume is found to be effective to reduce the dispersed fraction from the cavity. It means that the amount of debris injected into the containment is reduced and the heat transfer between debris and atmosphere in a containment decreases. Therefore, the pressure and temperature are expected to be lower than in the case of the cavity without the capture volume. From the above results, we find that the capture volume plays an important role in mitigating DCH phenomena during severe accidents in nuclear power plants.

3. Development of New Correlation

In the previous work [4], the correlation was developed to predict the dispersed fraction of molten corium from the cavity. The experimental data is correlated in terms of the nondimensional time period. This means that the dispersed fraction depends on the flight length, the average velocity and the effective time period is as follows.

$$t^* = \frac{t_e v_{avg}}{L_P} \tag{1}$$

The effective time period, t_e, was defined the time until the pressure reached the critical value at which the nondimensional number, N_6, is equal to 0.5. N_6 is the inception criteria of entrainment at annular flow according to Ishii [6]. In his paper, the entrainment criteria is recommended for N_6 to be 1 for the stratified flow. But, from our experimental results, the new inception criterion for entrainment in our complicated geometry for N_6 to be 0.5. Figure 4 shows experimental results for N_6 versus dispersed fraction and we can see that the entrainment starts at about 0.5 of N_6. N_6 is defined as follows,

$$N_6 = \frac{\frac{\mu_L u_R}{\sigma}\sqrt{\frac{\rho_R}{\rho_L}}}{N_\mu^{0.8}}, \qquad N_\mu = \frac{\mu_L}{\sqrt{\rho_L \sigma \sqrt{\frac{\sigma}{\rho_L} g}}} \tag{2}$$

where v_{avg} is the average velocity of debris entrained during the effective time period. Also, L_P is the flight length of debris entrained. The developed the correlation in terms of the nondimensional effective time period considers how long the entrainments occurs and whether the debris entrained travels from the cavity to the containment during this period. The correlation was as follows.

Dispersed Fraction

$$= 40\left\{1+\tanh\left[\ 3.79\log\left(\frac{t^*}{15}\right)\right]\ \right\} \tag{3}$$

Figure 5 shows that correlation is in good agreement with our experimental results as good as the data from KAIST [7] and Brookhaven National Laboratory [8].

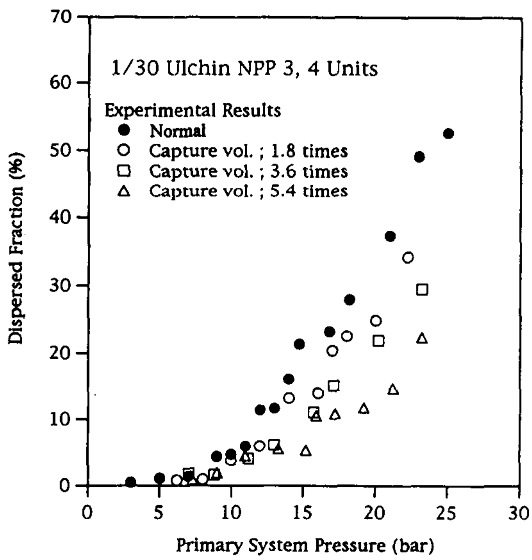

Fig. 3. Experimental Results for Capture Volume

The above correlation does not include the effect of the capture volume from our experiments. Therefore, we developed the new correlation to represent the effect of the capture volume. Figure 6 shows that the new correlation is in good agreement with our experimental data. The dispersed fraction from the cavity is correlated in terms of nondimensional effective period, t^*, and the volume ratio between the reference value of the capture volume, V_o, and the size of capture volume, V_c. The new correlation is as follows :

$$\text{Dispersed Fraction} = 40\left\{1+\tanh\left[\ 3.79\log\left(\frac{T}{15}\right)\right]\ \right\}$$

$$\text{where,}\quad T = t^*\cdot\left\{\exp\left[\ -0.065\left(\frac{V_c}{V_o}\right)\right]\ \right\}$$

$$t^* = \frac{t_e\cdot v_{avg}}{L_p} \qquad (4)$$

where, t_e, v_{avg} and L_p are the effective period, the average velocity of molten corium and the flight length of debris entrained, respectively. Figure 7 is the extension of the calculation result from Eq.(4) for the dispersed fraction in the experimental scale.

