U.S. NUCLEAR REGULATORY COMMISSION
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DETAILED TECHNICAL JUSTIFICATION TO SUPPORT EXEMPTION REQUESTS FOR SELECTED ZONES

10 CFR 50, APPENDIX R, SECTION 111G

H. B. ROBINS

CP&L

Carolina Power & Light

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H. B. ROBINSON, Unit No. 2

Prepared By

CAROLINA POWER & LIGHT COMPANY

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1. INTRODUCTION

1.1 Purpose

This report documents the active and passive fire protection features for four specific areas at H.B. Robinson Unit No. 2. The primary objective of this analysis is to provide the requisite technical justification for exemption from the detailed requirements of Section III.G 10CFR50 Appendix R. For the four areas addressed in this report verbatim compliance with Appendix R is adjudged to not enhance fire protection safety, and a detailed fire hazards analysis is presented per the instructions of the Nuclear Regulatory Commission in support of alternative measures of protection of public health and safety.

1.2 Scope

This section provides a summary of the investigation and findings of the fire hazards analysis for the four designated areas at H.B. Robinson Unit 2. Section 2 reviews the protection provided by the existing fire protection measures and administrative controls. Section 3 describes the analytical methods employed in demonstrating protection to the public health and safety equivalent to that provided by Appendix R for those configurations not in compliance with the detailed requirements of Section III.G. Finally, Section 4 presents the results of detailed analysis and offers a substantive basis for exemption from the specific requirements of Section III.G of Appendix R.

2. ALTERNATIVE FIRE PROTECTIVE FEATURES

2.1 Introduction

This section provides background material relative to fire protection analysis performed for H.B. Robinson Unit 2.

2.2 Background

In response to the fire at Browns Ferry in March 1975, the Nuclear Regulatory Commission formed a Special Review Group to investigate the incident and suggest appropriate measures for improvement in nuclear power plant fire protection. The Group issued its report, "Recommendations Related to Browns Ferry Fire (NUREG-0050)" in February 1976 and called for a comprehensive review and upgrade of the fire protection programs at operating nuclear power plants. In the course of its recommendations, the Special Review Group most clearly articulated the need for a balanced approach in achieving that upgrade in order to ensure the integrity of the plant's design basis. The balanced approach envisioned by the NRC was based upon multiple layers of active and passive protective measures such as detection, suppression, flame retardant coatings, fire barriers and baffles so as to ensure that failure of any single method would be compensated for by other measures.

The response by the nuclear industry and Carolina Power and Light Company, in particular, was a comprehensive review of existing fire protection programs with the objective of achieving substantive improvements where necessary. These improvements were defined as one of the outputs of the plant-specific analysis performed in accordance with Branch Technical Position APCSB 9.5-1 Appendix A issued in August 1976. This Branch Technical Position (BTP) reflected the recommendations of the Special Review Group for a defense-in-depth approach.

2. Alternative Fire Protective Features

By 1977, regulatory guidance in the area of fire protection resided in a number of documents. The fundamental document, General Design Criterion 3, "Fire Protection", of Appendix A, "General Design Criteria for Nuclear Power Plants", to 10CFR Part 50, "Licensing of Production and Utilization Facilities", required that structures, systems, and components important to safety be designed and located to minimize, consistent with other safety requirements, the probability and effect of fires and explosions. For new plants, additional Nuclear Regulatory Commission guidance concerning the implementation of a comprehensive fire protection program was contained in Regulatory Guide 1.120 (For Comment), Revision 1, "Fire Protection Guidelines for Nuclear Power Plants", November 1977, and in BTP APCSB 9.5-1. For operating plants, guidance was provided in Appendix A to BTP APCSB 9.5-1. All of these documents reflected the experience gained by the Browns Ferry incident and approached fire protection in nuclear power plants from the concept of defense-in-depth. This philosophy aims at achieving a proper balance in:

a) preventing fires from starting;

b) detecting fires quickly, suppressing those fires that occur, putting them out quickly, and limiting their damage; and,

c) designing plant safety systems so that a fire that starts in spite of the fire prevention program and burns for a considerable time in spite of fire protection activities will not prevent essential plant safety functions from being performed.

It was recognized that no single echelon could be perfect or complete in and of itself. Strengthening any one could, however, compensate in some measure for weaknesses, known or unknown, in the others. It was with this perspective that Carolina Power and Light Company reviewed the fire protection at H.B. Robinson and documented it in a report to the NRC Staff dated January 1, 1977.

2.3 Appendix R and the Exemption Process

In most cases, the modifications which were proposed by Licensees as a result of plant-specific analyses submitted in 1977 were deemed acceptable by the NRC Staff and documented in a safety evaluation report on each docket. In some situations, such as in the case of H.B. Robinson, technical disagreements between the Licensees and the Staff ensued reflecting differences in professional opinion. By early 1980, three years after the Carolina Power and Light submittal, the NRC decided to resolve those areas of disagreement through rulemaking. It should be noted that during the previous period of time, Carolina Power and Light Company had begun implementing those modifications which the Staff had agreed were appropriate. On October 27, 1980, the Commission promulgated the product of that rulemaking process in the form of an amendment to Part 50 (10CFR50.45) and a new appendix (Appendix R) codifying the requirements for nuclear power plant fire protection.

Appendix R took a prescriptive approach towards fire protection and issued rigid criteria for system separation. Notwithstanding the approach taken in the rule, the Commission also recognized the efficacy of alternative approaches.

> ...the Commission believes that the licensees should reexamine those previously approved configurations of fire protection that do not meet the requirements as specified in Section III.G to Appendix R. Based on this reexamination the licensee must either meet the requirements of Section III.G to Appendix R or apply for an exemption that justifies alternatives by a fire hazard analysis.
>
> USNRC, (4SFR76611, November 19, 1980)

In explicitly establishing an exemption process and calling attention to its existence, the Commission clearly served notice that it recognized the value and importance of the 1977 fire hazards analysis and that a large number of exemptions were to to expected:

> Satisfactory features and systems are already in place and in operation in many plants. There is a reasonable degree of uniformity among most of these approved features for all facilities since they were reviewed against the

> same criteria of Appendix A to BTP APCSB 9.5-1. In general, the features previously approved by the NRC Staff in its reviews of fire protection using the criteria of Appendix A to BTP APCSB 9.5-1 provide an equivalent level of fire protection safety to that provided under the specific provisions of Appendix R. Thus, the further benefit that might be provided by requiring that previously approved features be modified to conform to the specific language set forth in Appendix R is outweighed by the overall benefit of the early implementation of such previously approved features, which in many cases are currently being installed.
>
> Nevertheless, as a result of its continuing review of fire protection matters, the NRC Staff has indicated to the Commission that there are requirements in three sections in which the protection afforded by Appendix R over and above that previously accepted, <u>may be desirable</u>. The Commission has decided that these requirements should be retroactively applied to all facilities. <u>This decision is not meant to reflect adversely on previous licensee or staff evaluations</u>, rather its purpose is to take fully into account the increased knowledge and experience developed on fire protection matters over the last several years.
>
> (op. cit., emphasis added)

Relative to protection of the safe shutdown capability, two concepts were applied retroactively by the Commission: (1) the impermissibility of using fire retardant coatings as fire barriers; and (2) the required protection of associated circuits. The origin of the first issue lies in the assertion that some early reviews of licensee submittals in response to BTP APCSB 9.5-1 Appendix A may have inappropriately credited fire retardant coatings as ASTM-rated fire barriers when, in fact, they are not. The basis for the second issue rests in the possibility that protection of associated circuits may have been overlooked in the 1977 fire hazards analysis since it was never identified as a requirement in Appendix A. In a sense, the Appendix R process may be viewed as a revision of the guidelines of BTP APCSB 9.5-1 Appendix A to include the added protection of associated circuits and a more precise definition of the minimum standards for passive protective measures. To achieve this objective, the Commission stipulated three methods for providing this protection in Section III.G of 10CFR50 Appendix R. The methods defined therein are prescriptive and rigid reflecting the precise regulatory guidance for fire protection provided by the Commission. In offering such guidance, however, the Commission also recognized that alternative measures may be utilized just as effectively as those stipulated if their efficacy can be demonstrated by analysis. In effect, licenses were provided with a "fourth alternative" through the exemption process.

The reliance on exemptions to regulations is an important element to achieving the Commission's objectives of protecting the public health and safety. In general, such exemptions are granted under the provisions of 10CFR50.12 where authorized by law and where the proposed activity will not endanger life or property. The fire protection rule is unique, however, in offering its own exemption process from the requirements of Appendix R "based on an assertion by the licensee that such required modifications would not enhance fire protection safety in the facility or that such modifications may be detrimental to overall facility safety" [10CRF50.48(c)(6)]. This exemption process explicitly defined in the fire protection rule provides a "fourth alternative" to licensees seeking to meet the Commission standards for fire protection programs.

In reviewing the Commission's proceedings for the issuance of Appendix R, an additional perspective is provided by the Court of Appeals for the District of Columbia Circuit:

> Exemptions are to be granted by the Commission upon a showing by the licensee that the required plant modification [to comply with Appendix R] would not enhance fire protection safety or that such modifications may be detrimental to overall facility safety.

[The Connecticut Light and Power Company et al. v. Nuclear Regulatory Commission, 2d Cir (1982)]

The exemption procedure, however, indicates that the Commission did not intend to limit protective measures to the three methods stipulated in the rule, 10CFR50, Appendix R, Section III.G.2 (1980).

2. Alternative Fire Protective Features

> If the utility can show that some combination of protective measures provides protection equivalent to that afforded by one of the Commission's three stipulated methods, it will be entitled to an exemption, regardless of whether the combination of measures includes fire retardant coatings. (op.cit.)

Both the Commission and the court expended a great deal of effort to emphasize the availability of the exemption process. The Court's instructions, in particular, provided additional perspectives on the standards for fire protection:

> Fire retardant coatings may be used in combination with other features in lieu of the three methods of Section III.G.

2.4 Active and Passive Protective Measures

This analysis focuses primarily on the value of the passive protection provided by the existing configurations at H.B. Robinson Nuclear Plant. The objective of this analysis is to demonstrate the degree of inherent protection afforded by existing configurations against an unmitigated liquid hydrocarbon exposure fire assuming the nonoperability of active fire protection systems. Thus, although the actuation of automatic fire detection and prompt fire brigade response would be expected to occur in an actual fire scenario, the fire protection afforded by active protection is not assumed to be available in this analysis. In effect, the only protection assumed to exist, as the postulated fire burns unmitigated to self-extinguishment, is that provided by the use of distance, coatings, and thermal shields.

2.5 Passive Protection Analysis

This analysis concentrates on evaluating only the third aspect of the defense-in-depth approach to fire protection taken in response to the Browns Ferry fire. The goal of plant designs in this context is described in Regulatory Guide 1.120 Revision 1 (For Comment) as:

Designing plant safety systems so that a fire that starts in spite of the fire protection programs and burns for a considerable time in spite of fire protection activities will not prevent essential plant safety functions from being performed.

In order to demonstrate this protection, this analysis makes the following assumptions:

a) A breakdown of administrative controls in the uncontrolled introduction of hazardous material in unacceptable quantities;

b) The failure of health physics controls and security measures to inhibit access to safe shutdown areas leading to the introduction of extraneous material;

c) The spill of the combustible material at the worst location in a fire zone, coincidental with the presence of a credible ignition source;

d) The failure of detection systems to identify the presence of the fire;

e) Failure of onsite fire brigade to intervene and suppress the fire;

f) The assumption of optimal ventilation to fuel the fire at the worst stoichiometric fuel/air ratio combined with sufficient ventilation to maintain the compartment smoke-free (for optimized radiation) without mitigating the damaging effects of the hot buoyant diffusion plume.

In modeling fires involving such assumptions, one must essentially take an event whereby an infrequent slippage in administrative controls cascades through increasingly less likely circumstances and scenarios leading to fire initiation and continued burning in the worst possible manner without interference. Moreover, conflicting and even physically unrealistic conditions must be simultaneously met so as to ensure that the most damaging effects are modeled through optimum heat transfer from the fire to the component of concern.

The details of the modeling process will be discussed in Section 3, as well as in the appendices. Nonetheless, it should be emphasized that worst case combinations and values are utilized wherever appropriate so as to ensure that the calculations provide conservative or bounding estimates of anticipated conditions resulting from an exposure fire.

2. Alternative Fire Protective Features

While the fire hazards analysis described in this report focuses primarily on the efficacy of alternative measures of passive fire protection for safe shutdown systems and their associated circuits, it should be noted that these measures are complemented by other features including:

(1) administrative controls

(2) fire retardant coatings

(3) fire detection and alarm systems

(4) fire brigade and manual suppression

The role of each of these features will be briefly discussed so as not to overlook their value in a comprehensive fire program.

