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MEAN IMPORTANCE MEASURES FOR GROUPS OF EVENTS IN FAULT TREES

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The method of moments is applied to precisely determine the mean values of three importance measures: risk reduction, partial derivative, and variance reduction. Variance reduction calculations, in particular, are significantly improved by eliminating the imprecision associated with Monte Carlo estimates. The three importance measures are extended to permit analyses of the relative importance of groups of basic and initiating events. The partial derivative importance measure is extended by assessing the contribution of a group of events to the gradient of the top event frequency. The group importance measures are quantified for the overall fuel damage equation and for 14 dominant accident sequences from an independent probabilistic safety assessment of the K Production Reactor. This application demonstrates both the utility and the versatility of the group importance measures.

1. INTRODUCTION

Probabilistic safety assessments employ a variety of measures to quantify the relative importance of individual initiating and basic events in fault trees. Most of these importance measures indicate the sensitivity of a top event frequency to change in the value of an initiating event frequency or a basic event probability. Fullwood and Hall¹ discuss eight different sensitivity measures and show how they are interrelated. Andsten and Vaurio² provide a good illustration of the application of point-estimate sensitivity measures to a full scope risk assessment. They utilize a common extension of one point-estimate sensitivity measure (risk reduc-

tion) to assess the contribution of different groups of events to the top event (core damage) frequency.

Considerable attention has been devoted to the development of methods for quantifying uncertainties in top event frequencies. Such uncertainties can be quite large; for example, the interval between the 5th and 95th percentile core damage frequencies from a nuclear power plant risk assessment typically spans about two decades. Although less attention has been devoted to uncertainties in sensitivity measures, Monte Carlo methods indicate such uncertainties are also large. The widely used TEMAC code, which originates with Iman,³ estimates means and uncertainty intervals of top event frequencies and event sensitivity measures using stratified Monte Carlo methods. Importance measures have also been developed to estimate the contributions of individual initiating and basic events to the uncertainty in the top event frequency. A recent version of TEMAC incorporates the Monte Carlo based uncertainty importance measure developed by Iman and Hora.⁴

Analytic methods have been applied, primarily to estimate the means and variances of top event frequencies. For the case in which the individual failure rates are independent, Apostolakis and Lee⁵ use Taylor series expansions to develop approximate analytic expressions for quantifying the contributions of individual basic and initiating events to the mean and variance of the top event frequency. In a different formulation, Bier⁶ applies the method of moments to the problem of finding the mean and variance of the top event frequency given correlated basic event occurrence rates. Bier's formulation is exact when the correlations are total (equal occurrence rates). Zhang⁷ and Yeh⁸ present related formulations based on the use of moments to estimate the mean and variance of the top event frequency.

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This paper describes significant extensions of the moments method. Analytic expressions are developed to permit precise calculations of the mean and variance of the top event frequency. Expressions for the means of the risk reduction, partial derivative, and variance reduction importance measures are also developed. Finally, and perhaps most significantly, the three importance measures are extended in a self-consistent manner to apply to groups of events. Appropriately normalized versions of the three importance measures are defined.

Our formulation is applicable to two commonly encountered cases. In case 1, each basic and initiating event has a unique independent occurrence rate. In case 2, pairs of occurrence rates estimated from common failure data are treated as being equal (totally correlated). In both cases, the use of analytically generated moments eliminates the imprecision associated with Monte Carlo. The precise quantification of the variance and the variance reduction measures as well as the treatment of totally correlated failure rates are significant extensions of our previous formulation.⁹ The current formulation, which is developed in Secs. II, III, and IV, is illustrated for an example problem in Sec. V. Section VI presents results of a demonstration application to the overall fuel damage equation and dominant accident sequences from a recent risk assessment for K Reactor.¹⁰

II. TOP EVENT FREQUENCY

Sets of events that lead to a top event (specified damage state) are called cut sets. A minimal cut set is one that contains no extra events. If any event is removed from a minimal cut set, the remaining events do not lead to the top event. Using Boolean logic, each minimal cut set is represented as the intersection (Boolean AND or product) of an initiating event and specific basic events or their complements. The top event T is the union (Boolean OR) of the minimal cut sets. An example Boolean expression is presented in Sec. V.

The frequency Z_k of the k 'th minimal cut set is the product of its initiating event frequency and the probabilities of its basic and complement events. The frequency Z_T of the top event is bounded by the sum of the frequencies of the minimal cut sets:

$$Z_T \leq \sum_{k=1}^K Z_k \quad (1)$$

The equality holds when the minimal cut sets are disjoint. For example, initiating events are customarily defined to be disjoint, and cut sets having different initiating events are, therefore, disjoint. Two cut sets sharing the same basic event are disjoint if one contains the complement of a basic event contained in the other. Even if the minimal cut sets are not disjoint, the upper bound provided by the preceding equation is a good approximation (the so-called rare event approximation) to the actual top event frequency when the conditional

probability (conditional on the occurrence of the initiating event) of each nondisjoint minimal cut set is small. When the rare event approximation does not hold, algorithms are available to transform the top event expression into a disjoint form.¹¹ Thus, the following expression for the top event frequency is either exact or a good approximation for a wide variety of practical applications:

$$Z_T = \sum_{k=1}^K \prod_{l=1}^L X_l^{\beta_{kl}} (1 - X_l)^{\gamma_{kl}} \quad (2)$$

where

X_l = l 'th occurrence rate (initiating event frequency or basic event probability), which is subsequently assumed to be an independent random variable

β_{kl} = number of appearances of events assigned occurrence rate X_l in cut set k

γ_{kl} = number of appearances of complements of events assigned occurrence rate X_l in cut set k

K = number of cut sets in the top event equation

L = number of occurrence rates required to quantify the top event frequency.

Uncertainty in the values of the initiating event frequencies and basic event probabilities can be characterized by a joint probability density function. The marginal probability density function (distribution) for a particular occurrence rate X_l is the integral of the joint probability density function over the other occurrence rates. If all L occurrence rates are treated as independent random variables, the joint probability density function is simply the product of the marginal distributions.

The top event frequency has its own probability distribution whose parameters (mean, percentiles, variance, etc.) are often estimated by Monte Carlo. This involves evaluating the top event frequency at many points in the space of possible occurrence rates of initiating and basic events. Each point is selected by random sampling from the joint probability density function. The Monte Carlo method provides an approximation to the cumulative distribution of the top event frequency. To reduce the sample size required to provide accurate estimates of the parameters of the top event frequency distribution, Latin hypercube sampling can be used.³

In this paper, in lieu of Monte Carlo sampling, analytic expressions are developed to express the mean and variance of the top event frequency as functions of the known parameters of the marginal occurrence rate distributions. Analytic expressions for the means of three importance measures are also developed. All of these analytic expressions follow from Eq. (2) when the occurrence rates $X_1, X_2, \dots, X_L$ are treated as

independent random variables. In two special cases, some of the computations can be greatly simplified.

In case 1, each initiating or basic event E_e has a unique occurrence rate X_e that is independent of the occurrence rates of all other initiating and basic events. In this case X_l in Eq. (2) can, in effect, be read X_e . That is, there is a one to one correspondence between the basic and initiating events and their independent occurrence rates. Equation (2) is then a direct analog of the Boolean equation with each event E_e in the Boolean equation being replaced by its corresponding occurrence rate X_e . Because no event can occur more than once per cut set, such a top event frequency expression is first order in each occurrence rate ($\beta_{kl} + \gamma_{kl}$ is either zero or one for all k and l).

In case 2, the occurrence rates of certain pairs of initiating or basic events are constrained to be equal. The number of occurrence rates required for quantification is then less than the number of basic and initiating events, and Eq. (2) may be of higher order in some of the shared occurrence rates. Equation (2) remains first order in the nonshared occurrence rates. For example, if X_l represents a frequency assigned to two or more initiating events, Eq. (2) remains first order in X_l because there can be only one initiating event per cut set. Equation (2) may also remain first order in some shared occurrence rates. In particular, if X_l represents a probability assigned to two or more basic events, and if no minimal cut set contains more than one of these events or their complements, Eq. (2) remains first order in X_l .

When the top event frequency Z_T is first order in X_l , which is true for all values of l in case 1 and for some values of l in case 2, Eq. (2) can be rewritten in the form

$$Z_T = \Lambda_l + \Psi_l X_l . \quad (3)$$

Since X_l is presumed here to be independent of the other occurrence rates, Λ_l and Ψ_l are composite variables that are independent of X_l . It follows that the mean (expectation value) of the top event frequency is $\langle Z_T \rangle = \langle \Lambda_l \rangle + \langle \Psi_l \rangle \langle X_l \rangle$. In case 1, Z_T is first order in each of the occurrence rates $X_1, X_2, \dots, X_L$, and $\langle Z_T \rangle$ can be obtained by evaluating Eq. (2) at the means of the independent occurrence rates. That is, $\langle Z_T \rangle = Z_T(\langle X \rangle)$, where X is the vector of independent occurrence rates.

