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Technical Methods for a Risk-Informed, Performance-Based Fire Protection Program at Nuclear Power Plants

M. K. DEY*
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
United States of America

Abstract

TECHNICAL METHODS FOR A RISK-INFORMED, PERFORMANCE-BASED FIRE PROTECTION PROGRAM AT NUCLEAR POWER PLANTS.

This paper presents a technical review and examination of technical methods that are available for developing a risk-informed, performance-based fire protection program at a nuclear plant. The technical methods include "engineering tools" for examining the fire dynamics of fire protection problems, reliability techniques for establishing an optimal fire protection surveillance program, fire computer codes for analyzing important fire protection safety parameters, and risk-informed approaches that can range from drawing qualitative insights from risk information to quantifying the risk impact of alternative fire protection approaches. Based on this technical review and examination, it is concluded that methods for modeling fires, and reliability and fire PRA analyses are currently available to support the initial implementation of simple risk-informed, performance-based approaches in fire protection programs.

1. INTRODUCTION

Historically, requirements for fire protection programs in the general building industry and nuclear power plants have been formulated based on deterministic criteria and prescriptive in nature [1]. In many cases engineering judgment of experts was used in determining fire protection features such as the allowable minimum width of hallways and number of fire detectors and sprinklers for buildings, and the allowable minimum safe separation distance and

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fire barrier ratings for nuclear power plant safe-shutdown trains. Given the advances in probabilistic risk assessments (PRAs) and fire sciences, fire protection programs can now be revised from being deterministic and prescriptive to more risk-informed and performance-based [1, 2].

In a broad sense, risk-informed, performance-based fire protection programs can be thought of as more efficient in terms of expenditure of resources while at the same time focusing proper attention on risk-significant aspects of the programs. This means is achieved by an increase in risk-informed discrimination offered by PRAs and fundamental understanding of fire dynamics. The two main objectives of risk-informed, performance-based approaches [2, 3] are

(1) to provide flexibility by emphasizing the safety objective rather than the means for achieving the objective

(2) allocating resources to the most risk-significant areas and minimizing resource allocation to areas in which safety benefit is minimal

In order to achieve the above objectives, it is necessary to establish technical methods that can be used to demonstrate that higher level safety objectives are met. This paper examines and presents technical methods that can be used to implement risk-informed, performance-based fire protection programs.

2. RESULTS OF TECHNICAL REVIEW

In order to determine methods that could be used for risk-informed, performance-based approaches for fire protection, a technical review of the state of the art of fire dynamics and fire probabilistic risk assessments was initially conducted. Some general observations and conclusions from this technical review follow.

The general building industries in several countries (notably New Zealand, Japan, Australia, Canada, and UK) are in a transition from prescriptive to risk-informed, performance--based requirements for fire protection in order to facilitate the approval of innovative designs, reduce costs, and improve safety [4]. The transition taking place is evolutionary in that the prescriptive requirements are still maintained as a frame of reference to determine equivalency, and for approval of standard designs. At the present time, performance-based designs are used for constructing complex new facilities or making extensive modifications to current buildings. The programs initiated toward this goal have required a considerable investment of resources and the development of new engineering talent. Nuclear power plants can benefit from the experience of the building industry in adopting risk-informed, performance-based approaches for nuclear power plants fire protection programs.

The technology of modeling fires (and smoke resulting from fires) is being actively pursued in the general building industry in several countries and nuclear industries in some countries, notably France [5]. Several fire computer codes now available to predict important fire parameters are being validated through international cooperative efforts [6]. The credibility of the results from these codes is dependent on their use within the bounds and in a manner the developers intended. Fire models have been found to be a useful tool for estimating the average thermal environment that causes fire damage.

Several PRA methods and fire computer codes for risk-informed and performance-based evaluations of fire protection alternatives in the general building and nuclear power industries were reviewed. The absolute results of these methods vary significantly because of the uncertainties in the data and models, and because of the manner in which the calculations are conducted, however, the PRA methods are capable of providing useful insights about the relative importance of fire protection features and the risk-significant fire scenarios. Given this current state of the art of fire PRAs, it will be difficult to establish quantitative safety objectives for fire protection programs in such a manner that compliance with these goals can be easily measured. However, information on relative risks can be used with a high degree of confidence. Although certain refinements of fire models and PRAs are desirable, it will be too costly to address all uncertainties to establish quantitative risk goals, and doing so is not essential for initiating applications using results of relative risk. The technology will mature through applications to a stage and time when more sophisticated use of quantitative goals will become feasible.

Fire PRAs conducted in the past have shown that a substantial fraction of the risk from fires in nuclear power plants comes from only three or four areas such as the control room, cable spreading room, and the switchgear room. This risk-information can be used to focus plant resources on these critical fire areas. One means to implement such an approach would be to establish categories, or grades, for the current fire areas in a plant. In such a scheme, a higher level of fire protection would be extended to areas that contribute significantly to plant fire risk.

Changes in core-damage frequency (CDF) calculated in PRAs can also be useful toward determining the safety impact of utilizing alternative risk-informed, performance-based approaches compared to compliance with prescriptive requirements. However, generic conclusions regarding the acceptability of alternative implementation methods are not possible because the results of fire PRAs are dependent on plant-specific compartment and hardware configurations, even if the methods, data, and assumptions are the same. For plant-specific applications, it should be a reliable indicator when the uncertainties in evaluating both the performance-based and prescriptive implementation approaches are similar. Other factors should also be considered in determining the adequacy of alternative approaches, especially if the uncertainties in the analyses for comparing alternative approaches are not similar.

