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The Probabilistic Analysis on the Containment Failure by Hydrogen Burning at Severe Accidents in Nuclear Power Plants

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원자력발전소 중대사고시 수소연소로 인한 격납용기 파손에 대한 확률적인 분석

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Abstract

The containment failure probability due to hydrogen burning during severe accidents proceeding in a low pressure sequence is calculated using Monte Carlo method. The probability distribution functions for this Monte Carlo calculation is obtained from the statistical method. The calculations are performed for Kori unit 2, and the sensitivity studies on the input variables-the amount of hydrogen generated at SFD, corium diameter, corium length, oxidation rate at FCI, and the amount of hydrogen generated during MCCI-are also performed. It is revealed that SFD is the main factor in hydrogen generation, but the other sources also cannot be neglected. The containment failure probability due to the hydrogen burning lies within 6% in case of Kori unit 2.

요 약

원자력발전소 중대사고시 예상되는 수소생성과 이에 따른 수소연소로 인한 압력증가로 야기되는 격납용기의 파손확률을 몬테카를로 방법을 통하여 계산하였다. 몬테카를로 계산을 수행하기 위해서는 각각의 입력변수들에 대한 적절한 확률분포함수가 요구되는데, 통계적인 처리를 통하여 구하였다. 고리 2호기에 대한 계산을 수행하였으며, 입력변수들에 대한 민감도 분석도 실시하였다. 고리 2호기에서 수소연소로 인한 격납용기의 파손확률은 6%이하로 계산되었으며, 민감도 분석결과 SFD가 중요한 인자이긴 하지만 다른 인자들도 무시할 수 없는 영향을 미치고 있음이 밝혀졌다.

1. Introduction

The TMI accident resulted in the generation of an estimated 150 to 600kg of hydrogen, some of which burned inside the containment building, and caused a transient pressure rise of about 200 kPa(2atm). With this accident, the nuclear industry and the Nuclear Regulatory Commission initiated research programs to study hydrogen behavior and control during accidents in nuclear plants. The main concern with hydrogen combustion in nuclear reactor containments is that the resultant high pressure may cause containment failure and subsequent radioactivity release.

Several fundamental questions and issues arise when the hydrogen problem for light water reactors is examined: hydrogen production, transport, mixing, and combustion. Although much has been accomplished, some unknowns and uncertainties still remain, for example, the rate of hydrogen production during core degradation or melt progression, the effect of geometrical structures, and so on.

And many mechanistic codes(MAAP, MELPROG, HECTR, CONTAIN etc.) to analyze the hydrogen behavior were developed. However, even the mechanistic models cannot fully simulate the real situation, and therefore the calculated results include many uncertainties. Thus, a probabilistic analysis is used to explain the uncertainties and to complement the mechanistic models.

In this paper, a probabilistic analysis is performed to calculate the containment failure probability due to the hydrogen burning during the severe accidents proceeding in a low pressure sequence. Monte Carlo method is used for this purpose, and probability distribution functions for input variables are constructed through statistical treatment.

First, the probability distribution functions are constructed to determine the amount of hydrogen generated from hydrogen sources. Then, the concentrations of air, hydrogen and steam are calculated. And then, the flammability and detonation limits are considered, and the correlation based upon experimental hydrogen burning data is used to calculate pressure buildup resulting from hydrogen burning. Finally, the containment failure probability resulting from the pressure buildup is calculated using the PRA data for the individual plant.

Also, the sensitivity studies are performed on the input variables, which are the amount of hydrogen generated at SFD, corium diameter, length, oxidation rate, and the amount of hydrogen generated during MCCI.

2. Analysis Methodology

There are many probabilistic analysis methods. : convolution, moments method, Taylor's series, Monte Carlo, discrete probability distribution etc.[1]. In this study, Monte Carlo method is used to obtain the containment failure probability caused by hydrogen burning.

