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Probability-Based Evaluation of Selected Fire Protection Features in Nuclear Power Plants

Prepared by M. A. Azarm, J. L. Boccio

Brookhaven National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

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Prepared by
M. A. Azarm, J. L. Boccio

Brookhaven National Laboratory
Department of Nuclear Energy
Upton, NY 11973

Prepared for
Division of Engineering
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
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ABSTRACT

A probabilistic approach for the evaluation of major fire protection measures in nuclear power plants is described. The methods developed are applied to two representative fire areas -- one similar to a cable routing room and the other typical of a diesel generator room. The fire areas chosen for application, the fire scenarios described, and the various fire-damage states specified in the two illustrative examples are used to evaluate those fire-protection guidelines which deal with automatic/manual fire detection and suppression systems, rated barriers, divisional separation, drainage systems, dampers, and fire rating of electrical cables. Tabular results are presented, which reflect the relative merits of these systems/features in terms of conditional probabilities of achieving various room-damage states. The conclusions drawn and the lessons learned through the course of this study are discussed, and the areas that may need further investigation are identified.

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EXECUTIVE SUMMARY

This document describes a method which can be used to assess from a probabilistic point of view the relative merits of the NRC guidelines for fire protection. These guidelines are contained in Section 9.5.1 (Fire Protection) of the Standard Review Plant (SRP). The approach embodies a hybrid selection of physical models for fire propagation determinations and probabilistic models for active and passive fire-mitigation system reliability. The intention of this study is to investigate the practicality and usefulness of implementing probabilistic risk assessment techniques as an adjunct to the present fire-safety review process.

Two examples, employing the method described in this document, are presented. In each case, the fire areas chosen, the fire scenarios prescribed, and the fire-damage states specified in each example are designed to evaluate those fire protection features in the SRP which deal with automatic/manual detection and suppression systems, ventilation and exhaust systems, rated barriers, spatial separation of redundant divisions, curb/dike and drainage systems, and electrical cable rating.

For each of the two fire areas analyzed (a cable-routing room and a diesel generator room), tabular results reflect the relative merits of these systems/features. This is accomplished by determining the conditional probabilities of achieving prespecified room-damage states resulting from a fire. Accordingly, given a particular enclosure geometry, combustible fuel loading, and initiating fire and considering the combination of fire protection features and systems that are "designed into" the area of concern, coupled with a measure of system reliability and fire vulnerability, one obtains a quantitative basis for fire-safety evaluation.

In Sections 2 and 3, this general approach and basic methodology are further elaborated. Since evaluation of all the SRP Guidelines would not have been practical, judgment was used to limit those that can be addressed. This

judgment was tempered by the in situ combustible loading prescribed for each of the two fire areas. For example, the basic approach for the cable-routing room stresses the relative protection provided by spatial separation of redundant cable divisions; whereas for the diesel generator room, the emphasis is on the effectiveness of barriers in preventing the spread of the fire. In either case, the deterministic fire propagation and growth models used are considered state-of-the-art "zone" models which have been modified (see Section 3) to account for forced ventilation and spatial dependency of fire-induced gas dynamic parameters.

Probability distribution functions are assigned to several dependent fire parameters, e.g., fire initiation and growth times, and energy release rate. These are coupled to the transport models to judge the effectiveness of active and passive fire protection and fire mitigating systems. For example, Section 3 describes a probabilistic analysis of aerosol fire detection and water suppression systems. Correlation laws for detector response time, expressed as a function of detector spacing, room geometry, and energy release rate of the fire, are incorporated with a probabilistic function of detector reliability to assess detection time probabilistically as a function of fire growth. Likewise, empirical curves are used to assess the effectiveness of water suppression systems.

In Section 4, the method described is used to probabilistically evaluate fire protection systems and features typically used in a cable-routing room. In this case, the prespecified, or ultimate room-damage state (UDS) is defined as the failure of all redundant divisions. Locations of these divisions, relative to each other and to the distance below the enclosure ceiling, are the two basic parameters investigated. Table S-1 lists the fire-protection features and systems considered in this example as well as those for the diesel generator room example. Six of a total of 15 fire-protection measures are indicated along with a code identifier. Combinations of these identifiers are itemized in Table S-2 to indicate what protection systems/features are in place (or not in place) for the cable-routing room. Along with these combinations are the estimated probabilities for achieving the prespecified UDS. Pairwise comparison of the results for each case provides a rationale for evaluating a specific fire protection feature. For example, comparison between Case 1 and Case 4 indicates an order-of-magnitude reduction in UDS probability due to installation of an automatic water sprinkler system.

In Section 5, the method described is used to probabilistically evaluate fire protection systems and features typically used in a diesel generator room. In this example, the UDS is defined as failure of enclosure barriers and/or inoperability of dampers and doors. Accordingly, this example stresses the modeling employed to assess the conditional probability of containing the fire within the area of origin. Table S-3 summarizes the results obtained in this example. In this case, as compared to Table S-2, the results illustrate what fire protection systems/features are in place (or not in place) and what is the conditional probability for the fire to spread beyond the diesel generator room. Pairwise comparison provides a rationale for evaluating general system features. For instance, the effectiveness of a 3-hr barrier (Case 3) compared to a 1-hr barrier (Case 1) indicates the former is 40 times more effective than the latter in preventing further growth.

The conclusion of this evaluation, as to the usefulness of the approach, is contained in Section 6. For this limited study and only for the fire scenarios considered, it is shown that an automatic water suppression system, the use of qualified cables, and trained fire brigades are the more important protection features for the cable-routing room example. For the second example, a 3-hour-rated barrier, automatic operation of doors and dampers, and an effective suppression system were most important.

It must be stressed that these results are fire-scenario and enclosure-room specific. The prime purpose of this document is to describe a methodology that may be potentially useful in deterministic fire safety reviews and evaluating fire protection guidelines.

Table S-1

Fire Protection Features/Systems Considered

Identifier	System/Feature
1	Automatic Detection System (Aerosol Detectors)
2	Automatic Suppression Systems (Sprinklers; Total Flooding Halon)
3	Automatic Doors/Dampers
4	Electrical Cable; Proper Rating/Installation
5	Qualified vs Nonqualified Cables
6	Manual Fire-fighting Equipment Availability and Staff Familiarity
7	Cable Tray Location (within uniformly stratified layer)
8	Fire Brigade; adequate training and plant familiarity
9	High Capacity Drainage System
a	1-hr rated barriers; including doors and penetrations
b	2-hr rated barriers; including doors and penetrations
c	3-hr rated barriers; including doors and penetrations
d	Cable Tray Location (within nonuniform region); Separation - 10 ft
e	Cable Tray Location (within nonuniform region); Separation - 20 ft
f	Cable Tray Location (within nonuniform region); Separation - 30 ft

Table S-2

Probabilities of Room-Damage States for Various Fire Protection Design Features (Cable-Routing Room)

Case No.	Design Identification Code	First-Stage[(a)] Growth Probability	Second-Stage[(b)] Growth Probability
1	4/5/1/2/6/7/8*	1.5(-2)	5.7(-3)[+]
2	4/5/1/2/6/7/-	1.5(-2)	1.5(-2)
3	4/4/1/2/-/7/8	2.2(-2)	8.4(-3)
4	4/5/1/-/6/7/8	1.5(-1)	5.7(-2)
5	4/5/-/2/6/7/8	1.9(-2)	7.4(-3)
6	4/-/1/2/6/7/8	2.2(-2)	1.2(-2)
7	-/5/1/2/6/7/8	4.5(-2)	1.0(-2)
8	4/5/1/2/6/d/8	1.5(-2)	1.0(-2)
9	4/-/1/2/6/d/8	2.2(-2)	1.8(-2)
10	4/5/1/2/6/e/8	1.5(-2)	6.9(-3)
11	4/-/1/2/6/e/8	2.2(-2)	1.5(-2)
12	4/5/1/2/6/f/8	1.5(-2)	5.8(-3)
13	4/-/1/2/6/f/8	2.2(-2)	1.2(-2)

*Design identification as described in Table S-1.

[+] $5.7(-3) \equiv 5.7(10)^{-3}$.

(a)First-Stage Growth is defined as failure of one redundant shutdown cable division.

(b)Second-Stage Growth is defined as failure of all redundant shutdown cables, i.e., the Ultimate Room-Damage State (UDS).

Table S-3

Probabilities of Room-Damage States for Various Fire Protection Design Features (Diesel Generator Room)

Case No.	Design Identification Code	First-Stage(a) Growth Probability	Second-Stage(b) Growth Probability
1	1/2/3/c/8/9*	3.0(-2)	6.6(-4)[+]
2	1/2/3/b/8/9	3.0(-2)	9.6(-3)
3	1/2/3/a/8/9	3.0(-2)	2.7(-2)
4	1/-/3/c/8/9	0.33	1.0(-3)
5	1/-/3/b/8/9	0.33	0.1
6	1/-/3/9/8/9	0.33	0.3
7	-/-/3/c/8/9	0.66	2.0(-3)
8	-/-/3/b/8/9	0.66	0.2
9	-/-/3/a/8/9	0.66	0.6

*Design identification as described in Table S-1.

[+] 3.0(-2) $\equiv$ 3.0(10)$^{-2}$.

(a)First-Stage Growth is defined as the fire involvement of the diesel fuel.

(b)Second-Stage Growth is defined as the fire propagation beyond the original fire enclosure, i.e., the Ultimate Room-Damage State (UDS).

1. INTRODUCTION

1.1 BACKGROUND

The posture of the Nuclear Regulatory Commission (NRC) on nuclear power plant design and operability, as it has evolved over the years, has been grounded on traditional engineering practices supplemented by additional safety measures and analyses to ensure a sufficiently conservative approach to plant safety. To protect against various preconceived accident conditions, designers and plant operators were introduced to such concepts as the single-failure criterion and defense-in-depth. The success of this regulatory approach has been generally confirmed by studies on plant risk which have indicated that accidents within the design basis contribute a small portion of the risk.

However, the current regulatory structure is not without its problems. Because our understanding of the normal and various upset states is incomplete and because of the tendency to analyze plants, system by system, regulatory practices have been developed that are not always well integrated with each other. This can result in an uneven coverage of the safety issues, difficulty in assigning priority to new safety issues as they arise and in determining the actual level of risk that is attained, and to some extent, misinterpretation of certain safety requirements. In fact, as noted by Ernst and Murphy[1], conservative limits that have been instituted make it "difficult to relax requirements after further knowledge of plant behavior is acquired." They go on to note that Probabilistic Risk Assessment (PRA) techniques can offer the regulator a realistic, integrated description of the plant that is useful in the analysis of many safety issues. These techniques allow the regulator to focus attention on the uncertainties due to our lack of knowledge, which can sometimes provide vital information even if the level of risk is not well defined.

A case in point is the rule making issue dealing with fire protection. Here, a defense-in-depth posture has also been adopted. A balanced approach, as envisioned by the NRC, through general criteria[2] and specific requirements,[3,4] is based upon multiple layers of active and passive protective measures, such as detection, suppression, barriers, and spatial separation of redundant safety-related systems. The combination of guidance contained in Appendix A to Branch Technical Position (BTP) 9.5-1, as implemented by the staff in their fire protection review programs for operating reactors, and the requirements set forth in Appendix R to 10CFR50 define the necessary conditions for demonstration of compliance with General Design Criterion 3 of Appendix A to 10CFR50. Currently, fire protection requirements for new nuclear plants (those that commenced operation before January 1, 1979) are delineated in the Standard Review Plan (SRP), Section 9.5-1, "Fire Protection," Revision 3, July 1981.[5] This revision now incorporates all the technical requirements found in Appendix R which was appended to 10CFR50 to resolve several fire protection issues still undetermined since fire protection programs[6] were evaluated by the staff after the Browns Ferry fire.

However, in SECY-83-269, which summarizes the licensees' fire protection exemption requests to Appendix R requirements, the staff's disposition of those requests, and any generic issues that may be raised by these requests, Dircks[7] requested that the present guidelines should be revised to incorporate recent clarifications and to delete any requirements that are not applicable to new plants.

1.2 OBJECTIVE

Reflecting the increasing emphasis and use of probabilistic techniques in the assessment of fire risk at nuclear power plants, the NRC has embarked on a program for implementing the use of such techniques as an adjunct to their deterministic safety review process. Since PRA techniques can offer the regulator a realistic, integrated description of the plant, the objective of this phase of the overall program is to assess from a probabilistic point of view the safety advantages associated with each of the fire protection guidelines contained in Section 9.5-1 of the SRP. The purpose of the study is to develop an approach which can be used to respond to the request made in SECY-83-269.

1.3 SCOPE

Specifically, this study incorporates existing deterministic fire models with existing reliability techniques to evaluate some of the major SRP guidelines. Since it was deemed impractical to evaluate all the guidelines, judgment was used to limit the number of guidelines addressed. Those that have been stressed in this report deal with the effectiveness of automatic/manual detection and suppression systems, ventilation and exhaust systems, rated barriers, spatial separation of redundant divisions (the so-called 20-ft rule), curb/dike effectiveness, drainage systems, and electrical cable fire-resistant rating.

Two examples employing the method described in this report are presented. For each of the two fire areas analyzed (a cable-routing room and a diesel generator room), the results reflect the relative merits of various fire-protection systems and features.

For example, given that an enclosure, containing say two redundant safe shutdown divisions, is a priori specified with a specific fire load, geometry, and ventilation, the methodology employed herein attempts to answer the following questions:

1. Given an initiating fire, of a prespecified size, what will be the conditional probability that one of the two redundant trains is affected?

2. What will be the conditional probability that the ensuing fire, without fire suppression, will damage the remaining division if that division had been separated from the first by a) 10 ft, b) 20 ft, c) 30 ft, or d) any spatial separation; and, what will be the effect of (1) the vertical distance between the initiating fire and these divisions, and (2) the vertical distance between the enclosure ceiling and these divisions?

3. How much would this overall conditional probability change if each division were comprised of IEEE-353* rated cabling as compared to non-IEEE-383-rated cables?

4. How could manual and/or automatic detection and suppression methods change this probability, and what would be the effect of these methods during the various fire growth stages?

1.4 APPROACH

At the outset it must be emphasized that although the methodology employed to address these questions is somewhat general and implements what are construed as state-of-the-art deterministic fire models and probabilistic techniques with existing reliability data bases, the results presented are specific to the fire scenario selected and should not be taken out of context. Also, for these cited examples, only a few of the SRP guidelines have been addressed. Relative evaluation of each guideline, even for the few fire scenarios studied, is beyond the present scope of this project.

Accordingly, we start by selecting two representative fire areas, viz., a typical cable-routing room and a diesel generator room. Because of the relative fire loads in each of these areas, the ensuing study will emphasize the relative fire protection provided by fire barriers surrounding the latter enclosure, while analysis for the former enclosure will draw attention to the relative fire protection provided by spatial separation of redundant divisions. A hybrid deterministic/probabilistic approach is developed using existing "zone" models for assessing fire growth, coupled with existing reliability data on detection/suppression systems. Fire propagation and growth are based upon those unit models employed in COMPBRN[8] in conjunction with enclosure fire/radial jet-flow modeling as described by Cooper[9,10]. The latter model, which not only accounts for those fire plume and uniformly stratified zones within an enclosure fire but also considers the interaction of the fire plume with the enclosure ceiling, is

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*IEEE - Institute of Electrical and Electronics Engineers.

needed to investigate the effect of divisional separation. The former enclosure model, being basically a two-zone model, viz., fire plume and stratified hot layer, cannot be used to make assessments on fire protection provided by spatial separation. Certain aspects of the COMPBRN code and its attendant physical models have been used, however, in determining subsequent fire growth. Uncertainty bounds on the predicted results are established using bounding analysis and the results of past enclosure fire tests.

Coupled to these deterministic models for determining fire initiation, propagation, and growth are probabilistic analyses performed to judge the effectiveness of manual and automatic detection/suppression systems during various fire-growth stages. The results are then combined to estimate the probability of various room-damage states as a function of the implementation (or lack thereof) of specific fire-protection guidelines.

Further details of the overall methodology are provided in Section 2. Section 3 describes the specific approach taken. It also includes the rationale used in selecting the two representative fire areas investigated, a general description of the fire hazards in each area, and an identification of the specific SRP Section 9.5.1 guidelines under study.

Results from applying the methodology described in Sections 2 and 3 are discussed in the next two sections. Further discussions are provided regarding the assumptions made which may temper the conclusions.

Section 6 makes recommendations for improving the methodology for relative appraisal of fire protection features specified in current guidelines and also provides a general discussion on probabilistic fire analysis.

