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Nuclear Power Plant Fire Protection — Philosophy and Analysis

Dennis L. Berry

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Nuclear Power Plant Fire Protection -
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Abstract

This report combines a fire severity analysis technique with a fault tree methodology for assessing the importance to nuclear power plant safety of certain combinations of components and systems. Characteristics unique to fire, such as propagation induced by the failure of barriers, have been incorporated into the methodology. By applying the resulting fire analysis technique to actual conditions found in a representative nuclear power plant, it is found that some safety and nonsafety areas are both highly vulnerable to fire spread and important to overall safety, while other areas prove to be of marginal importance. Suggestions are made for further experimental and analytical work to supplement the fire analysis method.

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The author acknowledges the contributions made to this report by Ann W. Frazier of Sandia National Laboratories' Nuclear Fuel Cycle Safety Research Department and by Leo J. Klamerus and Lester D. Lambert of Sandia National Laboratories' Light Water Reactor Safety Department. Mr. Klamerus and Mr. Lambert helped to gather large volumes of data describing the equipment locations, fuel loads, ventilation rates, fire area adjacencies, room sizes, door openings, and heat loss areas associated with an actual power plant. This work entailed a tedious review of structural drawings, system descriptions, and plant mockups. Mrs. Frazier developed the computer programs needed to mathematically manipulate these fire data for further analysis, and she developed a computer program which can systematically determine the potential spread paths of fires throughout a power plant, given a particular set of fire barrier failure criteria.

In addition, the author acknowledges the contribution made by Dan V. Swenson of Sandia National Laboratories' Light Water Reactor Safety Department for his work in developing improved criteria for describing fire barrier failures (Appendix B). When combined with an analysis which predicts expected fire severities, Mr. Swenson's model suggests ways of improving the analysis techniques described in this report.

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Summary

This report prepared for the U. S. Department of Energy's Light Water Reactor Safety Technology Program, is the first of several reports aimed at providing an integrated methodology for assessing nuclear power plant fire safety. Since the Browns Ferry Fire in 1975, a concern and lack of phenomenological understanding about fires has resulted in what has been called a "defense in depth" regulatory policy for power plant fire protection. This policy has required the use of numerous measures to prevent and control fires, including requirements for fire retardancy, automatic detection, fire barriers, automatic suppression, and fire brigades. Despite these steps, however, recently completed fire testing indicates that some fire protection measures may be less effective than originally perceived and may require further study to identify their limitations.

Although research has been carried out to some extent for virtually every aspect of fire protection, no logical method has been developed to integrate a knowledge of fire phenomena with information about the relative vulnerability and safety-importance of particular power plant systems. Instead, unacceptable fire scenarios have been defined as being all fires which can occur in a plant area containing or threatening safety-related equipment, while efforts to prevent such scenarios have focused on breaking the chain of events leading from initiation to propagation. Such a philosophy can overemphasize the importance of some plant areas and ignore the importance of other areas.

One solution to this problem is offered by a new fire analysis technique presented in this report. The technique uses the following procedure:

1. The logical interdependence of all safety components is expressed in fault trees and then, based on the physical location of these components, the interdependence of each corresponding safety area is established.
2. The physical location of all plant areas is determined together with a description of the types of fire barriers which separate the areas from one another.
3. The ability of each fire barrier to prevent fire from spreading between adjacent areas is analyzed and combined with the results of step 1 to find which fire spread scenarios jeopardize critical safety areas.
4. The causes contributing most to each unacceptable fire spread situation are identified, together with options for eliminating the causes.

By applying this approach to data derived from an actual power plant, it was found that, in this example case, the protection of fourteen plant areas will eliminate all fire scenarios which could cause a release of radioactive material from the plant. In addition, it was concluded that it may be possible to achieve fire protection safety by protecting even fewer areas through a systematic selection of those areas common to several different fire spread paths. Such a refinement of the technique presented in this report would result in the identification of a minimum set of safety and nonsafety areas requiring fire protection. Work to identify this minimum set of areas is continuing.

1. Introduction

Nuclear power plants are complicated, containing numerous systems designed to operate reliably under various normal and abnormal conditions. Since a fire affecting some of these systems can jeopardize the ability of a nuclear power plant to operate safely,¹ the U. S. Nuclear Regulatory Commission (NRC) has focused considerable attention in recent years on assessing the adequacy of power plant fire protection. Some of this attention has taken the form of regulatory guidance issued soon after the Browns Ferry Fire in 1975,¹⁻³ while other work has proceeded with the long-term goal of understanding fire phenomena as they relate to nuclear power plant conditions.⁴⁻⁹ Despite these efforts, however, no logical method has been developed to integrate a knowledge of fire phenomena with information about the relative vulnerability and safety-importance of particular power plant systems. This report, prepared for the U. S. Department of Energy's Light Water Reactor Safety Technology Program is the first of several reports aimed at providing an integrated methodology for assessing nuclear power plant fire safety.

Any nuclear power plant fire which can initiate, grow, and propagate in a manner that ultimately degrades enough plant systems to jeopardize public health and safety must be viewed as unacceptable. Clearly, if steps could be taken to guarantee that all such unacceptable fire scenarios are identified and prevented, fire safety would be assured. Up to now, efforts to do this have followed the philosophy of defining unacceptable fire scenarios as all fires which can occur in a plant area containing or threatening safety-

related equipment, while efforts to prevent such scenarios have focused on both preventing fires from starting and breaking the chain of events leading from initiation to propagation.^{2 3} Although this approach is basically sound, problems arise in its application.