2.6 Administrative Controls

Administrative controls at H.B. Robinson, which are implemented through strict fire protection procedures, are geared to reduce the threat of fires, especially during plant operation; and serve to:

(1) Forbid the handling of flammable material in excess of a certain maximum quantity;

(2) Control the existence and storage location of allowable flammable materials;

(3) Establish the use of safety cans in the storage and transport of flammable materials;

(4) Limit the use of high heat release rate and low flash point liquids such as kerosene, gasoline, and related hydrocarbons which have no unique value at a nuclear facility;

(5) Prohibit the storage of flammable materials in fire areas identified as housing safety-related safe shutdown components;

(6) Govern the use of ignition sources in operating areas.

Not only are administrative controls directed towards reducing the threat of damaging fires within the power plant, but also to organize the fire fighting activities once a fire emergency has been declared.

Administrative controls are an invaluable tool in fire protection as they are "active" without the existence of a fire emergency. This human-based feature is continuously exercised at H.B. Robinson. It has been improved as a result of the Commission guidelines, and its dependability is based on a rational approach to defense-in-depth and the already proven and tested administrative control (procedural) structure within a nuclear power plant.

2.7 Fire Retardant Coatings in Cable Raceways

The adequacy of fire retardant coatings commercially available and extensively applied at H.B. Robinson Unit 2 has been recognized by the Commission in the BTP APCSB 9.5-1 as one of various methods of fire protection. Recent tests have concluded that flame retardant cable coatings are effective in the early stages of fire, by increasing the incident energy required for initiation of cable damage, ignition, and cable failure. Thus, cable coatings, in combination with other fire detection and protection methods, are to be considered when evaluating the characteristics of a particular fire area.

2.8 Fire Detection and Alarm Systems

The installed and planned fire detection and signaling system transmits alarm and supervisory signals to various locations within the plant, including the control room. Indications include not only affected fire zone and fire detection device, but also indication of abnormal events such as loss of power, undervoltage, etc. Power to the fire detection system is received from the plant's emergency power system. Smoke and temperature/rate of heat rise detectors are used in the system, which is designed to cover all areas that contain safety systems or that are open to areas which contain safety-related systems.

2.9 Conclusion

A rational consideration of available layers of active and passive fire protection activities and elements must be acknowledged to be as effective as the methods offered by 10CFR50 Appendix R, Section III.G. The remainder of this report will document the equivalency of the passive measures alone and, in so doing, fulfill the requirements of the "fourth alternative" for complying with the functional standards of Appendix R.

3. ANALYTICAL METHODS

3.1 Introduction

This section discusses the methodology utilized by Carolina Power & Light Company (CP&L) to demonstrate that verbatim compliance with Section III.G. of Appendix R would not enhance the fire protection of safe shutdown capability at H.B. Robinson Unit 2. In addition, this methodology will be used to quantify the degree of protection afforded by the existing plant configuration.

3.2 Assumptions Used in the Fire Modeling Process

When structuring a fire hazards analysis for fire zones at H.B. Robinson Unit 2, the main goal of the analysis is to demonstrate the value of inherent protection assuming the failure and/or the lack of certain active and passive fire protection systems. In effect, the analysis focuses solely on the value of separation of the components of interest from the postulated maximum fire.

In support of this objective, a properly performed fire hazards analysis must consider several factors, including:

- the combustion process itself
- the damage criteria
- the linkage between the two via a heat transfer process

These factors and the method of treating them is discussed in the following sections.

3.3 The Combustion Process

This section focuses on the fire itself and those assumptions and considerations which are important to the heat transfer and material damage processes. To maintain the bounding nature of a fire analysis, it is important that critical parameters assume a worst case condition wherever justification for a lesser case cannot be adequately documented. For analyzing the heat release rates in combustion, these parameters are the fuel mass loss rate, the convective-radiative fractions, the combustion efficiency, and the heat of combustion. Values for these parameters are keyed to the effects of ventilation, which this analysis treats in a unique manner as described below.

Classical analysis of building fires, especially those involving residential and office buildings, have attempted to realistically treat ventilation and the effects of drafts on fires. These analyses have extensively discussed the sensitivity of such fires to the effects of ventilation and the problems of modeling these effects. With a fundamental objective of bounding the conditions resulting from a fire, realistic or "best estimate" scenarios are merely of academic interest and tend to limit the reproducibility of the analysis. In order to bound the variety of conditions which may develop as a result of fire, this fire hazards analysis makes the following assumptions:

(1) Sufficient ventilation to support an optimum stoichiometric fuel/air ratio at every point in the liquid pool is always assumed, without regard to origin.

(2) Sufficient ventilation to maintain the compartment desmoked is always assumed, so as to maximize radiation effects without affecting the stability of any ceiling stratified layers or taking credit for any cooling effects.

The effect of these assumptions is to consider the impacts of over-ventilation on a fire without taking credit for the associated compensatory effects. The result is that ventilation, an important factor in determining a fire's heat release rate, is treated in a fashion which although not physically realistic, achieves the goal of conservatively bounding the effects of a fire.

3.4 Damage Criterion

A second critical element in the analysis process is that of establishing a damage criterion. The focus of the criterion should be oriented towards relating, in a directly-measurable sense, the damage process to the heat flux incident upon the target electrical cable. This approach offers the principal advantage of relating short, hot fires to long, cool fires on simular terms, i.e., the total energy absorbed by the material of interest necessary for a failure process to occur.

The failure concept utilized in this analysis is based on work performed at Factory Mutual Research Corporation (FMRC), and discussed in a report to the NRC staff by Dr. John Boccio of Brookhaven National Laboratory. This approach relates the accumulated damage in polymeric insulation in terms of a material's flammability parameters and, in particular, the following two parameters:

(1) Critical Heat Flux - The minimum heat flux below which the damage process essentially will not occur.

(2) Critical Energy - The total amount of energy required to effectively initiate and complete the damage process.

To develop an energy-based approach to material damage it is important to review the damage process relative to fire. When exposed to an external heat flux, electrical cable undergoes a series of damage stages. These stages include the onset of jacket degradation through offgassing, electrical failure, ignition, maximum burning, and fire decay. The incident heat flux and energy necessary for a cable to achieve each stage may be determined under controlled laboratory conditions. Once such method involves the use of the Factory Mutual Research Corporation combustibility apparatus.

The FMRC combustibility apparatus allows for the precise measurement of a material's flammability properties when exposed to incident heat fluxes ranging from 0 to 70 kW/m^2. Measured properties under a given heat flux include: (1) time to failure; (2) mass loss rate; (3) heat release rate; (4) generation rates for gaseous combustion products; and (5) optical transmission. With this data, it is possible to describe a material's fire hazard independent of configuration or the nature of the source of the incident heat flux. The basic procedure involves determining the relationship between external heat flux and the time to achieve a particular stage of damage.

3.5 Heat Transfer

This analysis focuses on heat flux as a mechanism for the damage process. The approach used reflects a developing trend in the combustion literature, i.e., the use of fire models to conservatively estimate heat flux conditions as a result of a fire, and the relationship of that heat flux to a material's damage process. The products of these efforts lay the foundation for a proceduralized evaluation of the effects of exposure fires in power plants based upon rigorous analysis and physically-based cable damage criterion, an approach which is developed further in this report.

In analyzing exposure fires within a nuclear power plant, the effects of three heat transfer processes must be considered:

- radiation
- convection
- conduction

In most cases involving exposure fires, conduction is generally of limited concern. This leaves essentially radiation and convection as heat transfer processes. The development of a thermal radiation field is the result of the band emission from a hot gaseous plume and the soot products associated with a pool fire. Given a knowledge of flame structure obtained from the literature, it is possible to define the region of influence for radiation which generally exists in the immediate vicinity of a fire. The results of analysis involving such pool fires indictes that the effects of radiation associated with liqued hydrocarbon exposure fires of under 20 gallons are generally less significant than those related to the convective heat transfer of the fire plume and stratified gas layers.

Flame and buoyant plume impingement is predominantly a turbulent convection problem whereby hot gases are driven vertically as a result of density differences relative to the ambient gas. As the plume rises, diffusion of the hot gases occurs which, when combined with some entrainment of cooler gases, results in a decline in the plume energy at higher elevations. This process is affected by the fuel's heat of combustion and the convective heat release ratio (themselves functions of the fire area), the stage of development of the fire, the fuel-air ratio, and fuel mass loss rate. The transfer of heat from the plume to any object immersed in it will also be affected by the creation of flow stagnation points, the presence of baffles, and the location of interest. With the impact of the buoyant plume on the ceiling of an enclosure, the vertical diffusion plume is converted into a horizontal jet which leads to the development of a stratified layer of hot gases extending symmetrically outward unless otherwise deflected by corners, walls, or baffles.

These processes may be effectively analyzed based on experimentally derived correlations and the classical methods of mathematical physics.

3.6 Summary of the Fire Modeling Process

The general approach taken in the fire hazards analysis is to determine the minimum quantity and geometry of liquid hydrocarbon spill which would exceed the damage criterion for electrical cables of interest. This is accomplished in the following manner:

(1) Identify the electrical cables of interest, their specifications, geometry, and the dimensions of the plant area.

(2) Specify the mixed and transient liquid hydrocarbon material of concern.

(3) Calculate the minimum quantity of the fuels of interest and the associated fire geometry (location, area, and depth) necessary to exceed the damageability criterion for the identified electrical cable, through the following mechanisms:

3. Analytical Methods

a) stratification

b) radiation

c) buoyant diffusion plume impingement

For the purposes of analysis, ignore the mitigating effects of actual room geometry, floor slope, and equipment layout, and assume the presence of a perfectly horizontal floor free of fire-inhibiting equipment. Also ignore the mitigating effects of pipes and ventilation systems in diverting the flow of hot gases, absorbing incident heat flux or blocking the free incidency of radiation on the cables of interest.

The objective of this process is to demonstrate that protection of the public health and safety equivalent to the requirements of Appendix R, Section III.G.2 may be provided using alternate means and that verbatim compliance with Section III.G.2 will not enhance fire protection of H.B. Robinson Unit 2 beyond the protection already provided by the existing or planned features.

4. ANALYSIS AND EXEMPTION REQUESTS

4.1 Introduction

A safe shutdown evaluation and associated fire hazard analysis has been completed for each of the four fire zones at the H.B. Robinson Unit 2 Nuclear Power Plant. The objective of this analysis is to demonstrate the efficacy of passive fire protection measures alone in protecting redundant safe shutdown systems from the effects of exposure fires involving spilled liquid hydrocarbons. No mitigation of the fire resulting from intervention by the fire brigade is credited at any time in the analysis.

This section describes the analysis employed and the conclusions derived. Section 4.2 describes the development of parameters used in the model and provides an overview of the analysis. Sections 4.3 through 4.6 individually describe the physical characteristics of the fire areas and provide specific data pertinent for each fire zone used during execution of the model.

4.2 Evaluation and Analysis

4.2.1 Safe Shutdown Evaluation

A safe shutdown evaluation was performed for all fire zones at H.B. Robinson Unit 2 as documented in the March 1982 report submitted to the NRC staff. In that analysis, the entire facility was reexamined to determine the degree of compliance with the specific separation requirements of 10CFR50 Appendix R for safe shutdown circuits. In a majority of the areas, the requisite separation either existed or was achieved by the proper routing of alternate/dedicated shutdown system cables as specified by Appendix R, Section III.G.3. The March

4.2 Evaluation and Analysis

1982 report did identify four areas where the detailed requirements of Appendix R were not met and for which exemptions would be requested. Those four areas are:

(1) Component Cooling Water Pump Room

(2) Residual Heat Removal Pump Pit

(3) Pipe Alley (226 ft elevation)

(4) Service Water Pump Area

4.2.2 Analysis

The objective of this analysis is to determine the ability of those areas not in compliance with the specific requirements of Appendix R to survive a postulated exposure fire without sustaining a loss of function of redundant safe shutdown systems and their associated circuits. The discussion in Section 3 outlines the methods of the fire hazards analysis including the conservatisms associated with the assumptions and the calculational techniques.

With regard to the specific application of these methods to H.B. Robinson, additional assumptions are made which are highlighted in the respective area analyses. These assumptions include:

(1) Cable Failure Criterion: Defined as the initiation of electrical failure of any two electrical cables for redundant divisions within a zone.

(2) Postulated Fire Location: The postulated exposure fire is always assumed to occur at the worst location relative to redundant division damage.

(3) Spill Confinement: In all fire hazards analyses, liquid spills are assumed to instantly confine themselves in the geometry which will cause the most damage to redundant divisions irrespective of the actual spill geometry expected.

These assumptions are used in this analysis in conjunction with a "back-calculation" approach. This approach starts with the failure criteria for redundant divisions and calculates the smallest quantity of liquid which must be spilled in the worst pool geometry and location in order to achieve this criteria. Effectively, this calculational technique measures the level of protection afforded by passive protection in terms of quantities of liquid hydrocarbons.

