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A COMPREHENSIVE UNCERTAINTY AND SENSITIVITY ANALYSIS FOR AN EX-VESSEL STEAM EXPLOSION-INDUCED PRESSURE LOADS

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ABSTRACT

An ex-vessel steam explosion has been considered one of the most challenging severe accident phenomena to the integrity of the reactor cavity and containment of a nuclear power plant. Due to its rapid and dynamic characteristics, however, a greater or lesser uncertainty was involved in phenomenological modeling to estimate the steam explosion-induced pressure loads. This paper provides plant-specific uncertainty analysis results on the ex-vessel steam explosion-induced pressure loads, which can be used as key input to assess the conditional failure probability if the fragility structures of interest is provided. The relevant uncertainty inputs have been mainly focused on key thermal-hydraulic conditions of the reactor pressure vessel and cavity, which can highly influence these pressure loads. A coupling of two different codes was utilized for the quantification of uncertainties, one is a steam explosion analysis code (TEXAS), and another is a sampling-based uncertainty quantification code (SAUNA). To get a more robust conclusion on the analysis results, sensitivity analyses have been performed for different probability types and sampling schemes. The uncertainty analysis results quantified for both pressure loads (cavity bottom pressure imposed on the reactor cavity and impulse pressure) and relevant insights are provided as a final result of the present study.

INTRODUCTION

An ex-vessel steam explosion may be induced when the molten material accumulated in the reactor lower head is injected through a lower head vessel breach into the water in the cavity. From the point of phenomenology, it occurs through several closely-related, but distinctive mechanisms: (a) a break-up of melt jet into several sizes of corium debris during its injection from the reactor pressure vessel into the water in the reactor cavity, (b) an interfacial heat transfer between the melt and the two-phase mixture during the mixing phase which occurs on an order of seconds, (c) the thermal-hydrodynamic fragmentation of melt debris submerged in water into finer particles and propagation, and (d) an explosive heat transfer between finer particles and water, which occurs at an order of milliseconds.

Over the past decades, several computer models have been developed to analyze the steam explosion-induced pressure loads. TEXAS-V (Corradini, 1997; 1999) is such a kind of computational model, and is widely used for estimation of the steam explosion load during a hypothetical severe accident of a nuclear power plant, when a molten core material of very high temperature interacts with water. The code employs a one-dimensional model, capable of analyzing the hydrogen generation caused by a melt oxidation, as well as a series of break-ups of melt jet, mixing with the surrounding water (typically occurring within a few seconds), propagation into the surrounding water, and an explosion causing a pressure pulse (typically occurring within a few milliseconds). To analyze the foregoing steam explosion phenomena, the TEXAS–V code employs two closely related, but separate, calculations of mixing and explosion: the mixing phenomenon is first calculated, after which the explosion is performed.

The thermal-hydraulic conditions of molten material in the lower head and water in the reactor cavity (e.g., temperature, density, and specific heat of molten material and pressure, temperature, and depth of water) are important factors in determining the possibility and strength of an ex-vessel steam explosion. In addition, the steam explosion in the reactor cavity that may threaten the integrity of the cavity structure can be influenced by various input parameters, including the size and velocity of the melt jet pouring into the reactor cavity, size distributions of fragmented particles, and the time of triggering.

The major concern of this paper is to determine the quantitative lower and upper bounds of the dynamic loading from a steam explosion to cavity structures resulting from different values of the input parameters, and in turn which input parameters give a greater impact on the integrity of the reactor cavity. For this, the TEXAS-V code has been utilized to analyze the dynamic pressure loadings to the cavity structure induced by a steam explosion for SKN units 3 & 4, which is a type of advanced power reactor (APR) in Korea, with a two-loop pressurized water reactor belonging to a type of 1400 MW_e (a rated thermal power of 4000 MW_{th}) (Lee, 2009). Then, a sampling-based uncertainty quantification code (SAUNA) (Park, 2009) has been coupled with the TEXAS code to quantify systematically uncertainties of the pressure loads resulting from the relevant inputs. Finally, several types of sensitivity analyses have been performed to get a more robust conclusion on the analysis results, taking into account different probability types and different sampling schemes. Many portions of the underlying approaches are based on the authors' previous study (Ahn, 2012).

