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Nuclear Power Plant Fire Protection — Fire-Hazards Analysis (Subsystems Study Task 4)

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ABSTRACT

This report examines the adequacy of existing fire-hazards analysis methodology in the context of nuclear power plant safety. By combining and simplifying a number of available analysis techniques and by demonstrating the technical merit of each technique, this report develops a conservative fire-hazards analysis method which can be easily used by both designers and regulators. As described, a suitable analysis method for nuclear power plants should involve three phases. These are: (1) a deterministic evaluation of passive fire barriers under limiting fuel load and ventilation conditions; (2) a probabilistic evaluation of supplementary fire protection measures (e.g., suppressions systems); and (3) a subjective evaluation of unquantified fire hazard conditions (e.g., cable arrangements). An example of each analysis phase is provided.

ACKNOWLEDGMENT

The authors acknowledge the contribution made to this report by Mr. Bert Cohn of Gage-Babcock & Associates, Inc. Mr. Cohn developed the probabilistic critical-path technique described on pages 49 through 60, 71 through 74, and 79 through 82.

CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY

An uncontrolled fire in a nuclear power plant can seriously jeopardize overall plant safety. Recognizing this, the Nuclear Regulatory Commission has undertaken a broad program in fire protection research, a portion of which focuses on the performance of fire-hazards analyses. This report examines the adequacy of existing fire-hazards analysis techniques in the context of nuclear power plant safety.

Traditionally, nuclear power plant designers have used a combination of fire codes, insurance agency requests, regulatory guidance, and fire consultant recommendations to assess the adequacy of fire protection system designs. This assessment process, often referred to as a fire-hazards analysis, normally has required engineers to balance a perceived level of fire risk against some degree of fire protection. Unfortunately, decisions regarding what constitutes an appropriate level of fire protection often have depended upon the experience and judgment of the engineer making the analysis, with the results being quite subjective.

A review of a large number of available analysis techniques has shown that no one method can satisfactorily circumvent the subjective nature of current fire-hazards analysis practice. Methods which prove conservative and technically sound are usually too complicated, while more easily applied techniques lack technical merit. Fortunately, it is possible to develop a new analysis methodology which combines the best attributes of conservatism and ease of application from several existing techniques.

By first performing a bounding deterministic evaluation under limiting fuel load and ventilation conditions, to establish the adequacy of passive fire barriers, an analyst can eliminate a number of "safe" fire conditions from further scrutiny. For those fire situations demonstrated to be too severe for passive-barrier containment, a second evaluation can be made to assess the probability that supplementary fire protection

measures (e.g., fire suppression) will be adequate. Finally, for those cases for which the probabilistic analysis proves unacceptable or inconclusive, a subjective evaluation can be made in accordance with a standardized format and logic sequence. This approach emphasizes the use of a conservative and technically sound deterministic method in preference to a purely subjective evaluation, but it is recognized that--under certain circumstances--a lack of either theoretical understanding or experimental precedents may require that one rely on subjective judgment.

NUCLEAR POWER PLANT FIRE PROTECTION -
FIRE-HAZARDS ANALYSIS (SUBSYSTEMS STUDY TASK 4)

1. Introduction

Based on the need to support near-term regulatory and licensing objectives for nuclear power plant fire protection, the Nuclear Regulatory Commission (NRC) Office of Standards Development requested Sandia Laboratories to develop the underlying logic and technical bases associated with four specific fire protection topics. The topics selected by the NRC were fire ventilation, fire detection, fire barriers, and fire hazards analysis. Separate reports addressing the findings of the first three study topics have been completed with recommendations for establishing suitable technical bases. The fourth topic, fire-hazards analysis, is the subject of this report.

Study Objective

Although it is important (1) to establish what levels of fire protection adequately reduce nuclear power plant fire risk to acceptable safety levels and (2) to perform a fire-hazards analyses of a complete nuclear facility, these evaluations fall outside the scope of this report. Instead, the major objective of this study was limited to assessing the adequacy of existing fire-hazards analysis techniques in the context of nuclear power plant safety.

Traditional Analysis Approach

Among those knowledgeable about fire protection, the term "fire-hazards analysis" conveys a meaning which, in principle, is understood universally, just as the term "marketing survey" is understood by most real estate developers. To a fire protection engineer or insurance underwriter, a fire-hazards analysis traditionally involves the application of basic fire protection principles and experience to particular conditions existing within an area in question. Numerous factors (including fuel load, suppression capability, detection reliability, fire brigade training, structural integrity, property value, life safety, fuel ignitability, oxygen availability, and insurance costs) are evaluated by fire protection engineers until, in their judgment, fire risk is balanced by appropriate fire protection measures.

Except in those cases where building codes are specific, decisions regarding what constitutes an appropriate level of fire protection can often depend upon the experience of the engineer performing the analysis. Just as a marketing survey can range from liberal to conservative with regard to both its technical basis and recommended course of action, a fire-hazards analysis can be unjustifiably harsh or lenient depending upon the particular experiences of the engineer performing the analysis. In practice, of course, the consultation services of consistently liberal or conservative fire protection engineers would not normally be sought, because their fire-hazards analysis results soon would be recognized as misaligned with accepted practice.

Unfortunately, the use of generally accepted practices in the performance and assessment of traditional fire-hazards analyses can lead to fire protection decisions which lack a technical basis. The accepted practice of using certain fire-retardant cable insulations and cable tray spatial separations are two examples wherein correct technical bases later were shown to be lacking.[1 2 3] Another example to be addressed more thoroughly in this report is the accepted practice[4] of equating a one-hour fire to a fuel load of 80,000 Btu/ft^2.

Since, in the context of nuclear power plant safety, it may be inappropriate to judge the adequacy of fire protection measures solely on the basis of "accepted practice," we tried to quantitatively assess each analysis situation by deterministically applying basic principles of fire phenomenon. The use of probabilistic and subjective analysis methods was limited to those cases where, because of limited state-of-the-art knowledge, a detailed understanding of the fire phenomena is lacking.

Study Description

A viable fire-hazards analysis method for nuclear power plant application

- Should be derived from, but not necessarily duplicate, available and proven techniques

- Should be defendable in terms of conservatism and technical basis

- Should be easily used by both designers and regulators.

From these analysis criteria, at least two questions arise.

1. What available fire-hazards techniques, if any, can be used to predict fire severity from a knowledge of the physical conditions existing in particular power plant areas?

2. What available analysis techniques, if any, can be applied consistently by designers and the NRC to yield conclusions that are straightforward, believable, conservative, and quantitative?

Answers to these questions are provided by this report for a large number of candidate analysis methods, each of which has been applied previously by other fire protection analysts to various types of residential, commercial, industrial, or nuclear power plant hazards. Since it was found that all of the available analysis methods reviewed proved deficient in meeting at least one of the analysis criteria, it was decided to select and combine from available analyses those attributes most responsive to the needs of nuclear power plant designers and regulators. It will be shown that the analysis method which resulted from this approach relies initially upon conservative assumptions and deterministic calculations of fuel load and ventilation conditions to bound expected fire severity. If such bounding conditions are found to be acceptable to plant safety, the analysis is terminated. If, however, plant safety cannot be assured under conditions of a conservative bounding analysis, other supplementary fire protection measures (e.g., detection, manual suppression, and automatic suppression) are evaluated in a probabilistic fashion to assess what level of fire protection can be derived from these measures. If the results of a probabilistic analysis also are found to be unsatisfactory or inconclusive, a subjective analysis is finally performed.

When plant safety cannot be assured by a bounding analysis, it must be recognized that, without a nuclear power plant safety systems analysis, it is difficult to judge what relative level of fire protection meets overall plant safety objectives. This uncertainty arises from the fact that some plant safety areas are of more importance to a safe shutdown than other areas, and therefore these important areas require a higher level of fire protection. As stated under "Study Objective," the determination of what is "safe enough," from the standpoint of overall nuclear plant fire protection safety, falls outside the scope of this report.

2. Analysis Methods Available

As stated in the last section, it was concluded early in this study that a viable fire-hazards analysis for nuclear power plant application should (1) be derived from, but not necessarily duplicate, available and proven analysis techniques; (2) be defendable in terms of being conservative and technically sound; and (3) be easily used by both designers and regulators. With these criteria established, a large number of analysis methods were reviewed. By limiting this review to only those methods which have received at least some practical scrutiny, the first criteria automatically is satisfied; only the second two criteria remain to be met. This section examines how well these remaining criteria are achieved by a number of existing analysis techniques.

For ease of understanding, it proved convenient to assign each candidate analysis method to one of three categories depending on whether a particular method was based on subjective judgments, deterministic calculations, or probabilistic logic. The analysis techniques falling within these categories are addressed in the following sections.

Subjective Analyses

This technique bases decisions for establishing satisfactory levels of fire protection strictly on the judgment of the individual performing the analysis. In practice this category of analysis is the most widely used, with successful precedents being set in the areas of fire insurance and public safety. The primary advantage of a subjective analysis stems from the flexibility and relative ease with which the analysis can be performed by a trained professional, while its main disadvantage is related to the strong dependence of the analysis on the qualifications of the professional. To overcome this, some precision has been added to a few subjective analyses through the establishment of strict analysis formats. However, it turns out that, even with improved formats, all subjective analyses must rely solely upon experienced judgment to defend the degree of technical merit and conservatism inherent in each fire protection decision.

In performing a subjective analysis, an analyst develops conclusions regarding which hazard situations are acceptable and which are not, but the analyst in no way is required to demonstrate, either analytically or empirically, that a particular judgment is both conservative and technically sound. While in some situations it is possible for a subjective analyst to cite codes or standards based on calculations and testing, it is more often the case that judgment alone must be invoked. This is particularly true in nuclear power plant fire-hazards analyses because few existing fire codes or standards were written with nuclear plant safety in mind. Fire protection measures which meet traditional monetary and life safety objectives for insurance purposes may be totally inadequate for meeting nuclear power plant safety goals.

The following sections describe several of the analytical methods which were categorized as subjective for purposes of this study. In each example, it can be seen that an analyst must judge whether a particular combination of fire hazard and fire protection results in an acceptable level of safety.

Preliminary Fire-Hazards Analysis Method -- This type of analysis presents a tabular listing of what are believed to be the primary hazards of concern, together with a qualitative estimate of the potential effects of these hazards on safety systems and of the "best" method to control the hazards. Table 1 shows a typical format for a preliminary fire-hazards analysis based on examples presented in References 5 and 6. In practice, the transition from a preliminary to a final hazards analysis of this type occurs after a proposed plant design has been built, thereby permitting some refinement of the column descriptions used in Table 1. This form of preliminary and final hazards analysis lacks quantitative support for estimates of hazards, safety impacts, and control effectiveness.

Fire-Hazards Analysis Outline Method -- This analysis method identifies what steps should be taken in performing a fire-hazards analysis, but it does not provide the technical basis for actually making the analysis. Each step of this analysis method usually asks the fire protection analyst to perform a task such as: list applicable codes and standards, develop the design criteria for suppression requirements, or analyze available backup protection systems. The method used for performing these tasks is left to the discretion of the analysts. Examples of this methodology are found in National Fire Protection Association (NFPA) Code 802, "Recommended Fire Protection Practice for Nuclear Reactors," and in the March 1978 draft of a proposed appendix to the American National Standard "Generic Requirements for Light Water Nuclear Power Plant Fire Protection," ANSI/ANS-59.4-1977. Although a step-by-step analysis procedure of this type will help a designer formulate a comprehensive analysis outline, it will not provide the technical guidance needed to accomplish the tasks of the outline. A complete analysis method should include both a step-by-step procedure outline and a technically defendable method for accomplishing each step of the outline.

TABLE 1

Preliminary Hazard Analysis*

Primary Hazard	Plant Operating Conditions	Hazard Initiation	Safety System Affected	Potential Effects	Level of Hazard	Method of Control
Cables in Head Access Area	At Power	Can of Cleaning Fluid	Control Rod System	Failure to Shut Down Reactor	Low--Cables are Fire Retardant and Rods will Drop Faster Than Fire can Disable Them	Fire Retardancy and Detection, Followed by Manual Suppression With Portable Extinguisher
Etc						

*Example based on References 5 and 6.

Hazard Inventory Method -- A hazard inventory analysis is similar to a preliminary fire-hazards analysis, except that in the inventory method an attempt is made to quantify levels of fire hazard and fire protection. Table 2 shows the format typically used. It can be seen from this table that the hazard inventory method quantitatively describes fuel loads and protective measures occurring in each fire zone. What the method lacks is a logical or calculational means of correlating the types and amounts of fuel in each zone with the numbers and kinds of selected detection and suppression measures. In practice, an analyst simply lists the fuel load and then states, without proof, that a certain combination of fire barriers, detection, and suppression will be adequate. Reference 7 illustrates the use of the hazard inventory technique.

Hazard Mode and Effects Analysis Method -- This technique is a refinement of the preliminary hazards analysis method discussed above, but still lacks mathematical rigor. Unlike a preliminary hazards analysis which views each fire zone as the basic element for study, a hazard mode and effects analysis often starts at a more detailed level with subsystems or components, as illustrated in Table 3. However, except for its depth of coverage, a hazard mode and effects analysis provides little fire protection information beyond that derived from a preliminary hazards analysis. This is because both methods lack the ability to quantitatively estimate fire hazards and fire protection effectiveness.

Deterministic Analyses

Unlike subjective analyses which base decisions on the judgment of the analyst, deterministic analyses base satisfactory levels of fire protection on testing and modeling of fire phenomena in terms of measurable parameters and physical theory. Typically, complications associated with characterizing fire initiation, growth, propagation, and extinguishment dictate the need for simplifying assumptions to approximate problem solutions. Often the degree of approximation and the level of complication are conflicting measures of the practical usefulness of a given model. If approximations are too crude, the resulting model may predict fire phenomena which are totally incredible. If, on the other hand, few

TABLE 2

Hazard Inventory Method

Fire Area/ Zone	Major Equipment	Material	Fire Hazard Quantity	Fuel Load (Btu)	Passive Detection	Suppression
1-B	Reactor Coolant Pump	Cable	55 ft^3	74.6×10^6	Smoke Detectors (4)	Sprinklers (0.2 gpm/ft^2),
		Grease	12 lb	0.23×10^6		Hose Stations (2)
		Oil	265 gal	150.7×10^6		

Etc

TABLE 3

Hazard Mode and Effect Analysis

Mode	Item	Subsystem	Function	Failure Mechanism	Effect Immediate/ Ultimate	Accident Conditions Required	Hazard Severity	Neutralization Measure
High Temperature	Instrument Panel	Pressurizing System	Maintain Plant Pressure	Indicate Incorrect Pressure	Overpressure or Underpressure	Fire in Nearby Equipment	Moderate: Backup Systems for Pressure Relief	Automatic Suppression

Etc

approximations are made, the resulting model may require very sophisticated computer calculations and a comprehensive data base to reach a solution.

Because of the need to combine ease of calculation with believability of results, most progress in the area of fire modeling has come from efforts to describe the effect of limiting fire severities on barriers, while attempts to characterize the mechanisms by which fires start, spread, and are extinguished, have been only marginally successful. This is understandable when one recognizes that minor variations in fuel type, fuel configuration, ventilation, and suppression system design can drastically affect the progress of a fire. Similar to the way in which a successful campfire depends on the initiating fire source (a match alone vs lighter fluid), the fuel arrangement (wood shavings vs a large log), and the fuel's fire retardancy (damp wood vs dry wood), minor variations from one room to the next and even variations within the same room can result in fire hazards ranging from innocuous to severe. Because of this difficulty, the approach most often applied to describe fire growth has been the use of scenario analyses which are deduced from a logical combination of test information and speculation.

The following sections describe examples of both the scenario analysis method for characterizing fire growth and the barrier analysis approach for defining limiting fire severities.

Scenario Analysis Method -- A scenario analysis may be viewed as a subjective analysis to which numbers have been added. For instance, an analyst simply may state in a subjective analysis that the size of a particular fire will be limited by its expected propagation rate and the response of a fire brigade. In a scenario analysis of the same situation, the analyst speculates what is believed to be a credible sequence of events for fire initiation, growth, and extinguishment and, at each juncture in the scenario, the analyst justifies subsequent fire events on the basis of related test data, calculations, or experience. It is this detailed justification that distinguishes scenario analyses from subjective analyses.

Numerous examples of the scenario technique applied to nuclear power plant situations are presented in Reference 8. As given there, a typical fire scenario may begin with a fire starting in one of two redundant cable trays in a particular plant location. By invoking test information on the propagation rate of fires burning along cable trays, the minimal cable tray separation distance to prevent propagation between trays, the response time of fire detectors, the effectiveness of available suppression schemes, and the safety importance of the cable trays involved, an analyst can ascertain whether a fire starting as described will jeopardize overall plant safety.

Unfortunately, germane test information rarely is available when developing a scenario, so it is necessary to make assumptions regarding the impact of any conditions which differ from those used during testing. These assumptions may involve differences in oxygen availability, fire retardancy, fuel configuration, initial fire size, detector arrangment, or suppression installation. Another uncertainty results from not knowing whether the assumed scenario is, in fact, conservative. Alternate scenarios can always be postulated which may or may not be more stringent than the original case.

Despite these drawbacks, a scenario analysis represents an improvement over a subjective analysis, since in the latter case fire protection conclusions are stated without reference to any technical bases except perhaps the experience of the analyst involved. On the other hand, a scenario analysis, as illustrated in Reference 9, provides a structured thought process in which the fire protection analyst states and technically defends all assumptions and conclusions. When used in conjunction with both deterministic and probabilistic data from closely related test cases, a scenario analysis provides the best mechanism for judging fire safety in those situations where total fire involvement cannot be tolerated (e.g., certain power plant control and cable spreading rooms). In cases where total fire involvement can be permitted (e.g., redundant areas separated by passive barriers), an attractive alternative to a scenario analysis would be to demonstrate barrier effectiveness under some limiting, worst-case fire conditions. This approach is discussed next.

Barrier Analysis Method -- In this report the term "barrier analysis" refers to analysis techniques which describe fire severity in terms of total involvement of combustibles in a room and in terms of total involvement effect on the room's structural integrity. Total involvement of combustibles, often referred to as flashover, has been recognized by numerous studies as the most severe condition for containing a fire.[10-20] Also, room flashover was considered by the National Bureau of Standards (NBS), as early as 1922, to be the design basis for judging barrier effectiveness.[12]

Out of this background have come two general approaches for predicting fire severity and its impact on barriers. One approach characterizes fire hazards as a function of fuel load, while the second defines fire hazards in terms of fuel load and available air for combustion. Each of these methods is discussed in the following sections.

Fuel Load Method. It seems logical that the more combustibles a room has, the more difficult it will be to contain a fire within that room. This reasoning forms the basis of the fuel load method for barrier analysis.

As described in Section 6, Chapter 8 of the National Fire Protection Association Handbook,[4] a fuel load analysis starts with adding up the weight of combustibles in a room and converting the weight to energy content of the fuel per unit floor area (e.g., Btu/ft^2). At this point, the measured fuel load is compared to a linear fire-duration scale in which a fuel load of 80,000 Btu/ft^2 corresponds to a fire of 1 hour's duration and a fuel load of zero corresponds to a fire of zero duration. On this basis, a measured fuel load of 240,000 Btu/ft^2 would be treated as a 3-h fire.