2. GENERAL APPROACH

This task entailed 1) a definition of two representative fire zones in nuclear power plants which comply with the SRP Guidelines, 2) an estimation of the probability of a fire damaging various components in these zones based upon a prescribed initiating fire, and 3) after sequential removal of the various fire-protection features, a reestimation of the probability of damage states in order to determine the effect of these fire protection measures. The following section describes the area layout, the fire loading, and the size of the two rooms selected for this study. Damage states depend on fire scenario as well as on what equipment in a given fire area should be protected from fire stressors. As such, specific damage states are defined in Section 4 for the two fire zones analyzed. Since evaluation of all SRP Guidelines would have been impractical, judgment was used to limit the number of SRP Guidelines that can be addressed in this study. This is discussed in Section 2.2

2.1 DESCRIPTION OF REPRESENTATIVE FIRE AREAS

The two representative fire zones selected have been based on the following considerations:

1) The equipment housed in these rooms is typical of equipment found in nuclear power plants.

2) The fire load and the size of the rooms are also typical of those in nuclear power plants.

3) The fire scenarios in these rooms address the potential for failure in redundant safe shutdown divisions.

4) The layout of the rooms is rather simple to be compatible with the assumptions employed in the existing computer codes used.

The first enclosure basically typifies a cable routing room in the auxiliary building, with electrical cabling as the major fire hazard but considered as a low fire loading relative to the other room under study. The other room represents a diesel generator room containing fuel oil and lube oil as the major fire hazards. Each room is described below.

Room 1 - This room, 15 m long, 12 m wide, and 6 m high, contains Divisions I and III power cables and control cables associated with shutdown method A along one side. Divisions II and IV power cables and the control cables associated with shutdown method B are located along the opposite side of the room. The other components in the room are assumed unimportant for fire hazard analysis. A simplified schematic diagram of the room is given in Figure 1. The cable trays are assumed to be 0.61 m wide (24 in.) and 15 m long. The trays containing power cables are assumed to contain only one layer of 24 single-conductor No. 2 cables. The trays containing control cables are assumed to be filled with two layers of 7 conductor No. 9 cables, totaling 52 per tray. The various other considerations for this room are:

Rating (Insulation/Jacket) : (IEEE rated (EPR/Hypalon); IEEE nonrated (PE/PVC)

Ventilation : Forced ventilation (6 room changes per hour)

Geometry : With openings; without openings

Auto. Detection : With smoke detectors (spacing 3 m); without detectors

Auto. Suppression : With automatic sprinkler systems; without automatic sprinkler system

Manual Suppression: With trained fire brigades and standby hose stations

Barriers : 1-, 2-, 3-, 4-, 5-hr ratings

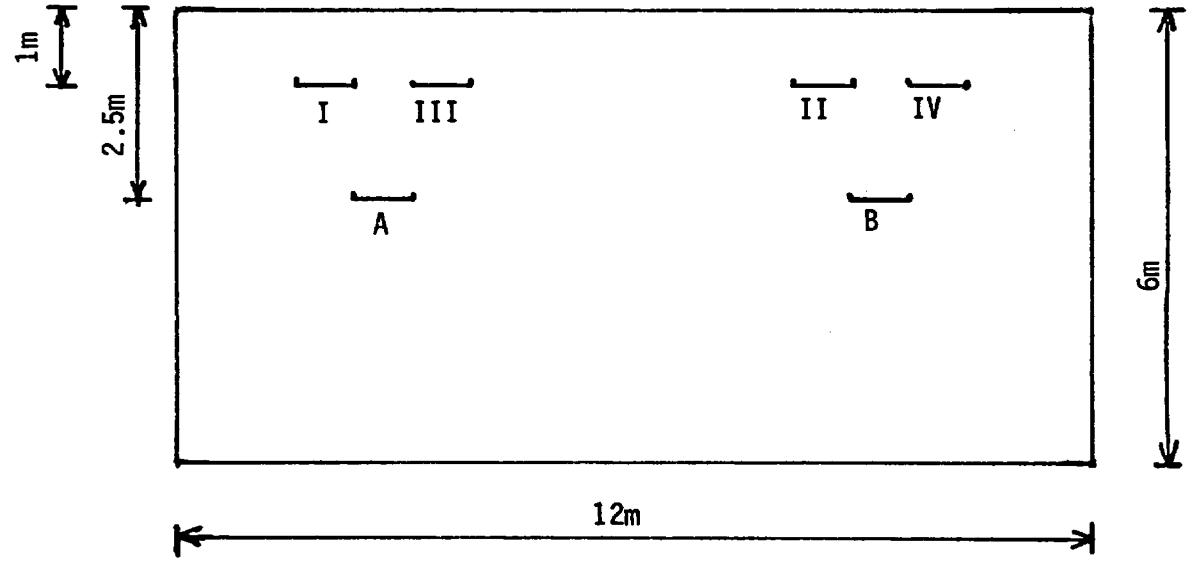

Figure 1. A schematic diagram of the representative cable-routing room.

Room 2 - The configuration for the representative diesel generator room is 12 m wide, 15 m long, and 7.6 m high. A common wall separating the two diesel generators in the plant is rated for 3-hr. The generator unit, centered within the room and set over an integral fuel supply day tank, with an additional day tank mounted on a wall, occupies an area measuring 3 x 10 m. The room contains nothing else except for a switching panel and a small number of cables running in metal conduit.

The 1100 gal of diesel fuel in the two-day tanks (max. inside storage allowed by SRP Section 9.5.1 guidelines), in addition to 250 gal of lube oil, are the major combustibles for this area. The small quantities of electrical cable located within control panels and conduits are not considered.

2.2 STANDARD REVIEW PLAN (SRP) GUIDELINES PROPOSED FOR EVALUATION

In accordance with General Design Criteria 3 and 5, the purpose of the fire protection program is to provide assurance, through a defense-in-depth design, that a fire will not interfere with shutdown functions or significantly increase the risk of radioactive release to the environment. A defense-in-depth design basically entails a) prevention of fires from starting; b) quick detection and suppression of those fires that occur, putting them out quickly, and limiting their damage; and c) plant safety systems designed such that a fire that starts despite the fire prevention program and burns for a considerable time despite the fire suppression activities will not interfere with the performance of essential plant safety functions.

The guidelines specified in Section SRP 9.5.1 which provide this defense-in-depth posture can be divided into five generic groups:

1) administrative controls and design provisions to prevent the existence of transient combustibles and undesirable ignition sources;

2) early detection of fire by means of reliable automatic detection systems and routine fire inspections;

3) early suppression of fire by means of reliable automatic suppression systems, experienced fire brigades, reliable manual suppression systems, safe removal and containment of liquid fuel spills, etc.;

4) passive protection of the components associated with redundant shutdown methods to ensure the performance of essential plant safety functions by means of separation and rated barriers; and

5) preventing propagation of smoke, products of combustion, heat, and toxic chemicals from suppression agents to the areas where the manual actions for bringing the plant to safe shutdown are required. This is done by means of dampers, rated penetrations, automatic closed doors, etc.

An item-by-item evaluation of all the SRP Section 9.5.1 Guidelines cannot be done at this time because of time limitations and lack of data and proper modeling. Thus, the SRP Guidelines found in Sections C.1, to C.4, which basically deal with fire protection requirements, administrative controls, fire brigade organization, and quality assurance, etc., have not been evaluated in this study. However, the following are addressed on a generic basis and are contained within Section C.5 of the Standard Review Plan Section 9.5.1:

1. IEEE-383 qualified cablings (C.5.e.3).

2. Barrier effectiveness and penetrations (C.5.a.1, C.5.a.2, C.5.a.3, C.5.a.4, C.5.b.2).

3. Separation (C.5.b.2).

4. Automatic suppression and detection system (C.6).

5. Ventilation and dampers (C.5.f).

3. BASIC METHODOLOGY

3.1 INTRODUCTION

To evaluate the NRC requirements regarding protection against fire events, two interrelated approaches are taken: fire dynamics and fire scenarios. The former describes fire phenomena in quantitative terms; the latter provides generalized descriptions of actual or hypothetical, but credible, fire incidents. Combining these two approaches into a tractable analysis entails 1) identification of various fire growth stages (fire scenario), 2) determination of the time required to reach each stage (fire dynamics/deterministic modeling), and 3) estimation of the likelihood of achieving each stage (fire dynamics/probabilistic modeling).

Definitions of the fire scenarios are made consistent with the layout of the safety equipment in the room. For example, if a room contains two redundant trains of safety cables, first-stage fire growth may be defined as fire involvement (or loss) of one division, whereas second-stage fire growth implies the loss of both divisions.

To determine the likelihood of achieving each fire growth stage, a probabilistic approach is used concomitantly with the deterministic models. Specifically, probabilistic models are used for detection and suppression systems, both manual and automatic. The successful operation of these systems depends on 1) the actuation mechanism's responsiveness to fire symptoms, and 2) the suppression mechanism's capability of limiting the fire growth at each growth stage. The time required for successful suppression is, therefore, compared with the time it takes to achieve the various stages of fire growth. Also taken into account are the related uncertainties needed to estimate the probabilities of reaching various room damage states. The interacting mechanism between the energy absorption rate due to suppression and the energy release rate as the fire progresses was not evaluated in this study and is at present beyond the state-of-the-art.

Finally, a fire barrier analysis is employed when the particular fire scenario (e.g., a high combustible fuel-load area) indicates the possibility of a barrier failure.

3.2 DETERMINISTIC FIRE ENCLOSURE MODELS

Deterministic enclosure fire-growth models are employed to address the following: ignition, flame spread, flame growth, maximum burning intensity, and subsequent product of combustion migration. Zone model approaches are employed, notably those developed by Siu[8] and Cooper[9,10]. Although their governing equations are readily solved with the use of a computer, these zone models do not lend themselves to generalized solutions which can be displayed "once and for all" by charts, graphs, or tables. Nevertheless, for specific fires [i.e., a fire of a specified energy release rate, Q(t)], solutions for arbitrary enclosure height and area and for arbitrary fire elevation can be obtained.

Siu's fire growth and fire propagation models are embodied in the computer code, COMPBRN. The fire scenario consists of a fire located at a distance H below the ceiling of an enclosure of area A. The ambient conditions in the enclosure are described by the density, ρ_0, the specific heat at constant pressure, C_p, and the absolute temperature, T_0. The fire is located at an elevation, Δ, above the floor (i.e., the total height of the enclosure is $H + \Delta$). Depending upon the combustible involved (in situ or transient), algorithms in COMPBRN can be used to determine the total energy release rate of the fire, Q(t). In COMPBRN, Siu uses a basic two-zone model, viz., a homogeneous, stably stratified, hot gas layer (upper gas layer) above a relatively quiescent and cool ambient air environment (lower gas layer) which is laterally entrained and mixed with the fire plume gases during its ascent to the ceiling. Since the modeling assumes that the gases in the upper layer are fully mixed at every instant, perturbations in the gas dynamic process propagate with infinite speed within the upper layer. Therefore, such effects as thermal plume/ceiling interaction do not become manifest and are masked by the modeling simplifications employed.

Cooper employs a three-zone model, namely, an additional zone, above the upper gas layer which accounts for the formation of a turbulent, laterally expanding ceiling jet brought about by the interaction of the fire plume with the ceiling. Adding another zone, by definition, entails reckoning with another characteristic length scale, viz., the width of the ceiling jet, δ, and therefore additional modeling complexity. The thickness of the jet flow is, however, determined using models derived by Alpert.[11] To evaluate those fire protection requirements that deal with spatial separation, this complexity, although still formulated by Cooper in a simple, mathematically tractable fashion, is indeed necessary.

At this juncture, the basic methodology mainly employed in determining fire growth in enclosures for the particular fire scenarios under investigation can be summarized as follows:

1. COMPBRN algorithms, where feasible, are used to predict the early stages of fire growth.

2. At the later stages of fire growth, Cooper's three-zone model is used to predict the enclosure environment and its impact on other combustibles located in upper layers. The bounds of heat release rates are determined on the basis of a ventilation-controlled burning model. To account for energy radiated from the fire zone and energy absorbed by the internal bounding surfaces, an empirical loss coefficient is used.

Uncertainties in the method stem primarily from 1) the uncertainty in the input parameters, 2) the uncertainty in defining the amount and location of the fuel that initiates the fire (pilot fire), 3) the systematic uncertainty resulting from the lack of complete understanding of fire behavior, and 4) the simplification required to develop the physical models and to make the mathematical models numerically tractable. It is beyond the scope of this study to attempt a systematic appraisal of all these sources of uncertainty. Hence, the uncertainty bounds, determined in various stages of this study, are judgmental.

3.3 DETERMINISTIC/PROBABILISTIC ANALYSIS OF BARRIER FAILURE

The generally accepted method for rating fire barriers is based on their survivability period when exposed to the thermal impact from standardized tests. If the structural element has a fire resistance which meets the required time of fire duration (rating), adequacy of the design is presumed.

To define equivalent fire severity of the ASTM (American Society for Testing and Materials) standard furnace test, NBS (National Bureau of Standards) concluded that the fuel load of 80,000 Btu/ft^2 of floor area will produce a fire impact (i.e., gas temperature) as severe as 1-hr ASTM furnace test. However, the method of testing and the definition of equivalent severity have a number of shortcomings which may render standardized test results inappropriate for nuclear power plant fire barrier analysis. For example:

(a) The equivalent furnace severity fuel load method neglects the actual time-temperature curve in the fire area. The actual time-temperature curve of a specific fire area is a function of many parameters such as ventilation rate, pyrolysis rate, and different types of combustibles, room geometry, and size, etc.[12]

(b) The standard test ignores the actual loading of the load-bearing structures and the effect of temperature on the mechanical properties and design capacities of the structural elements.

Admittedly, the traditional classification system is convenient and may provide a reasonable design for most situations. However, in nuclear power plants, the need to minimize the fire risk necessitates the development of a systematic procedure based on the specific characteristics of a fire area, taking into account the associated uncertainties. Such methodologies known as limit state design analyses have been the subject of several studies.[13-14] Although this subject has been understood theoretically, the complete application to actual fire analysis has not been fully performed. In fire barrier design one should be concerned with assuring that the barrier will meet certain functional requirements. These can be expressed in terms of limit states with respect to 1) load bearing capacity, 2) thermal insulation, and 3) integrity during fire exposure. Implicit in the third limit state could be the effectiveness of barriers in resisting the spread of smoke and toxic gases. In a deterministic sense adequacy is achieved when the resistance, R, to a particular fire stress (smoke, temperature, etc.) is greater than the barrier capacity, S, i.e., if $R > S$, design functionality has been achieved. However, in a general sense, fire engineering design is nondeterministic and one must recognize the impossibility of absolute compliance with a preset goal. Idealistically, performance has to be described and measured in probabilistic terms. Thus one is concerned with the probability of "failure," P_{fail}, which is indicative of the probability that $R < S$ or $P_{fail} = P\ (R-S\leq0)$. Verification that a particular functional requirement is achieved must then begin with an appropriate heat exposure model(s) and heat capacity model(s), recognizing that uncertainties are encountered because of a) intrinsic randomness, b) uncertainties with respect to the physical model(s), and c) uncertainties with respect to the stochastic model.

A number of available deterministic fire barrier analyses were reviewed to find an easily implemented approach, which addresses some of the concerns previously discussed and which can be readily coupled to the probabilistic approach. An approach for barrier analysis which represents a compromise between accuracy in real fire environment simulation and practicality of implementation was developed on the basis of the following assumptions:

1. Structural damage will occur during the post-flashover phase of a fire scenario. Although the pre-flashover phase conditions may likewise lead to serious structural damage, they are neglected.

2. The criterion used for the structural failure is defined as the product of the average gas temperature and the exposure period (baking time). The structural failure is then determined by comparison of this factor with the equivalent ASTM furnace time/temperature curve.

3. The activation of either an automatic or manual suppression system before flashover is assumed to prevent flashover from occurring.

Estimating the temperature signature during the flashover phase is based on an expression which accounts for the conservation of mass and energy within a control volume (the fire enclosure). The pressure change in the room is assumed to be small, and the assumption of an ideal gas is implemented. Hence, the conservation of mass equation is

$$\rho_a V + \int_o^t (\dot{m}_B + \dot{m}_a - \dot{m}_e)\, dt = \rho_f V \quad , \tag{3.1}$$

where ρ_a and ρ_f are, respectively, the global densities of air at temperatures T_a and T_f; $\dot{m}_B$ is the mass loss rate of the fuel which is not necessarily equivalent to the burning rate of the fuel; m_a is the mass flow rate of air entering through the ventilation system and is assumed to be constant; $\dot{m}_e$ is the mass flow rate of gas leaving the room through the exhaust. It will be shown later that $\dot{m}_e$ is a function of T_f and its time rate of change, $\dot{T}_f$. The volume of the room is given by V, the gas temperature in the room is given by T_f, and T_a is the temperature of air outside the room.

With the assumption of an ideal gas and taking the derivatives of the above with respect to time, yields

$$\dot{m}_e = \dot{m}_B + \dot{m}_a + (m_o T_a / T_f^2)\dot{T}_f \quad , \tag{3.2}$$

where m_o is the initial mass of the air in the room ($=\rho_a V$).

