Comparison of Phenomenological Parameters that are Influential to the Source Term Uncertainty for Station Blackout Accident

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1. Introduction

After the Chernobyl and Fukushima accidents, regulatory agencies began to require strict emergency preparedness for possible radioactive release severe accidents. Radioactive source term, any characterization of radioactive materials from the reactor core, includes environmental release timing and magnitude of the radioactive releases. Although this information is required for radiological emergency preparedness, it can only be predicted using simulation codes with integrated phenomenological models. Considerable efforts have been taken to estimate the source term realistically during severe nuclear reactor accidents, but large uncertainties still exist in using these codes. Therefore, uncertainty analyses are important when using the source term predictions.

The purpose of this research is to identify a set of phenomenological model parameters that significantly influences the source term overall uncertainty. For this research, MAAP4, a widely accepted severe accident code, was selected for the source term analysis. Then, the identified parameters with great influences on the overall uncertainty are compared for different types of pressurized water reactors (PWRs). This step would allow identification of influential parameters regardless of the plant configuration, and the use of resources may be focused on these key parameters to reduce uncertainty. While this research is focused on an unmitigated station blackout accident, the approach in this research is expected to be applicable for wider range of accident scenarios and plant configurations in the future studies.

2. Methods

7.1. Selection of Accident Scenario for the Analysis

Unmitigated station blackout (SBO) accident scenario was selected as a representative severe accident to simulate the core melt and the environmental radioactive release of a nuclear reactor. Unmitigated long-term SBO accident was chosen based on the State-of-the-Art-Reactor-Consequence-Analysis [1]. The analysis was made for the OPR-1000 and the Zion plant by using the MAAP4 model. The initiating event is expected to be caused by external events such as seismic events, which are more likely to result in immediate failure of safety systems compared with other external events. Loss of offsite power followed by the failure of all diesel generators was assumed for the analyzed accident scenario.

During the accident sequence, reactor would successfully trip, and the main steam isolation valves would close. Battery would provide DC power for the first 4 hours (minimum required time) before running out of electricity, and the turbine driven auxiliary feedwater pump would run, but the containment cooling systems were assumed inoperable due to lack of electricity. Recoveries of both the offsite and the onsite power were not expected for the unmitigated accident. For the containment failure, the size of the failure was determined from the Sandia National Laboratories containment integrity research [2].

Because significant amount of uncertainties exist in calculating the release time and the amount of the radionuclide being released into the environment, parameter uncertainties in simulating 1) the environmental release time 2) the amount of the radionuclide being released into the environment were analyzed in this research as part of uncertainty analyses. CsI was selected as the representative compound for the radioactive source term. The total amount of radioactive source term released into the environment was measured 48 hours after the initial environmental release to normalize the amount of time released for each simulation.

7.2. Identification of Influential Phenomenological Parameters

To identify key parameters affecting uncertainties and to assess their impact on the simulated output, following general steps were taken. First, the MAAP model parameters that may influence calculations for physical and chemical phenomenological processes were identified. The phenomenological model parameters listed in the “Uncertainty and Sensitivity Analysis” section of the MAAP4 Applications Guidance was used for the first step to identify the MAAP model parameters that may possibly have impact on the overall uncertainty [3].

Next, the influential model parameters were screened through integral analyses by using randomly sampled input valuess, where the value of each parameter were sampled from the probabilistic distribution of each parameter. Following assumptions were used in the analysis.

- All phenomenological model parameters have triangular probability distributions with appropriately selected values of the minimum, the maximum, and the mode. The MAAP4 recommended values were assumed as the mode of the distribution..
- All tested model parameters are independent of each other. Difficulties exist in identifying relationships between so many input variables. Therefore, only the bivariate relationship between each independent variable (i.e. input parameter) along with the dependent variable (i.e. output) were analyzed.
- No assumption is made of linear dependence between the input parameters and the output, but the relationship between dependent variables are monotonic.

The stratified Latin Hypercube Sampling (LHS) method was used to generate inputs for each simulation sample for the preliminary uncertainty analyses. Sandia National Laboratory's Latin Hypercube Sampling software was used for this purpose. To select the ranges of input parameters for the LHS sampling in uncertainty analysis, one must assume the probability distribution of the parameters. For MAAP code, each parameter is presented with its description in the code, a recommended value, a minimum, and a maximum. In this study, it was assumed that all tested parameters have triangular distribution with the values specified in the MAAP4 parameter file, so that LHS method can be used.

Spearman's rank correlation, a non-parametric test which measures the strength of dependence between two ranked variables, was used for analyzing the strength of the monotonic relationship between two variables. This correlation method does not assume linearity and is susceptible to the presence of outliers. For the significance testing, the Fisher transformation method was used for null hypothesis testing of statistical independence [4].