The "back-calculation" approach offers several advantages. First, it specifies the absolute quantity of liquid hydrocarbon which is necessary to cause failure. Using this technique and the same failure criteria, it is possible to measure the relative value of additional protection provided through modifications in units which are meaningful. Second, the implicit assumptions used in the approach tend to bypass much of the controversy generated in the review of the 1977 analysis such as the definition of a "credible" ignition source and the specification of a "realistic" fire hazard.

The remainder of this analysis exercises this method in conjunction with other analytical tools to determine the effectiveness of passive fire protection measures at H.B. Robinson Unit 2 for each of the four areas identified in the Safe Shutdown Evaluation.

4.3 Fire Zone 5

4.3 Fire Zone 5: Component Cooling Pump Room

A. Area Description

Fire Zone 5 is located in the southeast corner of the Auxiliary Building at elevation 226 ft 0 in. and is separated from zones to the north and west by reinforced concrete walls. All cables entering the zone have fire seals for combustible pathway penetration and all exposed cables have been coated with Flamemastic, a fire retardant material. Access to Zone 5 is via doorways equipped with three-hour-rated fire doors, and ventilation ducts are equipped with penetration fire dampers. The height of the ceiling is 15 ft. Pertinent room dimensional data are contained in the Section 4.3.1 summary table and Section 4.3.2 sketches.

B. Safe Shutdown Equipment

Fire Zone 5 contains two safety-related component cooling pumps, one non-safety-related alternate shutdown component cooling pump, two component cooling heat exchanges, the boric acid tanks and two boric acid transfer pumps. At least one component cooling pump and one component cooling heat exchanger is required for safe (hot) shutdown. The three component cooling pumps are located along the west wall of the zone oriented in an east-west direction with the motor end to the west and approximately 12 ft of horizontal distance between pump centerlines. A radiant heat shield in the form of a 7 ft high, 5 in. thick 1 hr-rated fire wall has been installed between alternative shutdown component cooling pump (A) and the remaining pumps (sketches in Section 4.3.2 contain all dimensional information pertinent to this analysis).

The safe shutdown evaluation performed for Fire Zone 5 identified the coexistence of redundant hot safe shutdown circuits with less than 20 ft horizontal separation. These circuits are the power supply cables for the three component cooling pumps and the location of these cables is shown in Section 4.3.2 sketches. All other circuits within Fire Zone 5 have functional redundancies outside of the zone and, therefore, do not require further analysis.

A fire hazards analysis has been performed to evaluate the existing configuration. The following sections document the considerations, assumptions, results, and conclusions of the analysis performed.

C. Fire Protection Systems

Fire Zone 5 is provided with smoke and heat sensitive fire detectors suitably arranged throughout the zone which alarm individually at a local control panel and subsequently provide a commmon fire zone alarm in the control room. A manual 1-1/2 in. hose reel station is located in the adjacent hallway to the northwest along with portable firefighting equipment, and every area of Fire Zone 5 is capable of being covered by a hose stream from the hose station.

D. Fire Hazards Analysis

The combustible loading considered in this analysis included both fixed and transient combustibles. Under the category of fixed combustibles are the lubricating oil within the pump sumps and the electrical cable in the area. Each component cooling pump contains approximately 1 qt of lubricating oil. The oil is contained with the pump and can only be considered combustible if it is sprayed upon a hot surface which raises its temperature to above its flash point, i.e., above approximately 480°F. Suitable hot surfaces do not exist within this zone; therefore, due to the limited quantities of lubricating oil and lack of credible ignition source (see Section 4.4), lubricating oil is not considered as a source of combustibles for Fire Zone 5.

The remaining fixed combustible loading within this zone is due almost entirely to cable insulation which has been completely covered with Flamemastic, a fire retardant coating. Previous fire hazards analysis estimated this fixed combustible loading at 15,600 BTU/ft^2 which relates to an NFPA standard maximum fire severity of 12 min. Recent laboratory studies on the efficacy of fire retardant coatings have indicated that the heat release rate of coated cables is significantly less than that of uncoated cables leading one to conclude that the combustible loading for Fire Zone 5 may actually be below that previously estimated. Due to the extremely light fixed combustible loading for this zone, the coated cable insulation does not appear to be a significant source of combustibles, either as a primary or secondary source of fire.

The remaining source of combustible material within the area falls under the category of transient combustibles. Storage of transient combustibles in Fire Zone 5 is not permitted by plant administrative control procedures, and significant accumulation of such material would be readily noticed and expeditiously removed. Therefore, the presence of such material does not appear to be a credible source for an exposure fire.

Notwithstanding these considerations, this fire hazards analysis postulates the presence of sufficient quantities of liquid hydrocarbons in the geometry necessary to damage critical cables of redundant divisions. In the performance of this analysis, the cables of interest were assumed to be cross-linked polyethylene insulated with polyvinylchloride jackets, although they comprise only a small portion of the total cables in the zone. Polyvinylchloride-jacketed cables were specifically selected primarily because they are more susceptible to fire-induced damage than cables with different jacket materials. Such considerations ensure that this analysis is bounding for all cable types.

After selection of cable type, the remaining issue of the particular fuel to be assumed to the calculation was considered. Although any fuel could have been used for the calculations, it was decided that especially meaningful results would be offered if the fuel was one which may be expected to be found within

Fire Zone 5. On this basis, gasoline and related liquid hydrocarbons such as heptane were excluded from consideration. Acetone was selected as the fuel to be modeled because of its occasional use as a cleaner and limited presence in the plant.

Acetone (C_3H_6O), an organic solvent which is also water soluble, is the simplest aliphatic ketone based on the carbonyl (C = 0) group. With a boiling point of 56°C (132.8°F), it easily vaporizes to form a combustible mixture close to its liquid surface. The appendices provide the basis for the rate at which heat is assumed to be released from the combustion of acetone. These values are extremely conservative so as to ensure that the bounding nature of the analysis is preserved. The combustible properties of acetone were assumed as follows:

<u>Heat of Combustion</u>	
Convective	12.0 kJ/g
Radiative	11.4 kJ/g
Actual	23.4 kJ/g
Theoretical	30.8 kJ/g
<u>Vaporization Rate</u>	
Highly Luminous Flame	40.0 g/m^2-sec
<u>Heat Release Rate</u>	
Convective	480 kW/m^2
Radiative	456 kW/m^2
Actual	936 kW/m^2

Except for the modeling of the buildup of the stratified layer near the ceilings, all analyses postulated instantaneous achievement of steady-state combustion conditions. For radiative and plume calculations, this translates to the instantaneous achievement of a gas temperature of 982°C (1800°F) with a total emissivity of 0.3 (0.2 for gaseous products, 0.1 for luminous soot). In addiition, steady-state buoyant plume velocities were assumed to be achieved at the same time. These assumptions result in maximizing the heat transfer rate and the cable damage process, thereby bounding less severe fires involving the same fuel quantity and geometry.

In analyzing the effects of these severe fires, the appropriate selection of a damage criteria is very important. This analysis focused on the minimum conditions necessary to cause a loss of function through electrical failure. To ensure that the severity of these conditions was maximized, no credit was taken for the use of conduit as a thermal shield from radiation or as a baffle from the effects of impingement of hot gases. Thus, these steel components were assumed to be completely transparent to radiation and to have absolutely no thermal lag.

The damage threshold for electrical cables is based on research performed by J.L. Lee of Factory Mutual Research Corporation (FMRC) on behalf of the Electric Power Research Institute.[1] Lee investigated the susceptibility of 20 different electrical cables to fail under varying thermal conditions. From this group, two cable specimens were identified as being similar to the assumed cross-linked polyethylene-insulated multiconductor cable with polyvinylchloride jackets. One of Lee's cable specimens indicated failure (short circuiting a 70 V dc signal under piloted ignition conditions) at an undetermined critical heat flux with a critical energy of 9,070 kJ/m^2. The second failed earlier with a critical heat flux of 24 kW/m^2 and a critical energy of 6,530 kJ/m^2. This analysis conservatively assumed the lesser criteria of the second cable as a failure criteria.

The effects of forced convection associated with fire plume impingement and stratification were first analyzed to determine the degree of passive protection

[1]J.L. Lee, "A Study of Damageability of Electrical Cables in Simulated Fire Environments," EPRI-NP-1767, Electrical Power Research Institute, Palo Alto, CA, March, 1981.

provided by the existing configuration for Fire Zone 5. In the case of stratification, horizontal separation offers little inherent protection at any given cable tray height. Postulating an exposure fire beneath the cable tray containing Component Cooling Pump "B" cables, direct plume impingement on the "B" pump cables would lead to rapid failure. In order to cause failure of "A" and "C" cables, the postulated exposure fire must be of sufficient size to stratify the hot combustion gases and damage the "A" and "C" pump cables. As illustrated in the sketch in Section 4.3.2, the minimum elevation is 13 ft 10 in. for the "A" pump cables.

Based on these assumptions, analysis indicates that the smallest quantity of acetone necessary for redundant failure would be 9.2 gal spilled over a circular area with an effective diameter of at least 5.9 ft. Under such circumstances, achievement of the failure criteria occurs within 235 sec after pool ignition. In this case the model fire would have to be approximately 12 mm deep, a depth which is almost 15 times greater than that expected from a spill of acetone on a horizontal surface of concrete.

This analysis focused on a combination of direct plume impingement and the effects of ceiling stratification in order to achieve the cable failure criterion for redundant divisions. An alternative fire location postulated to be midway between pumps "A" and "C" and assuming no obstructions between the fire and the power cables to these pumps would be feasible for cable damage. In this configuration, radiation acts as the dominant heat transfer mechanism. It should be noted that several additional assumptions must be made for this case.

(1) Ignore the existence of the 1 hr-rated wall between "A" and "B" pumps;

(2) Ignore the existence of "B" pump itself and the shielding afforded the power cables by the pump itself;

(3) Assume the failure of the "B" pump.

4.3 Fire Zone 5

Even with the foregoing assumptions the smallest quantity of acetone necessary for redundant failure would be 32.0 gal spilled over a circular area at least 11 ft in diameter with the failure criteria not achieved until at least 269 sec after pool ignition. The model fire would involve an acetone pool at least 13 mm in depth. Because the minimum required volume of acetone for radiation failure in this fire location is greater than that necessary for impingement stratification failure this analysis has demonstrated that further horizontal separation beyond that which presently exists would not provide additional protection.

It should be noted that the postulated fire diameter is as important as the volume in specifying the smallest quantity of fuel necessary to achieve the damage criteria. Increasing or decreasing the fire diameter would necessitate a fire involving greater quantities of fuel in order to provide the same energy flux at the locations of interest. Smaller diameters would require longer-burning fires with greater fuel depth in order to achieve the same incident energy flux on a cable while larger diameter fires would implicitly necessitate larger quantities of fuel to cover the wider area. These results further demonstrate that for the extremely conservative assumptions utilized in this model, it is not possible for lesser quantities of acetone to exceed the cable damage criteria for both divisions under any circumstances irrespective of fire location.

The stratification model results demonstrate that containment of 9.2 gal of acetone necessary to initiate damage in both divisions to 12 mm of depth, almost 15 times its unconfined spill depth, with a minimum 5.9-ft diameter is an unrealistic condition. Actual plant storage provisions and operating practices further demonstrate that it would be extremely difficult to accumulate 9.2 gal of acetone anywhere within the plant, much less at the precise location and in the precise geometry determined by this analysis to be necessary for redundant cable failure.

In reality, the existing configuration can be expected to provide sufficient passive protection against even greater quantities of acetone with the precise value depending on how realistically a "best estimate" analysis is performed. Elements to be considered in a more realistic analysis might include the response of automatic detectors and of installed manual suppression systems in the area, the value of administrative controls in reducing the likelihood of substantial fuel quantities, and anticipated operator actions relative to achieving safe shutdown while a fire is in progress.

Fire Zone 5 relies upon a properly balanced approach to fire protection which includes a comprehensive site fire prevention and combustible material control program, the inherent protection provided passively by the existing configuration, automatic detection, cable coatings and manual fire fighting. This balanced approach was developed in response to the Browns Ferry fire and reflects the guidance provided by Branch Technical Position APCSB 9.5-1.

The conservative quantitative fire hazards analysis described herein demonstrates protection of Fire Zone 5 safe shutdown cables from electrical failure resulting from any reasonable exposure fire postulated in the plant regardless of horizontal separation. The extremely light combustible loading of Fire Zone 5 together with fire protection features described in this analysis demonstrate that additional modifications would not enhance fire protection of the safe shutdown capability in Fire Zone 5.