The linear scale relating fuel load to fire duration was first proposed by the NBS in 1928 and was prompted by an effort to preserve the usefulness of a time-temperature test curve for testing building materials in furnaces. The test curve which had been adopted 10 years earlier (in

1918) by the American Society for Testing Materials (ASTM) is still in use today.[2] To establish the relationship between the ASTM time-temperature curve and the linear time-fuel load curve, NBS conducted numerous full-scale burn tests using cellulosic combustibles. From these tests NBS concluded that a fuel load of 80,000 Btu/ft^2 will produce a fire as severe as a 1-h ASTM furnace test. By adopting this conclusion, it is assumed implicitly that the time-temperature history of an actual fire is of no consequence to structural integrity provided that the predicted fire duration, linearly calculated from the fuel load per unit area, does not exceed the time limit to which the structures were furnace tested. In other words, as long as the integrated, time-averaged temperature for the predicted fire is equal to the integrated, time-averaged temperature for the furnace test, both fire severities are assumed to be equal, regardless of actual fire duration. Figure 1 schematically illustrates this assumption.

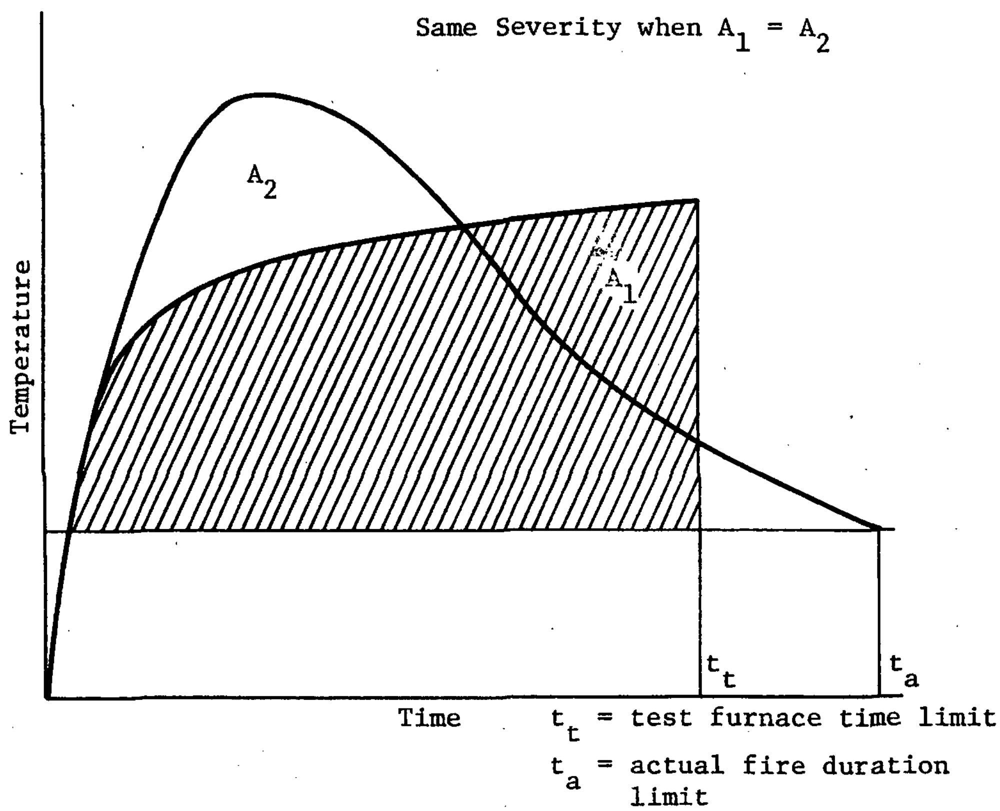

Figure 1. Illustration of Integrated Time-Temperature Curve Concept for Equating Fire Severities

The ease with which an analyst can convert a measured fuel load into a fire duration for purposes of selecting a standard, tested barrier has resulted in wide acceptance and use of the fuel load analysis method. Unfortunately, the method has a number of shortcomings which may render it inappropriate for nuclear power plant fire analysis.

1. The fuel load method ignores the effect of ventilation conditions on fire duration and intensity. When the linear scale relating fuel load to fire duration was developed by NBS, test conditions simulated offices and residences with open windows or doors to provide adequate air for combustion. Most safety areas of a nuclear plant have no direct openings to the outside and, therefore, the mechanisms by which air enters or heat leaves the fire zone differ from those originally tested.

2. The fuel load method ignores the detrimental effect which hot, short fires may have on structures. By using an integrated, time-averaged temperature, the fuel load method equates hot, short fires to cooler, long-lasting ones. Since structural steel and concrete have maximum temperature limits beyond which degradation of strength is accelerated,[21 22] it may be incorrect to equate fires on the basis of average temperatures, especially in those cases where an actual fire reaches temperatures above the standard ASTM furnace time-temperature test curve.

3. The fuel load method ignores the effect of different types of combustibles on fire severity. Since different combustibles burn at different rates whenever sufficient air is present (Reference 4, Section 6), the rate of heat release during a fire can vary depending on what is burning. The linear scale developed by NBS relating fire duration to fire load was based on tests

using cellulosic combustibles. Other materials, such as the cable insulation and oil found in nuclear power plants, can be expected to burn differently than cellulosics. Whenever a lack of sufficient air for combustion limits the rate of burning, differences between combustibles become less significant. However, as explained in item 1 (above), the situation of ventilation-limited fires was not addressed in the NBS testing.

From the above findings for this study, it was concluded that the fuel load method for analyzing the adequacy of fire barriers lacks the technical bases and conservatism needed for nuclear power plant application. Although the method is simple, the results lack credibility.

Fuel Load and Ventilation Method. The fuel load analysis method discussed in the previous section treated fire severity as a one-parameter problem--fuel load. Since simple fireplace drafts and dampers demonstrate the influence of ventilation on fire severity, it is reasonable to view limiting fire phenomena in terms of two parameters--fuel load and ventilation. Recognizing this, many fire protection researchers have attempted to measure or model the interrela-tionships between fuel load, ventilation, and fire severity.[10-20] Those efforts which have proven most productive have taken cognizance of the following facts.

- Fully developed fires burn at limiting rates determined by either (1) the kinetic limitations of combustion which are functions of the available fuel surface area (i.e., surface-controlled burning) or (2) the limitations of available oxygen for combustion (i.e., ventilation-controlled burning).

- Total involvement of the combustibles in a room (i.e., after flashover) represents the most severe condition for containing a fire with barriers.

- The time-temperature history of fire in a room must satisfy basic laws of physics which equate the rate of heat evolution to the rate of heat loss.

After applying these facts, a number of researchers found that fire severities differed significantly from those predicted by the one-parameter fuel-load analysis method.[10 12 15 16 20 23] This is not surprising since the addition of ventilation more closely approximates real fire phenomena. Unfortunately, most of the combined fuel load and ventilation analysis techniques developed to date have several major deficiencies which make them unattractive for nuclear power plant fire use.

- Most of the techniques are cumbersome. An analyst often has to apply first principles of fluid dynamics and heat transfer to solve a particular problem.

- Many of the techniques treat ventilation limitations for cases involving doors or windows which vent directly to the outside. Situations involving forced ventilation systems, rooms without windows, or doors connected to hallways are rarely treated. These factors can limit both the rate of combustion and the rate at which heat is removed from a room.

- Few of the techniques relate predicted fire severity to the conditions under which barriers are tested. As a result, an analyst must judge what combinations of fuel load and ventilation are acceptable for a given barrier.

In light of these deficiencies, it may appear that, although the addition of ventilation technically improves the one-parameter fuel load analysis technique, the improvement lacks practicality. To some extent this conclusion is correct. However, under the "Most Suitable Analysis" and "Example Fire Hazards" sections, we will demonstrate that a two-parameter barrier analysis method can be devised from available analysis techniques, can be defended both technically and conservatively, and can be easily implemented by both designers and regulators.

Probabilistic Analyses

Unlike subjective and deterministic analysis methods which describe and interpret each fire event in physical terms, probabilistic analyses make no effort to define numerically the temperatures, burn rates, ventilation limits, suppressant concentrations, or any other parameters characteristic of a fire. Instead, a probabilistic analysis establishes satisfactory levels of fire protection on the basis of various forms of graphs or logic charts which describe fire events in terms of their probability of occurrence. The probability values used are typically derived from historical data or by consensus.

There have been a number of different approaches to probabilistic fire analysis, ranging from complicated methods which employ detailed logic diagrams to less complicated methods which reduce fire event probabilistics to a few general categories. Similar to the deterministic-hazards analysis methods just discussed, the degree of simplification and level of credibility associated with probabilistic analyses often are conflicting measures of a particular method's usefulness. This point can be illustrated by a review of several probabilistic analysis examples.

Statistical Method -- This method has been applied for years by insurance underwriters. In practice, a fire-hazards analyst reviews statistical data regarding the probability of fire occurrence and the effectiveness of fire control measures under various conditions of fuel type, fuel arrangement, structural design, suppression availability, and detection system installation. The analyst then subjectively applies the statistical data base to the particular fire-hazard conditions under consideration.

For purposes of insuring against property losses, the statistical method strikes an ideal balance between degree of simplification and level of credibility. With relative ease, an analyst can statistically support trade-offs between the level of fire risk and the cost of insurance. Unfortunately, fire protection measures which have proven statistically satisfactory for monetary and life safety insurance objectives may be inadequate for meeting nuclear power plant safety goals.

National Fire Protection Association Decision Tree -- This approach is presented in Section 6, Chapter 2 of the NFPA Handbook[4] and shown in Figure 2. The method views fire events in a logical sequence leading to a predefined fire objective for life safety and property protection. To identify a suitable objective, the analyst must ask a number of questions regarding the replacement value of the property and the wishes of the property owner. Once a suitable safety objective has been established to the satisfaction of the analyst and property owner, the NFPA decision tree is used to analyze a logical set of fire events leading to the safety objective. At junctures where an event may or may not occur (e.g., automatically suppress fire), the analyst subjectively estimates the probability of the event occurring. These estimates are usually derived from the analyst's experience or knowledge of probability data from related historical events.

In comparison to the loosely defined Statistical Method discussed above, the NFPA decision tree represents an improvement in the overall logic used to perform probabilistic analyses. As a result, fire protection decisions based on the NFPA decision tree are more credible, although the decision-tree methodology is somewhat more tedious. However, because subjective judgments are needed to define the suitability of each safety objective and to establish the probability of each fire event occurring, a NFPA decision-tree analysis conclusion may vary from liberal to conservative, depending on the experience of the analyst and the wishes of the property owner. Such variances are undesirable for nuclear power plant fire-hazards analysis.

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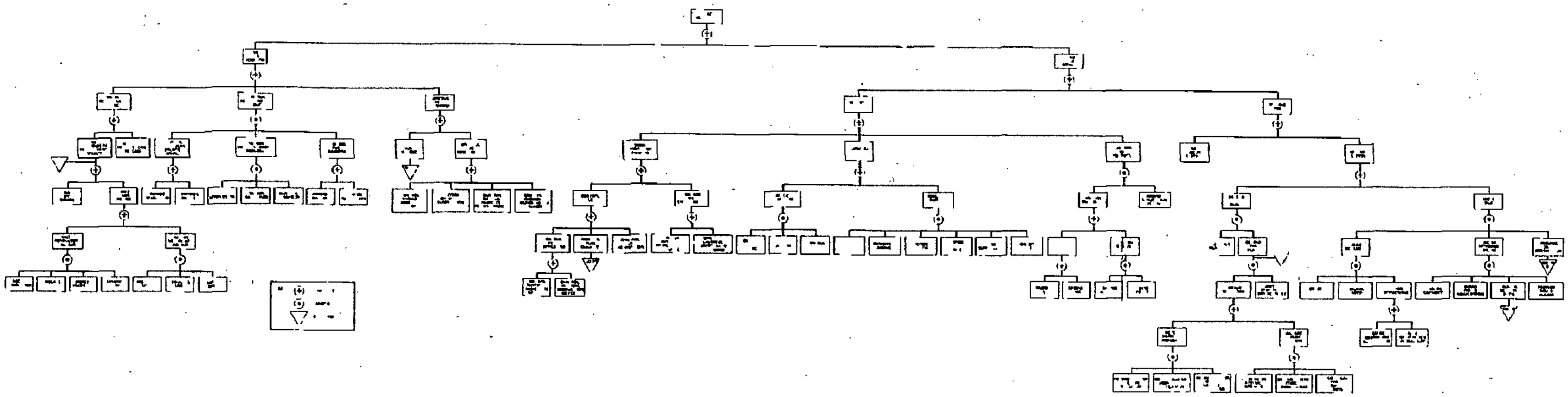


Figure 2 National Fire Protection Association Decision Tree

General Services Administration (GSA) Decision Trees -- Similar to the NFPA method just discussed, GSA decision trees use a logic network to define events leading to a predefined safety objective but, unlike the NFPA approach, the GSA technique predefines the probability values to be used at junctures in the decision tree. The GSA probability values originally were established by the consensus of several GSA fire protection consultants through their combined knowledge of the fire event probabilities. By applying these established probabilities and by following the logic of several generic GSA decision trees, an analyst can develop a probability chart, similar to the one shown in Figure 3, to reflect the progressively lower probability associated with increasing fire severity. If the probability of a particular fire severity is judged by the analyst or property owner to be unacceptable, steps are taken to upgrade overall fire safety by improving selected portions of the fire protection system (e.g., increased detection, reduced fire load, or improved separation). Reference 24 presents an example of the GSA-analysis method.

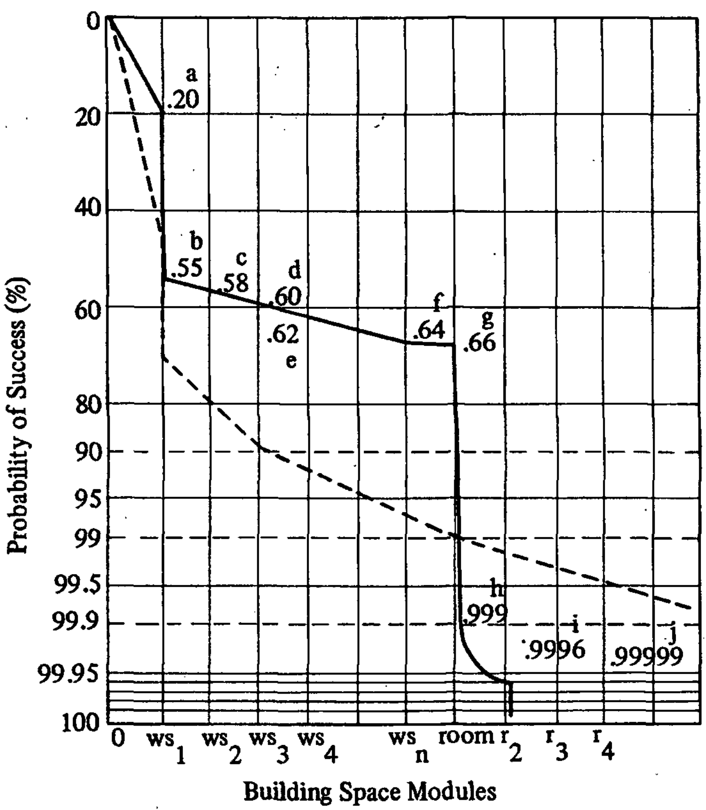


Figure 3. GSA Probability Chart for Fire Development Within a Building

Since GSA logic trees are more complicated than the NFPA decision tree shown in Figure 2 and since the GSA method would require the development of a probability chart for each nuclear power plant safety area and each fire protection system combination, it appears that the practical usefulness of the GSA methodology for nuclear power plant design and regulation is marginal, at best. When this is combined with questions concerning the validity of the established probability values and the acceptability of chosen safety objectives, it appears doubtful whether the sophistication of the GSA technique is warranted.

Fault Tree Analyses -- Fault tree analyses differ from NFPA and GSA decision trees primarily in terms of detail level and scope of coverage. Instead of viewing only fire events, fault tree analyses consider detailed component and system interactions from the standpoint of both fire occurrences and resulting safety system responses. Each fault tree is specific for a given set of power plant arrangements and safety system functions. As a result, considerable analysis effort is needed to carry out a comprehensive fault tree analysis of each nuclear power plant safety area. Figure 4 presents a portion of a fire-hazards analysis fault tree developed for the Clinch River Breeder Reactor Plant Risk Assessment.[25] From this figure, it is apparent that a large number of other safety-area fault trees could be devised, each requiring the analyst to have a thorough knowledge of fire event probabilities and safety system limitations.

Although a fault tree fire-hazards analysis would be based on proven methodology[26] and would be technically defendable, it is doubtful whether designers and regulators would consider the technique simple. For this reason, it was decided to reject fire-analysis fault trees as viable analysis alternatives for nuclear power plant design. This conclusion does not exclude the use of fault trees as part of a generic evaluation of fire protection in nuclear power plants. As indicated under "Study Description," a generic analysis would be useful in establishing what levels of fire protection adequately reduce nuclear power plant fire risk to acceptable levels for overall plant safety. Since an evaluation of overall fire risk lies outside the scope of this report, further consideration of fault trees is inappropriate here.

