Risk Management Application of Fire Risk Analysis

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ABSTRACT

Probabilistic risk assessment (PRA) has shown that the contribution of fires to the frequency of core damage and radionuclide release in some nuclear power plants can be significant. This article discusses the use of PRA results in fire risk management. The decomposition of these results leads to the identification of the most important contributors to the risk and, thus, allows for the identification of potential modifications that can have the greatest impact on risk. This paper discusses the process of generating these options and offers several insights that have been gained from an actual study.

Keywords: risk management, fire risk, nuclear power plants.

1. INTRODUCTION

Probabilistic risk assessment is a systematic approach to the quantification of the risk from complex industrial facilities and the identification of the major accident scenarios. PRA provides the means by which this risk, which may be economic as well as health-related, may be reduced. The decision to reduce this risk, and the process employed to achieve the desired reduction, fall within the realm of risk management. PRA, therefore, is a valuable source of information in terms of identifying and quantifying the impacts of various alternatives for the risk management process.

Recently, a number of PRAs have been performed for a variety of nuclear plants (Reference 1). In these PRAs, the risk is typically quantified in terms of the frequency of severe core damage and the frequencies of several public health effects; e.g., latent cancers. The conduct of a PRA requires the construction of a plant model; i.e., a logical representation of the plant that, using fault tree and event tree methods quantifies the response of the plant to a large number of disturbances (initiating events), including earthquakes, hardware failures, operator actions, and fires.

As a result of these studies, it has been shown, albeit with large uncertainties, that fires in a number of nuclear power plants can contribute significantly to those plants' total risk (e.g., References 2 and 3). More importantly, from a risk management standpoint, these studies indicate which fire scenarios are important and, therefore, what measures can be taken to decrease their importance in a verifiable manner. The ability to verify the impact of a candidate risk-reducing measure is an important risk management consideration, and will be further discussed in Section 2.

In the case of interest, one such plant-specific risk study showed that the mean frequency of fire-initiated accidents leading to core damage was about 20% of the total core damage accident frequency. Similarly, the same study showed that fires in that plant contribute roughly 50% to the total frequency of accidents leading to large-scale releases of radionuclides from the plant. The methodology employed to estimate the fire risk involves the evaluation of the frequency of each specific fire scenario in terms of the fire location, initial fire severity, fuel bed characteristics, suppression characteristics, and availability of additional plant systems that can mitigate the effect of the scenario on the plant's functioning (References 4 through 6).

From the standpoint of facility management, the results of PRAs are of interest when applied to the following questions:

- What possible options are there for reducing risk?
- How effective (and believable) are these options in reducing the risk?
- How desirable are these options?

This paper addresses these questions. It does not, however, address the selection of an optimal alternative; this decision is the province of management, which must weigh the benefits and disadvantages of each alternative with respect to economic, regulatory, operational, and risk considerations.

2. METHODOLOGY

2.1 Major Contributors to Risk

The different layers of a nuclear plant PRA's results are shown in Figure 1 (adapted from Reference 7). The decomposition process starts from the top (level 1), the final result, or risk curve level. Level 2 reveals the important release type (which characterizes how the radionuclides are released over time) where importance is measured in terms of degree of contribution to the risk curves. Level 2 also indicates the important degraded plant conditions (i.e., the plant damage states that lead to these release types), and the initiating events (e.g., a fire in a cable spreading room) that lead to these damage states. Level 3 identifies the important sequences of events (the accident scenarios) that lead to the various plant damage states. In levels 4 through 6, the important system and component failures, the causes of these failures, and the data supporting the quantified analysis of the frequencies of these causes and failures are respectively identified.

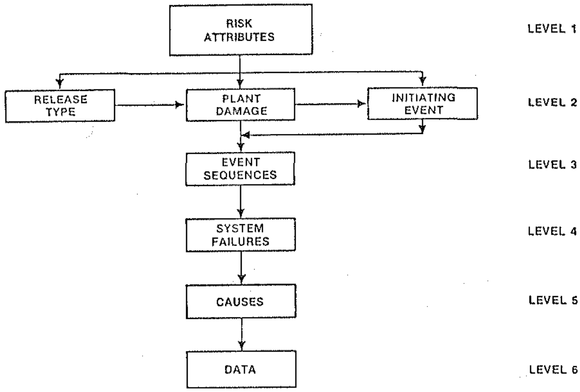

FIGURE 1. A graphical representation of the risk decomposition process (adapted from Reference 7)

In the following section, the fire risk analysis methodology employed in the base case PRA is described, giving attention to those factors (and groupings of factors) that may affect our choice of risk management options.

