A Probabilistic Approach to Quantifying Uncertainties in the In-vessel Steam Explosion During Severe Accidents at a Nuclear Power Plant

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Abstract

The uncertainty analysis for the in-vessel steam explosion during severe accidents at a nuclear power plant is performed using a probabilistic approach. This approach consists of four steps; 1) screening, 2) quantification of uncertainty, 3) propagation of uncertainty, and 4) output analysis. And the specific methods which satisfy the sub-objectives of each step are prepared and presented. Compared with existing ones, the unique feature of this approach is the improved estimation of uncertainties through quantification, which ensures the defensibility of the resultant failure probability distributions. Using this approach, the containment failure probability due to in-vessel steam explosion is calculated. The results of analysis show that 1) pour diameter is the most dominant factor and slug condensed phase fraction is the least and 2) fraction of core molten is the second most dominant factor, which is identified as distinct feature of this study as compared with previous studies.

1. INTRODUCTION

Steam explosion is a physical process that may occur when a high-temperature melt contacts water. The thermal energy content in the melt may be converted into mechanical work, which is done against the surroundings on an explosive time scale. Since the accident at Three Mile Island (TMI), the continuing efforts are put into to understand the mechanism of steam explosion and its mechanistic connection to containment failure (called α-mode failure), to improve the quantitative handling of both within the context of probabilistic safety assessment (PSA).

A probabilistic model is generally used to synthesize constituent parameters into the likelihood of the overall phenomenon in question. In case of limited amount of actual data, the key element of probabilistic approach is to subjectively quantify the degree of belief of a given parameter value on the basis of experimental data and theoretical evaluations.[1] In this process, it is natural that uncertainties due to lack of knowledge for a parameter of interest are tracked. To obtain better estimates, it is necessary to identify and systematically analyze these uncertainties. However, there is no generally accepted system of identifying and analysing the uncertainties which are inherent in unknown parameters.

In this study, a probabilistic method is developed to analyze the parameter uncertainties, and applied to the analysis of in-vessel steam-explosion in a hypothetical, unmitigated, low-pressure, core-melt scenario.

2. METHODOLOGY

2.1 Analysis Model of Steam Explosion

The model is based on an analysis model to α-mode failure as given in NUREG/CR-3369.[2] This model is restricted to low-pressure scenario and excludes multiple explosions. For this study it is assumed that except for five parameters (fraction of core molten, pour diameter, pour length, conversion ratio and condensed phase fraction), all parameters of the model are causally related. That is, the whole sequence of events is represented as a combination of such causal relationships. The proposed model is illustrated in Figure 1. And based on the model, a

simulation code, STEACO (STeam Explosion Analysis COde), is prepared.

2.2 Uncertainty Analysis Procedure

The uncertainty analysis procedure consists four step; screening, quantification of uncertainty, propagation of uncertainty, and output analysis.[3]

2.2.1 Screening

The screening is the process of determining the input parameters which are influential to the output results and reducing the number of input parameters for uncertainty analyses. For screening, the regression-based sensitivity technique with Latin hypercube sampling (LHS)[4] is employed. This technique mainly consists of two steps. The first step is the attachment of tentative probability distributions to input parameters, which are subjectively assessed to have potential impact upon the resultant output. These distributions are tentative in a sense that they are not necessarily adopted in the final characterization of uncertainty. Finite probabilities are attached to all potentially realizable (in the physical sense) ranges of input parameter. The uniform or loguniform distributions are selected for the tentative attachment. The latter selection is for the situation that the parameter uncertainty encompasses several orders of magnitude. The second step is the generation of Latin hypercube samples of input parameter level combinations and the output of the preliminary calculation are analyzed using the regression technique.

Standardized regression coefficient (SRC) and partial correlation coefficient (PCC) are used in evaluating importance measures for screening.[5] If the absolute value of PCC exceeds a prescribed value, the paired variables are sufficiently closely correlated and they will be considered further. Otherwise, they are considered to be insensitive and eliminated from further evaluation.