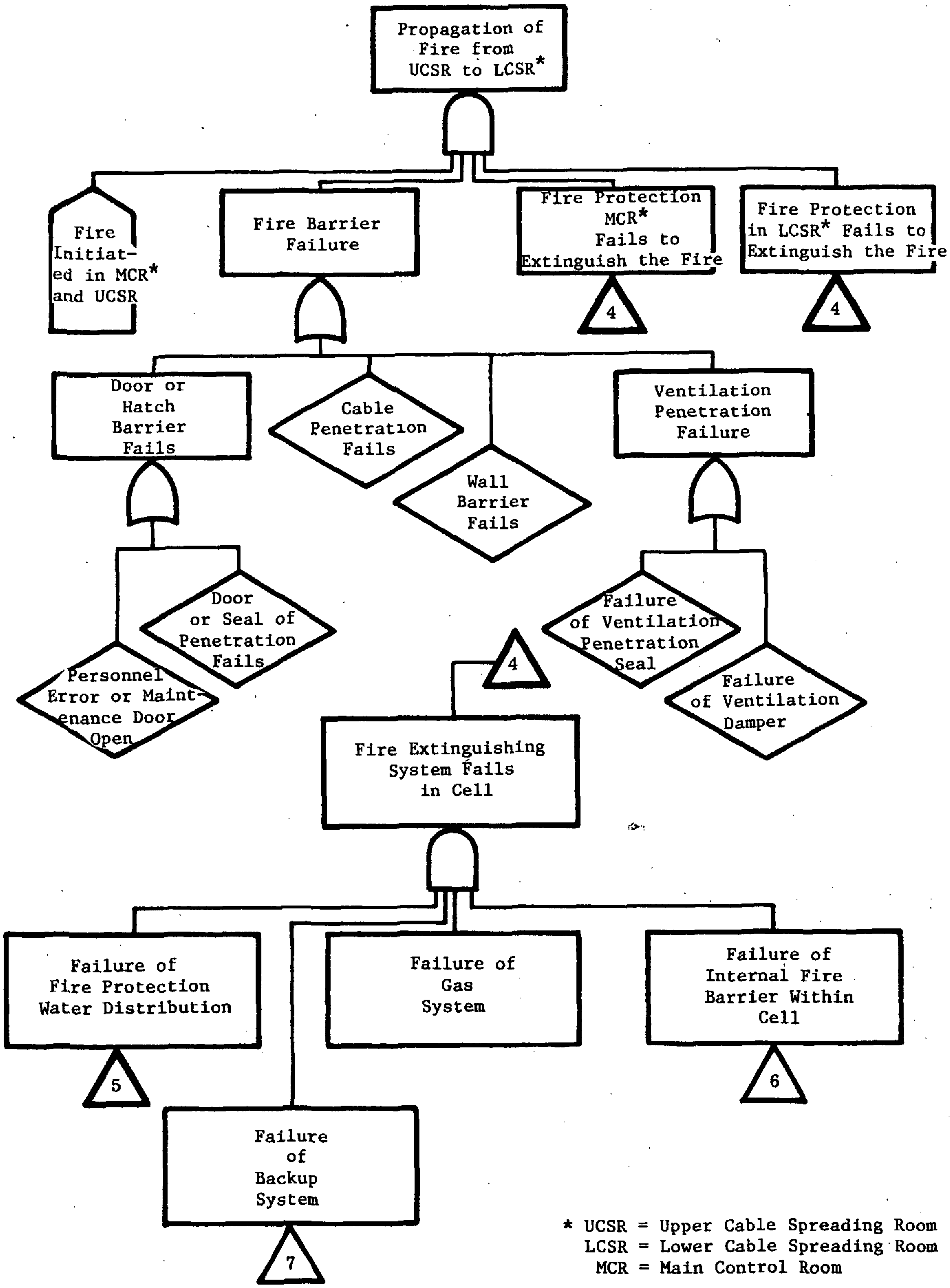


Figure 4. Typical Branches of a Fire-Hazards Analysis Fault Tree

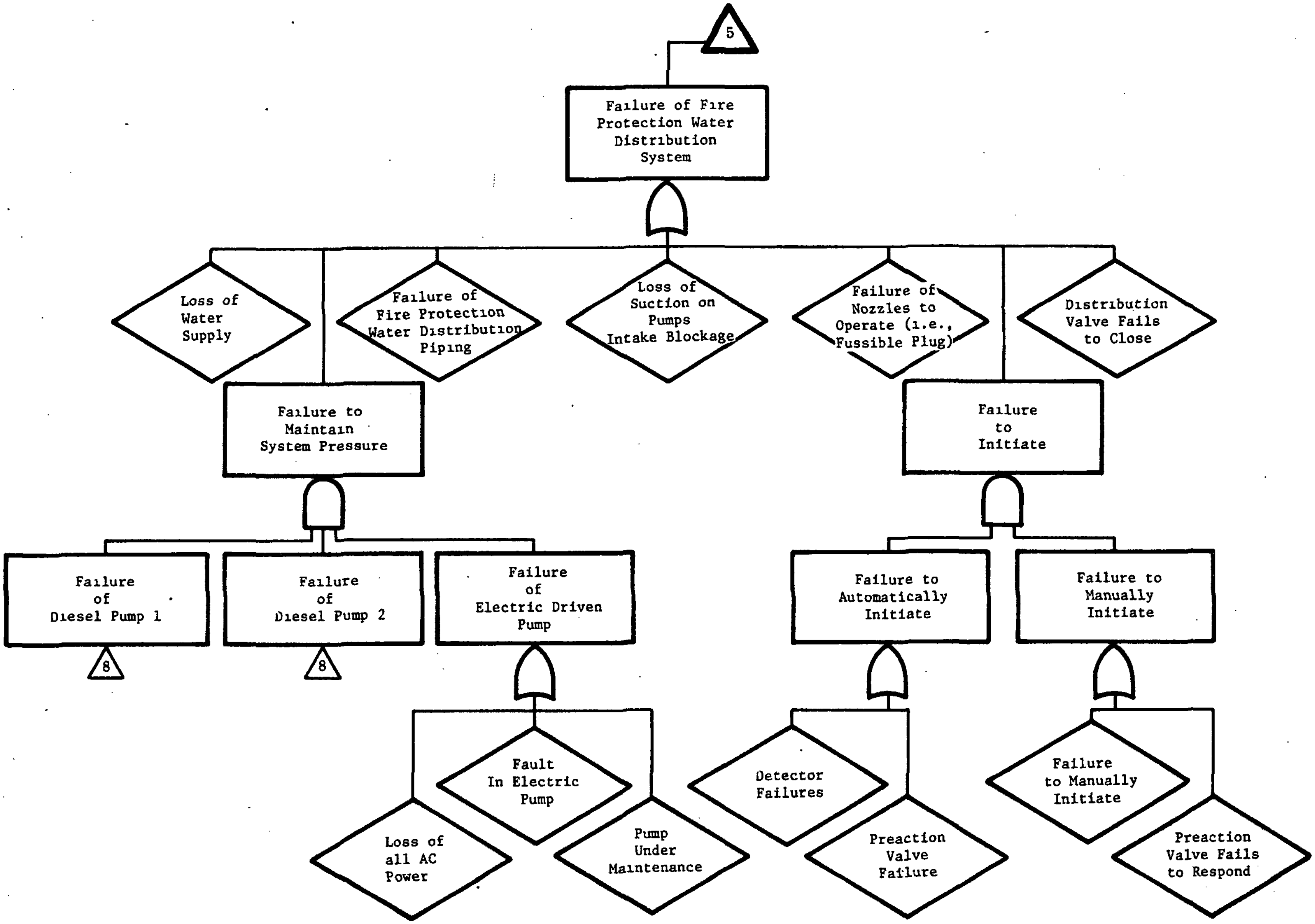


Figure 4. (Concluded)

3. Most Suitable Analysis Method

Under "Study Description" we listed three criteria for selecting a fire-hazards analysis technique for nuclear power plant application. To ascertain whether any presently available analysis methods can satisfy all three of these criteria, in Section 2 we reviewed examples of three categories of analysis; no single analysis approach appeared to meet the criteria. In all cases, those analyses which seemed technically sound proved to be difficult to apply, while those which seemed readily implemented lacked technical conservatism. Because of this, it was decided that the most suitable analysis method for nuclear power plant use would be one which combines the best attributes of several complementing analysis techniques.

Of the three criteria listed in "Study Description" for selecting an analysis method, the most important from the standpoint of public safety requires that the analysis be defendable in terms of conservatism and technical basis. If a combination of available analysis techniques can be shown as conservative and technically sound, the only remaining task is to simplify use of the techniques. Accordingly, the approach of (1) combining available techniques, (2) demonstrating their technical merit, and (3) simplifying their application was selected for this study as the most logical sequence to arrive at a straightforward yet credible analysis method.

Combining Available Analysis Techniques

The categories of analysis addressed in Section 2 were termed subjective, deterministic, and probabilistic. Deterministic analyses are those which describe fire events in physical terms (e.g., burn rates, temperatures, air requirements), while probabilistic analyses are those which describe fire events in terms of their chance of occurrence. To some extent, subjective analyses can be viewed as a combination of deterministic and probabilistic analyses, wherein an analyst judges both the expected physical severity of a fire and the probability that available fire protection measures will be adequate. Unlike most of the deterministic and probabilistic methods shown in Section 2, however, subjective analyses typically require no empirical or analytical justification for the conclusions reached by the analyst, and therefore it is difficult to demonstrate the technical merit of a subjective analysis. Similarly, it is often difficult to demonstrate the degree of conservatism and basis for many deterministic or probabilistic analysis decisions, primarily because of incomplete supporting data.

One way to circumvent this problem is through the use of a deterministic analysis to place a conservative upper limit on fire severity in each safety area of a nuclear power plant. If such bounding conditions are found to be acceptable to overall plant safety, further analysis is unwarranted. If, however, plant safety is found to be jeopardized under the bounding conditions, a probabilistic analysis would be needed to account for supplementary fire protection measures not considered deterministically. Only in those cases where a lack of theoretical or empirical information precludes the use of either a deterministic or probabilistic analysis should it be necessary to base fire safety conclusions solely on the subjective judgment of a fire protection analyst. Figure 5 schematically shows the resulting relationship between the three analysis categories.

To carry out a fire-hazards analysis according to Figure 5, a technically defendable and easily executable combination of deterministic, probabilistic, and subjective analysis methods must be specified. To do this, candidate analysis methods can be chosen from those reviewed in Section 2 by selecting a method from each analysis category which combines technical merit with the least complexity. Candidates selected on this basis are presented next.

Deterministic Analysis Candidate -- For this category, a barrier analysis technique using conservative assumptions for fuel load and ventilation appears most promising. This is because simpler deterministic techniques, such as scenario analyses or fuel load barrier analyses, cannot be easily demonstrated as conservative. Also, other more complicated analysis methods which attempt to describe the mechanisms by which fires start, propagate, and are extinguished have been only marginally successful.

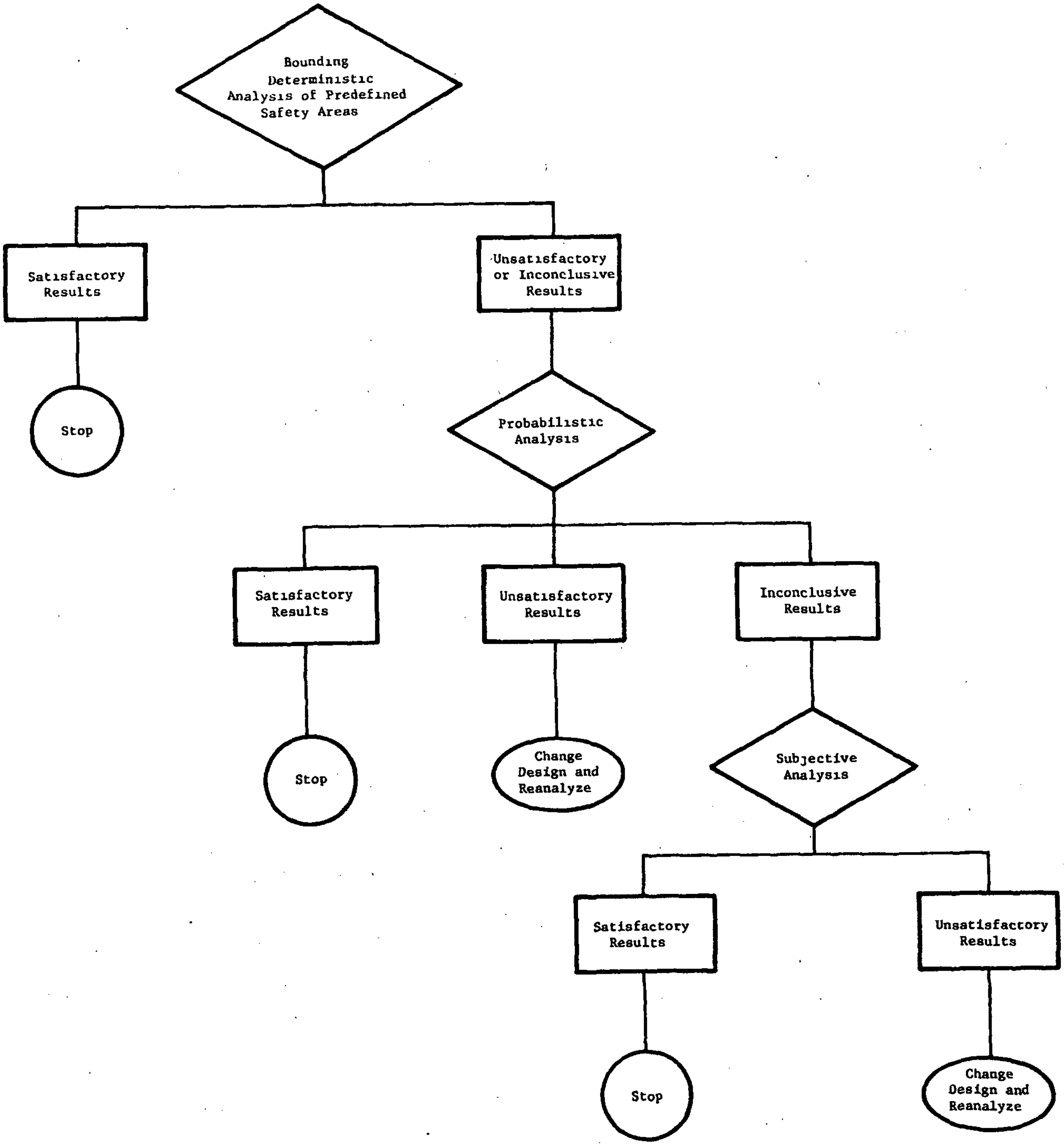


Figure 5. Analysis Sequence for Each Nuclear Power Plant Safety Area

Probabilistic Analysis Candidate -- For this category, an analysis technique which combines the numerical rigor of the GSA decision trees with a simpler logic format appears most practical. Less complicated methods, such as statistical analyses or NFPA decision trees, are not well enough defined in terms of either format or numbers to be consistently applied by power plant designers or regulators. On the other hand, fault-tree analyses require an extreme level of detail which cannot be justified in view of the meager statistical base available.

Subjective Analysis Candidate -- As presented in Section 2, subjective analyses constitute all techniques which rely solely on the experience and judgment of a fire protection analyst. Because it is difficult to justify the adequacy of this approach, the analysis sequence shown in Figure 5 has relegated subjective analyses to a position following both deterministic and probabilistic analyses and, therefore, subjective analyses come into play only when deterministic and probabilistic methods prove inadequate.

In this context, subjective analyses still have some value in defining problems such as monetary risk, but their value to nuclear safety is limited to case-by-case assessments. Because of this limitation, a complicated subjective analysis format is unjustified. Instead, a more reasonable approach would be to allow an analyst to recommend fire protection measures on the basis of a qualitative fire scenario. The fire scenario could be developed in a conservative manner dictated by a predefined analysis outline such as the type discussed in Section 2. By proceeding in this way, the analyst will be forced to document the basis for each fire protection decision in a manner which can be scrutinized by nuclear safety regulators.

The Technical Merit of Candidate Analysis Techniques

Figure 5 presented a proposed sequence for carrying out a nuclear power plant fire-hazards analysis in a way which, by being technically conservative and easily executed, emphasizes the best attributes of three complementary analysis categories. We then presented what appeared to be the most promising analysis technique for each of the three analysis categories:

Analysis Category	Candidate Technique
Deterministic Analysis	Barrier analysis using conservative limits for fuel load and ventilation
Probabilistic Analysis	Decision tree analysis applying the numerical rigor of GSA decision trees in a more simplified format
Subjective Analysis	Qualitative fire scenario analysis following a pre-scribed analysis outline

According to the criteria established in this report for assessing the viability of a fire-hazards analysis, the technical merit of any candidate analysis technique should be demonstrated in terms of its conservatism and technical basis. The following sections will demonstrate this for the three analysis candidates.

Fuel Load and Ventilation Barrier Analysis Method -- On the basis of considerable fire research,[10-20] it is more realistic to view fire phenomena in terms of two parameters, fuel load and ventilation, rather than to use only fuel load. Furthermore, as has been mentioned, total involvement of combustibles in a room (after flashover) represents the most severe condition for containing a fire with barriers; the actual level of post-flashover severity is a function of either fuel-surface-controlled burning or ventilation-controlled burning. Mathematically these facts can be expressed in general terms as follows:

Rate of heat buildup in a room = Rate of heat produced by the fire - Rate of heat lost from the room (1)

To solve this equation, a number of assumptions and physical theories must be cited to formulate each term in the equation. Since this has been done in many publications,[10-20] only the resulting expressions and underlying assumptions will be presented in this report.

First Term

$$\text{Rate of heat buildup in a room} = \rho_f V Cp_f \frac{\partial T_f}{\partial t}$$

where

ρ_f = density of fire gases in the room

Cp_f = heat capacity of fire gases in the room

T_f = temperature of gases in the room

t = time

V = volume of the room.

Second Term

Rate of heat produced by the fire = $R_p \Delta H_c$ for surface-controlled burning,

where

R_p = Rate of pyrolysis when combustion is limited by combustion kinetics of the fuel surface

ΔH_c = Net heat release upon fuel combustion,

or

Rate of heat produced by the fire = $M_{air} r \Delta H_C$ for ventilation-controlled burning

where

M_{air} = rate of air entering the room for combustion

r = stoichiometric mass ratio of fuel to air for combustion.

Third Term

Rate of heat lost from the room = Heat lost by radiation to walls + Heat lost by convection to walls + Heat lost through openings by radiation

+ Heat lost through openings by mass flow

$$\text{Heat lost by radiation to walls} = \frac{\sigma A_w \left(T_f^4 - Tw_i^4\right)}{\left(\frac{1}{\epsilon_f} + \frac{1}{\epsilon_w} - 1\right)}$$

where

σ = Stefan-Boltzmann constant

A_w = area of the walls

Tw_i = wall inside surface temperature

ϵ_f = emissivity of the fire gases

ϵ_w = emissivity of the wall.

$$\text{Heat lost by convection to walls} = UA_w(T_f - Tw_i) \quad ,$$

where

U = convective heat transfer coefficient..

$$\text{Heat lost through openings by radiation} = \frac{\sigma A_o \left(T_f^4 - T_o^4\right)}{\left(\frac{1}{\epsilon_f} + \frac{1}{\epsilon_w} - 1\right)}$$

where

A_o = area of the opening

T_o = air temperature outside the room

ϵ_o = emissivity of the air outside the room.

Heat lost through openings by mass flow $= M_f Cp_f T_f - M_{air} Cp_a T_o$,

where

M_f = rate of fire gases leaving the room

Cp_a = heat capacity of air outside the room.

Substituting these terms into Eq. (1) yields:

$$\rho_f V Cp_f \frac{\partial T_f}{\partial t} = \left\{ \begin{array}{l} R_p \Delta H_C \text{ (for surface-controlled burning)} \\ \text{or} \\ M_{air} r \Delta H_C \text{ (for ventilation-controlled burning)} \end{array} \right\}$$

$$- \frac{\sigma A_w \left(T_f^4 - Tw_i^4 \right)}{\left(\frac{1}{\epsilon_f} + \frac{1}{\epsilon_w} - 1 \right)} - UA_w (T_f - Tw_i) - \frac{\sigma A_o \left(T_f^4 - T_o^4 \right)}{\left(\frac{1}{\epsilon_f} + \frac{1}{\epsilon_w} - 1 \right)}$$

$$- M_f Cp_f T_f + M_{air} Cp_a T_o \qquad (2)$$

Assuming that numerical values or functional relationships can be found for all the physical parameters in Eq. (2), six undefined variables remain: T_f, R_p, M_{air}, Tw_i, T_o, and M_f. This implies that five more expressions beyond Eq. (2) are needed. If T_o is assumed to be known and constant in any particular problem and if R_p is known from experimental information, only three more expressions are required to relate T_f, M_{air}, Tw_i, and M_f.