In case 2, the probabilities of two or more basic events are constrained to equal X_l , and if two or more of these basic events or their complements appear in the same minimal cut set, Eq. (2) is greater than first order in X_l ($\beta_{kl} + \gamma_{kl} > 1$). In the presence of such higher order terms, $\langle Z_T \rangle$ cannot be obtained by evaluating Eq. (2) at the means of the independent occurrence rates. The value $\langle Z_T \rangle$ can, however, be determined from the moments $\langle X_l^m \rangle$ of the marginal occurrence rate distributions. The applicable equation, which follows from Eq. (2), is

$$\langle Z_T \rangle = \sum_{k=1}^K \prod_{l=1}^L \langle X_l^{\beta_{kl}} (1 - X_l)^{\gamma_{kl}} \rangle . \quad (4)$$

The variance of the top event frequency is defined as $Var(Z_T) = \langle Z_T^2 \rangle - \langle Z_T \rangle^2$. Substituting the right side of Eq. (1) for Z_T in this definition yields

$$Var(Z_T) = \sum_{k=1}^K [\langle Z_k^2 \rangle - \langle Z_k \rangle^2] + 2 \sum_{j=1}^{K-1} \sum_{k=j+1}^K [\langle Z_j Z_k \rangle - \langle Z_j \rangle \langle Z_k \rangle] . \quad (5)$$

Taking the occurrence rates in Eq. (2) to be independent random variables, the expectation values of the cut set cross products are given by

$$\langle Z_j Z_k \rangle = \prod_{l=1}^L \langle (X_l)^{\beta_{jl} + \beta_{kl}} (1 - X_l)^{\gamma_{jl} + \gamma_{kl}} \rangle . \quad (6)$$

Therefore, in case 1 and case 2, the variance, like the mean, of the top event frequency can be evaluated given the moments $\langle X_l^m \rangle$.

For a lognormally distributed occurrence rate, the m 'th moment is given by the simple expression

$$\langle X_l^m \rangle = \exp(m\mu_l + m^2\sigma_l^2/2) , \quad (7)$$

where the parameters $\mu_l \equiv \langle \ln X_l \rangle$ and $\sigma_l^2 \equiv Var(\ln X_l)$ of the normal distribution for $\ln X_l$ are related to the mean $\langle X_l \rangle$ and the error factor EF_l of the lognormal distribution for X_l by the relations

$$\sigma_l^2 \equiv Var(\ln X_l) = \left[\frac{\ln(EF_l)}{1.645} \right]^2 \quad (8) \quad \star$$

$$\mu_l \equiv \langle \ln X_l \rangle = \ln \langle X_l \rangle - \sigma_l^2/2 . \quad (9)$$

Moments can be determined analytically for many other distributions including the beta, binomial, exponential, gamma, Gaussian, inverse Gaussian, log-uniform, piecewise loguniform, Poisson, triangular, uniform, piecewise uniform, and Weibull distributions. No moment generating functions exist for some distributions including the extreme value, geometric, hypergeometric, negative binomial, and Pareto distributions. For such distributions, Monte Carlo methods can be used to evaluate the moments.

III. SENSITIVITY MEASURES

Two commonly applied sensitivity measures, the partial derivative and risk reduction measures, are discussed and extended to apply to groups of events in this section. Uncertainty importance measures are discussed in Sec. IV. A characteristic symbol is assigned to each importance measure. The symbol PD denotes a partial derivative, and RR denotes a risk reduction. Subscripts are used to denote the event or group of events being considered. For example, RR_e applies to a single basic or initiating event E_e , RR_l applies to the group of events

sharing occurrence rate X_l , and RR_g applies to a group of basic or initiating events, which may have different occurrence rates.

A sensitivity measure is used to rank order events or groups of events according to the magnitude of their associated sensitivities. These magnitudes and the associated rank ordering depend, however, on the particular point at which the sensitivities are evaluated. For example, different rank orderings may result from evaluating sensitivities at the point where all occurrence rates are at their mean values, the point where all occurrence rates are at their median values, or a point representing nominal values of the occurrence rates without reference to their marginal distributions. Instead of evaluating the sensitivity measures at a particular point, the practice adopted in this paper is to use the mean values of importance measures for rank ordering.

III.A. Partial Derivative

A partial derivative of the top event frequency Z_T indicates the change in Z_T per infinitesimal change in one of the independent occurrence rates with all of the others held constant. If E_e is an initiating event whose frequency is independent of the occurrence rates of other events, PD_e is the probability of the top event conditional on the occurrence of initiating event E_e . Taking the partial derivative of Eq. (2) with respect to the occurrence rate X_{l_e} of event E_e yields

$$PD_e = PD_{l_e} = \sum_{k=1}^K \left[\beta_{kl_e} \prod_{l=1}^L X_l^{\beta_{kl} - \delta_{ll_e}} (1 - X_l)^{\gamma_{kl}} - \gamma_{kl_e} \prod_{l=1}^L X_l^{\beta_{kl}} (1 - X_l)^{\gamma_{kl} - \delta_{ll_e}} \right], \quad (10)$$

where δ_{ll_e} denotes the Kroneker delta, which is one if $l = l_e$ and zero otherwise. In case 1, Eq. (2) is first order in each independent occurrence rate, Eq. (3) applies, and $PD_l = \Psi_l$ is first order in each of the remaining independent occurrence rates. In this case, the mean partial derivative $\langle PD_l \rangle$ is simply PD_l evaluated at the means of the other occurrence rates. In case 2, the probabilities of two or more basic events are constrained to be equal, and Eq. (10) may be higher order in the shared occurrence rate(s). The mean partial derivative then follows from the expectation value of Eq. (10), which can be quantified given the values of the moments $\langle X_l^m \rangle$.

III.B. Contribution to Mean Gradient

The gradient of a function of two or more independent variables is a vector quantity whose direction is that in which the function changes most rapidly (has the largest directional derivative). The magnitude of the gradient is equal to the largest directional derivative at the point of interest in multidimensional space. The

gradient of the top event frequency is the vector sum of components attributable to each of the independent occurrence rates. The square of the magnitude of the gradient is the sum of the squares of the partial derivatives of the top event frequency with respect to each of the independent occurrence rates:

$$|\nabla Z_T|^2 = \sum_{l=1}^L PD_l^2. \quad (11)$$

The contribution of a single occurrence rate X_l to the square of the gradient is simply PD_l^2 . Similarly, the contribution of a group G_g of basic and initiating events to the square of the gradient is the sum of the squares of the partial derivatives associated with the occurrence rates of events in the group:

$$|\nabla Z_{T,g}|^2 = \sum_{\{l_e | E_e \in G_g\}} PD_{l_e}^2. \quad (12)$$

An importance measure that is applicable to groups of events yet reduces to the mean partial derivative for a group containing only one event, is the component of the mean gradient attributable to events in the group:

$$|\langle \nabla Z_{T,g} \rangle| = \left[\sum_{\{l_e | E_e \in G_g\}} \langle PD_{l_e} \rangle^2 \right]^{1/2}, \quad (13)$$

or in normalized form $\eta |\langle \nabla Z_{T,g} \rangle| = |\langle \nabla Z_{T,g} \rangle| / |\langle \nabla Z_T \rangle|$. This importance measure indicates the relative rates of change in the top event frequency achievable by changing the occurrence rates of events in various groups. The maximum value of the normalized importance measure, which would be realized if all basic and initiating events were included in a single group, is one. For a group comprised of a single event E_e , the unnormalized importance measure is the same as the corresponding mean partial derivative $\langle PD_e \rangle$.

III.C. Risk Reduction

The risk reduction, RR_e , associated with a particular event E_e is the reduction in the top event frequency achieved by eliminating the minimal cut sets containing the event from the Boolean top event expression and removing the complement event $/E_e$ from the remaining minimal cut sets (in effect, making event E_e impossible). Using Eqs. (1) and (2), the top event frequency minus the modified top event frequency is

$$RR_e = \sum_{\{k | E_e \in S_k\}} Z_k + \sum_{\{k | /E_e \in S_k\}} \left[Z_k - \prod_{\{l | l \neq l_e\}} X_l^{\beta_{kl}} (1 - X_l)^{\gamma_{kl}} \right]. \quad (14)$$

Here S_k denotes the k 'th minimal cut set so that $\{k | E_e \in S_k\}$ denotes the cut sets containing event E_e , and $\{k | /E_e \in S_k\}$ denotes the cut sets containing the complement event $/E_e$. If the complement event $/E_e$ does not appear in the top event expression, RR_e is

merely the sum of the frequencies of cut sets containing event E_e .