2.2.2 Quantification of Uncertainties

Uncertainties are treated as random variables with appropriate probability density functions (pdf's). There have been various approaches in treating uncertainties. Each approach, however, falls broadly into one of two categories, namely, those associated with concepts of statistical variability[6] and those that have a subjective basis.[7] As previously mentioned, in case of limited amount of actual data as the present study, it seems to be natural to rely on the second approach. It is, however, sometimes argued that the resultant distributions are unjustifiably structured and are characterized by arbitrariness, inscrutability and, consequently, indefensibility. Therefore, the procedure utilized to formulate distributions should be one chosen both to maximize the transparency and the scrutability of subjectively assessed data directly into the analysis, and to maximize the defensibility of the resultant probability distributions. In this context, Unwin et al.[8] provides with a good guidance in formulating probability distributions. According to Unwin, the constraints on any one distribution are obtained in the form of uncertainty bands; credibility and reasonable uncertainty bands. Given the reasonable uncertainty bands, the resultant distribution is generally of a simple piecewise uniform or piecewise loguniform.[9,10]

2.2.3 Propagation of Uncertainties

The distributed uncertainties of each input parameter propagate through the models and consequently appear as the uncertainties in the output variables. Among various propagation techniques, it is generally recognized that the Monte Carlo method appears to offer an effective way of propagating distributions through physical models, provided that the cost of simulation is not excessive.[11] Also, the LHS rather than random sampling will improve the efficiency of such propagation. Therefore, the LHS is used in the propagation of uncertainties.

2.2.4 Output Analysis

In this stage, the importance ranking of sensitive input parameters and models will be established through an appropriate unit of importance. SRC and PCC may be used as the importance measure. To reduce the results and perform postuncertainty analyses, mathematical relationships are required between the model input and output. These relationships are obtained through stepwise regression and response surface method (RSM),[12] in which the original model is replaced by a simplified surrogate model. Ishigami et al. found that, in general, one of the most successful techniques is the response surface regression approach, especially when the data are limited.[10]

3. RESULTS

Through screening analysis, five uncertainty parameters are selected which are regarded as most influencing on the containment integrity due to in-vessel steam explosion. And from the NUREG/CR-3369, the credibility and reasonable uncertainty ranges for these parameters are obtained presented in Table 1. The range between lower and upper value used in NUREG/CR-3369 is taken as credibility range and the range which is called middle region in NUREG/CR-3369 as reasonable range. The pdf's obtained by applying these constraints are presented Table 2. For uncertainty propagation, 200 input data set for five uncertainty parameters are sampled using LHS. Except five uncertain parameters, other parameters are assumed to be constant. These input values are obtained from NUREG/CR-3369. The resultant estimations are compared with the ones of NUREG/CR-3369 in Table 3.

The final result is the containment failure probability. However, this result is inappropriate for an output sensitivity analysis because it is difficult to describe this result as output distribution. Therefore, as an alternative, residual slug energy after dissipation in upper internal structure (UIS), which may be thought to have indirectly influence on the containment failure, is employed as the analysis target. The response surface, which relates five uncertainty parameters to residual slug energy after dissipation in UIS, E_r, is expressed of the form;

$$\widehat{E_r} = 0.355691\,\widehat{X_{fc}} + 0.462731\,\widehat{X_{pd}} + 0.263490\,\widehat{X_{pl}}$$

$$+\,0.249199\,\widehat{X_{cr}} - 0.176790\,\widehat{X_{sc}}$$

(1)

where, $\widehat{E_r} = \dfrac{E_r - \overline{E_r}}{\sigma_{Er}}$ = standardized residual energy,

$\widehat{X_{fc}} = \dfrac{X_{fc} - \overline{X_{fc}}}{\sigma_{fc}}$ = standardized fraction of core molten,

$\widehat{X_{pd}} = \dfrac{X_{pd} - \overline{X_{pd}}}{\sigma_{pd}}$ = standardized pour diameter,

$\widehat{X_{pl}} = \dfrac{X_{pl} - \overline{X_{pl}}}{\sigma_{pl}}$ = standardized pour length,

$\widehat{X_{cr}} = \dfrac{X_{cr} - \overline{X_{cr}}}{\sigma_{cr}}$ = standardized conversion ration,

$\widehat{X_{sc}} = \dfrac{X_{sc} - \overline{X_{sc}}}{\sigma_{sc}}$ = standardized slug condensed phase volume ratio,

E_r = residual slug energy after dissipation in UIS (J),

$\overline{E_r}$ = mean of residual slug energy after dissipation in UIS,

σ_{Er} = standard deviation of residual slug energy after dissipation in UIS,

$\overline{X_x}$ = mean of each parameter X, and

σ_x = standard deviation of each parameter x.