First, by protecting everything safety-related, designers and regulators may lose sight of the relative importance of systems and their locations. Without knowing this relative ranking, protection efforts may be wasted on plant locations insignificant to fire safety. Second, there are some areas where a fire could destroy enough equipment to cause a safety problem without spreading to adjacent locations, and there are other areas from which fire must spread in order to jeopardize enough equipment to threaten plant safety. Clearly, single area vulnerabilities warrant special attention, as do combinations of adjacent areas which are important to safety. However, safety area combinations separated from one another by numerous fire barriers may require less analysis to demonstrate fire protection adequacy. Third, by focusing on safety-related areas, an analyst or regulator may overlook the importance of a nonsafety area which, because of its location, can allow the spread of fire to other areas that contain safety-related systems. Fourth, without demonstrating the actual effectiveness and reliability of measures taken to break the chain of events leading from initiation to propagation, neither an absolute nor relative assessment can be made of the level of fire safety achieved.

It is the purpose of this report to resolve these problems by providing an analysis methodology which (1) identifies plant areas where involvement in fire can significantly jeopardize safety, and

(2) establishes the relative effectiveness of measures to prevent initiation, growth, and propagation of fires.

2. Analysis Method

The methodology which was developed for this report for performing a fire hazards analysis follows four steps. These steps are:

1. Establish the importance and interdependence of all plant safety areas.
2. Determine the relative locations of all plant areas and the types of fire barriers separating the areas.
3. Find which fire spread paths between adjacent areas can jeopardize critical safety area combinations.
4. Identify contributing causes and solutions for each unacceptable fire spread situation.

Techniques for accomplishing each of these steps are discussed in this section.

Safety Area Importance and Interdependence

For several years work has been done to identify the vulnerability of nuclear power plants to sabotage.¹⁰⁻¹² By expressing the logical interdependence of plant areas in an overall safety-system fault tree, sabotage analysis techniques have identified which combinations of sabotage acts will lead to radioactive release and which plant areas a saboteur must enter to accomplish the required acts.

For fires, the situation is similar. An overall safety-system fault tree can be developed for plant safety systems. Then the fault tree can be expressed in terms of fire areas. Once completed, the fire area fault tree can be reduced using Boolean logic techniques to yield a list of critical area combinations whose involvement in a common fire will damage enough equipment to jeopardize safety. Finally, by taking the Boolean complement of the fault tree logic equation, a sufficient set of areas from the list of critical area combinations can be identified which require fire protection. In more physical terms, the Boolean manipulations assure that at least one fire area of each critical area combination is selected for protection to assure that a common fire cannot damage all equipment of any critical combination.

Area Locations and Barrier Identification

Because fires occurring in any safety or nonsafety plant area can potentially spread to a critical combination of other safety areas, it is important to establish the relative locations of all areas and to identify the types of barriers (i.e., walls) installed to prevent the spread of fire. For existing plants this information can be gathered through field surveys, while plants under design can be analyzed with the help of arrangement drawings.

For a typical plant currently under design, such as the one shown in Figure 1, about 85 different fire areas (See Table 1) can be found from design drawings. Since each of these areas normally will be adjacent to one or more other areas, a large number of adjacency combinations need to be determined and

Figure 1. Plant Layout of a Typical Nuclear Power Plant.

Table 1. Fire Areas Found Throughout a Typical Power Plant.

<u>Fire Area Designations</u>		<u>Number of Areas</u>
RB	Reactor Building	1
A1-A32	Auxiliary Building	32
C1-C36	Control Building	36
D1, D2	Diesel Building	2
F1-F7	Fuel Building	7
T1, T2	Turbine Building	2
RW1, RW2	Radwaste Building	2
CC1	Communications Corridor	1
AB	Auxiliary Boiler Room	1
HMS1	Hot Machine Shop	1
		—
		Total 85

Table 2. Fire Area Adjacency Matrix

[illegible]

expressed in a concise format for analyses. This can be done by adopting a matrix format such as that shown in Table 2. In this matrix, the columns and rows are designated as fire areas taken from Table 1, so that there are 85 rows and 85 columns. To show when fire areas are adjacent, black squares have been placed at the intersections of rows and columns for those areas which are adjacent. So reading from left to right across the row denoted as area D1, black squares indicate that D1 is adjacent to fire areas D2, A8, A16, A27, C10, C11, C15, C17, C21, and C23; these areas share common barriers with area D1.

Fire Spread Paths

In earlier work it was found that, because of a lack of experimental and analytical information about the initiation, growth, and extinguishment of fires, analysis techniques should focus on demonstrating the adequacy of passive fire barriers (i.e., walls) to contain fires under worst-case fire conditions.⁹ As explained in Appendix A to this report, one method for doing this combines information about the fuel load, ventilation rate, heat loss surface area, and fire barrier ratings associated with each power plant area, in order to establish whether the fire barriers surrounding each area can withstand limiting fire conditions. Figure 2 shows the results of this earlier effort.