4.3.1 Fire Zone 5

FIRE ZONE 5: COMPONENT COOLING PUMP ROOM

EVALUATION PARAMETERS SUMMARY

Table 4.3-1

A. Area description

1. Construction

a. Walls - reinforced concrete

b. Floor - reinforced concrete

c. Ceiling - reinforced concrete

2. Ceiling height - 15 ft

3. Room volume - 40 ft x 60 ft x 15 ft high

4. Ventilation - 7500 CFM; automatic dampers provided

5. Congestion - low; cables generally on room's west side at component cooling pumps

B. Safe Shutdown Equipment

1. Redundant systems in area - two safety-related component cooling pumps; one nonsafety-related alternate shutdown component cooling pump

2. Equipment in area required for hot shutdown: component cooling pumps required for hot and cold shutdown

3. Type of equipment involved - 480 V power and control cables for component cooling pump motors

C. Fire Hazards Analysis

1. Type of combustibles in area

a. Cable insulation coated with fire retardant coating

b. Pump lube oil

2. Quantity of fixed combustibles

a. Cable insulation (estimated at 66 ft^3)

b. One quart lube oil for each of three pumps

3. Transient combustibles: clothing

4. Suppression damage to equipment - no fixed suppression systems installed

D. Fire Protection Existing

1. Fire detection systems - redundant cross-zoned fire detectors

2. Fire extinguishing systems

   a. Local extinguishers

   b. Hose stations

3. Hose station/extinguisher - available

4. Radiant heat shields - wall separates alternative shutdown component cooling water pump (A) and remaining pumps

5. Propagation retardants - all exposed cables coated with fire retardant mastic

Prepared by: PON 4/15/82

Reviewed by: BC 4/15/82

Approved by: PhA 4/15/82

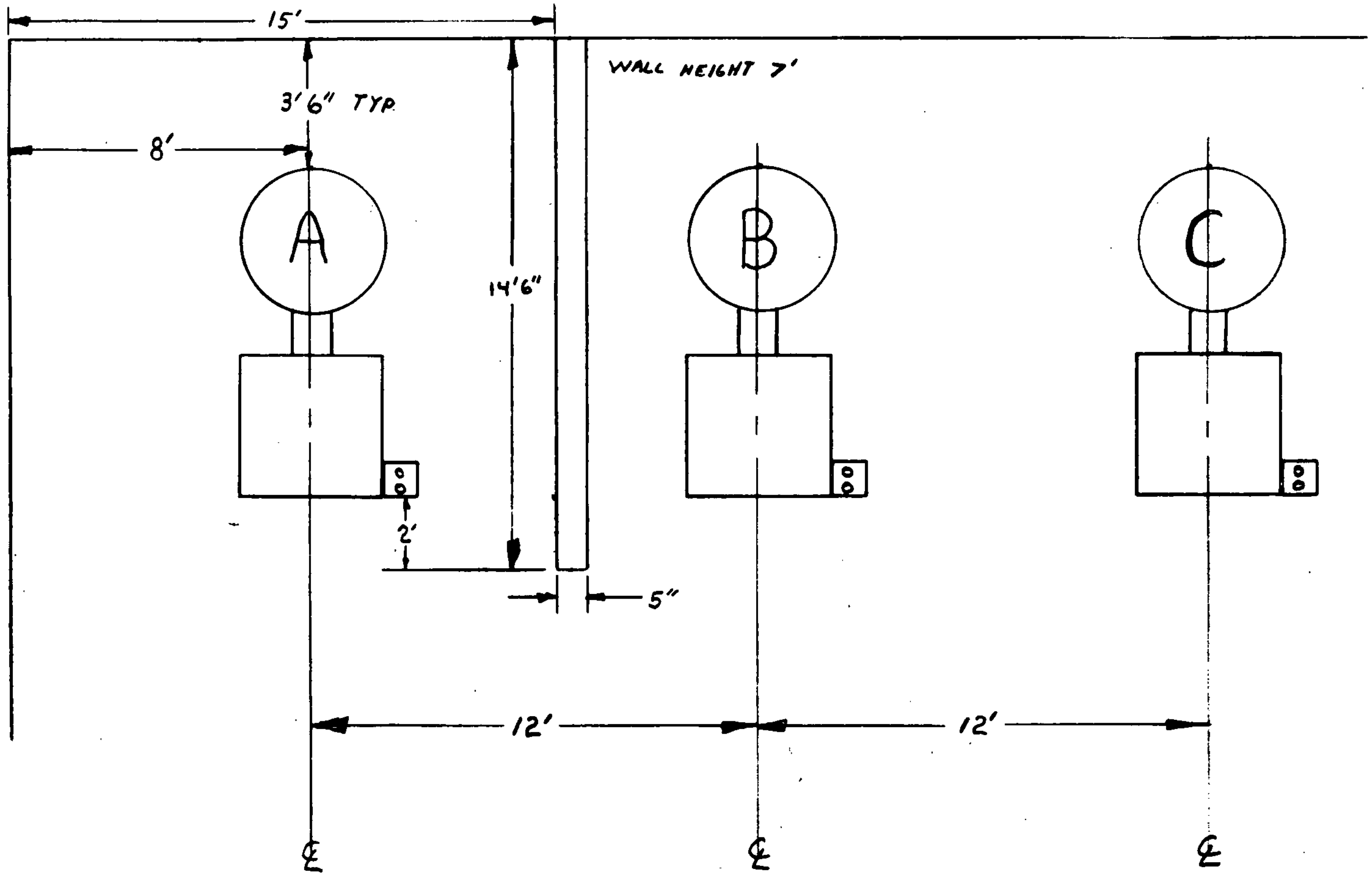


Figure 4.3-1. Fire Zone 5: Component Cooling Water Room

Prepared by: PON 4/15/82

Reviewed by: EC 4/15/82

Approved by: Pmf 4/15/82

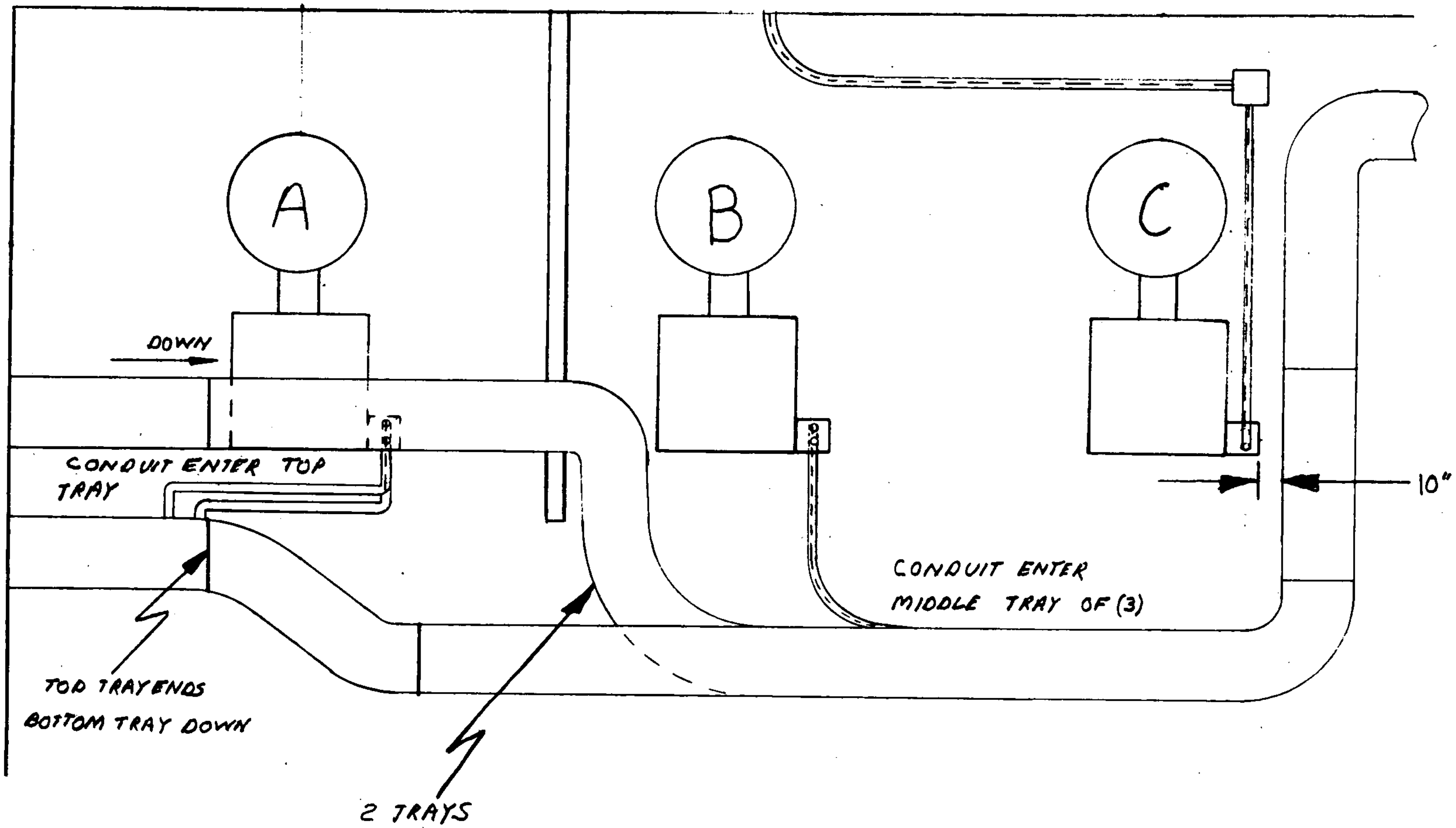


Figure 4.3-2. Fire Zone 5: Component Cooling Water Room

Prepared by: PON 4/16/82

Reviewed by: EC 4/15/82

Approved by: [illegible] 4/15/82

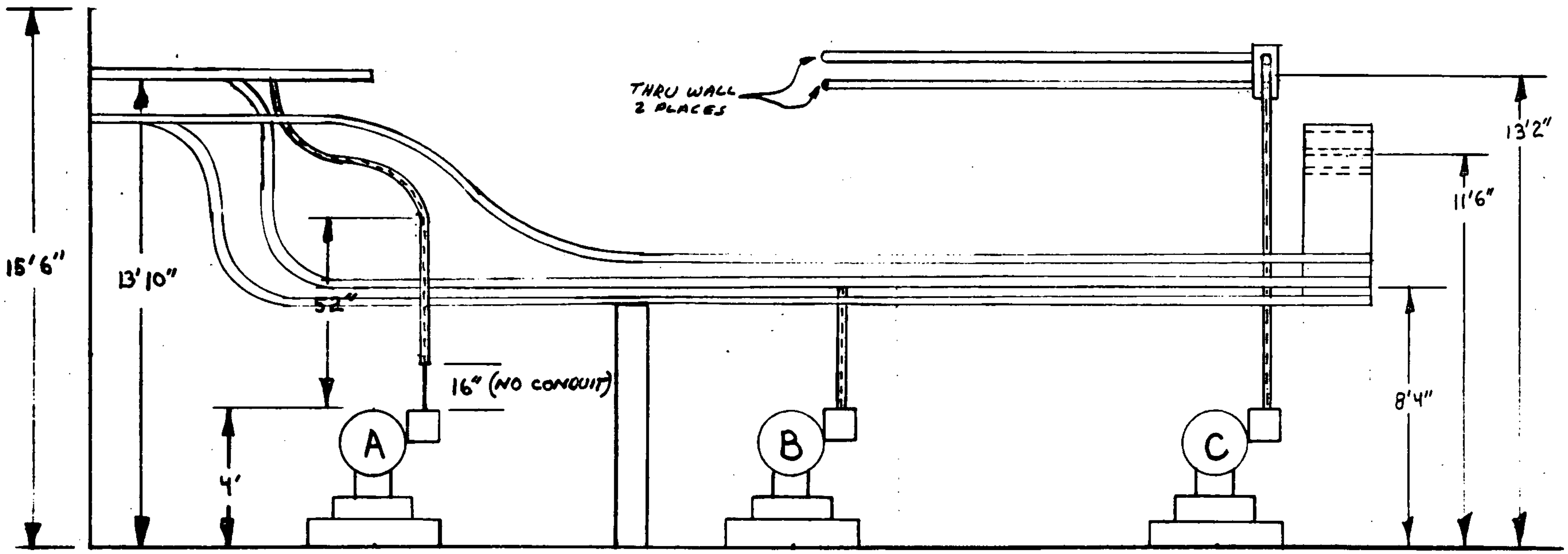


Figure 4.3-3. Fire Zone 5: Component Cooling Water Room

4.4 Fire Zone 27: RHR Pit

A. Area Description

Fire Zone 27 is located immediately west of the Auxiliary Building with a floor elevation of 203 ft 0 in. and is separated from other fire zones by reinforced concrete walls. All cables entering the zone have fire seals for combustible pathway penetration and what few cables are present in this zone are enclosed in conduit. The height of the ceiling is 26 ft 6 in. Pertinent room dimensional data are contained in the Section 4.4.1 summary table and Section 4.4.2 sketch.

