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QUASAR UNCERTAINTY STUDY

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1. INTRODUCTION

Over the last decade, substantial development and progress has been made in the understanding of the nature of severe accidents and associated fission product release and transport. As part of this continuing effort, the United States Nuclear Regulatory Commission (USNRC) sponsored the development of the Source Term Code Package (STCP), which models core degradation, fission product release from the damaged fuel, and the subsequent migration of the fission products from the primary system to the containment and finally to the environment.

In order to better establish the validity and potential applications of source term predictions from these phenomenological models, quantification of the uncertainties associated with the STCP calculated source terms is essential.

An initial attempt at quantifying the uncertainties in the source term estimates based upon the BMI-2104[1] methodology was completed at Sandia as part of the QUEST[2] program. However, this study was preliminary and limited in scope. Comparable studies have also been performed by the Nuclear Industry as part of the Industry Degraded Core Rulemaking (IDCOR) program using the MAAP code.[3]

The objectives of the QUASAR[4] (Quantification and Uncertainty Analysis of Source Terms for Severe Accidents in Light Water Reactors) program are: (1) to address the uncertainties associated with input parameters and phenomenological models used in the STCP,[5] and (2) to define reasonable and technically defensible parameter ranges and modelling assumptions for the use in the STCP.

The uncertainties in the radiological releases to the environment can be defined as the degree of current knowledge associated with the magnitude, the timing, duration, and other pertinent characteristics of the release following a severe nuclear reactor accident. These uncertainties can be quantified by probability density functions (PDF) using the Source Term Code Package[5] shown in Figure 1 as the physical model. An attempt will also be made to address the phenomenological issues not adequately modeled by the STCP, using more advanced, mechanistic models.

*Work performed under the auspices of the U.S. Nuclear Regulatory Commission. Views expressed are not necessarily those of the Nuclear Regulatory Commission.