3. SPECIFIC TECHNICAL METHODS AND APPLICATION AREAS FOR LESS PRESCRIPTIVE AND MORE RISK-INFORMED APPROACHES

Based on the above technical review, the following identifies generally categorized specific technical methods that can be used to support a less prescriptive and more risk-informed fire protection program at nuclear power plants. As stated above, given the state of the art of these technical methods, decisions regarding plant fire protection should not be made solely on results from these methods, but these results can be used toward making sound decisions based on performance and risk information. The applications of specific technical methods are presented in order of increasing technical complexity. More detailed examples of some of the applications are presented in the next section. The following list of applications illustrate the applicability of the technical methods and is not intended to be all inclusive.

3.1. Performance-Based Methods

The first general category of methods is those that would support performance-based approaches, but are not necessarily risk-informed, i.e., these methods will support implementation of less-prescriptive safety objectives, but do not directly analyze or utilize risk information.

3.1.1. "Engineering Tools" for Evaluating Fire Dynamics

These "engineering tools" are based on the principles of thermodynamics, fluid mechanics, heat transfer and combustion and are useful for analysis of unwanted fire growth and spread (fire dynamics). These analyses can be mostly conducted by hand without a computer program, or sometimes with simple computer routines of fire correlations. "Engineering tools" are available for calculating an equivalent fire severity, adiabatic flame temperature of the fuel in comparison to the damage temperature of the target, fire spread rate, pre-flashover upper layer gas temperature, vent flows, heat release rate needed for flashover, ventilation limited burning, and post-flashover upper layer gas temperature.

These tools can be used to demonstrate adequacy of deviations from prescriptive requirements for configurations with low fire loading, or to establish the basis for fire barrier ratings, safe separation distance, and need for fire detectors and suppression systems in protecting one train for safe shutdown. Since these tools employ bounding calculations, results will be conservative but can provide useful information to indicate areas where fire protection features have been grossly over-emphasized (or under-emphasized).

3.1.2. Reliability Methods

Feedback of operating experience and reliability modeling techniques can be used to evaluate the performance of alternate fire protection system designs or surveillance schemes. These methods can be used to determine an optimal maintenance and surveillance test interval for fire protection detection, suppression (including fire extinguishers, hoses, and pumps), and lighting systems.

3.1.3. Fire Computer Codes Based on Zone Models

These computer codes are based on plume correlations, ceiling jet phenomena, and hot and cold layer development and can predict the temperature of targets exposed to fires, detector and suppression system actuations, and smoke level and transport during fires. In cases where simple calculations (see *3.1.1*) cannot be used for evaluating fire dynamics to provide useful results (i.e. they are too conservative), these fire computer codes can be used for more detailed calculations to support an assessment of the fire hazard and predicting fire protection system response.

3.2. Risk-Informed, Performance-Based Methods

The second general category of methods is those that would support performance-based and more risk-informed approaches, i.e., these methods will support implementation of less-prescriptive performance criteria, and analyze or utilize risk information.

3.2.1. Use of risk insights in a qualitative manner

The results of PRAs, and other more limited analysis, e.g. using Fire Induced Vulnerability Evaluation (FIVE) method [7] can be used in a qualitative manner to provide risk insights regarding the risk significance or impact of alternate approaches.

An example is the use of fire PRA results, including human recovery modeling, to develop the basis for the plant emergency lighting program in lieu of prescriptive requirements (e.g., eight hours duration for all plant areas containing safe-shutdown equipment). Risk-significant accident sequences, e.g.; for fire induced station blackout, can be examined to determine the need and duration of emergency lighting. In some cases, lighting may be required for more than eight hours.

3.2.2. Risk-Graded Approach

Fire PRA and other methodologies have inherently in them screening processes which can progressively distinguish between and identify high and low risk fire areas. The screening methods employed in fire PRAs, and other methods such as FIVE, can be used toward formulating a risk-graded fire protection program by identifying and focusing on critical fire areas. Categories, or grades, can be established for currently identified fire areas in plants. A higher level of fire protection could then be extended to fire areas that contribute significantly to plant fire risk. An expert panel, consisting of plant fire protection personnel and PRA analysts, should use the results of fire PRAs toward establishing the grades, supplementing the information with engineering judgment, where necessary. This approach would be in contrast to prescriptive requirements that specify that all structures, systems, and components (SSCs) of one shutdown train be protected from fires by the same measures regardless of the extent of vulnerability of those SSCs to a fire or impact on plant risk if they are damaged.

3.2.3. Delta-CDF Calculations

Fire PRA methods can be used to calculate the change in core damage frequency (delta CDF) for alternative approaches to fire protection, including for evaluating the role of operators for recovery actions. These methods are useful for evaluating the extent to which repairs are appropriate to maintain one train of systems to achieve and maintain shutdown conditions, and the use of non-standard systems for shutdown. The methods can also be used to evaluate and compare alternate means of providing fire protection (by combining separation, fire barriers, and detection and suppression) to safe-shutdown systems.

4. EXAMPLES OF APPLICATION OF TECHNICAL METHODS

Trial applications have been conducted or reviewed to evaluate the feasibility of the methods listed above. The following is a discussion of examples of how these methods can be applied to plant fire protection programs.

