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A conceptual framework for formulating a focused and cost-effective fire protection program based on analyses of risk and the dynamics of fire effects☆

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Abstract

This paper proposes a conceptual framework for developing a fire protection program at nuclear power plants based on probabilistic risk analysis (PRA) of fire hazards, and modeling the dynamics of fire effects. The process for categorizing nuclear power plant fire areas based on risk is described, followed by a discussion of fire safety design methods that can be used for different areas of the plant, depending on the degree of threat to plant safety from the fire hazard. This alternative framework has the potential to make programs more cost-effective, and comprehensive, since it will allow a more systematic and broader examination of fire risk, and provide a means to distinguish between high and low risk fire contributors. © 1999 Elsevier Science S.A. All rights reserved.

1. Introduction

Nuclear power plant fire protection programs adopted since the early 1980s in the United States and most other countries were formulated based on a prescriptive and deterministic framework before PRA methods or fire models that can provide insights and information regarding risk (in probabilistic terms), and on the dynamics of the fire hazard were available (Dey, 1998; Dey et al., 1998). Since the early 1980s, significant developments have occurred in the fields of probabilistic risk analysis of nuclear power plant safety, and fire dynamics. The commercial building industries in many nations have adopted or are moving toward performance-based fire safety design methods (Society of Fire Protection Engineers, 1998a,b).

Nuclear power programs in many developed nations have become costly and, in some cases are no longer competitive with other power sources and are being prematurely decommissioned. A significant increase in cost for nuclear power gen-

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eration in advanced countries can be attributed to the public demand and expectation for a high level of safety from the potential hazards of nuclear power. Nuclear power safety has received a higher level of attention and a larger amount of resources than safety from most other industrial hazards. In order to meet the degree of excellence in nuclear safety expected by the public, and at the same time to allow nuclear power be economically feasible, it is necessary to establish and maintain cost-effective safety programs that focus on providing protection where the risk is the most significant. Based on available safety design methods, this paper proposes a cost-effective framework for formulating or modifying nuclear plant fire protection programs for new or operating plants.

2. Conceptual framework

Fire PRA and other methodologies have inherently in them screening processes which can progressively distinguish between high and low risk fire areas. The screening methods employed in fire PRAs, and other methods such as FIVE (Electric Power Research Institute, 1992), can be used toward formulating a risk-graded fire protection program by identifying and focusing on critical and important fire areas. Fig. 1 is a schematic of the proposed conceptual framework for formulating a fire protection program. An expert panel, consisting of plant fire protection personnel and PRA analysts, should use the results of a fire PRA toward establishing categories or grades for fire areas in nuclear power plants based on risk significance, supplementing the information with engineering judgment where necessary. A higher level of fire protection should be extended to fire areas that contribute significantly to plant fire risk. This approach would be in contrast to a prescriptive framework 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. Once the fire risk categories are established, different levels of sophistication for analyzing the hazard and determining appropriate protection features can be adopted. For critical areas, the most sophisticated (and costly) tools could be used, whereas qualitative analysis would suffice in non-critical or important areas where it is determined that a nominal amount of protection is adequate.

2.1. Fire PRA

A centerpiece of the proposed framework for formulating a fire protection program is a fire PRA. Fire PRAs typically follow a two-phase approach. In phase 1, a screening analysis is performed to identify the critical or important fire locations and screen out those areas that are not risk significant. In phase 2, a detailed analysis is performed for the important fire scenarios. The results of a fire PRA are usually obtained from the logic trees and models developed for internal event PRAs. For the fire PRA, the input probabilities to the PRA models are determined from an evaluation of the fire scenarios (propagation, damage, and suppression) and an analysis of fire