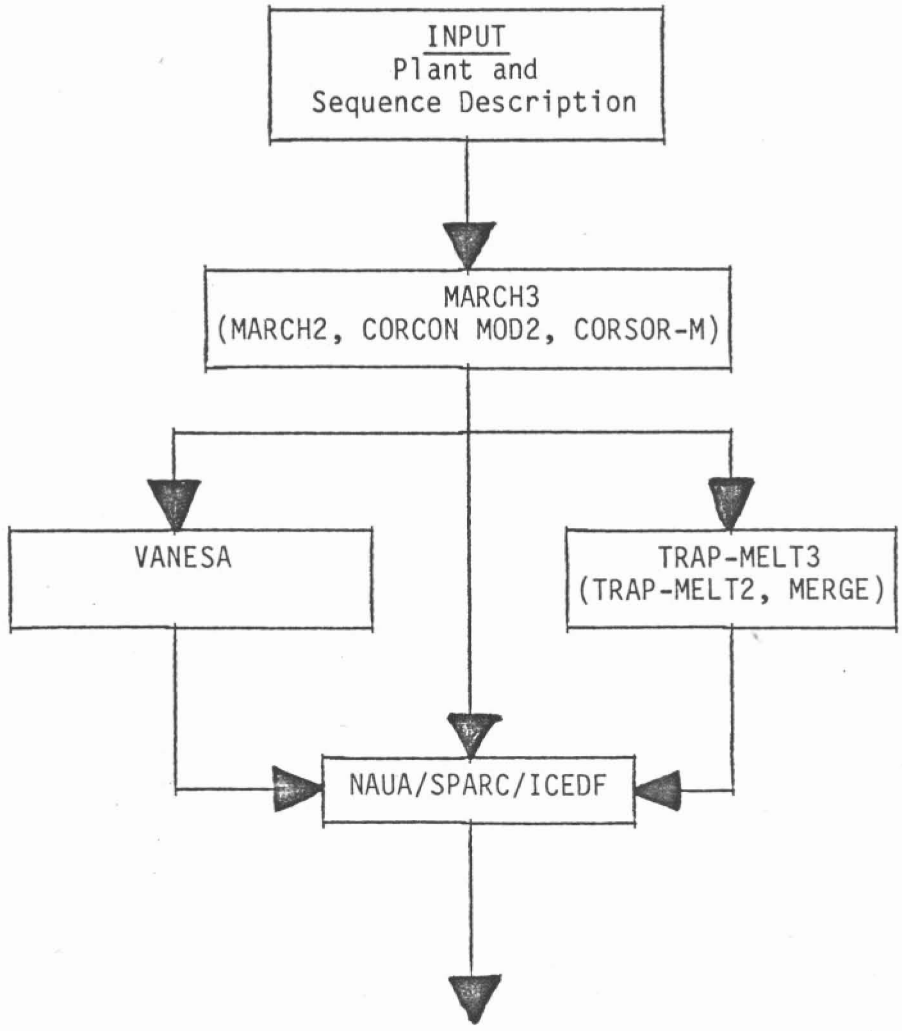

Figure 1 Source Term Code Package (STCP).

2. METHODOLOGY

The previous source term uncertainty studies [2,3] have suffered from a common criticism, i.e., the lack of well-defined, probabilistically defensible uncertainty bounds on the final results.

It is useful to review some of the complexities involved in source term uncertainty analysis before going into details of the methodology.

First, the STCP methodology consists of several large and complex computer codes with substantial computer cost requirements. Therefore, the uncertainty analysis method as applied to the STCP must be efficient and cost effective.

Second, there are a large number of input and output variables to the STCP. It is necessary to have a screening stage prior to the extensive uncertainty analysis in order to reduce the number of input variables to a more manageable level.

Third, the scales of input variables are different, i.e., linear vs. logarithmic.

Fourth, there are large modeling uncertainties. Because the phenomena involved in the accident sequences are not well understood, and often difficult to identify, various approximations and assumptions are often used in the mathematical formulations to make the problem tractable.

Fifth, the source term calculations are time, sequence, and plant specific.

A full scope uncertainty analysis requires: (1) the screening stage, (2) the uncertainty propagation stage, (3) the sensitivity analysis stage, and (4) the importance analysis stage.

2.1 Screening Analysis

The screening stage is necessary to reduce the number of input variables to a manageable level.

The general problem addressed by screening is one that is basic to the analysis of most large and complex computer codes. One is faced with solving a large system of equations requiring a vast amount of input data whose importance to the calculated results are not often quantitatively understood. Screening is thus designed to determine which data elements are important for a given calculated result. This will reduce the number of model parameters for which an extensive uncertainty analysis is needed.

For the mathematical models incorporated into the STCP, potentially important input parameters are identified using two different methods.

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For the mathematical models incorporated into the STCP, potentially important input parameters are identified using two different methods.

The first method is based on one-at-a-time variation of significant input parameters using the engineering insights gained from the existing source term studies, the QUEST results and experimental observations. Each input is varied assuming all of the others remain at their reference values.

In the second approach, all of the input parameters (with the exception of propagated variables, control variables and design related variables) are varied simultaneously using a stratified sampling technique. This approach provides additional insights as to the impact of covariations and interdependencies among the inputs.

Following the extensive sensitivity calculations, the most influential input parameters are identified for use in the next stage of the study.

2.2 Uncertainty Analysis

The uncertainty analysis of the source term estimation begins with the identification of possible sources of uncertainties in the STCP. The identified uncertainties could be classified by their sources or types from the quantification process. Those identified and/or classified uncertainties are then explicitly quantified with the proper measure of uncertainty. The PDF representation of uncertainty is the most extensively used measure of uncertainty. The propagation of these quantified uncertainties through physical and/or logical models is the final step in the uncertainty analysis. The final outcomes of the uncertainty analysis are, therefore, the PDFs of source terms. From the PDFs, corresponding statistical parameters can be calculated.

a. Identification and Classification of Uncertainties

Identification and classification of uncertainties in the prediction of radiological releases to the environment entail a detailed examination of the various models and their associated computer codes in the STCP. In general, uncertainties in radiological source terms to the environment can be classified according to:

- Input parameter uncertainty.
- Modeling option uncertainty.
- Unmodeled phenomenological uncertainties.