The conservation of energy can be expressed as

$$C_p \frac{d}{dt} (mT) = \dot{Q}_B (T,t) - \dot{Q}_L (T,t) \quad , \tag{3.3}$$

where $\dot{Q}_B$ is the heat release rate from burning C_p is the heat capacity of the air at constant pressure (assumed constant), and $\dot{Q}_L$ is the amount of heat lost by conduction through the walls and radiation through the openings.

With the assumption of an ideal gas, manipulations yield

$$\dot{T}_f = \alpha\, T_f - \beta\, T_f^2 \quad , \tag{3.4}$$

where

$$\alpha \equiv [(\dot{Q}_B-\dot{Q}_L) + \dot{m}_a\, C_p\, T_a] \,/\, [\dot{m}_o\, C_p\, T_a] \quad , \tag{3.5}$$

$$\beta \equiv [\dot{m}_a + \dot{m}_B]/\dot{m}_o\, T_a \quad . \tag{3.6}$$

The solution of the above equation (assuming weak time dependency during flashover) with the initial condition of $T_f(t=0) = T_a$ becomes

$$T_f = T_a \,\{\exp(\alpha t)/[1-(\beta/\alpha)T_a\, (1-\exp(\alpha t))]\} \quad . \tag{3.7}$$

The expression for α is treated as a random variable based on the distribution of $\dot{Q}_L$.

Deriving constitutive relations for the heat loss, Q_L, entails a degree of complexity not warranted for this preliminary study. Indeed, models and analyses are available which can take into account such parameters as wall thickness and its physical properties, convective heat transfer on the unexposed side as well as on the exposed side, which is, of course, related to the enclosure room geometry. The degree of sophistication needed, however, was not compatible with the zonal approach currently employed. In this regard, using engineering judgment and the insights gained from results presented in References 9 and 10, $\dot{Q}_L$ is assumed to be lognormally distributed with upper and lower bounds at the 5 percentiles to be $0.8\dot{Q}_B$ and $0.4\dot{Q}_B$ respectively. This implies a 90% probability that the value of $\dot{Q}_L$ is between these two values.

Thus the average room gas temperature, $\bar{T}_f$, is given by

$$\bar{T}_f = (1/\beta t)\ell n[(\beta T_a/\alpha)\ \exp(\alpha t)] \quad , \tag{3.8}$$

which for large times (i.e t→∞) becomes

$$\lim_{t \to \infty} \bar{T}_f = \alpha/\beta = [(\dot{Q}_B-\dot{Q}_L) + \dot{m}_a\ C_p\ T_a]\ [(\dot{m}_a + \dot{m}_B)\ C_p]^{-1} \quad . \tag{3.9}$$

The above two equations are used in Section 5 to determine the average gas temperature ($\bar{T}_f$) and the probability of structural failure for the representative diesel generator room.

3.4 PROBABILISTIC ANALYSIS OF DETECTION/SUPPRESSION

Early detection and fire suppression are two of the most important considerations that should be taken into account in performing an adequate fire probabilistic analysis. In state-of-the-art probabilistic models the probability of successful suppression and detection is usually estimated from existing data in nuclear power plants.[15-16] However, the data used apply primarily to manual suppression and do not totally reflect the effectiveness of automatic suppression. In addition, the data are aggregated such that the type and severity of the fire at the time of suppression initiation are not known. The inadequacy of data and the lack of modeling of fire propagation during suppression usually result in unsupported, conservative estimations of equipment damage states. Other studies, such as those by Gallucci[17] and Levinson,[18] provide a more systematic approach to the probabilistic analysis of detection and suppression systems. In those two studies, emphasis was placed on system operability rather than on the time the systems respond, which is a requisite parameter in this study.

The approach taken consists of two steps: establishment of the response time of detection/suppression system, and to evaluate their associated availabilities and effectiveness.

In determining the availability of the automatic detection system (smoke detectors are considered for this study), a binominal distribution is assumed to represent the probability that m detectors out of a total of n detectors are inoperable, i.e.,

$$P_f(m/n) = (n!)/[m!(n-m)!]\ P_f^m\ (1-P_f)^{n-m} \quad , \tag{3.10}$$

where P_f (m/n) defines the failure of m-out-of-n detectors, and P_f defines the demand failure of a given detector. Deterministic response time is probabilistically related to successful detection using the above distribution (or an approximated form thereof) in connection with a relation which describes the increase in detector spacing (or coverage area) as a function of the number of operable detectors, viz.,

$$W_D\ \{m/n\} = (A/n-m)^{1/2} \quad . \tag{3.11}$$

detector spacing, W_D, is deterministically related to detector response in the following way.

To estimate the response time of detectors, a model,[19] developed by Newman, is used in which the response time (t_R) of a smoke detector is composed of two separate times: a transit time (t_t) for the smoke front to reach the detector, and a detection or actuation (alarm) time (t_D), i.e.,

$$t_R = t_t + t_D.$$

If the convective fraction, $\dot{Q}_C$, of the overall heat release rate, $\dot{Q}_B$, can be approximated by a power law in time, i.e., by $\dot{Q}_C = \alpha t^P$, then Newman shows that

$$t_t = K\ (1.1W_D/H + 0.38) \tag{3.12}$$

which relates smoke transit time to ceiling height, H, and detector spacing, W_D. The other parameters in the above equation are defined as

$$K \equiv (A_g \alpha / H^4)^{1/(3+p)} \quad , \tag{3.13}$$

$$A_g \equiv g \rho_a T_a C_p \quad , \tag{3.14}$$

with g the acceleration due to gravity and the parameter α reflecting the fire growth rate.

For a typical smoke detector arrangement on a smooth ceiling, Newman derives the following correlation

$$t_D = (\dot{Q}c/H)^{-1} \ (45 W_D + 8.0) \quad , \tag{3.15}$$

for the expected value of t_D.

Having an expression for t_t and t_D (and therefore t_R) as a function of room geometry, detector spacing, and fire properties, ventilation is taken into account by using the following expression:

$$t_{R,f} / t_R = 1.0 + 2.1 \ (H^4 / \dot{Q}_c)^{1/3} \ t_v^{-1} \quad , \tag{3.16}$$

where $t_{R,f}$ is response time in a ventilated enclosure and t_v is the time required for volumetric change of the enclosure air and is equal to the ratio of the enclosure volume to the volumetric flow through the ventilation per unit time.

Thus, given a value of P_f and n, $[1-P_f(m/n)]$ determines the probabilistic distribution for (n-m) available detectors. Equation (3.11) then determines the probabilistic distribution of coverage area which, when incorporated in the above correlations, provides one with a distribution function for detector response time.

For the effectiveness of an automatic suppression system, Figure 2 from Reference 12 is used. These curves basically represent the probability of successful control of fire in an enclosure with a standard coverage vs the fuel load per unit area of the floor.

The probability of successful operation of an automatic suppression system, in addition to its effectiveness, is incorporated through the reliability data given in Reference 18.

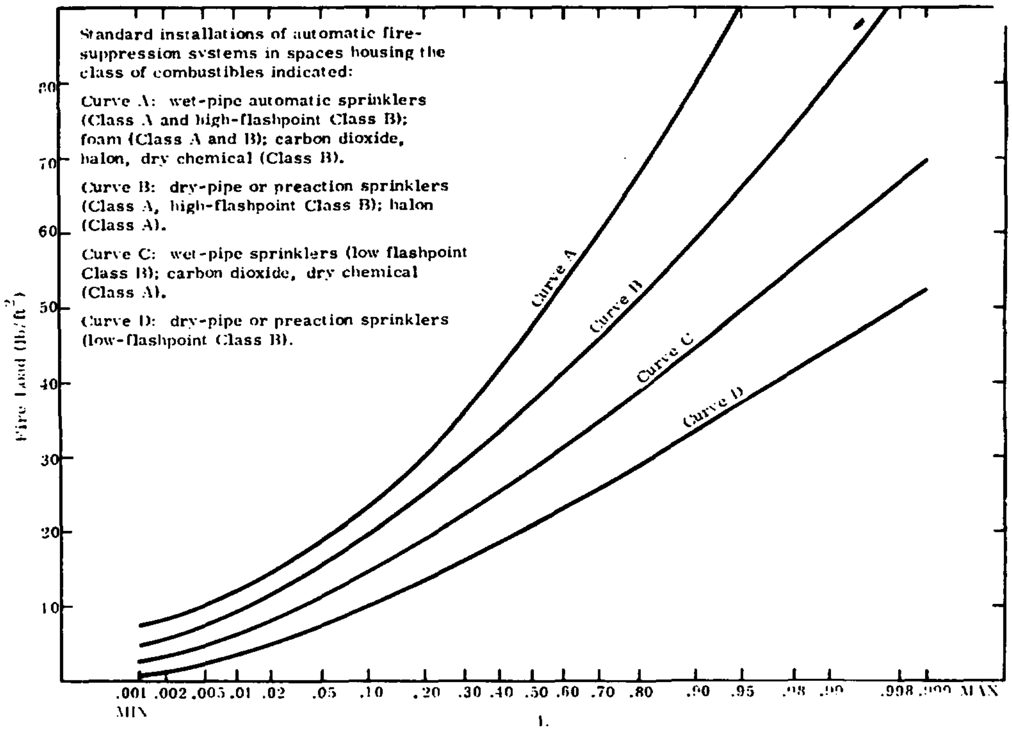

Figure 2. The effectiveness of automatic suppression system (reproduced from Reference 12).

The time required to detect and suppress a fire manually is considered probabilistically for two special cases (1) the automatic detection and suppression systems are unavailable and (2) the room is unoccupied. With regard to Case (2), the fire can be indirectly sensed manually through its impact on the operability of equipment located within this unoccupied area. It was assumed at this facility that the impact of the fire on equipment would be sensed by the control room operator. In this case, the probability of detection is assumed to be an increasing function of time after the equipment malfunctions. The time required for manual detection depends on the type of safety components affected by fire and their locations in the plant. It is assumed that the operator will dispatch the plant staff to those locations where the malfunction has occurred. The fire will then be visually detected by plant staff, and minor mitigation actions may take place. The bounds for the time required to detect the fire manually is determined from the data in the literature.[18]

Once the fire is detected, the probability that manual suppression will bring the fire under control can be estimated from the curve in Figure 3. This curve, developed from existing fire data in nuclear power plants,[16] basically indicates the probability of successful manual suppression vs available time. The manual suppression phase of an enclosure fire is therefore not modeled deterministically in this study.

The conclusions of this study regarding enclosure damage states are drawn from the comparison between the fire growth time (or stages in fire development) and time required for successful suppression. The following sections describe how this concept is applied by way of two examples.

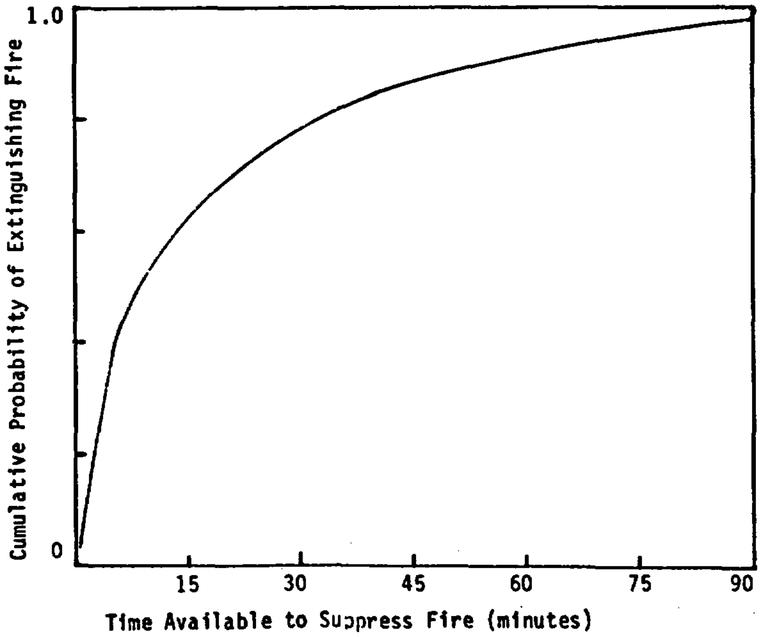

Figure 3. Manual fire suppression model.

4. REPRESENTATIVE CABLE-ROUTING ROOM ANALYSIS

Two stages of fire growth are defined for this analysis. The first stage indicates loss of one of the redundant shutdown divisions; the second stage requires the fire to propagate to the other redundant shutdown division. The time required for the fire to propagate to a first-stage fire growth is determined with the COMPBRN computer code. The uncertainties associated with the size and location of the initiating fire, the ignition criterion for the cables, and the other unit models in the COMPBRN code are qualitatively discussed and evaluated. The time required to reach a second-stage growth is determined by Cooper's enclosure fire model. The uncertainty in second-stage fire growth results largely from the wide uncertainty associated with the estimated burning rate.

To determine the likelihood of achieving each fire growth stage, a probabilistic approach is used concomitantly with the deterministic models. The operability, effectiveness, and response time of detection and suppression systems at each stage of fire growth are estimated through probabilistic analyses. The comparison between the fire growth time and time required for successful suppression is used to estimate the probability of achieving each fire growth stage.

To evaluate the relative importance of various fire protection measures, the change in probabilities of the room-damage states corresponding to growth stages, with or without a given fire protection measure, is estimated. Finally, the relative importance of various fire protection measures is estimated in the form of reduction factors in the probability of reaching each fire growth stage.

At the outset, the quantitative results obtained for the probabilities of various room-damage states in this representative room must be tempered with the existing limitations found in both probabilistic and deterministic fire analyses. However, since this study concentrates on evaluation by relative comparisons of various fire protection systems/features, it is expected that these limitations will not severely affect the conclusions drawn.

4.1 FIRST-STAGE FIRE GROWTH

For this analysis a combustible liquid spill is considered as the fire initiator. The spill is assumed to be located directly under one of the redundant divisions. The time required to achieve what is termed as first-stage growth is based upon when the three cable trays in one side of the cable routing room (Figure 1) become damaged.

Defining electrical cable damageability due to fire and establishing trends that are a function of physical parameters which define the dynamics of the fire and the surrounding environs have been the subject of many experimental studies conducted by the Factory Mutual Research Corporation (FMRC) and Sandia National Laboratories.[20-24] Damageability in these studies is defined as a change in the properties of a cable which cause impairment to its normal function. Four categories of electrical cable damageability have been defined[21]: cable insulation/jacket degradation (generation of combustible vapors), auto-ignition, piloted ignition, and electrical failure. Damageability is usually quantified in terms of 1) the critical heat flux at or below which damage is not expected to occur, and 2) the energy required to sustain the damage process. This latter quantity is simply defined as the product of the difference between the externally applied heat flux and the critical heat flux and the time required for the cable to reach the critical heat flux. For example, Tewarson[23] reports that the critical heat flux measured for a particular sample of EPR/Hypalon cable is 19 kW/m^2; the critical energy is 1420 kJ/m^2; and the critical temperature calculated for cable ignition is 488°C, which is based upon a simple radiative heat-flux model.

This temperature is used in this example to define the ignition temperature, T_{ig}, used in the ignition model in the COMPBRN I computer code, from which the time to achieve first-stage growth is derived. In COMPBRN I, the fuel elements (in this particular case EPR/Hypalon electrical cables) are modeled as homogeneous semi-infinite slabs. To find the time to ignition, t_{ig}, the heat conduction equation is solved. By assuming a constant heat flux at the cable boundary ($\dot{q}_0''$) and neglecting radiative and convective heat losses, a closed-form solution is obtained showing the timewise variation of fuel element surface temperature (T_s), viz.,

$$t = (\pi/4\alpha)[k(T_s - T_0)/\dot{q}_0''] \quad , \qquad (4.1)$$

where α and k are respectively the element's thermal diffusivity and conductivity. Substituting T_{ig} for T_s into the above expression, the ignition time, t*, is determined.

Employing this ignition model, and considering as the initiator a fire from a 3.81-ℓ (1 gal) spill of fuel oil, 0.3 m (1 ft) in diameter, COMPBRN I calculates that 330 sec are required to ignite the cable tray located 3 m directly above the liquid pool-spill fire. The other two cable trays, located 2 m further above, require an additional 90 sec. Appendix A presents the input data used for this example.

Judgmentally, a time of 420 sec to achieve a first-stage growth seems rather short. This is understandable when one considers that the ignition model [Eq. (4.1] does not consider the radiative and convective losses from the fuel element. In fact, the above equation indicates that for a given ignition temperature ($T_s \equiv T_{ig}$) the fuel element can ignite no matter how small the external heat flux is.

Toward the end of this study, the authors became aware of an improved version of COMPBRN I* which incorporates these added features. But, a closed form solution to the heat conduction equation [like Eq. (4.1)] does not exist. The fuel element temperature is found numerically in COMPBRN II.** An equilibrium point is established where the heat losses from the fuel element balance the heat gains in which case the surface temperature of the fuel levels off. If

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*Chung, G., Siu, N., and Apostolakis, G., COMPBRN II: Code Description and Simulation of Experiments, UCLA-ENG-8404, March 1984.

