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The Plant-specific Impact of Different Pressurization Rates in the Probabilistic Estimation of Containment Failure Modes

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Abstract

The explicit consideration of different pressurization rates in estimating the probabilities of containment failure modes has a profound effect on the confidence of containment performance evaluation that is so critical for risk assessment of nuclear power plants. Except for the sophisticated NUREG-1150 study, many of the recent containment performance analyses (through Level 2 PSAs or IPE back-end analyses) did not take into account an explicit distinction between slow and fast pressurization in their analyses. A careful investigation of both approaches shows that many of the approaches adopted in the recent containment performance analyses exactly correspond to the NUREG-1150 approach for the prediction of containment failure mode probabilities in the presence of fast pressurization. As a result, it was expected that the existing containment performance analysis results would be subjected to greater or less conservatism in light of the ultimate failure mode of the containment. The main purpose of this paper is to assess potential conservatism of a plant-specific containment performance analysis result in light of containment failure mode probabilities.

Key Words : level 2 PSA/IPE, containment performance, slow and fast pressurizations, containment failure modes & probabilities, plant-specific impact

1. Introduction

For the purpose of containment performance analysis, the Level 2 probabilistic safety assessment (PSA) or Individual Plant Examinations (IPE) back-end analyses take into account a range of potential severe accident progressions that can arise from different core damage accident sequences and some of the physical processes that take place in severe accidents can only be quantified with a limited degree of certainty. Of them, significant uncertainties impacting on the result of Level 2 PSA [1] come from magnitude of pressure loads to the containment and their types (quasi-static or dynamic), and potential containment failure modes (leak, rupture or catastrophic failures). Typical criteria of different failure sizes and timings are given elsewhere [2-4]. Then, a different combination of these uncertainties gives rise to different accident progression possibilities that result in different order of magnitude predictions for leakage rate of radioactive nuclides to the environment, and the consequences and risks associated with a severe accident. Obviously the source term release fraction that depends highly on the time and mode of containment failure will be quite different for each of these combinations.

For risk purposes of nuclear power plants, containment is considered to have failed to perform its function when the leak rate of fission products to the environment is substantial. Whether the structural response of the containment to the internal pressure loads is subjected to these different failure modes, is determined by the rate of pressurization as well as the magnitude of the pressure loads. Especially for concrete containments, the explicit consideration of different pressurization rates is essential in the characterization of containment performance, since they may have a significant influence upon determining the ultimate mode of containment failure [3,4].

For example, where gradual containment pressurization results in containment breach by leakage, the pressure relief associated with the leak prevents further pressurization and, thus, precludes more severe modes (i.e., rupture or catastrophic rupture) of containment failure. For rapid pressure rises, however, an induced leak would not preclude continued pressurization of the containment, and therefore, a more severe failure of the containment building could ultimately result. As a result, the leak probability reduces relative to the rupture probabilities as it marches through higher and higher pressures. Hence, while the distinction between gradual and rapid pressure rises will not influence the pressure at which failure first occurs, it may influence the ultimate severity of the failure. Even though the probability of rapid pressurization may be much lower than the one of a quasi-static condition, this issue is important, since rapid pressurizations are the accident sequences responsible for the higher consequence events (e.g., rupture or catastrophic rupture). Of course, for such dynamic loading there is a lack of consensual agreement among key aspects of containment overpressure behavior, particularly the definition of failure. While the existing containment performance analyses [3-4, 5-7] assumed that all failure modes are measured by the same input parameter (i.e., peak pressure), for example, the peak pressure may not be the appropriate forcing function for containment failure [4].

On the other hand, a careful investigation between the sophisticated NUREG-1150 study [3,8] and the recent containment performance analyses [5-7] shows that the recent containment performance analysis approaches exactly correspond to the NUREG-1150 approach for the prediction of containment failure mode probabilities in the presence of fast pressurization. As a result, it was expected that the recent containment performance analysis results might be subjected to greater or less conservatism in light of the ultimate failure mode of the containment. The main purpose of this paper is to assess potential conservatism of a representative plant-specific containment performance analysis result (more specifically the Korean Standard Nuclear Power Plant UCN 3&4) [6], in light of containment failure mode probabilities. In the present assessment, containment fragility curves obtained in the presence of slow pressurization are basically used to predict containment failure mode probabilities for both slow and fast pressurization rates. Whereas, answering the question on how to characterize containment failure modes and how the containment fragility curves for each containment failure mode are derived is beyond the context of this paper and the underlying approaches can be found in References [2,4].

