White Paper

Fire PRA Quantitative Uncertainty and Sensitivity Analyses

1. Introduction and Background

The development of Fire PRAs (NUREG/CR 6850) (Ref.1) is a complex process and can result in models consisting of on the order of 1000 fire damage states (similar to an internal events initiating event). The development and quantification of these fire damage states has considerable uncertainty, which has not been fully addressed in recently conducted fire PRAs. The ANS/AME standard requires fire PRAs to address uncertainty. While US industry and NRC documents (Ref 2 and 3) provide guidance for addressing uncertainties, neither guidance document explicitly addresses fire or other hazards with the same level of detail provided for internal events and internal flooding at power. Consequently Jacobsen Analytics have developed and implemented an approach for addressing parameter uncertainty during the course of various fire PRA projects being performed in conjunction with its associate US company Scientech, which is now under consideration by EPRI for refinement and extension to more fully characterize the uncertainties based on data provided in NUREG/CR 6850, NUREG/CR 1934 (Ref 4) as well as other published sources and expert judgment.

In particular detailed fire growth and suppression modelling to support fire PRAs (FPRAs) is generally forced to use conservative values for physical input parameters, such as heat release rates, fire growth rates and damage temperature and other general modelling assumptions. The rationale for this being that the use of best estimate values may incorrectly lead to the conclusion that damage or ignition will not occur and the scenario in question can be eliminated from further study, i.e. those scenarios which are at the cliff edge of causing damage, based on a best estimate prediction, may actually have a significant risk contribution when uncertainties are properly accounted for. This approach however, has contributed to excessively conservative predictions of the overall fire risk which has hindered the understanding of the driving risk factors and possibly resulted in inappropriate plant changes.

2. Fire Risk Quantification under Uncertainty

The CDF and LERF for each fire scenario are given by:

$$CDF = \lambda_{IS} \cdot W_{IS} \cdot \sum_i (SF \cdot P_{ns})_i \cdot CCDP_i \text{ and} \quad (1)$$

$$LERF = \lambda_{IS} \cdot W_{IS} \cdot \sum_i (SF \cdot P_{ns})_i \cdot CLERP_i \quad (2)$$

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where

λ_{IS}	=	Scenario ignition source bin frequency
W_{IS}	=	Scenario ignition source weighting factor
$(SF \cdot P_{ns})_i$	=	Probability of scenario fire damage state '*i*'
$CCDP_i$	=	CCDP for scenario fire damage state '*i*'
$CLERP_i$	=	CLERP for scenario fire damage state '*i*'

The summations are performed over the scenario damage states to quantify the total calculated CDF and LERF.

In the point estimate analysis, mean values are used for each of the parameters involved, giving estimates of the mean values of CDF and LERF for the scenario. The scenario CDFs and LERFs are summed over the scenarios to derive the overall mean CDF and LERF for the plant.

In the uncertainty analysis, the terms in the above expressions are replaced by probability distributions representing the uncertainty in each term. For the risk-significant scenarios, the uncertainty distributions for the total CDF and LERF are calculated by combining these probability distributions, as products in the above expressions for the scenario CDF and LERF and then as summations for the total CDF and LERF for risk-significant scenarios. Methods for accounting for correlations in the uncertainty distributions of the input parameters are addressed.

3. Detailed Fire Modelling Uncertainty Analyses

The fire modelling quantitative sensitivity and uncertainty analysis is performed using the simulation software Crystal Ball©. This works within Microsoft Excel and allows input and output parameters used within Excel Worksheets to be treated as random variables. In the terminology used by Crystal Ball©, input variables are termed "Assumptions" and output variables are termed "Forecasts".