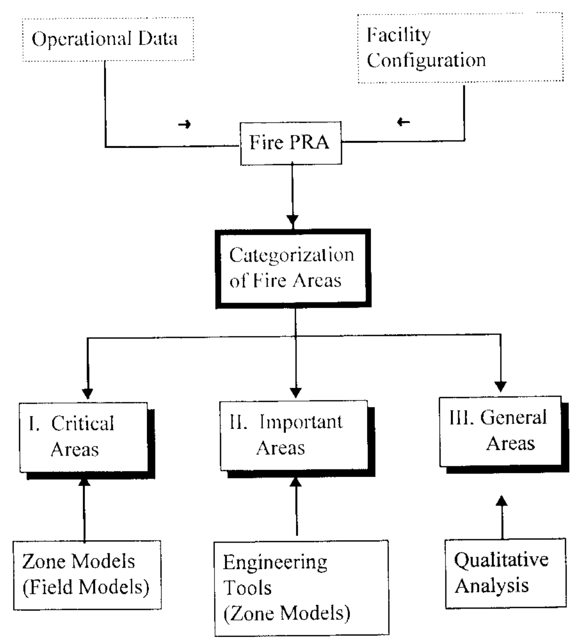

Fig. 1. Schematic of a conceptual framework for formulating a fire protection program.

frequencies. The performance evaluation models used in fire PRAs are based on reliability and/or state-transition models for suppression, and are partially based on deterministic phenomenological models (e.g. COMPBRN (Electric Power Research Institute, 1991)) for fire growth. Procedures for conducting fire PRAs are available (e.g. NRC, 1983a, 1985, 1990a), and there are several examples of comprehensive fire PRAs (e.g. Indian Point 2 PRA (Consolidated Edison, 1992), Limerick PRA (NUS Corporation, 1983), LaSalle PRA (NUREG/CR-4832), and the Peach Bottom and Surry PRAs (NRC, 1990b,c).

The screening process in a fire PRA includes an initial qualitative screening process that typically entails identifying fire areas: (1) that do not contain safe-shutdown equipment; and (2) in which a fire will not adversely impact safe-shutdown equipment in other fire areas or cause a plant trip or shutdown. These fire areas are eliminated from consideration. A second quantitative screening stage typically sets the fire occurrence frequency for all remaining fire areas to 1.0 and assumes that all equipment in the fire area is disabled by the fire. A truncation probability of 1 E-04 (equivalent to 1 E-08 for internal events) is typically used for screening and determining important or critical fire areas.

2.2. Categorization of fire areas

The results of the screening process in a fire PRA (or other methods such as FIVE) can be used to categorize fire areas in a nuclear power plant based on risk significance. The framework for the categories and screening criteria will be depend on many factors, including judgment on the degree of protection necessary based on the risk of a fire hazard in different areas of the plant. Therefore, the details of a categorization scheme should be developed by each facility. For the purposes of illustration, a specific categorization scheme is presented here:

1. critical areas: fire areas that contribute to the majority of fire risk (typically three or four areas) would be included in a critical category;
2. important areas: other fire areas that are not quantitatively screened using a 1 E-04 truncation probability described above could be included in a second important category; and
3. general areas: a general category could be developed for the remaining areas that are not screened using qualitative criteria such as those cited above.

It is widely acknowledged that fire PRAs have uncertainties associated with them. The specific uncertainties and limitations will depend on factors such as availability of operational data, assumptions made, and the quality of the analysis. Typical sources of uncertainty that will be associated with the proposed categorization scheme are: (1) fire ignition frequency; (2) fire models; (3) reliability and effectiveness of fire detection and suppression; (4) threshold for thermal equipment damage; (5) effect of smoke on equipment; and (6) operator actions. A critical element of the categorization process should be the work of an expert panel, consisting of plant fire protection personnel and PRA analysts, that should use the results of a fire PRA toward establishing the categories, supplementing the information with engineering judgment where necessary. The uncertainties associated with the results of the PRA and the screening process should be examined, and judgments made to address and compensate for these uncertainties in the categorization process.