The distribution of residual slug energy after dissipation, E_r, is estimated using a crude Monte Carlo simulation with the fitted response surface of Equation (1). The results of RSM with trial number, $n=1,000$ in the Monte Carlo simulation are shown in Figure 2. Figure 2 also contains the estimates based on LHS utilizing restricted pairings with $n=200$. From thess calculation, 90% confidence intervals are obtained as follows;

$$LHS\text{-}200 \quad [\,2.30\times10^6, \ 1.53\times10^9], \text{ and}$$
$$RSM\text{-}1,000 \quad [\,5.46\times10^7, \ 1.02\times10^9].$$

The results show that the response surface produces the narrower range than the LHS. This is caused by the difference of sampling scheme between crude Monte Carlo and LHS. The relative importance of five uncertainty parameters to the residual slug energy after dissipation in UIS are summarized in Table 4. As shown in Table 4, pour diameter is the most dominant factor and slug condensed phase fraction is the least.

4. DISCUSSION

This paper describes a probabilistic approach to quantifying uncertainties in the in-vessel steam explosion. This approach consists of four steps; 1) screening, 2) quantification of uncertainty, 3) propagation of uncertainty, and 4) output analysis. And the specific methods which satisfy the sub-objectives of each step are prepared and presented. Compared with existing ones, the unique feature of this approach is the improved estimation of uncertainties through quantification, which ensures the defensibility of the resultant failure probability distributions.

Through this work, it is identified that:
1) The overall probability of α-mode failure is in line with the previous study[2].
2) *Pour diameter is the most dominant factor among five uncertainty parameters and slug condensed phase fraction is the least.*
3) Fraction of core molten is found to be the second most dominant factors as seen in Table 4, which is different from the results of the previous study. Therefore, an intensive further effort is required in this area of study in the future.

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Table 1. Uncertain parameters selected for analysis and those credibility and reasonable uncertainty range

Uncertainty parameter	credibility uncertainty range	reasonable uncertainty range
fraction of core molten (%)	[0, 75]	[25, 50]
pour diameter (m)	[0, 3.4]	[1.13, 2.27]
pour length (m)	[0, 3.0]	[1.0, 2.0]
conversion ratio (%)	[0, 5]	[1.7, 3.3]
slug condensed phase volume fraction (%)	[25, 100]	[50, 75]