2.2 Fire Risk Analysis Methodology

The methodology for analyzing fire risk in nuclear power plants has been developed specifically to handle the fire-related characteristics of those plants. These plants typically consist of several large concrete buildings that are subdivided into rooms (fire zones) with relatively thick concrete walls and floors. Almost all fire zones contain numerous electrical cables in trays and conduits. In addition to cables, a zone may contain pumps, electrical switching gear, control panels, batteries, and/or piping and valves. The combustible loading of a typical zone is relatively low when compared to that of other commercial structures, such as office buildings.

For protection against the occurrence and consequences of a fire, nuclear plants must be designed and operated according to several strict regulations. The most important fire-related regulation is the Appendix R to Code Federal Regulation Title 10, Part 50 (Reference 8). As a result of these safety considerations and the low combustible loadings in a plant, fires have the potential to initiate serious accident sequences only in a small number of plant locations.

As described in References 4 through 6, the fire risk analysis methodology for these plants proceeds as follows. First, the potentially important fire scenarios are identified by establishing the exact locations of the components whose simultaneous failure may have a severe impact on the plant. For each such location, different fire scenarios (involving fires of varying severities at or near the location) are postulated and their frequencies of occurrence are quantified using both statistical data and judgment. The fraction of fires that damage the components is established by modeling the physical effects of fires. This involves identifying fire propagation patterns, modeling the components' thermal responses, and computing the likelihood of fire suppression before the important components are damaged. Finally, to assess the impact of the fire on the plant, the likelihood of the failure of components outside of the fire zone due to other causes, such as maintenance, mechanical failure, and human actions, is assessed. Thus, the frequency of plant damage of type X from a fire scenario can be written as

$$\lambda_X = \sum_j \lambda_j Q_{d|j} Q_{X|d,j} \tag{1}$$

where

λ_j = annual frequency of fires of class j, where the classes are determined both by the location and initial severity of the fire.

$Q_{d|j}$ = fraction of class j fires which lead to damage to a specified set of components.

$Q_{X|d,j}$ = fraction of class j fires causing damage to the specified set of components that lead to plant damage type X.

The fraction of fires that lead to damage, $Q_{d|j}$, is the fraction of fire scenarios where component damage from fire growth occurs prior to fire suppression. This can be written as (Reference 6)

$$Q_{d|j} = Fr\{T_G < T_H\} \tag{2}$$

where Fr{A} denotes the frequency of occurrences of event A, T_G is the time it takes for the fire to grow and damage the important components, and T_H is the total time required to detect and suppress the fire.

The third parameter of Equation (1), $Q_{X|d,j}$, is generally a function of numerous system and component unavailabilities, as well as operator action frequencies; indeed, the major portion of a nuclear plant PRA is dedicated to establishing these relationships. A very simple representation of these complex equations is

$$Q_{X|d,j} = Q_{CD|d,j}\, Q_{X|CD,d,j} \tag{3}$$

where

$Q_{CD|d,j}$ = fractions of class j fires that include additional component failures that lead to core damage.

$Q_{X|CD,d,j}$ = fraction of those fires that include additional failures that lead to damage state X.

An example for an event characterized by $Q_{X|CD,d,j}$ is the failure of containment cooling-related equipment. This failure does not influence the likelihood of core damage, but has a profound impact on the severity and the type of radionuclide release.

2.3 Development of Fire Risk Management Options

From the preceding discussion, it can be seen that the fire risk analysis methodology employed allows a decomposition of the risk down to the bottom level of Figure 1. Equation (1) represents a summation of risk contributions of different fire-initiated accident sequences (level 3); each product in Equation 1 contains terms that represent the level 4 system and component failures due to fire and to other causes, (level 5), and the analysis procedure used to quantify each term identifies the level 6 contribution to risk. Thus, the primary contributors to risk at each level can be identified, and the impacts of alternatives intended to reduce the risk at each level can be evaluated.