The Excel workbooks created for each fire compartment/ignition source as part of the detailed fire modelling task have first to be modified, essentially to convert parameters with fixed (but uncertain) values in the point estimate models to random variables in the MC simulation. However, it is also necessary to make certain changes to the structure of the model. For example, the point estimate methodology uses the probability distribution prescribed in Ref. 1 for the ignition source to calculate the probability of the peak HRR being above or below the critical value to cause damage. It also uses the probability distribution for the manual suppression time to calculate the probability of non-suppression within the time to cause damage to a given target. The simulation approach differs in that, on each trial, the ignition source peak HRR and manual suppression time are selected at random (like all the other uncertain parameters) from the defined distributions and are therefore fixed and known in advance so it can be determined definitely whether damage occurs or not. In the simulation approach, the probability of any given damage state occurring is thus not calculated as a single point estimate, but rather as the average number of times the damage state occurs over a large number of trials. As well as performing the sensitivity and uncertainty analysis, this technique simplifies the target damage failure probability calculations and dispenses with the need to make bounding assumptions about the ignition source peak HRR and suppression times in the fire growth event trees as is done in the existing point estimate method.

A flowchart of the overall simulation process for a given ignition source is shown schematically in Figure 1and is described in the following subsections.

Uncertainty distributions for the mean probability ($SF.P_{ns}$) of each damage state are derived using 2D simulation. In the 2D simulation, an inner loop is performed with sample values for the parameters that are modelled as random variables in the point estimate methodology as identified in Section 2 above. The inner loop is typically repeated 10,000 times to derive estimates of the mean $SF.P_{ns}$ value for each damage state. The outer loop simulates the uncertainty in the other parameters that are treated as constants in the point estimate methodology. Thus, sample values of the outer variables are selected and are frozen while the inner loops are performed. A new set of values is then selected for the outer variables from their prescribed distributions and the inner loops repeated to derive a new set of mean $SF.P_{ns}$ values. The outer loops are repeated (typically 100 times) to generate an uncertainty distribution for each damage state mean $SF.P_{ns}$ value. A continuous probability distribution can be fitted to each set of these forecast values to determine the type and shape of the distribution which best fits the $SF.P_{ns}$ values.

4. Overall Fire-Induced CDF & LERF Uncertainty Analyses

In the overall fire-induced CDF and LERF uncertainty analysis, the uncertainty distributions derived for each damage state $SF \cdot P_{ns}$ value are combined with those for the fire ignition frequencies and the CCDP and CLERF values in accordance with Equations (1) and (2) (see Section 2). The Fire PRA model takes account of the uncertainties associated with the basic event probabilities for which uncertainty distributions are defined for:

- Fire-induced circuit failure mode likelihood.
- Component random failure probabilities; and
- Human error probabilities.

The uncertainties are propagated through the Fire PRA model by Monte Carlo simulation to derive uncertainty distributions for CCDP and CLERP. Allowance is made for the state of knowledge correlation (SOKC) between the input data distributions where the input parameters are correlated, as for example, where the same bin frequency is used for two or more ignition sources of the same type.

To limit the number of fire scenarios for which uncertainty analysis is required, the scenario/damages states are ranked in descending order of their contribution to the total CDF and LERF and the overall uncertainty analysis is performed for the most significant fire scenario/damage states.

Figure 2 shows the uncertainty distribution derived for the overall fire-induced CDF for a typical Fire PRA.

5. Sensitivity Analyses

As well as calculating the forecast values for the mean probability of each damage state, Crystal Ball© also evaluates the sensitivity of the fire damage state forecast values to the input parameters. The sensitivity values are calculated according to the percentage contribution each parameter makes to the variance of a given forecast value. The variance of the forecast values depends on both the variance of each parameter and the sensitivity of the forecast values to changes in the parameter value. Thus, a parameter may contribute significantly to the variance in a forecast value because it has a high variance itself, even though the forecast may not be especially sensitive to changes in the parameter's value. Alternatively, a parameter may also contribute significantly to the variance in a forecast value because the forecast value is highly sensitive to changes in the parameter's value, even though the variance of the parameter may be small. The sensitivity values thus provide a means of ranking the parameters according to the relative magnitude of their overall effect on the forecasts. The results of the sensitivity analysis for a typical compartment fire scenario damage state $SF.P_{ns}$ value are shown in Figure 3.