Table 2. The pdf for each uncertain paramter

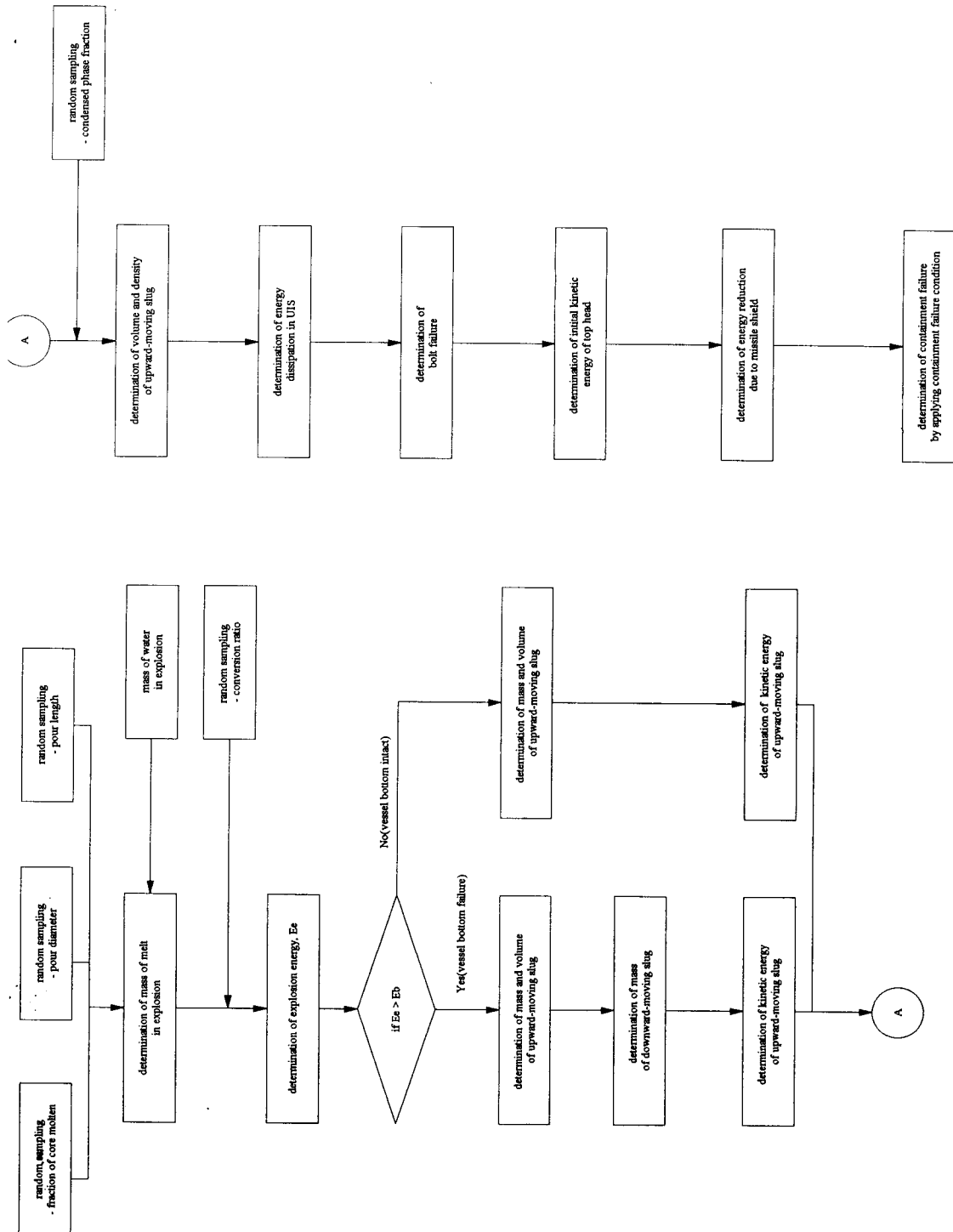| Uncertainty parameter	pdf
fraction of core molten (%)	$p(x) = 0.002$ if $0 \leq x < 25$ $p(x) = 0.036$ if $25 \leq x \leq 50$ $p(x) = 0.002$ if $50 < x \leq 75$
pour diameter (m)	$p(x) = 0.044$ if $0 \leq x < 1.13$ $p(x) = 0.789$ if $1.13 \leq x \leq 2.27$ $p(x) = 0.044$ if $2.27 < x \leq 3.4$
pour length (m)	$p(x) = 0.05$ if $0 \leq x < 1.0$ $p(x) = 0.90$ if $1.0 \leq x \leq 2.0$ $p(x) = 0.05$ if $2.0 < x \leq 3.0$
conversion ratio (%)	$p(x) = 0.029$ if $0 \leq x < 1.7$ $p(x) = 0.563$ if $1.7 \leq x \leq 3.3$ $p(x) = 0.029$ if $3.3 < x \leq 5$
slug condensed phase volume fraction (%)	$p(x) = 0.002$ if $25 \leq x < 50$ $p(x) = 0.036$ if $50 \leq x \leq 75$ $p(x) = 0.002$ if $75 < x \leq 100$

Table 3. The results of STEACO estimation

	NUREG/CR-3369	STEACO
1. Fraction of core molten (%)	37.5	37.3
2. Pour diameter (m)	1.70	1.74
3. Pour length (m)	1.50	1.49
4. Slug condensed phase volume fraction (%)	62.5	64.7
5. Conversion ratio (%)	2.50	2.49
6. Mean explosion energy (MJ)	584	647
7. Mean slug impact energy(MJ)	283	326
8. Mean slug volume (m^3)	31.5	31.8
9. Mean slug mass (1000 kg)	53.1	55.2
10. Vessel bottom failure number	2017	31
11. Bolts failure number	466	6
12. Large missle # V > 50 m/sec	460	6
13. Large missle # V > 90 m/sec	267	4
14. Probability of containment failure	0.0460	0.030

