A METHODOLOGY FOR REVIEWING PROBABILISTIC RISK ASSESSMENTS

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ABSTRACT

The starting point for peer review of a Probabilistic Risk Assessment (PRA) is a clear understanding of how the risk estimate was prepared and of what contributions dominate the calculation. The problem facing the reviewers is how to cut through the complex details of a PRA to gain this understanding. This paper presents a structured, analytical procedure that solves this problem.

The effectiveness of this solution is demonstrated by an application on the Zion Probabilistic Safety Study. The procedure found the three dominant initiating events and provided a simplified reconstruction of the calculation of the risk estimate. Significant assessments of uncertainty were also identified. If peer review disputes the accuracy of these judgments, then the revised risk estimate could significantly increase.

The value of this procedure comes from having a systematic framework for the PRA review. Practical constraints limit the time and qualified people needed for an adequate review. Having the established framework from this procedure as a starting point, reviewers can focus most of their attention on the accuracy and the completeness of the calculation. Time wasted at the start of the review is reduced by first using this procedure to sort through the technical details of the PRA and to reconstruct the risk estimate from dominant contributions.

INTRODUCTION

Reviewers of probabilistic risk assessments (PRAs) must sift through a complex blend of computer codes and logical models to understand how the risk estimate was developed. The accuracy of the estimate is then judged by considering three aspects of the calculation:

1) Whether the dominant accident sequences are accurately calculated;

2) Whether errors in the calculation significantly increase the contribution of minor sequences;

3) Whether the analysis is complete, having included all important possibilities for accident sequences.

The problem facing the developing of any review methodology is finding a structured way to cut through the hierarchy of complex details so that the reviewer can understand the calculation and can evaluate the dominant factors. Their understanding of how the estimate was prepared is the framework that must be used to consider the three aspects of PRA accuracy. This paper presents a solution to this initial problem of developing a sound understanding of how the risk estimate was prepared. An application to the Zion Probabilistic Safety Study (PSS)[1] demonstrates the effectiveness of the approach.

The value of this solution comes from reducing the time spent setting up the framework for the PRA review. By establishing this framework systematically and quantitatively, the reviewers can put more focus on evaluating the accuracy of dominant contributors without first considering the entire set of possible contributors. They can judge the importance of errors in the calculation of minor contributions by comparing the effect of changes relative to the dominant contributions. Their search for important omissions is directed by first understanding what is included in the calculation. Understanding how the risk estimate was prepared and identifying the dominant contributions is only the initial step in a PRA review. A quantitative analysis that aids this step establishes a sound basis for addressing the other aspects of PRA accuracy.

This paper describes a procedure called a "PRA audit analysis". The name was chosen to emphasize the purpose of providing a formal examination of how a PRA risk estimate was prepared. The steps in the audit analysis are briefly described in the next section. The following sections describe the steps in more detail and illustrate the description by an example analysis of the Zion PSS.