Monte Carlo method is to calculate output variables according to input variables selected randomly from probability distribution functions. Thus, it is important that the probability distribution functions for input variables should be properly constructed.

There are several methods to construct the probability distribution functions for input variables: the method using maximum entropy, statistical assessment, fuzzy method[2]. The statistical treatment method, called as 'the general lambda distribution (GLD)', was suggested by Hastings et al.(1947) and generalized by Dudewitz et al.(1974).

The probability distribution functions, which fit raw data very well, can be obtained by matching 'percentile' or 'moment' of each data with GLD. In this study, the 'percentile' is used for matching factor with GLD to obtain the experimental distribution. The GLD is defined in terms of its 'percentile' function as,

$$y_p = R(p) = \lambda_1 + \frac{p^{\lambda_1} - (1-p)^{\lambda_4}}{\lambda_2} \quad 0 \leqq p \leqq 1 \qquad (1)$$

where, y_p = arbitrary variable
p = probability = $F(y_p)$
$R(p)$ = $F^{-1}(p)$ $0 \leqq p \leqq 1$
$F(y)$ = cdf

Coefficients λ_1, λ_2, λ_3, and λ_4, of function y_p or $f(y_p)$ are obtained by matching four 'pecentile' in raw data with y_p. Conventional 'pecentile' sets, which are 5, 25, 75, 95, are given using Equation(1) as,

$$y_{0.95} = \lambda_1^* + \frac{0.95^{\lambda_3^*} - 0.05^{\lambda_4^*}}{\lambda_2^*} \tag{2}$$

$$y_{0.25} = \lambda_1^* + \frac{0.25^{\lambda_3^*} - 0.75^{\lambda_4^*}}{\lambda_2^*} \tag{3}$$

$$y_{0.75} = \lambda_1^* + \frac{0.75^{\lambda_3^*} - 0.25^{\lambda_4^*}}{\lambda_2^*} \tag{4}$$

$$y_{0.05} = \lambda_1^* + \frac{0.05^{\lambda_3^*} - 0.95^{\lambda_4^*}}{\lambda_2^*} \tag{5}$$

where, λ_1^*, λ_2^*, λ_3^*, λ_4^*, = trial solutions

This equations are solved for λ_1^*, λ_2^*, λ_3^*, and λ_4^*, the percentile estimators of λ_2^*, λ_3^*, and λ_4^*, respectively. Then, the density function of y_p can be given in the same way as,

$$f(y_p) = \frac{1}{R'(p)} = \frac{\lambda_2}{\lambda_3 p^{\lambda_3 - 1} + \lambda_4 p^{\lambda_4 - 1}} \tag{6}$$

3. Hydrogen Behavior

The mechanism for hydrogen production in nuclear reactor during severe accidents can be grouped into rapid sources capable of generating hundreds of kilograms of hydrogen in tens of minutes or less, and slow sources capable of generating substantial amounts of hydrogen in tens of hours or longer[3]. The reaction between the zirconium fuel cladding and steam is believed to be the main source of the hydrogen for many accident scenarios. But the amount of hydrogen generated by its sources includes many uncertainties.

A major uncertainty in hydrogen production rate would occur if the accident progressed to the point that a molten core dropped into a water-filled lower plenum. Bird observed hydrogen partial pressure of about 0.2 to 0.4 MPa, through steam experiment using the melts of UO_2(80%)/molybdenum(20%) in quantities of 24kg[4]. Also, Corradini has conducted experiments on hydrogen generation from melt/coolant interactions, using either alumina or corium as the melt simulants[5].

The hydrogen transport problem is important because generated hydrogen could be locally concentrated or stratified[6]. Therefore, some mechanistic codes to simulate the hydrogen behavior calculate hydrogen distribution by meshing containment atmosphere into about ten[7]. The hydrogen generated in reactor vessel can be released into containment atmosphere through primary loop or safety valve system, and then be transported in the containment by the natural convection or forced convection by fans etc.