After the initial screening of the influential parameters, final detailed analyses of the screened parameters were performed. This was done through sensitivity analysis to see the impact of each parameter on the output data. Because the number of screened parameters from the integrated uncertainty analysis was small, one-at-a-time (OAT) simple deterministic sensitivity analysis method was used for each parameter to see what impact each parameter produces on the output. By changing just one input variable with the other variables kept constant, the impact of the tested variable could be analyzed. Each parameter range was divided into 20 equally spaced intervals, and the sensitivity of each parameter was analyzed.

3. Results

The unmitigated station blackout accident scenario was analyzed both for OPR-1000 and Zion, with each accident scenario having 250 simulations.. The results of the sensitivity analysis for the screened parameters are shown in Figures 1 and 2.

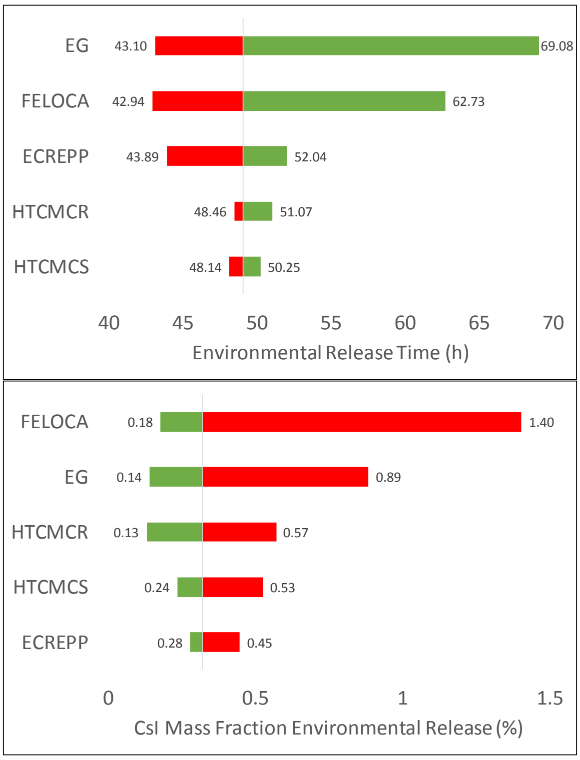

Figure 1. Results of sensitivity analysis for screened model parameters for the OPR-1000 unmitigated SBO accident

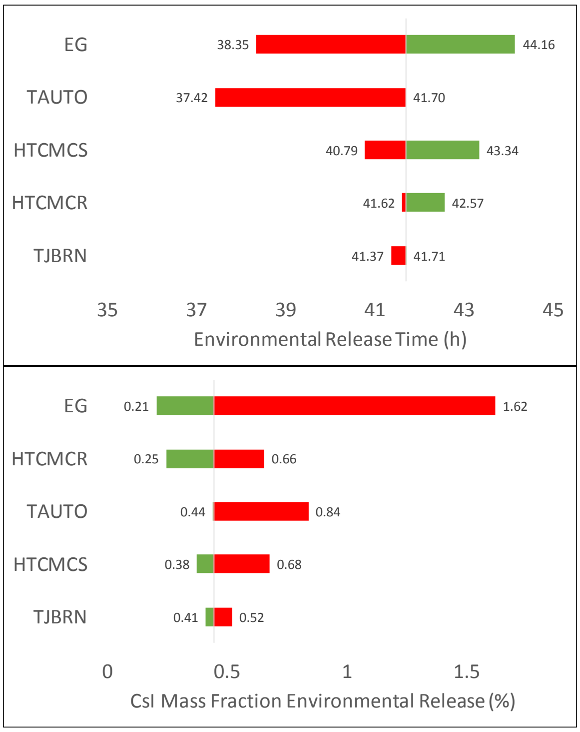

Figure 2. Results of sensitivity analysis for screened model parameters for the Zion unmitigated SBO accident

For the unmitigated station blackout accident which has resulted in containment failure, significant source of uncertainties came from the phenomenological parameters that were used to model the molten core-concrete interaction phenomena (HTCMCR, HTCMCS) and containment radiation heat transfer phenomena (EG). The result of the OPR-1000 source term uncertainty was influenced by the suspended water droplets (FELOCA) inside the containment, but it wasn't the case for the Zion plant. The result of the Zion source term uncertainty was influenced by containment hydrogen burning (TJBRN, TAUTO), which wasn't the case for the OPR-1000.

4. Conclusions

Because the phenomenological models of the molten core-concrete interaction, water entrainment, and hydrogen burning had significant impact on the source term uncertainty, researching and designing safety systems to reduce the impact of these phenomena may result in significant reduction of the released source term if another accident like Fukushima occurs, however unlikely such event may be. Molten core-concrete interaction was influential in the source term simulations for both plant configurations, but some model parameters that have significantly impacted the global uncertainty of source term uncertainty for one plant did not necessarily had same impact for another. For unmitigated station blackout accident, the parameters that were related to the entrainment of water inside the containment significantly contributed to the global uncertainty of the OPR-1000 simulations, whereas the parameters that were related to the hydrogen burning contributed much more to the global uncertainty of Zion simulations. Therefore, uncertainty analysis for each plant design should be done separately to identify the model parameters that may significantly impact the source term analysis.

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