**M. Kazarians (Pickard, Lowe, and Garrick) - private communication.

this temperature is below T_{ig}, then by definition the cables would not ignite, but of course they could be degraded (for example, by melting). The results* indicate that a larger size (0.84 m instead of 0.3 m) would be needed to ignite the cables. However, although losses are accounted for, the time required to reach first-stage growth is reduced (270 sec) owing to an increased flame height resulting from a larger-diameter spill.

One must understand, however, that although an improved heat transfer model is employed, accurate modeling of ignition time and temperature is highly complex. Before ignition, polymers undergo several phase transitions. No well-defined melting point exists, since transition of a solid polymer to a viscous liquid can consist of several phase transitions before subsequent evolution of combustible vapors. These vapors must mix with air in proper stoichiometry for ignition to occur. Also, the temperature of the surrounding air is crucial for either auto or piloted ignition. Experiments performed to establish some measure of the critical heat flux to cables usually employ a thermal radiative source to simulate the heat flux from a fire. The predominant heat transfer mechanism in these experiments is through radiation. Thermal energy transferred to the surrounding gas environment is through convection processes occurring in the vicinity of the heated cable and not, as in a real fire, through large-scale convection resulting from the initiator fire plume. Thus, the experiments differ from the actual case in the sense that the cable sample is not engulfed by a hot gas plume and, hence, the convective heat transfer to the sample is not simulated. Judgmentally, the actual critical heat flux is expected to be lower than those established from small-scale, radiative-type experiments.

Because of uncertainties associated with existing fire models, empirical correlation for flame and plume characteristics, cable properties, and the possibility of various types and sizes of pilot fires, it is judgmentally assumed that the timing for first stage fire growth would be between 4.5 and 7.5 min. Therefore, the timing for the first-stage fire growth is considered probabilistically by a lognormal distribution with 5 and 95 percentiles of 4.5 and 7.5 min, respectively.

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*M. Kazarians (Pickard, Lowe, and Garrick) - private communication.

4.1.1 Detection Time

To estimate the probability of successful detection and its associated timing, both possibilities, i.e., automatic and manual detection, are considered. The following are summary discussions on each of the possible detection mechanisms:

(a) Automatic Detection System - The room is assumed to be equipped with ceiling-mounted smoke detectors spaced every 3 meters. Using the data found in Reference 18, the mean value for failure of a smoke detector per demand is assumed to be 0.13. For the room under consideration (180-m^2 ceiling area), a total of 20 smoke detectors are presumed to be installed. Such a dense installation of smoke detectors may not be typical in nuclear power plants, and it may be more applicable to fire test facilities. However, the sensitivity of final results to the number of smoke detectors installed is minimal.

The relation between failure of smoke detectors and their response time is based on the average coverage of the available detectors, i.e., if all the 20 detectors are operable the spacing is 3 m. However, if we assume 10 detectors are not operable, then the average spacing for the remaining detectors is about 4.2 m. In this section, we apply the probability distribution laws and correlations indicated in Section 3.4.

The failure of m out of n detectors can be estimated from the binomial distribution [Eq. 3.10] or approximately by an equivalent Poisson distribution, i.e.,

$$P_f(m/n) = \binom{n}{m} P_f^m (1-P_f)^{n-m} , \qquad (4.2)$$

where P_f (m/n) = failure of m detectors out of n, and P_f = failure of a detector per demand. For large n and small P_f, this equation can be approximated by

$$P_f(m/n) \approx e^{-\mu} \mu^m/m! \qquad (4.3)$$

where $\mu = n \cdot p^f$.

The associated coverage area for the case in which m detectors have failed is simply

$$W_D(m/n) = (A/n-m)^{1/2} \quad , \tag{4.4}$$

where A is the ceiling area and (n-m) is the number of available detectors.

Using the equations given in Section 3.4 for detector response time (in seconds) and the following information: $\rho_0 = 1.2$ kg/m³, $Cp = 1008$ J/kg °K, $g = 9.81$ m/s², $\alpha = 126$ kW, $T_0 = 300$°K, $Q_C = 126$ kW, and $H = 6$ m, the relation between response time and the number of operable detectors is

$$t_R = 215\ (n-m)^{-1/2} + 30.8\ . \tag{4.5}$$

The above equations are used to drive the cumulative probability distribution for response time of the smoke detectors, as shown in Table 1. Since the probability distribution function calculated for the detector response time has a very low spread, a point estimate of 1.5 min (90 sec) will be used for the rest of the analysis.

Table 1
Response-Time Cumulative Distribution Function
for Automatic Detection System

t_R(sec)	Pdf	Cdf
78.8	6.2×10^{-2}	6.2×10^{-2}
80.1	0.193	0.253
81.5	0.25	0.505
82.9	0.217	0.722
84.6	0.14	0.862
86.3	0.07	0.932
98.9	0.0028	0.977

(b) Manual Detection of Fire - The room under consideration is assumed to be normally unoccupied [case (2) in Section 3.4]. Hence, manual detection of the fire would be due to a component failure signal or would occur randomly by plant staff. The timing for observing an abnormality in the plant due to a fire in this area is estimated from the electrical failure of the nearest cable tray to the transient fuel. From the results discussed in the preceding Section, this is estimated to be between 3 and 6 min. However, after the abnormality is detected, a plant staff member would be sent to assess the cause. The time required for plant personnel to reach the affected area is judged to be 3 to 5 min.[18] Hence, manual detection of this fire may take between 6 and 11 min. A lognormal distribution with 5 and 95 percentile corresponding to 6 and 11 min, respectively, is therefore used in this case for the time required to detect the fire manually.

4.1.2 Suppression Time

There are three possibilities for extinguishing the fire before it reaches first-stage growth:

(a) Automatic Suppression/Automatic Detection - In this scenario the fire will be detected and suppressed automatically. A water sprinkler system is considered as the only means for automatic suppression in this room. The probability that the sprinkler system will fail to operate can be estimated from existing data summarized in Table 2. A failure probability in the range of 0.01 to 0.1 for sprinkler systems is indicated. Similar failure data from Reference 18 for Halon systems indicate a failure probability of 0.0536 to 0.142. Hence a range of failure probabilities from 0.01 to 0.15 is assigned for the inoperability of automatic suppression systems.

The estimated effectiveness of the automatic suppression system is based on the curves presented in Reference 12 (Figure 2 of this report.) The probabilities for successful suppression vs the fuel load per unit floor area for the various types of suppression systems are given by these curves. The equivalent heat of combustion per pound of fuel used for generating these curves is not

Table 2
Successful Sprinkler Operation

Data Source	Rate of Success, %	Time Period
NFPA	95.8	1892-1924
NFPA	96.2	1925-1970
U.K. Fire Statistic	91.7	1965-1969
IRI (Industrial Risk Insurers)	91.06-99.35	1973-1977
U.S. Navy	94.8	1966-1970
Australia	99.76	1886-1968
FM	76-91	1970-1972

known. However, in the same reference, curves are shown indicating the effectiveness of rated barriers, under the assumption that a fuel load of 80,000 Btu/ft^2 is required to fail a 1-hr-rated barrier. Hence, the equivalent heat of combustion per pound of fuel for generating these curves is expected to be about 3.01 MJ (2857 Btu). The fuel load estimated for the representative cable-routing room is about 15,000 MJ and the floor area is 180 m^2. This corresponds to an equivalent fuel load of about 2.6 lb/ft^2. The failure probability for successful suppression from the curves is therefore about 1.0×10^{-3}.

From the above discussion, it can be concluded that the failure of a suppression system to extinguish the fire during first-stage fire growth is between 0.01 to 0.15 and is dominated by the failure of a suppression system to actuate rather than its delivered suppressant density.

(b) Automatic Detection/Manual Suppression - The response time of an automatic detection system, as discussed previously, is estimated to be about 1.5 min. It is also assumed that it takes 3 to 5 min for plant personnel to reach the fire area and observe the extent of the fire. If the fire is small, it is assumed that it can be extinguished with a portable extinguisher. For the personnel to find the portable extinguisher and use it properly, Reference 18 estimates a 2-min time limit of 2-min. Hence, it takes between 6.5 and 8.5 min before the fire can be extinguished manually. As noted before, the timing for the first-stage fire growth is lognormally distributed with the bounds between 4.5 and 7.5 min. Using the lognormal distribution function for successful manual suppression with the 5 and 95 percentile of 6.5 to 8.5, one can then estimate the probability of successful manual suppression.

(c) Manual Suppression/Manual Detection - The estimated timing for manual detection is estimated based on lognormal distribution with 6 and 11 min as the two bounds. The same discussion for manual suppression/automatic detection also applies here. Hence, the 5 and 95 percentile bounds of lognormal distribution in this case would be 8 to 13 min, respectively.

4.1.3 Probability for Room-Damage State(s)

The room damage state (RD1) is considered as loss of one redundant safe shutdown division. This, by definition, corresponds to a first-stage fire growth. Its probability can be functionally expressed as the probability that the time required to reach RD1 is less than the suppression time, i.e.,

$$P(RD1) = P[(t_{RD1} - t_{supp}) < 0] \tag{4.6}$$

or

$$\begin{aligned} P(RD1) &= \int_0^\infty [1-P(t_s<t)]\, P[t_g \epsilon\ (t,t+dt)]\, dt \\ &= \int_0^\infty [1-F_{t_s}(t')]\, f_{t_g}(t')\, dt' \quad , \end{aligned} \tag{4.7}$$

where $P(t_s<t) = F_{t_s}(t)$ is the probability of successful suppression before time t, and $P[t_g \varepsilon (t,t+dt)] = f_{tg}(t)dt$ is the probability that the time required for first-stage fire growth is between t and t+dt.

The integration in the above equation is obtained by means of a discretized probability distribution function. Table 3 gives the discretized points of the cumulative probability distribution for the growth and suppression of the fire.

As previously discussed, the failure probability for automatic detection/automatic suppression is not sensitive to the timing of first-stage fire growth. It is defined by a probability distribution with the bounds at 0.01 to 0.15, and it shall be treated differently. To simplify the calculations, a point estimate equivalent to the mean plus one standard deviation is conservatively used for this case. Table 4 provides the probability of the first-stage fire growth based on various protection measures.

4.2 SECOND-STAGE FIRE GROWTH

For this stage, we consider the propagation of fire from one redundant division to the other. To calculate the timing required for second-stage growth, Cooper's fire enclosure model is used, requiring as input the burning rate from the first stage. For this particular example, the burning rate was determined on the basis that only the three cable trays on one side of the room (one shutdown division) are fully involved. Two case runs were performed. In the first, the maximum value for the heat of combustion of electrical cables was used in conjunction with the liquid transient fuel that initiated the fire. In the second, an average value for the heat of combustion for the cables in addition to a small amount of transient fuel considered just sufficient to ignite the cable tray nearest to the initiating fire was used.

The burning rates resulting from these two runs are depicted in Figure 4. In our judgment these burning rates are unrealistically high. Ostensibly, this is due to the following inadequacies within the COMPBRN computer code:

Table 3
Discretized Cumulative Distribution Function
for Fire Growth and Suppression

Time	$f(t_g)$	$F(t_{AD}+t_{MS})$	$F(t_{MD}+t_{MS})$
4.5	0.05	ε	ε
5.0	0.059	ε	ε
5.5	0.37	ε	ε
6.0	0.60	0.004	ε
6.5	0.79	0.05	ε
7.0	0.9	0.24	0.01
7.5	0.95	0.57	0.02
8.0	0.986	0.84	0.05
8.5	0.995	0.95	0.11
9.0	0.998	0.994	0.21
9.5	0.999	0.999	0.32
10.0	1.	1.	0.45
10.5	1.	1.	0.58
11.5	1.	1.	0.80

$f(t_g)$ - Cumulative distribution function for the timing of first-growth stage.

$F(t_{AD}+t_{MS})$ - Cumulative distribution function for the timing of automatic detection/manual suppression.

$F(t_{MD}+t_{MS})$ - Cumulative distribution function for the timing of manual detection/manual suppression.

Table 4

The Probability of First-Stage Fire Growth

Automatic Detection/Automatic Suppression*	0.10
Manual Detection/Manual Suppression	0.94
Automatic Detection/Manual Suppression	0.89
Automatic/Manual Suppression and Automatic/Manual Detection	0.068

* The failure probability for automatic suppression system with the bounds of 0.01 to 0.15 is fitted to lognormal distribution with associated normal parameters of (-3.25, 0.824) or lognormal parameters of (0.054, 0.053). The value indicated is mean plus one standard deviation of lognormal distribution.

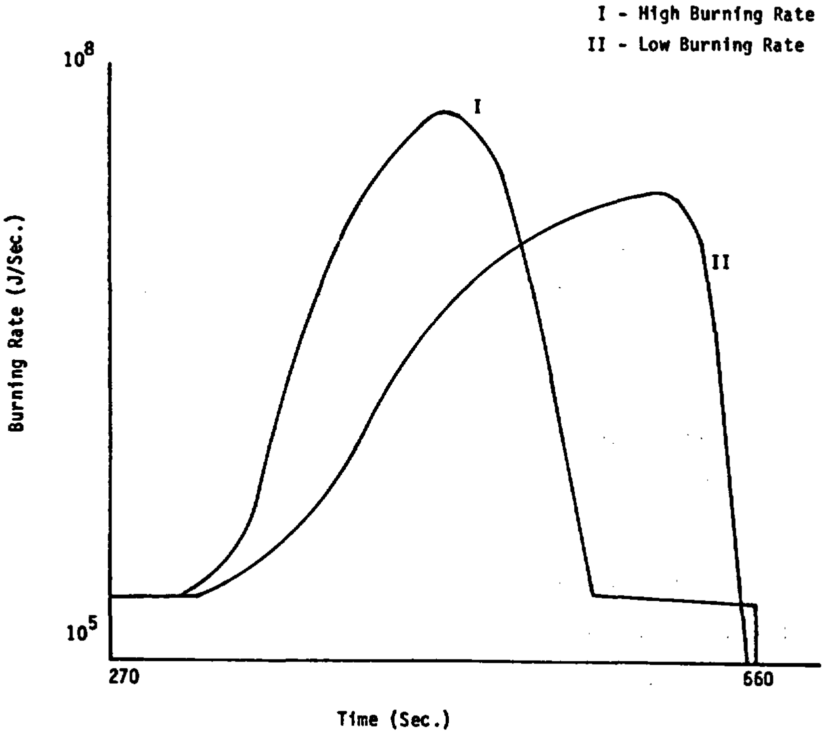

Figure 4. Estimated range of burning rate predicted by COMPBRN.

1. An unrealistically high horizontal flame spread is predicted.

2. No feature is built into the computer code to distinguish the transition from surface-controlled to ventilation controlled burning.

To avoid this difficulty and because of inherent characteristics of the probabilistic assessment which deals with the uncertain elements rather than accurate ones, an alternative approach for estimating the bounds on the burning rates is implemented. This is discussed in the following section.

4.2.1 Determination of Bounds on Burning Rates

For the purpose of probabilistic fire analysis, given the lack of accurate estimates for the enclosure heat generation rate (burning rate), it has been decided to define the enclosure heat release rate for the second stage of fire growth as a pulse with duration of W_B (minutes) and amplitude of Q_B (kW). Although other shapes such as Maxwellian, Gamma, Exponential, etc., could have been used for the enclosure heat release rate, however, the calculations are much simpler if the time characteristic of the burning rate is defined as a pulse.

The bounds on the burning rate can be translated to a range of values for W_B and Q_B. One simple relation that can be established between Q_B and W_B is to equate their product to the total heat of combustion available during second-stage fire growth. That is, for each cable tray, the following equation can be established:

$$W_{Bi} Q_{Bi} = Q_{ti} \quad \text{for the } i^{th} \text{ cable tray} \quad . \qquad (4.8)$$

The bounds for the heat of combustion of EPR/Hypalon are estimated to be between 2.96×10^7 J/kg and 1.7×10^7 J/kg which provide the bounds on a per tray basis. To estimate the average amplitude of the fire, it is conservatively assumed that all the oxygen entrained up to the flame height is consumed. Knowing the mass of oxygen entrained, the heat release rate can be determined on the assumption that 1 kg of oxygen (burning with a hydrocarbon) would produce 12.5 MJ of energy.[22] Hence, the mass of air entrained into the plume (up to the flame height) establishes the heat release rate through the following plume equations:

$$\dot{m}_p = 0.21 \rho_o (gZ)^{1/2} Z^2 (\dot{Q}_Z)^{1/3} , \quad (4.9)$$

$$\dot{Q}_Z \equiv (1-\lambda_r) \dot{Q} / \rho_o C_p T_o (gZ)^{1/2} (Z)^2 , \quad (4.10)$$

$$\dot{Q} = (12.5) (0.21) (\rho_{o_2}/\rho_a) , \quad (4.11)$$

where ρ_{02} and ρ_a are the densities of oxygen and air at 300°K, respectively, and ρ_o is the density of the air in fire environment. Using standard thermodynamic data, manipulations yield

$$\dot{Q} = 3.15 (T_a/T_o)^{2/3} (1-\lambda_r)^{1/2} Z^{5/2} . \quad (4.12)$$

To estimate the flame height (Z), we consider a right-angle circular cone where the area of the flame base is equivalent to the area of the cable tray. A semi-apex angle of 30° is used for estimating flame height. The calculated equivalent radius for each of the cable trays is equivalent to 1.7 m. This yields a flame height of about 0.98 m. Inserting this value for Z in the above equation gives the following expression

$$\dot{Q} = 3.0 (T/T_o)^{2/3} (1-\lambda_r)^{1/2} , \quad (4.13)$$

which is then used to estimate the burning rate (in MW) of each of the cable trays.