The risk reduction concept can be extended to a group of events in a straightforward manner. The risk reduction RR_g associated with events in group G_g is the reduction in the top event frequency achieved by eliminating the minimal cut sets containing events in G_g from the Boolean top event expression and removing any complements of these events from the remaining minimal cut sets:

$$RR_g = \sum_{\{k|S_k \cap G_g \neq \emptyset\}} Z_k + \sum_{\{k|S_k \cap C_g \neq \emptyset, S_k \cap G_g = \emptyset\}} Z_k - \prod_{\{l|l \neq l_e \forall E_e \in G_g\}} X_l^{\beta_{kl}} (1 - X_l)^{\gamma_{kl}} \quad (15)$$

Here S_k denotes the k 'th cut set and C_g denotes the set of complements of events in group G_g ; that is, the second sum is over cut sets containing complements of events in group G_g but none of the uncomplemented events comprising group G_g .

Rank ordering of event groups based on the magnitudes of their risk reductions can be based on the mean risk reduction $\langle RR_g \rangle$ or the normalized form $\eta \langle RR_g \rangle = \langle RR_g \rangle / \langle Z_T \rangle$, which is the fractional reduction in the top event frequency achievable by eliminating events in group G_g .

In case 1, RR_g is first order in each of the independent occurrence rates, and the mean risk reduction $\langle RR_g \rangle$ is equal to RR_g evaluated at the means of the independent occurrence rates. In case 2, Z_T may remain first order in some X_l , and Eq. (3) implies the risk reduction for the group of events sharing X_l is $RR_l = PD_l X_l$ with $\langle RR_l \rangle = \langle PD_l \rangle \langle X_l \rangle$. If RR_g is higher order, the mean risk reduction $\langle RR_g \rangle$ can be determined from the moments $\langle X_l^m \rangle$ by taking the expectation value of Eq. (15).

Events that are constrained to have equal (totally correlated) occurrence rates need not have equal risk reductions. That is, RR_e is determined by eliminating the single event E_e not by forcing its otherwise shared occurrence rate X_{l_e} to zero. For example, a plant might contain a number of valves that are virtually identical. Although failures of the valves might be treated as independent events, the valve failure rates might be presumed to be equal. The risk reduction measure for any one valve would reflect the reduction in the top event frequency associated with replacing that valve alone with a hypothetical failure-proof valve. Since some of the valves might provide far more important functions than others, the risk reductions associated with individual valves in the group could differ appreciably. Of course the risk reduction associated with making all of the valves failure proof can also be determined from the group risk reduction. Mathematically, $RR_e \leq RR_{l_e}$ with the equality holding when the occurrence rate of event E_e is unique to that event. This characteristic is not shared by the partial derivative sensitivity measure.

The partial derivative is taken with respect to an occurrence rate, and the same partial derivative applies to all events that share the same occurrence rate, that is, $PD_e = PD_{l_e}$.

IV. UNCERTAINTY IMPORTANCE MEASURES

IV.A. Variance Reduction

The uncertainty in the top event frequency Z_T is a composite uncertainty attributable to the underlying uncertainties in all of the initiating event frequencies and basic event probabilities. It is reasonable to ask how much each of these underlying occurrence rates contributes to the overall uncertainty in Z_T . A measure of this contribution is the reduction in the variance of Z_T achieved by fixing the value of one of the occurrence rates X_l . The unconditional variance of a random variable can be expressed in terms of the conditional variance as follows¹²:

$$Var(Z_T) = \langle Var(Z_T | X_l) \rangle + Var[\langle Z_T | X_l \rangle] \quad (16)$$

In other words, the unconditional variance is equal to the mean of the conditional variance plus the variance of the conditional mean. This implies that the mean variance reduction is equal to the variance of the conditional mean; that is,

$$\langle VR_l \rangle = Var[\langle Z_T | X_l \rangle] \quad (17)$$

This importance measure can be normalized by expressing the mean variance reduction as a fraction of the unconditional variance: $\eta \langle VR_l \rangle = \langle VR_l \rangle / Var(Z_T)$. If the top event frequency equation is first order in the l 'th independent occurrence rate, Eq. (3) applies, and the conditional mean is $\langle Z_T | X_l \rangle = \langle \Lambda_l \rangle + \langle PD_l \rangle X_l$. It follows from Eq. (17) that the mean variance reduction associated with fixing the occurrence rate X_l is $\langle VR_l \rangle = \langle PD_l \rangle^2 Var(X_l)$. If the top event frequency equation is higher order in a particular occurrence rate, the associated variance reduction can be obtained by the method of moments as described as follows for an arbitrary group of events.

The variance reduction associated with fixing the occurrence rates of events in group G_g is

$$\langle VR_g \rangle = Var[\langle Z_T | X_{l_e} \forall E_e \in G_g \rangle] \quad (18)$$

That is, the expectation value of the variance reduction achieved by fixing the occurrence rates of all events in group G_g is the variance of the corresponding conditional mean. To evaluate the mean group variance reduction analytically, the conditional mean can be written in the form

$$\langle Z_T | X_{l_e} \forall E_e \in G_g \rangle = \sum_{k=1}^K \langle \Xi_{kg} \rangle \Gamma_{kg} \quad (19)$$

Here each cut set Z_k has been factored into two terms. The term Ξ_{kg} contains those failure rates that are not associated with events in group G_g , and Γ_{kg} contains

those failure rates that are associated with events in group G_g . Specifically,

$$\Xi_{kg} = \prod_{\{I_e | E_e \in G_g\}} X_{I_e}^{\beta_{kl_e}} (1 - X_{I_e})^{\gamma_{kl_e}} \quad (20)$$

and

$$\Gamma_{kg} = \prod_{\{I_e | E_e \in G_g\}} X_{I_e}^{\beta_{kl_e}} (1 - X_{I_e})^{\gamma_{kl_e}} \quad (21)$$

The variance reduction associated with fixing the occurrence rates of events in group G_g can then be expressed as

$$\begin{aligned} \langle VR_g \rangle &= \sum_{k=1}^K \langle \Xi_{kg} \rangle^2 [\langle \Gamma_{kg}^2 \rangle - \langle \Gamma_{kg} \rangle^2] \\ &+ 2 \sum_{j=1}^{K-1} \sum_{k=j+1}^K \langle \Xi_{jg} \rangle \langle \Xi_{kg} \rangle \\ &\times [\langle \Gamma_{jg} \Gamma_{kg} \rangle - \langle \Gamma_{jg} \rangle \langle \Gamma_{kg} \rangle], \quad (22) \end{aligned}$$

where

$$\langle \Gamma_{jg} \Gamma_{kg} \rangle = \prod_{\{I_e | E_e \in G_g\}} \langle X_{I_e}^{\beta_{jl} + \beta_{kl}} (1 - X_{I_e})^{\gamma_{jl} + \gamma_{kl}} \rangle. \quad (23)$$

All of the expectation values on the right side of the preceding equation for $\langle VR_g \rangle$ can be evaluated provided that the moments $\langle X_{I_e}^m \rangle$ are known.

IV.B. Iman-Hora Uncertainty Importance

Iman and Hora observe that the normalized variance reduction can be estimated from a Monte Carlo sample by the coefficient of regression (R^2 statistic) calculated from a linear regression of sample values of Z_T versus sample values of X_e (Ref. 4). When long-tailed distributions such as the lognormal distribution are used to characterize the input uncertainties, however, Monte Carlo estimates of $\langle VR_e \rangle$ vary significantly from sample to sample (for samples of manageable size). To circumvent this lack of precision, Iman and Hora recommend a Monte Carlo-based estimate of the variance reduction in the logarithm of the top event frequency. This uncertainty importance measure is denoted by the symbol UI_e and calculated as the coefficient of correlation (R^2 statistic) of a fit of sample values of $\ln(Z_T)$ versus sample values of X_e . Because UI_e measures the variance reduction in the logarithm of Z_T not the variance reduction in Z_T itself, the Iman-Hora uncertainty importance measure cannot readily be extended to groups of events. Also, as shown in Sec. V, the Iman-Hora uncertainty importance measure still suffers from the imprecision associated with Monte Carlo estimates.