The results of the screening analysis of the Surry fire PRA (NUREG/CR-4550, Vol. 3) is used here to illustrate the analytical part of a categorization process, and the possible makeup of fire protection program categories. In the Surry fire PRA, the screening analysis identified fire areas containing equipment or cables associated with safety-related systems which mitigate the effects of the unscreened fire-induced 'off-normal' plant states (Table 1). This set of fire areas could be categorized as important fire areas. The set of fire areas for the important category using this method would be conservative and contain more areas than if a quantitative criteria set at 1 E-04 was used.

The overall fire-induced core damage frequency (CDF) for Surry Unit 1 was calculated to be 1.13 E-05 per reactor year. The dominant contributing

Table 1
Surry fire areas containing vital safety related components

Fire area	Number	Physical description
Cable vault/tunnel	1	Outside containment penetration vault; Cable tunnel; Service building cable vault
Emergency switchgear room	3	Contains switchgear area, 2 battery rooms, relay room, and auxiliary shutdown panel
Main control room	5	In service building
Emergency diesel generator rooms	6, 7, 8	Room # 1 for Unit 1, Room # 2 for Unit 2, and Room # 3 as backup for Unit 1 or 2
Primary containment	15	Multilevel structure with personnel airlock access hatch to auxiliary building
Auxiliary building	17	Includes auxiliary building, fuel building, and decontamination building located adjacent to each another
Safeguards area	19	Consists of main steam valve house, containment spray pump house, and safeguards area
Turbine Building	31	Consists of 3 elevations; basement, mezzanine, and turbine deck
Mechanical equipment room # 3	45	In service building
Charging pump service water pump room	54	On level adjacent to main turbine building and mechanical equipment room # 3

plant areas are listed in Table 2 and comprise 99% of the total fire risk. In the case of the emergency switchgear room, cable vault/tunnel, and auxiliary building, a reactor coolant pump seal loss-of-coolant accident (LOCA) leads to core damage. For the control room, a general transient with a subsequent stuck-open power-operated relief valve leads to a small LOCA and failure to control the plant from the auxiliary shutdown panel results in core damage. These dominant contributing plant areas could be categorized as critical. All other areas that pass the qualitative screening criteria described above, and that are not in the critical or important category, would fall into a general category.

A categorization process conducted by a facility will require an in-depth understanding of the fire PRA screening process, and this knowledge will then need to be supplemented with engineering judgment to compensate for the limitations and uncertainties of the fire PRA. The above example illustrates the general makeup of the categories for a fire protection program that would result utilizing the proposed framework. Such a framework will provide a more comprehensive and systematic basis for a fire protection program benefiting from insights that a fire PRA can provide about the specific vulnerabilities of a plant to fires.

2.3. *Designing fire protection features based on analyses of the dynamics of fire effects*

Once the categories are established, a higher level of fire protection should be extended to fire areas that contribute significantly to plant fire risk. Different levels of sophistication for analyzing the hazard and determining appropriate protection features can be adopted depending on the risk significance of the area. For critical areas, the most sophisticated (and costly) tools would be used, whereas qualitative analysis would suffice in non-critical or important areas where it is determined that a nominal amount of protection is adequate.

2.3.1. *Critical areas*

In order to determine a comprehensive, but cost-effective degree of protection in these vital areas, the state of the art methods for modeling the dynamics of fire effects should be employed. In general, the most cost-effective solution will be to use fire computer codes or worksheets based on zone models, however, in some instances an evaluation using field models may be useful to verify and confirm some specific aspects of the problem.

Fire computer codes or worksheets using zone models are based on plume correlations, ceiling jet