The value of the local gas temperature (T_o)is unknown. However, COMPBRN computer runs, for first-stage fire growth, indicate that at the end of this stage the hot layer thickness and temperature are 1.4 m and 757°K, respectively. Accordingly, the lower tray of the second division is not within the hot gas layer. The upper bound for the heat release rate can be estimated by assuming the value of T_0 for the two cable trays at the 5-m elevation to be 757°K where the cable tray at the 3-m elevation is 300°K. For the lower bound, all cables are assumed to be in the hot gas layer. With λ_r for EPR/Hypalon cables prescribed ($\lambda_r = 0.62$), the bounds on the average burning rate for each cable tray can be estimated using the above expression. The pulse width for the burning rate of each cable tray is established using these bounding values in conjunction with the upper and lower bounds for the heat of combustion of the EPR/Hypalon cables. The estimated results for the ranges of the burning rates and durations are given in Table 5. This approach, although simplistic, seems to reasonably envelop the possible heat release rates for this representative room.

Table 5
The Burning Rates for Various Cable Trays
in the Representative Cable-Routing Room

Cable Tray		Total heat of combustion		Characteristic of Heat Release Rate (Q,W)	
No.	Height	Lower Bound	Upper Bound	Lower Bound	Upper Bound
1	3 m	1.77(+3) MJ	3.08(+3) MJ	(0.83 MW, 35 min)	(1.85 MW, 27 min)
2	5 m	1.30(+3) MJ	2.20(+3) MJ	(0.83 MW, 26 min)	(1.0 MW, 36 min)
3	5 m	1.30(+3) MJ	2.20(+3) MJ	(0.83 MW, 26 min)	(1.0 MW, 36 min)

4.2.2 Determination of Cable-Damageability Times

The enclosure fire analysis is used to estimate the local gas temperature and the convective heat flux to the cable trays. The cable tray surface temperature is estimated by means of a one-dimensional heat conduction model for a slab with a thickness equivalent to cable outside diameter. The convective heat transfer coefficient is assumed to be 2 kW/m^2 °C for a cable tray located inside the hot layer. If the cable trays are within the radial jet flow region, the convective heat transfer coefficients are estimated on the basis of Cooper's model. The radiation heat transfer to a cable tray having a separation distance greater than 3 m from the fire axis is assumed to be negligible. Three divisional separation distances are considered in this study, viz., 3, 6, and 9 m from the fire axis. For trays inside the hot layer but below the jet layer, separation effectiveness cannot, by definition, be assessed. Figures 5 and 6, respectively, depict the target temperature and heat flux as a function of time for the lower burning rate scenario. Similarly, the results for the case with the upper bound burning rate are given in Figures 7 and 8.

The estimated burning rates used for exercising the Cooper's model for the second-stage fire growth do not account for the interaction between the hot layer environment and the burning of the cables. The burning rate for the cables engulfed in the hot layer is governed by the amount of oxygen available in the hot layer. Lower oxygen concentration in the hot layer is expected to yield lower burning rates. Assuming that the oxygen concentration is inversely proportional to gas temperature, a cutoff hot layer gas temperature of 900°C is assumed to yield zero burning.

A single cable-damageability criterion could not have been identified for EPR/Hypalon cables. Therefore, the cable-damageability criterion used in this study is either a cable surface (target) temperature of 440°C or an integrated surface heat flux between 1800 and 4000 kJ/m^2, depending on the size of external heat flux. Tables 6 and 7 present the associated timing for cable-damageability criteria vs separation distance. A point estimate for the timing of cable damageability for each case is calculated on the basis of the mean of three estimated timings. The lower and upper bounds calculated in this manner are then used as 5 and 95 percentile of a lognormal distribution. These results are given in Table 8.

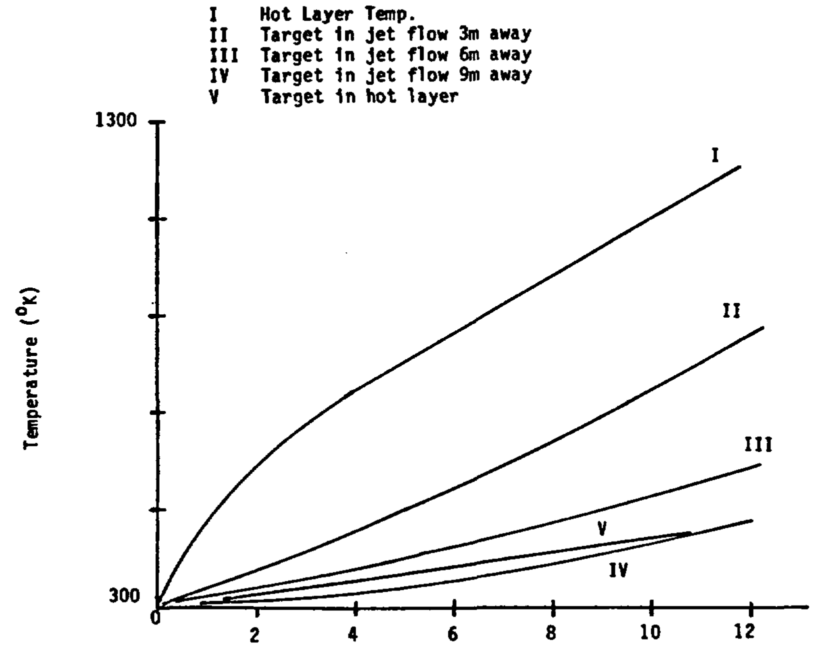

Figure 5. The target temperature vs time for the second-stage fire growth (lower bound of burning rate).

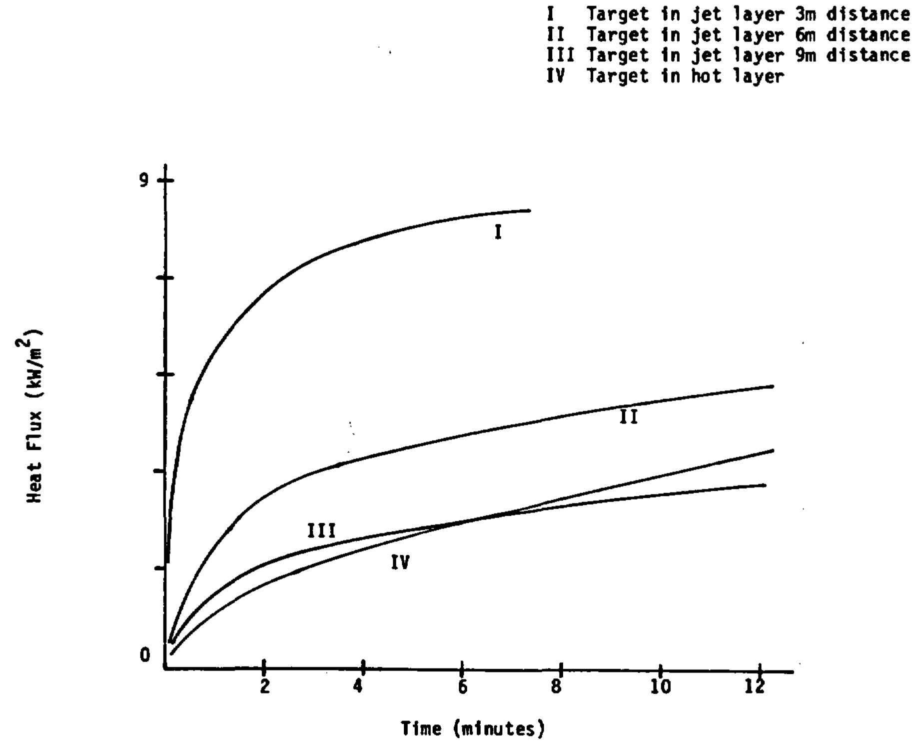

Figure 6. The target heat flux vs time for the second-stage fire growth (lower bound of burning rate)

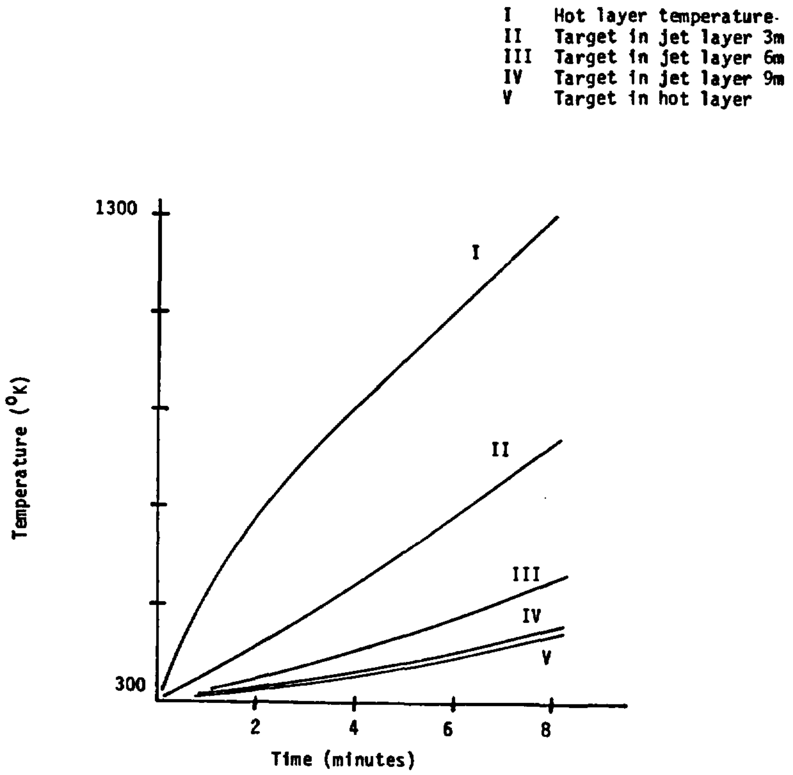

Figure 7. The target temperature vs time for the second-stage fire growth (upper bound of burning rate).

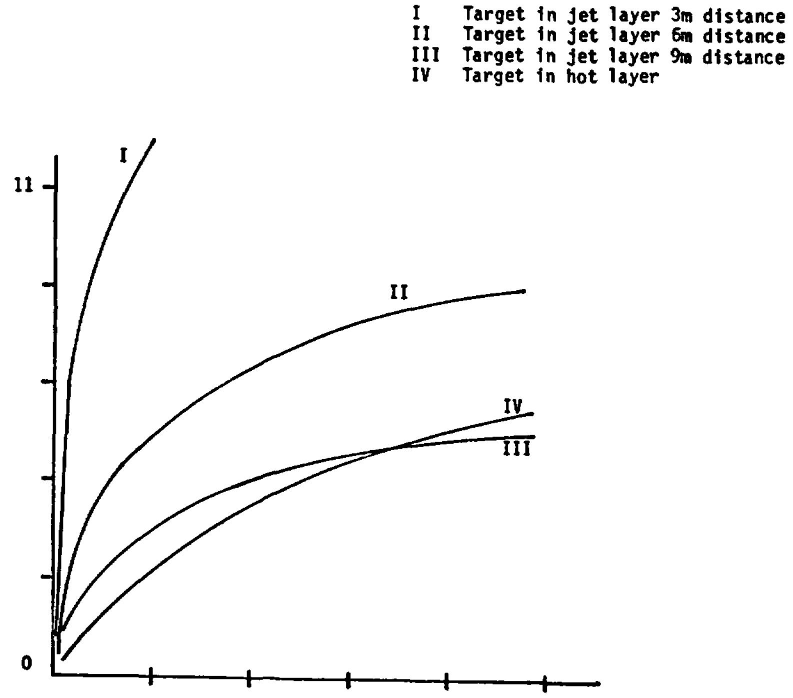

Figure 8. The target heat flux vs time for the second-stage fire growth (upper bound of burning rate).

Table 6

The Timing for Cable Damageability for the Lower Bound Burning Rate

Distance From Fire Axis (m)	Location	Temp. Criteria >440°C (min)	Integrated Heat Flux Criteria		Mean Time (min)
			$1800\ \text{kJ/m}^2$ (min)	$4000\ \text{kJ/m}^2$ (min)	
3	J•L*	9	4	9	7.3
6	J•L*	18	6	14	12.7
9	J•L*	32	11	19	20.5
≥ 3	H•L**	32	12	19	21.

*J•L - Jet Layer

**H•L - Hot Layer

Table 7

The Timing for Cable Damageability for the Upper Bound Burning Rate

Distance From Fire Axis (m)	Location	Temp. Criteria >440°C (min)	Integrated Heat Flux Criteria		Mean Time (min)
			$1800\ \text{kJ/m}^2$ (min)	$4000\ \text{kJ/m}^2$ (min)	
3	J•L*	6.5	3.5	6.	5.3
6	J•L*	12.	6.	11.	9.7
9	J•L*	21.	8.	11.4	13.4
≥ 3	H•L**	21.	9.	15.4	15.1

*J•L - Jet Layer

**H•L - Hot Layer

4.2.3 Suppression Analysis in Second-Stage Fire Growth

Beyond first-stage growth, the only mechanism assumed to be effective in extinguishing a fire is manual suppression by the fire brigade using standby hoses. From the discussion given in Section 4.1.2, it can be assumed that manual detection is achieved with a high probability (an approximate probability of 1) by the end of first-stage fire growth. The time required to bring the fire under control is estimated from the data given in Reference 15. The suppression success probability distribution as a function of time is generated on the basis of the Weibull distribution function with parameter (σ,η) equal to (0.615, 13.5), respectively. However, the suppression curve generated does not differentiate between the two stages of fire growth. Hence, to estimate the successful suppression in second-stage growth, a conditional probability distribution describing the successful suppression in this stage given failure to suppress in the first stage is needed. This conditional probability can be formally expressed as

$$P(t_s \leq t_1 + t_2 \Big|_{t_s \geq t_1}) = \frac{P(t_1 < t_s \leq t_1 + t_2)}{P\,(t_s \geq t_1)} \quad , \qquad (4.14)$$

where t_1 is the time required to reach the first stage fire growth [distributed lognormally by $f_1(t_1)$], t_2 is the time required to reach second stage fire growth [distributed lognormally by $f_2(t_2)$], and t_s is the time required for successful suppression [given by a Weibull distribution denoted by $f_s(t_s)$].