But the hydrogen transport process varies with the containment type of each plants. In large dry containments of typical PWR, hydrogen is transported from the lower compartment of the containment to upper compartment. Also, the melt/concrete reaction is capable of creating the hydrogen at reactor cavity. Therefore, the hydrogen concentration is higher at lower compartment, where the hydrogen concentration is one and half as high as that of completely steady state distribution[8] and therefore, hydrogen burning probability is much higher at this point.

The hydrogen released in the containment atmosphere burns, if the concentrations of air, hydrogen, and steam satisfy flammability condition. In case air does not exist in atmosphere, the hydrogen burning does not occur. As steam concentration grows in containment atmosphere, the flammability limit band becomes narrower. If the steam concentration exceeds 60 percent, the burning is terminated.

Maximum pressure buildup due to hydrogen burning can be predicted by AICC(adiabatic isochoric complete combustion), and actual pressure buildup does not exceed this pressure. The practical flammability and the pressure buildup by hydrogen burning are influenced by the concentrations of air, hydrogen, and steam, initial temperature and pressure, and boundary condition.

4. Modeling

Fig. 1 shows the algorithm to calculate the containment failure probability due to the hydrogen burning. It is assumed that the effective hydrogen sources does not include the slow sources, because they do not generate large amount of hydrogen and have a long generation time. Thus, the hydrogen sources are limited to zirconium/steam, melt/water, and melt/concerete interaction, which are confronted with SFD(severe fuel damage), FCI(fuel/coolant interaction), DCH(direct dontainment heating), and MCCI (molten core/concrete interaction) during severe accidents.

The mechanisms of hydrogen generation in reactor vessel are SFD and FCI. The mechanisms of the hydrogen generation outside the vessel are ex-vessel FCI, DCH, and MCCI. In this study, DCH is not considered because it occurs only when corium is ejected under high pressure condition. The accident mode adopted in the current work is a low pressure sequence. After the amount of hydrogen generated is determined, the concentrations of air, hydrogen, and steam are calculated under the assumption that hydrogen is locally concentrated and its concentration is three times as high as that of completely steady state distribution: this is conservative consideration because the hydrogen concentration at lower compartment is one and half as high as that of completely steady state distribution by past study[8].

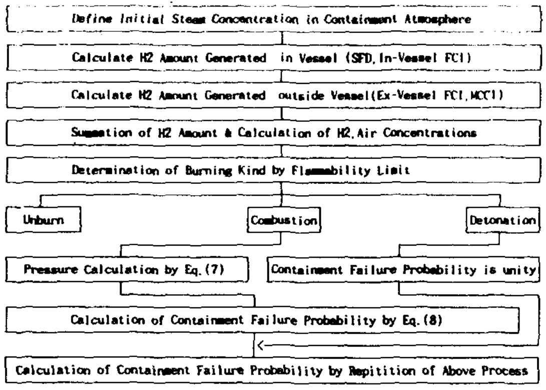

Fig. 1. Flow Chart of Modeling Hydrogen Behavior in PWR

Now, the flammability condition is considered to determine which kind of hydrogen burning may occur. When detonation occurs, the containment failure probability will be unity. If burning without detonation (combustion) occur, pressure buildup by hydrogen combustion is calculated using the correlation constructed from experimental data. Then the containment failure probability will be calculated using the correlation constructed based upon PRA data.

4.1. Input Variable

In this paper, the input variables considered are the amount of hydrogen generated by SFD, corium diameter, length, oxidation rate during FCI, and the amount of hydrogen generated during MCCI. DCH known for important hydrogen source is not considered because it occurs in a high pressure sequence.

Figs. 2~6 represent pdf's for each input variables mentioned above. These pdf's are converted into analytical probability distribution functions through the statistical treatment.

The amount of hydrogen generated at SFD is obtained from KSAD[9] that includes experimental and analytical data concerned with severe accident.