The treatment of the first two classes of uncertainties is nearly identical in that the parametric and model option selection process can be based on two sources of uncertainties; namely, (1) insufficient knowledge, and (2) physical variability.

On the other hand, the treatment of uncertainties due to unmodeled or poorly modeled physical phenomena in the STCP entails development of alternative physical models or using an alternate model/computer code which addresses the phenomenological issue of interest. However, the modeling uncertainties are treated in the same manner as the parameter uncertainties; since different models are governed by different sets of input parameters.

Having identified and classified these uncertainties, one can then proceed with the quantification process. Each individual computer code in the STCP must be thoroughly examined to identify the important sources of uncertainties with regard to phenomenological models and parametric variations.

b. Quantification of Uncertainties

The measure of uncertainty is the probability density function. The PDF represents the degree of belief, or the frequency of occurrence depending on the sources of uncertainties.

The quantification process in QUASAR will use the available experimental data base to establish reasonable upper and lower bound estimates for the various input parameters to the STCP using extensive expert review. In the absence of sufficient experimental data, fundamental physical principals together with expert opinions will be utilized. A PDF can now be assigned according to the established ranges.

The assignment of PDFs can be justified provided sufficient data exists. In the absence of such justification, uniform or loguniform (depending on the parameter range) distributions will be utilized.

It is recognized that the choice of PDF functional type may be important in the overall uncertainty estimation; therefore, a post uncertainty sensitivity study is planned in order to address any distributional dependency.

c. Propagation of Uncertainties

The uncertainties of each input variable and parameter quantified in the previous step are propagated through models utilized by the computer codes.

Monte Carlo techniques appear to offer effective ways to propagate distributions through either physical or logical models provided the simulation costs do not become excessive. Latin Hypercube Sampling (LHS) rather than random sampling can be used as a possible way to improve the efficiency of such propagation.

Latin Hypercube Sampling (LHS), a stratified sampling technique,[6] has recently been used in the uncertainty and sensitivity analyses of various computer models.[7,8]

LHS operates in the following manner to generate a sample of size n from the k input variables $X_1 \ldots, X_k$:

1. The range of each variable is divided into n nonoverlapping intervals of equal probability.

2. One value from each interval is selected at random with respect to the probability density in the interval.

3. The n values thus obtained for X_1 are paired in a random manner (i.e., equally likely combinations) with the n values of X_2. These n pairs are combined in a random manner with the n values of X_3 to form n triplets, and so on, until a set of n k-tuples is formed.

4. If certain inputs are correlated, step 3 is modified to account for these conditions.

It is convenient to think of the LHS as forming a nxk matrix of inputs where the i^{th} row contains specific values of each of the k input variables to be used on the i^{th} run of the computer model. Likewise, the j^{th} column of the nxk input matrix contains the complete stratified sample for the j^{th} input variable, that is:

$$\bar{X} = \begin{bmatrix} X_{11} & X_{21} & X_{31} & \cdots & X_{k1} \\ X_{12} & X_{22} & X_{32} & \cdots & X_{k2} \\ & & & & \\ & & \cdots\cdot & & \\ X_{1n} & X_{2n} & X_{3n} & \cdots & X_{kn} \end{bmatrix}$$

During the process of constructing the nxk input matrix, the dependencies between input variables would be carefully examined. There are two ways to treat the dependencies depending on the available information in the LHS. If the available information is given as a correlation (in terms of rank) structure among the input variables, it is possible to include the desired dependency directly from the LHS77 computer code. Such a method is based on the restricted pairing technique of Iman and Connover.[7] The restricted pairing technique for inducing a desired rank correlation matrix on a multivariate input random variable for use in a simulation study is simple to use, it is distribution free, it preserves the exact form of the marginal distributions on the inputs, and may be used with any type of sampling scheme for which correlation of input variables is a meaningful concept.