OVERVIEW OF AUDIT ANALYSIS

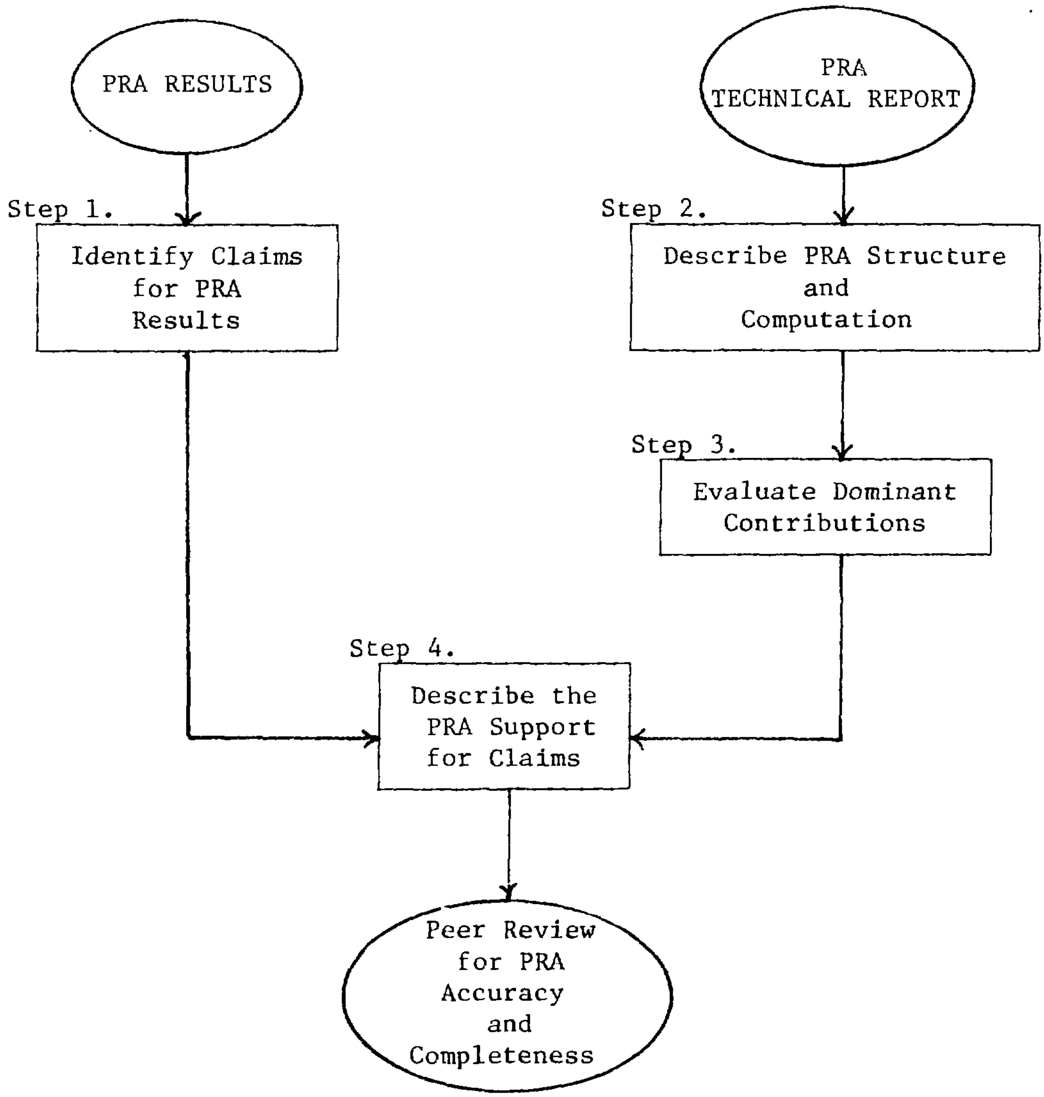
The important quality of a PRA is that it represents a broad evaluation of knowledge that describes nuclear power accidents. When the PRA analysis reduces this broad knowledge to specific descriptions of dominant risk contributors, there must be sound reasons for that reduction. The reasons behind this narrowing are found in the key assumptions and evaluations made in the preparation of the PRA. Bringing out why information is insignificant is as important as determining why a particular set of information becomes dominant. The key purpose of the audit analysis is to examine both sides. The factors that make the risk contributors dominant are the initial focus of the PRA peer review. The factors that make other risk contributors insignificant can guide reviewers in their further consideration of accuracy of minor contributions and the completeness of the calculation.

The audit analysis answers four questions so that the peer review can judge the PRA for its quality. The first question asks what claims must be supported by the PRA. The claims should be presented in the PRA report as proposed resolutions to safety issues that give the purpose for calculating a risk estimate. The second question asks how the technical evaluations were combined to prepare the risk estimate. The technical evaluations are the system analyses of plant response to initiating events, accident analyses of containment response, and site analysis of public consequences. The third question asks what dominant contributions determine the value of the risk estimate. These contributions are key assumptions and evaluations that lead to the conclusions presented by the PRA. The fourth question asks how these dominant contributions to the risk estimate support the claims made from the PRA results.

The next sections describe the four steps in the audit analysis that answer these questions. Figure 1 gives a flow chart of how these steps combine to give a clear understanding of the PRA. This understanding gives a framework for reviewing its accuracy and completeness.