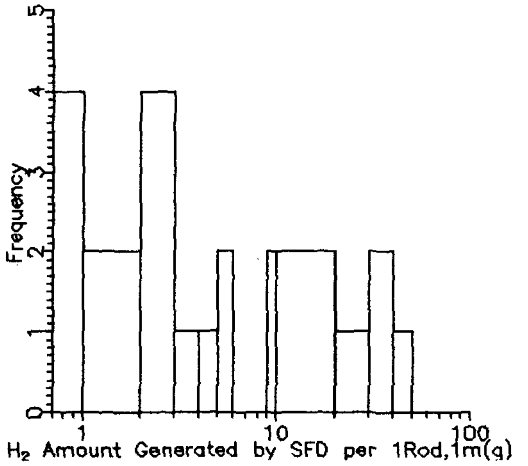

Fig. 2. pdf for H_2 Amount at SFD

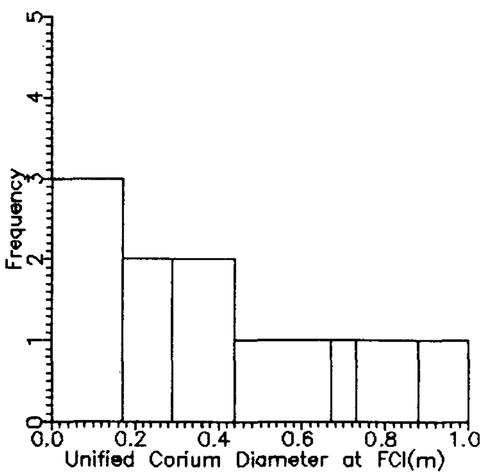

Fig. 3. pdf for Corium Diameter at FCI

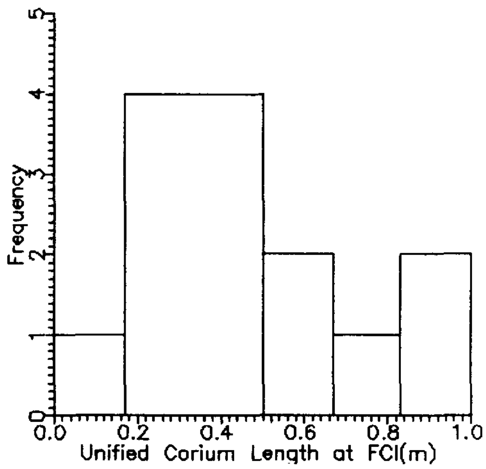

Fig. 4. pdf for Corium Length at FCI

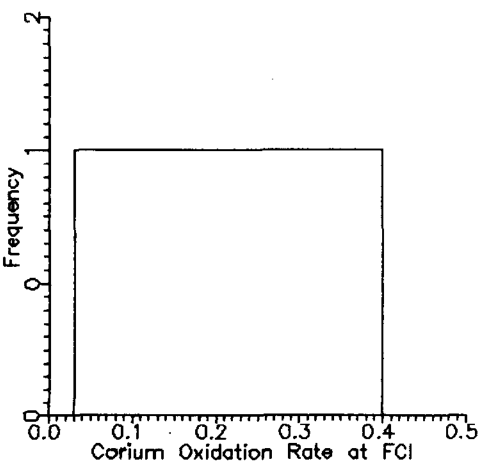

Fig. 5. pdf for Corium Oxidation Rate at FCI

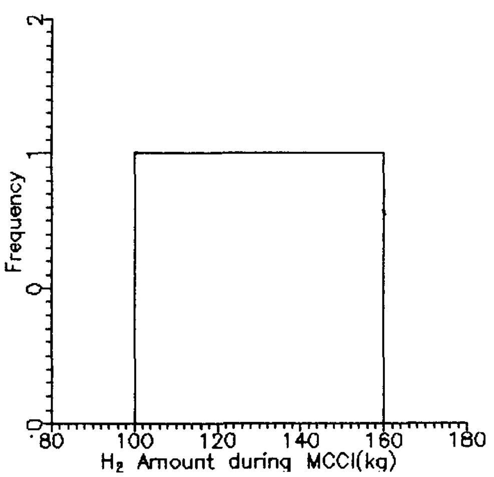

Fig. 6. pdf for H_2 Amount During MCCI

In most SFD experiments the number of fuel rods is about thirty that is 1/1000 of actual fuel rods in reactor fuel assembly. Therefore, the actual amount of hydrogen is arithmetically scaled up with the ratio.