THE UNDERLYING APPRACH AND RESULTS

Features of the TEXAS-V Model

The TEXAS-V model is a one-dimensional mechanistic model for fuel-coolant interaction; mixing, rapid fragmentation/vaporization, shock propagation and expansion during the steam explosions developed by Corradini and co-workers (Corradini, 1997; 1999). The model has the basic sub-models to simulate a steam explosion process that includes (a) a complete two-fluid Eulerian model for coolant liquid and vapor phases, (b) the Lagrangian particle model for molten fuel, (c) various jet breakup models, (d) the pressure-trigger model for triggering a steam explosion after mixing, (e) the explosion model induced by the pressure trigger for the rapid fragmentation process during the explosion, and (f) the oxidation model for the metallic fuel with the coolant vapor.

The models employed in the code have been extensively verified with a range of experimental data and validated their key physical models such as a jet breakup model for mixing and a rapid-fragmentation model for explosion. Nevertheless, the current FCI models including the TEXAS-V code are still lacking in the capability of providing fundamental reasons of substantially lower energetics of molten corium than those observed in various simulants. Thereby steam explosion energetics for reactor applications estimated by the current mechanistic models can be considered to be conservative. In the one-dimensional TEXAS calculation, the calculation of the explosion was carried out by parametrically varying the diameter of the mixing zone to maximize the explosion energetics for the given initial and boundary conditions, providing further conservatism on its estimation of steam explosion energetics. Nevertheless, the code has recently been successfully employed to analyze in-vessel and ex-vessel steam explosions in new and advanced reactor applications (Diab, 2010; Murphy, 1997) including AP600 and US-APWR.

Framework for the Uncertainty Analysis

A sampling-based method (Helton, 2002; Ahn, 2010) has been applied for an uncertainty analysis of the TEXAS-V code. As the first step, four uncertainty parameters employed in the TEXAS-V code models have been chosen for the uncertainty analysis and both uniform and normal PDFs have been assumed for each input parameter, based on their state of knowledge. These parameters cover the initial and boundary conditions that influence the magnitude of a steam explosion. For these uncertain parameters, the specified sets of uncertainty samples have been generated by applying a sampling module of the SAUNA code. An operation of the coupled system of TEXAS and SAUNA is illustrated in Fig.1.

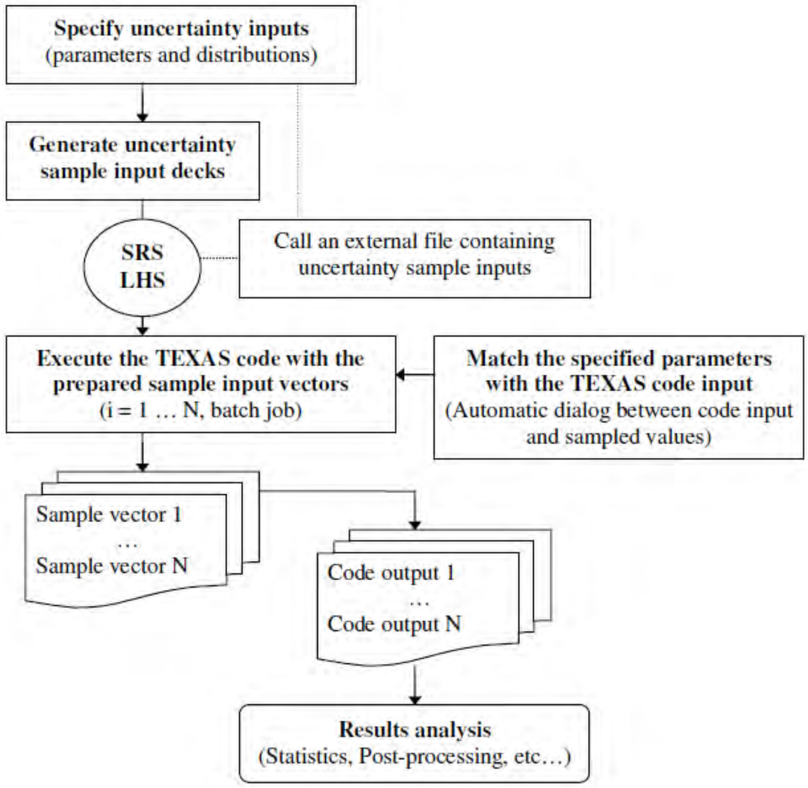


Figure 1. Operation of a TEXAS-SAUNA coupled system.