FIGURE 1

FLOWCHART FOR AUDIT ANALYSIS PROCEDURES



STEP 1: IDENTIFY CLAIMS FOR PRA RESULTS

A PRA leads to conclusions about safety. This step identifies the claims made in the PRA report that must be supported by the PRA results. The purpose here is to list the safety issues that can be addressed with the PRA. If the PRA is found to be an acceptable analysis for regulatory decisions, then the claims made and the safety issues listed under this task are the areas that can use the PRA for regulatory decisions and resolution of safety issues.

The Zion Probabilistic Safety Study

The NRC staff held the opinion that nuclear power plant sites near high population areas represented "an unusual and excessive contribution to the risk from nuclear power generation".(2) Zion Station, owned by Commonwealth Edison, fit this description. The plant site is on Lake Michigan between Chicago and Milwaukee. The NRC staff began studies that looked at ways to add safety features to the plant to reduce this risk. These studies were support for regulatory decisions on continued operation of Zion.

The first claim in the Zion PSS asserts that the operation of the plant is well below the risk calculated by the Reactor Safety Study for generic pressurized water reactors. Zion has an estimated probability of core melt that is comparable to that calculated by the Reactor Safety Study. However, the Zion analysis claims to show that the containment building is much more effective in retaining radioactive releases than the containment in the generic study.

The report asserts that the most likely mechanism for a serious nuclear accident at Zion would be caused by an extremely severe earthquake in Northern Illinois. The remote chance of such an earthquake assures that the risk from the Zion Station is extremely small.

The effects from the release of radioactivity from an accident was "conservatively specified" in the analysis.(2) This claim suggests that any peer review will find that alternative descriptions of the magnitude and severity of the release are comparable to or less than that used in the analysis.

The Zion PSS also examined the risk reduction from adding new safety features to the plant. Four new features were examined:

1. Devices, such as a core ladle, to hold up molten material from a core melt;

2. Devices, such as filtered vents, that controlled the release of radioactivity from the containment to regulate pressures that cause failures;

3. Devices that control hydrogen concentration in the containment; and

4. Devices, such as a diesel-driven spray, to improve the reliability of containment cooling systems.

In each case, the analysis of risk reduction showed only slight safety improvement.[3]

STEP 2: DESCRIBE PRA STRUCTURE AND COMPUTATION

Table 1 outlines the hierarchy of a PRA calculation. Each level of the hierarchy represents a major step in the analysis that leads to the risk estimate. The levels are arranged in reverse order from how the estimate was calculated, a top-down hierarchy. At the top is the result of the calculation, the risk estimate. At the bottom is the starting point for the calculation, the accident initiating events.

Each level is described by its input and output: the different possible initial conditions and the different possible results from these inputs. For the Zion PSS Level 1, ten possible release categories are evaluated by the site consequences analysis to determine the risk of five different types of public consequences. Level 2 has 21 initial plant damage states that lead to ten possible release categories. Level 3 has initial conditions from the fifteen internal events and the two external initiating events. The possible results are the plant damage states used as initial conditions for Level 2.

Table 1 also gives the probabilistic notation that is used to define the equations for the contribution of dominant accident sequences. The information in the Zion Probabilistic Safety Study that supplies the numbers used for the probabilistic expressions are shown next to the notation.

STEP 3: EVALUATE DOMINANT CONTRIBUTIONS

The analysis starts at Level 1 to find which release categories contribute most to the calculation of the risk estimate. These dominant categories are selected for further analysis at Level 2. At Level 2, each of the selected categories is analyzed to find the contribution from each plant damage state. The dominant states for each category are then selected for further analysis at Level 1. At Level 1, each selected plant damage state is analyzed to find the contribution from each of the possible initiating events.

In this way, the review analysis follows a path into the levels of complexity in the PRA calculation. The paths that do not significantly contribute to the risk calculation are not followed. Thus, the complexity of the review is significantly reduced by only considering the important contributors to the risk calculation.