B. Safe Shutdown Equipment

Fire Zone 27 contains two residual heat removal (RHR) pumps and associated piping. No equipmment or circuit within this zone is required for safe hot shutdown, but one train of the RHR system is necessary to achieve and maintain cold shutdown. Each RHR pump is mounted on a concrete pedestal approximately 4 ft high with the top of the pummp about 10 ft above floor elevation. The redundant pumps are separated by a 22 ft-high concrete barrier which completely bisects the RHR pit into two individual pump bays. Each pump bay has a sump approximately 3 ft x 3 ft x 6 in. deep with an installed sump pump. The sumps are adjacent to each other and separated by the same barrier which divides the zone. A hole approximately 4 in. in diameter joins the sumps so each sump pump can serve as a backup to the other.

The concern for Fire Zone 27 is a single exposure fire which could cause damage to the redundant RHR pumps. Demonstration of RHR pump repair in the 72-hr time frame required by Appendix R for repair of cold shutdown equipment would be difficult. All other components in this zone are either not necessary for safe shutdown or are repairable in the allowed 72 hr period. Therefore, this analysis will focus exclusively on the demonstration of adequate protection of the RHR pumps.

4.4 Fire Zone 27

C. Fire Protection System

A manual 1-1/2 in. hose reel station is located adjacent to the zone and portable equipment is located nearby.

D. Fire Hazards Analysis

Consideration of the fixed and transient combustible loadings in this zone must take into account the general accessibility features of the fire zone. Such access is extremely difficult considering the administrative controls and health physics requirements which must be met prior to entry. A radiological work permit is necessary for access because this fire zone has a fairly high general radiation field.

In addition the security procedures and controls for entering this zone are extensive. A security guard is required to escort all personnel entering this zone up to the radiological health control point and the security guard remains at this post until all personnel have left the zone. Several key-card locked access doors must be traversed just to get to the zone hatch which is itself double locked. The shift foreman has custody of one key to the RHR hatch and security department personnel must open the second lock. Casual access and, hence, storage of significant quantities of transient combustible material to this zone is simply not credible given the existing security procedures and area radiation levels.

The principal concern in this and in the previous analysis of this zone are the effects of a postulated exposure fire due to ignition of the lubricating oil contained in each RHR pump. This treatment focuses on the issue of ignition of this lubricating oil. The approach is by Modak[1], who demonstrates the difficulty in igniting high fire point liquid hydrocarbon spills on concrete surfaces.

[1]A.T. Modak, "Ignitability of High Fire Point Liquid Spills," NP-1731, Electric Power Research Institute, January, 1981.

For this analysis the following scenario was developed ignoring the very low probability of occurrence for this event:

- A failure occurs in the lubricating oil system of a single RHR pump which releases the entire 8 gal of lubricating oil contained in the pump.

- The oil spreads evenly over the floor and does not fill the sump.

- A sufficient quantity of a low fire point liquid hydrocarbon is then spilled adjacent to the oil to serve as an ignition source and the second spill is confined artificially to an optimum geometry so as to raise the surface temperature of the spilled oil to its autoignition point.

- An ignition source is assumed to exist for the low fire point hydrocarbon.

The first step in determining the volume of the ignition source required to ignite the lubricating oil is to determine the depth of the oil spill itself. Using the dimensions of the individual pump bay extracted from scale drawings of this fire zone, the confined spill depth was calculated to be a thin spill of approximately 1.8 mm, a depth greater than the unconfined spill depth for lubricating oils. This assumed oil spill depth has a significant impact in determining the surface temperature of the spill as a result of an exposure to a sustained, external heat source. For a thin spill of the depth calculated above for the RHR pump, that temperature is given as a function of the thermal properties of the substrate, due to the transfer of heat from the oil surface to the concrete. Hence, for the spill to ignite, it is necessary to raise both the spill surface temperature and the concrete substrate to the ignition temperature.

The relationship which describes the temporal response of the spill surface temperature to an external heat flux is given by Modak as:

$$\Delta_T = 2\dot{q}_n'' \left[\frac{\tau}{\pi\rho\lambda c}\right]^{1/2}$$

where Δ_T = difference in temperature between the spill surface and ambient (initial) conditions

$\dot{q}''_n$ = net incident heat flux at the spill center = 0.65 external heat flux

λ = thermal conductivity of the substrate

ρ = density of the substrate

c = heat capacity of the substrate

t = duration of spill's exposure to an incident heat flux

The values of these constants are as follows for the case of concrete:

Thermal conductivity (λ) = 1.8 W/m K

Volumetric heat capacity (ρc) = 2.1 mJ/m^3 K

Assuming an unmitigated exposure duration of 10 min, the smallest quantity of acetone required to achieve the ignition temperature of Pennzoil (SAE-30) at 640°K is well in excess of 50 gal confined to a circular area with an effective diameter of at least 21 ft.

The hazard presented by this ignition source fire is obviously much more severe than the combustion of the 8 gal of lubricating oil itself. It is also obvious that postulation of lubricating oil ignition without investigating the consequences of the ignition source itself lacks meaning. In other areas where hot surfaces such as unlagged steam pipes exist, high fire point liquid hydrocarbons can more easily be raised to ignition temperatures, and for such areas an oil fire is a credible event. It is necessary to keep in mind, however, that this fire zone is relatively unique in that such hot surfaces which could cause oil ignition simply cannot exist.

The results of this analysis are fairly conclusive concerning the relative fire hazard of the RHR pump lubricating oil. It is useful to relate these circumstances to acutal plant conditions which would be necessary prerequisites to ignition:

(1) The RHR pit must be open for general access in order to introduce the postulated ignition source. This area is open only a few days a year due to the radiation field in the zone, and it is a vital area where routine access is not required; therefore, security precautions dictate that it remain locked.

(2) The RHR pump must spill all of its lubricating oil even when it is not running: a mechanical impossibility considering the design of the pump. If the pump was running, then condition (1) could not be met because the high radiation levels during system operation prohibit routine access.

(3) A quantity of acetone well in excess of 50 gal must be carried down a 26 ft high ladder; the only means of access to the fire zone. This volume of acetone is incredible considering the administrative control procedures in effect at the H.B. Robinson site. In addition, the mandatory security guard at the access hatch could be expected to prevent the introduction of this quantity of flammable material into an obviously vital area.

(4) The acetone must be precisely confined to a circular area with an effective diameter of 21 ft. A smaller diameter will require a burn time in excess of 10 min and a larger diameter will require a greater quantity of acetone.

(5) A suitable ignition source must be present for the acetone spill.

(6) The acetone fire must burn for a minimum of 10 min without response from the site fire brigade. The security guard would quickly detect a fire of this magnitude.

In conclusion, this section has demonstrated that the fire protection for the existing configuration of Fire Zone 27 provides adequate protection to the public health and safety for the fire hazards which may realistically be present. To propose any additional modifications in this area would result in sizable costs and radiation exposure without providing significant additional protection. This analysis has demonstrated that ignition of the lubricating oil contained in

4.4 Fire Zone 27

the RHR pumps is not credible, and even if ignition were to be somehow achieved, a best engineering estimate is that the redundant RHR pump would not be damaged. For these reasons no modifications are proposed for Fire Zone 27.

FIRE ZONE 27: RHR PIT

EVALUATION PARAMETERS SUMMARY

Table 4.4.1

A. Area description

1. Construction
    - a. Walls - reinforced concrete
    - b. Floor - reinforced concrete
    - c. Ceiling - reinforced concrete
2. Ceiling height - 26 ft
3. Room volume - 400 ft^2 x 26 ft high
4. Ventilation - 500 CFM
5. Congestion - low

B. Safe Shutdown Equipment

1. Redundant systems in area - two RHR trains
2. Equipment in area required for hot shutdown - none; one train required for cold shutdown only
3. Type of equipment/cables involved - 480 V power and control cables

C. Fire Hazards Analysis

1. Type of combustibles in area
    - a. Pump lube oil
    - b. Cable insulation
2. Quantity of fixed combustibles
    - a. Pump lube oil, 8 gal lube oil each side of divided pit
    - b. Cables routed in conduit
3. Transient combustibles: none
4. Suppression damage to equipment - no fixed suppression

4.4.1 Fire Zone 27

D. Fire Protection Existing

1. Fire detection systems - none required

2. Fire extinguishing systems - manual hose station (existing)

3. Hose station/extinguisher - available (existing)

4. Radiant heat shields - reinforced concrete wall to 22 ft height installed between pumps to prevent possibility of heat transfer by radiation (existing)

5. Propagation retardants - none

Prepared by: *PDW 4/15/82*
Reviewed by: *EC 4/15/82*
Approved by: *[illegible] 4/15/82*

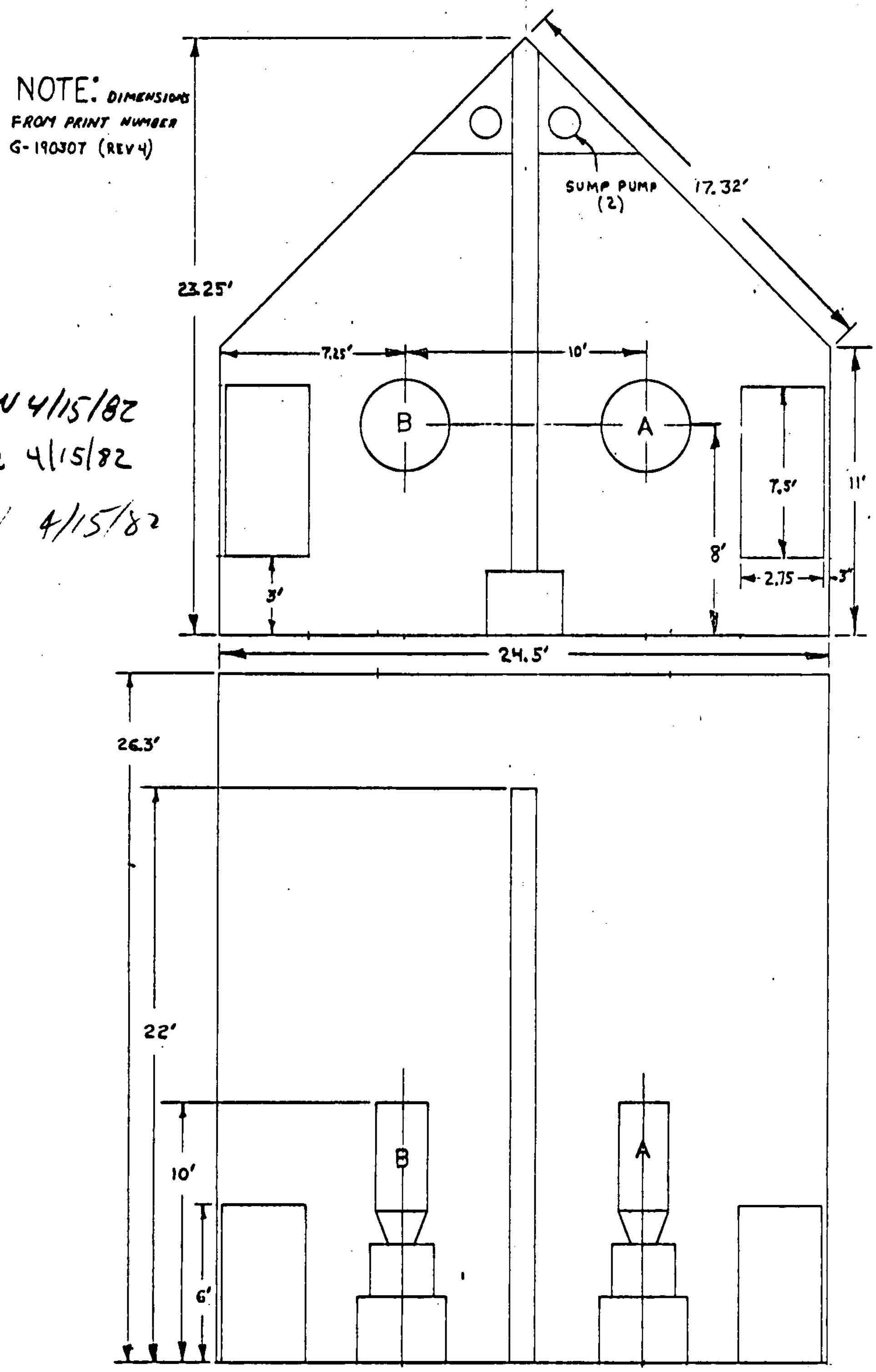


Figure 4.3-1. Fire Zone 27: RHR Pit

4.5 Fire Zone 28

4.5 Fire Zone 28: Pipe Alley

A. Area Description

Fire Zone 28 is located in the west station of the Auxiliary Building at elevation 226 ft 0 in. and is basically a long hallway aligned in a north-south orientation. This zone is separated from other zones by reinforced concrete walls. All cables entering the zone have fire seals for combustible pathway penetration and all exposed cables have been coated with Flamemastic, a fire retardant material. Access to Zone 28 is via a single fire-rated door. The height of the ceiling is 18 ft and the floor area is approximately 1500 ft^2. Pertinent room dimensional data are contained in Section 4.5.1 summary table.