We applied this new correlation to the full scale Ulchin NPP units 3 and 4, where the liquid phase is molten corium and the gas phase is steam. Figure 8 shows the prediction of the dispersed fraction from the cavity in full scale of Ulchin NPP units 3 and 4. From these results, we also conclude that the cap-

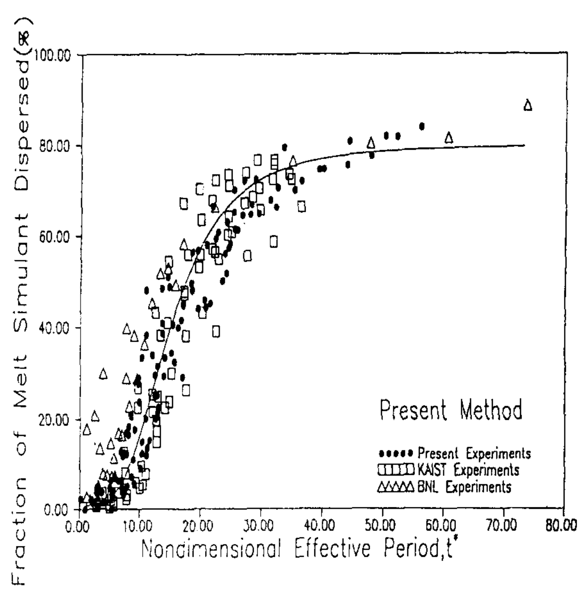

Fig. 5. Apply the Correlation to Other Experiments

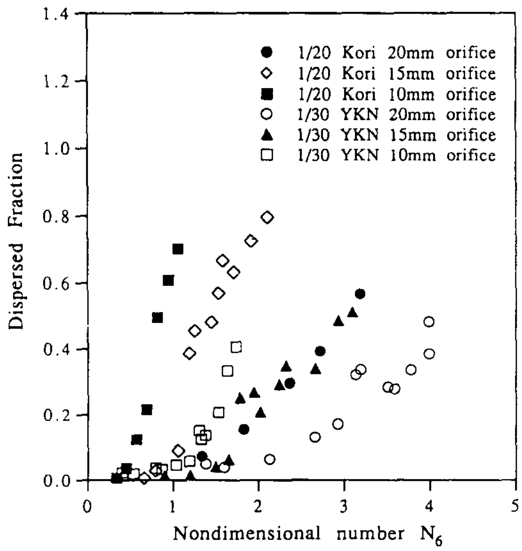

Fig. 4. Dispersed Fraction Versus Nondimensional Number N_6

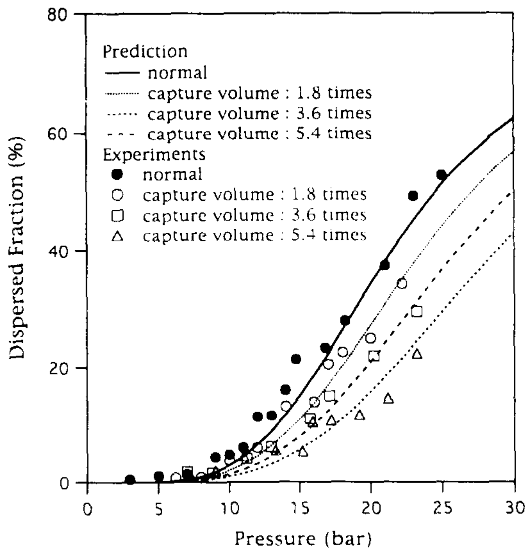

Fig. 6. Prediction of Dispersed Fraction Based on Correlation for Capture Volume

ture volume is the effective factor to retain the molten corium in the cavity. This means that temperature and pressure in the containment with the capture volume are lower than the normal cavity without the capture volume. Specially in the expected operating primary side pressure range (30～150 bar), the capture volume is expected to be effective to reduce the dispersed fraction of molten corium from the cavity to the containment. The larger capture volume is more effective until 5 times larger volume than the reference volume. For example, the dispersed molten corium is supposed to be reduced about 30～40% with 5 times larger volume capture volume of the reference volume if the primary pressure at the time of the vessel breach was about 75 bar.