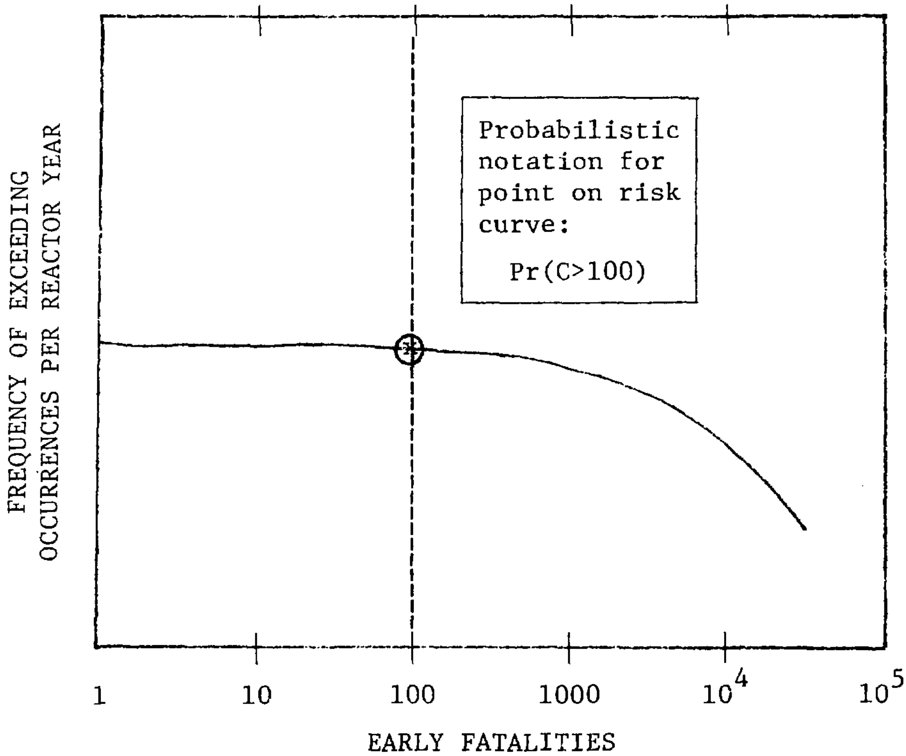
Definition of Contribution

At each level of the hierarchy, the calculated result is determined from the sum of contributions from each initial condition. For example, the probability (or expected frequency) of exceeding 100 fatalities, Pr(C>100), is a point on the risk curve shown in Figure 2. This point is

TABLE 1

HIERARCHY OF
ANALYTICAL AND LOGICAL MODELS

	HIERARCHY	PROBABILISTIC NOTATION	ZION PSS INFORMATION
Level 1	Public Consequences Exceed a Level: $(C>x)$	$Pr(C>x)$	Frequency of Damage Index: MCS
	↑		
	Site Consequences Model	$Pr(C>x \mid RC_i)$	Site Matrix: S
	↑		
	Release Categories: (RC_i)	$Pr(RC_i)$	Frequency of Release Categories Vector: ϕMC
Level 2	↑		
	Accident Analysis Models and Containment Response Model	$Pr(RC_i \mid PD_j)$	Containment Matrix: C
	↑		
	Plant Damage States: (PD_j)	$Pr(PD_j)$	Frequency of Plant Damage States Vector: ϕM
Level 3	↑		
	Plant Response Models	$Pr(PD_j \mid IE_k)$	Plant Matrix: M
	↑		
	Initiating Events: (IE_k)	$Pr(IE_k)$	Frequency of Initiating Events Vector: ϕ



Example Risk Curve for Public Consequences:
Early Fatalities

FIGURE 2

calculated at Level 1 by the sum of contributions from each of the ten possible release categories:

$$\Pr(C>100) = \sum_{i=1}^{10} \Pr(C>100|RC_i)\Pr(RC_i)$$

Each term in this sum is a product of two factors: the probability of the consequence given that the release occurs, $\Pr(C>100|RC_i)$, and the probability (or expected frequency) of the release category, $\Pr(RC_i)$. The relative contribution of each release category is calculated by its fraction of the sum:

$$\begin{bmatrix}\text{Contribution from} \\ \text{Release Category } RC_i \\ \text{to } \Pr(C>100)\end{bmatrix} = \frac{\Pr(C>100|RC_i)\Pr(RC_i)}{\Pr(C>100)} .$$

The dominant release categories are the ones that make up the largest contribution to the total.