The diagonal lines in Figure 2 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. The curved line in Figure 2 corresponds to combinations of fuel load and ventilation

Figure 2. Acceptable Fuel Load and Ventilation Combinations Assuming Heat Loss Into Walls Only.

rate whose time-temperature histories just reach but do not exceed the standard time-temperature curve used for testing barriers.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.

In order to use Figure 2, a designer must be able to relate a room's actual fuel load and ventilation conditions to the coordinates of the figure. 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 should be 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. For ventilation rates, forced ventilation, fire-induced ventilation, or a combination of both effects must be estimated. Appendix A and Reference 9 present simplified techniques for making these estimates.

By using Figure 2 together with a knowledge of a room's wall and ceiling area, fuel load, and ventilation characteristics, it can be determined whether fire barriers alone will contain a total-involvement fire and therefore, which fire spread scenarios can be expected.

Causes and Solutions for Fire Spread Problems

For those cases where a fire spread path involves a critical combination of safety areas, Figure 2 can be used to identify specific causes and solutions for each problem. Options available are:

1. Reduce fuel loads to limit fire duration or fire intensity or both.
2. Adjust ventilation rates to reduce fire duration or fire intensity or both.
3. Increase barrier ratings to withstand hotter fires or longer fires or both.
4. Detect and extinguish fires to limit fire duration or fire intensity or both.
5. Relocate safety components to eliminate common fire vulnerabilities.

By using Figure 2 with a knowledge of the fuel loads, ventilation rates, barrier ratings, and locations of those fire areas involved in unacceptable fire spread scenarios, it is possible to focus attention on major problem causes and to choose appropriate solutions for each problem situation.

3. An Example Analysis

In order to carry out the analysis method described in Section 2, detailed information about safety systems, plant arrangements, and fire hazards must be gathered and analyzed. To demonstrate how this can be done in practice, it was decided to perform the proposed fire hazards analysis method on an actual power plant

currently under design. Sources of information used to do this included, system descriptions, piping and instrumentation drawings, general arrangement drawings, structural drawings, logic diagrams, equipment identification and location lists, and cable tray drawings. With this information, the safety importance of each plant area was established, together with numerical estimates of a number of parameters needed to characterize worst-case fire severities, including the type and weight of fuel, ventilation rates, door sizes, heat loss areas, and types of fire barriers associated with each fire area. This section describes how the analysis was carried out and some of the typical analysis results obtained.

Safety Area Importance and Interdependence

The plant selected for analysis was referred to earlier in Section 2 as having 85 different fire areas (See Figure 1 and Tables 1 and 2). Through a fault tree analysis of the plant's safety systems, it was found that 26 different combinations of 23 fire areas (out of the original 85 areas) are important to preventing the release of radioactive material from the plant under certain fire conditions (see Table 3). For some of the 26 combinations, the loss of a single fire area could cause a radiological release, while in other instances a combination of as many as four different areas must be lost to cause a problem. By taking the Boolean complement of the location equation containing 26 terms, it was found that by protecting fourteen of the 23 critical areas all fire spread paths which could cause radiological release can be eliminated (see Table 4).

Table 3. Combinations of Areas for Which a Common Fire Could Initiate Release of Radioactive Material From the Plant.

Area Combinations

<u>Singles</u>	<u>Multiples</u>	
A1	A15 * C9	C10 * C16
A23	C15 * C16	C10 * D1
A28	D1 * C15	C9 * C10
A29	C9 * C15	A14 * C10
A30	A14 * C15	A17 * A18
C27	D2 * C16	A13 * A15 * C16
F1	D1 * D2	A13 * A15 * D1
RB	C9 * D2	A13 * A14 * A15
	A14 * D2	F2 * F3 * F6 * F7

Note: * = Logical AND.

Table 4: Areas Whose Protection Will Ensure Fire Safety

A1	A15
A23	A17
A28	C10
A29	C15
A30	D2
C27	F6
F1	
RB	

Of course, these numerical results apply only to the particular plant being analyzed, and for other plants, more or fewer areas may require protection. In addition, other areas beyond those listed in Table 4 can be selected for protection from the combinations in Table 3 and still ensure fire safety. For example, instead of protecting area A15, areas C9 and A13 can be protected. Depending upon plant conditions, it may be more attractive to protect both C9 and A13 then to guarantee the protection of A15 alone.

Area Locations and Barrier Identification

Regardless which plant areas are chosen for protection, the locations of these areas relative to each other and to other areas must be determined, together with an identification of the fire barriers protecting each area. For the example power plant, Table 2, which was discussed in Section 2, identifies the relative locations all plant areas. Barrier data for each adjacency were gathered in the following format: D1-A8, 4 hr, 24-inch reinforced concrete. In this case the barrier separating areas D1 and A8 is constructed of 24-inch reinforced concrete, thus corresponding to a barrier successfully passing a 4-hour furnace test in accordance with Reference 13. For the example power plant 325 separate adjacencies were treated in this way. Since all components installed in fire barriers (e.g., doors and seals) have the same fire duration test rating as the barriers, it was assumed in this example fire analysis that if fire conditions exceed test conditions the entire barrier fails.

Fire Spread Paths

As explained in Section 2 and Appendix A, an analysis of fire barriers can be conducted using a knowledge of the fuel, ventilation, heat loss area, and barrier rating of each fire area. Since the type and extent of barrier information gathered has been explained already, only fuel, ventilation, and heat loss area data remains to be discussed.