Selection of Key Uncertainty Parameters

The strength of an ex-vessel steam explosion is affected by various initial and boundary conditions including severe accident scenarios, failure modes and sizes of the reactor pressure vessel, and thermal hydraulic properties of corium in the reactor pressure vessel and the water temperature in the reactor cavity, velocity of the corium jet being ejected into the cavity, and atmospheric pressure in the containment. As shown in Table 1, the plant-specific inputs for the TEXAS calculations were prepared, based on the MAAP analysis results for various accident scenarios (KHNP, 2002): (a) a limiting case subjected to 200 Psia (1.361 MPa) of the RCS pressure at the instant an RPV bottom failure occurs was selected as a reference case and (b) the ranges of input parameters for the uncertainty analysis were selected through a series of sensitivity analyses.

- Four code input parameters related to the initial and boundary conditions have been taken into account: (a) TPIN (temperature of the corium jet at the time of the reactor vessel failure), (b) TLO (initial water coolant temperature in the reactor cavity) and TWO (initial cavity wall temperature), (c) RPARN (initial radius of the corium jet being released from the reactor vessel breach into the reactor cavity), and (d) UPIN (initial velocity of the corium jet discharging from the reactor vessel breach). The same sample values are applied to both TLO and TWO (see Table 2).
- All the input parameters are assumed to be mutually independent, and are subject to either normal or uniform distributions (see Table 2).
- Two target parameters for uncertainty quantification are taken into account: (a) ImpulBottom (peak impulse pressure in the cavity) and (b) PresBottom (peak pressure in the cavity bottom). While the

impulse pressure is utilized to assess its impact on the integrity of the reactor cavity, which is time-integrated pressure over a given time, the peak pressure is the pressure of the reactor cavity assessed at a given instant in time.

- To take into account the impact of different sampling schemes, two types of sampling methods were applied in the sampling process: one for a simple random sampling (SRS) and another for a stratified Monte Carlo sampling (Latin Hypercube Sampling, LHS) (Iman, 1984).

Table 1: Initial Conditions of the RPV and Cavity at the instant of the RPV breach for the representative severe accident sequences (SKN 3&4).

Initial Conditions	LOFW	SBLOCA	MBLOCA	LOOP	SBO
RPV failure time after accident initiation (sec)	22,705	117,186	126,245	24,032	64,255
RPV conditions					
RPV pressure (MPa)	1.361 ~ 17.1 (conditional on the failure number of ICI tubes)				
RPV failure size in diameter (m)	0.173 0.219 (conditional on the failure number of ICI tubes)				
Ejection rate of corium into the cavity (kg/s)	1,84 ~ 12,91 (conditional on the failure number of ICI tubes)				
Ejection time of molten corium into the cavity (sec)	4.4 ~ 29.0 (conditional on the failure number of ICI tubes)				
Temperature of steam (K)	395.69	397.72	375.03	396.74	392.33
Total amount of molten corium in the RPV (ton)	172.1	170.5	191.4	167.2	162.0
Composition of molten corium in the RPV (ton)					
UO_2	102.9	10.6.3	117.8	99.4	96.1
Zr	14.8	16.0	24.1	14.0	11.4
ZrO_2	17.1	13.2	7.5	18.7	20.0
S/S	34.2	34.0	41.9	33.8	33.8
Cr_2O_3	0.58	0.20	0.04	0.29	0.14
FeO	2.36	0.81	0.13	1.18	0.58
Temperature of molten corium in the RPV (K)					
Metallic layer	2,204	1,750	2,264	2,233	2,276
Oxidic layer	2,719	2,712	2,639	2,739	2,737
Cavity pressure (MPa)	0.187	0.171	0.121	0.173	0.167
Water in the cavity					
Mass (ton)	~ 413.7				
Depth (m)	1.2 ~ 6.4				
Temperature (K)	304.15				

[Note] ICI (In-core Instrumentation); LOFW (Loss of Feed Water); SBLOCA (Small Break Loss of Coolant Accident); MBLOCA (Medium Break Loss of Coolant Accident); LOOP (Loss of Offsite Power)); SBO (Station Blackout).