4.1. Example for Using "Engineering Tools" for Evaluating Fire Dynamics (3.1.1)

In many cases, configurations with low fire loadings (including transient combustibles) can be distinguished from high risk areas through the use of "engineering tools" that represent fire dynamics in a gross manner. The following is an illustration of how simple tools can sometimes be sufficient to predict the degree of threat from fires. A cable spreading room in a nuclear power plant toured by the author is used as an example.

The room is about 6.1 m (20 ft) x 6.1 m x 5.2 m (17 ft) high. The upper half of the room is crowded with cable trays, each of which has an array of cables. There is no observable fuel below the lowest cable tray which is about 3.1 m (10 ft) above the floor. Some cable trays do descend to floor mounted cabinets, but there are only terminal strips in these cabinets, not electrical equipment that could fail and cause a fire. The cables are steel jacketed with no flammable insulation outside the jacket. Although a persistent source of heat could degrade the insulation around individual conductors in the cables, it is unlikely that they can be ignited since air cannot get to the flammable wire insulation.

Since there is nothing combustible in the lower half of the room, a fire can only occur with a "transient" fuel, such as spilled cleaning fluid. Assuming a worst case situation in which the liquid fuel pool is directly below the lowest cable tray, a plume correlation in FPETOOL (a compilation of correlations for fire protection calculations) [8] can be used to estimate the temperature of the plume at the 3.1-m height of the tray for a series of fire sizes. If it is assumed that the wire insulation will start to degrade at 200 °C, and the fuel would burn long enough for the insulation to reach the plume temperature, the corresponding fire size from the correlation is 400 KW. If the fuel is gasoline (most solvents used for cleaning have a significantly lower burning rate than gasoline, e.g., methyl alcohol burns at 1/4 the rate of gasoline), one can use correlations developed for hydrocarbon pool fires [9] to determine that the pool would be about 1.1 m (3.5 ft) in diameter and the liquid surface would burn at about 4.5 mm/minute (7.5×10^{-5} m/sec). The volume of the fuel can be determined from the following correlation for the maximum pool diameter.

$$D_m = 2[V^3 g'/y^2]^{1/8}$$

where g' is the effective acceleration due to gravity = 9.8 m/s^2, y = fuel burning rate (m/s)

Solving for V, $V = 1.9 \times 10^{-4}$ m^3 = 0.2 liters

However, this pool, about 2.5 mm thick, will only burn for about 4 seconds which is insignificant compared to the time that would be required to heat the lowest cable tray to near the plume temperature. These bounding calculations can provide useful information toward plant decisions in terms of the degree of fire protection necessary for different configurations and thermal loads. The tools allow using some information representing the fire dynamics of the problem, and can be used to prevent over-emphasis (or under-emphasis) that can occur when such considerations are omitted and the hazard from all fire areas are equally treated.

4.2. Examples for Using Reliability Methods (3.1.2)

Fire detectors in safety-related areas must be tested periodically, sometimes as frequently as every 3 months in the U.S. Test intervals for all detectors are equally prescribed regardless of performance in codes of the National Fire Protection Association (NFPA), and incorporated into plant technical specifications. Test intervals established based on performance, have been used in other testing programs in nuclear plants [3] and offer opportunities for cost optimization and a focused fire protection surveillance program.

The use of reliability engineering models supported by actual failure data for evaluating appropriate tests intervals for fire detectors has been considered and implemented in a U.S. plant [10]. This plant used fire detector testing records covering a period of five years to establish plant-specific fire detector failure rates. Three types of detectors were considered - ionization, heat, and photoelectric detectors. The surveillance records covered 3 years of semi-annual testing, followed by 2 years of annual testing. Based on the analysis of this performance data, an alternative testing methodology was implemented by the utility by using 10-percent rotating sampling at an annual test interval, with provisions for expanding the sample population if a decline in performance was observed.

More formal reliability methods have been used elsewhere [11] that illustrate the feasibility and benefit of performance-based strategies for fire protection system surveillance. Based on a reliability model, detector failures were classified into random, test-generated, and test-independent faults. Effectiveness of various test strategies for detecting failures was then evaluated, and finally, the parameters of the reliability models (including the uncertainties) were estimated through statistical techniques. These parameters were them included in the reliability model to determine an optimal test strategy. The results indicated that extending the test interval from quarterly to annually, supplemented by daily self-verification and quarterly inspection, would increase the reliability of the detectors and decrease testing costs.

4.3. Example for Using Fire Computer Codes Based on Zone Models (3.1.3)

Fire protection regulations [12] of the U.S. Nuclear Regulatory Commission (NRC) require that one train of systems necessary to achieve and maintain hot shutdown conditions be free of fire damage. The regulation provides three options for meeting this requirement including one that allows for separation of cables, equipment, and associated non-safety circuits of redundant safe-shutdown trains by a horizontal distance of more than 6.1 m (20 ft) with no intervening combustible materials or fire hazards. In addition, fire detectors and an automatic suppression system should be installed. Experience from the early 1980's indicated that some utilities in the U.S. found it difficult to implement this prescriptive requirement (it would be too costly), and requested the U.S. NRC that they be exempted from this requirement. In almost all cases, some combination of low combustible loading, a high compartment ceiling, or negligible intervening combustible was used as justification. Utilities indicated that in some cases compliance with the prescriptive requirement would require forced outages and cost up to $ 24 million. The U.S. NRC approved several of the requests for exemptions based on the arguments provided.