One relation is the following unsteady-state heat flow equation written for the room walls:

$$\rho_w Cp_w \frac{\partial Tw}{\partial t} = \frac{\partial}{\partial x}\left(k_w \frac{\partial Tw}{\partial x}\right) \quad , \tag{3}$$

With the boundary conditions

$$T_w(x,0) = T_o$$

$$-k_w \frac{\partial Tw_i}{\partial x} = U(T_f - Tw_i) + \frac{\sigma\left(T_f^4 - Tw_i^4\right)}{\left(\frac{1}{\epsilon_f} + \frac{1}{\epsilon_w} - 1\right)}$$

$$-k_w \frac{\partial Tw_o}{\partial x} = U(Tw_o - T_o) + \frac{\sigma\left(T_w^4 - T_o^4\right)}{\left(\frac{1}{\epsilon_w} + \frac{1}{\epsilon_o} - 1\right)} \quad ,$$

where

ρ_w = density of the wall

Cp_w = heat capacity of the wall

T_w = temperature at any time, t, or distance, x, within the wall

Tw_o = outside wall temperature

k_w = thermal conductivity of the wall

A second relation is the following steady-state mass balance on the room:

$$\left\{\begin{matrix} R_p \text{ for surface controlled burning} \\ \text{or} \\ M_{air} r \text{ for ventilation-controlled burning} \end{matrix}\right\} = M_f - M_{air} \qquad (4)$$

The third and final relationship needed for T_f, M_{air}, Tw_i, and M_f describes M_{air} in terms of the physical characteristics of the room under consideration. Obviously, in a room having shut openings with only forced ventilation airflow, M_{air} is simply the ventilation system flow rate. On the other hand, if airflow into the room results from natural convection through openings, M_{air} must be related to the gas temperature in the room through buoyancy and fluid dynamic expressions. This has been done in Reference 27 to yield the following expression:

$$M_{air} = \left(A_o\sqrt{h_o}\right)^{2/3} C_d \sqrt{2g}\ \rho_o \left\{ \frac{1 - \frac{\rho_f}{\rho_o}}{\left[1 + \left(\frac{\rho_o(1 + r)^2}{\rho_f}\right)^{1/3}\right]^3} \right\}^{1/2} \qquad (5)$$

where

h_o = the length of the opening

C_d = fluid dynamic discharge coefficient (0.68)

g = gravity acceleration

ρ_o = density of entering air

By solving Eqs. (2) through (5) simultaneously, it is possible to find the temperature of fire gases in a room as a function of time for specified room dimensions, fuel characteristics, wall construction, and air and gas properties. In practice, a solution is found only after a number of simplifying assumptions have been made which are shown as conservative and technically sound. Assumptions typically involved are

1. The temperature, T_f, of the hot gases within a burning room is assumed to be uniform with no spatial variations. This assumption is based on observations that postflashover fire conditions are characterized by large-scale turbulence which mixes hot gases to the point of neutralizing temperature gradients.[15-17 23 27] Except where cool air is being drawn into the combustion zone in the immediate vicinity of the floor, T_f can be assumed as independent of horizontal or vertical displacement.

2. The heat capacity, density, and thermal conductivity of the walls are assumed functions of temperature only and not functions of distance inside the wall. This means that the wall can be represented as a homogeneous slab.[28]

3. The heat capacity and density of the fire gases inside and leaving the room are assumed the same as those for air under the same temperature conditions. This assumption is prompted by a lack of information regarding the exact composition of the fire gases. If it is recognized that 79% of air entering a combustion zone leaves as uncharged nitrogen and that the density and specific heat of flue gases are comparable to air at the same temperature and pressure conditions, the validity of this assumption is justified.[29]

With these assumptions and some experimental values for H_c, R_p, ϵ_f, ϵ_w, and U, Eqs. (2) through (5) can be solved with the aid of a computer. This has been done in References 15, 23, and 27 for a number of cases involving combustible loadings, ventilation conditions, and construction materials characteristic of residential and commercial buildings. For nuclear power plants, similar calculations can be carried out by selecting physical parameters representative of power plant conditions. However, for a nuclear power plant barrier analysis to be conservative, additional adjustments to the governing equations, beyond those involving physical parameters, must be made.

In typical residential and commercial buildings, windows and doors provide direct openings between a burning room and the outside environment. As a result, heat is lost from a burning room through the radiation and convection of heat from hot gases within and leaving the room and by the introduction of cool air into the room. These heat loss mechanisms prompted the inclusion of the following terms in Eq. (2):

$$+ M_{air} Cp_a T_o \quad \text{(cool air)}, \quad - M_f Cp_f T_f \quad \text{(flow heat loss)}, \quad \text{and} \quad - \frac{\sigma A_o \left(T_f^4 - T_o^4\right)}{\left(\frac{1}{\epsilon_f} + \frac{1}{\epsilon_o} - 1\right)} \quad \text{(opening radiation heat loss)}$$

Nuclear power plant safety areas usually have no windows or doors opening to the outside. Instead, safety areas connect to a maze of hallways and stairways which may lead to other internal plant areas before reaching the outside. Because this situation has not been modeled generically, it is difficult to predict how closely it approximates cases where windows and doors open directly outside. What can be stated is that less heat will be lost from the nuclear power plant area than predicted by Eq. (2). Since the amount of actual heat loss reduction cannot be readily predicted, a conservative approach is to assume that no heat is lost from the fire area by the entrance of cool air, by radiation outward through openings, or by outflow of hot gases. This is equivalent to saying that heat is lost only through convection and radiation into the walls of the room.

For the above assumption to be conservative, a second assumption must be made relating to the effect of internal partitioning on airflow to the fire zone. Although it is conservative to consider that a lack of doors and windows will hamper heat loss from a fire area, it is not conservative to assume that a lack of direct openings to the outside will reduce burning rates by limiting airflow. Accordingly, for purposes of calculating airflow to a nuclear power plant fire, assume that all openings lead directly to the outside.

Figure 6 presents a ranking of the overall conservatism inherent in a fuel load and ventilation barrier analysis that incorporates the above assumptions for heat loss and air inflow. Such an approach will be conservative and will approximate actual fire severities more closely than either instantaneous or surface-controlled burn rate analyses which are more conservative, but less realistic. Obviously, as ventilation rates approach surface-controlled burning limitations, the distinction between the surface-controlled burning and ventilation-controlled burning disappears. It should also be recognized that, if a nuclear power plant ventilation scheme can be shown capable of removing a specified amount of heat during a fire, such a scheme would warrant reduced conservatism in the fuel load and ventilation barrier analysis model. These points will be taken up again under "Simplifying the Candidate Analysis Techniques."

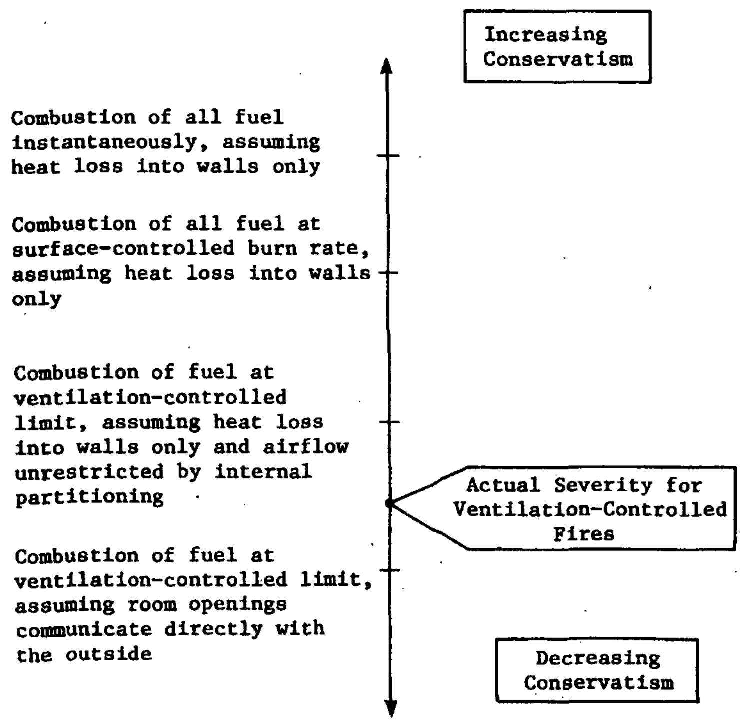


Figure 6. Comparison of Models for Assessing Fire Severity in Nuclear Power Plants

As part of this study, fire severity calculations were made for several representative nuclear power plant safety areas using the fuel load and ventilation barrier analysis technique just discussed. A computer program,[27 30] originally developed for residential and commercial application, was used to make the calculations; however, it was modified to limit heat losses to only radiative and convective heat removal by the walls of a burning room. It was found from the calculations that a wide range of fire severities (as characterized by time-temperature fire histories) can be predicted, depending upon fuel load, ventilation availability, and heat loss wall area. Unfortunately, the significance of the predicted severities and the usefulness of this computer program are both dubious for nuclear power plant designers and regulators. In particular, the following questions must be resolved:

- How can different fuel loads, ventilation rates, and room configurations be related to fire severity for easy application by designers and regulators?

- What criteria should be used to ascertain whether a conservatively predicted time-temperature fire history is acceptable from the standpoint of barrier integrity?

These two questions are addressed later in the context of simplifying the fuel load and ventilation barrier analysis method for nuclear power plant application. Before this is done, however, the technical merit of the candidate probabilistic and subjective analyses will be demonstrated.

Modified Decision-Tree Analysis Method -- In those instances where a fuel load and ventilation barrier analysis proves inconclusive or predicts barriers alone to be inadequate, Figure 5 suggests that a probabilistic analysis should be done to ascertain whether other supplementary fire protection measures will meet fire safety objectives. The review of existing probabilistic analysis methods in Section 2 was the basis for a conclusion that an analysis technique which combines the numerical rigor of the GSA decision tree with a more simplified logic format appears most promising.

One analysis method which does this was proposed in 1976 at the annual meeting of the Society of Fire Protection Engineers by John Campbell and Bert Cohn from the firm of Gage-Babcock & Associates, Inc. The proposed technique is called a critical-path technique and is shown schematically in Figure 7. In principle, the critical-path method follows a fire event from initiation to the point at which the fire is either extinguished or breaches the barrier surrounding the fire area being analyzed.

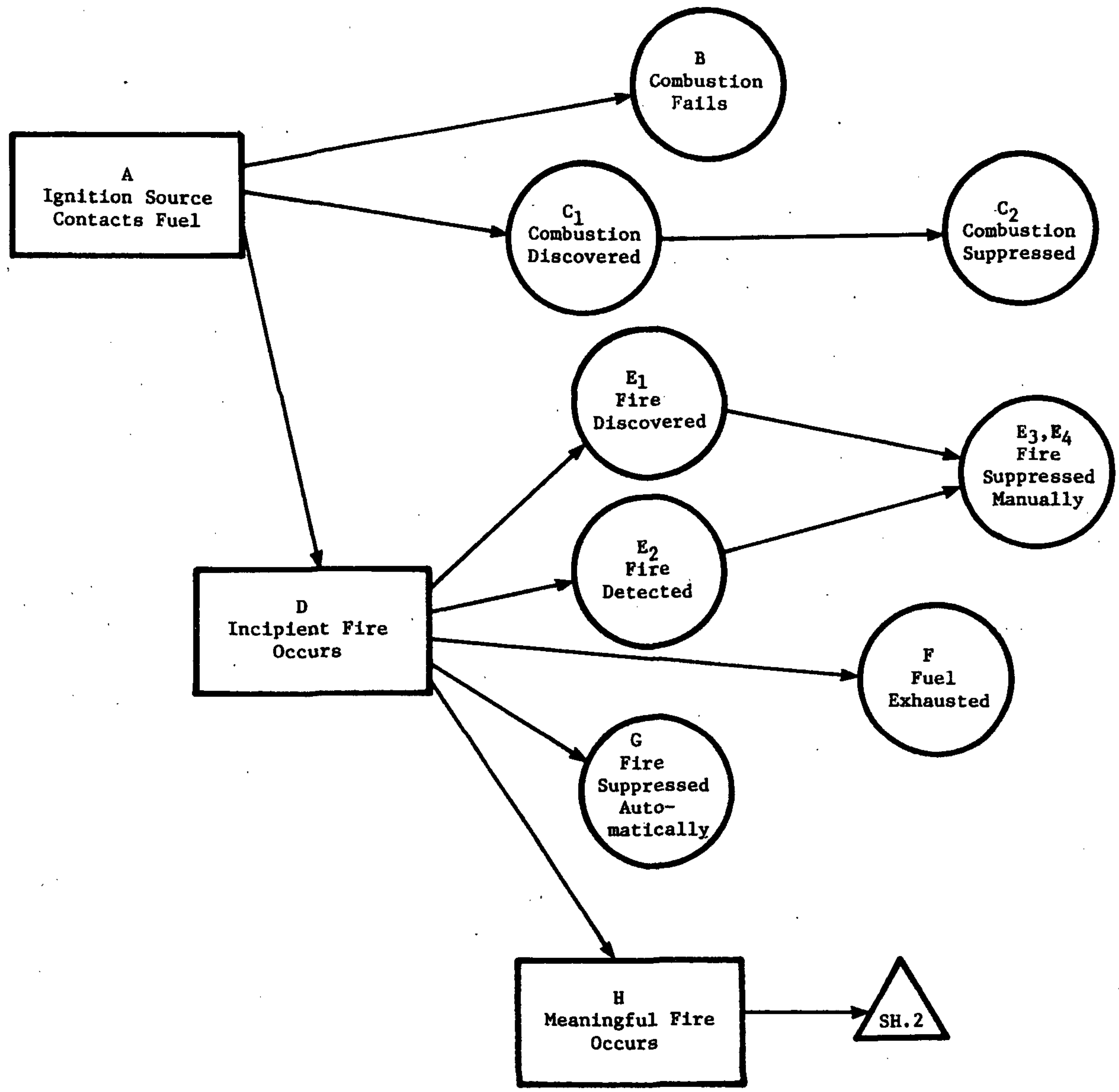


Figure 7. Critical Path Diagram for Fire Development in a Building

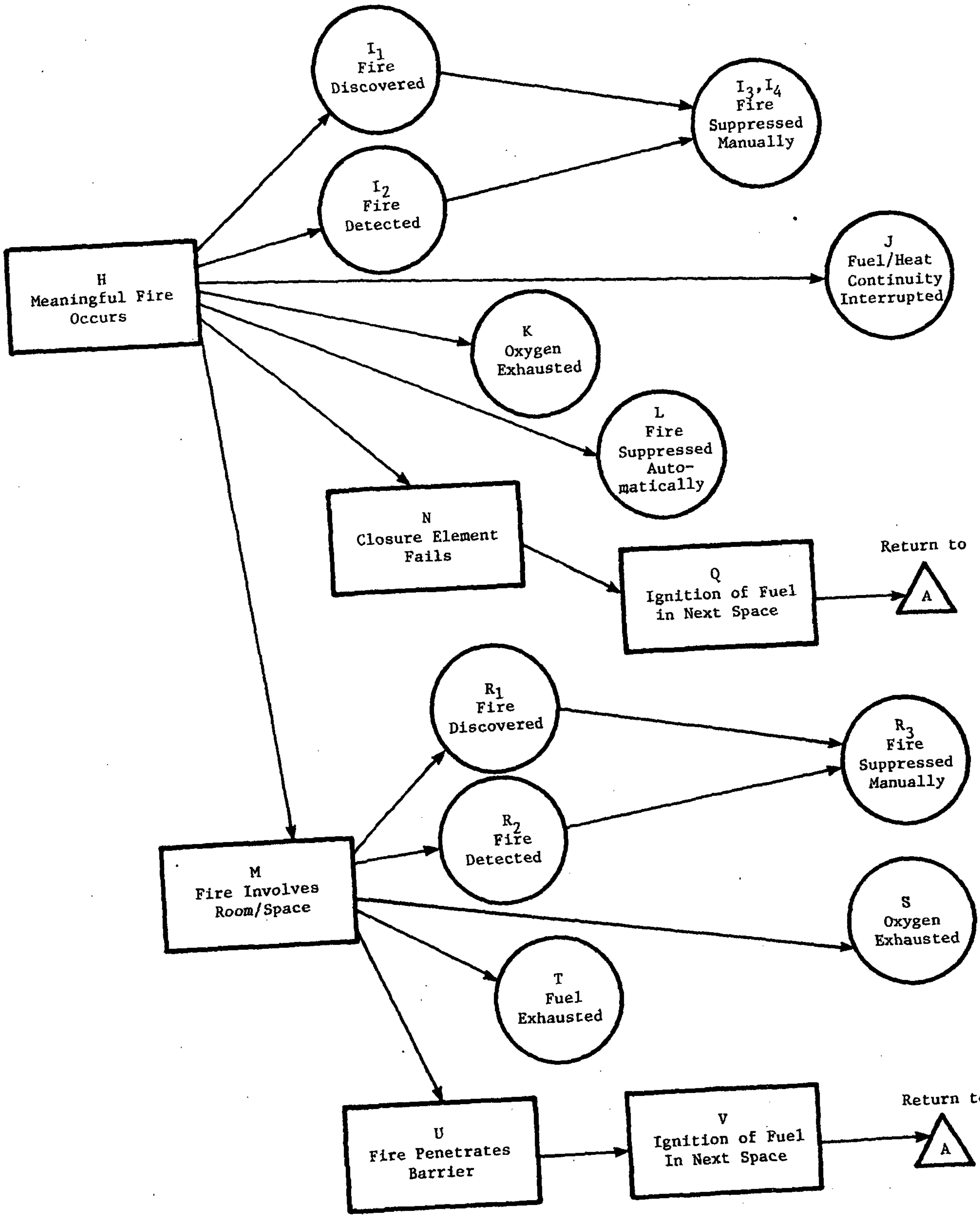


Figure 7. (concluded)

As shown in Figure 7, the critical-path analysis starts with paths radiating out from a point representing the initial contact of a source of ignition with a source of fuel. Possible outcomes at this point are the igniting source may be too brief or of too low an intensity; there may be inadequate fuel or the fuel may be too difficult to ignite; somebody may notice the igniting flame or spark and remove the fuel from the danger zone before it can ignite; the fuel may ignite and the fire may progress to an incipient state. As the fire progresses from incipiency to the next stage, its progress can be interrupted by insufficient fuel, manual extinguishment, or automatic suppression, each of which is represented by a different path. As before, one of the paths represents the continuing fire which now is referred to as a "meaningful" fire, because it is well established in a fuel supply. Using similar logic, subsequent fire events can be traced through Figure 7.

In comparison to the logic of the other probabilistic analyses reviewed in Section 2, the critical-path method is much simpler; there are only 21 individual fire events for which probabilities must be defined. As a result, implementation and acceptance of the technique is greatly facilitated. However, the technical basis and conservatism provided by a critical-path analysis remains a function of the individual probability values assigned to each fire event; the usefulness of any probabilistic analysis method results from the assignment of conservatively reasonable probabilities. If realistic probabilities are ignored and instead all event probabilities are defined as either zero (never occurring) or one (always occurring), the resulting analysis would be classified as deterministic. Such an approach ignores the fact that no event occurs with 100% assurance, especially those events involving people or automatic systems. Recognizing this, at this point it was decided to present a discussion of the technical basis and degree of conservatism that can be assigned to probability values on the critical-path diagram.

The events shown in Figure 7 were analyzed by Gage-Babcock & Associates, Inc., starting with the probability of fire being initiated when a source of ignition contacts a source of fuel. This depends on (1) whether fuel is available at the point of ignition and how easy it is to ignite, and (2) whether someone notices the ignition and prevents the incipient fire. Automatic detection and automatic extinguishment of a fire at this stage is rare and was not considered.