The Zion PSS Dominant Contributions

Level 1 Audit Analysis. The analysis separated the contributions from the internal and external risks. Table 2 shows the contribution of external seismic risks and internal risks to the probability of exceeding 100 early fatalities, Pr(C>100). Seismic risks contribute over 90% of the estimate. Evaluation of other consequence types leads to this same conclusion.

TABLE 2

LEVEL 1 ANALYSIS

CONTRIBUTION FROM SEISMIC AND INTERNAL EVENTS TO RISK ESTIMATE

	External Events		Internal Events		
Contribution to Risk Estimate	Point Estimate	% of Total	Point Estimate	% of Total	Total
Pr(C>100)	5.84^{-8} †	93.6	4.09^{-9}	64.4	6.24^{-8}

† The notation 5.84^{-8} means 5.84×10^{-8}.

The external risks are from a single initiating event, seismic. This initiating event causes a single plant damage state, core melt without containment cooling. This plant damage state leads to a single release category, 2R, the release of radioactivity from the containment failure from pressure caused by the core melt conditions. The analysis of contributions from seismic events is, therefore, unnecessary because of this simplicity. The audit analysis for internal events is more complex.

Table 3 shows the results for internal risks. Two release categories (2 and 2R) are dominant contributions. These two categories describe radioactivity released from core melt accident conditions that cause containment failure by overpressure (2R) and from accident conditions that bypass the containment.

TABLE 3

LEVEL 1 ANALYSIS

CONTRIBUTION FROM RELEASE CATEGORIES TO RISK ESTIMATE
INTERNAL EVENTS

Contribution to Risk Estimate	Release Categories 2	2R	All Others
Pr(C>100)	37.7%	62.2%	0.1%

Level 2 Audit Analysis. The two dominant release categories are selected for the Level 2 analysis. At this level, the probability of a release category is calculated from the sum of contributions by each of the 21 possible plant damage states:

$$Pr(RC_i) = \sum_{j=1}^{21} Pr(RC_i|PD_j)Pr(PD_j)$$

Each term in this sum is the product of two factors: the probability of the release category resulting from the initial condition of a plant damage state, $Pr(RC_i|PD_j)$, and the probability (or expected frequency) of the plant damage state, $Pr(PD_j)$. The relative contribution of each plant damage state is calculated from its fraction of this sum:

$$\begin{bmatrix}\text{Contribution from} \\ \text{Plant Damage State } PD_j \\ \text{to Release Category} \\ RC_i\end{bmatrix} = \frac{Pr(RC_i|PD_j)Pr(PD_j)}{Pr(RC_i)}$$

The dominant contributors are the ones that make up most of the total sum.

Table 4 shows the results of this Level 2 analysis for the two release categories selected in this example. Only one plant damage state (out of 21 possible) dominates the contributions to a category, with each category having a different dominant state.

TABLE 4

LEVEL 2 ANALYSIS

CONTRIBUTIONS FROM PLANT DAMAGE STATES TO RELEASE CATEGORIES

	Plant Damage State		
Contribution to Release Category	Core Melt Without Containment Cooling	Core Melt Bypassing Containment	All Others
Pr(2R)	~100.0%	0.0	~0.0005%
Pr(2)	0.1%	96.1%	3.8%

<u>Level 3 Audit Analysis</u>. These two plant damage states are selected for the Level 3 analysis. At this level of the PRA hierarchy, the probability (or expected frequency) of a plant damage state is calculated from the sum of contributions by each of the 16 possible internal initiating events:

$$Pr(PD_j) = \sum_{k=1}^{16} Pr(PD_j | IE_k) Pr(IE_k)$$

Each term in this sum is the product of two factors: the probability of the damage state resulting from the initial condition of an initiating event, $Pr(PD_j | IE_k)$, and the probability (or expected frequency) of the initiating event, $Pr(IE_k)$. The relative contribution of each initiating event is calculated from its fraction of this sum:

$$\left[\begin{array}{l}\text{Contribution from} \\ \text{Initiating Event } IE_k \\ \text{to Plant Damage} \\ \text{State } PD_j\end{array}\right] = \frac{Pr(PD_j | IE_k) Pr(IE_k)}{Pr(PD_j)}$$

The dominant contributors are the ones that make up most of the sum.