2. Two Approaches for Containment Performance Analysis

In the probabilistic safety assessments of nuclear power plants, there are two distinctive approaches that have been used to predict probabilities for three containment failure modes (i.e., leak, rupture, and catastrophic rupture): one is for the NUREG-1150 approach, and another for recent containment performance analyses. While the first approach is an explicit consideration of slow and fast pressurization within the containment, there is no discrimination in the second approach. Basically, both approaches utilize probabilistic information for containment failure modes that were obtained in the presence of a slow pressure rise.

2.1. Characterization of Pressurization Rate

The two following types of pressurization rate have been typically taken into account for nuclear power plant risk assessment [3,4]:

- Slow (or quasi-static) pressurization is defined as the pressure rise that is slow compared to the time it takes a leak to depressurize the containment. This type of pressure load stems from gradual production of steam and non-condensable gases through the interaction of molten core material with the concrete floor beneath the reactor vessel. This pressurization process could last from several hours to several days, depending on accident-specific factors such as the availability of water in the containment and the operability of the engineered safety features;
- Rapid (or dynamic) pressurization is defined as the pressure rise that is fast compared to the time it takes a leak to depressurize the containment, and this type of pressure load is fast with respect to thermodynamic time constants, but quasi-static with respect to structural response. The high-pressure expulsion of molten material from the vessel (e.g., high pressure melt ejection), the detonation or deflagration of combustible gases (e.g., hydrogen burn), and the rapid generation of steam through the interaction of molten fuel with water in the containment (e.g., ex-vessel steam explosions) are phenomena that could lead to the rapid pressure rises (i.e., impulse pressure loads). Interactions between the dynamic pressure wave resulting from these phenomena and the containment structures could significantly affect the peak impulse. While the ex-vessel steam explosion pressure rise is always assumed to be rapid, hydrogen burns are not always expected to qualify as "rapid" except for the case of detonation, but to be conservative they are assumed to be "rapid".

As shown in the NUREG-1150 study [3], the probability of rapid pressurization may be much lower than the one of a quasi-static condition during a severe accident in nuclear power plants.

2.2. The NUREG-1150 Approach

The NUREG-1150 containment performance analyses were conducted using plant-specific accident progression event trees (APETs) [3,8]. These consist of a series of questions about physical phenomena (static or dynamic) affecting the progression of the accident and three containment failure modes (leak, rupture, and catastrophic rupture) characterizing the source term risks. Regarding the containment failure prediction, the APET analysis method requires estimation of the conditional probabilities of each of the failure modes given the occurrence of failure, with explicit consideration of slow and fast pressurization. For a quasi-static pressure rise, the NUREG-1150 experts were asked to construct "failure probability" curves and conditional probability curves of leak versus rupture and catastrophic rupture. Then, the estimated probability of failure and probability of failure mode are treated in two distinct ways:

- The question of probability of failure is asked from a containment performance standpoint, irrespective of leakage, rupture, or catastrophic rupture designation. If the containment fails to hold pressure, it has failed; the definition is binary;
- The question of failure mode is dealt with entirely on the basis of conditional probability. The conditional probabilities for each failure mode are breakdown of probability between leakage, rupture, and catastrophic rupture, given that a failure occurs. At low pressures, the leak failure becomes the dominant mode with a conditional probability of 1.0. At high pressures, only reachable by the rapid pressurization that may "leap-frog" over the leak mode, rupture conditional probability eventually surpasses leakage.

When the expert judgment elicitation process was made to obtain probabilistic information for the containment performance, the structural behavior discussions for a dynamic pressurization case was non-quantitative because little work has been done to experimentally or analytically investigate containment subjected to steam explosions or hydrogen deflagrations. Instead, an extension for the probabilistic information obtained from a static analysis was made to reflect the impact of the fast pressurization on the containment behavior. In the presence of a fast pressure rise, for example, the bulk of the failures are initially considered as leaks, and for them the pressure rises to the next step of higher-pressure value, where again a fraction is converted to rupture or catastrophic rupture. The process stops at the load pressure under consideration. The leak fraction remaining at that pressure is the total leak probability. The rupture probability is the total of all the rupture fractions at all the steps, and similarly for catastrophic rupture. Once the total conditional probabilities for failure mode are computed, the random number is used to choose the failure mode as in the slow pressure rise case. This is necessary because of the definition of the failure mode probabilities in the expert elicitation process of NUREG-1150.