V. EXAMPLE PROBLEM

The system depicted in Fig. 1 can be used to illustrate the concepts introduced in the preceding section. The system provides flow from point 0 to either point

1 or point 2. The terms I_1 and I_2 are used to denote initiating events. Event I_1 occurs when flow is demanded at point 1. Event I_2 occurs when flow is demanded at point 2. These initiating events are presumed to be mutually exclusive. Terms B_a , B_b , B_c , and B_d are used to denote the basic events, which correspond to flow blockages in the respective lines. Considering only the events just listed, the top event (failure to provide a required flow on demand) is given by the Boolean expression

$$\begin{aligned} T &= I_1 * B_a * B_b + I_1 * B_a * B_c + I_1 * B_a * B_d \\ &+ I_2 * B_a * B_c + I_2 * B_a * B_d + I_2 * B_b * B_c \\ &+ I_2 * B_b * B_d. \quad (24) \end{aligned}$$

Denoting the occurrence rates of events I_1 , I_2 , B_a , B_b , B_c , and B_d by X_1 , X_2 , X_a , X_b , X_c , and X_d , respectively, the frequency of the top event under the rare event approximation is

$$\begin{aligned} Z_T &= X_1 X_a X_b + X_1 X_a X_c + X_1 X_a X_d + X_2 X_a X_c \\ &+ X_2 X_a X_d + X_2 X_b X_c + X_2 X_b X_d. \quad (25) \end{aligned}$$

Each of the occurrence rates is taken to be lognormally distributed with means $\langle X_1 \rangle = 1$, $\langle X_2 \rangle = 2$, $\langle X_a \rangle = \langle X_b \rangle = 0.2$, $\langle X_c \rangle = \langle X_d \rangle = 0.1$, and error factors $EF_1 = 5$, $EF_2 = 3$, $EF_a = EF_b = 2$, $EF_c = EF_d = 3$. If all six occurrence rates are treated as independent random variables, the means of the top event frequency, the partial derivatives, and the risk reductions are the respective functions evaluated at the means of the independent variables. Also, $\langle RR_e \rangle = \langle PD_e \rangle \langle \theta_e \rangle$ and $\langle VR_e \rangle = \langle PD_e \rangle^2 \text{Var}(X_e)$ for each of the independent variables. The quantitative results are summarized in Table I under the caption "Independent Event Occurrence Rates."

An alternative quantification is obtained by forcing the total correlations $X_a = X_b$ and $X_c = X_d$. The top event frequency equation then becomes

$$Z_T = X_1 X_a^2 + 2X_1 X_a X_c + 4X_2 X_a X_c. \quad (26)$$

The quantitative results presented for this case in Table I indicate the tendency of all expectation values to increase because $\langle X^2 \rangle$ is greater than $\langle X \rangle^2$. Note

Fig. 1. Simple flow delivery system.

TABLE I
Importance Measures for the Example Problem

$T = I_1 * B_a * B_b + I_1 * B_a * B_c$ $+ I_1 * B_a * B_d$ $+ I_2 * B_a * B_c + I_2 * B_a * B_d$ $+ I_2 * B_b * B_c + I_2 * B_b * B_d$				Total Correlations $\theta_a = \theta_b$ and $\theta_c = \theta_d$		
Independent Event Occurrence Rates				$\langle \Phi_T \rangle = 0.24$	$ \langle \nabla \Phi_T \rangle = 1.736$	$Var(\Phi_T) = 0.05416$
Event	$\langle \theta_c \rangle$	EF_c	$Var_{(oe)}$	$\langle RR_c \rangle$	$\langle PD_c \rangle$	$\langle VR_c \rangle$
B_a	0.2	2	0.007771	0.16	0.8	0.004974
B_b	0.2	2	0.007771	0.12	0.6	0.002798
B_c	0.1	3	0.005621	0.1	1	0.005621
B_d	0.1	3	0.005621	0.1	1	0.005621
I_1	1	5	1.604	0.08	0.08	0.01027
I_2	2	3	2.248	0.16	0.08	0.01439
Event Group				$\langle RR_g \rangle$	$ \langle \nabla \Phi_{T,g} \rangle $	$\langle VR_g \rangle$
B_a, B_b				0.24	1	0.007832
B_c, B_d				0.20	1.414	0.01124
B_a, B_b, B_c, B_d				0.24	1.732	0.02021
I_1, I_2				0.24	0.1131	0.02466
				$\langle RR_g \rangle$	$\langle PD_g \rangle$	$\langle VR_g \rangle$
				0.1678	1.4	0.01828
				0.1278	2	0.02248
				0.1		
				0.1		
				0.0878	0.0878	0.01236
				0.16	0.08	0.01439
				$\langle RR_g \rangle$	$ \langle \nabla \Phi_{T,g} \rangle $	$\langle VR_g \rangle$
				0.2478	1.4	0.01828
				0.2	2	0.02248
				0.2478	2.441	0.04513
				0.2478	0.1188	0.02675

that the sensitivity measures corresponding to initiating event I_2 are unaffected by the induced correlations.

Several observations are identical or similar for both quantifications. In particular, although $\langle X_a \rangle = \langle X_b \rangle$ for the first quantification and $X_a = X_b$ for the second quantification, the corresponding mean risk reductions for events B_a and B_b are not equal because the top event expression is not symmetric in B_a and B_b . On the other hand, due to symmetry, all of the importance measures for B_c and B_d are equal in both quantifications. The rank ordering of group importance measures is the same in both quantifications, except the basic events as a group have a larger expected variance reduction than the initiating events in the second quantification where $X_a = X_b$ and $X_c = X_d$. Because of the cross product terms indicated in Eqs. (5) and (6), the variance reductions do not sum to the total variance for either quantification. This would only be the case if the top event frequency equation were linear (as opposed to first order) in all of the uncertain failure rates. Finally, the initiating events contribute the most to the top event uncertainty in both quantifications. This is due to the relatively large variances of the initiating event frequencies not to their partial derivatives, which are relatively small.

Table II compares the Iman-Hora uncertainty importance results for the example problem to the precise variance reductions obtained by the method of moments. Because the Iman-Hora measure indicates the reduction in the variance in $\ln(Z_T)$ rather than Z_T itself, it should not be surprising that the rankings obtained by the two methods differ even for this simple example. It is clear, however, from the symmetry of the example problem that the uncertainty importance measures should be equal for events B_c and B_d . The lack of equality of the Iman-Hora measures in Table II (16.6% for B_c versus 13.4% for B_d for using a Latin hypercube sample of size 200) indicates the difficulty associated with precisely estimating uncertainty importance by Monte Carlo methods.

VI. DEMONSTRATION APPLICATION

The importance measures developed in the preceding sections have been applied in a variety of different ways to top event equations from a complete accident sequence analysis for K Reactor, which is located at the U.S. Department of Energy Savannah River Site.¹⁰ The results presented here are used to illustrate the types of analyses permitted by the group importance measures. For details regarding the system models and the implications of sensitivity and uncertainty analysis results, the interested reader should refer to the original report.¹⁰

A principal objective of the accident sequence analysis was to estimate the contribution of electrical and nonelectrical failures to each of the dominant

TABLE II

Comparison of Uncertainty Importance Measures
for the Example Problem with Independent
Occurrence Rates

Event	Mean Variance Reduction in Φ_T Based on Method of Moments (%)	Iman-Hora ⁴ Estimate of Mean Variance Reduction in $\ln(\Phi_T)$ Based on Latin Hypercube Sample of Size 200 (%)
B_a	9.18	15.4
B_b	5.17	7.4
B_c	10.4	16.6
B_d	10.4	13.4
I_1	19.0	16.8
I_2	26.6	35.1

accident sequences and to the overall fuel damage frequency. For this purpose, the basic and initiating events were divided into seven groups: initiating events, electrical failures, mechanical failures, instrumentation failures, common cause failures, human errors, and nonrecovery events. The assignment of events to these groups is fairly unambiguous; however, it does not account for common cause or initiating events that are predominately electrical or mechanical in nature. To obtain the results presented in this paper, the TEMAC computer code³ was modified to compute mean risk reduction, gradient, and variance reduction importance measures by the method of moments.

To aid in understanding the results from the various group sensitivity and uncertainty analyses, equivalent rankings are included in the tables. The event or group of events yielding the largest value of a given im-

portance measure for a particular top event is assigned the rank 1.0, indicating that it is the most important event or group of events by that measure. Similarly, the event or group yielding the second largest value is assigned the rank 2.0, the event or group yielding the third largest value is assigned the rank 3.0, and so on. In the case of a tie, the rank assigned is the average of the ranks that would have been assigned had there been no tie. For example, there are several sequences for which 100% risk reduction is associated with two groups, which are, therefore, assigned the rank of 1.5.

VI.A. Fuel Damage Equation

To assess sensitivities and uncertainties associated with the overall fuel-damage frequency, a reduced fuel damage equation was formed by taking the Boolean sum of the 14 dominant accident sequences. The resulting equation contains 218 cuts sets and 143 basic and initiating events. It accounts for >99% of the overall mean fuel damage frequency. Table III presents the group risk reduction, gradient, and variance reduction measures for this fuel damage equation for case 1 in which each initiating or basic event is assigned an independent occurrence rate.