Table 2
Dominant Surry fire area contributors to CDF

Fire Area	CDF/RY			
	Mean	5th Percentile	Median	95th Percentile
Emergency switchgear room	6.09E-6	3.93E-9	3.15E-6	1.98E-5
Control room	1.58E-6	[illegible]	4.68E-7	6.95E-6
Cable vault/tunnel	1.49E-6	6.51E-10	6.99E-7	5.79E-6
Auxiliary building	2.18E-6	5.32E-7	1.59E-6	5.64E-6
Total	1.13E-5	5.27E-7	8.32E-6	3.83E-5

phenomena, and hot and cold layer development and can predict the temperature of targets exposed to fires, detector and suppression system actuation, and smoke level and transport during fires. In the US, COMPBRN IIIe and the worksheets in the FIVE methodology are available. These models divide the compartment into at least two zones (an upper layer of hot gas and a lower layer). Depending on the model, the fire and its plume may be separate zones or may be included in the upper zone. The gas layers are assumed to be well mixed. Other zone models (e.g. CFAST (Peacock et al., 1993, 1997)) that are being used to support non-nuclear plant applications (e.g. fire regulation of buildings) exist and, depending on the application, have different strengths and weaknesses.

A number of 'field' models for application to fire problems are currently under development. The field model is a complex fluid mechanics model of turbulent flow derived from classical fluid dynamics theory. This type of model solves the fundamental equations of mass, momentum, and energy. In order to facilitate the solution of the equations, the space being analyzed is divided into a three-dimensional grid of small cells. Field models typically use hundreds to thousands of cells or zones; zone models use two or three. The field model calculates the physical conditions (temperature, gas velocity, species concentration) in each cell, as a function of time. The size of the space can range from an area within a room to a large portion of the outdoors (Stroup, 1993, 1995). Field models are being used to analyze a number of fire protection issues such as the placement of heat and smoke detectors, and the interaction of sprinklers, vents, and draft curtains. These codes have not as yet been used in the US nuclear industry.

COMPBRN IIIe is a deterministic fire hazard computer code designed to be used in a probabilistic analysis of fire growth in a compartment. Its primary application to date has been the assessment of fire risk in the US nuclear power industry. COMPBRN IIIe follows a quasi-static approach to simulate the process of fire growth during the pre-flashover period in an enclosure. Physical models, which quantify the thermal hazard (including temperature and heat fluxes) during a compartment fire, are developed. The dimensions of the compartment, location, quantity of fuel, layout of cables, locations and sizes of doorways, and ventilation rates through ventilation ports are user specified.

Possible outputs of COMPBRN IIIe include the total heat release of the fire, the average temperature and thickness of the hot gas layer formed near the compartment ceiling, the mass burning rate for individual fuel elements (affected by thermal radiation from the ceiling layer), and the surface temperature of non-burning elements. The time until the target (e.g. cable tray) reaches its damage temperature is the time available for fire suppression. Fire suppression data can be used to determine a probability distribution for the time to suppression, and the probability that a fire is not suppressed before it propagates can be determined using such a curve. Siu and Apostolakis (1986) give more detail on how fire detection and suppression can be modeled in a fire PRA.

Experimental data from the UL/SNL series (NRC, 1983b) have been used (Electric Power

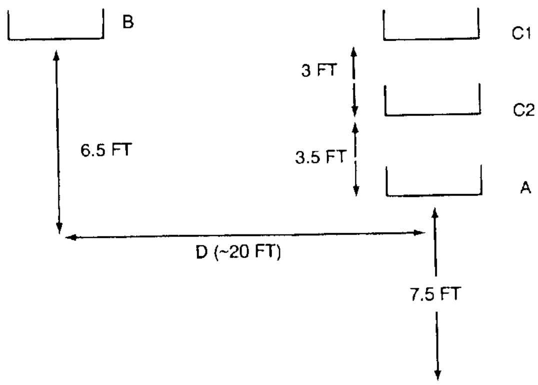

Fig. 2. Illustration of critical cable locations in the representative emergency switchgear room.

Research Institute, 1991) to validate the calculation of flow through a doorway (driven by the buoyancy of the hot gas), the gas temperature in the hot layer, and heat transfer from the hot layer to cables in trays.