2.3. The UCN 3&4 Approach

Most Level 2 PSAs that have been carried out in Korea (including the UCN 3&4 Level 2 PSA[6]), employ a concept of a small and general containment phenomenological event tree (CPET) for accident progression analysis, and of the detailed large supporting event tree (DSET) for its quantification [9,10]. The CPET is used to calculate the failure probability of the containment considering systematically every phenomenon of the severe accidents occurring within the containment from the core damage to the containment failure. Thus, the input of CPET is plant damage conditions (given in the form of plant damage state, PDS) and the output is the containment failure mode and probability. The approach for containment or accident progression analysis produces not only a traceable and understandable model of containment failure mechanisms but also enough details to analyze important factors for containment performance of severe accidents. Then, containment pressure buildup is assigned to the summary events by which the containment failure probabilities for each failure mode are evaluated through a comparison with the corresponding containment fragility curves. Two types of containment failure modes (i.e., leak and rupture) are defined in the UCN 3&4 Level 2 PSA. The containment fragility curves are given in the form of independent distributions for one another. However, the impact of different pressurization rates (i.e., quasi-static and fast pressure rise) was not explicitly taken into account in the quantification process of the containment failure mode probabilities.

2.4. Different Formulations for the Prediction of Containment Failure Modes

In most severe nuclear accident sequences, the failure of a containment structure is determined by two factors: (a) the magnitude of the pressure loads imposed to the containment, and (b) the response of the containment structure to those pressure loads. Then, the containment failure probabilities are determined by the magnitude of pressure load imposed to the containment, regardless of a slow or fast pressure rise, but the presence of a fast pressure rise can cause additional transition from a leak failure mode to a rupture failure (or catastrophic rupture) mode. Here, typically two cases of formulations that have been used for the prediction of containment failure mode probabilities are summarized, which reflect available probabilistic information for containment failure modes.

Case 1 : A joint distribution (a failure distribution and conditional probabilities for each failure mode) for containment failure pressure and failure modes (f_i, $i=1,2,3$) is available, and all of them are obtained in the presence of a slow pressure rise. This condition was utilized in the NUREG-1150 study [3,8,11].

The NUREG-1150 Approach for a Slow Pressure Rise

For a slow pressure rise, the NUREG-1150 assumes that a leak (i.e., mode 1) during a slow pressure will arrest the pressure rise, and thus the occurrence of a leak precludes the subsequent occurrence of rupture (i.e., mode 2) or catastrophic rupture (i.e., mode 3). For a fixed pressure load p_l, the final probability $P_s(m_i \mid p_l)$ of the containment failure by the slow pressure rise is computed by combining the conditional probabilities $G_s(m_i \mid p)$ of slow failure modes with the distribution $f_s(p)$ for containment failure pressure being considered with the formula,

$$P_s(m_i \mid p_l) = \int_0^{p_l} G_s(m_i \mid p) f_s(p) dp \qquad (1.1)$$

Then, the total failure probability is given by

$$P_{s,tot}(p_l) = [\sum_{j=1}^{3} P_s(m_j \mid p_l)] = \int_0^{p_l} f_s(p)dp \, . \qquad (2.1)$$

The NUREG-1150 Approach for a Fast Pressure Rise

For a fast pressure rise, the NUREG-1150 assumes that the occurrence of a leak (mode 1) in the presence of a fast pressure rise has no effect on subsequent pressure rise of failures (mode 1, 2 or 3) associated with that pressure. This assumption is based on the belief that a leak will not arrest the pressure rise, with the result that additional failures by leak, rupture or catastrophic rupture are possible. Also, this assumption is more conservative than the belief that the occurrence of a leak during a fast pressure rise precludes the subsequent occurrence of rupture or catastrophic rupture as assumed in the case of slow pressure rise. For the load pressure p_l, a leak failure occurs at a pressure $p_l < p$. Then the mathematical formulation of the preceding assumption is that the probability $P(p_l, p)$of an additional failure (mode 1, 2 or 3) as the pressure continues to rise above p_l is given by