Because an initiating event appears in every cut set, the initiating event group has a risk-reduction measure of 100% as indicated in the risk-reduction column of Table III. This column also indicates that the elimination of nonrecovery events would reduce the mean fuel damage frequency by ~69%, the elimination of human errors would provide a 64% reduction, the elimination of mechanical failures would provide a 20% reduction, and similar reductions are shown for common cause (16%) and electrical (15%) failures. These electrical failures, however, do not include initiating events related to the loss of electric power. If two initiators, loss

TABLE III

Group Importance Measures for the Fuel Damage Equation with No Correlated Occurrence Rates

Event Group	Mean Risk Reduction		Mean Contribution to Gradient		Mean Variance Reduction		Mean Conditional Variance Reduction ^a	
	$\eta\langle RR_g \rangle$ (%)	Rank	$\eta\langle \nabla \Phi_{T,g} \rangle$ (%)	Rank	$\eta\langle VR_g \rangle$ (%)	Rank	(%)	Rank
Initiating events	100	1	4.2	3	42.3	1		
Nonrecovery events	69.2	2	0.0	6.5	4.8	3	26.2	2
Human errors	63.8	3	50.0	2	5.1	2	27.7	1
Mechanical	20.3	4	0.5	4	4.7	4	26.0	3
Common cause	16.5	5	86.5	1	1.0	5	5.7	4
Electrical	15.0	6	0.1	5	0.4	6	2.0	5
	(35.7) ^b							
Instrumentation	0.7	7	0.0	6.5	0.1	7	0.2	6

^aConditional on initiating event frequencies being fixed at their mean values.

^bInitiators involving loss of electrical power included with electrical group.

of site power and loss of river water resulting in loss of power, are included in the electrical group, the electrical risk-reduction measure increases to ~36%.

The common-cause and human error event groups make the largest contributions to the mean gradient of the fuel damage frequency, 87 and 50%, respectively. That is, the fuel damage frequency is most sensitive to changes in the estimated frequencies of common cause failures and human errors. Other event groups have relatively minor gradient importance measures.

Uncertainties in initiating-event frequencies typically contribute the most to the uncertainty in a top event frequency because every cut set contains an initiating event, and the magnitudes of the uncertainties in initiating event, frequencies generally exceed those for basic event probabilities. The variance reduction column of Table III indicates that eliminating uncertainties in initiating events would reduce the variance of the top event frequency by an average of >42%. This is nearly an order of magnitude greater than the mean variance reduction for any of the basic event groups. To clarify the uncertainty importance associated with basic event groups, conditional uncertainty importance calculations were performed in which the initiating-event frequencies were fixed at their mean values. Conditional variance reductions are largest for human errors (28%), nonrecovery events (26%), and mechanical events (26%). With the assumption of independent failure rates, electrical failures are relatively small contributors to the uncertainty in the top event frequency.

Table IV presents an alternative quantification, case 2, in which failure rates based on common failure data for similar components are constrained to be equal. For the most part, changes in the magnitudes of the importance measures from those shown in Table III are small. The importance rankings for the risk reduction and gra-

dient importance measures are unchanged. Correlating the failure rates of similar components does, however, increase the variance of the fuel damage frequency by more than a factor of 3, and as indicated by the variance reductions in Tables III and IV, a smaller fraction of the increased variance can be attributed to any single event group (16.6% in Table IV versus 42.5% in Table III for the initiating events group). Another noteworthy change is the increase in conditional variance reduction for those groups having several events with totally correlated occurrence rates. By this measure, the mechanical group, which contains 15 events with totally correlated occurrence rates (4 pairs, 1 triplet, and 1 quadruplet), moves from third in Table III (26% and behind human errors and nonrecovery events) to first (32%) in Table IV. Similarly, the electrical group, which contains 25 events with totally correlated occurrence rates (11 pairs and 1 triplet), ranks second (15%) by the conditional variance reduction measure in Table IV. This contrasts with Table III in which the electrical group ranks fifth (2%) by the same measure.

VI.B. Dominant Accident Sequence Results by Group

The importance measures for each event group can be compared for the 14 dominant accident sequences and the fuel damage equation. Table V provides such a comparison for the human errors group. This table includes the ranking of the human errors group by each importance measure for each accident sequence. In Table V and subsequent tables, case 2, which accounts for totally correlated occurrence rates, is used for quantification. This differs from earlier results^{9,10} based on case 1 in which all initiating and basic event occurrence rates are presumed independent.

The risk reduction results shown in Table V reveal that human errors occur in 100% of the cut sets for

TABLE IV
Group Importance Measures for the Fuel Damage Equation with Totally Correlated Occurrence Rates

Event Group	Mean Risk Reduction		Mean Contribution to Gradient		Mean Variance Reduction		Mean Conditional Variance Reduction ^a	
	$\eta\langle RR_g \rangle$ (%)	Rank	$\eta\langle \nabla \Phi_{T,g} \rangle$ (%)	Rank	$\eta\langle VR_g \rangle$ (%)	Rank	(%)	Rank
Initiating events	100	1	3.4	3	16.6	1		
Nonrecovery events	70.2	2	0.0	6.5	1.7	4	11.3	3
Human errors	62.6	3	40.8	2	1.7	5	11.2	4
Mechanical	22.2	4	0.5	4	5.0	2	32.3	1
Common cause	16.0	5	91.2	1	0.6	6	4.2	5
Electrical	15.0	6	0.3	5	2.2	3	14.6	2
	(35.0) ^b							
Instrumentation	0.7	7	0.0	6.5	0.0	7	0.1	6

^aConditional on initiating event frequencies being fixed at their mean values.

^bInitiators involving loss of electrical power included with electrical group.

TABLE V
Importance Measures for Human Errors with Correlated Occurrence Rates

Top Event Equation	Mean Risk Reduction		Mean Contribution to Gradient		Mean Variance Reduction		Mean Conditional Variance Reduction ^a	
	$\eta\langle RR_g \rangle$ (%)	Rank	$\eta\langle \nabla \Phi_{T,g} \rangle$ (%)	Rank	$\eta\langle VR_g \rangle$ (%)	Rank	(%)	Rank
Sequence 1	100	2	1.5	2	29.2	2	64.8	1
Sequence 2	24.0	3	40.8	2	7.5	2	7.7	2
Sequence 3	34.9	4	1.4	4	0.1	5	0.6	4
Sequence 4	100	2	1.6	2	7.9	3	24.9	2
Sequence 5	0.0	7	0.0	7	0.0	7	0.0	7
Sequence 6	20.1	4	1.7	4	0.0	5	0.4	4
Sequence 7	1.0	6	0.0	6	0.0	6	0.0	5
Sequence 8	100	1.5	25.6	2	8.8	2	100	1
Sequence 9	100	2	4.2	2	6.9	3	23.5	2
Sequence 10	100	2	0.1	2	9.0	2	97.1	1
Sequence 11	100	2	1.8	3	0.2	5	1.6	4
Sequence 12	100	1.5	0.3	5	0.6	3	5.0	2
Sequence 13	100	2	30.0	2	5.8	2	52.3	1
Sequence 14	15.9	4	40.8	2.5	0.1	5	0.4	4
Fuel damage	62.6	3	40.8	2	1.7	5	11.2	6

^aConditional on initiating event frequencies being fixed at their mean values.

eight of the fourteen dominant accident sequences. If human errors could be eliminated, the mean fuel damage frequency would be decreased by ~64%. Table V also shows that human errors rank second by the gradient importance measure for the fuel damage equation and eight of the dominant accident sequences. In addition, uncertainties in the probabilities of human errors are significant contributors to the uncertainties in some of the dominant accident sequence frequencies, ranking second (to the initiating events group) by the variance reduction measure for 5 of the 14 dominant accident sequences.

VI.C. Other Group Analyses

Events can be grouped in any manner desired by the analyst. This is particularly useful for analyzing the importance of various groupings of components of interest. Table VI shows the results of an importance analysis in which all of the initiating and basic events were grouped by system. The systems used in the analysis are the process water system (PWS), which provides normal cooling to core components; the emergency cooling system (ECS), which provides backup core cooling; the cooling water system (CWS), which cools the process water heat exchangers and numerous other components; electrical power systems; the water disposal system (WDS), which removes water from pump and motor rooms and provides water to the ECS; the moderator recovery system, which provides makeup coolant to the moderator tank for small loss-of-coolant

accidents (LOCAs); the River Water System, which is the ultimate heat sink; components and subsystems required for scram; and the instrument air system. Based on the risk-reduction measure, the most important systems are the CWS and the ECS. Elimination of CWS failures would reduce the mean fuel damage frequency by >58%. Elimination of ECS failures would reduce the fuel damage frequency by >50%. The PWS group includes all of the LOCA initiators and has a risk reduction measure of 40%. The CWS failures totally dominate the gradient importance measure. This is due primarily to common cause failures of valves required to isolate pipe breaks in the CWS. The PWS group accounts for >19% of the variance in the top event frequency; however, this is largely due to uncertainties in the frequencies of large, medium, and small LOCA initiators. The conditional variance reduction measure, for which initiating event frequencies are fixed at their mean values, is dominated by WDS failures, which account for almost 38% of the conditional variance. Given results like those in Table VI, the analyst can review the dominant sequences and cut sets to determine the most important events or conduct an importance analysis of each basic event assigned to the dominant systems.