A study was conducted (Dey et al., 1998) to evaluate the capability of three fire models for developing insights regarding the dynamics of fire effects: (1) FIVE—a compilation of fire correlations in worksheets for use in screening fire areas; (2) COMPBRN IIIe—a fire computer code developed for fast computations for use in fire PRAs; and (3) CFAST—a fire computer code developed mainly for use in modeling fires in buildings. The case study examined the 20-ft safe-separation requirement in the US. A representative pressurized water reactor (PWR) emergency switchgear room (ESGR) was used for the study (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, 2 and 3 MW with a linear growth taking 1, 2 and 3 min, 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. Fig. 3 shows the hot layer and cable surface temperatures for a 3-MW fire as a function of time. Considering the critical damage temperature of 643 K and the extrapolation of the results of the 1, 2 and 3 MW cases, it was concluded that a fire of more than 3 MW is required to damage the target cables at a 20-ft separation in less than 1 h, and a fire less than 2 MW will not damage redundant cable trays even if they are separated by less than 6.1 m (20 ft), e.g. by 15 ft.

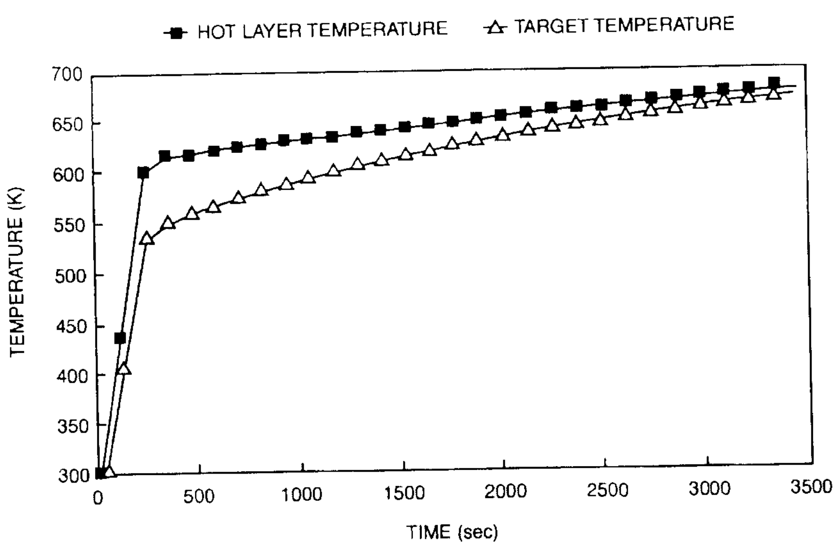

Fig. 3. CFAST prediction of 3-MW source target and hot layer temperature.

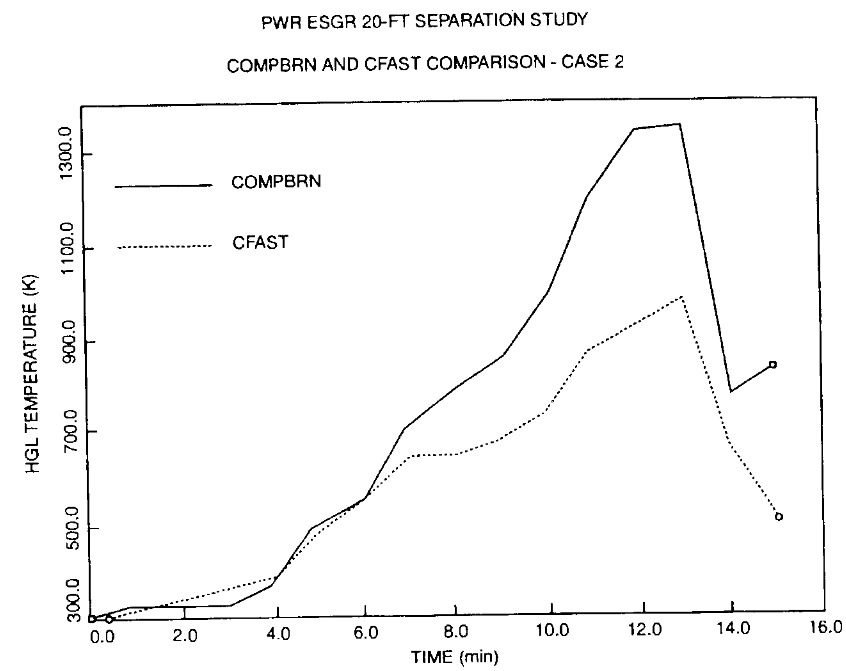

Fig. 4. Comparison of CFAST and COMPBRN prediction of hot gas layer temperatures.