As a conservative assumption the probability of an ignition source contacting the fuel was set equal to 1, because it is difficult to demonstrate a lesser probability for this event. Similarly, the condition of fuel being always available in the area under consideration and easy to ignite was also assigned a probability value of 1; thus, any ignition source is considered adequate to sustain a fire in an easily ignitable fuel. If there were absolutely no fuel in a space or no reasonable way to ignite it, a probability of zero would apply. However, because some transient burnable material may be introduced into such a pristine space, a probability of .01 was assigned to the possibility that a transient fuel supply will be available at the time of ignition.

For the situation where someone notices ignition and prevents an important fire, it was estimated that for spaces attended at all times the ignition would be discovered in the fuel supply in 99 cases out of a hundred. If the space is seldom attended, the probability of discovering the initial ignition was estimated as essentially 0. For conditions in between these extremes, it was reasoned that the vast majority of ignitions occur as a result of people being present. Thus, a probability of .9 was assigned to the discovery of the ignition even when a space is attended only 1/3 of the time.

Although the above probabilities for discovering a fire are capable of being refined, it is doubtful whether better information is available at this time. Statistics for this event normally are not recorded because fires that do not progress beyond the incipient stage are so insignificant that they are not likely to be reported or even remembered.

In a manner similar to that just described for the occurrence of an incipient fire, the probabilities for other events shown in Figure 7 were estimated. Each estimate was derived by Gage-Babcock & Associates, Inc. from available statistical or test data or from the experience and judgment of fire protection engineers at Gage-Babcock. Table 4 summarizes the results of this effort.

For each probability shown in Table 4, it was necessary to visualize events at particular stages of fire development so that a valid estimate of the probability of success or failure could be made. As an example, automatic sprinklers have a statistical success rate in excess of 96%; success is defined as the sprinklers operating to extinguish or control a developed fire. However, in practice there is a very low probability that a sprinkler will operate while a fire is still in the incipient stage. Accordingly, it is estimated that there is only a 20% chance that sprinklers will operate and control a fire while the fire still is small enough to be extinguished with a hand-held fire extinguisher. Beyond this stage, the probability that the sprinklers will operate approaches rapidly the 96% figure usually cited. These operating characteristics of sprinklers are well known and have been reflected in the probability values selected for Figure 7.

Undoubtedly, the probabilities of failure or success assigned to events in Table 4 can be challenged. However, it is anticipated that differences of opinion will be relatively small, and even large differences of opinion will produce only minor effects on final results. One example of a typical office occupancy was calculated where the probability assigned to successful suppression of a small fire with hand extinguishers was changed from .95 to .50. Although the assumed probability of success for this event was cut almost in half, the probability of total room involvement changed by only .00001%. To two significant places, the probability for total room involvement remained 1.5×10^{-5}.

Although some may argue that it would be better to abandon the use of a probabilistic analysis until better statistical fire data are available, such an argument ignores two facts. By estimating probabilities on the basis of the best information available and by applying probabilities in a systematic manner, the practice of individual analysts making unsupported or irrational subjective judgments regarding fire protection requirements is avoided. This represents significant progress in the area of performing fire-hazards analyses. The critical-path diagram shown in Figure 7 and the probability figures presented in Table 4 constitute a simplified format for accomplishing a probabilistic analysis.

TABLE 4

Probability Values Corresponding to Figure 7 Events*

Values for Event D, Probability of Incipient Fire

Event B, Combustion Succeeds Event C_2, Combustion Suppressed	B	C_2
Fuel always available and very easy to ignite	1.0	.5
Fuel always available and easy to ignite	.1	.9
Fuel always available but difficult to ignite	.01	.99
Fuel transient and easy to ignite	.01	.99
Event C_1, Combustion Discovered	**C_1**	
Space attended at all times	.99	
Space attended most of the time	.95	
Space attended 1/3 of the time	.90	
Space seldom attended	.0	

Values for Event H, Probability of Meaningful Fire

Event E_1, Fire is Discovered	E_1
Space attended at all times	.90
Space attended most of the time	.20
Space attended 1/3 of the time	.01
Space seldom attended	.00
Event E_2, Fire is Automatically Detected	**E_2**
Early warning fire detection, thorough coverage of room/space	.90
Early warning fire detection, minimal coverage of room/space	.45
Rate-of-rise heat detection, standard coverage	.40
Fixed-temperature heat detection (including auto. sprinklers), standard coverage	.20

*The numerical values shown in Table 4 and Figures 8 and 9 were provided by Gage-Babcock & Associates, Inc. (Bert Cohn).

TABLE 4 (Contd)

Events E_3 and E_4 Fire Manually Suppressed	E_3 If Fire Is Discovered	E_4 If Fire is Automatically Detected and Response Normally is Within -- 1 min	3 min	10 min	>10 min
1. Standard installation of fire extinguishers suitable for the hazard and personnel trained in their use	.95	.95	.90	.20	.05
2. As 1., but substandard coverage	.85	.85	.80	.20	.05
3. Improper fire extinguisher type:					
Class B or C ext for Class A fire	.80	.80	.70	.10	.02
Class A ext for Class B fire	.50	.50	.40	.10	.02
Class A ext for Class C fire	.80	.80	.70	.20	.05
4. No training in extinguisher use	.50	.50	.45	.15	.04

Event F, Fuel Available	
Fuel available throughout the space	.98
Fuel available in much of the space	.80
Fuel available in half of the space	.50
Fuel available in some of the space	.10
Transient fuel only	.05

Event G, Automatic Fire Suppression Fails	
Standard Automatic Fire Extinguishing System Installed -	
Thorough coverage, early-warning actuation	.11
Thorough coverage, rate-of-rise actuation	.21
Thorough coverage, fixed-temperature actuation	.61
Area coverage, early-warning actuation	.56
Area coverage, rate-of-rise actuation	.61
Area coverage, fixed-temperature actuation	.81
Substandard System or Installation	.90
No Automatic System	1.00

TABLE 4 (Contd)

Values for Event M, Probability of Total Room Involvement

Event I_1, Fire Discovered	I_1
Space attended at all times	.90
Space attended most of the time	.20
Space attended 1/3 of the time	.01
Space seldom attended	.00

Event I_2, Fire Automatically Detected

Use .99 for any standard installation of automatic Fire detectors or sprinklers (with waterflow alarm). Use lower value for installation not conforming to standards.

Events I_3 and I_4 Fire Manually Suppressed	I_3 If Fire Is Discovered	I_4 If Fire is Automatically Detected and Response Normally is Within -- 1 min	3 min	10 min	>10 min
1. Standard installation of fire extinguishers suitable for the hazard and personnel trained in their use	.95	.95	.90	.20	.05
2. As 1., but substandard coverage	.85	.85	.80	.20	.05
3. Improper fire extinguisher type:					
Class B or C ext for Class A fire	.80	.80	.70	.10	.02
Class A ext for Class B fire	.50	.50	.40	.10	.02
Class A ext for Class C fire	.80	.80	.70	.20	.05
4. No training in extinguisher use	.50	.50	.45	15	.04

Event $\overline{J}$, Fuel Continuity Favorable

Ceiling Flame Spread Rating	Values of $\frac{(\text{Average Fire Load})^{3/2}}{\text{Room Height}}$: 1 or Less	Over 1, Up to 2	Over 2, Up to 5	Over 5, Up to 10	Over 10, Up to 20	Over 20
25 or Less	.001	.05	.10	.25	.50	.90
26 to 75	.01	.10	.25	.50	.90	.99
76 to 200	.05	.25	.50	.50	.99	.999
201 to 400	.10	.50	.90	.99	.999	.999
Over 400	.25	.90	.99	.999	.999	.999

TABLE 4 (Contd)

Event $\overline{K}$, Oxygen Available

Average Fire Load (PSF)	Area of Potential Air-Intake Openings (Windows, Doors, Ducts, Louvers, Etc) As Percentage of Total Wall and Ceiling Area		
	Under 3%	3% to 10%	Over 10%
Under 7	.95	.99	1.00
7 to 15	.90	.95	.99
16 to 30	.50	.90	.95
Over 30	.20	.50	.90

Event L, Automatic Suppression Fails

(See Figure 8)

Event N, Closure Element Fails

Fire Resistance of Closure Element	N
None: no closure or combustible closure	1.00
Noncombustible but nonfireresistant (glass, aluminum)	.99
Noncombustible and fireresistant (wired glass, steel)	.97
10-min. fire-resistance rating	.70
20-min. fire-resistance rating	.40
30-min. or greater fire-resistance rating	.10

NOTES:

1. A "closure element" is a portion of the enclosing walls, floor, or ceiling (or floor-ceiling assembly), and includes doors, dampers, windows, cable penetration seals, etc.

2. Multiply N value by 0.2 if there are no ignitable (combustible) materials normally on the outside in proximity to the closure element.

3. Multiply N value by 0.1 if closure element is inside a steel duct.

TABLE 4 (Contd)

Event R_1, Fire Discovered

If Fire Room or Adjoining Spaces are -

Attended at all times	.999
Attended most of the time	.98
Attended 1/3 of the time	.80
Seldom attended	.50

Event R_2, Fire Automatically Detected

Area automatic fire detection or automatic sprinklers in space communicating with fire room:	.80
Instrumentation which would give overheat or other trouble signals likely to be interpreted as a fire signal:	.40
None of the above:	.00

Event R_3, Fire Manually Suppressed

'Standard' Fire Department or Equivalent Fire Brigade Response -

Within 3 min.	.50
Within 10 min.	.40
In more than 10 min.	.30
Fixed water extinguishing system installed in space under consideration; manually controlled from outside immediate fire area	.70

Event S, Oxygen Available

Average Fire Load (PSF)	Area of Potential Air-Intake Openings (Windows Doors. Ducts. Louvers Etc) As Percentage of Total Wall and Ceiling Area		
	Under 3%	3% to 10%	Over 10%
Under 7	.95	.99	1.00
7 to 15	.90	.95	.99
16 to 30	.50	.90	.95
Over 30	.20	.50	.90

Event T, Fire Barrier "Wear Out" Failure

(See Figure 9)

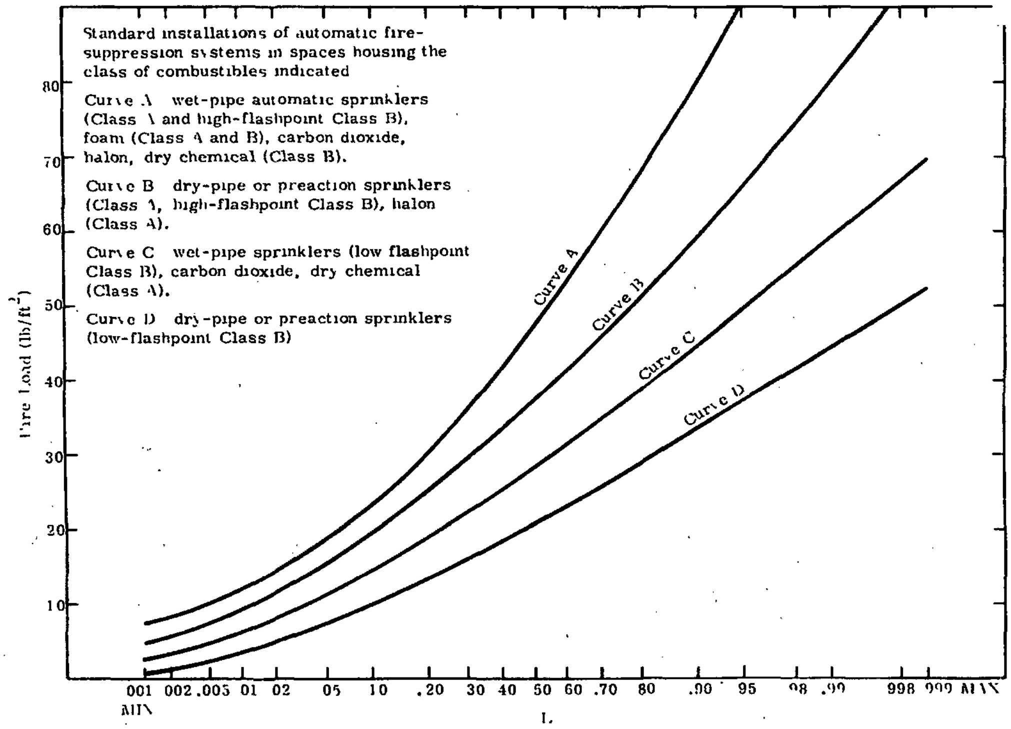


Figure 8. Event L, Automatic Fire Suppression Fails

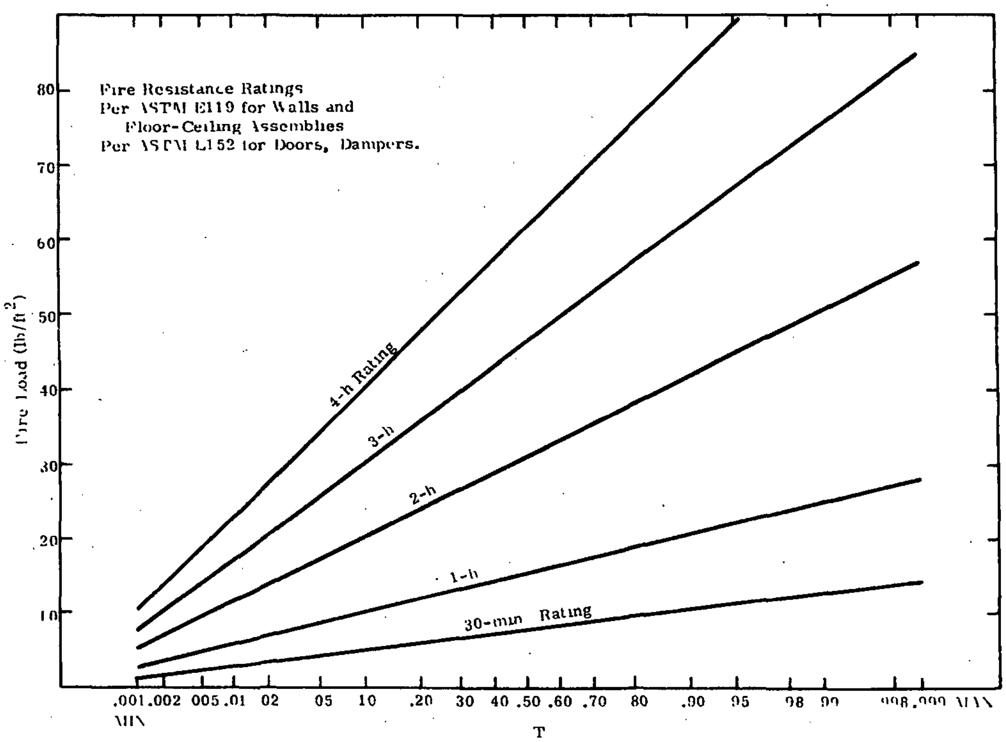


Figure 9. Event T, Fire Barrier "Wearout" Failure

Qualitative Fire Scenario Analysis Method -- Figure 5 suggests that a subjective analysis should be tried only after efforts to demonstrate fire safety by deterministic or probabilistic methods have failed. This is because subjective analyses are not easily shown as technically sound and conservative. Consequently, we concluded that, whenever subjective analyses are used, a predefined analysis outline for postulating fire scenarios should be followed on a case-by-case basis.

Although following an analysis outline and postulating fire scenarios does not guarantee that an analyst will be technically correct and conservative, the approach does assure that each analysis is pursued in the same manner and that each analysis decision is defended and available for scrutiny. In addition, by following an analysis format which has been developed through the consensus of a number of fire protection authorities, there is reasonable assurance that decisions will be based on the most appropriate and best available fire protection codes and standards. Beyond this, however, little can be said to support the tech-nical merit of the qualitative fire scenario analysis method.

In the preceding pages the technical merit of three candidate fire-hazards analysis techniques have been considered: (1) fuel load and ventilation barrier analysis, (2) modified decision-tree (critical-path) analysis, and (3) qualitative fire-scenario analysis. From the standpoint of technical merit, it was shown that the barrier analysis is preferable for nuclear power plant use. Despite this, there are a number of situations where a barrier analysis is inadequate and where a critical-path analysis or even a qualitative fire-scenario analysis must be used. For example, redundant safety equipment may occupy the same safety area and thereby preclude the use of barrier analysis for a flashover fire in the entire room. In this case, a critical-path analysis would be needed.

Simplifying the Candidate Analysis Techniques

For any fire-hazards analysis technique to be worthwhile, it must be usable by those individuals responsible for designing and regulating the installation of fire protection systems. If an analysis method is too complicated, mistakes will be made in its application and interpretation. It would be unreasonable to require an analyst to solve a set of unsteady-state heat balance equations for each safety area of a nuclear power plant or to require an analyst to develop probability values for each critical-path analysis. Accordingly, it was decided as part of this study that the three chosen analysis techniques should be reduced to more simplified formats. The results of this effort are presented in this section.

Simplified Fuel Load and Ventilation Barrier Analysis -- Equations for those physical parameters of fire phenomena which govern the severity of fire under conditions of full room fire involvement have been presented. When solved, the equations predict the time-temperature history of a fire as a function of three variables--fuel load, ventilation rate, and room size. Of course, to reduce the total number of variables to three, other parameters (such as heat capacities, emissivities, thermal conductivities, and densities) must be defined. This can be done with relative ease, however, by applying conservative values of published data which most closely approximate nuclear power plant conditions and by noting that the actual values selected for some parameters are often of little consequence to the problem results. For example, flame emissivity values can range from 0.3 to 0.9 with only a 20°C difference in the resulting fire-gas temperature; wall heat capacity values can vary by a factor of 4 with virtually no difference in fire-gas temperature after 1 h.[27] On this basis, the physical parameters listed in Table 5 were selected to help calculate time-temperature histories for various nuclear power plant fuel loads, ventilation rates, and room sizes. Figures 10 and 11 show typical resulting time-temperature curves which were calculated on the basis of the assumptions listed in Section 3.

Table 5

Selected Physical Parameters

WALLS (Concrete):

Density	ρ_w = 1920 kg/m^3 (Ref. 31)
Heat Capacity	Cp_w = 1052 J/kg-K (Ref. 31)
Thickness	= 0.202 m
Emissivity	ϵ_w = 0.65
Convective Transfer Coefficient	$U = 5.0\,(T_f - Tw_i)^{1/3}$ J/s-m^2-K (Refs 28 and 30)
Thermal Conductivity	$K_w = \begin{cases} 1.878 \text{ J/s-m-K @ } 273 \text{ K} \\ 0.609 \text{ J/s-m-K @ } 1473 \text{ K} \end{cases}$ (assumed linearly variable - Ref. 31)

FUEL (Cable Insulation):

Net Combustion Heat	$H_c = 25.9 \times 10^6$ J/kg fuel burned (Ref. 3)
Surface Pyrolysis Limit	$R_p = \frac{\text{kg Fuel}}{600 \text{ s}}$ (Ref. 3)
Fraction of Pyrolysates That Burn	= 0.7 (Ref. 27)
Stoichiometric Fuel-to-Air Ratio	= 14.8 $\frac{\text{kg fuel}}{\text{kg air}}$ (assuming complete combustion of polyethylene to CO_2 plus H_2O)

AIR AND FIRE GASES:

Emissivity	ϵ_f = 0.9 (assuming a smoky fire)
Heat Capacities	Cp_a = functions of temperatures as shown in Refs. 30 and 32.