The region of integration for the fixed value of t_s and the joint distribution function of t_1 and t_2 is shown in Figure 9. Hence, for all values of t_s (assuming that t_1 and t_2 are independent variables), the conditional probability for successful suppression is given by the following expression:

Table 8

Upper and Lower Bounds on the Timing of Cable Damageability and the Associated Lognormal Parameters

Distance From Fire Axis (m)	Location*	Lower Bound 5%	Upper Bound 95%	Parameters of Lognormal Distribution** $\bar{x}$ (μ)	v (σ)
3	J•L	5.3 min	7.3 min	6.6 (1.83)	2.3 (0.34)
6	J•L	9.7 min	12.7 min	11.4 (2.4)	3.1 (0.27)
9	J•L	13.4 min	20.6 min	18.3 (2.8)	9.1 (0.47)
≥ 3	H•L	15.1 min	21. min	19.2 (2.98)	6.7 (0.34)

*J•L: Jet Layer; H•L: Hot Layer

**The parameters of lognormal distribution are μ and σ. The mean ($\bar{x}$) and variance (v) are estimated on the basis of the following expressions.

$$\bar{x} = e^{\mu+\sigma^2/2}$$

$$v = e^{2\mu+\sigma^2}[(e^{\sigma^2}-1)]$$

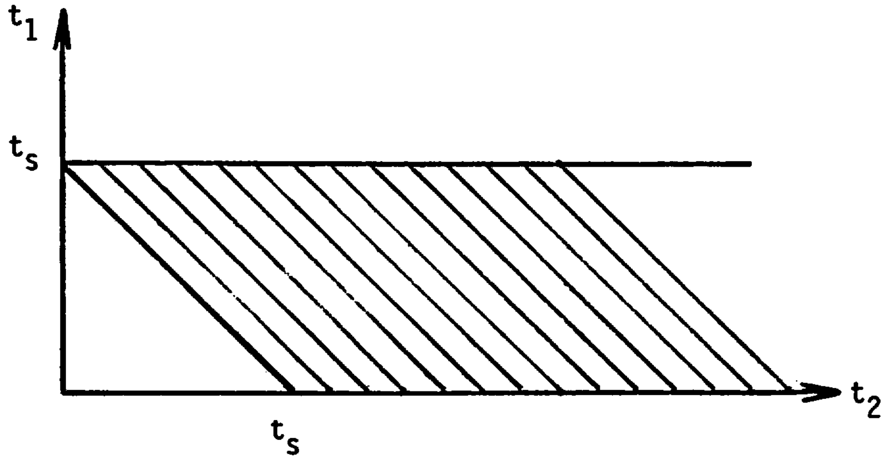

Figure 9. Region of integration for Eq. 4.15

$$P(t_s \leq t_1+t_2 \Big|_{t_s \geq t_1}) = \frac{\int_{t_s=0}^{\infty} \int_{t_1=0}^{t_s} f_1(t_1)[1-F_2(t_s-t_1)]dt_1 \; f_s(t_s)dt_s}{\int_{0}^{\infty} \int_{t_1=0}^{t_s} f_1(t)dt \;\; f_s(t)dt} \qquad (4.15)$$

The above equation can be simplified if the average values of t_1 and t_2 instead of their distributions are used. In this analysis, the ranges for t_1 and t_2 determined in the previous section are comparatively much smaller than the range for t_s. Hence, for the first order approximation, the values of t_1 and t_2 are assumed fixed and equal to the mean of their distributions given by t_1* and t_2*, respectively, which simplifies the above expression, viz.,

$$P(t_s \leq t_1+t_2 \Big|_{t_s > t_1}) = \int_{t_s=t_1*}^{t_2+t_1*} f_s(t)dt \quad \int_{t_s=t_1*}^{\infty} f_s(t)dt \quad . \qquad (4.16)$$

Using this expression, the probability for failure to suppress during second-stage fire growth (before cables are damaged) is given in Table 9.

Table 9

Probability of Successful Suppression in Second-Stage Growth for IEEE-Qualified Cable

Distance From Fire Axis (m)	Location*	t_1*	t_2*	Probability of Failure Suppression
3	J•L	6.7	6.6	0.69
6	J•L	6.7	11.4	0.46
9	J•L	6.7	18.3	0.39
≥ 3	H•L	6.7	19.2	0.38

*J•L - Jet Layer; H•L - Hot Layer.

4.3 MISCELLANEOUS FACTORS

The purpose of this section is mainly to discuss the impact of IEEE qualified vs non-IEEE-qualified cables on fire safety. In addition, the importance of using proper by rated cables and splices for reducing the fire frequency is evaluated. The three major parameters for cables are

C_s - mass loss rate per rate of energy absorbed (g/kJ),

E_{id} - total energy required for damageability (kJ), and

H_f - actual heat of combustion (kJ/g).

If it is assumed that a constant portion of the heat release rate is absorbed by the fuel to sustain the fire, then the value of C_s multiplied by H_f is an important measure for estimating the transition probability from a small incipient fire to a sustained one. The value of E_{id} basically determines how quickly damage occurs under a fire environment. This is especially important for the evaluation of second-stage fire growth times.

To differentiate or ascertain the effect of IEEE rating, nonqualified PE/PVC cables are compared with qualified EPR/Hypalon cables. The value of "C_s" for EPR/Hypalon is 0.17 g/kJ where for PE/PVC it is 0.22 g/kJ. The values of H_f for EPR/Hypalon cables are between 29.6 and 17.4 kJ/g, whereas for PE/PVC cables they are between 30.8 and 22.1 kJ/g. Using the average value for H_f, it is expected that the frequency of self-ignited IEEE qualified cable fires is lower, by a factor of 1.5, than IEEE-nonqualified cables.

The probability for reaching second-stage fire growth when the cables are not IEEE qualified is estimated on the assumption that the burning rate after first-stage fire growth is independent of the cables' characteristic parameters (see Section 4.2.1). Hence, the timing and the probability of second-stage fire growth can be calculated from the results given in previous sections modified for the energy damageability index of PE/PVC. The energy damageability indexes for EPR/Hypalon and PE/PVC cables are between 1800 and 4000 kJ/m^2 and 530 and 1000 kJ/m^2, respectively, depending on the size of external heat flux.[20,21] The final results for PE/PVC cables are given in Table 10.

The fire data from past experience in nuclear power plants[16] indicate that the use of proper splices and rated cables can reduce the frequency of self-ignited cable fires by a factor of 3. This is an important reduction in cable self-ignited fires that has to be accounted for in fire analysis. Although it may change as more data becomes available, a factor of 3 reduction is credited in this study for proper rating and splices of the cables.

4.4 RANKING OF FIRE PROTECTION MEASURES IN THE CABLE-ROUTING ROOM

The analyses performed thus far facilitate the probabilistic ranking of those fire protection measures deemed important for this type of a room. Here, emphasis is on the following:

1. electrical design of cables such as proper rating and proper installation of splices,
2. use of IEEE-qualified cables,

3. automatic detection,
4. automatic suppression,
5. accessibility of portable extinguishers and standby hoses, and also the plant staff's familiarity with the fire-emergency and fire-fighting procedures.
6. 10-ft separation,
7. 20-ft separation,
8. 30-ft separation,
9. proximity of cable tray to ceiling, and
10. trained, well-drilled fire brigades familiar with the plant layout.

Table 10

The Timing and Probability of Cable Damageability in Second-Stage Fire Growth for Cables that are not IEEE Qualified

Distance From Fire Axis (m)	Location*	Lower/Upper Bounds on Timing	$(\mu,\sigma)^x$	Probability of Second-Stage Growth
3	J•L	(3., 4.5) 4.**	(1.3, 0.42)	0.8
6	J•L	(5.9, 9.2) 8.	(2.0, 0.47)	0.68
9	J•L	(9.6, 15.3) 13.7	(2.5, 0.49)	0.52
>3	H•L	(10., 15.3) 13.5	(2.5, 0.45)	0.53

*J•L - Jet Layer, H•L - Hot Layer.

**The numbers in the parenthesis are the lower and upper bounds, and the number outside the parenthesis is the mean of the timing for the second-stage growth and are expressed in minutes.

^{x}The parameters of the lognormal distribution are defined by μ and σ. For more information, refer to Table 8.

Table 11 gives the probability of first- and second-stage room damage states for various combinations of the above fire protection measures. Inclusion of all possible combinations of fire protection would make the table unmanageable, and thus the following considerations are taken into account to limit the table's size without loss of information:

(a) If manual suppression (Item 10 above) is removed from the analysis, then the probabilities of first-and second-stage growth would be the same. This stems from the assumption that second-stage growth can be prevented only by fire brigades (manual suppression).

(b) If the cables are not in proximity of the ceiling (Item 9), namely, if they are located in hot layer region, the change in separation distance (Items 6,7,and 8) would not change the probability of either first- or second-stage growth.

(c) The importance of automatic detection/suppression system and proper cable rating/splices (Items 3, 4, and 1) would affect only the probability of first-stage fire growth.

(d) In general, Items 1 to 5 would affect the probability of first-stage fire growth, and Items 6 to 10, in addition to Item 2, would affect the probability of second-stage fire growth.

Given the above considerations, a total of 13 cases have been analyzed with the results depicted in Table 11. These results are summarized in Table 12 which identifies the important fire protection measures and their associated reduction factors that can be implemented to fire frequency of a room to estimate the probability of second-stage fire growth. The reduction factor basically indicates a multiplicative change in the probability of ultimate room damage state when a specific fire protection feature is implemented.

Table 11

Conditional Probabilities of Achieving First- and Second-Stage Fire Growth Based on Various Fire Protection Systems/Features Implemented (Cable-Routing Room)

Case No.	Design Identification Code (c)	First Stage Growth Probability (a)	Second Stage Growth Probability (b)
1	4/5/1/2/6/7/8	1.5(-2)	5.7(-3)
2	4/5/1/2/6/7/-	1.5(-2)	1.5(-2)
3	4/5/1/2/-/7/8	2.2(-2)	8.4(-3)
4	4/5/1/-/6/7/8	1.5(-1)	5.7(-2)
5	4/5/-/2/6/7/8	1.9(-2)	7.4(-3)
6	4/-/1/2/6/7/8	2.2(-2)	1.2(-2)
7	-/5/1/2/6/7/8	4.5(-2)	1.0(-2)
8	4/5/1/2/6/d/8	1.5(-2)	1.0(-2)
9	4/-/1/2/6/d/8	2.2(-2)	1.8(-2)
10	4/5/1/2/6/e/8	1.5(-2)	6.9(-3)
11	4/-/1/2/6/e/8	2.2(-2)	1.5(-2)
12	4/5/1/2/6/f/8	1.5(-2)	5.8(-3)
13	4/-/1/2/6/f/8	2.2(-2)	1.2(-2)

(a) First-Stage Growth is defined as failure of one shutdown cable division.

(b) Second-Stage Growth is defined as failure of all redundant shutdown cables, i.e., the Ultimate Room-Damage State (UDS).

(c) The design identification code indicates what fire protection system/features are in place. The following identifier codes are used in this study:

Identifier	System/Feature
1	Automatic Detection System (Aerosol Detectors)
2	Automatic Suppression Systems (Sprinklers; Total Flooding Halon)
3	Automatic Doors/Dampers
4	Electrical Cable; Proper Rating/Installation
5	Qualified vs Nonqualified Cables
6	Manual Fire-fighting Equipment Availability and Staff Familiarity
7	Cable Tray Location (within uniformly stratified layer)
8	Fire Brigade; adequate training and plant familiarity
9	High Capacity Drainage System
a	1-hr-rated barriers; including doors and penetrations
b	2-hr-rated barriers; including doors and penetrations
c	3-hr-rated barriers; including doors and penetrations
d	Cable Tray Location (within nonuniform region); Separation - 10 ft
e	Cable Tray Location (within nonuniform region); Separation - 20 ft
f	Cable Tray Location (within nonuniform region); Separation - 30 ft

Table 12

Reduction Factors That Can be Credited For Various Fire Protection Measures at Different Cable Tray Configurations For Estimating The Probability of Second-Stage Growth

SEPARATION DISTANCE (ft)	DISTANCE FROM CEILING (ft)	AUTOMATIC SUPPRESSION SYSTEM (ITEM 4)	PROPER ELECTRICAL DESIGN (ITEM 1)	EARLY SUPPRESSION MANUAL & AUTOMATIC DETECTION (ITEM 5)	TRAINED FIRE BRIGADES & IEEE QUALIFIED CABLES	TRAINED FIRE BRIGADES & NON-QUALIFIED CABLES	OVERALL* REDUCTION FACTOR	
							IEEE QUALIFIED	NON-QUALIFIED
≥ 10	≥ 4	10	3	1.4	4.5	2.1	189	88.2
≥ 10	≤ 4	10	3	1.4	2.25	1.25	94.5	52.5
≥ 20	≤ 4	10	3	1.4	3.25	1.47	136.5	61.7
≥ 30	≤ 4	10	3	1.4	3.9	1.9	163.8	79.8

*For the fire scenarios simulated, the conditional probability of a fire reaching the ultimate damage state (UDS) can be expressed by

$$P(UDS|_{fire}) = (1)/\prod_i fi = 1/f_t .$$

fi's are the reduction factors associated with various fire protection features.

f_t is the overall reduction factor.

4.5 QUALITATIVE APPRAISAL OF FLAME-RETARDANT COATING AND RATED BARRIERS

The important fire protection measures for preventing specific room damage states under specific fire scenarios have been identified for the representative cable-routing room. This is done probabilistically from the existing modeling and data. However, several important aspects of fire protection measures have not been included in this study. These are discussed in the following.

Flame-retardant coatings - The primary purposes of flame-retardant coatings are to prevent the ignition of electrical cable insulation and to stop the propagation of the flame along the cable bundle. This is done through various processes. First, an ablative process consisting of dehydration and other endothermic chemical reactions, coupled with the formation of a carbonaceous char, reduces the heat transmission to the protected cable. Second, the carbon char and the inorganic components of coating form a surface of high emissivity that results in the radiation of a significant amount of heat away from the protected cable. Third, the fire-retardant additives in the coating form products in the fire which inhibit the combustion process and minimize the flammability of materials in the vicinity of the cable.

If the first-stage fire growth is considered as the damageability of one division of safe shutdown cables directly above the pool fire rather than their ignition, then the use of flame-retardant coatings would not affect the probability of first-stage growth significantly. However, its effect on second-stage fire growth would be significant because of expected reduction in burning rate. This effect has not been considered in this study. Some potential disadvantages of coated cables may need further study: 1) reduction in cable amperage, 2) aging due to radiation or harsh environment (effective age of 10 years in normal environment is specified by a coatings manufacturer), and 3) the coating can be removed by water (inadvertent suppression).

Rated Barriers - The primary purpose of rated barriers is to separate the divisional cables in the room by means of passive noncombustible obstacles. This may be a 3-hr rated wall separating the east and west sides of the representative cable-routing room, or a blanket-type barrier which is wrapped around the divisional cables required for one train of safe shutdown systems. Considering that the cable routing room is a low fuel load area, it is safe to assume that the barrier would be effective at least for the duration of time for which it is rated. Regardless of the type of barriers (a rated blanket or wall), it is our judgment that the first-stage fire growth probability will not change. However, the probability of second-stage fire growth could be drastically reduced. The probability of second-stage fire growth for the case that a 3-hr-rated wall separates the two zones within the cable routing room would be most influenced by the probability of a connecting door being open, or the failure of ventilation dampers to close. For the blanket type of rated barrier, the probability of second-stage fire growth would be strongly influenced by the possibility of burning in a hot layer in the vicinity of the blanket. The effectiveness of the rated blankets cannot be estimated properly given the existing modeling.

5. REPRESENTATIVE DIESEL GENERATOR ROOM ANALYSIS

In a typical diesel generator room, several scenarios of fire initiation and progression can be envisaged. According to a review of reported incidents as documented in Licensee Event Reports (LERs) for the period of 1978 to 1982, most of the fires in this area are caused by ruptures in the fuel or lube-oil lines. A likely fire-initiation scenario would then be the subsequent ignition of lube oil issuing from a ruptured line (e.g., 0.5-in.-diam break) in the form of an atomized spray. The ignition source considered is the hot diesel exhaust ducting (exhaust temperature ~1000°F). This, of course, presupposes that the diesels are running. For this particular study, a loss-of-offsite-power (LOOP) initiating event is assumed to be in progress.*

Two stages of fire growth are considered: one deals with the eventual involvement of the day tank (having an assumed 550-gal capacity); the other assumes the involvement of total engine fuel and oil inventory (1100 gal of fuel oil and 250 gal of lube oil). For the first, involvement of fuel stored in the day tank is through radiative heat transfer from the initiating (pilot) fire to the day tank surfaces. This pilot fire is, again, caused by a fuel mist generated by a break in a high pressure fuel line (85 to 100 psig) settling onto (or interacting with) hot diesel surfaces (the exhaust duct). Subsequent involvement of the engine fuel located within the day tank is due to the eventual evaporation and escape of this engine fuel (through tank venting and possible rupture) as a result of the radiative thermal energy being absorbed. Second-stage growth simply considers that the total fuel inventory in the room is suddenly and readily available and burns under ventilation-limited conditions.

The fire protection features qualitatively and quantitatively analyzed in this example include automatic detection systems, Halon flooding systems, operation of doors and dampers, rated barriers of 1-, 2-, or 3-hr rating, drainage systems, and fire brigades.

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*Discussions regarding the quantification of subsequent and probable room-damage states, given this plant-initiating event, form a requisite factor for the observations made and conclusions drawn therefrom.

To assess the various fire protection features required in the SRP guidelines now under evaluation, an additional characteristic time besides those identified previously must be defined and quantified. Thus, in addition to times associated with barrier failure (termination of second-stage fire scenario for this example), and various forms of detection and suppression activities, one has to define a time, t*, when the engine fuel in the day tank becomes involved. This is discussed in the following section on first-stage fire growth.

5.1 FIRST-STAGE FIRE GROWTH

Without exact knowledge of the fuel spray dynamics and the amount of atomized fuel that interacts with hot surfaces, a probability distribution is ascribed to the size of the pilot (or initiating) fire. The size of the fire, Q_p (in megawatts), is assumed lognormally distributed with values of 2 and 12 MW, respectively, at the 5 percentile lower and upper bounds.