B. Safe Shutdown Equipment

Fire Zone 28 contains no equipment required for safe shutdown but does have power, control and instrumentation cables for redundant hot and cold safe shutdown systems. These cables are separated by a horizontal distance of less than 20 ft and require modification or analysis as mandated by 10CFR50 Appendix R. The hot shutdown cables within this area which do not meet the prescriptive requirements of Appendix R are dedicated shutdown system cables for primary system instrumentation, pressurizer heater and reactor coolant system valve operators. These cables all have functional redundancies with normal plant cables and will be enclosed within an ASTM 1 hr rated fire barrier.

C. Fire Protection Systems

Fire Zone 28 is provided with redundant cross-zone smoke and heat sensitive fire detectors suitable arranged throughout the zone which alarm individually at a local control panel and in the control room. A manual 1-1/2 in. base reel station is located in the adjacent zone to the east along with portable extinguishers.

D. Fire Hazards Analysis

The fixed combustible loading within this zone is due almost entirely to cable insulation which has been completely covered with Flamemastic, a fire retardant coating. Recent laboratory studies on the efficacy of fire retardant coatings have indicated that the heat release rate of coated cables is significantly less than that of uncoated cables. In addition the majority of cables present in this zone are totally enclosed in conduit as are all of the dedicated shutdown system cables. Due to the extremely light fixed combustible loading for Fire Zone 28, cable insulation is not considered as a significant source of combustibles.

Storage of transient combustibles in Fire Zone 28 is not permitted by plant administrative control procedures and in addition, this zone is not a logical place for unauthorized storage of combustible material for several reasons. First, this zone is a locked high radiation area and therefore requires a key from the shift foreman, and is within the radiologically controlled area which necessitates meeting the radiological control requirements prior to entry. There is only one door for access to Fire Zone 28, thereby excluding its use as a passageway. Furthermore, frequent operation or maintenance activities within this zone are not anticipated and it is routinely traversed only for operations tours. Finally, none of the adjacent zones have significant accumulations or use of transient combustibles so Fire Zone 28 is not regarded as a convenient unauthorized storage area. On this basis, it is concluded that the undetected accumulation of significant quantities of combustible material within this zone is not likely.

The existing fire protection features for Fire Zone 28 as described in this section provide protection of public health and safety which is equivalent to

4.5 Fire Zone 28

that which would be provided by the prescriptive requirements of Section III.G.2 of Appendix R. This conclusion is in agreement with the NRC Staff guidance provided in Secy 82-13 of January 11, 1982:

> III.G requires a fixed suppression system in areas containing redundant systems required for shutdown if they are not separated by 20 ft free of combustibles. If the area does not contain a high concentration of combustibles, the fire severity is 15-30 min, and a 1 hr barrier is provided for the protected equipment, we would grant an exemption for the lack of a fixed suppression system.

Therefore, an exemption from the suppression system requirement of Appendix R should be granted for Fire Zone 28.

FIRE ZONE 28: PIPE ALLEY

EVALUATION PARAMETERS SUMMARY

Table 4.5-1

A. Area description

1. Construction

   a. Walls - reinforced concrete

   b. Floor - reinforced concrete

   c. Ceiling - reinforced concrete

2. Ceiling height - 18 ft

3. Room volume - approximately 1,500 ft^2 x 18 ft high

4. Ventilation - nominal 750 CFM

5. Congestion - high due to piping, cables trays and conduit

B. Safe Shutdown Equipment

1. Redundant systems in area - cables for normal shutdown and dedicated shutdown systems are physically separated within area, but less than 20 ft

2. Equipment in area required for hot shutdown - normal and dedicated cables for redundant hot and cold instrumentation, pressurizer heater, and RCS valve operator

3. Type of equipment/cables involved - 480 V power, control, and instrumentation cables

C. Fire Hazards Analysis

1. Type of combustibles in area - cable insulation coated with fire retardant coating

2. Quantity of fixed combustibles - 130 ft^3 of cable insulation

3. Transient combustibles: none during plant operation

4. Suppression damage to equipment - not applicable

4.5.1 Fire Zone 28

D. Fire Protection Existing or Planned

1. Fire detection systems - redundant cross-zoned detection system (existing)

2. Fire extinguishing systems

   a. Local extinguishers (existing)

   b. Manual hose station (existing)

3. Hose station/extinguisher - available (existing)

4. Radiant heat shields - 1 hr barriers to be applied to dedicated shutdown cables (planned)

5. Propagation retardants

   a. Electrical penetrations provided with rated fire stops (existing)

   b. Cable is coated with fire retardant coating (existing)

4.6 Fire Zone SWP: Service Water Pump Area

A. Area Description

This fire zone is located within the plant intake structure in the Service Water Pump (SWP) enclosure. This structure is formed by metal walls, a reinforced concrete floor, and an open roof. Access to the SWP area is via a key card locked security door in one of the sheet metal walls. Pertinent dimensional data are contained in Section 4.6.1 summary table and Section 4.6.2 sketches.

B. Safe Shutdown Equipment

This fire zone contains four service water pumps with "D" pump being the dedicated shutdown system component. No other equipment or cables are located within the SWP enclosure. The service water intake structure is in a fenced-in area with security key card limited access and entrance to the SWP enclosure requires an additional level of special access control. No other equipment within the intake structure is required for safe shutdown.

Because the existing configuration within Fire Zone SWP does not comply with the specific requirements of 10CFR50, Appendix R, Section III.G.2, a fire hazards analysis has been performed to evaluate the existing configuration. The following paragraphs document the assumptions, results, and conclusions of the analysis performed.

C. Fire Protection Systems

The security control procedures for the intake structure require that a guard be present whenever personnel enter the intake structure fence. This feature, combined with fire detection for the SWP enclosure in the form of camera surveillance system for the intake structure, provides this fire zone with additional fire protection beyond those inherent in the existing administrative controls. Manual firefighting capability exists for this area using a yard hydrant or portable extinguishers from nearby areas and completes the overall fire protection systems.

D. Fire Hazards Analysis

The fixed combustibles within the SWP enclosure are mainly due to the 6 gal of lubricating oil contained within each service water pump. The only cables in this fire zone are the two cables per pump which rise out of floor penetrations and terminate directly above into the motor end of the service water pump. The oil contained in each service water pump can be considered a combustible hazard only if it is sprayed upon a hot surface which raises its temperature to above its flash point, i.e., approximately 480°F. Suitable hot surfaces do not exist within this zone. Due to the limited quantities of lubricating oil and lack of a credible ignition source (see Section 4.4), lubricating oil is not considered as a source of combustibles for this fire zone. Storage of transient combustibles in the SWP area is not permitted by administrative control procedures and insurance carrier requirements.

In the performance of this analysis, the cables of interest were assumed to be cross-linked polyethylene insulated with polyvinylchloride jackets, as in Section 4.3. The postulated fuel for the fire hazard analysis is acetone, a fuel used in the analysis whose flammability parameters are also described in Section 4.3.

The postualated exposure fire in Fire Zone SWP is an open air fire hazard analysis. Relative to protection of redundant safe shutdown systems and associated circuits, the important parameters are horizontal separation and cable elevation. Under such circumstances, the limiting location for the postulated fire is midway between pumps "A" and "D". In order to maximize the effects of the postulated fire, no obstructions were assumed to exist between the fire and the power cables to these pumps.

Using these assumptions, the results of analysis indicate that the smallest quantity of acetone necessary for redundant failure would be 17 gal spilled over a circular area at least 8 ft in diameter with the failure criteria not achieved until at least 271 sec following pool ignition with redundant cable failure occurring at fire self-extinguishment.

It should be noted that the postulated fire diameter is as important as the volume in specifying the smallest quantity of fuel necessary to achieve the damage criteria. Increasing or decreasing the fire diameter would necessitate a fire involving greater quantities of fuel in order to provide the same energy flux at the locations of interest. Smaller diameters would require longer-burning fires with greater fuel depth in order to achieve the same incident energy flux on a cable while larger diameter fires would implicitly necessitate larger quantities of fuel to cover the wider area. These results further demonstrate that for the extremely conservative assumptions utilized in this model, it is not possible for lesser quantities of acetone to exceed the cable damage criteria for both divisions under any circumstances irrespective of fire location.

In reality, the existing configuration can be expected to provide sufficient passive protection against even greater quantities of acetone with the precise value depending on how realistically a "best estimate" analysis is performed. Elements to be considered in such realistic analyses might include the response of detection systems and of installed manual suppression systems in the area, the value of administrative controls in reducing the likelihood of substantial fuel quantities, and anticipated operator actions relative to achieving safe shutdown while a fire is in progress.

4.6 Fire Zone SWP

The SWP zone relies upon a properly-balanced approach to fire protection which includes a comprehensive site fire prevention and combustible material control program, the inherent protection provided passively by the existing configuration, detection, and manual firefighting. This balanced approach was developed in response to the Browns Ferry fire and reflects the guidance provided by Branch Technical Position APCSB 9.5-1.

The conservative quantitative fire hazards analysis described herein demonstrates protection of this fire zone safe shutdown cables from electrical failure resulting from any reasonable exposure fire. The extremely light combustible loading of the SWP zone together with fire protection features described in this analysis demonstrate that additional modifications would not enhance fire protection of the safe shutdown capability in this fire zone.

FIRE ZONE SWP: SERVICE WATER PUMP AREA

EVALUATION PARAMETERS SUMMARY

Table 4.6-1

A. Area description

1. Construction

a. Walls, floor, and ceiling - outside area, floor is reinforced concrete; service water pumps are enclosed by sheet metal enclosure with an open roof

2. Ceiling height - N/A

3. Room volume - N/A

4. Ventilation - outside

5. Congestion - low

B. Safe Shutdown Equipment

1. Redundant systems in area - four pumps in area; both normal system and alternative

2. Equipment in area required for hot shutdown - one pump for hot or cold shutdown

3. Type of equipment/cables involved - 480 V power and control cables

C. Fire Hazards Analysis

1. Type of combustibles in area - pump lube oil

2. Quantity of fixed combustibles - only pump oil reservoirs in immediate area of pumps (6 gal of lube oil per each of four pumps)

3. Transient combustibles - only present during pump maintenance with personnel in attendance

4. Suppression damage to equipment - none

4.6.1 Fire Zone SWP

D. Fire Protection Existing

1. Fire detection systems - camera surveillance of intake structure (existing)

2. Fire extinguishing systems

   a. Portable extinguisher (existing)

   b. Manual hose stations (existing)