The amount of corium involved in in-vessel FCI can be calculated using the corium diameter and corium length, which is obtained from expert's opinions and limited core diameter and reactor vessel length respectively. The corium oxidation rate is the experimental result of Corradini who reported corium oxidation between 4~30% at FCI experiments. And from his report, it can be known that the corium of 1kg results in hydrogen generation of about 22g at FCI[5]. The amount of hydrogen generated from in-vessel FCI can be obtained by mutiplying the oxidized mass of corium by 22g.

At the ex-vessel FCI, the mass of non-oxidated corium is the difference of the corium mass before and after in-vessel FCI. The amount of hydrogen generated at ex-vessel FCI can be calculated in the same way as in-vessel FCI.

According to the results of the Zion plant, the amount of hydrogen generated form MCCI was about 130kg for 5 hours. In this study, the amount of hydrogen generated by this mechanism has uniform disribution from 100 to 160kg.

4.2. Hydrogen Concentration

The total amount of hydrogen becomes the sum of the amount of hydrogen generated by above mechanisms. After the amount of hydrogen is determined, the concentrations of air, hydrogen, and steam are calculated under the assumption that hydrogen is locally concentrated and its concentration is three times as high as that of completely steady state distribution.

4.3. Peak Pressure by Hydrogen Burning

After the concentrations of air, hydrogen, and steam are determined, the flammability and detonation limits are considered. If the detonation occurs, the containment failure probability is unity. Fig. 7 shows the flammability and detonation limits according to the concentrations of air, hydrogen, and steam.

If the hydrogen combustion occurs, Eq. (7), which is the correlation between the hydrogen concentration and hydrogen combustion peak pressure based upon KSAD[9], is used for the calculation of peak pressure. Fig. 8 shows the relationship between the hydrogen concentration and the peak pressure.

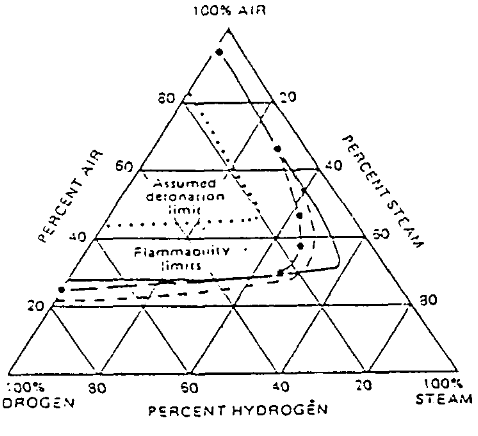

Fig. 7. H₂ Flammability & Detonation Limit

$$P_B(X) = -0.00832284 + 0.0199069 \times X + 0.000262381 \times X^2 + 1.43688E-06 \times X^3 \quad (7)$$

where, $P_B(X)$ = burning peak pressure(Mpa)

X = hydrogen concentration(%)

estimated standard deviation = 0.02290

4.4. Containment Failure Probability

As mentioned above, the detonation brings about the containment failure. The combustion causes pressure buildup by which the containment may fail.