Table 5 shows the results of this level 3 analysis for the two plant damage states selected from Level 2. Each damage state is dominanted by a single initiating event.

TABLE 5

LEVEL 3 ANALYSIS

CONTRIBUTIONS FROM INITIATING EVENTS TO PLANT DAMAGE STATE

Contribution to Plant Damage State $Pr(PD_j)$	Initiating Events: Turbine Trip with Loss of AC Power	Interface LOCA	All Others
Pr(Core Melt W/O Containment Cooling)	82.6%		17.4% (Largest single contribution is 3.8%)
Pr(Core Melt Bypassing Containment)	0.0	100.0%	0.0

This Level 3 analysis identifies the two dominant internal initiating events. Combining the results from each level gives a simple reconstruction of the calculation of the risk estimate, which considers only internal events.

The Zion PSS Dominant Uncertainties

Level 1 Analysis. The method of analyzing dominant contributions is also applied to the other factors in the contribution: the conditional probability of exceeding 100 fatalities given that release category "2R" occurs, $Pr(C>100|RC_i)$.

The analysis found that the dominant uncertainty is from expert judgments describing the effects of the release categories. These judgments substantially reduced the effective value of Pr(C>100|"2R").

Table 6 gives the relative comparison of mean value and point estimate for the risk of early fatalities. Including uncertainty from the expert judgment of the effective source strength for release categories reduces the mean value of the base case risk to less than 10% of the point estimate. The median value is reduced even further, to less than 0.2% of the point estimate.

TABLE 6

COMPARISON OF POINT ESTIMATE AND MEAN VALUE OF RISK ESTIMATE OF EARLY FATALITIES

Risk Estimate	Mean Pr(C>x)	Point Estimate Pr(C>x)	Relative Comparison†
Pr(C>100)	$5.57E^{-9}$	$6.24E^{-8}$	11.2

†Point estimate divided by mean.

The Zion study introduces this uncertainty to account for expert opinion that the "point estimate" description of these categories, found in the 1974 Reactor Safety Study, significantly overestimates the severity of the release.(4)

The effect of including this uncertainty reduces the effects of these release categories to less than 10% of the levels estimated by the methodology from the Reactor Safety Study. If peer reviewers found that this expert judgment was overconfident, then the estimated risks from all types of consequences would significantly increase, more than an order of magnitude.

Level 3 Analysis. The audit analysis found one significant uncertainty assessment, the probability for electric power recovery following loss of all AC power (both offsite and backup diesel generators). The high confidence, greater than 95%, placed in recovery of off-site power in less than one hour significantly reduces the risk from a six-hour delay needed to recover power from diesel generators. The sensitivity of the electric power recovery model used is shown in Table 7 below.

TABLE 7

SENSITIVITY OF ELECTRIC POWER RECOVERY MODEL TO PLANT DAMAGE STATE FREQUENCY

Plant Damage State Frequency	Electric Power Recovery Model: Base Case Model	Electric Power Recovery Model: 1-Hour Recovery Model	Electric Power Recovery Model: 6-Hour Bounding Model
Core melt without containment cooling	2.4×10^{-7} per year	6.1×10^{-7} per year	1.2×10^{-5} per year
Relative change	1.0	2.5	50.0

The accuracy of estimated risk from dominant internal initiating events rests on the accuracy of this uncertainty in electric power recovery.

STEP 4: DESCRIBE THE PRA SUPPORT FOR CLAIMS

Summary of Results from Preceding Steps

The purpose of the audit analysis is to identify dominant contributions to the risk estimate and provide a simple reconstruction of the PRA calculation. The results from this analysis are summarized in Figure 3. The complexity of the risk calculation is reduced to only the dominant contributions from three initiating events, two plant damage states, and two release categories. Over 95% of the contribution to the risk estimate is captured by this small portion of the complete calculation.