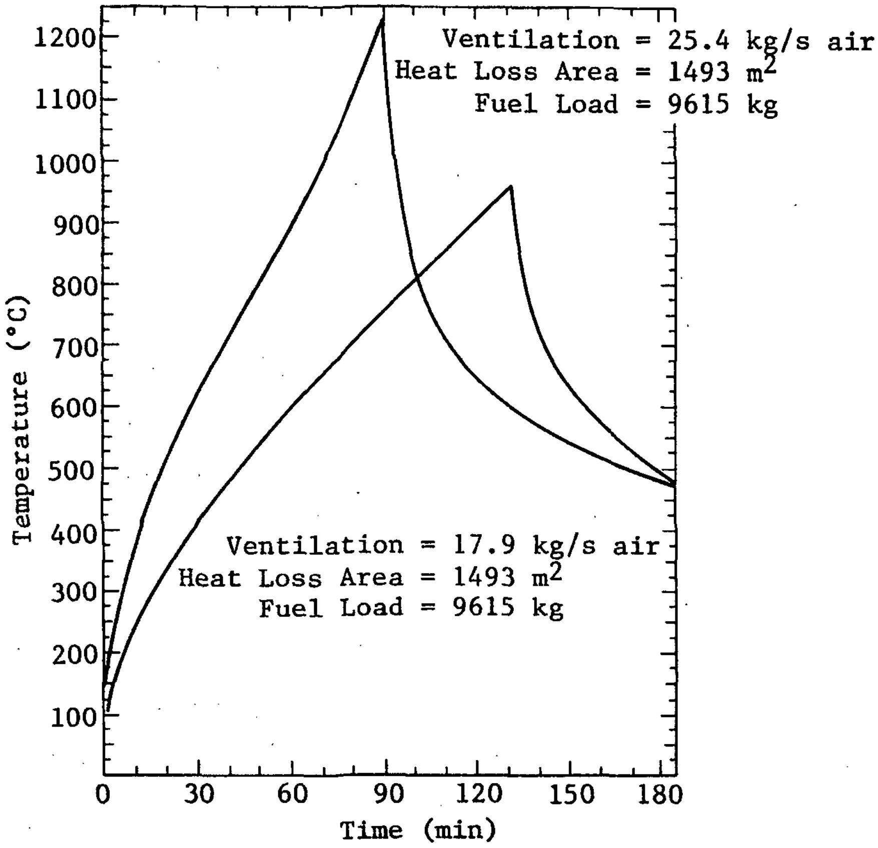
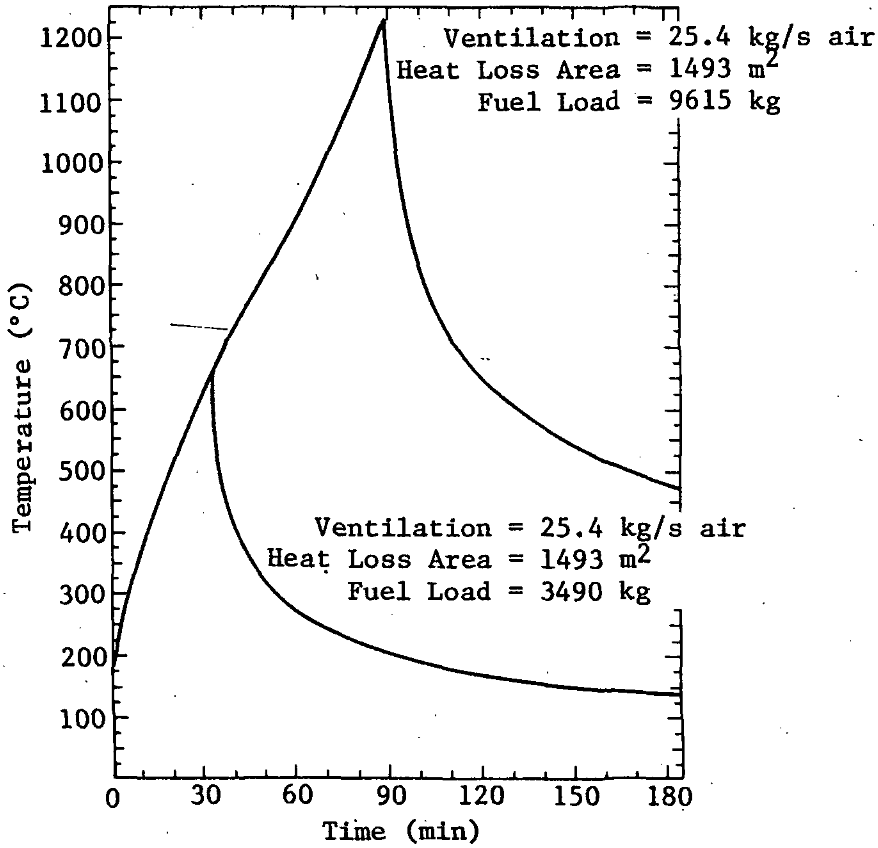


Figure 10.

Typical Time-Temperature Response Curves for Different Ventilation Rates

Figure 11.

Typical Time-Temperature Response Curves for Different Fuel Loads



In reviewing Table 5 and Figures 10 and 11, several points should be noted.

- The combustible used for the example calculations was cable insulation. This selection covers the bulk of combustibles found in nuclear power plant safety areas, when supplemented by a separate treatment of fuel oil combustibles.

- Cable properties and surface-controlled burn rate limits in Table 5 were derived from cable burn test data measured at Sandia Laboratories.[3] This information establishes an upper burn rate limit for conditions of open burning with unrestricted air availability. However, a straightforward calculation can show that, on the basis of stoichiometric air requirements alone, surface-controlled burning under conditions of total involvement will not occur in most nuclear power plant areas because of airflow restrictions. Such air restrictions cause total-involvement burning to occur at a rate less than the surface-controlled limit observed during open burning. Viewed another way, one may assume that a portion of a room is burning at its surface burn limit instead of the <u>total</u> room burning at an air-restricted limit. From the standpoint of calculating fire severity time-temperature histories, either viewpoint is equally valid but, since ventilation phenomena are more easily treated mathematically, it is convenient to treat room-burn phenomena as ventilation-controlled total involvement.

- Figures 10 and 11 show how changes in fuel load, ventilation rate, and room size affect the resultant time-temperature history. This is understandable, considering how each variable enters into the governing heat balance equations, Eqs. (2) through (5). To simplify these results, it was decided to eliminate one variable by normalizing both the fuel load and ventilation rate with respect to room size. Practically, this means that fuel loads and ventilation should be determined in terms of the heat-loss area of a room and not the floor area of a room.

Although time-temperature histories can be calculated for various combinations of normalized fuel load and ventilation, a method is needed to relate the normalized variables in a simplified manner that does not require a computer for solutions by designers and regulators. Such a method should identify what numerical values of each variable are satisfactory for design purposes.

Since a basic premise of the fuel load and ventilation barrier analysis requires that barriers be adequate under conditions of a worst-case fire, the criteria for design should be

- A barrier shall not be exposed during a fire to a higher temperature than the one to which it was originally tested.

- A barrier should not be exposed to a fire longer than the time for which it was originally tested.

In other words, a time-temperature history for a room calculated with the conservative heat balance Eqs. (2) through (5) should never exceed the temperature or test duration of the standard time-temperature curve specified in Reference 2 for barrier and barrier-element testing. For various conditions of fuel load and ventilation, the above criteria can be applied to ascertain which combinations are acceptable for a particular barrier rating. Figure 12 shows the results of such an effort.

The diagonal lines in Figure 12 correspond to fire durations on the basis of a selected duration and a stoichiometric air balance. For a specified ventilation rate, increasing fuel load increases fire duration--it takes longer to burn more fuel.

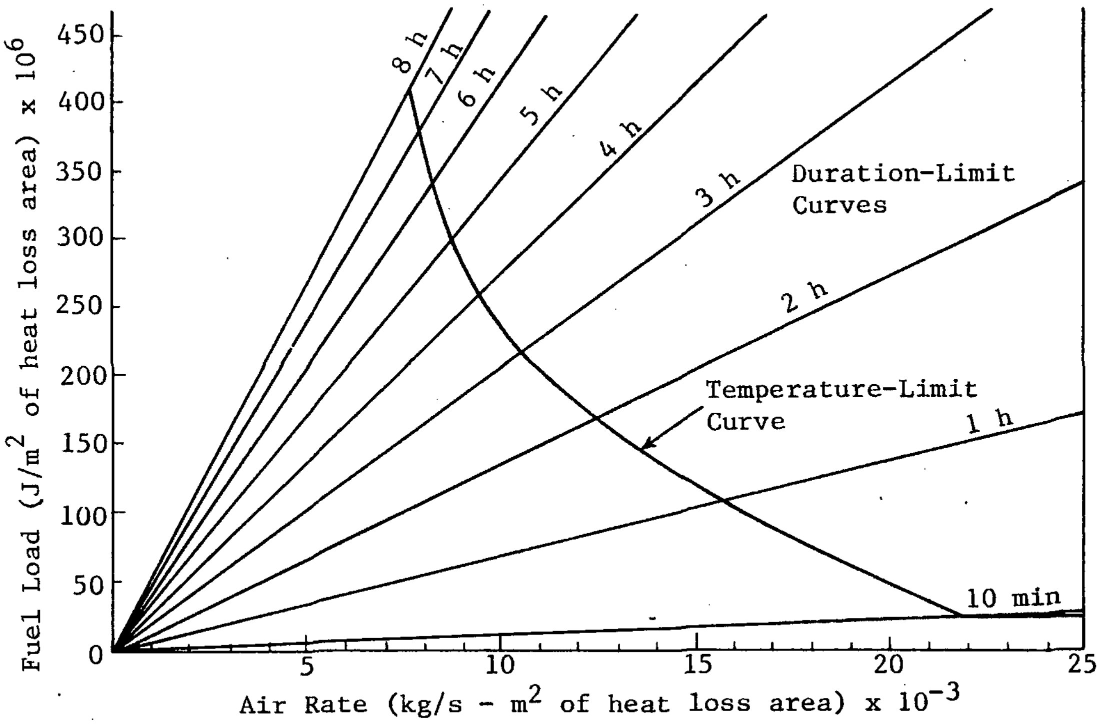


Figure 12. Acceptable Fuel Load and Ventilation Combinations Assuming Heat Loss Into Wall Only

The curved line in Figure 12 corresponds to combinations of fuel load and ventilation rate whose time-temperature histories just reach but do not exceed the standard time-temperature curve (see Figure 13). For a specified fuel load, increasing ventilation rates cause the fire temperature to exceed the standard time-temperature test curve. If a nuclear power plant safety area has a fuel load and ventilation rate combination lying to the left of the temperature-limit curve and lying to the right of the governing fire-duration line, the fire barriers surrounding the room should withstand total-room fire involvement of all fuel within the room.

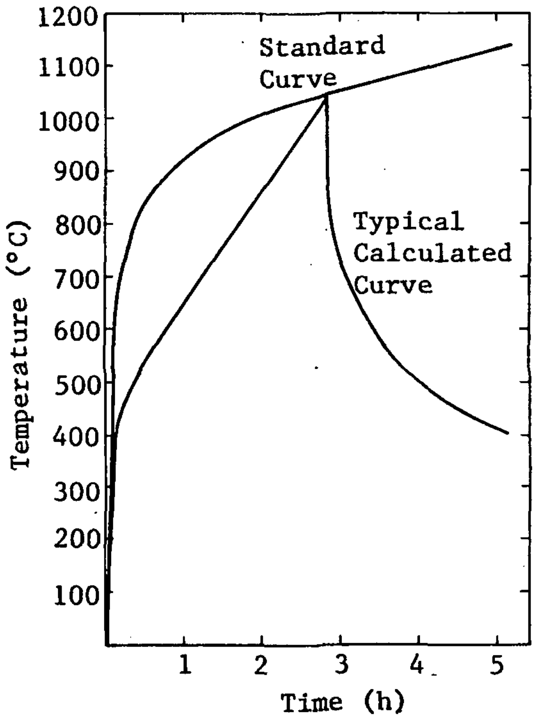


Figure 13. Typical Temperature Limitation for Calculated Time/Temperature Curves

As was pointed out in Section 3, the equations used to develop Figure 12 contain a number of conservative assumptions. One assumption of major importance involved the limitation of heat loss to convection and radiation to the walls of the room. If, through ventilation system design, the removal of heat from a burning room can be assured, higher combinations of fuel load and ventilation rate can be tolerated without exceeding the standard time-temperature test curve. Figure 14 shows cases where additional heat is removed by venting 50 and 100% of the hot gases produced during a fire. The difference between Figures 12 and 14 is striking.

In order to use Figures 12 and 14, a designer must be able to relate a room's actual fuel load and ventilation conditions to the coordinates of the figures. For fuel load, this can be done by adding up the weight of combustibles in a room and converting this to fuel combustion energy per unit area of wall and ceiling. The room floor area is conservatively excluded, because cool air entering the fire zone will tend to enter along the floor; also the fuel itself will shield the floor from the hot gases in the room.

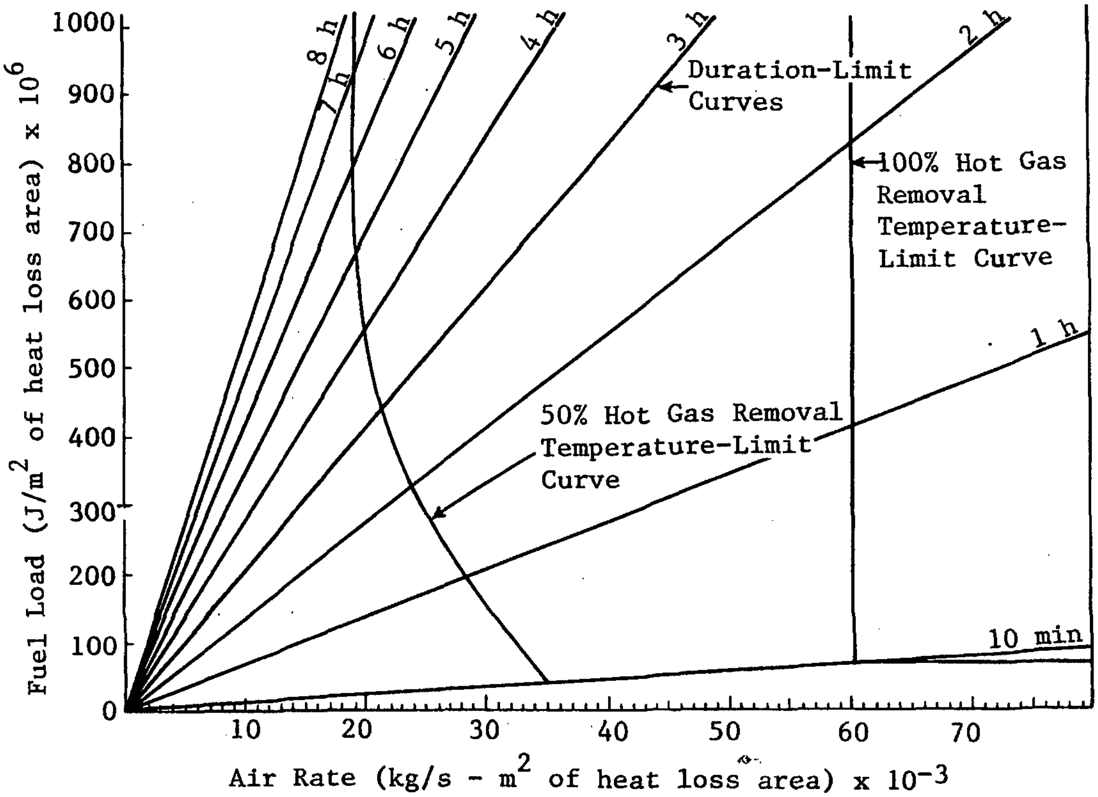


Figure 14. Acceptable Fuel Load and Ventilation Combinations Assuming Heat Loss Into Walls and Either 50% or 100% of Hot Gases Removed

For ventilation rates, three situations exist:

1. If a room has only forced ventilation with either sealed or small openings, the ventilation system flow rate can be used directly in Figures 12 and 14.

2. If a room has only fire-induced natural ventilation through door or vent openings, Eq. (5) in Section 3 can be used. Unfortunately, since the density terms in Eq. (5) are functions of temperature and since the

variation of temperature in a burning room requires solution of the other equations in Section 3, the use of Eq. (5) for design purposes is unattractive. An alternate approach derived from Eq. (5) is presented in Figure 15.

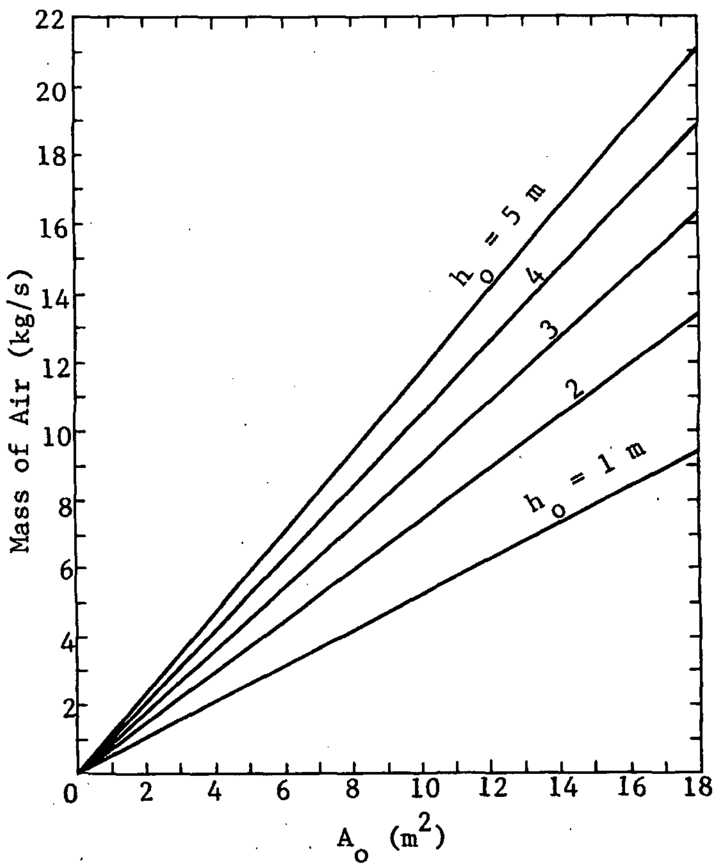


Figure 15. Airflow Rate Induced by a Fire in a Room Having an Opening of Height h_o and Area A_o

This figure, relating fire-induced ventilation rates to opening size, was calculated by conservatively noting that the density square root term in Eq. (5) has a maximum value of 0.2144 for air entering at a temperature of 20°C.[27] Recognizing this, Eq. (5) can be reduced to

$$M_{air} = 0.522 \; A_o \sqrt{h_o} \text{ kg/s} \quad .$$

This equation was used to produce Figure 15.

3. If a room has both fire-induced natural ventilation through openings and forced ventilation, it is theoretically possible to account for the interrelationship between these two effects by recognizing that both natural and forced ventilation are related to the static pressure of gases within a room. For natural ventilation, which results from a temperature-induced buoyancy gradiant between the inside and outside of a burning room, an increase in room static pressure will tend to reduce the flow of induced draft air entering the room. Similarly, an increase in room static pressure will tend to reduce the flow of forced draft air being blown into the room by a ventilation fan.