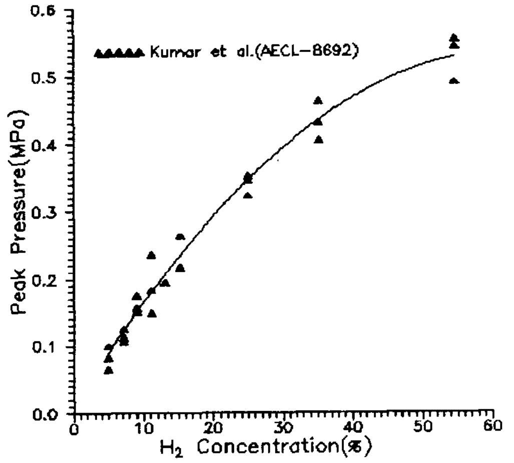

Fig. 8. Pressure Buildup by H₂ Combustion

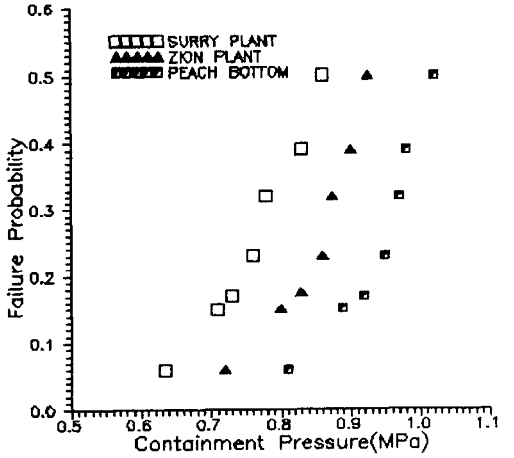

Fig. 9. CF Probabiltiy vs Pressure Buildup

CESSAR has reported the containment failure probability caused by pressure buildup for NUREG-1150 plants[11]. The failure probability distribution is quite different according to the inherent containment type of each plant. Fig. 9 shows the failure probability which is different in each plant. The results of Zion plant can be applied to the Kori unit 2, because they have the same containment type(large dry). The failure probability function is Eq. (8) as

$$P_F(X) = 0.00500743 \times \mathrm{Exp}(4.47306 \times X) \qquad (8)$$

where, $P_F(X)$ = CF probability

X = pressure buildup(MPa)

estimated standard deviation = 0.017475

5. Results and Disscussion

Figs. 10 and 11 represent the hydrogen burning probability and the containment failure probability by hydrogen burning. As shown in these figures, the resultant probabilities cannot be calculated as one value because the steam concentration is modeled as external variable. This problem can be settled by the implicit treatment of the steam concentration.

The burning and containment failure probabilities considering only SFD are lower than results considering all hydrogen sources(SFD, FCI, and MCCI). The steam concentration has a large effect upon the hydrogen burning. At severe accidents, the operation of containment spray can reduce the containment pressure and temperature, but the containment failure probability due to hydrogen burning is higher because steam concentration becomes lower.

The sensitivity studies on the input variables are accomplished (Figs. 12~16). This results are obtained by following method; fixing a input variable to be analyzed and sampling other variables randomly. SFD is revealed as the key parameter in the hydrogen burning, which is the anticipated result. The parameters related to FCI have an effect upon the hydrogen burning to some extent, but MCCI affects the hydrogen burning little.