Dominant Contributions. The simple reconstruction of the Zion PSS risk estimate uses only 3 of 18 initiating events: the external seismic event and the two internal events of turbine trip with loss of offsite power (LOP) and the interface loss of coolant accident (LOCA). Both the seismic event and the turbine trip-LOP event can cause a single plant damage state - core melt without containment cooling. The dominant contributor from the plant response that causes this type of core melt from the turbine trip-LOP event is the lack of electric power recovery.

A core melt from the interface LOCA will bypass the containment and lead directly to the serious release of radioactive material - described by release category "2".

The plant damage state of a core melt without containment cooling leads to containment failure by overpressure and the category "2R" that describes the types and amount of radioactive material released. These two (out of ten) release categories account for over 99% of the contribution to serious levels of public hazards.

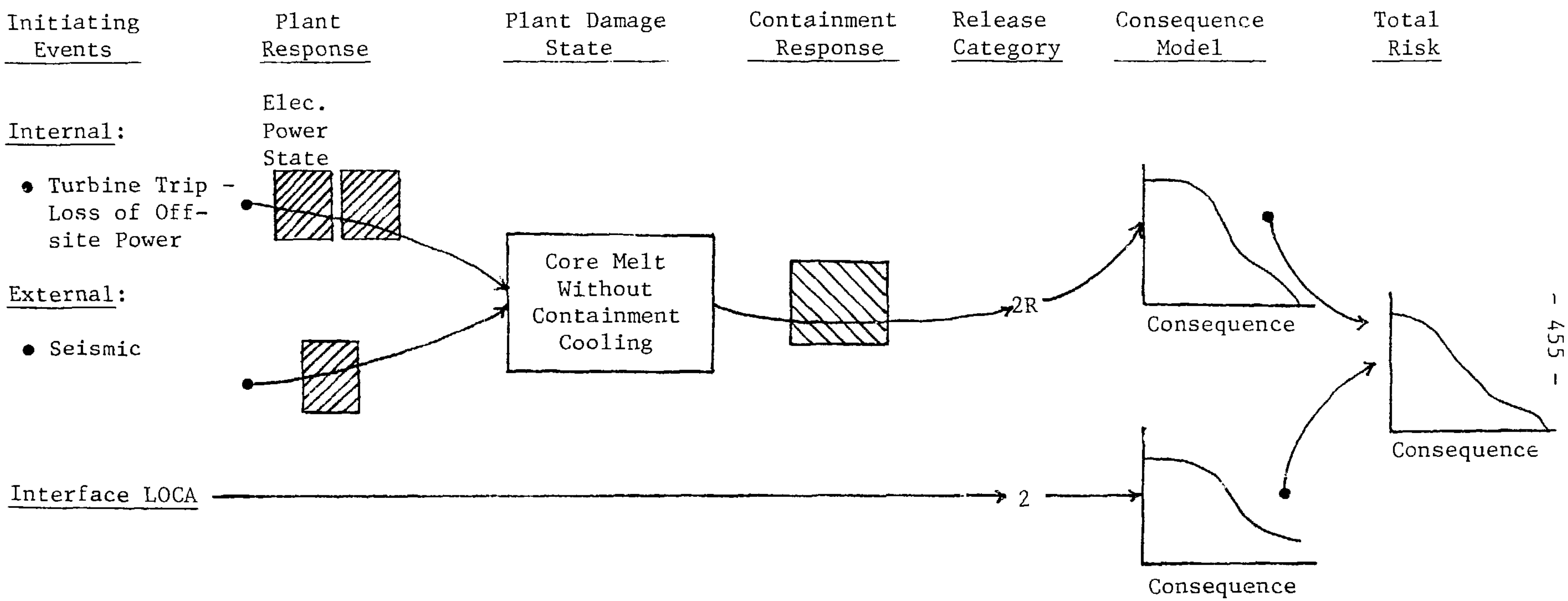
Dominant Uncertainties. The PRA reconstruction was used as a basis to identify significant uncertainties in the calculation. Two dominant uncertainties were found: the uncertainty for the effective source for the release categories and the uncertainty for the electric power recovery following the turbine trip with loss of offsite power.