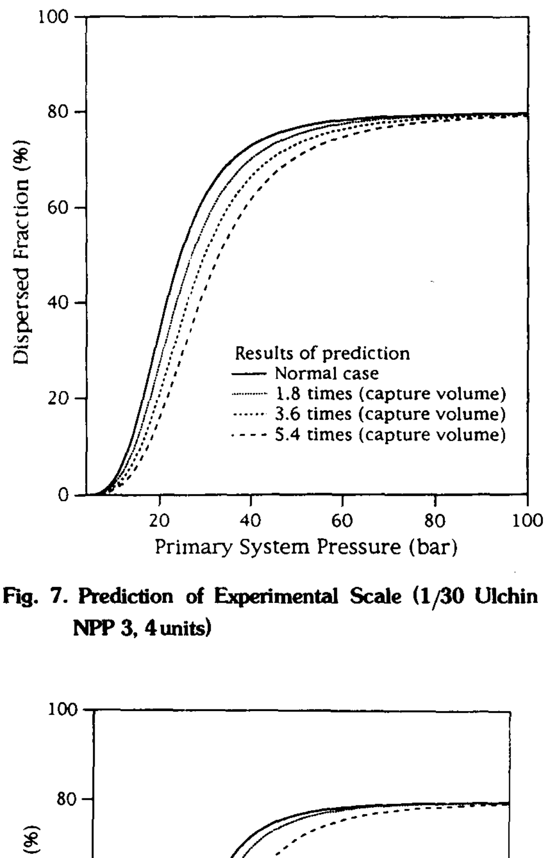

Fig. 7. Prediction of Experimental Scale (1/30 Ulchin NPP 3, 4 units)

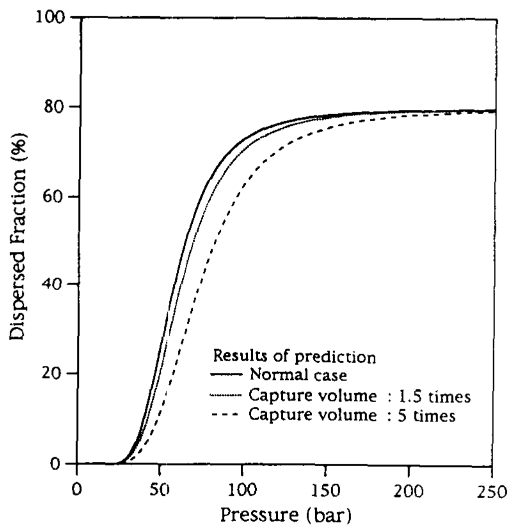

Fig. 8. Prediction of Full Scale of Ulchin NPP Units 3, 4

4. Calculation by Using CONTAIN 1.2

We investigated the effects of the capture volume on the temperature and pressure response after DCH phenomena in the containment in Ulchin NPP units 3 and 4 by performing the numerical analysis with CONTAIN 1.2. The size of capture volume at Ulchin NPP units 3 and 4 is 1.5 times as large as the reference value. We, also, consider the capture volume of 5 times as large as the reference value to evaluate the possible maximum effect to reduce the dispersed fraction. Molten corium consists of uranium dioxide, chromium, iron and zirconium and is expected as a source of entrainment in the cavity. We assume that the debris is dispersed from the cavity with the constant rate during the effective period. Total weight of molten corium is 122.65 tons for Ulchin NPP units 3 and 4 [5] : uranium dioxide is 85.64 tons, zirconium 25.35 tons, iron 9.34 tons and chromium 2.32 tons. The temperature of molten corium is assumed to be 2500 K.