$$P(p_l, p) = \int_{pl}^{p} f_s(\tau) / [1 - F_s(p_l)] d\tau \qquad (3.1)$$

According to Helton et al. [11], the probability $P_f(m_i \mid p_l, p)$ that for a fixed load p_l an additional containment failure occurs by m_i as the pressure continues to rise above p is given by

$$P_f(m_1 \mid p_l, p) = \left\{ \frac{1 - F_s(p)}{1 - F_s(p_l)} \right\} \left\{ \exp\left[\int_{p_l}^{p} u(\tau) d\tau \right] - 1 \right\}, \qquad (4.1)$$
$$u(\tau) = \frac{G_s(m_1 \mid \tau) f_s(\tau)}{1 - F_s(p_l)}$$

$$P_f(m_i \mid_{2,3} p_l, p) = \int_{p_l}^{p} \frac{G_s(m_i \mid \tau)}{1 - F_s(p_l)} \exp\left[\int_{p_l}^{\tau} u(\tau_1) d\tau_1 \right] d\tau \qquad (4.2)$$

Based on the above formulation, a discrete form [3,11] can be obtained for the conditional probability $G_f(m_i \mid p_r, p_l)$ that the containment will fail by failure mode m_i given that it has failed at p_r due to fast pressurization resulting from a pressure load p_l.

Case 2: Independent containment failure distributions for two or three failure modes are given in the form of probability density functions, and all of them are obtained in the presence of a slow pressure rise.

The UCN 3&4 Approach

Originally, the explicit consideration of different pressurization rates in estimating the probabilities of containment failure was not made for the UCN 3&4 containment performance analysis[6]. Instead, the study took the following assumptions: a failure mode 1 (i.e., leak) is considered just for the non-occurrence of larger modes 2 or 3; mode 2 (i.e., rupture) can occur for the non-occurrence of mode 3 (i.e., catastrophic rupture), of which failure first occurs; but mode 3 can occur regardless of the occurrence of mode 1 or 2, of which failure first occurs. For a fixed pressure load p_l, the final probability $P(m_i \mid p_l)$ by each failure mode is then computed by combining the probabilities $F_i(p_l)$ of each failure mode m_i being considered with the formula,

$$P(m_i \mid p_l) = F_i(p_l) \cdot \prod_{j>i}^{3} (1 - F_j(p_l)), \qquad (5.1)$$
$$F_i(p_l) = \int_0^{p_l} f_i(p) dp$$

Then, the total failure probability is given by

$$P_{tot}(p_l) = \sum_{j=1}^{3} P(m_j \mid p_l) = 1 - \prod_{j=1}^{3} [1 - F_j(p_l)] \qquad (5.2)$$

In the above formula, $F_i(p_l)$ express independent probabilities (or cumulative probabilities) for the i-th failure mode m_i, and $f_i(p)$ is the probability density function for the failure mode m_i.

The Helton et al.' Approach

On the other hand, Helton et al. [11] took an assumption that for a slow pressure rise the containment fails by whichever failure mode occurs at the lowest pressure. By the assumption, when three independent distributions are obtained for the slow pressure rise, the probability that failure will occur by mode m_i is given by

$$P_s(m_i \mid p_l) =$$
$$\int_0^{p_l} \int_{\tau_i}^{\infty} \int_{\tau_i}^{\infty} f_{s,i}(\tau_i) f_{s,j}(\tau_j) f_{s,k}(\tau_k) d\tau_j d\tau_k d\tau_i, \quad i \neq j, k \qquad (6.1)$$

$$P_s(m_i \mid p_l) =$$
$$\int_0^{p_l} f_{s,i}(p)[1 - F_{s,j}(p)][1 - F_{s,k}(p)] dp, \quad i \neq j, k \qquad (6.2)$$

For fast pressure rise, they take an assumption that mode 2 or 3 (i.e., rupture or catastrophic rupture) can follow mode 1 (i.e., leak) but mode 1 failure cannot follow mode 2 or 3 failure. In that case, the probability that failure will occur by mode m_i is given by

$$P_f(m_1 \mid p_l) = F_{s,1}(p_l) \cdot \prod_{j=2}^{3} [1 - F_{s,j}(p_l)] \qquad (7.1)$$

$$P_f(m_i \mid_{2,3} p_l) = \int_0^{p_l} f_{s,i}(p)[1 - F_{s,j}(p)]dp\,, \quad i \neq j \qquad (7.2)$$