Importance analyses were also performed on the initiating events. As shown in the risk reduction column of Table VII, initiators associated with pipe breaks in the CWS and PWS account for most of the mean fuel damage frequency. The loss of site power (LOSP) and loss of river water (LORW) initiators account for over

TABLE VI
System Importance Measures with Correlated Occurrence Rates

System	Mean Risk Reduction		Mean Contribution to Gradient		Mean Variance Reduction		Mean Conditional Variance Reduction ^a	
	$\eta\langle RR_g \rangle$ (%)	Rank	$\eta \langle \nabla \Phi_{T,g} \rangle $ (%)	Rank	$\eta\langle VR_g \rangle$ (%)	Rank	(%)	Rank
Cooling water system	58.4	1	99.9	1	2.6	4	5.9	3
Emergency cooling system	50.1	2	0.2	6	2.7	3	17.5	2
Process water system	40.0	3	2.6	2	19.2	1	4.4	4
Electrical power systems	32.9	4	0.8	3	0.5	6	0.7	6
Water disposal system	15.1	5	0.0	8	5.8	2	37.8	1
River water system	12.5	6	0.3	5	0.7	5	3.4	5
Moderator recovery system	5.8	7	0.0	8	0.0	7	0.3	7
Scram system	1.6	8	0.6	4	0.0	8	0.1	8
Instrument air system	0.2	9	0.0	8	0.0	9	0.0	9

^aConditional on initiating event frequencies being fixed at their mean values.

16 and 12% of the mean fuel damage frequency, respectively. The LOSP initiating-event frequency represents the loss of normal power at the reactor while power is maintained at the river water pumps. The LORW initiating-event category represents loss of power to the river water pumps. It was estimated that ~50% of the time, power is lost to the river water pumps, and power also would be lost to the reactor site (site grid blackout). The remainder of the LORW initiator frequency is expected to involve a localized loss of power to the river water pumps, which does not affect normal power supplies to the reactor.

Finally, a risk reduction analysis of the importance of various subgroups of electrical events was performed. As indicated in Table VIII, the dominant electrical events are the loss of site power initiator, events associated with General Motors (GM) diesel generators, loss of power coincident with the LORW, and the loss of normal power following LOCA initiators. Most of

the GM diesel generator contribution is related to failures caused by the lack of automatic load-sequencing equipment.

VII. CONCLUSIONS

The method of moments can be used to precisely determine the mean values of three traditional importance measures: risk reduction, partial derivative, and variance reduction. Variance reduction calculations, in particular, are significantly improved by eliminating the imprecision associated with Monte Carlo estimates. All three importance measures can be extended to permit analyses of the relative importance of groups of basic and initiating events. The group importance measures can be used to rank groups of events according to different attributes: the potential to reduce the top event frequency (risk reduction), the potential for inducing

TABLE VII
Initiating Event Risk Reduction Measures

Event Group	Mean Risk Reduction		Mean Contribution to Gradient		Mean Variance Reduction	
	$\eta\langle RR_g \rangle$ (%)	Rank	$\eta \langle \nabla \Phi_{T,g} \rangle $ (%)	Rank	$\eta\langle VR_g \rangle$ (%)	Rank
Secondary CWS break	31.4	1	2.0	2	1.7	3
Medium LOCA	24.9	2	0.8	4	11.5	1
Loss of site power	16.1	3	0.0	6	0.0	6
Loss of river water	12.5	4	0.9	3	0.4	4
Small LOCA	12.5	5	0.1	5	2.9	2
Large LOCA	2.7	6	2.5	1	0.1	5

TABLE VIII
Electrical Event Group Risk Reductions

Electrical Event Group Description	Mean Risk Reduction	
	$\eta\langle RR_g \rangle$ (%)	Rank
Loss of site power initiators	16.1	1
GM diesels	12.6	2
Site power fails during loss of river water	8.9	3
Site power fails during LOCA	6.8	4
Starter failures	2.0	5
Automatic transfer switch failures	0.5	6
Bypass switch failures	0.5	7
Relay failures	0.3	8
Electrical bus failures	0.1	9
Other electrical	<0.1	10

change in the top event frequency (gradient importance), and the potential for reducing the uncertainty in the top event frequency (variance reduction). Events may be grouped by system, by event type (initiating, mechanical, electrical, etc.), by component type (pumps, valves, switches, etc.), or by subtypes within a type. Representative quantitative results illustrate the utility of the group importance measures. For example, for K Reactor, both human errors and recovery actions proved much more important than expected, while mechanical failures proved less important than expected. This indicates that group importance measures can be used to provide insights that refute preconceived expectations and might otherwise be missed.

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44: Location of Chang Chung Institute?

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Introduction to Probabilistic Risk Assessment

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October 28, 1993

Risk Assessment Concepts

Basic Considerations

PROTECTION: Prevent Loss or Damage

- **Fire Extinguisher**
- **Pipe Restraints**
- **Protective Clothing**
- **Decontamination Facility**
- **Emergency Planning**
- **Vaccines**

SAFETY: Level of risk

SAFE: Having an acceptable level of risk

Why Perform Risk Assessments?

Accidents do happen:

- Chernobyl, Challenger, Bophal, Three Mile Island, etc.

Somebody overlooked something!

Risk assessment methods are tools that

- help us look
- help us think
- help us make decisions
- do not look, think, or make decisions for us

Risk assessment is necessary if we want to prevent or mitigate future accidents via prudent decision making.

*Satisfy DOE safety goals.
Provide input to risk based decision making*

Different Approaches to Risk Assessment

Consequences: Qualitative

- **Catastrophic**
- **Critical**
- **Marginal**
- **Negligible**

Quantitative

- **Data**
- **Models**
 - Parametric**
 - Mechanistic**

Terminology

- **Conventional:**

- **Probability** of failure on demand or over a specified time interval
- **Frequency** of failure (probability per unit time)

- **Frequentist**

- **Frequency** of failure on demand, over a specified time interval, or per unit time
- **Probability** that "true" frequency falls in a specified interval

Interpretations of Risk

Risk is the likelihood of a hazard causing a specific set of consequences.

- **Special Cases:**
 - **The risk of a specific scenario is its probability**
 - **If all scenarios have one of two outcomes (bad or good), risk is the probability of the bad outcome**
- **Consequence-Weighted (Actuarial) Risk**
- **Risk Curve**
 - **Complementary Cumulative Distribution Function (CCDF) (Exceedance Frequency versus Consequence Level).**

Consequence-Weighted Risk Calculation A Simple Example

Accident Scenario	Estimated Frequency ϕ_i (yr ⁻¹)	Estimated Consequences x_i (\$)	Consequence-Weighted Risk $\phi_i x_i$ (\$/yr)	Cumulative Frequency $x \geq x_i$ (yr ⁻¹)
s_1	20×10^{-6}	1×10^6	20	3.1×10^{-5}
s_2	2×10^{-6}	3×10^6	6	1.1×10^{-5}
s_3	3×10^{-6}	5×10^6	15	0.9×10^{-5}
s_4	6×10^{-6}	7×10^6	42	0.6×10^{-5}
Total =			83	

Complementary Cumulative Distribution Function

Frequency of Man-Caused Events Involving Fatalities

Accident Delineation

Tools for Delineating Accident Scenarios

Bottom Line: Different tools have different virtues; give emphasis to different aspects of problem.

Best Strategy: Choose the right mix of tools for each application (as much art as science).

Event Tree Analysis

Purpose: Delineate sequences of events (scenarios) and their associated damage levels.

Method: For a selected initiating event, use inductive (what can happen) logic to identify sequences of failures of features that protect against the hazard.

Example: What scenarios could result from a fire outside a vault in which special nuclear material is stored?

Event Tree Development Process

- **Identify Initial and Boundary Conditions for Analysis**
 - **Hazard(s) Posing Risk**
 - **Initiating Event**
 - **Level of Damage Resolution Sought**

- **Identify Success & Failure States**
 - **Protective Functions**
 - **Facility features that perform each function**
 - **Minimum performance required for success**

- **Delineate Possible Sequences of Successes and Failures Accounting for**
 - **Timing dependencies**
 - **Conditional dependencies**

Example

Success & Failure States

Protection Features: Containers
Storage Vault
Local Fire Detectors
Portable Fire Extinguishers
Automatic Fire Suppression System
Facility Fire Department

Success Criteria: Vault Door Shut
Portable Extinguishers in 2 min
One of two automatic fire pumps
Deluge spray within 4 min

Fault Tree Analysis

Definitions

"A fault tree is a logic diagram that provides a concise and orderly description of the various combinations of possible occurrences within a system that can result in a predefined undesired outcome." EPRI NP-79-1-LD

"Fault tree analysis is an analytical technique, whereby an undesired state of the system is specified (usually a state that is critical from a safety standpoint), and the system is then analyzed in the context of its environment and operation to find all credible ways in which the undesired event can occur."

NUREG-0492

Example Fire Protection System

- **Area Near Vault Protected by Fire Sprays**
- **Two Diesel Pumps**
 - Each 100% capacity
 - Run continuously, except for maintenance
 - Gate valves are shut only for pump maintenance
- **Fire water tank TK01 holds sufficient water for 1 hour of spray and combined manual hose operation.**
- **In case of fire**
 - Alarm AL01 sounds locally and at nearby fire station
 - Temperature sensor TS01 signals motor-operated valve MV01 to open.