Five volumes are used for the calculation of CONTAIN 1.2. Cell 1 and 2 are reactor vessel and cavity and cell 3 is a steam generator room, cell 4 is a subcompartment without a steam generator room and cell 5 is the dome area in a containment. A hydrogen-burn model is allowed for all cells except cell 1. Also a DCH trapping model is used at walls.

Figure 9 shows the numerical results of the pressure in the containment dome. The pressure of the subcompartment is almost the same as the pressure in the containment dome at any time. Figure 10 and

11 show the numerical results of the temperature at subcompartment and containment dome with the initial pressure of 50 bar. Because of fast heat transfer from the dispersed small particles of molten corium to atmosphere in the containment, the pressure and temperature increase rapidly during the effective period. With the capture volume, the pressure and temperature are calculated to be lower than in the normal state. The temperature and pressure in a containment with 5 times capture volume of the reference value are estimated to lower than those with 5 times capture volume of the reference value. This means that capture volume is one of the major factor for promoting safety of a containment by mitigat-

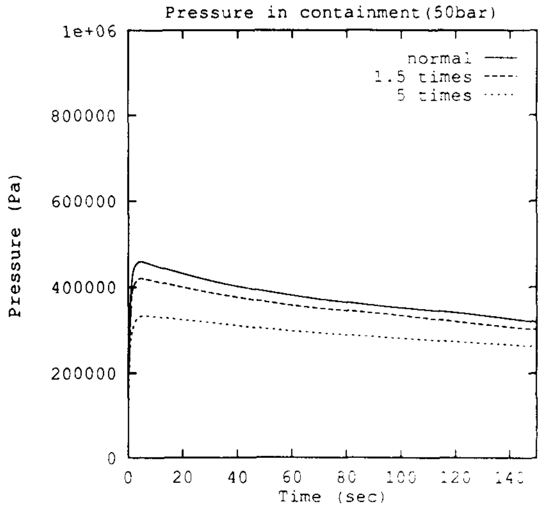

Fig. 9. Calculation Results of Pressure in Containment Dome

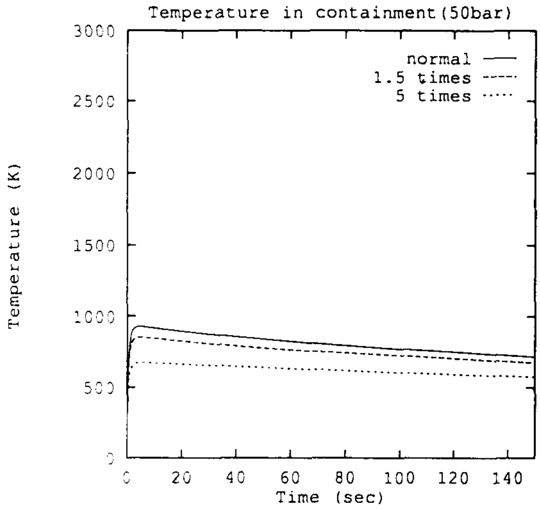

Fig. 11. Calculation Results of Temperature in Containment Dome

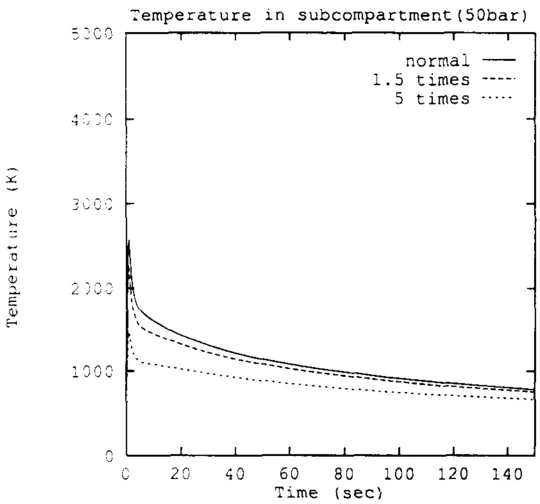

Fig. 10. Calculation Results of Temperature in Subcompartment

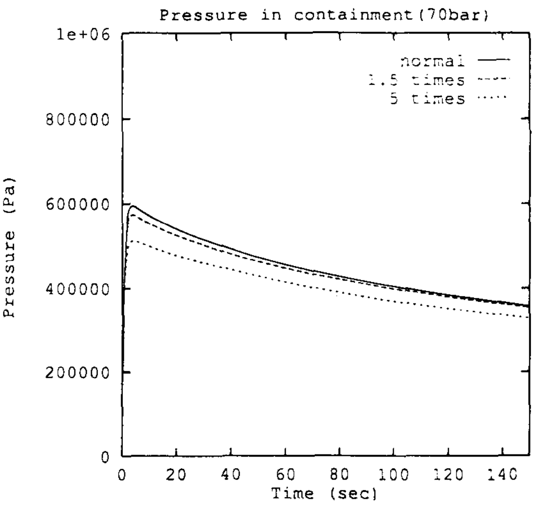

Fig. 12. Calculation Results of Pressure in Containment Dome

ing DCH phenomena during severe accident scenario at nuclear power plants.

Figure 12 shows the numerical results of the pressure in the containment dome. Figure 13 and 14 show the temperature response in the subcompartment and containment dome with the initial pressure of 70 bar. From the results, the effect of the capture volume at 70 bar is less significant than that at 50 bar. This is already expected from Figure 8. Therefore, we consider that the debris captured in the capture volume decreases by increasing the initial pressure of the primary system.