Most of the arguments provided by the utilities were qualitative, although at least one utility used correlations in FPETOOL [8] to quantitatively estimate the fire hazard. Since the early 1980's, several fire models and computer codes have been developed that have been used in PRAs and other applications. A study was conducted to evaluate the capability of the following three fire models for developing insights regarding the 20-ft safe-separation requirement: (1) FIVE - a compilation of fire correlations in worksheets for use in screening fire areas [7]; (2) COMPBRN IIIe - a fire computer code developed for fast computations for use in fire PRAs [13]; and (3) CFAST - a fire computer code developed mainly for use in modeling fires in buildings [14].

A representative PWR emergency switchgear room (ESGR) was used for the study.

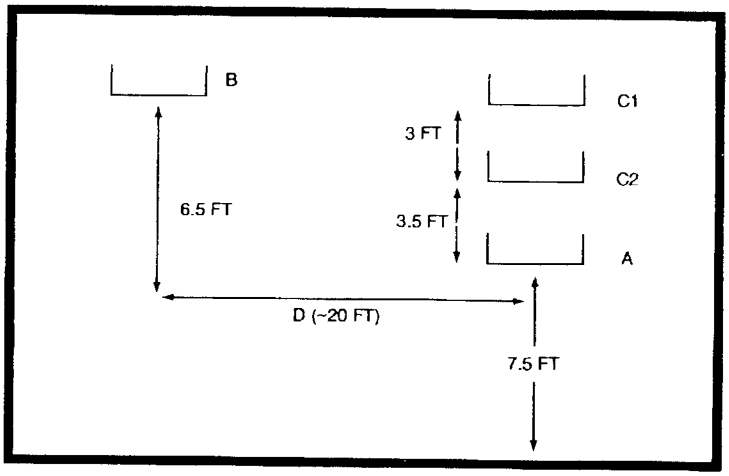

Figure 1 **Illustration of Critical Cable Locations in the Representative Emergency Switchgear Room**

The room is 15.2 m (50 ft) x 9.1 m (30 ft) x 4.6 m (15 ft) high. The room contains the power and instrumentation cables for the pumps and valves associated with motor-driven auxiliary feedwater trains, all three high-pressure injection trains, and both low-pressure injection trains. A simplified elevation of the ESGR room, illustrating critical cable locations, is shown in Figure 1. The power and instrumentation cables associated with safe-shutdown equipment are arranged in separate divisions and are separated horizontally by a distance, D, in Tray B. The value of D is varied in this evaluation. The analysis was conducted for different elevations of Tray B so that it was either in the ceiling jet sublayer or in the hot gas layer for different cases.

The postulated ignition source is either a self-ignited cable (as a result of a fault) or cable ignition as a result of a transient fire. Cable Tray A is considered to be the source. Although, most rooms will be isolated by the automatic closing of fire dampers and the shutdown of the ventilation system, a small opening 2 m (6.5 ft) high x 0.2 m (0.7 ft) wide was assumed to prevent pressure buildup in the room and facilitate the use of the COMPBRN and CFAST codes.

The ESGR contains smoke detectors and a manually actuated Halon system. Considering the fire initiating frequency and suppression (including fire brigade) probability, it can be estimated that if equipment affecting redundant trains is not damaged within 1 hour, then the resulting core-damage frequency (CDF) for this scenario will be less than 1.2E-5 per reactor-year. This damage frequency and time is used as a measure for determining the adequacy of the safe separation distance.

The FIVE method predicts that an effective fire source intensity of about 6.5 MW is required to damage cables that are separated by 20 ft, and 3.5 MW if separated by 10 ft, for cables that are in the ceiling jet layer (see Table 1). The FIVE screening method does not differentiate between the various separation distances in the hot gas layer and only conservatively estimates, based an adiabatic heating of the gas, the total energy release needed to raise the average hot gas layer temperature to the threshold damage temperature. In the present case, the total energy needed is about 286 MJ, which is much less than 3150 MJ corresponding to the energy released from a 3.5 MW fire during a 15-minute period. Therefore, none of the cases pass the screening criteria if the target is the hot layer.

Table 1 Summary Results From FIVE Analyses

Effective Fire Intensity KW	Ceiling Jet Temperature K	Target Damage Temperature K	Separation Distance ft
3500	526	643	20
6500	643	643	20
7000	660	643	20
3500	660	643	10
6500	843	643	10
7000	871	643	10

The COMPBRN analyses predict (see Table 2) that the effective fire intensity, capable of damaging redundant cables separated by 6.1 m (20 ft), is about 4 MW for the representative configuration, and that damage occurs in about 12 minutes. The COMPBRN code also predicts that a cluster of two cable trays in one side of the room (Case 5 listed in Table 2) will result in a peak burning rate of about 1.8 MW, which is not sufficient to damage cable trays

Table 2 Summary of COMPBRN Results

I. Damaged (D) and Ignition (I) Time (minutes)

Tray	Case 1		Case 2		Case 3		Case 4		Case 5	
	D	I	D	I	D	I	D	I	D	I
A (Source)	0	0	0	0	0	0	0	0	0	0
C2	2	2	2	3	2	2	2	2	2	2
C1	4	4	5	5	4	4	4	4	-	-
B (Target)	8	9	9	10	12	No	8	9	No	No

II. Total Heat Release Rate at the Time of Target Damage

	Case 1	Case 2	Case 3	Case 4	Case 5
Q, MW	4.8	4.0	8.2	4.7	1.8*

III. Description of Cases

	Case 1 (Base Case)	Case 2	Case 3	Case 4	Case 5
Pilot fire size (ft x ft)	4 x 2	2 x 2			
Door	Open		Closed		
Trays above pilot fire	C1 and C2				C2 only
Target elevation (m)	4.27			2.29	

* Maximum heat release rate with no damage to target cables

separated by 20 ft. The heat release rate predicted by COMPBRN for Case 2 is given in Fig. 2.