References

1. NUREG/CR-6850, EPRI/NRC-RES Fire PRA Methodology For Nuclear Power Facilities, Volume 2: Detailed Methodology.
2. EPRI 1016737 – "Treatment of Parameter and Model Uncertainty for Probabilistic Risk Assessments".
3. NUREG 1855, Vol. 1- "Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decision Making".
4. NUREG/CR -1934 "Nuclear Power Plant Fire Modeling Application Guide".

Figure 1 Flow Chart of Crystal Ball© Analysis

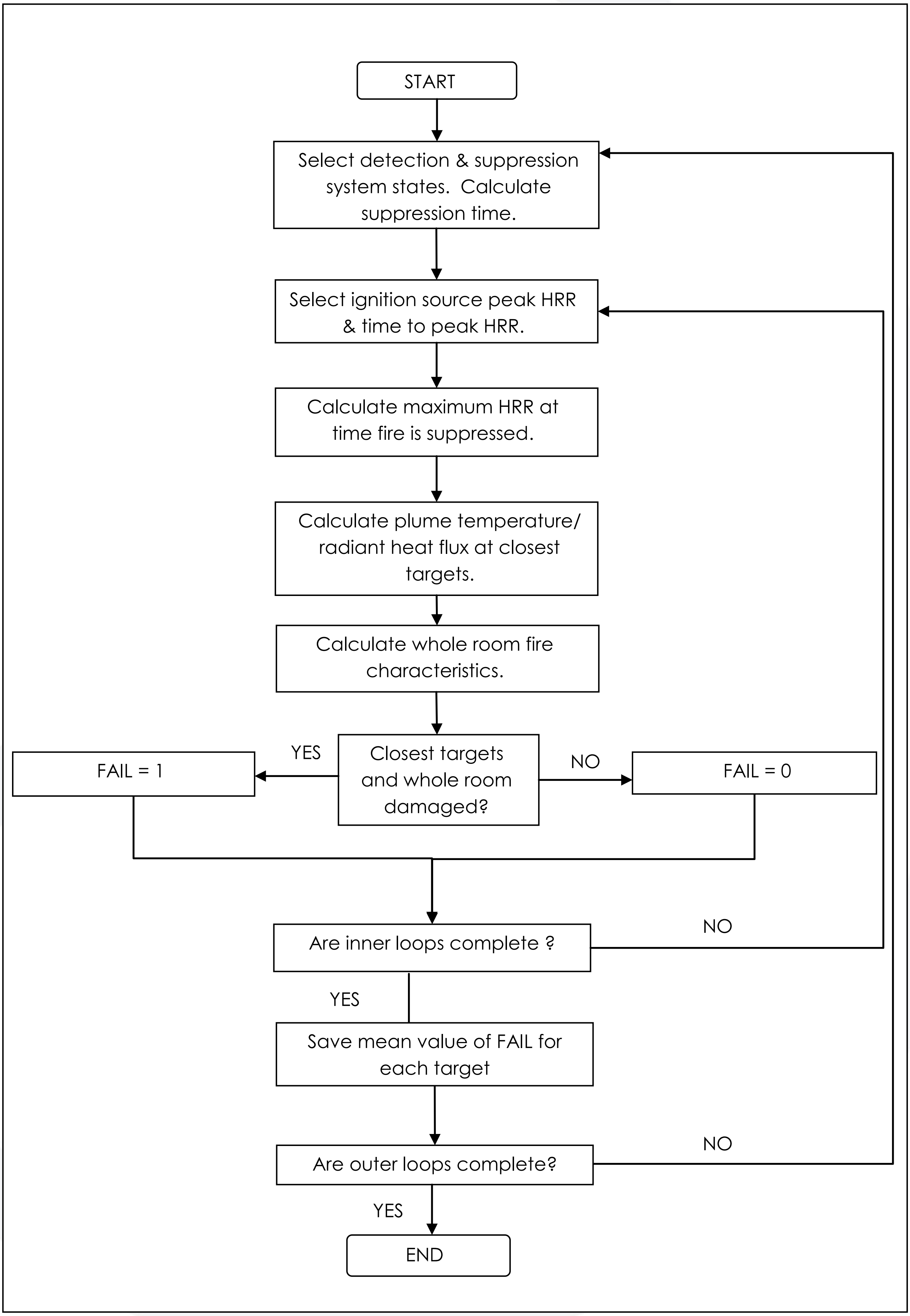

Figure 2 Total CDF Uncertainty Distribution

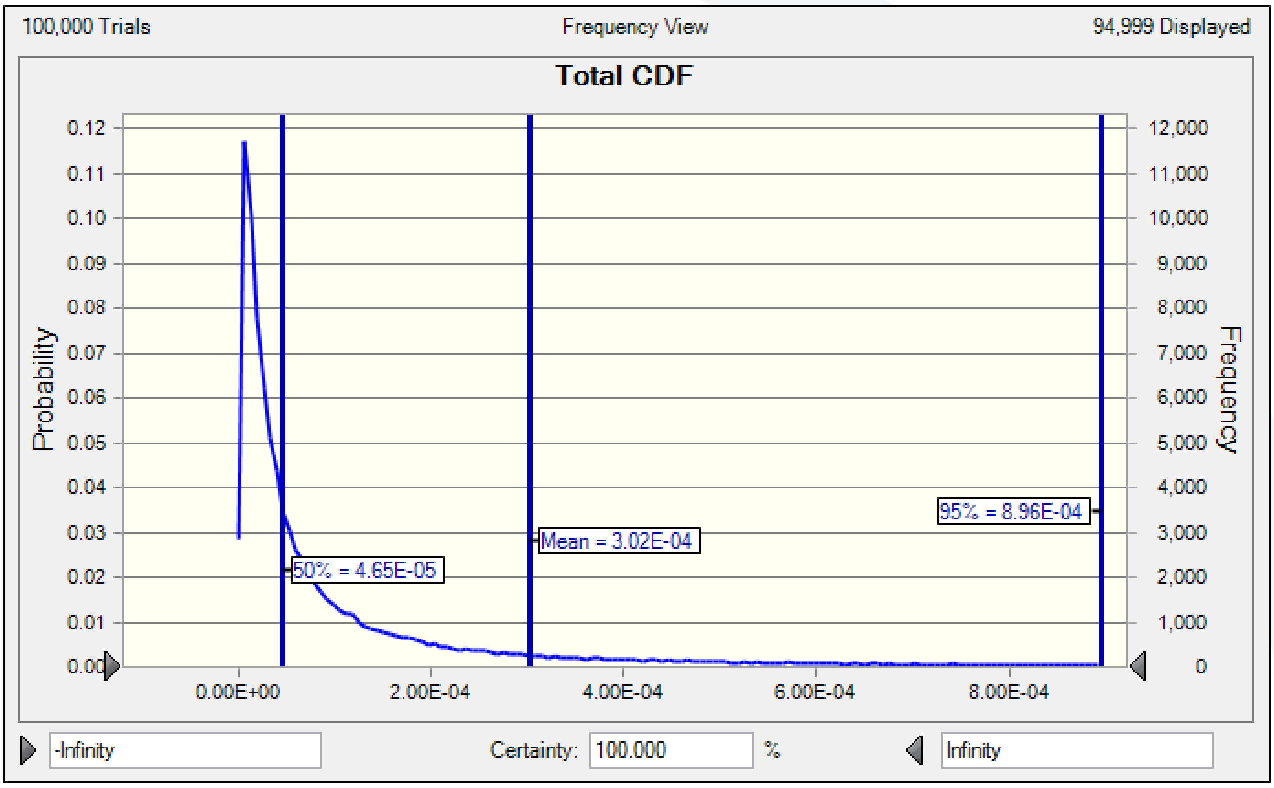

Figure 3 SF.P_{ns} Sensitivity Chart