Table 2: Summary of inputs employed for the present uncertainty analyses.

x_i	Uncertainty Inputs	PDF (Probability Density Function)		Description (Default value)
		Type	[Min, Max]	
1	TLO	Case1: Normal Case2: Uniform	[294.0, 344.0] Mean: 319.0	Initial water coolant temperature in the cavity (304 K). This acts as heat sink of steam explosion.
2	RPARN	Case1: Normal Case2: Uniform	[0.05, 0.15] Mean: 0.1	Initial radius of corium jet (0.1 m). This is determined by the break size of the reactor vessel.
3	TPIN	Case1: Normal Case2: Uniform	[2750, 3150] Mean: 2950.0	Initial temperature of corium jet (2750 K). This is related to the degree of super heat of corium melt
4	UPIN	Case1: Normal Case2: Uniform	[-12, -1] Mean: -6.5	Initial injection velocity of corium jet (-9.55 m/sec). This affects the jet breakup and mixing

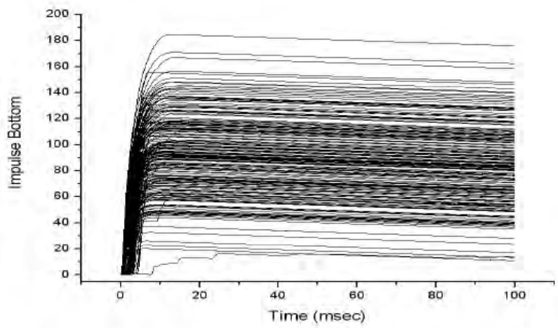
[Note] The default inputs used for the TEXAS calculations (default values): mass of oxidic corium in the RPV before ejection into the cavity (55 ton); depth of the cavity water from the bottom (6.4 m); initial reactor cavity pressure (0.2 MPa); user-specified triggering pressure for steam explosion (1.5 MPa).

Analysis Results: Base Case

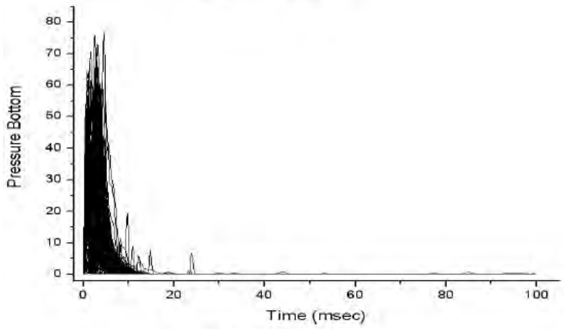
When a long computation time is taken to obtain the relevant output values of a complex physical model (or code), the number of statistical samples that must be evaluated through it may be a critical factor for a sampling-based uncertainty analysis. Although there is some guidance to determine the appropriate number of statistical samples from a statistical or empirical view (Ahn, 2010), it would be recommended to utilize as many samples as possible to reduce the potential variance in the code predictions, and consequently to obtain a more robust conclusion. From this point of view, the 200 SRS and LHS samples were sufficient for the present uncertainty input parameters.

Based on the foregoing reason, a TEXAS code simulation for each of the 200 sample input decks was performed for up to 10 seconds. While all code input samples (200 SRS and LHS samples) generated the corresponding 200 pressure loads in Case 1 (normal PDF), five random sample inputs, and ten LHS input decks led to failed calculations in Case 2 (uniform PDF). Careful investigation of these samples shows that most of these failed runs are caused when the two input parameters 'RPARN' and 'UPIN' approach their upper and lower bounds, respectively: 0.15 around for 'RPARN' and -12.0 around for 'UPIN'. Highly nonlinear and one-dimensional thermal-hydraulic models employed in the current TEXAS version might lead to some limitations in treating a combination of these uncertainty sample inputs. No additional code runs to replace these failed calculations were made in the present study, and consequently the failed code runs were discarded manually in the final analysis of the figure-of-merit.