Fig. 4 shows a comparison of the results from the CFAST and COMPBRN codes. In this case, the heat release rate due to fire predicted by COMPBRN is provided as input to the CFAST code for the comparison analysis. After the COMPBRN-predicted ignition of Tray C2 at 5 min and Tray B (the target tray) at 10 min, Fig. 4 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 results of the case study, it was concluded that if the maximum cluster of source cables results in a heat-release rate less than about 2 MW (this corresponds to a maximum cluster of three cable trays), then redundant cable trays will not be damaged, even if they are separated by less than 20 ft (e.g. by 15 ft). The dominant factor for all the fire models for predicting damage to cables 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 in calculating the thermal environment for predictions of cable damage.

The study illustrated the capability of fire computer codes and worksheets based on zone models to analyze and provide insights that are useful for designing fire protection features, such as safe separation distance.

2.3.2. *Important areas*

In most cases 'engineering tools' should be appropriate to determine protection features in areas that are important, but not critical, without the costs associated with computer code analysis. In some cases, zone models may be useful to investigate particular parameters if more detailed information is necessary. 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 establish the basis for fire barrier ratings, safe separation distance, and need for fire detectors and suppression systems.

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 can provide information about the dynamics of fire effects 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 and determine the protection needed. 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) × 6.1 m × 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 (Deal, 1995)) 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 in the 'Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering' (SFPE, 1995) 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/min (7.5×10^{-5} m/s) (from Figs. 3-11.2 and 3-11.3 in the SFPE Handbook). The volume of the fuel can be determined from the following correlation for the maximum pool diameter (Equation 11, p. 3-203 in SFPE Handbook).

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

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

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

However, this pool, about 2.5 mm thick, will only burn for about 4 s 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.

2.3.3. General areas

Fire protection for the remaining general fire areas, that are categorized as requiring nominal protection, can be provided with qualitative analysis and detailed investigations of the fire dynamics should generally not be necessary.

2.4. Feedback of operating experience

A fire protection program formulated with the framework presented above will be based on a fire

PRA which includes operating data for fire event frequencies, and reliability data for fire suppression and detection systems. As plant operational experience is generated, the fire PRA should be periodically updated, and the basis for the fire protection program should be re-examined to determine whether modifications to the program are necessary.

3. Methods to examine and modify existing programs

For many operating facilities, it may not be feasible or economical to invest in the resources that will be required to completely revise their fire protection programs based on the framework described above. The analytical methods for examining the dynamics of fire effects described above can also be used to examine issues and making modifications in operating facilities by providing insights about key parameters associated with the modifications. Fire PRA methods can also be used to calculate the change in core damage frequency (delta CDF) for alternative approaches to fire protection, including 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 (Dey et al., 1998). 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.

In order to limit the amount of repairs to equipment for achieving safe shutdown in the event of a fire, current fire regulations in the US require that a plant have the capability to reach cold shutdown conditions within 72 h (US NRC, 1980). The following illustrates a method to evaluate alternatives to meet the intent of this requirement.

The LaSalle fire PRA analysis (US NRC, 1993) 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 h 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-h requirement would necessitate that one RHR train be removed from the fire area, or that it be protected. An alternative approach is postulated to include re-establishing 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 h 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 Fig. 5) was developed for 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 = 1.1 E-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 re-establish 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 prescrip-

[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.