<NOTE>
1) the estimates using crude Monte Calro simulation with n=10,000
2) the estimates using LHS with n=200

Table 4. SRC, PCC and rank of uncertain parameters

Uncertainty parameter	SRC	PCC	RANK
fraction of core moltem	0.356	0.482	2
pour diameter	0.463	0.578	1
pour length	0.263	0.374	3
conversion ration	0.249	0.356	4
slug condensed phase volume faction	-0.177	-0.261	5

determination of containment failure by applying containment failure condition

determination of energy reduction due to missile shield

determination of initial kinetic energy of top head

determination of bolt failure

determination of energy dissipation in UIS

determination of volume and density of upward-moving slug

random sampling
- condensed phase fraction

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random sampling
- pour length

random sampling
- pour diameter

random sampling
- fraction of core molten

mass of water in explosion

random sampling
- conversion ratio

determination of mass of melt in explosion

determination of explosion energy, Ee

if Ee > Eb

No(vessel bottom intact)

Yes(vessel bottom failure)

determination of mass and volume of upward-moving slug

determination of mass and volume of upward-moving slug

determination of mass of downward-moving slug

determination of kinetic energy of upward-moving slug

determination of kinetic energy of upward-moving slug

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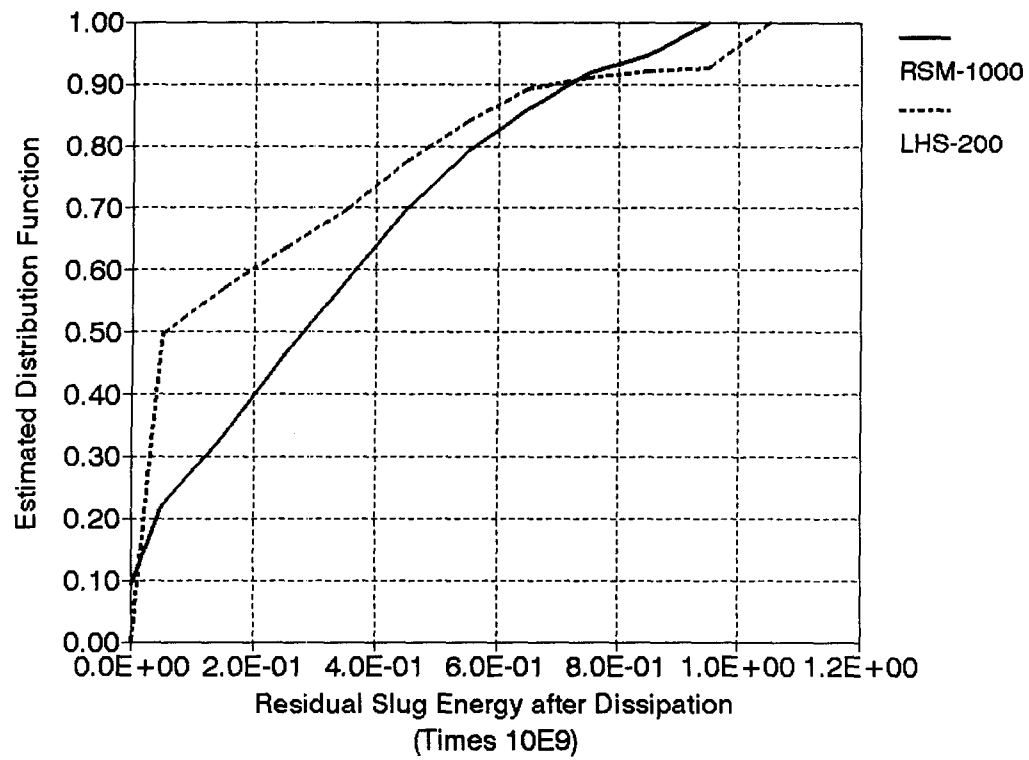Legend Eb : threshold explosion energy for vessel bottom failure

$-515-$

Figure 2. The distribution of residual slug energy after dissipation