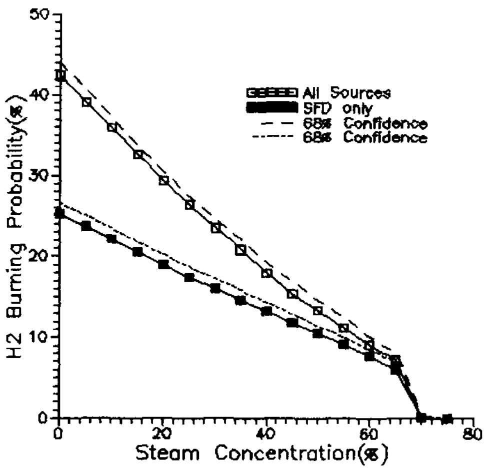

Fig. 10. H2 Burning Probability

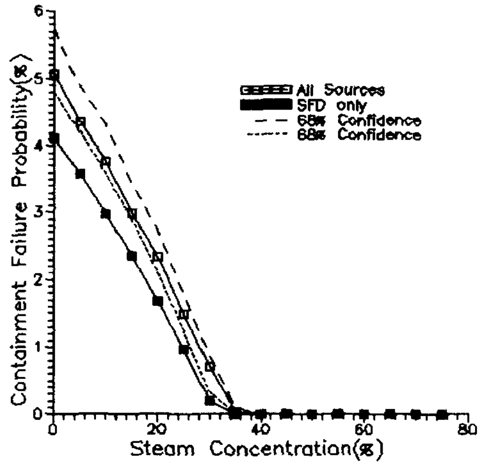

Fig. 11. Containment Failure Probability

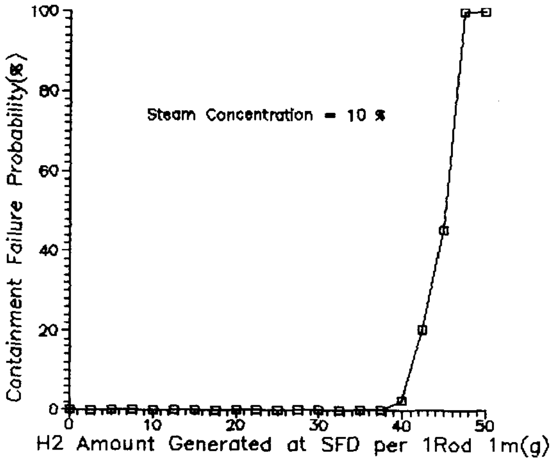

Fig. 12. Effect of SFD on CF

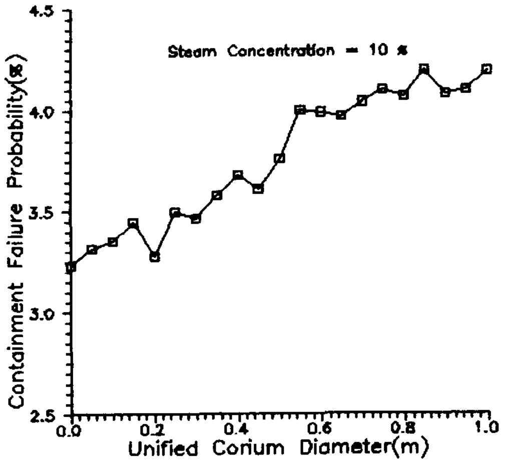

Fig. 13. Effect of Corium Diameter on CF

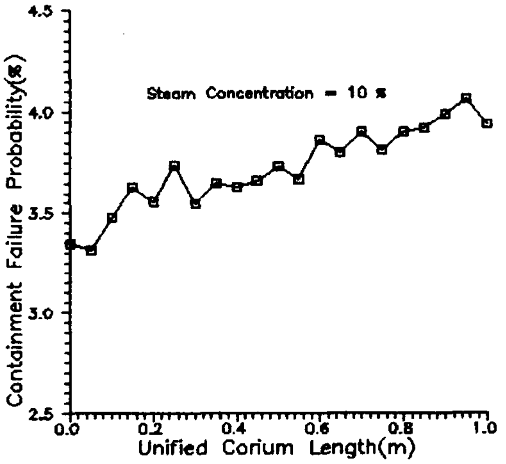

Fig. 14. Effect of Corium Length on CF

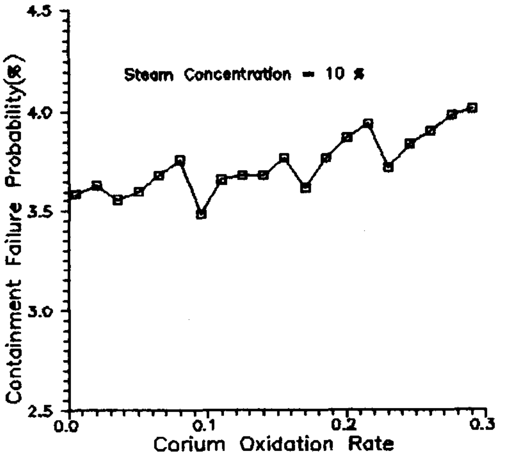

Fig. 15. Effect of Corium Oxidation Rate oin CF

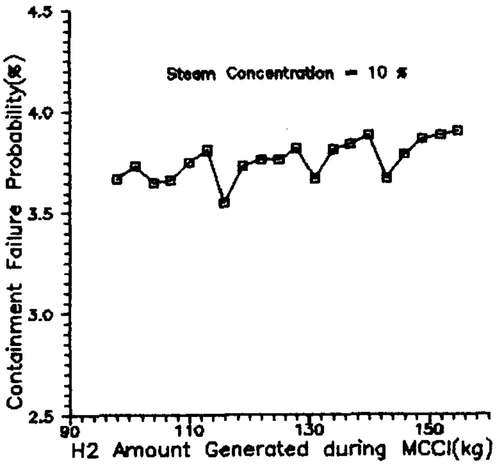

Fig. 16. Effect of MCCI on CF

6. Conclusions

In this study, the containment failure probability is calculated with the Monte Carlo method, and the analytical probability distribution functions are constructed using the statistical treatment method. The calculations are performed for Kori unit 2, and the sensitivity studies on input variables are also performed.

The calculation model has some limits as following; the amount of steam is not calculated but given externally, the ignition phenomena are not considered, a current accident sequence is limited to a low pressure sequence, the correlation, Eq.(8), is not always applicable because it is based upon Zion plant PRA, and hydrogen generation during MCCI is limited for several hours. These problems should be overcome by more study, and before that, the data involved in each phenomenon must be added up.

References

1. 이광형, 오길록 공저, "퍼지이론 및 응용", 홍릉과학출판사