Symbol		Description
<p>Output</p> <p>Inputs</p>	"Or" Gate	Logic gate providing the Boolean representation of the union of input events. The output will occur if at least one of the inputs exists.
<p>Output</p> <p>Inputs</p>	"And" Gate	Logic gate providing the Boolean representation of the intersection of the input events. The output will occur if all of the inputs co-exist.
<p><i>Developed</i> Event <i>GATE</i></p>	A fault event resulting from the combination of more basic faults acting through the input logic gates.
Basic Event	A basic component fault which requires no further development.

Guidelines for Developing Fault Trees

- **Start from the output end of the system**
- **Step-by-step development**
- **No gate-to-gate construction.**
 - **Logic gates should not be directly connected to other logic gates.**
 - **Write entries in event boxes as faults, stating "what" and "when."**
- **Complete the gate.**
 - **All gate inputs should be defined before further analysis of any input is begun.**
- **Model to the level for which you have data.**

Generating Minimal Cutsets

Boolean Algebra

Variables only take on values of 0 or 1.

Three Operations: $+$, $*$, $/$

A	B	$A+B$
0	0	0
0	1	1
1	0	1
1	1	1

A	B	$A*B$
0	0	0
0	1	0
1	0	0
1	1	1

A	$/A$
0	1
1	0

Boolean Law of Absorption

$$A + A*B = A$$

A	B	$A*B$	$A + A*B$
0	0	0	0
0	1	0	0
1	0	0	1
1	1	1	1

$$A \cup (A \cap B) = A$$

Generating Minimal Cut Sets

- Step 1** **Generate all of the intermediate event equations defined by the fault tree.**
- Step 2** **Generate an equation for the selected intermediate event as a function of only primary events by repeated substitution into the intermediate event equations generated in step 1.**
- Step 3** **Reduce the equation resulting from step 2 by applying the Boolean absorption identities $A * A = A$ and $A + A * B = A$**

Generating Minimal Cut Sets

Step 2 **Generate an equation for the selected intermediate event as a function of only primary events by repeated substitution into the intermediate event equations generated in step 1.**

To do this, systematically eliminate each intermediate event on the right side of the equation for G1 by repeated substitution:

$$G1 = G2 * G3$$

$$G1 = (E1 + E2) * (E3 + G4)$$

$$G1 = (E1 + E2) * (E3 + G5 * E5)$$

$$G1 = (E1 + E2) * (E3 + (E2 + E4) * E5)$$

$$G1 = (E1 + E2) * (E3 + E2 * E5 + E4 * E5)$$

Minimal Cut Sets for Example Fire Protection System

Minimal Cutset Number	Number of Variables	FTOP-FT =
1	1	FTK01-WF +
2	1	FTK01-FC +
3	1	FMV01-FO +
4	1	FSP01-CL +
5	2	FMV01-DC * FAL01-FO +
6	2	FMV01-DC * FMV01-HE +
7	2	FST01-FO * FAL01-FO +
8	2	FST01-FO * FMV01-HE +
9	2	FDP01-FF * FDP02-FF +
10	2	FDP01-FF * FDP02-FR +
11	2	FGV04-RO * FDP01-FF +
12	2	FGV03-RO * FDP01-FF +
13	2	FDP01-FR * FDP02-FF +
14	2	FDP01-FR * FDP02-FR +
15	2	FGV04-RO * FDP01-FR +
16	2	FGV03-RO * FDP01-FR +

Cut Sets for Accident Sequences

T	B	C	Damage State	Scenario Likelihood

Let's look at Sequence T*B*C

Minimal Cut Sets for Sequence $T*B*C$

Suppose events B and C are failures of systems B and C respectively, and in Boolean notation are

$$B = (Pump-1 + Valve-X)$$

$$C = (Pump-1 * Pump-2)$$

Then $B*C$ is given by

$$B*C = (Pump-1)*(Pump-1)*(Pump-2) + (Valve-X)*(Pump-1)*(Pump-2)$$

Or, by the Boolean laws of absorption

$$B = (Pump-1)*(Pump-2)$$

Assuming event T is the initiating event, so the Boolean representation for sequence $T*B*C$ is

$$T*B*C = T*(Pump-1)*(Pump-2)$$

Example Problem Failure Sequence Cutsets

FTOP-FT =

I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FMV01-FO		* VO-NRCV +
I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FMV01-DC	* FMV01-HE	* VO-NRCV +
I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FST01-FO	* FMV01-HE	* VO-NRCV +
I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FSP01-CL		* VO-NRCV +
I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FTK01-WF	+	
I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FTK01-FC	+	
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FMV01-FO		* VNO-NRCV +
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FMV01-DC	* FMV01-HE	* VNO-NRCV +
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FST01-FO	* FMV01-HE	* VNO-NRCV +
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FSP01-CL		* VNO-NRCV +
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FTK01-WF	+	
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FTK01-FC	.	

Quantification

The "Bathtub" Curve

Plant-Specific Data Issues

- **Adequacy of sample size**
- **Accuracy/uniformity of reporting**
- **Difficulty in interpreting "raw" failure data**
- **Uncertainty issues**

Basic Event Quantification (cont'd)

Basic Event:

- FSP01-CL, Spray nozzles are clogged

Component Type:

- Spray nozzles are untested standby components (i.e, their status is verified only upon demand).

Unavailability Model:

- Probability of failure per demand.

Failure Data:

- Q, probability of failure = $3 \times 10^{-4}/d$ per NUREG/CR-4550 (ASEP)

Unavailability:

$$Q = 3 \times 10^{-4}$$

Basic Event Quantification

Basic Event:

- FTS01-FO, Temperature sensor TS01 failure to operate.

Component Type:

- Standby

Unavailability Model:

- Probability of failure per demand.

Failure Data:

- Probability of failure, $Q = 1.9 \times 10^{-3}$ per demand
- Source: Swedish reliability data book, RKS85-25

Unavailability:

$$Q = 1.9 \times 10^{-3}$$

References

I. A. Papazoglou, et al, "Probabilistic Safety Analysis Procedures Guide," NUREG/CR-2815, BNL-NUREG-51559, Brookhaven National Laboratory, Upton, NY, January 1984.

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D. M. Ericson, et al, "Analysis of Core Damage Frequency: Internal Events Methodology," NUREG/CR-4550, Rev. 1, SAND86-2084, Sandia National Laboratories, Albuquerque, NM, December 1989.

Common Cause Failures

Deterministic Dependencies

- **Support System Failures**
 - Cooling water
 - Electric power
 - Interlocks
 - Control air
- **Environments**
 - Fires and Explosions
 - Flood
 - Radiation levels
 - Vibration
- **Treatment**
 - Event tree structure
 - Fault tree structure

Common Cause Methods

- **Beta factor (subset of multiple Greek letter)**

$$\beta = \frac{\text{Number of common cause failures}}{\text{Total number of failures}}$$

- **Similar for three or more failures**
- **Apply to cut sets containing same failure mode for component type**
 - Diesel generators
 - MOVs, AOVs, PORVs, SRVs
 - Pumps
 - Batteries
 - Breakers

Beta Factor Example

- **High pressure pumps**
 - $\beta = 3 \text{ CCF} / 60 \text{ total failures} \sim 0.05$
 - Diesel driven pump failure to run given start
 $Q = 4.8 \times 10^{-5}$

- **Cut set 14: FDP01-FR * FDP02-FR**

- **Independent failure probability**

$$Q * Q = (4.8 \times 10^{-5}) * (4.8 \times 10^{-5}) = 2.3 \times 10^{-9}$$

- **Common cause failure probability**

$$Q * \beta = (4.8 \times 10^{-5}) * (0.05) = 2.4 \times 10^{-6}$$

Human Reliability Analysis

Human Reliability Analysis (HRA)

- **Starts with a basic premise**
 - **Humans are, in effect, part of the system, the "man-machine system"**
- **Identifies and quantifies the ways in which human actions initiate, propagate, or terminate accident sequences.**

Categories of Human Errors (Continued)

- **Errors of omission**
- **Errors of commission**
- **Errors of cognition**

Definitions (cont'd)

- **Skill-Based Behavior - Performance of more or less subconscious routines governed by stored patterns of behavior.**
- **Rule-Based Behavior - Requires a more conscious effort in following stored (or written) procedures.**
- **Knowledge-Based Behavior - Task situation is somewhat unfamiliar, thus involving more cognition.**
- **Task Analysis - The analytical process for determining the specific behaviors required of the human components in the man-machine interface.**

Hypothetical Relationship of Psychological Stress and Performance Effectiveness

Sources of Human Reliability Data

- **Actual facility operating experience**
- **Laboratory experiments**
- **Simulators**
- **Allied industries**
- **Military**
- **Expert judgement**