For failure mode 1, the formulation (5.1) gives the same result as formulation (7.1), but not for the other failure modes as given in the above formulations (5.1) and (7.2). However, it is also noted that when two failure modes (i.e., leak and rupture) are just taken into account for the containment performance analysis, there is no difference between containment failure probabilities for the two failure modes. According to Helton et al. [11], the above formulations for slow pressurization (i.e., Equation (6.2)) and fast pressurization (i.e., Equations (7.1) and (7.2)) provide the same results as the NUREG-1150 approaches (i.e., Equation (1.1) for slow pressurization, and Equations (4.1) and (4.2) for fast pressurization) for the corresponding conditions, respectively. As a result, it is concluded that the formulations for the prediction of containment failure mode probabilities in the UCN 3&4 containment performance analysis exactly corresponds to the NUREG-1150 approach for the prediction of containment failure probabilities in the presence of fast pressurization.

3. Plant-specific Impact of Different Pressurization Rates

In order to assess quantitatively the impact of two different pressurization rates (slow and fast) on the containment failure mode probabilities, the two distinctive formulations above for fast and slow pressurization were applied to the UCN 3&4 containment performance analysis, i.e., Equation (5.1) for the case of a fast pressure rise, and Equation (6.2) for the case of a slow pressure rise.

3.1. The UCN 3&4 Prediction of Containment Peak Pressure and Failure Probabilities

In the UCN 3&4 containment performance analysis [6], a computer code MAAP4 was used to evaluate the pressure loads expected at the early and late phases of severe accident progression, and the NUREG-1150 results of similar plants or expert judgments were used for the quantification of the important phenomena which can not be calculated by the MAAP4 code. The early containment phase was defined as failure of containment shortly before, at or just after vessel breach and the late containment phase was defined as failure of containment after 3 days from the accident's initiation. The early containment failure can primarily come from a combination of energetic processes and events that may occur at the reactor vessel breach (i.e., fast pressure rise), including high pressure melt ejection, hydrogen combustion, and steam explosions in the cavity. Of course, the resulting pressure buildup may be greater or less different for accident sequences. The ex-vessel steam explosion was defined so that the occurrence of the event results in a direct rupture mode failure. The late containment failure was primarily caused by long-term pressurization by steam and non-condensable gases (i.e., slow pressure rise) and the possibility of late hydrogen burn was also considered for relevant accident sequences (i.e., fast pressure rise). The peak containment pressure expected at each phase of potential containment failure (i.e., early and late) was evaluated for every

Table 1. Containment Fragility Curves for Leak and Rupture Modes (UCN 3&4)

Categorization	Leak mode (f_{lk})	Rupture mode (f_{rp})
Failure mode probability distribution function: Lognormal type*	p_m : 169 psig β : 0.15	p_m : 178 psig β : 0.13
	Containment design pressure: 54 psig	
Failure location/type	Equipment hatch ring/ The liner plate tearing	Containment hoop failure due to membrane stresses in the cylindrical wall
Nominal break size	0.04 ft^2 (6 in^2)	Not clearly defined Approximately 1.0 ~ 2.0 ft^2
Failure mode definition (for quasi-static loads)	A containment breach that would arrest a gradual pressure buildup, but would not result in containment depressurization in less than 2 hours	A containment breach that would arrest a gradual pressure buildup and would depressurize the containment within 2 hours
Containment Type	A large-dry, pre-stressed, reinforced concrete in the shape of a cylindrical with a hemispherical dome	

Note * $F(p)=\frac{1}{\beta\sqrt{2\pi}}\int_0^p \exp[-\frac{1}{2}(\frac{\ln x-\ln p_m}{\beta})^2]/xdx$, p_m = median, β =log standard deviation

$$F(p)=1/\sqrt{\pi}\int_{-\infty}^{z}\exp[-u^2]du \;=\; [1-erf\,|z|]/2, \text{ if } x<p_m,\; z=\ln(x/p_m)/\sqrt{2}/\beta$$

$$[1-erf(z)]/2, \text{ if } x>p_m,\; erf(z) = \text{error function}$$

accident sequence. Finally, Equation (5.1) for the case of a fast pressure rise was used to calculate the containment failure mode probabilities, regardless of the pressurization rate. TABLE 1 shows the definitions of two containment failure modes (leak and rupture) and the corresponding containment fragility curves that were utilized for the UCN 3&4 containment performance analysis.