2. S.S. Shapiro, "Statistical Modeling Techniques",

Marcel Dekker, Inc. (1981)

3. M.P. Sherman, "Hydrogen Combustion in Nuclear Plant Accidents and Associated Containment Loads", *Nuclear Engineering and Design*, **82**, 13−24 (1984)
4. M.J. Bird, "An Experimental Study of Scaling in Core Melt/Water Interactions," The American Society of Mechanical Engineers, 345E. 47 St., New York, N.Y. 10017
5. M.L. Corradini, D.E. Mitchell, and N.A. Evans, "Hydrogen Generation during a Core Melt-Coolant Interaction," SAND 83−0779c
6. R.P. Prior, P.N. Kirby, R.J. Lutz, Jr., "Severe Accident Analysis of a 1300 MWe PWR to Address the Hydrogen Issue," *Nuclear Engineering and Design*, **130**, pp. 51−58 (1991)
7. Min Lee and Chen Tsung Fan, "Containment Pressurization and Burning of Combustible Gases in a Large, Dry PWR Containment during a Station Blackout Sequence," *Nuclear Technology*, **99**, pp. 43−57 (1992)
8. L.B. Thompson, J.J. Haugh, and R.G. Zalosh, "Hydrogen combustion and control in Nuclear Reactor Containment Building," *Nuclear Safety*, **25**, No. 3 (1984)
9. 박군철 외, "중대사고 분석용 DATA생산/전산체계화 및 구조특성분석 연구", 서울대학교, KINS/HR−019 (1992)
10. 박군철 외, "원자력발전소 중대사고시 증기폭발에 관한 연구," 원자력발전소 중대사고에 관한 연구, 서울대학교, KOSEF 90−0700−02 (1993)
11. "System 80^+ IPE 보고서", CESSAR
12. M. Berman, D.V. Swenson and A.J. Wickett, "An Uncertainty Study of PWR Steam Explosion", NUREG/CR−3369, SAND 83−1438
13. 박군철외, "Monte Carlo 법을 사용한 격납용기의 건전성에 영향을 미치는 Parameters의 불확실성 및 민감도분석", 서울대학교, KINS/HR−091(1993)