    Since a balance must be reached between the room static pressure and the flow of air and hot gases into and out of the room during a fire, it is possible to relate these phenomena through fluid dynamic and material balance equations for specified fan characteristics and opening sizes. The Appendix has done this for an example case involving a room with one door open and a forced ventilation fan in operation. Using the relationships in the Appendix, a designer may use known ventilation system and fan characteristics to relate ventilation flow to the static pressure in a room. Once this static pressure is found, corresponding fire-induced flow can be calculated and the sum of the two flows may be used in Figures 12 or 14 to determine the expected fire severity.

    In practice, however, a conservative and simpler approach involves the direct addition of forced and fire induced airflows by assuming that the flows do not interact. As described in the Appendix, the flows of both forced ventilation and fire induced ventilation will tend to reduce because of their combined effects on room static pressure during a fire. By assuming no interaction between the two flow mechanisms, the resulting flow obtained by addition will be conservative.

By using either Figure 12 or 14 together with a knowledge of a safety area's wall and ceiling area, fuel load, and ventilation characteristics, a designer or regulator can determine whether fire barriers alone will contain a total-involvement fire within the area in question. Application of this technique to a power plant area is the first example in Section 4.

Simplified Critical-Path Analysis -- Earlier in this section Figure 7 showed a critical-path diagram describing the logic of fire initiation, growth, and extinguishment. At each logic juncture, there exists a probability that certain subsequent fire events will occur, and Table 4 proposed a number of probabilities for use with the critical-path diagram.

To further simplify the critical-path analysis method, it was decided to develop the analysis worksheet shown in Table 6. This worksheet combines event probabilities according to the critical-path analysis logic in a manner which can be easily applied in combination with the probabilities presented in Table 4.

For purposes of a nuclear power plant fire-hazards analysis, the use of Table 6 by analysts can be made most consistent by precalculating representative probability values for a number of similar power plant areas. Because of its overwhelming importance to the analysis results, the probability of Event H (occurrence of a meaningful fire) was chosen to be precalculated for a number of plant safety areas. To limit the analysis variation possible, several assumptions were made to group similar design conditions into common categories.

TABLE 6

Critical Path Analysis Work Sheet

I. PROBABILITY OF INCIPIENT FIRE (Event D)

$D = B(1 - C_1C_2)$

D = [ ](1 - [ ][ ]) = ____

II. PROBABILITY OF MEANINGFUL FIRE (Event H)

$E = (1 - E_1E_3)(1 - E_2E_4)$

E = (1 - [ ][ ])(1 - [ ][ ]) = ____

$H = D \cdot E \cdot F \cdot G$

H = [ ][ ][ ][ ] = ____

III. PROBABILITY OF TOTAL ROOM INVOLVEMENT (Event M)

$I = (1 - I_1I_3)(1 - I_2I_4)$

I = (1 - [ ][ ])(1 - [ ][ ]) = ____

$$\text{Fire Load/Height Ratio} = \frac{[\text{Average Fire Load}]^{3/2}}{\text{Room Height}}$$

$$= \frac{[\quad \text{lbs/ft}^2]^{3/2}}{[\quad \text{ft}]} = \_\_\_\_$$

$M = H \cdot I \cdot J \cdot K \cdot L$

M = [ ][ ][ ][ ][ ] =

IV. PROBABILITY OF FIRE COMMUNICATING TO ADJOINING SPACE (Events Q and U)

Q (before Event M); U (after Event M)

$Q = H \cdot N$ if significant fuel source normally is present in the fire room directly under or adjoining the closure element.

$Q = M \cdot N$ otherwise.

Multiply N by factor as given in Notes.

Q = [ ][ ][ ] = ____

$R = (1 - R_1R_3)(1 - R_2R_3)$

R = (1 - [ ][ ])(1 - [ ][ ]) = ____

$U = M \cdot R \cdot S \cdot T$ Multiply by 0.2 if there are no ignitable (combustible) materials normally on the outside in proximity to the room enclosure. Otherwise, use 1.0.

U = [ ][ ][ ][ ][1.0 or 0.2] = ____

It was assumed that typical values for H probabilities could be obtained by limiting the probability entries for Events B through G to not more than three sets of conditions. In addition, some of the event probabilities for Events B through G can be combined to yield more generic categories of events for which probabilities can be assigned. Proceeding in this manner, the following categories and events were determined:

		Probability	
Combustibility:	Low	.001 (BXF)	
	Moderate	.01	
	High	.1	
Room Attended:	At all times	.90 (E_1)	.99 (C_1)
	Over 1/4 of time	.05	.90
	1/4 or less of time	.00	.00
Response Time (when room is unattended):	Under 3 minutes	.90 (E_3 & E_4)	
	3 to 10 minutes	.20	
	Over 10 minutes	.05	
Automatic Detection:	Early-warning type	.45 (E_2)	
	Heat-actuated type	.20	
	None	.00	
Combustion Suppressed:	Fuel available, easy to ignite	.90 (C_2)	
	Fuel available, difficult to ignite	.99	
	Fuel transient	.99	
Automatic Suppression:	Area sprinklers	.80 (G)	
	Special hazard suppression system	.40	

In arriving at the above probabilities, it was assumed that in every nuclear power plant being considered, portable fire extinguishers of the proper type and size will be distributed throughout the plant in the required numbers and that personnel will receive training in their use. It was also assumed that any automatic fire-detection or fire-extinguishing system installed in the areas under consideration will conform to recognized standards.

Using the above event probabilities, Table 7 was prepared by following the logical relationship for Event H shown in Table 6. By selecting the occupancy most representative of a particular safety area being analyzed, a designer can determine directly the probability that a meaningful fire will occur (Event H) and then proceed with a determination of subsequent fire events (e.g., fire manually suppressed, etc) on a case-by-case basis. Application of this method is the second power plant area example in Section 4.

Simplified Qualitative Fire Scenario Analysis Method -- In Section 3 we stated that, even though subjective analyses are not readily defended in terms of conservatism or technical merit, it is often necessary to conduct a subjective analysis whenever deterministic and probabilistic approaches prove inappropriate. In those instances where a subjective analysis must be followed, we concluded that a qualitative fire scenario would be the best candidate if it is based on either NFPA 802, "Recommended Fire Protection Practice for Nuclear Reactors," or the March 1978 draft proposed appendix to the American National Standard "Generic Requirements for Light Water Nuclear Power Plant Fire Protection," ANSI/ANS-59.4-1977. For outlining the many diverse factors affecting satisfactory fire protection, both the NFPA 802 and the ANSI/ANS documents are reasonably complete. However, neither guideline helps an analyst to develop the underlying reasoning needed for a scenario analysis.

One way to overcome this shortcoming would be through the use of a fire scenario logic chart. Such a chart could lead an analyst from beginning to end of a fire in a step-by-step sequence. It was found that, of the logic sequences available, the one least complicated for a subjective analysis has been described already in Section 3 as part of the critical-path probabilistic analysis (Figure 7).

TABLE 7

Probability Values for Event H, Occurrence of Meaningful Fire

	1	2	3	4	5	6
				Probability of Event H		
Typical Occupancies	Combustibility	Attended	Response	No Auto. Protection	Heat Det. or Spklrs.	Early Warn. Fire Det.
	Low	All Times	Under 3 min	3.8×10^{-6}	3.1×10^{-6}	2.2×10^{-6}
Control Room, Small (Constant Surveillance)	Mod			1.2×10^{-4}	1.0×10^{-4}	$.7 \times 10^{-4}$
	High			2.1×10^{-3}	1.7×10^{-3}	1.2×10^{-3}
	Low	Over 1/4 of time	Under 3 min	1.0×10^{-4}	$.85 \times 10^{-4}$	$.62 \times 10^{-4}$
Control Room, Parts Not Under Surveillance	Mod			.0057	.0047	.0034
	High			.018	.015	.011
	Low	Over 1/4 of time	3-10 min	1.1×10^{-4}	1.0×10^{-4}	1.0×10^{-4}
Offices	Mod			.0059	.0057	.0054
Supply Rooms	High			.019	.018	.017
	Low	Over 1/4 of time	Over 10 min	1.1×10^{-4}	1.1×10^{-4}	1.1×10^{-4}
	Mod			.0060	.0060	.0058
	High			.019	.019	.019
	Low	1/4 or less of time	Under 3 min	.0010	.00082	.00060
	Mod			.010	.0082	.0060
	High			.10	.082	.060
Machinery, Elec. Equipment Rooms	Low	1/4 or less of time	3-10 min	.0010	.00096	.00091
Storerooms, Cable Spreading Rooms	Mod			.010	.0096	.0091
	High			.10	.096	.091
	Low	1/4 or less of time	Over 10 min	.0010	.00099	.00098
	Mod			.010	.0099	.0098
Paint, Oil Storage	High			.10	.099	.098

Multiply probability of event H by 0.8 if space is protected with a normal automatic sprinkler installation; multiply by 0.4 if hazards are protected with a special hazard system using fast-acting fire detection (smoke, flame, or rate-of-rise). Multiply by 0.32 if both.

By qualitatively following Figure 7, an analyst would be forced to consider a number of logical fire event outcomes and, at each logic juncture, the analyst would have to defend subjectively any assumptions affecting subsequent fire progress. In this way, each fire protection decision would be derived from a consistent thought process which qualitatively considers the most likely sequence for a fire's development. By combining the scenario logic for specific fire events with the generic analysis outlines provided in NFPA 802 and the ANSI/ANS 59.4 document, subjective analyses could be performed in a repeatable manner that provides a documented basis for design and regulatory decisions. The application of this method is the third example situation outlined in Section 4.

4. Example Fire Hazards Analyses

Because in this study we have tried to develop a fire-hazards analysis that can be carried out in a straightforward fashion, it is important to demonstrate that the three analysis methods selected can be easily executed. To do this, examples of fire-hazards analyses of three typical nuclear power plant areas have been completed using the analysis techniques described in the last section.

Example Fuel Load and Ventilation Barrier Analysis

For this example, a cable spreading room adjacent to a control room will be considered. Since the fuel load and ventilation barrier analysis stipulates limiting conditions of total room involvement, this spreading room must be one of two redundant spreading rooms serving the control room. In this analysis, it will be assumed that the adequacy of a fire barrier between the spreading room and the control room is to be evaluated. Figure 16 illustrates the situation.

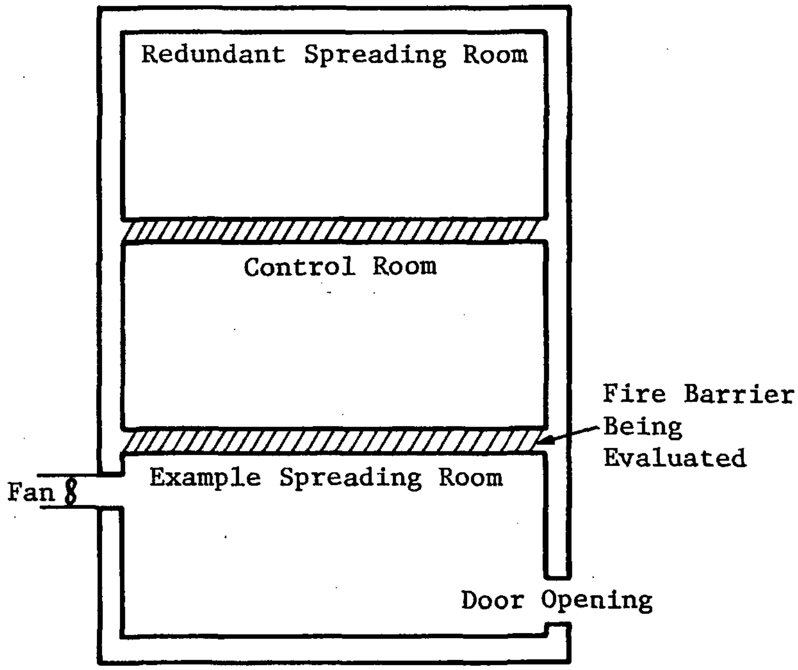


Figure 16. Layout for Fuel Load/Ventilation Barrier Analysis Example

The following parameters are selected as typical:

Spreading Room Size = 35 x 25 x 5 m

Total Fuel = 10 000 kg insulation

Net Combustion Heat = 25.9 x 10^6 J/kg

Size of One Open Door = 1 x 2.5 m

Normal Forced Ventilation = 4.3 kg/s at 0°C and 1 atm

From these parameters, the heat loss area is calculated as 1475 m^2 and, from Figure 15, the fire-induced ventilation airflow for the selected door opening is about 2.1 kg/s, yielding a combined airflow of 6.4 kg/s. In terms of the units used in Figure 12, the normalized airflow is 4.34 x 10^{-3} kg/s-m^2.

For the fuel, the normalized fuel load can be determined

$$\frac{10\ 000\ \text{kg}}{1475\ \text{m}^2} \times 25.9 \times 10^6\ \frac{\text{J}}{\text{kg}} = 175 \times 10^6\ \frac{\text{J}}{\text{m}^2}$$

In terms of more familiar units, the airflow rate and fuel load in this example convert to:

$$\text{Air Rate} = 10\ 500\ \frac{\text{standard ft}^3}{\text{min}}\ \text{(SCFM)}$$

$$\text{Fuel Load} = 26\ 000\ \frac{\text{Btu}}{\text{ft}^2\ \text{floor area}}$$

From Figure 12, the above airflow rate and fuel load result in a fire where the duration is about 5-1/2 h and where the temperature severity never exceeds the standard time-temperature test curve.

Since a 5-1/2 h fire rating lies beyond the range of 1 to 3 h for most commercially available barriers, one or more of four corrective options should be invoked. The options are:

1. Reduce the fuel load to about 90×10^6 J/m^2 (13 300 Btu/ft^2) floor area.

2. Insure that the fire is extinguished so that it burns no longer than the selected barrier rating.

3. Increase the air rate to between 8.3×10^{-3} and 60×10^{-3} kg/s-m^2 (20 000 and 145 000 SCFM) and simultaneously guarantee removal of all hot gases from the burning room (see Figure 14).

4. Increase the air rate to between 8.3×10^{-3} and 12×10^{-3} kg/s-m^2 (20 000 and 29 000 SCFM) without guaranteeing hot gas removal (Figure 12).

The selection of an appropriate option depends upon the particular case in question. For an existing power plant, Option 2 is most attractive; but, for a newly designed plant, Options 1, 3, or 4 may be more appropriate. In any event, the analysis technique has shown the conditions of fuel load and ventilation under which a barrier alone can be expected to contain a fully developed fire. This information is of significant value to both designers and regulators in determining what additional fire protection measures, if any, are needed to supplement passive fire barriers.

Example Critical-Path Analysis

For this example, a control room will be considered. By using the worksheet (Table 6) derived from the critical-path logic diagram (Figure 7), it is possible to proceed with the control room analysis in one of two ways. The analyst may either start with Step I of the worksheet, "Probability of Incipient Fire," or the analyst may start with Step III, "Probability of Total-Room Involvement." If it is decided to start with Step I, event probability values from Table 4 must be combined to calculate the probability of a meaningful fire (Event H) for use in subsequent worksheet calculations. If Step III is chosen as the starting point, the probability of Event H may be selected from the precalculated H values shown in Table 7. In this example, the results of both techniques will be shown.

In order to proceed, a number of assumptions are necessary to sufficiently define the control room arrangements under consideration. These assumptions are:

- The room is attended at all times and is small enough to be observed throughout by operators in attendance.

- The room combustibles are spread throughout the room for an average fuel load of 10 kg/m^2 floor area (2 lb/ft^2).

- The room is enclosed with fire-resistant construction rated at 2 h.

- The room has area smoke detectors at the ceiling level.

- The room has an adequate number of fire extinguishers of the proper type and personnel are trained in their use.

- The room interior finish is noncombustible.

- The plant has a fire brigade capable of responding to the control room within 3 min.

- The room ceiling height is about 3.5 m (12 ft).

Using these assumptions, Table 8 was developed for the control room by selecting appropriate probability values from Table 4 or Table 7. From Table 8 it can be seen that the probability of a meaningful fire in a control room is about 10^{-4} or 1 chance in 10 000 that the contact of an ignition source to moderately ignitable fuel will result in a meaningful fire. As indicated in the table, this probability estimate could be deduced from precalculated H values in Table 7 or from a recalculation of H as shown in Table 8. From the standpoint of total control room fire involvement, Table 8 indicates a probability of less than 10^{-9}.

By comparing this result with the probabilities for total room fire involvement in other plant areas, an analyst can determine, on a relative basis, which areas are overly or inadequately protected. In addition, an analyst may readily review Table 8 for each plant area to determine which portions of fire safety systems (fire retardancy, barriers, suppression, etc.) should be modified to give a consistent level of safety.

TABLE 8

Nuclear Power Plant Control Room
CPM Fire Hazard Analysis Work Sheet

I. PROBABILITY OF INCIPIENT FIRE (Event D)

$D = B(1 - C_1C_2)$

$D = [\ .1\ ](1 - [\ .99\ ][\ .9\ ]) = \underline{.0109}$

II. PROBABILITY OF DEVELOPING FIRE (Event H)

$E = (1 - E_1E_3)(1 - E_2E_4)$

$E = (1 - [.90][.95])(1 - [.45][.95]) = \underline{.083}$

$H = D \cdot E \cdot F \cdot G$

$H = [.0109][.083][.10][1.0] = \underline{.000090}$

H = 0.000072 from Table 7 for moderate combustibility control room occupancy.

III. PROBABILITY OF TOTAL ROOM INVOLVEMENT (Event M)

$I = (1 - I_1I_3)(1 - I_2I_4)$

$I = (1 - [.90][.95])(1 - [.99][.95]) = \underline{.00863}$

$$\text{Fire Load/Height Ratio} = \frac{[\text{Average Fire Load}]^{3/2}}{\text{Room Height}}$$

$$= \frac{[\ 2\ \text{lbs/ft}^2]^{3/2}}{[\ 12\ \text{ft}]} = \underline{.24}$$

$M = H \cdot I \cdot J \cdot K \cdot L$

$M = [.00009][.00863][.001][.95][1.0] = 7.4 \times 10^{-10}$

IV. PROBABILITY OF FIRE COMMUNICATING TO ADJOINING SPACE (Events Q and U)

Q (before Event M); U (after Event M)

$Q = H \cdot N$ if significant fuel source normally is present in the fire room directly under or adjoining the closure element.

$Q = M \cdot N$ otherwise.

Multiply N by factor as given in Notes.

$Q = [.00009][.97][.2] = \underline{1.7 \times 10^{-5}}$

$R = (1 - R_1R_3)(1 - R_2R_3)$

$R = (1 - [.999][.50])(1 - [.80][.50]) = \underline{.30}$

$U = M \cdot R \cdot S \cdot T$ Multiply by 0.2 if there are no ignitable (combustible) materials normally on the <u>outside</u> in proximity to the room enclosure. Otherwise, use 1.0.

$U = [7.4 \times 10^{-10}][.30][.95][.001][1.0 \text{ or } \underline{0.2}] = \underline{4.2 \times 10^{-14}}$

As indicated in Section 1 of this report, the significance of fire involvement probabilities cannot be determined on an absolute safety basis without a knowledge of the importance of the affected safety area and without a definition of what constitutes an acceptable level of fire risk. These uncertainties, together with uncertainties regarding the selected probability values for detection response, barrier effectiveness, and oxygen depletion, preclude deriving any absolute fire safety conclusions from Table 8.