● Fuel -

The amounts of cable insulation, lube oil, fuel oil, cleaning solvents, paper, rags, and other combustibles found in each fire area were added on an energy equivalent basis to yield the total permanent and transient fuel that could contribute to a fire initiating within each fire area. Table 5 shows the energy equivalent values used and the typical fuel quantities found for several areas. Energy equivalent information was gathered for all 85 areas shown in Table 2.

● Ventilation -

Ventilation contributions come from two sources - air flows induced by fire and air flows forced by ventilation system fans. For the induced flows, the sizes and numbers of door openings for each fire area were found and used to yield air flow rates (see Appendix A, Figure A6). For the forced flows, ventilation system design data was gleaned from the system descriptions and flow diagrams of the example power plant. Typical flow values derived in this manner are in kilograms per second:

Table 5. Fuel Energy Equivalents and Typical Fuel Quantities.

	<u>Energy Equivalent</u>
Cable Insulation	6.2×10^6 J/kg
Lube Oil	4.0×10^7 J/l
Fuel Oil	3.3×10^7 J/l
Cleaning Solvents	2.4×10^7 J/l
Paper	3.6×10^6 J/kg
Rags	3.6×10^6 J/kg
Charcoal Filters	6.7×10^6 J/kg

Area A6: 1.0×10^{10} Joules, Fuel Energy Equivalent.

Area C9: 1.3×10^{11} Joules, Fuel Energy Equivalent.

Area F6: 6.0×10^{10} Joules, Fuel Energy Equivalent.

	<u>Induced</u>	<u>Forced</u>	<u>Total</u>
Area 6	10.2	-	10.2
Area C9	14.3	2.0	16.3
Area F6	2.0	-	2.0

Similar ventilation information was gathered for all 85 fire areas.

● Heat Loss Area -

As explained in Section 2 (page 10), heat loss areas for each fire area should include the ceiling and perimeter wall areas. For the example power plant, this information was scaled directly from architectural drawings. A typical range of values included:

	<u>Heat Loss Area (m²)</u>
Area A6	610
Area C9	612
Area F6	260

Before the above fuel load and ventilation information can be used in Figure 2 to establish barrier adequacy, each value must be normalized by the associated heat loss area. Doing this for three of the 85 areas yields:

	<u>Fuel Load (joules/m²)</u>	<u>Ventilation (kg/s-m²)</u>
Area A6	20 x 10 ⁶	17 x 10 ⁻³
Area C9	210 x 10 ⁶	27 x 10 ⁻³
Area F6	232 x 10 ⁶	8 x 10 ⁻³

The significance of these values can be seen in Figure 3 and summarized as follows:

Area A6: A barrier rated in excess of about 1/2 hour should satisfactorily contain a full involvement fire within A6.¹³

Figure 3. Pass/Fail Coordinates for Example Fire Areas A6, C9, and F6.

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Area C9: No barrier tested in accordance with Reference 13, regardless of its hourly rating, can be shown to be satisfactory, because a full-involvement fire in C9 will yield a temperature condition which exceeds that used in testing.

Area F6: A barrier rated in excess of about 4 hours should satisfactorily contain a full-involvement fire within F6.¹³

Since the fire barriers installed around A6, C9, and F6 are rated at 3 hours, only those barriers surrounding A6 can satisfactorily contain a full-involvement fire--those around C9 are expected to fail from excessive temperatures and those around F6 can fail from excessive exposure duration.

In a similar manner, the 325 separate barriers surrounding all 85 areas can be analyzed and the results presented in a "fire spread adjacency matrix." This has been done in Table 6. Upon reviewing Table 6, it can be seen that the symmetry expressed in Table 2 no longer exists. For example, a fire in C9 can spread to C13, C14, and elsewhere, while fires in C13 and C14 will not spread to C9. This asymmetry follows from the fact that the fire spread adequacy of a particular barrier depends on the barrier rating and the fire hazards threatening the barrier. The fire hazard inherent in C9 is large and can cause barrier failure, while the hazard levels in C13 and C14 constitute an acceptable barrier threat. Another observation that can be made from Table 6 is that fire spread adjacencies can be analyzed in sequence to yield "fire spread paths." For example, a fire starting in Area D1 can spread

to D2, from there to C10, C15, C21, and C36 and from these areas to many others. A computer code was developed to carry out the systematic enumeration of all fire spread paths, and it was found that 1) under the conservative assumptions used in the fire spread model, and 2) in the absence of fire suppression measures, fires starting in most of the plant areas can spread to most other areas.