On the other hand, when the foregoing accident scenarios employed in the UCN 3&4 CPET/DSET are explicitly treated for slow and fast pressurization, the resulting total failure probability for rupture mode will be placed in between the one obtained from an assumption that all accident scenarios are subjected to slow pressurization and the one obtained from an assumption that all accident scenarios are subjected to fast pressurization, vice-versa for the case of leak mode failure. That is,

$$\sum_{i=slow}P_{s,i}(m_2)\le \sum_{i=slow,fast}P_{r,i}(m_2)\le \sum_{i=fast}P_{f,i}(m_2) \quad (8.1)$$

for rupture mode

$$\sum_{i=fast}P_{f,i}(m_1)\le \sum_{i=slow,fast}P_{r,i}(m_1)\le \sum_{i=slow}P_{s,i}(m_1) \quad (8.2)$$

for leak mode

where,

$P_{s,i}(m_2)$ = rupture mode failure probability for the i-th scenario when all accident scenarios employed in the CPET/DSET are assumed to follow slow pressurization (optimistic in view of rupture failure);

Table 2 Joint Containment Failure Probabilities for Leak and Rupture Modes (UCN 3&4)

Pressure	Slow Pressure Rise			Fast Pressure Rise		
Load (psig)	Total	Leak	Rupture	Total	Leak	Rupture
66.0[1]	0.0	0.0	0.0	0.0	0.0	0.0
88.0	6.827E-6[7]	6.797E-6	3.001E-8	6.825E-6	6.795E-6	2.980E-8
117.0	7.730E-3	7.109E-3	6.209E-4	7.733E-3	7.109E-3	6.239E-4
127.0[2]	3.297E-2	2.834E-2	4.622E-3	3.298E-2	2.827E-2	4.704E-3
150.0[3]	2.871E-1	2.052E-1	8.194E-2	2.872E-1	1.932E-1	9.400E-2
169.0[4]	6.723E-1	4.317E-1	2.406E-1	6.725E-1	3.275E-1	3.449E-1
178.0[5]	8.175E-1	5.101E-1	3.074E-1	8.176E-1	3.176E-1	5.000E-1
200.0	9.758E-1	5.913E-1	3.845E-1	9.758E-1	1.608E-1	8.150E-1
250.0[6]	1.000E0	6.031E-1	3.969E-1	1.000E0	4.469E-3	9.955E-1

Note Superscript 1: Low limit for the hydrogen-burn pressure during the early accident phase
Superscripts 2,3: Maximum pressure for the early and late accident phases, respectively
Superscripts 4,5: Median pressures for the leak and rupture failure, respectively
Superscript 6: The criterion for the ex-vessel steam explosion was assumed to be the rupture failure
Superscript 7: Read as 6.827×10^{-6}

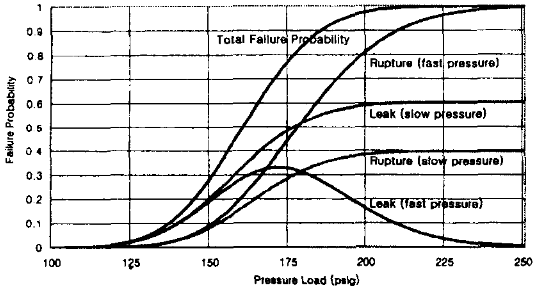
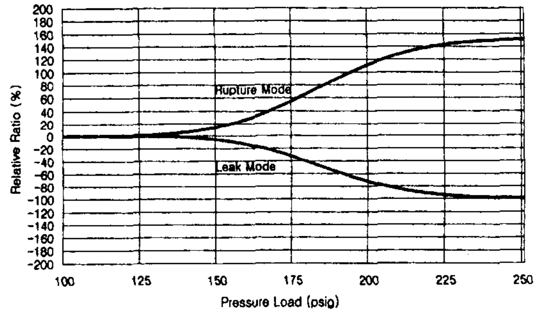