Example Qualitative Fire Scenario Analysis

In the section titled "Simplifying the Candidate Analysis Techniques," we stated that an uncomplicated fire scenario analysis could be carried out by combining the logic of the critical-path analysis (Figure 7) with the generic analysis outlines provided in NFPA 802 and ANSI/ANS 59.4. Since the generic analysis portion of this approach primarily provides a prosaic method for identifying potentially hazardous areas and for organizing fire protection information associated with these areas, only an example of the qualitative critical-path analysis portion will be discussed in this section. For an example of the generic analysis outline, any of several current nuclear power plant safety analysis reports may be consulted.

As explained earlier, a qualitative fire scenario analysis should be invoked only after the conclusions of deterministic and probabilistic analyses prove unacceptable or inconclusive. One example would be the analysis of a fire within a cabinet containing two redundant electrical circuits. By following the logic shown in Figure 7, a scenario analysis describing the most likely progress of a cabinet fire can be performed so that, at each juncture in the fire development, the required technical basis for predicting subsequent fire progress is clearly stated. An example of this is shown in Table 9.

It can be seen that the scenario analysis in Table 9 clearly indicates the need for additional technical basis in the form of testing. Without this information, an analyst must conclude that a cabinet fire involving non-IEEE 383 tested wiring may detrimentally affect more than one redundant circuit within the same cabinet. Any other conclusion would be based on conjecture without supporting merit.

TABLE 9

Example Qualitative Fire Scenario Analysis of a Cabinet Fire

Event	Likely Outcomes	Basis
Ignition Source Contacts One Redundant Circuit	No incipient fire occurs if IEEE 383 wiring is involved Incipient fire occurs if non-IEEE 383 wiring is involved	The use of wiring qualified to IEEE 383 (Ref. 1), requires very large and prolonged ignition sources to initiate a fire (Ref. 3)
Incipient Fire	Fire discovered and manually suppressed before redundant circuit is damaged	Testing must demonstrate this capability
	Fire automatically suppressed before redundant circuit is damaged	Testing must demonstrate this capability
	Meaningful fire occurs in one circuit	Without the testing called for in the preceding statements this outcome is unavoidable
Meaningful Fire Occurs in One Circuit	Fire is contained by separating barrier or distance within the cabinet, so that the redundant circuit remains unaffected	Testing must demonstrate this from the standpoint of heat and corrosive combustion products
	Redundant circuit is unacceptably degraded by the fire	Without the testing called for above, this outcome is unavoidable

Although the results of this example scenario analysis are inconclusive, they clearly indicate design weaknesses requiring further scrutiny. Such findings are of importance to both designers and regulators in determining obvious fire protection deficiencies.

5. Conclusions

A viable fire-hazards analysis methodology for nuclear power plant application

- Should be derived from, but not necessarily duplicate, available and proven techniques

- Should be defendable in terms of conservatism and technical merit

- Should be easily used by both designers and regulators.

Applying these criteria, the authors reviewed a large number of candidate-analysis techniques, each of which has been used by other fire protection analysts for various types of residential, commercial, industrial, and nuclear plant fire hazards. It was found that all of the available analysis methods reviewed proved deficient in meeting at least one of the analysis criteria and, therefore, it was decided to select and combine from available techniques those analysis attributes most responsive to the needs of nuclear power plant designers and regulators.

In Section 3 we developed what appears to be the most suitable analysis method for nuclear power plants. The method can be summarized as follows:

- First: A bounding deterministic evaluation is made under limiting fuel load and ventilation conditions to establish the adequacy of passive fire barriers.

- Second: If the results of the bounding deterministic evaluation prove unacceptable for plant safety, a probabilistic analysis is performed to assess the effectiveness of supplementary fire protection measures (e.g., fire suppression).

- Third: If the results of the probabilistic analysis prove unacceptable or inconclusive, a subjective analysis is carried out using a standard format and logic sequence.

To apply this methodology, an analysis technique was developed, technically defended, and simplified in Section 3 for each of the above analysis segments. Section 4 then demonstrated the usefulness of the analysis procedure.

On the basis of this study and a review of the fire-hazards analyses performed to date for several nuclear facilities, it is concluded that improvements can be made in most of the analysis techniques presently used. These improvements are important in eliminating the lack of both conservatism and technical merit inherent in many traditional analysis approaches.

The analysis methodology suggested in this report (Section 3) represents the first analysis procedure derived with the specific objective of ensuring conservative, yet credible, analysis results for achieving nuclear power plant fire safety. As a result, the objective of plant safety has remained unclouded by the monetary incentives typically associated with many traditional analyses performed for insurance purposes. Within the state of the art, the analysis approach suggested in this report has been shown as conservative and technically sound, while simultaneously being easily applied by designers and regulators.

6. Recommendations

As explained in the previous section, the most suitable fire-hazards analysis methodology for nuclear power plants appears to be a sequential technique made up of three segments termed deterministic, probabilistic, and subjective. Although we concluded that this approach combines the best attributes of several existing analyses for technical merit and ease of application, a number of recommendations should be cited regarding the limitations and potential areas of improvement of the overall analysis sequence and of each analysis segment.

Overall Analysis Sequence

The fire-hazards analysis procedure presented in this report enables an analyst to evaluate bounding fire conditions and to compare the relative effectiveness of various fire protection alternatives. The methodology does not provide guidance for determining what nuclear power plant areas actually require fire protection or what levels of fire protection are sufficient to meet overall plant safety objectives. Since, as explained in the introduction of this report, the answers to these questions lie beyond the scope of this study, two recommendations are appropriate.

1. Before any of the fire-hazards analysis procedures developed in Section 3 are applied to a nuclear power plant area, an evaluation should be made to ascertain the relative safety importance of the area being analyzed. Preferably this evaluation should be based on a systems analysis of the area in question. The only areas or area combinations requiring a thorough fire-hazards analysis are those whose systems are shown to be (a) important to accomplishing a safe plant shutdown, (b) functionally jeopardized by a fire, and (c) backed up by no other system elsewhere.

2. Before any fire protection scheme is adopted, a minimum fire safety objective should be established. One way

to do this would be through the designation of a maximum acceptable probability for fire risk to public safety, while another way would be through the use of common-mode or single-failure criteria, similar to those used for other postulated design-basis accidents (i.e., redundant systems philosophy).

Fuel Load and Ventilation Barrier Analysis Segment

The fuel load and ventilation barrier analysis technique developed in Section 3 was based on general principles of fire phenomena, up to the point at which the technique was simplified for easier application. At this stage, a number of assumptions were made to demonstrate the usefulness of the analysis methodology and, although the assumptions were chosen to represent certain typical power plant conditions, some other situations are recommended for examination.

1. Cable insulation was selected as the combustible for the bounding barrier analysis. Other combustibles, such as diesel oil and lubricating oil, should also be considered.

2. Reinforced 8-in. concrete walls were chosen to represent the barriers for analysis. Other barriers, such as block walls or panels having different physical properties, should also be analyzed.

Probabilistic Analysis Segment

In addition to the recommendation above for establishing an acceptable overall fire-risk probability objective, several recommendations for carrying out the probabilistic analysis are appropriate.

1. Actual tests should be run to refine the probability values for automatic detection system effectiveness. This program should focus on defining what effect

nuclear power plant conditions have on detection probabilities derived from nonnuclear applications.

2. The probability values associated with room flashover (Event J - fuel continuity interrupted) should be modified to account for the rate of fire development. Even at the same average fuel load, concentrated combustibles will promote flashover more quickly than dispersed combustibles, because the rate of fire development is often enhanced by concentrated fuel conditions.

3. The probability that a fire will penetrate a fire barrier depends on both the tested rating of the barrier in comparison with actual fire conditions and the probability that all portions of the barrier function as tested. As part of the deterministic fuel load and ventilation barrier analysis, the probability of barrier failure was taken as unity when a barrier is exposed to a fire more severe than rated test conditions. However, no probability values have been assigned to barrier failures which result from random failure of barrier elements such as doors, dampers, and penetration seals. These failures will occur with a finite probability even though an actual fire severity lies below the conditions used for testing.

   Probabilities are needed to establish the chance for this type of failure to determine what numbers and types of openings degrade a "passive" fire barrier to a point at which active fire-protection measures are more reliable.

Subject to the recommendations outlined in this section, the fire-hazards analysis procedure developed in this study appears to be the best approach available for evaluating fire protection effectiveness in the context of nuclear power plant safety.

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APPENDIX

Combined Induced Draft Plus Forced Ventilation

The flow through a room opening as the result of pressure within the room can be expressed as

$$P_1 - P_2 = \frac{C_d P_1 W_1}{2RT_1} v_1^2 \quad \text{(see Figure A-1)} \quad , \tag{A-1}$$

where

T_1 = the average temperature inside the room

P_1 = the pressure of gases inside the room averaged vertically over the opening

P_2 = the pressure of air outside the room averaged vertically over the opening

W_1 = the molecular weight of gas inside the room

C_d = the opening discharge coefficient, usually around 0.7

R = the universal gas constant

v_1 = the average velocity of gases through the opening as shown in Figure A-1.

It is possible to express P_1 and P_2 as

$$P_1 = P_1^s + \frac{P_1 W_1 g h_1}{2RT_1} \quad , \tag{A-2}$$

$$P_2 = P_2^s + \frac{P_2 W_2 g h_1}{2RT_2} \quad , \tag{A-3}$$

where

P_1^s = the static pressure of gases at the top of the opening inside the room

g = the acceleration of gravity

P_2^s = the static pressure of air at the top of the opening outside the room

W_2 = the molecular weight of air outside the room

h_1 = the vertical portion of opening through which ventilation system flow is forced in combination with induced draft flow from the room

T_2 = the temperature of air outside the room.

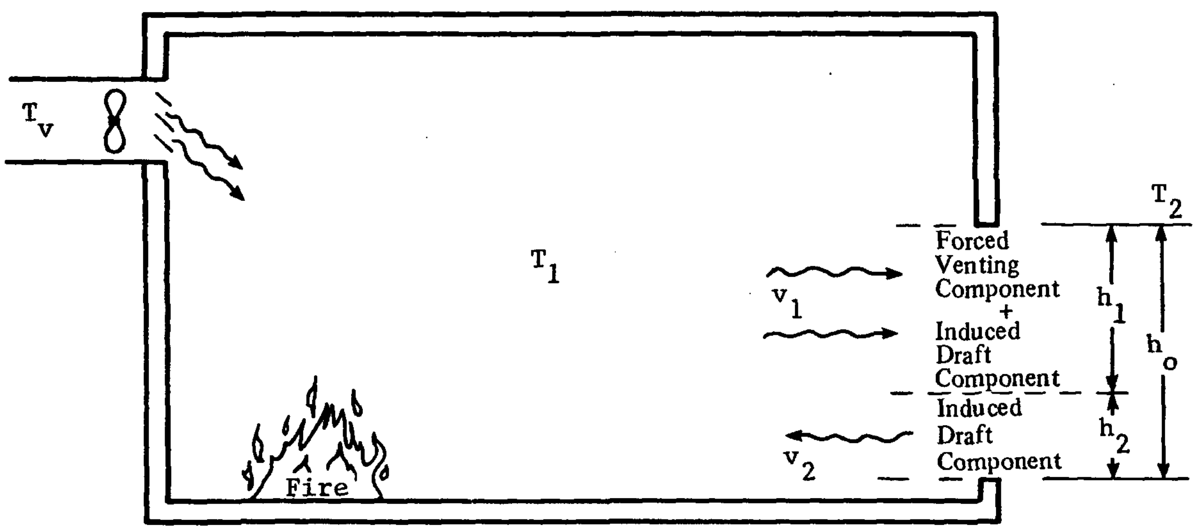

Figure A-1. Combined Case of Induced Draft Plus Forced Ventilation Air Supply

Substituting Eqs. (A-2) and (A-3) into (A-1) for P_1 and P_2:

$$P_1^s\left(\frac{2RT_1}{2RT_1 - W_1gh_1}\right) - P_2^s\left(\frac{2RT_2}{2RT_2 - W_2gh_1}\right) = P_1^s\left(\frac{2RT_1}{2RT_1 - W_1gh_1}\right)\frac{C_dW_1v_1^2}{2RT_1}$$

Solving for v_1:

$$v_1 = \left\{\frac{2RT_1}{C_d W_1}\left[1 - \left(\frac{P_2^s}{P_1^s}\right)\left(\frac{T_2}{T_1}\right)\left(\frac{2RT_1 - W_1 g h_1}{2RT_2 - W_2 g h_1}\right)\right]\right\}^{1/2} \quad \text{(A-4)}$$

For a given T_2, P_2^s, W_2, and C_d,

$$v_1 = f_1\left(T_1,\ P_1^s,\ h_1, \text{ and } W_1\right)$$

where

f_1 = the functional relationship shown in Eq. (A-4).

In a similar way v_2 can be expressed as

$$P_2 - P_2 = \frac{C_d P_2 W_2}{2RT_2} v_2^2 \quad ,$$

where

$$P_2 = P_2^s \left(\frac{2RT_2}{2RT_2 - 2W_2 g h_1 - W_2 g\ (h_0 - h_1)}\right) \quad ,$$

$$P_1 = P_1^s \left(\frac{2RT_1}{2RT_1 - 2W_1 g h_1 - W_1 g\ (h_0 - h_1)}\right) \quad ,$$

or

$$v_2 = \left\{\frac{2RT_2}{C_d W_2}\left[1 - \left(\frac{P_1^s}{P_2^s}\right)\left(\frac{T_1}{T_2}\right)\left(\frac{2RT_2 - 2W_2 g h_1 - W_2 g\ (h_0 - h_1)}{2RT_1 - 2W_1 g h_1 - W_1 g\ (h_0 - h_1)}\right)\right]\right\}^{1/2} \quad \text{(A-5)}$$

For a given T_2, P_2^s, W_2, h_0, and C_d,

$$v_2 = f_2 \left(T_1,\ P_1^s,\ h_1,\ \text{and } W_1\right) \quad ,$$

where

f_2 is the functional relationship shown in Eq. (A-5).

If, on the basis of assumption 3 on page 47, the molecular weight of the room gases is taken to be equal to the molecular weight of air, W_1 can be eliminated as a variable. Also, T_1 can be eliminated as a variable for design purposes by selecting a conservative average temperature representative of the standard time-temperature test curve. As a result of these assumptions,

$$v_1 = f_1(P_1^s,\ h_1) \quad ,$$

$$v_2 = f_2(P_1^s,\ h_1) \quad .$$

To solve these equations involving four variables, two more relationships are needed.

One relation can be derived from known characteristics of the ventilation system, relating the discharge backpressure of the ventilation system fans to their flow characteristics. Such information is expressed usually as pressure-flow curves supplied by fan manufacturers, or in mathematical terms for the room shown in Figure A-1:

$$F = q(\Delta P_s + P_1) \quad ,$$

where

q = a functional relationship characteristic of a particular fan

ΔP_s = the ventilation system pressure drop to the room

P_1 = the pressure in the room

F = the volumetric flow rate of the fan at the discharge temperature and pressure of the fan.

If it is noted that, for typical room pressure conditions and for reasonably insensitive fan performance, P_1 can be taken as equal to P_1^s, F may be expressed as

$$F = q(\Delta P_s + P_1^s) \tag{A-6}$$

Unfortunately Eq. (A-6) has introduced another variable F, so that two more equations are still needed.

One equation can be found by rewriting Eq. (5) in the body of the report in terms of the pressures, temperatures, heights, and velocities shown in Figure A-1. Assuming W_1 equals W_2, the resulting equation is

$$v_2 = \frac{2}{3} C_d \sqrt{2gh_0} \left\{ \frac{1 - \dfrac{P_1^s T_2}{P_2^s T_1}}{\left[1 + \left(\dfrac{(r+1)^2 P_2^s T_1}{P_1^s T_2}\right)^{1/3}\right]^3} \right\}^{1/2} \tag{A-7}$$

A final relation can be expressed as an overall material balance, assuming $W_1 = W_2$. This gives

Mass of Air Entering + Mass of Fuel Burning = Mass of Gases Leaving, or

$$(r + 1)\left[\frac{F\left(P_1^s + \Delta P_s\right)}{T_v} + \frac{v_2\left(h_0 - h_1\right)w_o P_2^s}{T_2}\right] = \frac{v_1 h_1 w_o P_1^s}{T_1} ,$$

where

T_v = the ventilation system temperature

w_o = the width of the opening.

Solving this equation for F:

$$F = \left[\frac{v_1 h_1 w_o P_1^s}{T_1 (r + 1)} - \frac{v_2\left(h_0 - h_1\right) w_o P_2^s}{T_2}\right]\left(\frac{T_v}{P_1^s + \Delta P_s}\right) \qquad \text{(A-8)}$$

Equations (A-4) through (A-8) can be solved simultaneously for v_1, v_2, F, P_1, and h_1. To effect a solution, Eq. (A-5) should be rearranged as follows:

$$h_1 = \frac{\left(2RT_1 - W_1 g h_0\right)\left[1 - \frac{v_2^2 C_d W_2}{2RT_2}\right]\left(\frac{P_2^s T_2}{P_1^s T_1}\right) - 2RT_2 + W_2 g h_0}{W_1 g\left[1 - \frac{v_2^2 C_d W_2}{2RT_2}\right]\left(\frac{P_2^s T_2}{P_1^s T_1}\right) - W_2 g} \qquad \text{(A-9)}$$

One procedure for solving these equations:

1. For a particular opening size (w_o and h_o specified), pick a value of P_1 and solve Eq. (A-7) for v_2.
2. Substitute v_2 into Eq. (A-9) and solve for h_1.
3. Substitute h_1 into Eq. (A-4) and solve for v_1.
4. Substitute h_1, v_1, and v_2 into Eq. (A-8) and solve for F.

5. Compare the calculated F to the F value obtained from Eq. (A-6) for a particular ΔP_s and the P_1 assumed in Step 1.

6. Assume a new P_1 and repeat Steps 1 through 5 until the F values calculated in Steps 4 and 5 agree.

By converting v_2 and F into mass flow rates of air, it is possible to produce theoretical curves relating the mass flow of air from forced ventilation and induced-draft ventilation to the static pressure in the burning room. Once a designer, through trial-and-error solution, finds values of ventilation system flow rate and room static pressure which satisfy the theoretical curves and the corresponding pressure/flow characteristics of the ventilation system fan, the resulting static pressure can be used to find the induced draft flow. The forced and fire-induced draft flows then can be added for use in Figures 12 and 14 to predict fire severity.

Unfortunately, in most cases it would be impractical to use the theoretical curves relating static pressure to flow rates, primarily because of the sensitive nature of the fire-induced draft airflow rates to slight changes (approximately 1-Pa range) in static pressures. To compound this problem, a designer seldom knows ventilation system pressure drops and fan-performance characteristics to an accuracy greater than about 50 Pa.

As a result of these practical limitations, the only reasonable approach available for conservative calculation of combined airflow rates is to assume that forced draft and fire-induced draft air components can be added without interaction. This approach is conservative, since a forced-ventilation system blowing air into a room will tend to increase the room's static pressure and thereby reduce the fire-induced draft airflow. At the same time, changes in forced-draft flow as a result of static pressure changes will be insignificant because of the overwhelming effects of ventilation system pressure drop and fan performance.

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