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The plant-specific uncertainty analysis for an ex-vessel steam explosion-induced pressure load using a TEXAS–SAUNA coupled system

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ABSTRACT

An ex-vessel steam explosion has been considered as one of the most challenging severe accident phenomena to the integrity of the reactor cavity and containment of a nuclear power plant, owing to its rapid and dynamic characteristics. The purpose of this paper is to provide 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 APR1400, a two-loop pressurized water reactor, has been selected as a reference plant for an uncertainty analysis. For this purpose, a comprehensive uncertainty analysis has been performed for key thermal–hydraulic conditions of the reactor pressure vessel and cavity, which can highly influence on these pressure loads, with the help of a coupling of a steam explosion analysis code (TEXAS-V) with a sampling-based uncertainty quantification code (SAUNA). To get a more robust conclusion based on the analysis results, various sensitivity analyses have been applied to both probability types (e.g., normal and uniform PDF) and sampling schemes (e.g., random and Latin Hypercube sampling). Key contributors (i.e., physical and model parameters) to the underlying pressure loads have been determined by assessing the six currently available types of importance measures.

1. 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. This has been considered as one of the most challenging severe accident phenomena to the integrity of a reactor cavity and the containment of a nuclear power plant because of its rapid and dynamic characteristics. In terms of phenomenology, an ex-vessel steam explosion occurs through several closely related, but distinctive mechanisms: (a) a break-up of a 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 (Corradini et al., 1997; Young, 1987; Angelini et al., 1995; Yuen and Theofanous, 1995; Park et al., 2000) have been developed to analyze the steam explosion-induced pressure loads. TEXAS-V (Corradini et al., 1997) is such a kind of computational model, and is widely used for an 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 hydrogen generation, which is 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 occurs.

On the other hand, 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, the size distributions of the fragmented particles, and the time of the triggering. The major concern of this study is to determine the quantitative lower and upper

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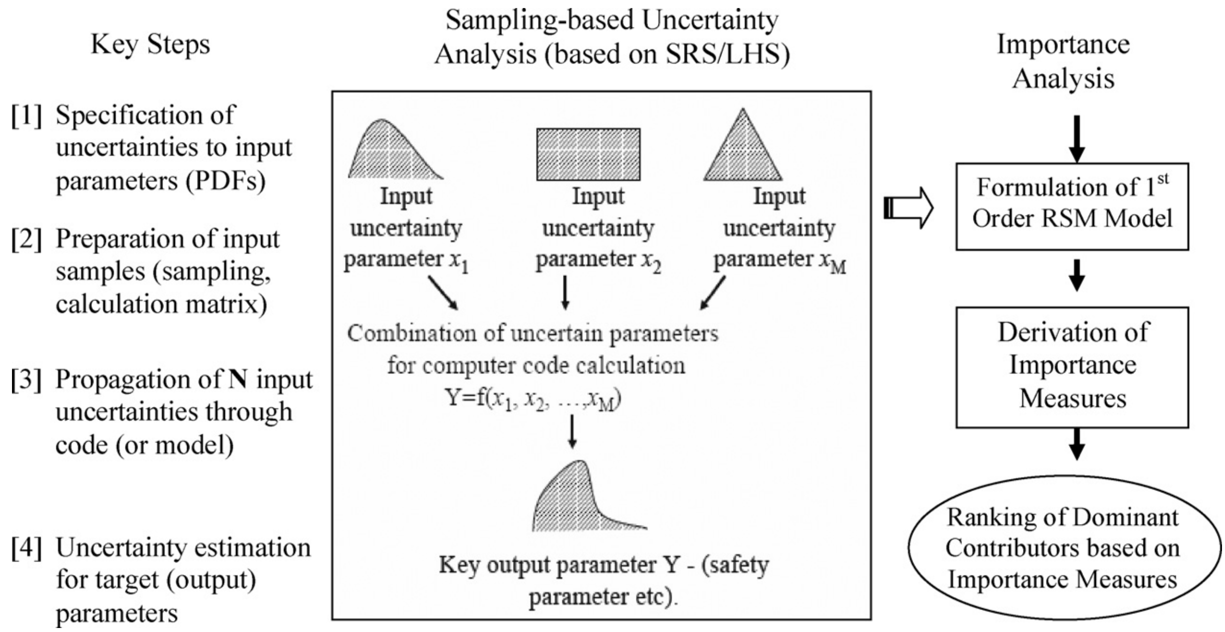

Fig. 1. A statistical approach for uncertainty assessment.

bounds of the dynamic loading from a steam explosion to the cavity structures, resulting from different values of input parameters, and in turn, which input parameters have a greater impact on the integrity of the reactor cavity. The TEXAS-V code has been utilized to analyze the dynamic pressure loadings on the cavity structure induced by a steam explosion for SKN units 3&4 (a type of advanced power reactor (APR) in Korea), and an uncertainty analysis was performed to assess the impact. Similar efforts (Zuchuat et al., 1997; Moriyama et al., 2004) to assess the uncertainty involved in the evaluation of an ex-vessel steam explosion in nuclear power plants were performed.

The purpose of this paper is to provide 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 are provided. The APR1400, a two-loop pressurized water reactor, has been selected as a reference plant for an uncertainty analysis. For this purpose, a comprehensive uncertainty analysis has been performed for key thermal–hydraulic conditions of the reactor pressure vessel and cavity, which can highly influence on the pressure loads, with the help of a coupling of a steam explosion analysis code (TEXAS-V) with a sampling-based uncertainty quantification code (SAUNA) (Park et al., 2009). In order to achieve a more robust conclusion on the analysis results, various sensitivity analyses have been applied to both probability types (e.g., normal and uniform PDF) and sampling schemes (e.g., random and Latin Hypercube sampling). Key contributors (i.e., physical and model parameters) to the underlying pressure loads have been determined by assessing quantitatively the six importance measures: (a) four importance measures are obtained by formulating the first order regression models from the TEXAS code calculations and (b) the other two measures come from a nonparametric statistical approach relying straightforwardly on the pairs of sample input–output values.

2. The present approaches for uncertainty analysis

2.1. Framework for the present study

A sampling-based method (Helton and Davis, 2002; Ahn et al., 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 the art. These parameters cover 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.

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 et al., 1981a,b; Iman and Shortencarier, 1984). The LHS approach is especially useful in computationally demanding and time-consuming models because its stratified sampling scheme allows for the extraction of a sufficient amount of uncertainty information with a relatively small size and much less dependency on the size of the statistical samples than simple random sampling on the uncertainty analysis results. A dependency between parameters was not considered in the sampling process. Finally, the TEXAS-V code calculations were performed one by one for each sample set through an uncertainty quantification module of the SAUNA code, consequently leading to the corresponding code outputs for a statistical analysis and graphical treatment. The foregoing process for an uncertainty analysis is summarized in Fig. 1.

Importance and sensitivity analyses are used to assess quantitatively the extent of contributions of code (or model) input parameters to the code (or model) outputs, which are generally made by formulating either the correlation between uncertainty inputs and outputs, or the relevant regression models (Iman et al., 1981a,b; Ahn et al., 2010). The foregoing process for an importance analysis is summarized on the right hand side of Fig. 1. While there are several kinds of importance measures expressing the relative contributions to the outputs, the six importance measures summarized in Table 1 were taken into account in this study.

2.2. Brief description of the TEXAS-V model

The TEXAS-V model is a one-dimensional mechanistic model for fuel-coolant interaction; mixing, rapid fragmentation/