Fig. 1. Variation of Containment Failure Mode Probabilities (Slow and Fast Pressures) (Joint Containment Failure Probabilities for Leak and Rupture Modes)

$P_{r,i}(m_2)$ = rupture mode failure probability for the i-th scenario when all accident scenarios employed in the CPET/DSET are assumed to follow their definition for slow and fast pressurizations (realistic in view of rupture failure);

$P_{f,i}(m_2)$ = rupture mode failure probability for the i-th scenario when all accident scenarios employed in the CPET/DSET are assumed to follow fast pressurization (pessimistic in view of rupture failure).



Relative Ratio (%) = $[CFP(p_{slow}) - CFP(p_{fast})]/CFP(p_{slow}) \times 100$

Fig. 2. Percentile Variation of Failure Mode Probabilities Between Slow and Fast Pressures

Speaking once more, the two relationships above show that the relative magnitude of probabilities of different containment failure modes (i.e., leak and rupture) is substantially affected by the type of severe accident scenarios employed in the CPET/DSET (i.e., slow and fast pressurizations) as well as the magnitude of pressure loads imposed to the containment.

3.2. The Impact of Different Pressurization Rate on the Failure Mode Probabilities

As a result of the UCN 3&4 containment performance analysis, typical peak containment pressures were evaluated as given in the first column of TABLE 2. Then the other columns of TABLE 2 give the containment failure mode probabilities with an assumption of slow and fast pressure rises. As shown in the table, the containment failure probabilities are the same for both pressurization rates, but as the containment pressure increases the rupture mode probabilities increase in the case of fast pressure pressurization. In similar fashion, as the containment pressure increases the leak mode probabilities decrease due to a partial transition of leak probability to the rupture probability. For pressure less than the peak pressure for the late accident progression phase (150 psig), however, the impact of two different pressurization rates on the failure mode probabilities are negligible and the peak pressures for all accident sequences that were evaluated in the UCN 3&4 containment performance analysis did not exceed this pressure. In the case of UCN 3&4, this result means that conservatism due to the application of fast pressurization formula to all accident sequences is negligible and thus there is no need for the discrimination between fast and slow pressurizations. In other words, a substantial impact of different pressurization rates is expected for the peak pressure exceeding the median value of the leak mode failure distribution. Figures 1 and 2 more specifically justify the foregoing conclusion. For the fast pressurization rate, the increasing rate of the rupture mode probability is much more rapid than the decreasing rate of the corresponding leak mode probability. Whereas, for the slow pressurization rate both leak and rupture mode probabilities slowly increase as the containment peak pressure increases.

4. Concluding Remarks

Except for the sophisticated NUREG-1150 study, many of the recent containment performance analyses have not taken into account an explicit distinction between slow and fast pressurization in their analyses. From this point of view, a plant-specific impact of different pressurization rates (slow and fast) on the prediction of containment failure mode probabilities has been assessed in this paper, more specifically the Korean Standard Nuclear Power Plant UCN 3&4. Major findings drawn from this study are as follows,

- As mentioned previously, many containment performance analyses performed recently, follow an approach similar with the UCN 3&4 Level 2 PSA presented in this paper, in which all accident sequences leading to containment failures have been implicitly treated as fast pressurization sequences according to the analogy with the NUREG-1150 fast pressurization approach. For both cases, containment failure due to rapid pressurization is treated as if the load is statistically applied to the containment. The probability of rapid pressurization may be much lower than the one of a quasi-static condition during the severe accident of nuclear power plants.
- This study provides the fact that the substantial impact of the explicit treatment for different pressurization rates on the containment failure mode probabilities reveals that when the containment peak pressure approaches or is greater than the median pressure of the containment fragility curves (more specifically for leak mode failure). Otherwise, its impact is negligible as shown in the plant-specific investigation. For high containment capacity, the impact on the containment failure mode

probabilities is relatively less even when the containment peak pressure becomes high.

- This study has not taken into account potential uncertainty for peak pressure. When uncertainties for the peak pressure are considered, the impact of different pressurization rates needs to be explicitly analyzed because of the potential possibility for the existence of higher containment pressures. The potential impact of uncertainties that would be addressed in the peak pressure can be viewed from the present plant-specific analysis results.

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