A modified version of the CFAST code, which accounts for radiation heat transfer to a target, was utilized for this evaluation. The CFAST code requires input of the heat-release rate for the fire source. Values of 1 MW, 2 MW, and 3 MW with a linear growth taking 1, 2, and 3 minutes, respectively for the heat released rate were used for three cases. The hot layer temperature, the radiative and convective heat transfer calculated by CFAST, was used in a transient conduction model for a thin slab to estimate the target surface temperature. Figures 3, 4, and 5 show the hot layer and cable surface temperatures for a 1, 2, and 3-MW fire as a function of time. Considering the critical damage temperature of 643 K and the extrapolation of the result shown in Figs. 3, 4, and 5, a fire of more than 3 MW is required to damage the target cables at a 20-ft separation in less than 1 hour, and a fire less than 2 MW will not damage redundant cables separated by less than 6.1 m (20 ft).

In order to understand the reason for the difference in the predictions of the CFAST and COMPBRN codes, the availability of oxygen to support the burning rates predicted by COMPBRN (see Figure 2) was examined. The CFAST code is capable of calculating the concentration of various species of air and combustible products in the hot layer region, whereas COMPBRN does not account for oxygen depletion and possible starvation of the fire. Using burning rates predicted by COMPBRN, CFAST predicts that, at about 5 minutes, the hot gas layer descends to the level of the lowest burning tray and the concentration of oxygen in the hot layer is below 10 percent (ordinary air is 21 percent). Therefore, the heat release rate will