3. Hose station/extinguisher - available (existing)

4. Radiant heat shields - none

5. Propagation retardants - none required

Prepared by: PBW 4/15/82

Reviewed by: RC 4/15/82

Approved by: [illegible] 4/15/82

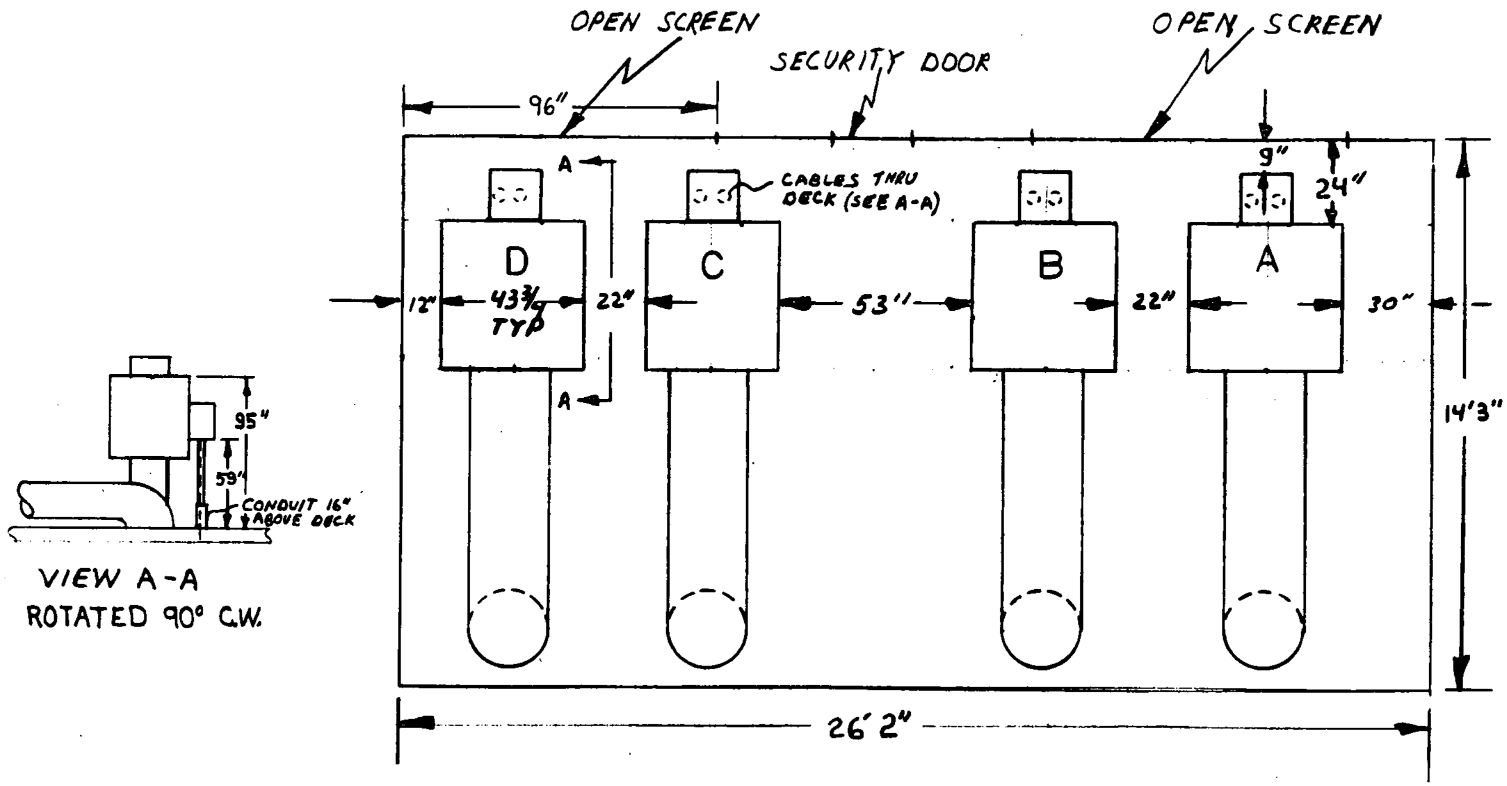


Figure 4.5-1. Fire Zone SWP: Service Water Pump Area

APPENDIX A

Basis for Heat Release Rates

This appendix provides the basis for the fuel heat release rates utilized in fire models described in this analysis. The quantities reported herein and the underlying concepts are from the combustion literature and reflect the current state of knowledge in the fire sciences. In areas of uncertainty, conservative assumptions are made so as to ensure that the integrity of the analytical method is maintained.

The heat release rate associated with a fire is related to the fuel's mass loss rate (pyrolysis) and the heat of combustion [Tewarson (1)] by the following relationship:

$$\dot{Q}_T'' = \dot{m}_b'' H_T$$

where $\dot{Q}_T''$ = total theoretical heat release rate

$\dot{m}_b''$ = mass loss rate in burning

$\dot{H}_T''$ = total theoretical heat of combustion

The mass loss rate itself is a variable which in a realistic sense is dependent upon multiple factors such as fire stage, gaseous temperature and fuel type. In general, the mass loss rate may be described by the net heat flux delivered to the fuel's surface and its heat of gasification.

$$\dot{m}_b'' = \frac{\dot{q}_n''}{L}$$

where $\dot{q}_n''$ = net heat flux received by the fuel

L = heat required to generate a unit mass of fuel vapors

The dependency of the mass loss rate on the net heat flux delivered to the fuel surface and the associated feedback effects illustrates the historical difficulty of analysts to derive a meaningful and precise model of flame behavior. The net heat flux itself represents a heat balance at the fuel surface and is given as the difference between the total heat flux received by the fuel and that flux lost through a variety of processes. This balance under steady state conditions may be modified, however, by such factors as the relative concentration of oxygen entrained in the combustion zone, the externally applied heat flux and the optical path length of the gases. The principal effect of these considerations becomes evident in the actual heat of combustion which reflects different oxidation reactions.

At a detailed level these multiple parameters are all interrelated. However, it is possible to select a single parameter for the purpose of illustrating the sensitivity of the heat release rate to its variation. That single parameter would be the fraction of stoichiometric oxygen to fuel ratio given by:

$$\phi = \frac{\dot{M}''_{O_2}(\alpha)}{\dot{m}''_b K_{O_2}}$$

where ϕ = fraction of stoichiometric oxygen to fuel ratio

α = fraction of oxygen entrained in combustion

K_{O_2} = stoichiometric mass oxygen to fuel ratio

$\dot{M}''_{O_2}$ = mass flow rate of oxygen to fire vicinity

The effect of variation of this parameter on combustion may be illustrated for the case of polymethylmethacrylate over a range of values of the stoichiometric oxygen/fuel fraction:

ϕ	Fuel Condition	Chemical Reactions	Combustion Efficiency	H_A (kJ/g)
≥ 1.0	Lean	$C_5H_8O_2 + 6O_2 \rightarrow 5CO_2 + 4H_2O$	100	24.9
0.81	Lean	$C_5H_8O_2 + 4.9O_2 \rightarrow 4CO_2 + 35H_2O$	80	19.9
0.63	Rich	$C_5H_8O_2 + 3.8O_2 \rightarrow 4CO_2 + 3.5H_2O$ $+ 0.25CO_2 + 0.25CH_4 + 0.75C$	60	14.9
0.42	Rich	$C_5H_8O_2 + 2.5O_2 \rightarrow 2CO_2 + 2H_2O$ $+ CO + CH_4 + C$	35	8.7

As may be evident from this table, oxygen and combustion efficiency have a significant effect on the overall heat release rate. Moreover, it should be noted that lower combustion efficiencies produce increasing amounts of carbon which lead to higher smoke rates, lower optical transmission path lengths, and higher soot concentrations, thereby reducing even further the effect of the released heat on a target material.

The stoichiometric oxygen/fuel fraction affects heat release rates through its influence on the value of χ_i in the standard equation:

$$\dot{Q}_i'' = \chi_i \, (\phi) \left(\frac{H_T}{L} \right) \dot{q}_n''$$

where χ_i = fraction of total theoretical heat release rate associated with mode i

This equation and the influence of χ on its results is the fundamental relationship for bounding the rate energy is released in a fire. The remainder of this appendix will focus on each of the following three elements in developing an appropriate rate for the fuels used in this analysis:

(1) χ_i - fraction of energy released in mode i

(2) $m_b = \dfrac{\dot{q}_n''}{L}$ - fuel mass loss rate

(3) H_A - actual heat of combustion

The objective of the discussion will be to provide a scientific basis for selecting bounding values for each parameter in subsequent analyses.

The close relationship between parameters and the associated feedback effects was presented earlier in this appendix where the inherent difficulties in precisely modeling fires was demonstrated. Ideally, if bounding values for χ_i, $\dot{m}_b''$ and H_A could be selected, then one may be assured that the heat release rate is adequately bound through the assumption of a suitably intense fire. In order to achieve this goal, it is important to relate the three parameters of interest to experimental data and sensitivities. For the purpose of illustrating a general concept, the case of acetone will be discussed beginning with the mass loss rate.

The mass loss rate for a liquid hydrocarbon was previously given by:

$$\dot{m}_b'' = \frac{\dot{q}_n''}{L} \quad \text{[from Tewarson (1)]}$$

$$\text{where } \dot{q}_n'' = \dot{q}_e'' + \dot{q}_{fr}'' + \dot{q}_{fc}'' + \dot{q}_o'' - \dot{q}_l''$$

$\dot{q}_e''$ = external heat flux incident on the fuel

$\dot{q}_{fr}''$ = flame radiative heat flux incident on the fuel

$\dot{q}_{fc}''$ = flame convective heat flux incident on the fuel

$\dot{q}_o''$ = other heat flux incident on the fuel

$\dot{q}_l''$ = heat flux lost

For small fires, $\dot{q}''_{fc} >> \dot{q}''_{fr}$ while for larger fires, $\dot{q}''_{fr} >> \dot{q}''_{fc}$ where turbulent effects are dominant.

In the region where radiative heat flux to the fuel's surface is significant, it has been found on the basis of experimentation that all important parameters are independent of oxygen concentration [Tewarson (4)]. The affected parameters include:

(1) Those parameters with slight oxygen dependency
- Actual heat of combustion (H_A)
- CO_2 yield (Y_{CO_2})

(2) Those parameters which decrease with increasing oxygen concentration
- Convective heat of combustion (H_C)
- Convective heat flux incident on the fuel ($\dot{q}''_{fc}$)
- CO yield (Y_{CO})
- Optical path length - fuel vapor concentration ratio

(3) Those parameters which increase with increasing oxygen concentration
- Radiative heat of combustion (H_R)
- Fuel vaporization rate ($\dot{m}''_b$)
- Radiative heat flux incident on the fuel ($\dot{q}''_{fr}$)

From this important result, it is apparent that if a conservative assumption is made for ventilation, i.e., that ideal fuel-oxygen ratios above a minimum value (> .5 mole fraction O_2) is always postulated to exist, then it is possible to bound the value for a liquid hydrocarbon's heat release rate. Further, one also obtains asymptotic values for the fuel steady state mass loss rate as a function of fire area and the associated heats of combustion (radiative, convective and actual). From this result the remaining parameter is the value of χ_i. The method of determination for this parameter will be illustrated for the case of acetone, although the nature of the selected hydrocarbon is unimportant.

It has been shown experimentally that the mass loss rate for most liquid hydrocarbons approaches an asymptotic limit at higher rates of $\dot{q}''_n$ [Tewarson (4)], especially for aromatic, i.e., benzene-like compounds [Tewarson (3)]. In particular, Tewarson (1) demonstrated that acetone, an aliphatic ketone, exhibits characteristics similar to such aromatic liquids which suggests the validity of the asymptotic limit assumption for its fuel vaporization rate. This characteristic limit appears to be related to the maintenance of a constant $\dot{q}''_n$ ratio as surface radiation achieves a dominant role in fuel vaporization. For most hydrocarbons, this limit is bounded by vaporization rates of $40 g/m^2$-s, a mass flux supported by experimental data by Tewarson (3, 5), where a value of $30 g/m^2$-s is suggested, and by Blinov and Khudiakov (7). The steady-state fuel vaporization rate used in this analysis is $40\ g/m^2$-s.

With this parameter in mind, it is necessary at this point to focus on the heat of combustion associated with the fuel; in this case, acetone. Using a bomb calorimeter which accounts for idealized heat measurement resulting from total molecular dissociation, Weast (2) reports a theoretical heat of combustion (H_T)

of 426.8 kG-cal/GMW or 30.8 kJ/g. Turning to the experimental literature for the purpose of obtaining a value of X_A, Tewarson (2) reports a value of $_AH_T/L=36$ for acetone while Tewarson (1) reports $H_T/L=47.48$. This suggests that X_A has a laboratory value of 0.76. On this basis, the following heats of combustion may be calculated:

Actual Heat of Combustion:	23.4 kJ/g
Theoretical Heat of Combustion:	30.8 kJ/g

These calculated values may be compared to experimental data obtained by Tewarson (6) for acetone:

Actual Heat of Combustion:	21.71 kJ/g
Theoretical Heat of Combustion:	28.49 kJ/g

Recognizing the relatively consistent values obtained under different circumstances and assumptions, this analysis utilizes the higher heats of combustion for purposes of conservatism.

It should be noted at this point that Tewarson (6) also reports the following data for acetone in the experiments performed:

Actual Heat Release Rate:	262	kW/m^2
actual =	0.762	
convective =	0.5666	
radiative		
luminous =	0.20	
highly luminous =	0.37	

It is apparent from a review of this data that a fuel vaporization rate for acetone of 12.1 g/m^2 was characteristic of the tests reported in Tewarson (6). This vaporization rate may be best described as non-turbulent or transitory, a condition which would be expected to occur at lower oxygen concentrations where flame convection is the dominant mechanism for fuel vaporization. In larger fires where flow is truly turbulent, it has been seen [Tewarson (4)] that radiation begins to dominate convective heat release. Utilizing the higher value of 37% for the radiative component associated with highly luminous flames, the following values are assumed for acetone:

actual	=	0.76
radiative	=	0.37
convective	=	0.39

This yields the following results for acetone:

Heat of Combustion (kJ/g)

convective	=	12.0 kJ/g
radiative	=	11.4
actual	=	23.4
complete combustion	=	30.8

Vaporization Rate (g/m^2-sec.)

highly luminous flame	=	40.0

Heat Release Rate (kW/m^2)

convective	=	480.0
radiative	=	456.0
actual	=	936.0

In a similar fashion, one may obtain heat release rate data for other fuels. For lubricating oil, Tewarson (4) reports the following data as representative for typical high-temperature hydrocarbons:

	Laboratory Scale	Large Scale
Heat of Combustion (kJ/g)		
convective	18.2	-
radiative	20.4	16.3
actual	38.6	-
complete combustion	46.3	-
Vaporization Rate (g/m^2-s)		
highly luminous flame	40.0	26.8

	Laboratory Scale	Large Scale
Heat Release Rate (kW/m^2)		
convective	728	534
radiative	816	415
actual	1544	949

Tewarson (4) reports the following data for heptane:

	Laboratory Scale	Large Scale
Heat of Combustion (kJ/g)		
convective	21.6	-
radiative	17.4	14.4
actual	39.0	-
complete combustion	44.6	-
Vaporization Rate (g/m^2-s)		
highly luminous flame	70	70.1
Heat Release Rate (kW/m^2)		
convective	1512	1514 (estimated)
radiative	1218	1009 (estimated)
actual	2730	2523 (estimated)

This analysis utilizes the laboratory scale turbulent values for fuel vaporization rate and heat release rates in calculating the effects of exposure fires on electrical cables and plant equipment. The impact of this practice is that this effectively assumes that the most efficient combustion achievable in the laboratory occurs in general plant areas as well.