Causes and Solutions for Fire Spread Problems

In order to prevent fire spread or eliminate safety problems associated with fire spread, one or more of five different courses of action may be followed as described in Section 2, including changes in fuel loads, ventilation rates, and barrier ratings; addition of detection and extinguishment capability; and relocation of safety components. The viability of the first three of these options can be evaluated for the two fire spread cases just discussed (i.e., areas C9 and F6). For these example cases, Figure 3 shows the following:

Options for C9

1. Fuel load in C9 must be reduced by 88%, or
2. Ventilation rate in C9 must be reduced by 60%, or
3. Barriers surrounding C9 must be tested to temperatures well in excess of those currently used.¹³

Options for F6

1. Fuel load in F6 must be reduced by 18% for 3-hour rated barriers, or
2. Ventilation rate in F6 cannot be adjusted by itself to prevent fire spread, unless a barrier rated at 4-1/2 hours or more is employed, or

3. Barriers surrounding F6 must be upgraded to a rating of about 4-1/2 hours.¹³

A review of these options reveals several "unwieldly" problems for design and construction. Specifically:

1. A reduction of fuel by more than a few percent may entail significant rerouting of cable and relocation of equipment.
2. Ventilation sources often are needed to control space temperatures and to provide personnel access openings.
3. Barrier qualification testing under "nonstandard" conditions of temperature or duration cannot be accomplished using existing test equipment and procedures.^{8 13}
4. Barriers and barrier components (e.g., penetration seals, dampers, and doors) fail quickly under extreme temperature or long duration testing.⁸

There are several possible ways of either solving these problems or entirely avoiding them. Unfortunately, however, the available alternatives are not easily shown to be foolproof.

One alternative would be to apply the fourth course of action mentioned above to prevent fire spread -- detection and extinguishment. By doing this, one could argue that fires in areas C9 and F6 will be detected and extinguished before more than 12% or 82%, respectively, of the fuel in these areas burns. Work to demonstrate the reliability of detection and extinguishing systems within nuclear power plants, however, remains to be completed.^{7 14}

Another alternative would be to apply the fifth course of action mentioned above -- relocate safety components. By doing this, redundant safety systems could be moved to locations which

are not susceptible to common fire spread paths. In this case problems again arise. As discussed earlier, the interconnected nature of fire areas results in an enormous number of fire spread paths potentially threatening redundant safety systems. Without an efficient analysis technique to guide the relocation of safety components, a hopelessly tedious trial and error method would need to be followed, with no assurance that optimum relocations could be found. In addition to this, operational and construction difficulties must be recognized before any relocation scheme can be implemented.

A final alternative which can affect each of the five options discussed would be to reduce the level of conservatism contained in the baseline fire protection policy. As explained in Section 2 and Appendix A, a number of analysis assumptions were needed before a conservative fire barrier evaluation could be undertaken. These assumptions included:

1. Total fuel involvement burning conditions (i.e., post flashover).
2. Unrestricted air inflow for combustion.
3. No heat loss by convection.
4. Immediate barrier failure when fire temperature or duration exceeds barrier test conditions.

For various reasons, including a lack of experimental information or complexity of analysis, each of these assumptions were judged to be necessary. Even if some of these conservations are reduced by performing a structural analysis of concrete barriers under fire conditions (Appendix B), uncertainties regarding the failure

mechanisms of barrier components (e.g., doors, dampers, and penetration seals) rule out the use of a structural analysis for all but the simplest concrete fire barriers.

4. Recommended Analytical and Experimental Options

As stated in Section 1, this report is the first of several reports aimed at providing an integrated methodology for assessing nuclear power plant fire safety. Based on the analysis problems and conservatisms presented in the previous section, however, it appears that improvements need to be made in three major categories. These categories are: analysis of barrier effectiveness, analysis of active fire control measures, and analysis of safety area vulnerability. Recommendations for further analytical and experimental work for each of these categories follows.

Analysis of Barrier Effectiveness

In order to improve the barrier analysis model presented in Section 2 and Appendices A and B, testing should be performed to increase the understanding of the phenomena governing barrier failure and fire severity.

- Testing of barriers and barrier components (e.g., seals, dampers, and doors) under nonstandard¹³ test conditions to confirm barrier performance characteristics for long exposures and for high temperatures is needed. This information could be used to expand the region of acceptance in Figure 2 and reduce the overall number of potential fire spread paths.

- Testing to confirm the contention made in Appendix A regarding flashover (i.e., total involvement) within power plant areas as a worst-case fire condition is needed. Although other research cited in Appendix A appears to support this contention, the limited ventilation available for fire in nuclear power plant areas may preclude achievement of total involvement burning and may contradict the implication of fire spread throughout an area by flashover.
- Testing to assess the adequacy of barriers, other than walls (e.g., partitions within electrical cabinets or between cable trays) is needed. By demonstrating the suitability of such barriers, large fire areas may be rationally subdivided into smaller fire areas, containing separate trains of redundant systems with lower fuel loads and reduced fire threat.

Analysis of Active Fire Control Measures

Despite efforts to demonstrate fire safety through the use of passive fire barriers, barrier analysis and testing uncertainties and equipment relocation problems will necessitate continued reliance upon some active fire control measures. In support of this, testing should be performed to demonstrate the effectiveness of active suppression options.

- Testing of combined automatic fire detection and suppression systems to confirm their reliability and effectiveness for the types of fuels and conditions found in nuclear power plant areas is needed. This work should yield criteria governing the use of active fire control systems, as func-

tions of fuel type, required speed of response, permissible fire growth proportions, and potential exacerbating effects (e.g., shorting of surrounding electrical equipment).

- Testing to establish the vulnerability of equipment to fire environments is needed. Since active fire control measures are important primarily for plant locations which cannot achieve safety system separations with passive fire barriers, knowledge must be gained to establish to what extent a fire within an area can jeopardize surrounding equipment.