The choice of the sample size n depends on a number of considerations but will be dominated by the cost of making a single computer run and the number of input variables k. Though it is not an absolute rule, it is suggested that n be greater than or equal to (4/3)k.[8] If the model is inexpensive to run, then n could be larger such as between 2k and 5k. If, on the other hand, k is quite large and the model is expensive to run, as is the case for the STCP, then it may be necessary to choose n in a judicious manner.

2.3 Sensitivity and Importance Analysis

Following the completion of the uncertainty analysis stage, a sizeable number of STCP generated samples become available which enables the use of a regression type technique, such as the Response Surface Method (RSM) for sensitivity analysis. In this stage, the sensitivity of the output PDFs to the input PDFs are established. Furthermore, an importance ranking of the sensitive input parameters/models is also performed.

The resulting PDFs for the radionuclide releases are then used to calculate corresponding statistical parameters such as the mean, median, and upper and lower percentiles.

3. RESULTS

The sequence of events leading to a core melt accident and subsequent release of radionuclides is not addressed by QUASAR, however, given an accident sequence, QUASAR is aimed at providing the uncertainties associated with the radiological releases to the environment.

The present analysis uses the STCP to determine the most sensitive input parameters for a TC-sequence in a BWR4/MARK I.

In this sequence, failure to scram is accompanied by the failure to achieve early power reduction as well as failure to achieve emergency depressurization. The primary coolant inventory is maintained by the combination of high pressure core injection (HPCI), (RCIC), and the control rod drive (CRD) coolant systems. As the suppression pool heats up due to the continuing large steam input through the safety/relief valves (SRVs), failure of the safety system could take place due to loss of lubrication oil cooling, seal overheating, etc. In this analysis, HPCI is assumed to fail at a suppression pool temperature of 200°F, and the RCIC is assumed to fail at a containment pressure of 25 psia, due to high turbine exhaust back pressure. The CRD system, which takes its suction from the condensate storage tank, would continue to operate as long as the water in the tank is available.

Extensive, one-at-a-time sensitivity calculations have been performed, results of which are being compared with detailed sensitivity calculations based on the simultaneous variations using a stratified sampling technique.

Table 1 lists the most sensitive input parameters/variables to the STCP using the one-at-a-time variation method.

TABLE I

Sensitive Input Parameters/Variables to the STCP for a TC-Sequence (ATWS) in a BWR with Mark I Containment

STCP Code	Input	Definition
MARCH2	TMELT	Fuel melting temperature
	TFUS	A temperature reflecting energy content of the molten fuel
	FDROP	Whole core melt fraction upon core slump
	WGRIDX	Mass of steel that falls with the melt into the bottom head
	FZMCR	Zr fraction in the central core of debris particles in the bottom head
	DPART	Debris particle size in the bottom head
	FHEAD	Fraction of the lower head steel available for ex-vessel interaction
	AVBRX	Break area of drywell
	C3	Break area of reactor building
CORCON/MOD2	TW	Concrete ablation temperature
	RAD	Radius of corium pool
	EO, EM, EW	Emissivities of melt phases and concrete
CORSOR		Transient release rate coefficients for I, Cs, Te
		Te-cladding interaction threshold
TRAPMERGE	VD	Te group deposition velocity
	CHI	Dynamic shape factor
	GAM	Collision shape factor
SPARC	DIAM	Mean bubble diameter
	RATIO	Bubble aspect ratio
	VSWARM	Bubble swarm velocity
VANESA		Condensed phase diffusivities
		Condensation coefficient
		Activity coefficients
NAUA	FORM	Dynamic shape factor
	FORMC	Coagulation shape factor
	DELD	Diffusional boundary layer thickness

These sensitivity calculations, together with recommendations for reasonable ranges and probability density functions (PDFs), have been put to an extensive expert review process.

Based on the comments received from the reviewers, input PDFs will be formulated to propagate uncertainties through the STCP. Work has also started to identify and quantify important phenomenological uncertainties.

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