Sequence Quantification

Quantification Inputs

- **Initiating events**
- **Event trees to delineate accident sequences**
- **Fault trees and Boolean expressions for all systems -**
- **Occurrence Rate Data**
 - **initiating events**
 - **component failures**
 - **human errors**

Fire Protection Example Initiating Event Frequency

- Data - No fires adjacent to vault in 10 years
- Conservative estimate of frequency

$$f_{I-FIRE} \approx \frac{2N + 1}{2T}$$

$$f_{I-FIRE} = 0.05 \text{ yr}^{-1}$$

Probability Vault Door Is Left Open After Evacuation, VO-OPEN

- **Data - Interviews with facility personnel**
 - **Emphasis on securing special nuclear materials**
 - **If vault is occupied when the fire occurs, the occupants would be expected to close the vault door when they evacuate.**
- **Data - Human Reliability Handbook**
 - 10^{-2} =** **Probability of general human error of omission when there is no display in the control room of the item omitted, e.g. failure to return manually operated test valve to proper configuration after maintenance.**
 - 0.2-0.3 =** **Probability of error given very high stress levels, where dangerous activities are occurring rapidly.**
 - 1.0 =** **Probability operator fails to act correctly in the first 60 seconds after the onset of an extremely high stress condition.**
- **Quantification - $Q_{VO-OPEN} = 0.2$, engineering judgement**

Probability Fire Is Extinguished Early, With Portable Fire Extinguishers

- **Most fires are caused by human error and most fires are extinguished early, before major damage occurs.**
- **Personnel are trained to extinguish small fires using portable extinguishers.**
- **As an initial estimate, the probability of failure is taken to be the probability of human error given very high stress levels, where dangerous activities are occurring rapidly, $P_{VNO-FS} = 0.2$.**
- **If the vault is occupied, a slightly lower failure probability, $P_{VO-FS} = 0.1$ is used to account for the fact that more people are in the vicinity.**

Recovery Analysis

- **Analysis on accident sequence level**
 - **Examination of contributors to failure**
 - **Identification of potential for recovery**
- **Recovery factors**
 - **Critical time for recovery**
 - **Action required**
 - **Time for action**
 - **Time versus probability of recovery**
- **Final accident sequence probability includes recovery**

Example Problem Failure Sequence Cutsets

FTOP-FT =

I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FMV01-FO		* VO-NRCV +
I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FMV01-DC	* FMV01-HE	* VO-NRCV +
I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FST01-FO	* FMV01-HE	* VO-NRCV +
I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FSP01-CL		* VO-NRCV +
I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FTK01-WF	+	
I-FIRE	* V-OCC	* VO-OPEN	* VO-FS	* FTK01-FC	+	
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FMV01-FO		* VNO-NRCV +
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FMV01-DC	* FMV01-HE	* VNO-NRCV +
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FST01-FO	* FMV01-HE	* VNO-NRCV +
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FSP01-CL		* VNO-NRCV +
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FTK01-WF	+	
I-FIRE	* /V-OCC	* VNO-OPEN	* VNO-FS	* FTK01-FC	.	

Sensitivity and Uncertainty Analysis

Importance Measures

- **Qualitative importance measures are derived from the logic structure of the PRA**
 - **Key components and plant situations that impact risk**

- **Quantitative importance measures are derived from the quantitative results of the PRA**
 - **Can be based on many things**
 - **System failure probabilities**
 - **Accident sequence frequencies**
 - **Consequences of key scenarios**
 - **Entire risk curve**

Risk Reduction

1. Event I-FIRE

- Initiating event, occurs in each cut set
- $RR_{I-FIRE} = 5.18 \times 10^{-7}$
- $RR_{I-FIRE} = \text{top event frequency}$

2.5 Event VO-OPEN

- Vault occupied, door left open when occupants evacuate vault during fire.
- $P_{VO-OPEN} = 0.2$
- $RR_{VO-OPEN} = 5.10 \times 10^{-7}$
- Tie with event VO-FS

2.5 Event VO-FS

- Vault occupied, fire spreads (not extinguished with portable extinguishers)
- $P_{VO-FS} = 0.1$
- $RR_{VO-FS} = 5.10 \times 10^{-7}$
- Tie with event VO-OPEN

Risk Reduction (Cont'd)

Event	Occur	Prob/Freq	RR	Rank
I-FIRE	12	0.05	5.18E-07	1
VO-FS	6	0.1	5.10E-07	2.5
VO-OPEN	6	0.2	5.10E-07	2.5
V-OCC	12	0.057	5.09E-07	4
VO-NRCV	4	0.2	5.08E-07	5
FMV01-FO	2	0.0425	4.93E-07	6
FMV01-HE	4	0.9	2.03E-08	7
FMV01-DC	2	0.001	1.04E-08	8
FST01-FO	2	0.00095	9.91E-09	9
VNO-FS	6	0.2	8.43E-09	10.5
VNO-OPEN	6	0.0001	8.43E-09	10.5
VNO-NRCV	4	0.2	8.41E-09	12
FSP01-CL	2	0.0003	3.48E-09	13
FTK01-FC	2	0.00001	5.79E-10	14.5
FTK01-WF	2	0.00001	5.79E-10	14.5

Risk Increase (Achievement)

Event	Occurrences	Prob/Freq	RI	Rank
VNO-OPEN	6	1.00E-04	8.43E-05	1
FTK01-WF	2	1.00E-05	5.79E-05	2.5
FTK01-FC	2	1.00E-05	5.79E-05	2.5
FSP01-CL	2	3.00E-04	1.16E-05	4
FMIV01-FO	2	4.25E-02	1.11E-05	5
FST01-FO	2	9.50E-04	1.04E-05	6.5
FMIV01-DC	2	1.00E-03	1.04E-05	6.5
V-OCC	12	5.70E-02	8.42E-06	8
VO-FS	6	1.00E-01	4.59E-06	9
VO-OPEN	6	2.00E-01	2.04E-06	10
VO-NRCV	4	2.00E-01	2.03E-06	11
VNO-FS	6	2.00E-01	3.37E-08	12
VNO-NRCV	4	2.00E-01	3.36E-08	13
FMIV01-HE	4	9.00E-01	2.26E-09	14

Partial Derivatives

Event	Occur	Freq./Prob.	PD	Rank
VNO-OPEN	6	1.00E-04	8.43E-05	1
FTK01-WF	2	1.00E-05	5.79E-05	2.5
FTK01-FC	2	1.00E-05	5.79E-05	2.5
FMV01-FO	2	4.25E-02	1.16E-05	4.5
FSP01-CL	2	3.00E-04	1.16E-05	4.5
FST01-FO	2	9.50E-04	1.04E-05	7
I-FIRE	12	5.00E-02	1.04E-05	7
FMV01-DC	2	1.00E-03	1.04E-05	7
V-OCC	12	5.70E-02	8.93E-06	9
VO-FS	6	1.00E-01	5.10E-06	10
VO-OPEN	6	2.00E-01	2.55E-06	11
VO-NRCV	4	2.00E-01	2.54E-06	12
VNO-FS	6	2.00E-01	4.22E-08	13
VNO-NRCV	4	2.00E-01	4.21E-08	14
FMV01-HE	4	9.00E-01	2.26E-08	15

Accident Initiators

Possible External Initiators

Event	Usual cause for exclusion
Aircraft	-
Avalanche	Physically impossible for most sites
Earthquake	-
Fire inside plant	-
Fire outside plant but on site	-
Fire off site	No means to propagate to plant
Flammable fluid release	Considered under fire (onsite) or pipeline accident (offsite)
Fog	Included in aircraft or ship impact
Flooding, external (including seiche, storm surge, dam failure, and tsunami)	-
Flooding, internal	-

Possible External Initiators (cont'd)

Event	Usual cause for exclusion
Pipeline accident	-
Sabotage	Outside scope - impossible to assess frequency
Ship impact	Impossible to damage more than water intake
Toxic gas release	-
Transportation accident	-
Turbine missile	Only for facilities with turbines
Volcanic activity	Geologic setting of most sites makes this impossible
War	Outside scope - impossible to assess frequency

Importance of External Events

- **External events can initiate accidents with large consequences.**
- **External events can negate or compromise the systems or procedures used to prevent or mitigate accident consequences.**

PRA Strengths and Limitations

Specific Strengths of PRA

- **Rigorous, systematic analysis tool**
- **Information integration (multidisciplinary)**
- **Allows consideration of complex interactions**
- **Develops qualitative insights**
- **Develops quantitative measures for decision-making**
- **Provides a structure for sensitivity studies**

Types of Information Generated by PRA

- **Quantitative measures of the likelihood of specific accident sequence**
- **Probabilities of system failures**
- **Identification of dominant contributors to accident sequences**
- **Insights into how systems interact with one another**
- **Estimates of the risks posed by external events such as fires, floods, earthquakes, etc.**
- **Areas in which simple fixes in hardware or personnel training may substantially reduce risks.**
- **Estimates of accident consequences in terms of radiological doses to public and associated health effects.**

**DATE
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END