Analysis of Safety Area Vulnerability

The fourteen safety-related areas listed in Table 4 of Section 3 represent a sufficient set of areas to protect, but not necessarily the minimum set requiring protection. It might be possible to break all fire paths of concern by protecting a smaller set of areas which includes non-safety areas through which fire must spread in order to reach the critical combinations of safety areas. To do this and to establish the best ways of ensuring adequate protection:

- Analysis techniques to identify combinations of plant areas where protection both will ensure safety and will cause a minimum impact on plant construction and operability is needed.
- Analysis techniques to judge the relative merit of active versus passive protection measures is needed.

By pursuing the testing and analysis efforts outlined above, the fire hazards analysis technique described in this report can be used to assess the degree to which fire can threaten the safety

of a particular nuclear power plant and the manner in which unacceptable fire scenarios can be avoided.

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Appendix A

Barrier Evaluation Technique

On the basis of considerable fire research,^{A1-A11} it can be concluded that fire phenomena should be viewed in terms of two parameters, fuel load and ventilation rate. Research efforts which have proven most successful in correlating these parameters have considered the following facts:

- Fully developed fires burn at rates limited by either (1) kinetic combustion limitations which are a function of the surface temperature and available fuel surface area (i.e., surface-controlled burning), or (2) oxygen limitations (i.e., ventilation-controlled burning).
- Total involvement of the combustibles in a room (i.e., post flashover) represents the most severe challenge to barriers.
- The time-temperature history of fire in a room must satisfy fundamental conservation laws (i.e., the rate of heat evolution must equal the rate of heat loss plus the rate of heat buildup).

Unfortunately, most of the current analysis techniques derived from these facts have several major deficiencies which make them unattractive for nuclear power plant fire barrier analysis:

- Most of the techniques are cumbersome. An analyst often has to apply principles of fuel dynamics and heat transfer to solve some problems.
- Many of the techniques are able to treat ventilation limitations only 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 which combinations of fuel load and ventilation are acceptable for a given barrier.

Despite these shortcomings, Reference A12 presents a deterministic barrier evaluation technique which is shown to be conservative and readily implementable. This technique is restated here for completeness.

Mathematically, fire severity for judging barrier integrity can be viewed as:

$$\begin{array}{lcl} \text{Rate of heat} & \text{Rate of heat} & \text{Rate of heat lost} \\ \text{buildup in a} & = \text{produced by} & - \text{from the room} \\ \text{room} & \text{the fire} & \end{array} \quad (1)$$

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,^{A1-A11} only the resulting expressions and underlying assumptions will be presented here.

First Term

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

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 = $R_p \Delta H_c$ for surface-controlled burning,
by the fire

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 = $M_{air} r \Delta H_c$ for ventilation-
by the fire 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 loss through openings by radiation + Heat lost through openings by mass flow

$$\begin{array}{l} \text{Heat lost by} \\ \text{radiation to} \\ \text{walls} \end{array} = \frac{\sigma A_w (T_f^4 - T_{w_i}^4)}{\left(\frac{1}{\epsilon_f} + \frac{1}{\epsilon_w} - 1 \right)}$$

where

σ = Stefan-Boltzmann constant

A_w = area of the walls

T_{w_i} = temperature of walls inside the room

ϵ_f = emissivity of the fire gases

ϵ_w = emissivity of the wall

$$\begin{array}{l} \text{Heat lost by} \\ \text{convection to} \\ \text{walls} \end{array} = U A_w (T_f - T_{w_i}),$$

where

U = convective heat transfer coefficient

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

where

A_o = area of the opening

T_o = air temperature outside the room

ϵ_o = emissivity of the air outside the room

$$\begin{array}{l} \text{Heat lost through} \\ \text{openings by} \\ \text{mass flow} \end{array} = M_f C_{p_f} T_f - M_{air} C_{p_a} T_o$$

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:

$$\rho_f V C p_f \frac{\partial T_f}{\partial t} = \left\{ \begin{array}{l} R_p \Delta H_C \text{ (for surface-controlled burning)} \\ \text{or} \\ M_{air} r \Delta H_C \text{ (for ventilation-controlled burning)} \end{array} \right\} \\ - \frac{\sigma A_w (T_f^4 - T_{w_i}^4)}{\left(\frac{1}{\epsilon_f} + \frac{1}{\epsilon_w} - 1 \right)} - U A_w (T_f - T_{w_i}) - \frac{\sigma A_o (T_f^4 - T_o^4)}{\left(\frac{1}{\epsilon_f} + \frac{1}{\epsilon_w} - 1 \right)} \\ - M_f C p_f T_f + M_{air} C p_a T_o \quad (2)$$

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} , T_{w_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} , T_{w_i} , and M_f .

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

$$\rho_w C p_w \frac{\partial T_w}{\partial t} = \frac{\partial}{\partial x} \left(k_w \frac{\partial T_w}{\partial x} \right). \quad (3)$$

With the boundary conditions

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

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

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

where

ρ_w = density of the wall

Cp_w = heat capacity of the wall

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

T_{wo} = outside wall temperature

k_w = thermal conductivity of the wall

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

$$\left\{ \begin{array}{l} R_b \text{ for surface} \\ \text{controlled burning} \\ \text{or} \\ M_{air} \text{ for ventilation-} \\ \text{controlled burning} \end{array} \right\} = M_f - M_{air} \quad (4)$$

This relationship assures that the volume of air in the room is small compared to the amount required for combustion of all fuel within the room. An abbreviated calculation on Page A15 illustrates the points.