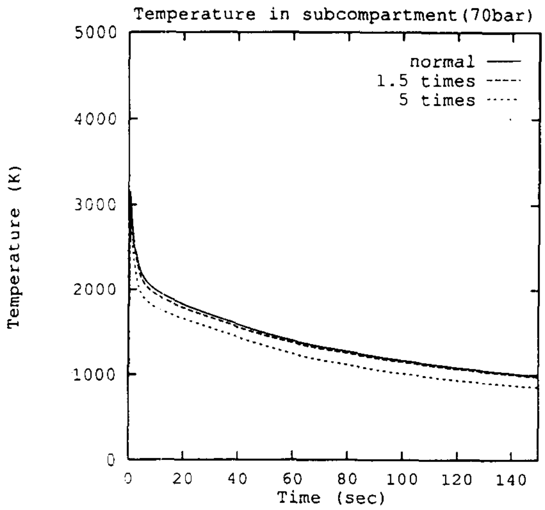

Fig. 13. Calculation Results of Temperature in Subcompartment

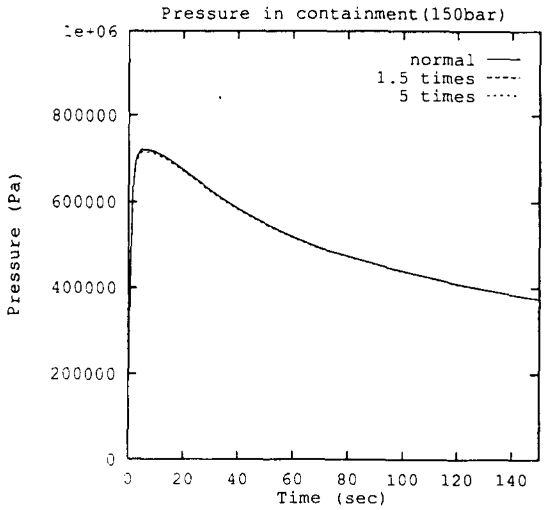

Fig. 15. Calculation Results of Pressure in Containment Dome

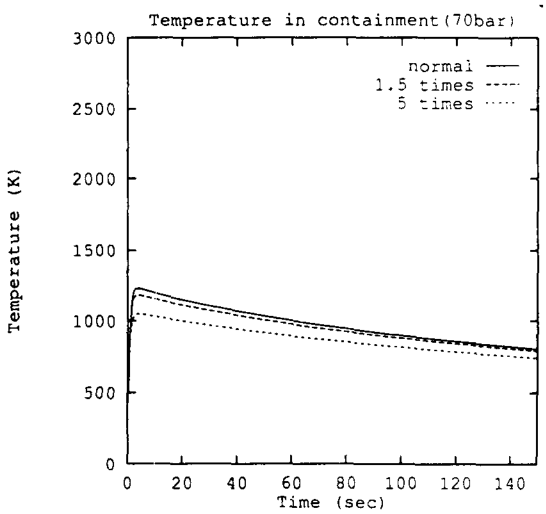

Fig. 14. Calculation Results of Temperature in Containment Dome

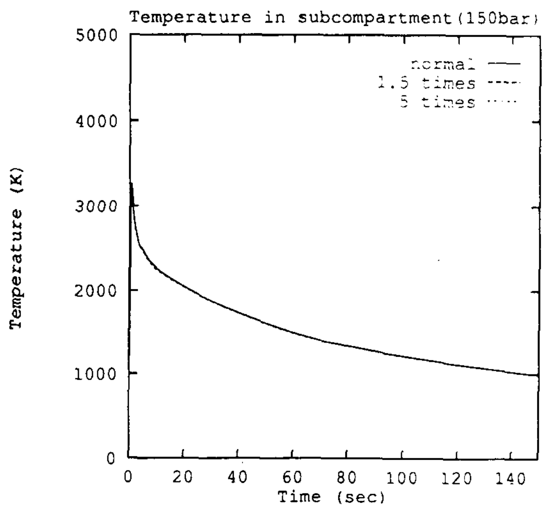

Fig. 16. Calculation Results of Temperature in Subcompartment

Figure 15 shows the numerical results of pressure in the containment dome with the initial pressure of 150 bar. Figure 16 and 17 show the results of temperature in the subcompartment and containment dome respectively. From these results, the effect of capture volume is not effective to reduce the pressure and temperature in the containment dome above 150 bar as expected from Figure 8.

In the above numerical results, we can find that the capture volume is expected to be effective until the initial pressure of the primary system is lower than 100 bar. If we consider that the lower limit of the initial pressure is, at least, 20 bar to occur DCH phenomena and the expected upper limit is about 100~150 bar, this capture volume is expected to be effective at this range of the initial pressure. So we think that simple modification of the cavity design may be very effective for promoting containment safety.