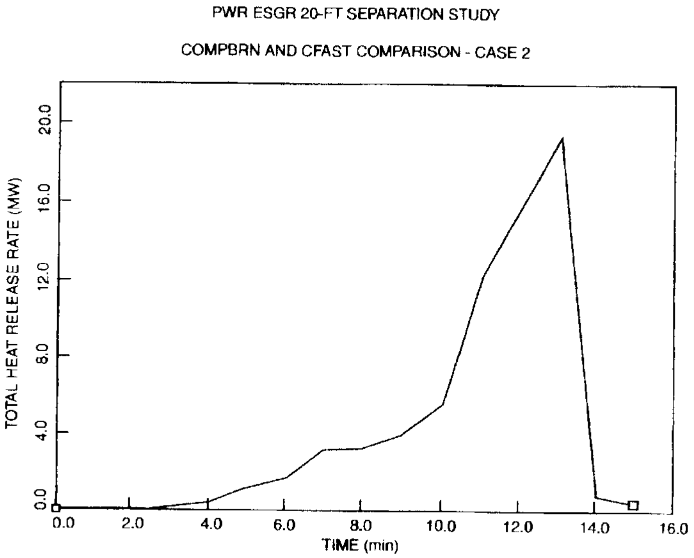

Figure 2 Heat Release Rate Predicted by COMPBRN - Case 2

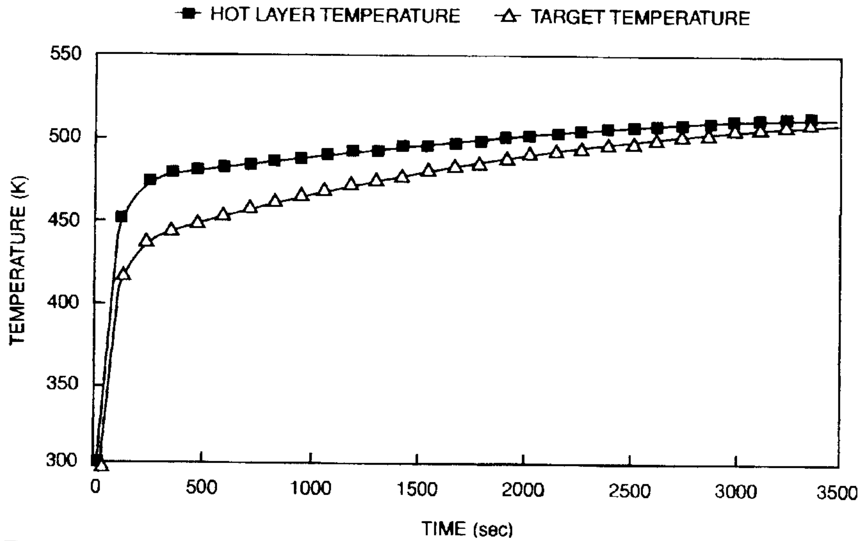

Figure 3 CFAST Prediction of 1-MW Source Target and Hot Layer Temperature

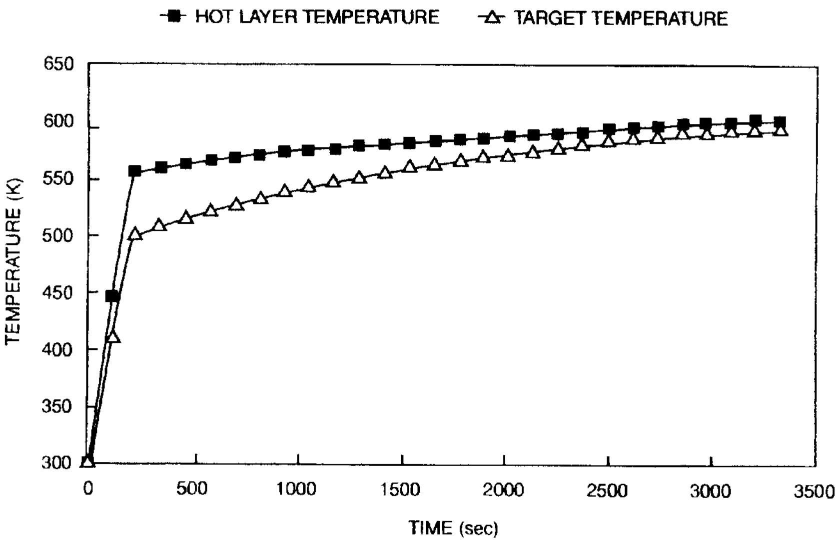

Figure 4 CFAST Prediction of 2-MW Source Target and Hot Layer Temperature

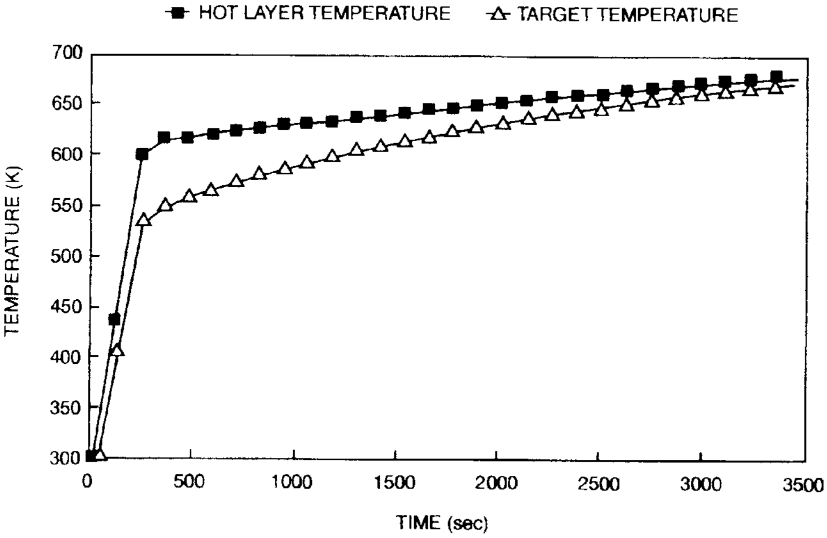

Figure 5 CFAST Prediction of 3-MW Source Target and Hot Layer Temperature

not increase after 5 minutes because of oxygen depletion and the fire would eventually be extinguished when insufficient oxygen is available to support combustion. Accordingly, the peak

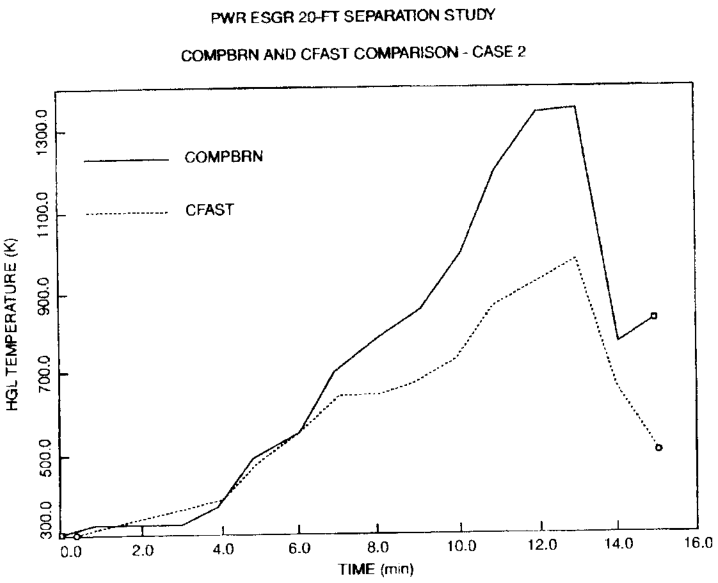

Figure 6 Comparison of CFAST and COMPBRN Prediction of Hot Gas Layer Temperatures

heat-release rate for this specific case will be below 2 MW and the heat-release rate predicted by COMPBRN after 5 minutes is overly conservative.

Figure 6 shows a comparison of the results from the CFAST and COMPBRN codes for Case 2 (see Table 2 for case conditions). In this case, the heat release rate due to fire predicted by COMPBRN (Figure 2) is provided as input to the CFAST code for the comparison analysis. After the COMPBRN-predicted ignition of Tray C2 at 5 minutes and Tray B (the target tray) at 10 minutes, Figure 6 shows that the hot gas layer temperature predicted by COMPBRN is much higher than that predicted by CFAST. This may be due to the conservative assumptions regarding heat losses from the hot layer in the COMPBRN code, however, the reason for this large difference in hot layer temperature was not examined further.