Considering further that 46% of this energy is released in the form of thermal radiation (λ_r=0.46), the radiative heat flux absorbed by the 550-gal capacity day tank (the target) can be assessed. This tank, cylindrical in shape, 2 m in length (L), and 0.6 m in radius (R), is assumed located, generally, a distance, d, from the radiating pilot flame (the source). Subsequent fire involvement of the fuel within the day tank occurs at a time, t*, when the fuel temperature reaches its evaporation threshold ($T_{evaporation}$=470°F). Conservatively assuming that all this radiative energy is absorbed by the liquid fuel within the day tank, conservation of energy principles coupled with constitutive radiant-flux laws indicate that

$$t^* = 15.3(10^{-3})/\dot{Q}_p \text{ (sec)} \quad . \qquad (5.1)$$

A separation distance (source to target) of 3 m is assumed. This equation was derived by integrating the following energy equation, viz.,

$$d/dt\ (mC_pT) = Q_{tr} = F_{t\to p}\ Q_p\ \lambda_r = [(L)(R)/\pi d^2]Q_p\lambda_r \quad , \qquad (5.2)$$

where Q_{tr} is the radiative heat transmitted to the day tank as a result of pilot fire of Q_p MW; m is the mass of day tank fuel (m=6148 lb for 550-gal capacity); and C_p is the specific heat of the fuel assumed linearly proportional to the fuel temperature, T. The radiative view factor, $F_{t\rightarrow p}$, is obtained considering a cylindrical-shaped vessel for the target and a radiating point source located a distance, d, away. This expression, viz., $F_{t\rightarrow p} = [(L)(R)/\Pi d^2]$ assumes that the distance between target and source is much greater than the radius of the target. With the pilot fire size considered as lognormally distributed, the probability of t*, i.e., the probability that t* is less than some prespecified time, is shown in Figure 10.

Fire-mitigating actions, such as detection and suppression, and probabilities associated with reaching this first-stage fire growth are then dependent upon the probability that these actions are taken before t*.

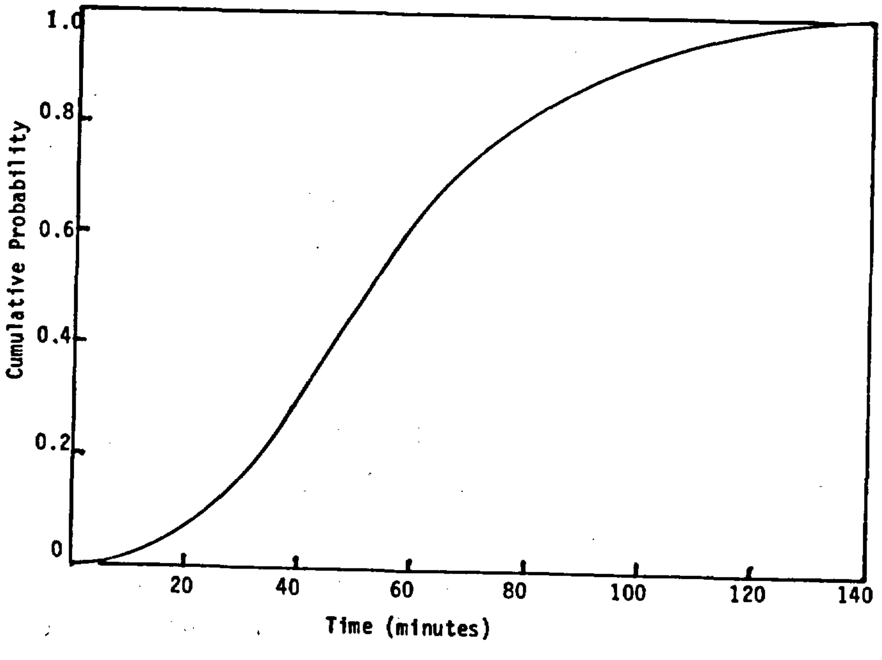

Figure 10. The cumulative probability distribution for first-stage fire growth.

On the basis of the possible fire protection features available in this zone, the probabilities for successful detection and suppression of the fire, before it reaches first-stage growth, are estimated for the following three different scenarios of extinguishment: a) automatic detection and suppression, b) automatic detection and manual suppression, and c) manual detection and suppression.

(a) Automatic Detection and Suppression - Detection time is determined using the same approach discussed in Section 4 for the representative cable-routing room. The parameters needed are the ventilation rate, room height, convective heat-release rate, and detector spacing. For this example, the corresponding values of these parameters are 18 room changes per hour, 7.6 m, 2.6 MW, and 3 m, respectively. The convective heat-release rate is based on the median value of the lognormal distribution for the size of the pilot fire. This results in an estimated detection time of ~5 min. Suppression is provided by automatic operation of a total flooding Halon system. During first-stage fire growth, this system is assumed to be effective in extinguishing the fire in a short period of time (less than a minute). However, the functional reliability associated with successful suppression depends on the reliability of the automatic Halon system as well as of both rated doors and dampers to close on demand. Failure of doors or fire dampers to close on demand reduces the effectiveness of the total flooding features of this suppression system.

The probabilities assigned to such failure are not available at the present time. Therefore, the probability of each of these failures is assumed to be the same as for the failure of a motor-operated valve to close on demand which, from the WASH-1400 Reactor Safety Study, is 1.0×10^{-3}.

The failure probability of an automatic Halon suppression system is estimated to be 8.7×10^{-2} based on the geometric mean of upper and lower bounds reported in Reference 18. Hence, the probability for reaching first-stage growth is estimated to be 8.9×10^{-2} for the case where failure of one damper and one door to operate is of concern.

(b) Automatic Detection and Manual Suppression - The response time of automatic detection systems is estimated, using the same approach given in Section 3.4, to be ~5 min. Assuming that it takes 3 to 5 min for the plant staff to reach the fire area and report the extent of fire, the fire in this scenario could not be extinguished by hand-held extinguishers. Hence, manual fire suppression will primarily be accomplished by the fire brigade using other firefighting equipment. The probability for manual suppression of the fire before it reaches first-stage growth is thus based on the cumulative probability distribution functions given in Figures 2 and 9. Here the initiation time for suppression is the sum of detection time (5 min) and the time required for the plant staff to reach this zone (3 to 5 min). This time period is conservatively assumed to be 10 min. With this information, the probability of a fire reaching first-stage growth is 0.33.

(c) Manual Detection and Suppression System - Manual detection of the early stages of a fire in the diesel generator room during a loss of offsite power transient is considered to have a low probability. The fire will be detected manually with high probability only if the diesel generator stops running, since the plant staff would then be dispatched to investigate the cause. The time required for detection of fire, based on the above scenario, is judgmentally estimated to be about 30 min from the initiation of fire. From the results presented in Figures 2 and 10, the estimated probability for manual suppression of the fire before it reaches the first-growth stage, given this detection time, is 0.66.

5.2 SECOND-STAGE FIRE GROWTH

Second-stage fire growth is defined as a fire starting in one of the diesel generator rooms, propagating to the other diesel generator room, and disabling the redundant unit. Three possible scenarios are considered for the occurrence of second-stage growth: a) propagation of the fire through the rated barriers, b) propagation of the fire through the open dampers and doors, and c) failure of the redundant unit because of independent or common-mode failure.

(a) Second-Stage Propagation Through Rated Barriers - For this large fire (1100 gal of fuel oil and 250 gal of lube oil), the burning rate is expected to be controlled by the amount of oxygen available. Given the ventilation rate of 18 room changes per hour and the room size to be 40 ft W x 50 ft L x 25 ft H, the estimated heat release rate is 22 MW, assuming that 12.5 MJ of energy are generated for each kilogram of oxygen consumed.

The amount of fuel evaporated during a post flashover phase is taken to be approximately 0.061 kg/m^2 sec on the basis of information in Reference 8. The area available for the fuel spill is calculated by subtracting the area occupied by the diesel generator unit from the floor area. The value of m_B is thus ~9.4 kg/sec. Using the ratio of total mass of fuel to the equivalent mass loss rate of fuel due to burning, and assuming the heat of combustion to be about 4.67×10^7 J/kg, the maximum duration of post-flashover burning is ~2.7 hr, although the actual duration is expected to be much less because of the unburned vapor fuel lost through the ventilation system. Figure 11 presents the cumulative probability distribution function for the average room temperature during post-flashover fire, based on the approach discussed in Section 2.1. The estimated probability distribution for the failure of 1-, 2-, and 3-hour-rated barriers vs the duration of fire are given in Figure 12. The criteria and the approach for estimating the failure probability of a rated barrier are discussed in Section 3.3.

The failure probability of a rated barrier can be determined from these curves, if the duration of flashover phase is known. However, the duration of the flashover phase cannot be simply determined for a ventilation-limited fire because of lack of modeling for evaluating the amount of unburned fuel that may leave the room through the ventilation ducts and the interactive effect of fire-fighting activities on controlling the fire. In addition, the problem is more complex if one considers the high probability for the recovery of loss of off-site power (the reason why the diesels were operating) within the first few hours. Given the above concerns and for the sake of comparison, of the equivalent duration of flashover phase is 1.5 hours. Hence, the failure probabilities

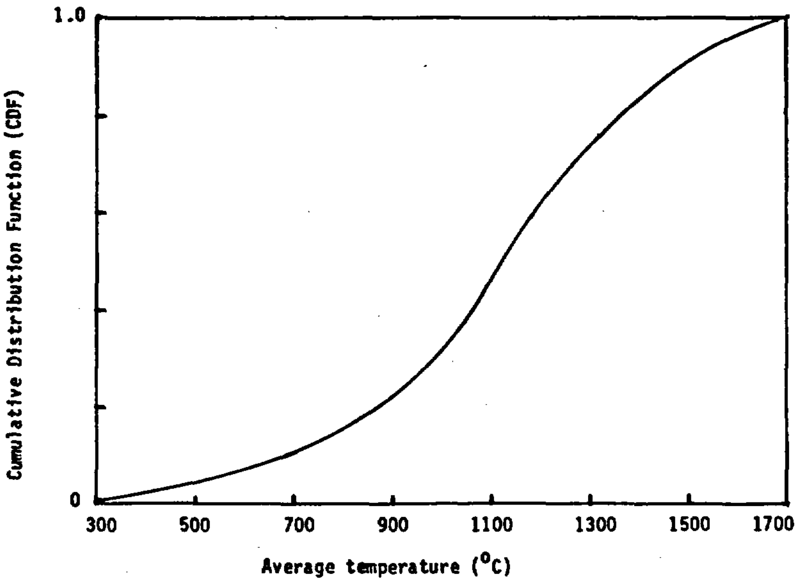

Figure 11. The cumulative distribution function for the average room temperature during post-flashover phase.

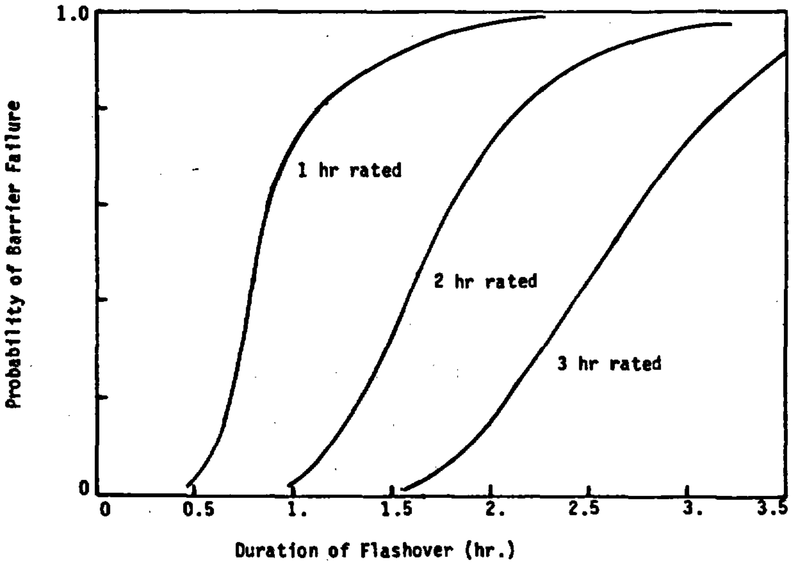

Figure 12. Fragility of rated barrier vs. the duration of flashover phase for the representative diesel generator room.

for 3-, 2-, and 1-hr-rated barriers, assuming 1.5 hr for the duration of flashover phase, are estimated to be 1.0×10^{-3}, 0.31, and 0.9, respectively.

(b) Second-Stage Propagation Through Open Dampers and Doors - As discussed previously, the probability of doors or dampers failing to close automatically when required is about 2.0×10^{-3}. Given this failure, it is conservatively assumed that the automatic suppression system would not be effective. Therefore, the probability of fire propagation to the redundant diesel generator unit due to failure of automatic doors and dampers is conservatively estimated to be 2.0×10^{-3}.

(c) Second Room Damage State Due to Independent or Common Cause Failure of Diesel Generators - The estimated probability for the failure of both diesel generator units in the last two cases (a, b) assumes a fire initiated in one unit propagates to the redundant unit. However, the failure of both diesel generators can also take place without the need for the fire to propagate from one unit to the redundant unit. This can happen as the result of independent or common-cause failure of the second unit when the first unit is disabled by a fire.

The average probability of independent failure of a diesel generator unit is estimated for the nuclear industry[23] to be approximately 2.5×10^{-2}. The data for estimating the probability of the second diesel generator catching fire, given the first unit has been failed because of fire, are not available. However, it is known that the overall conditional probability of the second diesel unit failure given that the first has already failed for various failure modes is about 0.15. Thus, this type of failure for both diesel units is expected to dominate the others previously discussed if the enclosure walls are rated for 3-hr (cases a and b). However, since this scenario of failure is not totally dependent on the impact of fire, it is not included in the quantitative results of this study. The discussion here is intended to emphasize the importance of non-fire-related failure of redundant diesel generators compared to fire-related failures.

5.3 CONCLUSIONS (DIESEL GENERATOR ROOM)

For the representative diesel generator room as described, and based on the analysis performed, some of the important fire protection features given in Table 13 are addressed. The importance of the drainage system (Item 7) that it reduces the duration of fire in second-stage growth by removing the spilled fuel. For example, if the drainage system capacity (average flow rate) is about 50 gpm, the duration of the flashover phase is expected to be reduced by 25%. The proper analysis for the quantitative evaluation of the drainage system effectiveness cannot be made at the present time. However, it is included in the list in Table 13 to indicate the relative importance of this system based on our qualitative judgment.

Table 13
The Fire Protection Measures Considered for the Analysis
of the Representative Diesel Generator Room

1 - Automatic Detection System
2 - Automatic Suppression System (Halon Flooding System)
3 - Automatic Doors and Dampers
4 - 1-Hr-Rated Barriers Including Doors and Dampers
5 - 2-Hr-Rated Barriers Including Doors and Dampers
6 - 3-Hr-Rated Barriers Including Doors and Dampers
7 - High-Capacity Drainage System
8 - Trained Fire Brigades

In general, this study is indicative of an important conclusion in regard to the adequacy of the SRP Section 9.5.1 guidelines for protecting the redundant diesel generator units from a single-exposure fire. It is shown here that in nuclear power plants for which the diesel generator units are separated by 3-hr-rated barriers, and each diesel generator room is equipped with automatic suppression and detection system, the probability of both diesel generator units being damaged by a single-exposure fire is comparatively much smaller than the probability for non-fire-related failures. It should also be noted that these observations are based on an accident scenario initiating with the loss of offsite power and the possibility for a diesel generator to catch fire subsequently. The recovery of offsite power within the period of fire propagation plays an important role in deriving and interpreting results for these rather specific scenarios.

Finally, a ranking scheme similar to the one used for the cable-routing room cannot be devised here. To estimate the reduction factors, certain conditions must be met. For example, in a cable-routing room, if the redundant cables are separated by 20 ft, are located in proximity of the ceiling, and are IEEE qualified, then the probability of second-stage growth can be estimated by multiplication of the failure probabilities for automatic, early manual, and late manual suppressions. This multiplicative nature allows us to define the reduction factors which, in most cases, are the reciprocal of the failure probabilities.

To examine whether the same type of multiplicative rule exists for the representative diesel generator room, an event tree depicting the possible fire scenarios for reaching the first and the second-stage growth is constructed in Figure 13. The size and the number of the branches in this event tree are reduced by eliminating the highly improbable scenarios. For a well designed diesel generator room, consisting of 3-hr-rated barriers and an automatic detection/suppression system, the probability of second-stage growth can be expressed by

$$P(SSG) = P(EMS)[P(\overline{DDC})P(SSGR) + P(DDC)] \quad , \qquad (5.3)$$

where the notations of the events are described in the Figure 13, and the bar over the event DDC (dampers and doors closed) indicates "failure to operate." The above expression is not a simple multiplication. The main reason for this is the dependence between the failure of doors and dampers to close and the effectiveness of the automatic suppression system.