The uncertainty for the effective source strength of release categories reduces the risk estimate to 10% of the nominal calculation. This nominal calculation used the methodology from the Reactor Safety Study (RSS). The uncertainty accounts for the judgment of the Zion PSS experts that the RSS calculation significantly overestimates the effects of the two dominant release categories.

The uncertainty for the electric power recovery reduces the contribution of the turbine trip-loss of offsite power event to the risk estimates. The high confidence that electric power will be restored within one hour is a key reason that the risk from internal initiating events is small when

FIGURE 3

DIAGRAM OF RISK CALCULATION



compared to the risks of seismic events. If this confidence is overstated, then the internal risk can substantially increase.

Support for Claims and Conclusions from the PRA

The Zion PSS report made three general claims for the risk estimate: the risk is well below the Reactor Safety Study estimate (Zion's containment is better), the dominant risk is from earthquakes, and the dominant possibility for radioactive release is "conservatively" estimated.

The audit analysis found that the support for the first and third claims is inconclusive. The difference between the "point estimates" and the "effective values" for the severity of the radioactive releases account for the support behind the claims. Because the reduction in severity was not supported by much more than general assertions, the claims should be carefully examined by peer review. Such a significant change needs to be supported by two analyses. First, a physical analysis of the radioactive transport mechanisms should establish the range of reduction in the amounts released in a category. Second, the evidence that the range of values for dose conversion factors are valid must be presented.

The second claim is supported by the analysis. Peer review should study the risk estimate for internal, operational events to see if the analysis has completely considered all possibilities. The sensitivity of the internal risk to the electric power recovery is an important aspect of the Zion analysis that must be considered.

The claim that the base case risk estimate is marginally reduced by the new safety features is supported by the analysis. Peer review should evaluate the adequacy and completeness of this evaluation of risk reduction. The audit analysis only finds the results of risk reduction consistent with changes in the dominant risk contributions to the Zion risk estimate. Finding consistency in the PRA calculation is important to understand how the risk estimate was prepared. Accuracy is then judged by peer review that begins with this understanding.

CONCLUSION

The value of PRA risk estimates are from identifying the main contributions to risk, not from predicting accurate rates of future fatalities. The method presented here gives an analytical procedure for drawing out this important information from the complex details of a PRA calculation. The most important value comes from improving the way that PRA reviewers establish a framework for their evaluation.

The initial step in the review of a PRA is to understand how the risk estimate was prepared. This understanding leads to a framework for considering the major issues in the review, the accuracy and completeness of the PRA. The analytical procedure demonstrated here can improve the normally informal way that the reviewer gains this understanding. Instead of sifting through the details of the PRA, the reviewer can rely on this formal procedure to identify the dominant contributors to the risk estimate.

The demonstration of the audit analysis on the Zion PSS gives some credibility to the idea of having an analytical framework aid the PRA review. As with all new ideas, peer review and validation will determine the strength of the concept and whether its potential value can be practically realized. The next step in the development of analytical procedures for PRA review is an evaluation of its practicality in the review process. This study has demonstrated the feasibility of the audit analysis.

NOTES

1. Page 3.12-1, Volume 10; Reference 1. The objective of the study was to include the design features that are characteristic to the Zion plant. This improvement in the analysis was thought to counter the NRC studies that used a general description of PWR containment.

2. Page 9.0-5, Volume 10; Reference 1.

3. Page 9.0-6, Volume 10; Reference 1.

4. Section 5.6, Volume 8; Page 6.3-10, Volume 9; Page 8.6-3, Section 8.6.2, Volume 10; Reference 1. The full description of this significant contribution to the risk estimate is spread out among several discussions in the Zion PSS. Only an example of what effect it has on the calculation is provided. The actual numbers used to calculate the risk estimate are not presented. The audit analysis estimated the mean from the example in the report.

REFERENCES

1. Zion Probabilistic Safety Study, Commonwealth Edison Company, 1981. (10 Volumes)