Based on the above results, it is concluded that if the maximum cluster of source cables results in a heat-release rate less than about 2 MW, then redundant cables will not be damaged, even if they are separated by less than 20 ft (e.g. 15 ft). The dominant factor for all the fire models for predicting damage to cables that are separated by 20 ft is the effective intensity of the fire source, not the total combustible loading in the fire area. Uncertainties in the fire intensity will dominate other uncertainties, such as in calculating the thermal environment, for predictions of cable damage.

The above study illustrates the capability of these fire computer codes to evaluate alternative approaches to the 20-ft separation criteria, although at different levels of resolution. The FIVE method is adequate for screening purposes but does not have sufficient resolution to address the problem in this evaluation if it is assumed the target is in the hot layer. The CFAST code provides a better non-conservative estimate for this problem than the COMPBRN code. However, both COMPBRN and CFAST estimate that a fire of about 1.8 MW or less will not damage redundant cables with 20-ft separation. This corresponds to a maximum cluster of three cable trays. Although the accuracy of these codes should be improved further, they can already provide approximate results, with a reasonable degree of confidence, that are useful for investigating parameters of interest in fire protection, e.g. the 20-ft separation criteria.

4.4. Example for Using Delta-CDF Calculations (3.2.3)

In order to limit the amount of repairs to equipment for achieving safe shutdown in the event of a fire, current fire regulations of the U.S. NRC require that a plant have the capability to reach cold shutdown conditions within 72 hours [12]. Experience from the early 1980's in implementing this requirement indicates that some U.S. plants found it difficult (it would be too costly) to meet this prescriptive requirement, and therefore requested the U.S. NRC that they be exempted from this requirement based on qualitative arguments that indicated that alternatives that included the use of non-standard systems and repairs, and would require more than 72 hours to reach cold shutdown, would provide an equivalent level of safety. These requests for exemptions based on qualitative arguments were accepted by the U.S. NRC.

Since the early 1980's methods, methods for fire PRAs have become available and can be used to quantify, through delta-CDF calculations, the impact of using alternative methods for achieving the higher level safety objective. The following illustrates this method.

The LaSalle fire PRA analysis [15] for the fire area for the cable shaft room adjacent to the Unit 2, Division 2, essential switchgear room was used for the purpose of this illustration. It was postulated[1] that the fire area contains equipment associated with both trains of the Residual Heat Removal (RHR) System, and that the fire damage is extensive and it will take more than 72 hours to restore one RHR train. This study adopts the LaSalle PRA assumption that a small fire anywhere in the fire subject area will cause the rapid formation of a hot gas layer that causes all critical cabling to fail. Prescriptive compliance with the 72-hour requirement would necessitate that of one RHR train be removed from the fire area, or that it be protected. An alternative approach is postulated to include reestablishing the condenser (Power Conversion System - PCS) for long-term decay heat removal to allow sufficient time for the repair of one train of RHR shutdown cooling. This approach would take more than 72 hours to reach cold shutdown.

The LaSalle fire PRA used conservative assumptions and excluded credit for operator recover actions for modeling the subject fire area since it was a non-dominant contributor to the fire-induced CDF. Therefore a more detailed event tree (shown in Figure 7) was developed for

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[1] It was necessary to assume some changes to the configuration of this fire area in order to allow data from the LaSalle fire PRA to be used for this illustration. Therefore, this analysis does not model the LaSalle plant.