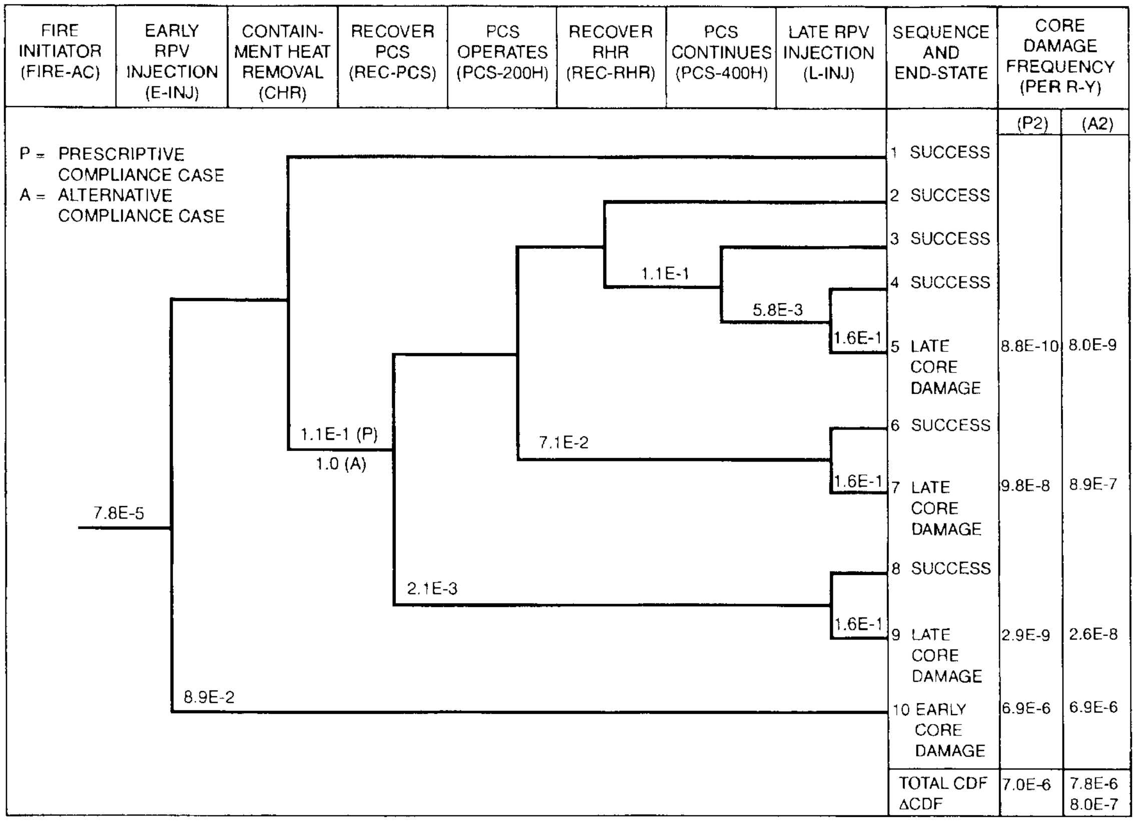

Fig. 5. Quantified event tree for the 72-h case study.

tive and alternative approaches. The final result is given at the bottom of the Fig. 5; 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 re-examination 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 systematic framework in which key issues, assumptions, sensitivities and uncertainties[2] can be identified and examined.

[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.

4. Technical education and training

This paper has presented technical methods that are available for formulating or modifying a fire protection program at a nuclear plant. The technical methods include, probabilistic risk assessments of the threat from fires, 'engineering tools', and fire computer codes. Nuclear plant staff that will use the above technical methods will need to have an adequate level of education and training in these fields. Since fire protection programs have historically been based on a prescriptive and deterministic framework, 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 at present 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 results for formulating or modifying fire protection programs.

5. Concluding remarks

Fire protection programs that have been formulated since the early 1980s have mostly been based on a prescriptive and deterministic framework. Additional analytical methods for examining the quantitative risk from fires, and the dynamics of fire effects are now available. These methods can provide an alternative framework for a fire protection program which has the potential to be more cost-effective and comprehensive since it will allow a more systematic and broader examination of fire risk, and provide a means to distinguish between high and low risk fire contributors.

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