The third and final relationship needed for T_f , M_{air} , T_{wi} , and M_f describes M_{air} in terms of the physical characteristics of the room under consideration. Obviously, in a room having all openings

shut with airflow only by 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 A13 to yield the following expression:

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

where

h_o = the height 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. 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.^{A6-A8 Al3 Al4} 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.^{Al5}
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 unchanged 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.^{Al6}
4. The rate of pyrolysis during surface-controlled burning, R_p , is assumed to be independent of temperature for solid fuels, and a function of vapor pressure, as related to surface temperature, for liquid fuels.^{Al3} If R_p has been measured under the temperature conditions expected to occur in a room being analyzed, this assumption is conservative. Otherwise, R_p could vary significantly. Fortunately, as explained later, the ventilation rates in most power plant areas are limited, thereby resulting in ventilation-controlled burning for which R_p does not apply.

With these assumptions and some experimental values for ΔH_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 A6, A13, and A14 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 outdoors. 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):

$$\begin{array}{lll}
 + M_{\text{air}} C_{p_a} T_o, & - M_f C_{p_f} T_f, & \text{and} - \frac{\sigma A_o (T_f^4 - T_o^4)}{\left(\frac{1}{\epsilon_f} + \frac{1}{\epsilon_o} - 1 \right)} \\
 \text{(cool air)} & \text{(flow} & \text{(opening radia-} \\
 & \text{heat} & \text{tion heat loss)} \\
 & \text{loss)} &
 \end{array}$$

Nuclear power plant safety areas usually have no windows or doors opening outdoors. 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, it will be assumed that plant areas surrounding a burning room can supply sufficient air to support combustion and that air flowrates are limited only by the sizes of openings leading into a burning room.

Figure A1 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

Figure A1. Comparison of Models for Assessing Fire Severity in Nuclear Power Plants.

less realistic. Obviously, as ventilation rates approach surface-controlled burning limitations, the distinction between 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 barrier analysis model.

The equations developed above can be solved to predict the time-temperature history of a fire, under conditions of full room involvement, 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 for typical fuel loads and burn rates, flame emissivity values can range from 0.3 to 0.9 with only a 20°C difference in the resulting fire gas temperature, and wall heat capacity values can vary by a factor of 4 with virtually no difference in fire-gas temperatures after 1 h.^{A13} On this basis, the physical parameters listed in Table A1 were selected for use in calculating time-temperature histories for various nuclear power plant fuel loads, ventilation rates, and room sizes. Figure A2 and A3 show typical resulting time-temperature curves.

Table A1

Selected Physical Parameters

Walls (Concrete):

Density	$\rho_w = 1920 \text{ kg/m}^3$ (Ref. A18)
Heat Capacity	$C_{p_w} = 1052 \text{ J/kg-K}$ (Ref. A18)
Thickness	$= 0.202 \text{ m}$
Emissivity	$\epsilon_w = 0.65$
Convective Transfer Coefficient	$U = 5.0 (T_f - T_{w_i})^{1/3} \text{ J/s-m}^2\text{-K}$ (Refs. A15 and A19)
Thermal Conductivity	$K_w = \begin{cases} 1.878 \text{ J/s-m-K @ 273 K} \\ 0.609 \text{ J/s-m-K @ 1473 K} \end{cases}$ (assumed to vary linearly between 273 K and 1473 K, Ref. A18)

Fuel (Cable Insulation):

Net Combustion Heat	$\Delta H_c = 25.9 \times 10^6 \text{ J/kg fuel burned}$ (Ref. A17)
Surface Pyrolysis Limit	$R_p = \text{All available fuel burning in 10 minutes}$ (Ref. A17)
Fraction of Pyrolysates That Burn	$= 0.7$ (Ref. A13)
Stoichiometric Air-to-Fuel Ratio	$\approx 15 \frac{\text{kg air}}{\text{kg fuel}}$ (assuming complete combustion of polyethylene to CO_2 plus H_2O)

Air and Fire Gases:

Emissivity	$\epsilon_f = 0.9$ (assuming a smoky fire)
Heat Capacities	$C_{p_a} = \text{functions of temperature}$ (Refs. A19 and A20)

Figure A2. Typical Time-Temperature Response Curves for Different Ventilation Rates

Figure A3. Typical Time-Temperature Response Curves for Different Fuel Loads

In reviewing Table A1 and Figures A2 and A3, several points should be noted.