To reduce the risk from a fire of specified initial severity and location, options can be chosen to reduce any one or more of the factors shown in Equation (1). For example, the likelihood of fire occurrence may be decreased by increasing administrative controls over the movement of combustibles and the performance of maintenance-related activities in the location of interest. The likelihood of component damage can be addressed by slowing down the fire growth rate, say by reducing combustible loadings or by installing fire barriers, or by speeding up the rate of detection and suppression, e.g., by installing automatic sprinklers. The likelihood of further component failures, given a certain number of fire-induced failures, can be decreased by increasing the redundancy of important equipment in areas independent of the location of interest.

A somewhat different risk management option is suggested by the fact that the exact value of each term in Equation (1) is not known with certainty. If the uncertainties in any term of a dominant product in Equation (1) are very large, a potential risk-reducing measure may be a more detailed analysis of those terms characterized by large uncertainties. Thus, if the risk from a scenario involving an uncertain fire damage threshold for electrical cables is large, it may be more efficient to test the cables under appropriate conditions than to actually make changes in the plant. Of course, it is not certain that a reduction in risk will result from further analysis; thus, this measure may be less desirable than others that guarantee some degree of reduction.

It is important to realize that the uncertainties in the quantification of the effectiveness of each risk management option must be included as an integral part of the analysis. If the expected reduction in risk from a particular alternative is small with respect to the uncertainty bands about the original value, or the new value, there clearly will be doubts as to the actual effectiveness of the alternative.

3. CASE STUDY

3.1 Base Case Decomposition

Only three potentially significant fire scenarios were identified and explicitly analyzed in the base case. Because of this, the event sequence structure of Equation (1), the decomposition of the base case results from level 1 (where fires, as a group of events, are recognized to contribute significantly to the total risk) to level 4 (the "system failure" level) is straightforward.

In the base case study, two of the three fire scenarios analyzed contributed significantly to the total plant risk. We refer to the two fire zones housing these contributing scenarios as zones 1 and 2; the total contributions from these two zones as well as the breakdowns of these contributions, are given in Table 1. It can be seen that, in both cases, the state-of-knowledge uncertainties in the component frequencies can be very large.

TABLE 1. Summary of the case study decomposition results

Zone Designator/ Scenario	Percentile	Frequency, Events Per Year		λ_j	$Q_{d\|j}$	$Q_{CD\|d,j}$	$Q_{R\|CD,d,j}$
		λ_{CD}*	λ_R**				
1. Fire Under Cables Damaging Switch-Gears and Power Cables to Component Cooling and Safety Injection Pumps	5th	4.6-8	4.6-8	1.1-7	0.32		
	50th	7.9-6	7.9-6	1.3-5	0.62		
	95th	4.2-4	4.2-4	3.7-4	0.90		
	Mean	7.1-5	7.1-5	1.2-4	0.62	1.0	1.0
2. Fire in the Aisle Damaging Power Cables to Component Cooling and Safety Injection Pumps	5th	5.5-8	5.5-8	1.2-7	0.20		
	50th	4.7-6	4.7-6	8.4-6	0.55		
	95th	1.0-4	1.0-4	1.6-4	0.87		
	Mean	2.4-5	2.4-5	4.2-5	0.57	1.0	1.0
3. Fire on the Floor Damaging Control Cables 10 Feet Above the Floor and Failing All Control and Instrumentation Capability	5th	3.0-10	<1.0-10	5.3-7	0.12	2.5-4	0.02
	50th	7.3-8	7.3-9	3.3-5	0.45	5.0-3	0.1
	95th	3.3-6	5.9-7	5.0-4	0.80	1.0-1	0.5
	Mean	1.9-6	3.0-7	1.5-4	0.48	2.6-2	0.16

*Core damage frequency; $\lambda_{CD} = \lambda_j Q_{d|j} Q_{CD|d,j}$.

**Radionuclude release frequency; $\lambda_R = \lambda_j Q_{d|j} Q_{CD|d,j} Q_{R|CD,d,j}$.

NOTE: Exponential notation is indicated in abbreviated form; i.e., 4.6-8 = 4.6×10^{-8}.

The contributions to risk from fires in other zones (other than the three that were analyzed) were judged to be much smaller, due to a variety of reasons (e.g., independent critical equipment lie outside of the zone of interest). Although the contributions from these latter fire scenarios are not important when quantifying the base case risk, they do become visible when the risk from the dominant scenarios is reduced. In other words, as the magnitude of one particular problem is lowered, other, formerly less important problems, become more noticeable. This interesting observation indicates that PRAs cannot be completely bottom-line oriented if they are to be used in risk management.