The present uncertainty propagation provides two types of analysis results: one is the time history of the cavity pressures evaluated over the calculation time of 10 seconds and the other is the statistics of their peak values (such as mean, median, and 5/95 percentiles). The former is summarized in Figures 2 and 3 for the SRS case, and Figures 4 and 5 for the LHS case. The latter is summarized through Tables 3 and 4, including impacts for the two different sampling schemes (SRS and LHS) as well as the two different PDFs (Normal and Uniform). On the basis of the aforementioned results,

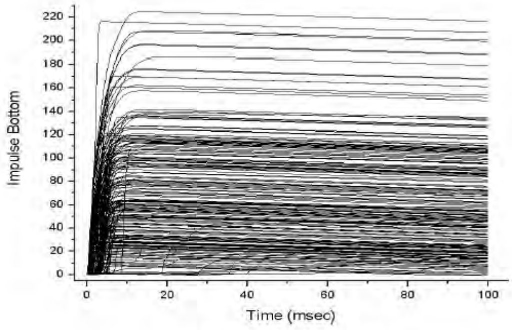


(a) ImpulBottom (kPa-s)

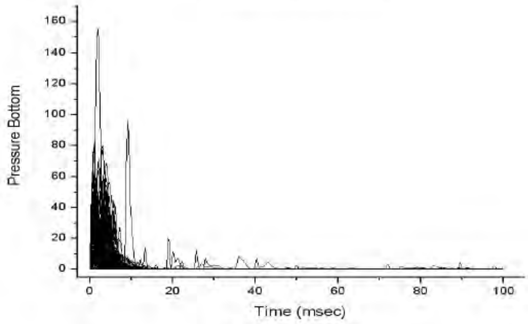


(b) PresBottom (MPa)

Figure 2. Cavity pressure with Time (Case 1, SRS).

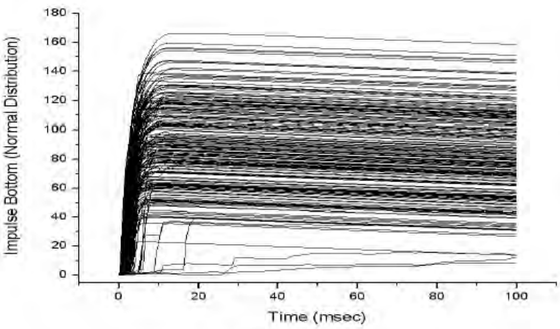


(a) ImpulBottom (kPa--s)

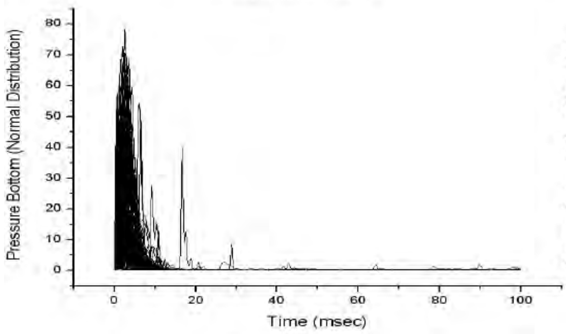


(b) PresBottom (MPa)

Figure 3. Cavity pressure with time (Case 2, SRS).

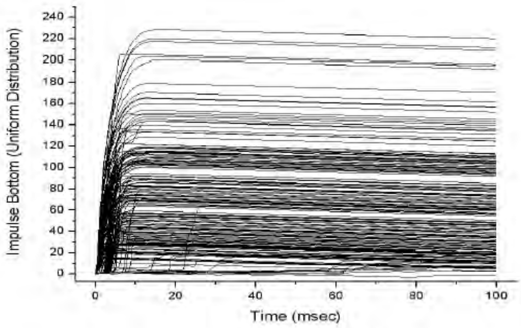


(a) ImpulBottom (kPa-s)

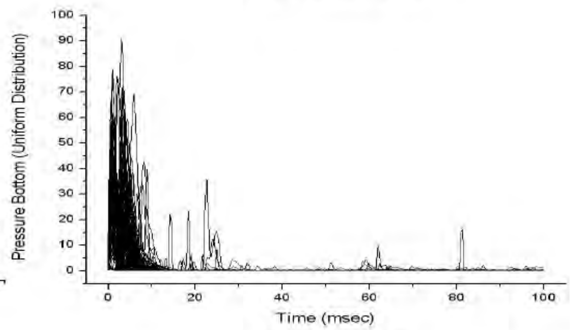


(b) PresBottom (MPa)

Figure 4. Cavity pressure with time (Case 1, LHS).



(a) ImpulBottom (kPa-s)



(b) PresBottom (MPa)

Figure 5. Cavity pressure with time (Case 2, LHS).

Table 3: Statistics for the peak pressures (Case 1, Normal PDFs).