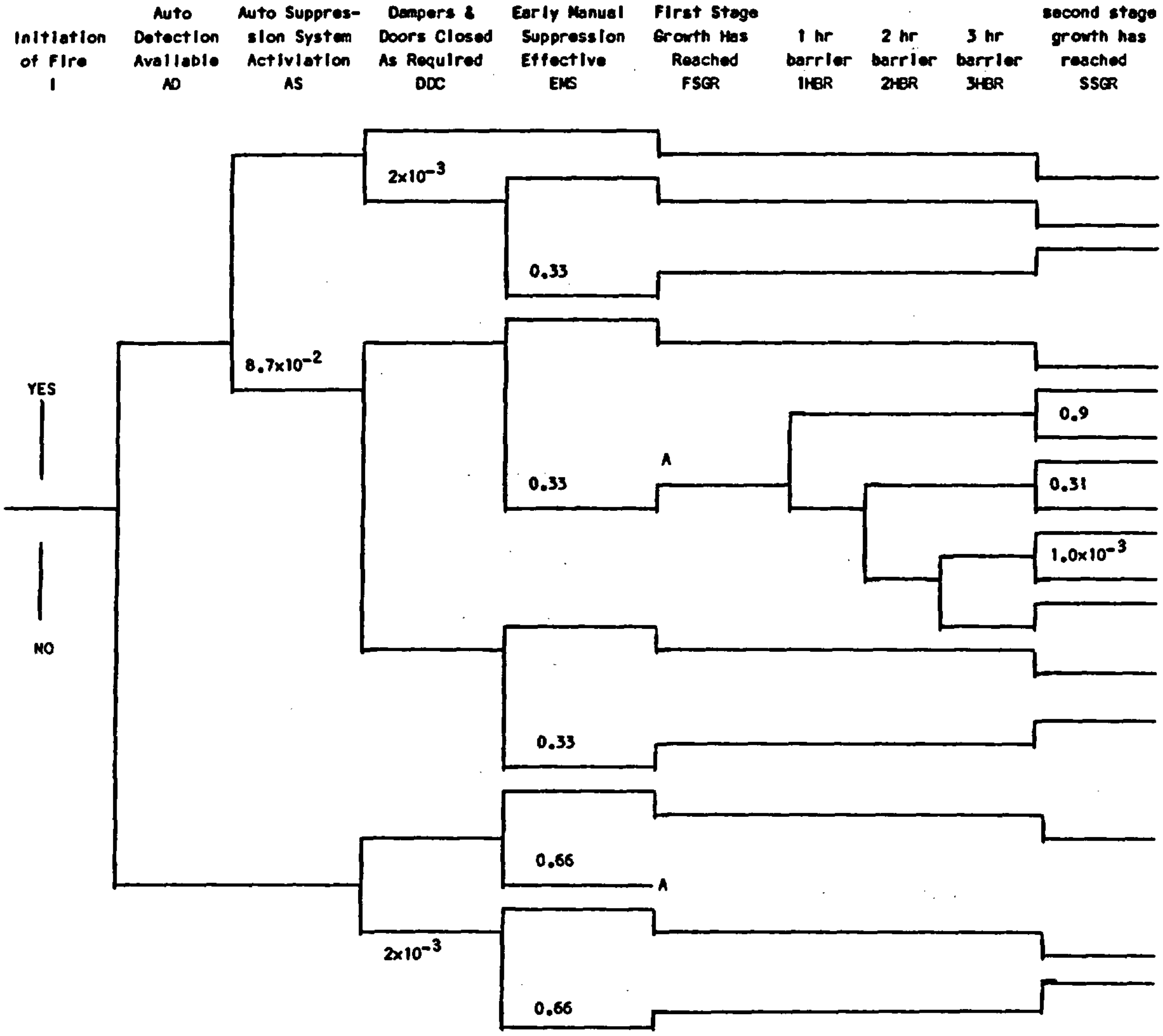

Figure 13. Event tree constructed for the various fire scenarios in diesel generator rooms.

Hence, in order to define reduction factors somewhat similar to those employed for the cable-routing room, the following expression has been used:

$$f_J = \frac{\text{Prob. (SSG; when system } S_J \text{ is removed)}}{\text{Prob. (SSG; when system } S_J \text{ is not removed)}} \quad , \qquad (5.4)$$

where SSG represents the first stage growth.

The values for f_J's for various fire protection systems are given in Table 14. In addition, the probabilities for first- and second-stage growth for a number of typical fire protection designs are given in Table 15.

Table 14

The Modified Reduction Factors (Importance Factors)

for Diesel Generator Room

Rating of the Walls	Fire Protection Features from Table 13						
hr	1	2	3	4	5	6	7
3	3.03	1.52	500.00	---	---	46.50	3.03
2	20.80	10.40	34.40	---	3.20	---	3.02
1	22.20	11.10	12.20	1.14	---	---	2.97

Table 15
Probabilities of Room-Damage States for Various Fire Protection Design Features (Diesel Generator Room)

Case No.	Design Identification Code	First-Stage(a) Growth Probability	Second-Stage(b) Growth Probability
1	1/2/3/c/8/9*	3.0(-2)	6.6(-4)+
2	1/2/3/b/8/9	3.0(-2)	9.6(-3)
3	1/2/3/a/8/9	3.0(-2)	2.7(-2)
4	1/-/3/c/8/9	0.33	1.0(-3)
5	1/-/3/b/8/9	0.33	0.1
6	1/-/3/9/8/9	0.33	0.3
7	-/-/3/c/8/9	0.66	2.0(-3)
8	-/-/3/b/8/9	0.66	0.2
9	-/-/3/a/8/9	0.66	0.6

+3.0(-2) ≡ $3.0(10)^{-2}$.

(a)First-Stage Growth is defined as the fire involvement of the diesel fuel.

(b)Second-Stage Growth is defined as the fire propagation beyond the original fire enclosure, i.e., the Ultimate Room-Damage State (UDS).

*The design identification code indicates what fire protection system/features are in place. The following identifier codes are used in this study:

Identifier	System/Feature
1	Automatic Detection System (Aerosol Detectors)
2	Automatic Suppression Systems (Sprinklers; Total Flooding Halon)
3	Automatic Doors/Dampers
4	Electrical Cable; Proper Rating/Installation
5	Qualified vs Nonqualified Cables
6	Manual Fire-fighting Equipment Availability and Staff Familiarity
7	Cable Tray Location (within uniformly stratified layer)
8	Fire Brigade; adequate training and plant familiarity
9	High Capacity Drainage System
a	1-hr rated barriers; including doors and penetrations
b	2-hr rated barriers; including doors and penetrations
c	3-hr rated barriers; including doors and penetrations
d	Cable Tray Location (within nonuniform region); Separation - 10 ft
e	Cable Tray Location (within nonuniform region); Separation - 20 ft
f	Cable Tray Location (within nonuniform region); Separation - 30 ft

6. LIMITATIONS OF THE RESULTS/METHODS

This study has presented a method and rationale that can be used to evaluate the relative importance of certain fire protection features found in nuclear power plants. It has considered certain design features required for mitigating the consequences of particular fire scenarios in two predefined enclosure configurations. This analysis, although performed conservatively, by no means envelops all the varieties of enclosure configurations found in nuclear power plants. Various sources of uncertainty have been discussed, some qualitatively and some quantitatively. It should be noted, however, that these cautionary notes in no way discredit or reduce the importance, applicability, and the potential usefulness of the method described. Rather our intent is to caution against misinterpretation of the results and their extrapolation to other fire scenarios.

Before an attempt is made to use the results tabulated in Tables 11, 12, 14, and 15, and the conclusions drawn therefrom are applied to other fire safety situations, the following must be considered:

a) Assure that the distribution and the heat of combustion for the in situ combustibles are not drastically different from those considered herein.

b) Assure that the ceiling height and the floor area of the actual room are comparable to those of the representative room.

c) Examine the fire protection features in the room of concern and assure their compatibility with those modeled in the analysis.

Conceivably, by using the probabilistic results of this study (or applying the method specifically) and a parallel deterministic assessment of the particular fire-protection system, the regulatory body may make recommendations about whether or not additional fire-mitigation features are required.

It should also be noted that until the approaches described are further used and the results investigated, i.e., additional room geometries, in situ combustible loadings, and fire scenarios, the results presented thus far cannot be summarily used to evaluate the relative merits of the fire protection guidelines found in Section 9.5-1 of the SRP. Indeed, those fire protection features and systems that have been addressed can be analyzed with the method described on a case-by-case basis.

7. SUMMARY OVERVIEW AND FUTURE RECOMMENDATIONS

In a general sense, fire engineering design is nondeterministic. Some level of risk is virtually unavoidable. Historically, fire safety requirements and design criteria have been written without actually stating their objective safety levels and even without any analytical measurement of the objectives involved. Indeed, a defense-in-depth philosophy is generally implemented through varying combinations of active and passive fire protection features. Admittedly the traditional classification of, say, fire barriers is convenient and may provide a reasonable design basis for certain types of structures and occupancies, the risks of which are well experienced. But the design becomes questionable in cases where the exposure and/or the structural response, as well as the associated uncertainties, may seriously affect the impact from fire, in turn affecting the performance of other systems. Safety or economy may be affected even more if conditions governing the frequency of fire or the exposure of a structure and its internals to a fire differ from average conditions and are thereby not adequately accounted for. For these reasons there is an urgent need to evaluate the levels of safety inherent in present nuclear power plant fire protection regulations. Thus, to design in and appraise "fire safety," performance has to be described and measured in probabilistic terms.

Idealistically, the essential components of a probability-based fire protection/fire safety review methodology include the following:

(1) Analytical modeling of relevant processes, verification of the models, their validations, and accuracies; determination of critical design parameters.

(2) Formulation of functional requirements, expressed either in deterministic or probabilistic terms.

(3) Determination of design parameters.

(4) Verification by reliability analysis that the choice of safety factors leads to safety levels which are consistent with expressed functional requirements.

The major objective of this study has been to use existing physical and probabilistic fire models to develop an integrated methodology through which the relative importance of various fire protection features can be investigated. A limited study has been performed which provided insights regarding the relative importance of several active and passive fire protection systems and identified where future implementation of somewhat more detailed modeling efforts is warranted.

On the basis of this study, which entails a hybrid fire scenario and fire dynamics approach applied to two representative fire areas in nuclear power plants, we conclude that an overall general ranking of fire protection systems and measures cannot be fully determined. However, for a given enclosure and for a given fire scenario, a relative ranking for each is listed (Sections 4.4 and 5.3). These two lists have been developed on the basis of investigating what each fire protection feature or combinations thereof contribute in reducing the probability for fire-induced failure of redundant shutdown equipment. Indeed, importance ranking of fire-protection systems with respect to some risk measure can be different depending upon the level (and the measure) of application, viz., component level, system level, fire area level, accident sequence frequency level, etc. In this study, the measure used was the conditional probability of achieving various fire-damage states in specific fire areas.

It has been shown that 20-ft separation between redundant safe shutdown cables does not provide passive protection equivalent to a 1-hr-rated barrier. However, the level of fire protection probabilistically achieved by combinations of the various fire protection systems investigated is indeed assuring.

Finally, several areas in both deterministic and probabilistic fire analysis which are in need of further investigation can be identified. The lack of knowledge and accurate modeling in these areas is the prime contributor to the overall uncertainty of the results. The following provides summary discussions on some of these deficiencies and recommendations for improving the existing models.

1. Deterministic analysis: the need for improving the existing deterministic computer codes for the modeling of an enclosure fire is inevitable. The major area of concern which may require immediate improvement is the model used for estimating the burning rate via ignition and flame spread algorithms. In addition, a built-in mechanism in the models to account for the transition of a surface-controlled to a ventilation-controlled burning is of great importance. Understandably, other areas of deterministic analysis need improvement as well. In most cases, these improvements yield themselves to a complex mathematical model such as the use of three-dimensional field models instead of two- or three-zone stratified models. The degree of model complexity may be reduced to a more moderate level by taking the importance of the various phenomena into consideration by means of sensitivity or perturbation analysis.

2. Probabilistic risk analysis: fire propagation and component damageability are best described by time-dependent probabilistic analyses. The overall plant risk caused by fire-initiating events shall be estimated via time-dependent probabilistic models as well. For a component which is required to perform its safety function within the first half-hour of an accident, any fire-induced failure of the component beyond that time is of no concern. Therefore, plant risk may be evaluated properly if and only if the timing of an accident progression is to be compared with the timing of fire propagation. Such time dependent probabilistic analyses have yet to be determined.

In addition, suppression and detection models need more realistic treatment. The probabilistic models implemented for these systems depend heavily on engineering judgment and data with minimum effort devoted to the physical modeling of the process. Such a heavy reliance on data requires more reliable data properly classified to perform accurate estimations. Such data sources are not available at this time. Therefore, combined efforts consisting of improving the existing data sources and developing the required physical models for suppression and detection systems are recommended.

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APPENDIX A

PARAMETERS USED FOR THE ANALYSES

The nominal values for major physical parameters used for the fire analyses are listed here. In cases where the nominal values are not well defined, acceptable ranges are generally determined. To avoid repetition, the specific parameters of a fire area such as ventilation rate, dimensions of the room, etc., have not been included in the list. In addition, data used for the probabilistic analysis such as reliability and effectiveness of fire detection and suppression systems are determined in concert with the associated fire zone. Therefore, those data are not included here but are part of the main body text of this report.

Table A-1

The Values for Physical Parameters Used in the Study

1. Properties of Air at Temperature T=300°K and p=1 atm	
Density :	$\rho = 1.18$ kg/m^3
Specific Heat :	$C_p = 1004.8$ J/kg°K
Ideal Gas Assumption :	$\rho T\|_p = \rho' T'\|_p$
2. Properties of EPR/Hypalon Cables	
Heat of Combustion :	$1.7\text{x}10^7 \leq H_f \leq 2.96\text{x}10^7$ (J/kg)
Fraction of Radiation Heat Release Rate:	$\lambda_r = 0.62$
Density :	$\rho = 1436$ kg/m^3
Specific Heat :	C = 1600. J/kg-°K
Thermal Conductivity :	K = 0.1 W/m-°K
Surface-Controlled Specific Mass Loss Rate :	$0 \leq m_o \leq 0.003$ (kg/m^2-s)
Specific Mass Loss Rate Radiation Augmentation :	$C_s = 0.17\text{x}10^{-6}$ kg/J-m^2
Pilot-Ignition Temperature :	$T_p = 440$°C
Auto-Ignition Temperature :	$T_s = 488$°C
Total Energy of Damageability :	$1800 \leq E_{id} \leq 4000$ (Kj/m^2)
3. Properties of PE/PVC Cables	
Heat of Combustion :	$2.21\text{x}10^7 \leq H_f \leq 3.08\text{x}10^7$ (J/kg)
Fraction of Radiation Heat Release Rate :	$\lambda_r = 0.56$
Density :	$\rho = 1715$ kg/m^3
Specific Heat :	C = 1632.7 J/kg-°K
Thermal Conductivity :	K = 0.08 W/m-°K
Surface-Controlled Specific Mass Loss Rate :	$0 \leq m_o \leq 0.003$ kg/m^2-s
Specific Mass Loss Rate Radiation Augmentation :	$C_s = 0.22\text{x}10^{-6}$ kg/J-m^2
Pilot-Ignition Temperature :	$T_p = 430$°C
Auto-Ignition Temperature :	$T_s = 478$°C
Total Energy of Damageability :	$530 \leq E_{id} \leq 1000$ (kJ/m^2)

TABLE A-1 (Cont'd.)

4. Properties of Fuel Oil	
Density :	$\rho = 900$ kg/m^3
Specific heat (T in °K) :	$C = 1716.5 + 3.54\ T$ J/kg-°K
Boiling Temperature :	$T_B \approx 244$°C
Surface Controlled Specific Mass Loss Rate :	$m_o = 0.06k$ kg/m^2 sec
Heat of Combustion :	$H_f = 4.67 \times 10^7$ J/kg
Fraction of Radiation Heat Release Rate:	$\lambda_r = 0.4$
5. Additional Data	
Mass Ratio of Oxygen to Air :	$\alpha = 0.21$
Heat of Combustion for 1 kg of Oxygen Burning with Hydrocarbons :	$H_f \approx 12.5$ MJ
Density of Oxygen (Ideal Gas Assumption) at Temperature T=300°K :	$\rho(02) = 1.3$ kg/m^3
Fraction of Heat Lost by Conduction Through Walls and Radiation Through Openings :	$0.4 \leq \lambda_c \leq 0.8$
	$\lambda_c(\text{average}) = 0.6$

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A probabilistic approach for the evaluation of major fire protection measures in nuclear power plants is described. The methods developed are applied to two representative fire areas -- one similar to a cable routing room and the other typical of a diesel generator room. The fire areas chosen for application, the fire scenarios described, and the various fire-damage states specified in the two illustrative examples are used to evaluate those fire-protection guidelines which deal with automatic/manual fire detection and suppression systems, rated barriers, divisional separation, drainage systems, dampers, and fire rating of electrical cables. Tabular results are presented, which reflect the relative merits of these systems/features in terms of conditional probabilities of achieving various room-damage states. The conclusions drawn and the lessons learned through the course of this study are discussed, and the areas that may need further investigation are identified.

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