A resulting task from this observation, therefore, is the quantification of the risk contributors from the "next level" of fire scenarios. The total mean frequency of core damage (λ_{CD}) for the next 17 fire zones is estimated to be 6.0×10^{-6} per reactor year; the corresponding release frequency (λ_R) is 8.9×10^{-7} per reactor year.

3.2 Identification of Potential Options

Four general categories of the fire risk management options can be identified, based on the discussion of Section 2.3. They are options to:

1. Improve the models employed in the original analysis.

2. Reduce the frequency of occurrence and the potential severity of fires in the critical location of interest.

3. Reduce the likelihood of important component damage, given a fire.

4. Reduce the likelihood of subsequent plant system failures, given the loss of important components.

The first option stems from the recognition that the original PRA was performed under specific time, budget, and state-of-knowledge constraints. It is conceivable that further investigation of the critical fire scenarios will result in the identification and elimination of conservatisms in the original analysis. On the other hand, it is also conceivable that further study will corroborate the earlier results or may even identify some optimistic assumptions. However, because of the uncertainty in the outcome of this option, and because the then current state of knowledge in fire risk modeling did not allow any simple improvements in the analysis (in other words, a major research project would have to have been undertaken), this option was not pursued.

The frequency of fire in a particular zone (λ_j) may be reduced by changing the design of equipment in the zone or by improving administrative procedures. For example, zone 1 of our case study contains oil-lubricated compressor sets. If the system is changed such that oil need not be brought into the room, the likelihood of a severe fire would be decreased. Another option would be to introduce a permanent fire watch into the zone. None of these options was pursued in this study, primarily because significant decreases in the fire frequency could not be verified. We note that current administrative procedures for fire prevention in nuclear power plants are already quite strict, and that the long-term effectiveness of using a fire watch to prevent the occurrence of very rare fires (see Table 1) is dubious.

From Equation (2), it can be seen that the likelihood of component damage can be reduced by increasing the growth time, T_G, or by reducing the hazard time (the sum of the detection and suppression times), T_H. The installation of protective barriers serves the former purpose and is relatively cheap. This option will be further discussed in Section 3.3.

Improvements to the existing automatic detection and suppression system would reduce T_H, but are fairly expensive. The possibility of spurious suppression system actuation also reduces the desirability of this option from an operations and maintenance point of view. Furthermore, detailed detection and suppression time models needed to formally analyze the improvement in T_H (Reference 5) were not available at the time the analysis was performed. This option, therefore, was not investigated further.

The last set of potential modifications concentrates on improving the plant system response to the loss of critical components due to fire; i.e., on reducing $Q_{X|d,j}$. Since the essential characteristic of the dominant fire scenarios is that a single fire damages a large number of important components and thereby renders unavailable many safety systems, a natural solution is to ensure that one or more critical safety systems are entirely independent of the dominant fire zone. In this case study, zones 1 and 2 contain the power cables for the "component cooling" and the "safety injection" pumps. If these cables are damaged by a fire, these pumps would lose all power, the "charging pumps," which are cooled by the component cooling system, would be lost, and severe core damage would eventually result. Two relatively efficient plant modifications to mitigate the effects of a severe fire in either zone are (1) the installation of an independently cooled and powered charging pump that does not depend on the component cooling system and (2) the provision of an alternate electrical power source for the component cooling system.

3.3 Fire Barriers

The installation of fire barriers in zones 1 and 2 is intended to perform essentially the same function as the plant system modifications discussed in Sections 3.4 and 3.5; the barriers are to render the selected power cables for the component cooling and safety injection pumps independent (or nearly so) of the remainder of the two zones. However, because the barriers are supposed to prevent, rather than mitigate, component damage, their effectiveness is modeled in the analysis of $Q_{d|j}$ instead of $Q_{X|d,j}$.

The fire barriers considered for this option are thermal insulating boards composed of noncombustible material, and are about 1.3 cm thick. These barriers would enclose the cable tray holding the power cables to one of the three pumps of both the component cooling and the safety injection systems. The same type of barriers would also separate redundant switchgear cabinets. In zone 3, the barriers are to extend the length of the room and enclose two sets of three cable trays. This would protect the power cables for two of three component cooling and safety injection pumps.