Output variables	Min.	5%	50%	95%	Max.	Mean	S.D
ImpulBottom (kPa-s)							
SRS[1)]	22.6	**54.2**	**99.5**	**148.4**	184.7	**105.0**	**29.9**
LHS[2)]	8.19	**40.3**	**87.7**	**139.0**	166.3	**89.3**	**31.3**
SRS[3)]	27.5	**48.2**	**96.4**	**161.8**	210.4	**96.4**	**33.5**
ALL[4)]	8.19	**50.1**	**94.9**	**156.3**	210.4	**97.7**	**32.2**
PresBottom (MPa)							
SRS[1)]	11.3	**22.5**	**40.1**	**62.1**	76.8	**41.3**	**12.7**
LHS[2)]	1.46	**20.8**	**39.9**	**65.6**	78.2	**40.5**	**13.6**
SRS[3)]	1.15	**20.9**	**39.7**	**68.7**	91.0	**41.6**	**14.2**
ALL[4)]	1.15	**21.4**	**40.0**	**67.2**	91.0	**41.1**	**13.5**

[Note] SRS[1)] and LHS[2)]: Base and sensitivity cases for two different sampling schemes, respectively;
SRS[1)] and SRS[3)]: Base and sensitivity cases for two different sets of 200 SRS samples, respectively;
SRS[1)] and ALL[4)]: Base and sensitivity cases for two different numbers of samples, respectively.

Table 4: Statistics for the peak pressures (Case 2, Uniform PDFs).

Output variables	Min.	5%	50%	95%	Max.	Mean	S.D
ImpulBottom (kPa-s)							
SRS[1)]	15.7	**23.6**	**79.0**	**208.3**	224.9	**86.1**	**46.5**
LHS[2)]	1.18	**14.0**	**65.4**	**160.4**	228.2	**72.3**	**48.6**
PresBottom (MPa)							
SRS[1)]	0.57	**7.2**	**29.7**	**64.6**	155.1	**32.8**	**20.4**
LHS[2)]	0.72	**6.1**	**31.3**	**66.7**	91.0	**31.6**	**18.4**

[Note] SRS[1)] and LHS[2)]: Base and sensitivity cases for two different sampling schemes, respectively;
SRS[1)] and ALL[4)]: Base and sensitivity cases for two different numbers of samples, respectively.

Analysis Results: Sensitivity Cases

(1) Impacts of different input PDFs (Normal and Uniform)

As given in Tables 3 and 4, the uncertainty analysis *for SRS* shows that when the input parameters are subject to a normal PDF (Case 1), the mean value for the cavity bottom pressure (PresBottom) is estimated to be 41.3MPa, while the 5% lower bound and 95% upper bound are 22.5MPa and 62.1MPa, respectively. The mean value for the corresponding impact load (ImpulBottom) was estimated to be 105.0kPa-s, while the 5% lower bound and 95% upper bound are 54.2kPa-s and 148.4kPa-s, respectively. The mean for the cavity bottom pressure in the case of a uniform PDF (Case 2) was estimated to be 32.8MPa, while the 5% lower bound and 95% upper bound are 7.2MPa and 64.6MPa, respectively. The mean for the corresponding impact load (ImpulBottom) was estimated to be 86.1kPa-s, while the 5% lower bound and 95% upper bound are 23.6kPa-s and 208.3kPa-s, respectively. These two different results reflect a general tendency that while the sampled input values for Case 1 are populated at around their mean values, the sampled input values for Case 2 are more evenly distributed over the uncertainty ranges for the given inputs.

(2) Impacts of different sampling schemes (SRS and LHS)

As given in Tables 3 and 4, the uncertainty analysis *for LHS* shows that when the input parameters are subject to Case 1, the mean value for the cavity bottom pressure (PresBottom) was estimated to be 39.9MPa, while the 5% lower bound and 95% upper bound were 20.8MPa and 65.6MPa, respectively. The mean value for the corresponding impact load (ImpulBottom) was estimated to be 87.7kPa-s, while the 5% lower bound and 95% upper bound are 40.3kPa-s and 139.0kPa-s, respectively.

The mean for the cavity bottom pressure in the case of a uniform PDF (Case 2) was estimated to be 31.3MPa, while the 5% lower bound and 95% upper bound are 6.1MPa and 66.7MPa, respectively. The mean for the corresponding impact load (ImpulBottom) was estimated to be 65.4kPa-s, while the 5% lower bound and 95% upper bound are 14.0kPa-s and 160.4kPa-s, respectively. The foregoing results indicate that compared to the SRS case, the corresponding LHS case does not show any consistent trend except for the lower percentile values (i.e., min, 5%, and mean).