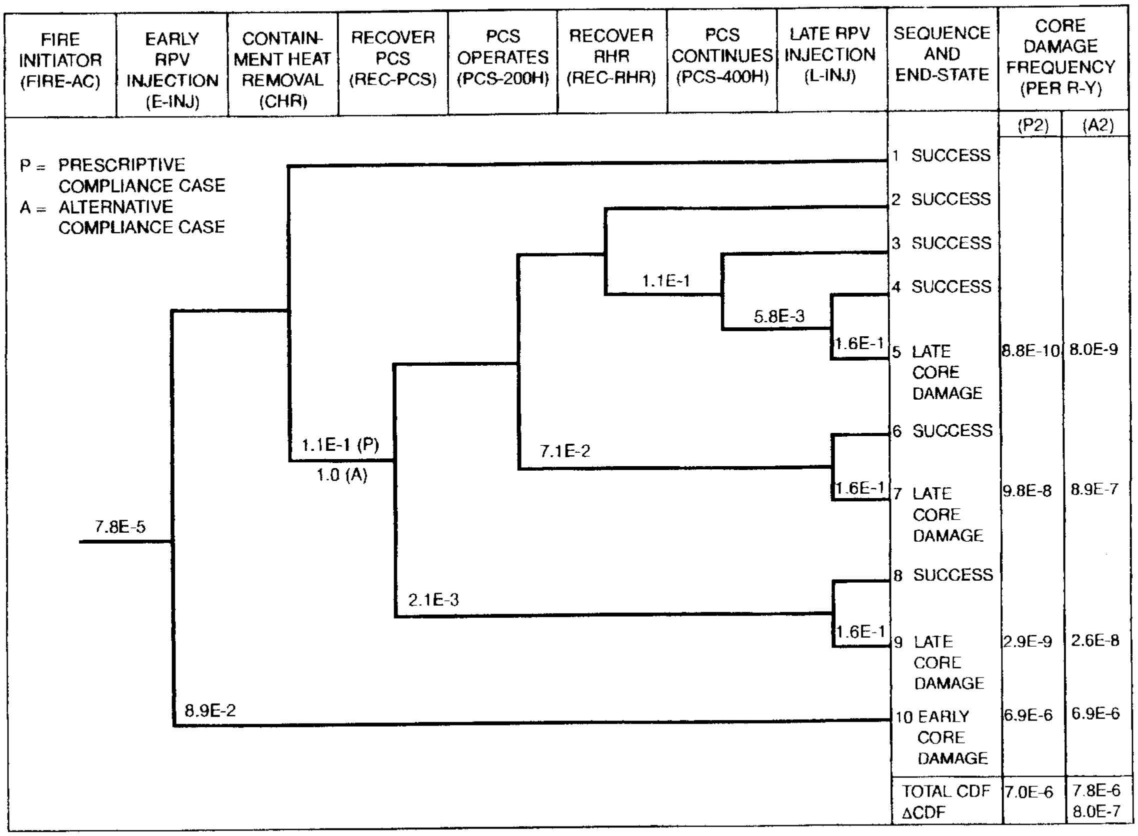

Figure 7 Quantified Event Tree for the 72-Hour Case Study

this example which included manual actions to recover PCS and RHR. The prescriptive compliance case assumes one RHR train is removed from the fire area or otherwise protected. Therefore, a failure of the Containment Heat Removal (CHR) function requires additional RHR random failures. The estimated unavailability is CHR = 1.1E-1. The alternative case does not protect the RHR system. All containment heat removal is assumed lost due to the fire, and CHR = 1.0. Operator actions to reestablish the condenser and to recover one train of RHR are critical issues in this analysis. Detailed plant-specific human reliability analysis would be required to accurately represent important operator actions and potential systems interactions. For illustrative purposes, conservative failure estimates were used for these restorations for this study. The four sequences leading to core damage are quantified for both the prescriptive and alternative approaches. The final result is given at the bottom of the Figure; it is ΔCDF = 8.0E-7.

The above example illustrates the PRA method and the feasibility of using ΔCDF as a tool toward evaluating the safety equivalence of an alternative approach to a prescriptive requirement. As is the case for this example, alternate approaches can be expected to require reexamination of non-dominant sequences, and use of a finer level of modeling resolution to credit certain operator recovery actions. The purpose of this example was not to only determine a bottom-line ΔCDF (in any case this analysis is not based on a real plant configuration or conditions) but to show that a probabilistic approach provides a consistent framework in which to identify key issues, examine assumptions, sensitivities and uncertainties[2].

5. TECHNICAL EDUCATION AND TRAINING

This paper has presented technical methods that are available for developing a risk-informed, performance-based fire protection program at a nuclear plant. The technical methods include "engineering tools" for examining the fire dynamics of fire protection problems, reliability techniques for establishing an optimal fire protection surveillance program, fire computer codes for estimating fire protection safety parameters, and risk-informed approaches that can range from drawing qualitative insights from risk information to quantifying the effectiveness of alternative fire protection approaches.

Nuclear plant staff that will use the above technical methods will be required to have an adequate level of education and training in these fields. Since fire protection requirements have historically been prescriptive and deterministic, fire protection staff may currently lack the necessary education and skills that are required for accurate and effective use of these methods. Education in the fundamentals of fire dynamics (that mainly includes applications of thermodynamics and heat transfer to fire problems) is necessary to develop the capability to effectively use the "engineering tools" and fire computer codes, and drawing useful and accurate conclusions from such analyses. This field of study has only recently been developed, and there are only a few colleges in the U.S. that offer a curriculum that would provide the necessary education. The knowledge and capability to conduct or understand fire PRAs is also normally not possessed by fire protection staff. Training in PRA techniques, including the basics of probability and statistics, will be necessary in order to use PRA and reliability techniques for developing risk-informed, performance-based fire protection programs.

6. CONCLUSION

Methods for modeling fires, and reliability and PRA analyses are currently available to support the initial development of a risk-informed, performance-based fire protection program. Some of these methods require the use of fire computer codes and fire PRAs which will require adequate education and training of the fire protection staff that will use these methods. However, the initial development of a risk-informed, performance-based program does not necessarily require extensive calculations using fire PRAs and models. In many cases, the use of simple performance-based analysis (e.g., “engineering tools” based on fundamental principles of fire dynamics) or application of risk insights in a qualitative manner (e.g., for emergency lighting requirements) is sufficient to examine and implement alternative approaches.

Given the economic status of the nuclear power industry in many countries, including the U.S., the use of risk-informed, performance-based approaches for fire protection programs in nuclear power plants should be implemented in phases. Initially, methods that do not require a

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[2] The results of the uncertainty analysis for this example is not presented here, but showed that the uncertainty of this analysis is dominated by the uncertainty associated with continued injection after containment failure.

significant investment of resources (e.g. in research and training) should be implemented, and the benefits from these applications should be assessed. Based on the assessment of these initial simple applications, the benefits of further investments and development of a risk-informed, performance-based fire program can be evaluated. A phased transition will allow plant resources to be focused for better protection, and the program to be more efficient without the need for a large investment of resources.

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