To evaluate the impact of these barriers, the same procedure as used for the original study is employed. The thermal calculations underlying the analysis of $Q_{d|j}$ indicate that not only is the time to damage longer with the installation of the barriers, but the initial severity of the initiating fire must be greater as well. Thus, this modification also leads to a reduction in λ_j. The results of this analysis are given in Table 2.

TABLE 2. Summary of the case study final results

Option	Description	Percentile	λ_{CD} Events Per Year	Reduction Factor	λ_R Events Per Year	Reduction Factor
0	Base Case	5th	2.2×10^{-6}		1.5×10^{-6}	
		50th	3.0×10^{-5}		2.6×10^{-5}	
		95th	1.1×10^{-3}		9.7×10^{-4}	
		Mean	1.0×10^{-4}	1.0	9.6×10^{-5}	1.0
1	Fire Barriers	5th	5.9×10^{-7}		2.1×10^{-7}	
		50th	9.1×10^{-6}		7.4×10^{-6}	
		95th	2.3×10^{-4}		2.1×10^{-4}	
		Mean	3.9×10^{-5}	2.6	3.3×10^{-5}	2.9
2	Self-Contained Charging Pump	5th	1.6×10^{-6}		3.6×10^{-7}	
		50th	8.8×10^{-6}		3.4×10^{-6}	
		95th	9.9×10^{-5}		9.2×10^{-5}	
		Mean	1.9×10^{-5}	5.3	1.2×10^{-5}	8.0
3	Alternate Power Source	5th	1.7×10^{-6}		5.7×10^{-7}	
		50th	7.1×10^{-6}		3.0×10^{-6}	
		95th	4.8×10^{-5}		2.6×10^{-5}	
		Mean	1.4×10^{-5}	7.1	6.9×10^{-6}	14.0

3.4 Self-Contained Charging Pump

A diesel engine-driven charging pump that does not require any external plant systems for motive power or cooling is proposed as an addition to the original charging system. The pump must be located in an area that does not contain any portions of the component cooling system. The new pump would provide cooling to crucial plant components in the case of fire damage to the component cooling system.

To analyze the risk reduction of this modification, the unavailability of this pump is calculated from data for existing diesel engine-driven pumps. This unavailability is then multiplied with the original value of $Q_{X|d,j}$ for those zones where total loss of component cooling due to a fire is possible. The final results are summarized in Table 2.

3.5 Alternate Power Source

The main purpose of this modification is to provide an alternate source of electrical power to some of the important pumps that can be affected by fires in zones 1 and 2. The modification can be implemented using an existing switchgear in an independent zone as the source of power; new power cables are to be routed from this switchgear, through areas outside of zones 1 and 2, to one component cooling pump and one safety injection pump. The unavailability of this new power source is computed by taking into consideration possible equipment failures and the potential errors that the personnel could make during the hookup. Also accounted for is the time window available to them to correct their errors. Personnel errors are the main contributors to the unavailability of the alternative power source. The risk impact of this modification is shown in Table 2.

3.6 Discussion of Options

As can be seen from Table 2, all three options provide a measurable reduction in risk. It can also be seen that the alternate power source option is the most effective of the three. The fire barrier option is less effective, primarily because of the analysis uncertainties in quantifying the frequency of very severe fires. The diesel-driven charging pump option is more effective than the fire barrier option, but it has less impact than the alternate power source option because the unavailability of the diesl engine is somewhat greater than the operator error rate in attaching the alternate feed cables. Coincidentally, the alternate power source option also was the most desirable alternative for both the plant operations and licensing personnel. This option was eventually chosen for implementation by the plant management.

4. CONCLUDING REMARKS

In this paper, some of the desired features of a PRA that enhance its use in a fire risk management study have been addressed. These features include the ease and extent to which the results can be disassembled to determine the principal contributors to risk, the inclusion of sufficient detail to allow analysis of the effectiveness of various risk-reducing options, and the complete treatment of uncertainties to express our confidence in the results. These uncertainties can significantly affect the rankings of a number of alternatives. If the uncertainties in the risk-reducing benefits of a particular modification (e.g., administrative improvements in the control of combustibles) are sufficiently large, the decision makers may opt for a somewhat more expensive change (e.g., hardware additions), whose benefit is more clear cut.

The case study identification and analysis of fire risk management options from the results of a nuclear power plant PRA serves to underline these arguments. For example, the necessity to quantify risk sequences of secondary importance indicates that purely bottom-line oriented studies may require additional work before they may be used to evaluate the effectiveness of the various options.

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