5. Conclusions and Remarks

From the 1/30-linear scale down experiments, the capture volume is shown to be able to reduce the dispersed fraction from the cavity into a containment. The new correlation for the dispersed fraction from the cavity with capture volume into a containment was developed by using the nondimensional time and the ratio of the capture volume to the reference volume. With the calculated amount of molten corium by using the new correlation, the pressure and temperature response of the containment of Ulchin (NPP)units 3 and 4 are calculated by using CONTAIN 1.2. From these experiments and calculations, the volume of capture volume is shown to be sensitive to reduce the dispersed fraction of molten-corium. The 5 times capture volume is estimated to be effective specially in the range of the primary initial pressure of 20~100 bar.

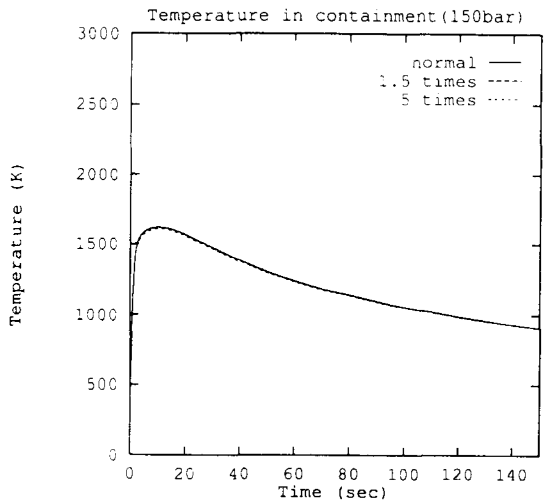

Fig. 17. Calculation Results of Temperature in Containment Dome

Nomenclature

g	=gravitaional force
L_P	=flight length of debris
t^*	=nondimensional effective time period
t_e	=effective time period
u_R	=velocity of gas phase
V_{avg}	=average velocity of debris
μ_L	=viscosity of liquid phase
ρ_L	=density of liquid phase
ρ_R	=density of gas phase
ρ	=surface tension

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