- The fuel used for the example calculation is cable insulation. This selection has a heat of combustion representative of the bulk of combustible solids found in nuclear power plants. For areas dominated by liquid fuels a separate analysis may be needed to reflect the fact that liquids extinguish more readily than solids under conditions of limited ventilation.
- The cable properties and surface-controlled burn rate limits presented in Table A1 were derived from cable burn test data.^{A17} Although the surface-controlled burn rate has been included in Table A1 for completeness, a straightforward calculation for a typical power plant area will show that surface-controlled burning involving all combustibles in a room will not occur because of airflow restrictions. For example, in order to burn 4,600 kg of cable insulation found in one power plant corridor within the ten-minute surface-combustion period observed in Reference A17, air must be supplied at a rate of 115 kg/s. Air cannot easily enter a burning room at such a high rate, and therefore burning occurs at a rate less than the surface-controlled limit observed during open burning. Viewed another way, one may assume that a portion of the fuel in a room is burning at its surface burn limit instead of all of the fuel in a room burning at an air-restricted limit. From the standpoint of calculating fire severity time-

temperature histories, either viewpoint is equally valid. However, since ventilation phenomena are more easily treated mathematically, it is convenient to treat room-burn phenomena as ventilation-controlled total involvement.

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. Such a method should identify what numerical values of each variable are satisfactory for design purposes. Reference A12 has developed such a methodology based on the following criteria:

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

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 A21 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 A4 shows the results of such an effort.

The diagonal lines in Figure A4 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. The curved line in Figure A4 corresponds to combinations of fuel load

Figure A4. Acceptable Fuel Load and Ventilation Combinations Assuming Heat Loss Into Walls Only.

and ventilation rate whose time-temperature histories, as calculated from Eqs. (2) through (5), just reach but do not exceed the standard time-temperature curve used for barrier testing.^{A21} Figure A5 shows a calculated time-temperature history, for a particular fuel load and ventilation combination, which satisfies the temperature limitation defined by the standard test curve. By finding other combinations of fuel load and ventilation rate which produce time-temperature histories just touching the test curve, the temperature-limit curve shown in Figure A4 can be defined. 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 exposure to a fire which involves all of the fuel within the room.

In order to use Figure A4, 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.

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 Figure A4.

Figure A5. Typical Temperature Limitation for Calculating Time/Temperature Curves.

2. If a room has only fire-induced natural ventilation through door or vent openings, Eq. (5) 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, the use of Eq. (5) is unattractive. An alternate approach derived from Eq. (5) is presented in Figure A6.

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.^{A13} Recognizing this, Eq. (5) can be reduced to $M_{air} = 0.522 A_O \sqrt{h_O}$ kg/s. This equation was used to produce Figure A6.

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 gradient 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.

Figure A6. Airflow Rate Induced by a Fire in a Room Having an Opening of Height h_o and Area A_o

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. This was done in detail in Reference A12, and it was found that since the flow of both forced and induced ventilation tend to decrease because of their combined effects on room static pressure during a fire, a conservative and simpler approach results by first assuming no interaction between the two flow mechanisms, and then by adding the two contributions.

By using Figure A4 together with a knowledge of wall and ceiling area, fuel load, and ventilation characteristics, it can be determined whether fire barriers alone will contain a total-involvement fire within the area in question.

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Appendix B

Improved Barrier Analysis Technique

In an effort to eliminate some of the conservations inherent in the barrier analysis method discussed in Appendix A, an analysis was carried out to predict the extent to which concrete fire barriers actually are degraded by fire conditions which exceed test conditions. To do this, an 8-inch concrete wall was mathematically modeled as a structure supporting a vertical load corresponding to 25% of its compressive yield strength (i.e., a safety factor of four). Then, while maintaining this vertical load and accounting for the variation of strength, heat capacity, and thermal conductivity with changes in temperature, temperature-induced stresses within the wall structure were calculated for various time-temperature driving functions. When the temperature-induced stresses within the wall caused the wall strength to be reduced below that needed to support the vertical load, the wall was assumed to fail. Since each time-temperature driving function could be correlated to a unique combination of fuel load and ventilation rate, a pass/fail region could be defined on the basis of a predicted wall response for time and temperature conditions beyond those used in testing.^{B1} This has been done and the results are shown in Figure B1.

A review of Figure B1 shows that at very low ventilation rates, less than about 2.2×10^{-3} kg/s-m², all concrete barriers will withstand full-involvement burning conditions, regardless of fuel load. This is because the rate of heat evolution from

Figure B1. Acceptable Fuel Load and Ventilation Combinations Based on Structure Strength Model.

combustion is limited by the ventilation rate (i.e., air supply), and it is balanced at a fairly low temperature by conductive-heat losses from the room. It is also of interest, to note that the temperature limit curve derived from barrier test criteria and the predicted structural analysis curve intersect at about a 3-1/2-hour duration. This result is somewhat fortuitous, considering the simplicity of the structural model, since 8-inch concrete barriers have been found in testing^{B1} to fail between three and four hours.

Although, these results are encouraging and it appears that the expanded region of acceptance defined in Figure B1 may reduce the overall number of fire spread paths, the structural analysis results remain inconclusive for all but the simplest fire barriers. The installation of doors, dampers, and penetration seals in barriers has not been addressed by the concrete-wall structural analysis, and, therefore, barriers containing these elements may fail sooner than predicted by Figure B1. Unfortunately, a mathematical analysis of complicated seals, doors, or dampers may lack credibility, considering the failure mechanisms of elements is not well understood.^{B2}

Appendix B References

- B1. Standard Methods of Fire Tests of Building Construction and Materials, ASTM E 119-76.
- B2. Nuclear Power Plant Fire Protection - Fire Barriers (Subsystems Study Task 3), SAND78-1990/NUREG/CR-0468, Sandia Laboratories, Albuquerque, NM, September 1979.

Appendix C

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