(3) Impact of different sets of SRS samples

For a normal PDF (Case 1), a sensitivity analysis has been performed to investigate the impact of the different sets of random samples on the resultant output uncertainties. For this, another set of 200 SRS samples has been propagated through the TEXAS code. As indicated in the third rows of each output variable of Table 3, the sensitivity analysis results for SRS shows a similar trend with the base case samples for SRS, especially for the mean and 5%/95% bounds of PresBottom. The foregoing results reflect more or less the dependency of the output uncertainties on the sampling schemes employed in the uncertainty quantification.

(4) Impact of different numbers of samples

The fourth rows of each output variable of Table 3 show statistical quantities and percentiles for three sets of uncertainty samples whose number of uncertainty samples is integrated to 600 (e.g., 200 base case samples for each of SRS and LHS, and 200 sensitivity samples for SRS). The foregoing approach reflects the dependency of the output uncertainty on the number of samples employed in the uncertainty quantification, generally leading to a more robust result for a larger number of uncertainty samples. The present integration of uncertainty samples to 600 provides a more similar trend with the sensitivity case for SRS than its base case samples for SRS, consequently leading to a mean value of 41.1MPa and 21.4MPa/67.2MPa corresponding to 5%/95% bounds (PresBottom), respectively, and the mean value of 97.7kPa-s and 50.1kPa-s /156.3kPa-s corresponding to 5%/95% bounds (ImpulBottom), respectively.

From this point of view, all of the currently available uncertainty samples were again integrated into a single set of samples whose number is set at 985 to get more robust results for plant-specific uncertainty. Table 5 provides an integral impact of the integrated number of uncertainty samples, consequently leading to a mean value of 37.6MPa and 11.3MPa/65.7MPa corresponding to 5%/95% bounds (PresBottom), respectively, and a mean value of 90.5kPa-s and 24.5kPa-s /90.5kPa-s, corresponding to 5%/95% bounds (ImpulBottom), respectively.

Table 5: Peak pressures (all sampling schemes and PDFs, 985 samples1)).

Output variables	Min.	5%	50%	95%	Max.	Mean	S.D
ImpulBottom (kPa-s)	1.18	**24.5**	**89.2**	**156.6**	228.2	**90.5**	**40.2**
PresBottom (MPa)	0.57	**11.3**	**37.6**	**65.7**	155.1	**37.6**	**16.7**

[Note] Superscript 1): sum of samples utilized for the base and sensitivity cases for SRS and Normal PDFs

SUMMARY AND CONCLUSION

An uncertainty analysis for the ex-vessel steam explosion-induced pressure loads were evaluated based on the SAUNA-TEXAS coupled system, taking into account key thermal-hydraulic conditions of the reactor pressure vessel and cavity, which can highly influence these pressure loads. In addition, sensitivity analyses have been applied to both probability types and sampling schemes. As a result, the uncertainty of pressure loads of interest shows (a) a mean value of 37.6MPa with 11.3MPa/65.7MPa corresponding to 5%/95% bounds in case of PresBottom, and (b) a mean value of 90.5kPa-s with 24.5kPa-s/90.5kPa-s corresponding to 5%/95% bounds in the case of ImpulBottom.

However, it should also be noted that variations in pressure loads from the use of different statistical methods employed in the present study are largely within uncertainty of modeling of a steam explosion because of the highly non-linear and stochastic mechanisms involved in a steam explosion (not specific to TEXAS). Thus, the necessary deterministic aspect of the computations might not be assured, and the models themselves might also be so. This is the reason why we tried several statistical methods with different sampling method, and different correlations to indentify these modeling uncertainties involved in a steam explosion and to the outputs of the code itself, and finally integrated all the available uncertainty samples into a single set of samples to get a more robust conclusion. Although the present results may not be very robust in terms of the uncertainty analysis because of modeling uncertainties involved in a steam explosion and to outputs of the code itself, it is an important work to identify the range of uncertainties involved in the evaluation of the ex-vessel steam explosion as a source of plant risk, and thus the range of currently available ex-vessel steam explosion energetics.

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