References:

(1) A. Tewarson, "Heat Release Rate in Fires", Fire and Materials, V4, pp. 185-191 (1980).

(2) R.C. Weast, Editor, "Handbook of Chemistry and Physics", 61st Edition (1980-81), Chemical Rubber Company, Cleveland, OH, 1980.

(3) A. Tewarson, "Physico-Chemical and Combustion/Pyrolysis of Polymeric Materials", Report RC80-T-9, Prepared for U.S. Department of Commerce, National Bureau of Standards, Center for Fire Research by Factory Mutual Research Corporation, Norwood, MA, November, 1980.

(4) A. Tewarson, "Fire Behavior of Transformer Dielectric Insulating Fluids", DOT-TSC-1703, Prepared for U.S. Department of Transportation, Transportation Systems Center by Factory Mutual Research Corporation, Norwood, MA, September, 1979.

(5) A. Tewarson and R.F. Pion, "A Laboratory-Scale Test Method for the Measurement of Flammability Parameters", FMRC 22524, Factory Mutual Research Corporation, Norwood, MA, October, 1977.

(6) A. Tewarson, "Experimental Evaluation of Flammability Parameters of Polymeric Materials", Report FMRC J.1.1A6R1, Prepared for Products Research Committee, National Bureau of Standards by Factory Mutual Research Corporation, February, 1979.

(7) V.I. Blinov and G.N. Khudiakov, "Diffusion Burning of Liquids", Moscow Academy of Sciences (1961).

APPENDIX B

Stratification

The stratification model used in this section has its origins in work performed by J.S. Newman and J.P. Hill of Factory Mutual Research Corporation on behalf of the Electric Power Research Institute (1). This EPRI research related the radiative and convective heat flux associated with stratified layers of hot gases developed in an enclosure fire to the room's dimensions, the height above the floor, the fuel's flammability parameters and the ventilation rate. Data was obtained in a series of experiments involving 14 methanol and heptane enclosure fires at elevations ranging from 30%-98% of the ceiling height for up to 12 room air changes per hour. Among the general observations, FMRC scientists noted the following:

(1) Varying the location of the pan fire within the enclosure had no appreciable effect on the measured heat fluxes or gas temperatures at any given position. This suggests the lack of sensitivity of stratified heat flux to horizontal separation.

(2) Differences in gas temperature or heat flux measurements at the same vertical position at different locations were, in general, inconsequential and within the variation expected from the measuring instrument.

(3) In terms of horizontal variation, measurements indicate a tendency for the enclosure corners to be slightly cooler and receive lower total heat fluxes than at other locations within the enclosure.

(4) The ventilation rate does not appear to have a dominant effect on gas temperatures or heat fluxes within the enclosure, with ventilation rates below approximately one and one-half room changes per hour having virtually no effect.

(5) The total heat flux measured at any point in the enclosure is approximately 5-10% radiative and 90-95% convective for all conditions investigated independent of fuel. Since the heat flux data collected was for an exposed sphere, this suggests predicted values which would actually be conservative for cylindrical cable bundles found in cable trays.

(6) Because of the observed stratification, the application of these empirical results would be appropriate for any room shape as long as the floor area of the particular room is greater than or equal to the floor area of a comparable room of the same height with dimensions of 2:1:1.

Newman and Hill reported empirical spatially dependent transient and steady state heat fluxes. Figure B-1 illustrates the course of heat flux over time following ignition. The transient heat flux was shown to be related to a time constant unique to each fuel that was obtained by a power curve fit to the fire diameter. Heskestad (2) provides the basis for such a response in the early stages of a fire.

Correlations of the data were obtained by Newman and Hill (1) and are reproduced below:

$$(1) \quad \frac{\dot{q}''_{ss} H^2}{\dot{Q}''_T A} \left[\frac{h}{H}\right]^{-1/2} = 0.24 - \frac{4.73 \dot{V}_f}{H^{5/2}} \qquad \text{(Steady State)}$$

$$(2) \quad \frac{\dot{q}''_t}{\dot{q}''_{ss}} \left[\frac{h}{H}\right]^{-1/2} = \left[0.52 + \frac{13 \dot{V}_f}{H^{5/2}}\right]\left[\frac{t}{\tau}\right]^{0.9} \qquad \text{(Transient)}$$

These results were reviewed for accuracy against the original data in the EPRI report presented in Table 3-4 of Newman and Hill (1), which is reproduced as Table B-1. Plotting the reported data onto Newman and Hill's Figure 3-2 (reproduced herein as Figure B-2) suggests that the original EPRI correlation defines a poorly behaved function with respect to the ventilation component such that with higher ventilation rates, a refrigeration effect may be noted. In reality, while higher ventilation rates will in general have a disruptive effect on any enclosure fire to the point where some mitigation is possible, it was felt that use of the EPRI correlations would be non-conservative at some points. It should be noted, however, that for relatively small exposure fires which are not ventilation-limited, the fire severity is reduced as ventilation increases. This point is discussed in some detail by T.Z. Harmathy (2,3).

Nevertheless, to provide assurance that the function remains well behaved in a conservative fashion and that the experimental data provides bounding results, a modified correlation was obtained as follows:

$$(3)\quad \dot{q}''_{ss} = \begin{cases} 0.7854\ \dot{Q}''_T \dfrac{D^2}{H^2}\left[\dfrac{0.05585}{(1.193 - \frac{h}{H})^{1/2}} \cdot \left[0.01161 - \dfrac{0.01031}{(2.13 - \frac{h}{H})^{1/2}}\right]^{-0.153}\right]; \\ \qquad \dot{V}_f \le H^{5/2}\left[0.01161 - 0.01031(2.13 - \frac{h}{H})^{-1/2}\right] \\ \\ 0.7854\ \dot{Q}''_T \dfrac{D^2}{H^2}\left[\dfrac{0.05585}{(1.193 - \frac{h}{H})^{1/2}} \cdot \left[\dfrac{\dot{V}_f}{H^{2.5}}\right]^{-0.153}\right]; \\ \qquad \dot{V}_f \ge H^{5/2}\left[0.01161 - 0.01031(2.13 - \frac{h}{H})^{-1/2}\right] \end{cases}$$

(4) $\dot{q}_t'' = \dot{q}_{ss}'' \left(\frac{t}{\tau}\right)^{0.9} \left[\frac{h}{H}\right]^{1/2} \left[0.52 + \frac{13\dot{V}_f}{H^{5/2}}\right]$; $\dot{q}_t'' \leq \dot{q}_{ss}''$

Utilizing these revised correlations, the analysis applies classical optimization techniques for non-linear functions to determine the minimum fuel volumes and associated geometries (i.e., fire area and spill depth) necessary to exceed the damage criteria for the cables of concern at the elevations of interest within an enclosure.

References:

(1) J.S. Newman and J.P. Hill, "Assessment of Exposure Fire Hazards to Cable Trays", EPRI-NP-1675, Electric Power Research Institute, Palo Alto, CA, January, 1981.

(2) G. Heskestad and M.A. Delichatsius, "The Initial Convective Flow in Fire", Report RC79-T-2, Factory Mutual Research Corporation, Norwood, MA, January, 1979.

(3) T.Z. Harmathy, "Some Overlooked Aspects of the Severity of Compartment Fires", Fire Safety Journal, 3(1980/1981), pp. 261-271.

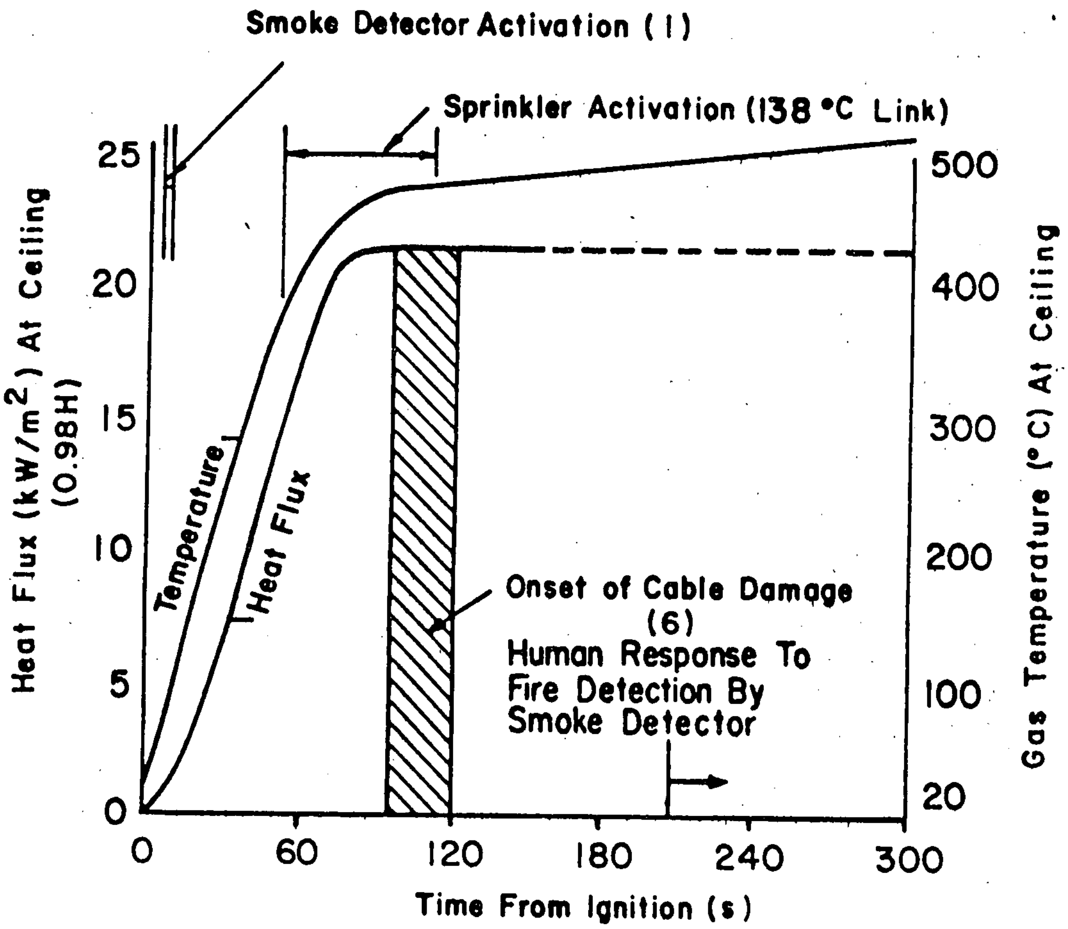
(3) T.Z. Harmathy, "Effect of the Nature of Fuel on the Characteristics of Fully Developed Compartment Fires", Fire and Materials, V3, N3 (1979), pp. 49-60.

GAS TEMPERATURES, GAS VELOCITIES AND TOTAL HEAT FLUXES
VERSUS POSITION FOR ENCLOSURE FIRE TEST EP008
(70 s AFTER IGNITION)

Station	Vertical Position	Gas Temperature (°C)	Gas Velocity (m/s)	Total Heat Flux (kW/m^2)	Percent Radiative
1	0.98H	387	5.0	20.4	7.9
2		458	6.4	24.9	9.4
3		429	5.1	20.5	6.5
4		457	5.3	23.1	7.9
5		406	2.8	17.1	7.1
1	0.90H	364	1.5	12.5	6.5
2		356	1.9	12.2	6.8
3		328	2.1	11.8	5.2
4		342	1.9	12.5	6.0
5		385	1.4	13.4	7.1
1	0.70H	315	1.5	11.0	7.4
2		294	1.5	9.7	4.3
3		299	1.5	10.0	7.3
4		297	1.9	11.0	7.6
5		311	1.1	10.1	9.9
1	0.50H	269	2.4	10.9	8.9
2		268	2.7	10.9	9.1
3		267	1.7	9.1	5.6
4		258	1.3	7.9	3.9
5		256	0.8	7.1	5.7
1	0.30H	232	1.7	8.0	5.0
2		241	2.8	9.2	4.7
3		218	2.2	7.7	5.8
4		222	1.7	6.1	7.5
5		217	0.5	4.7	5.0

Table B-1

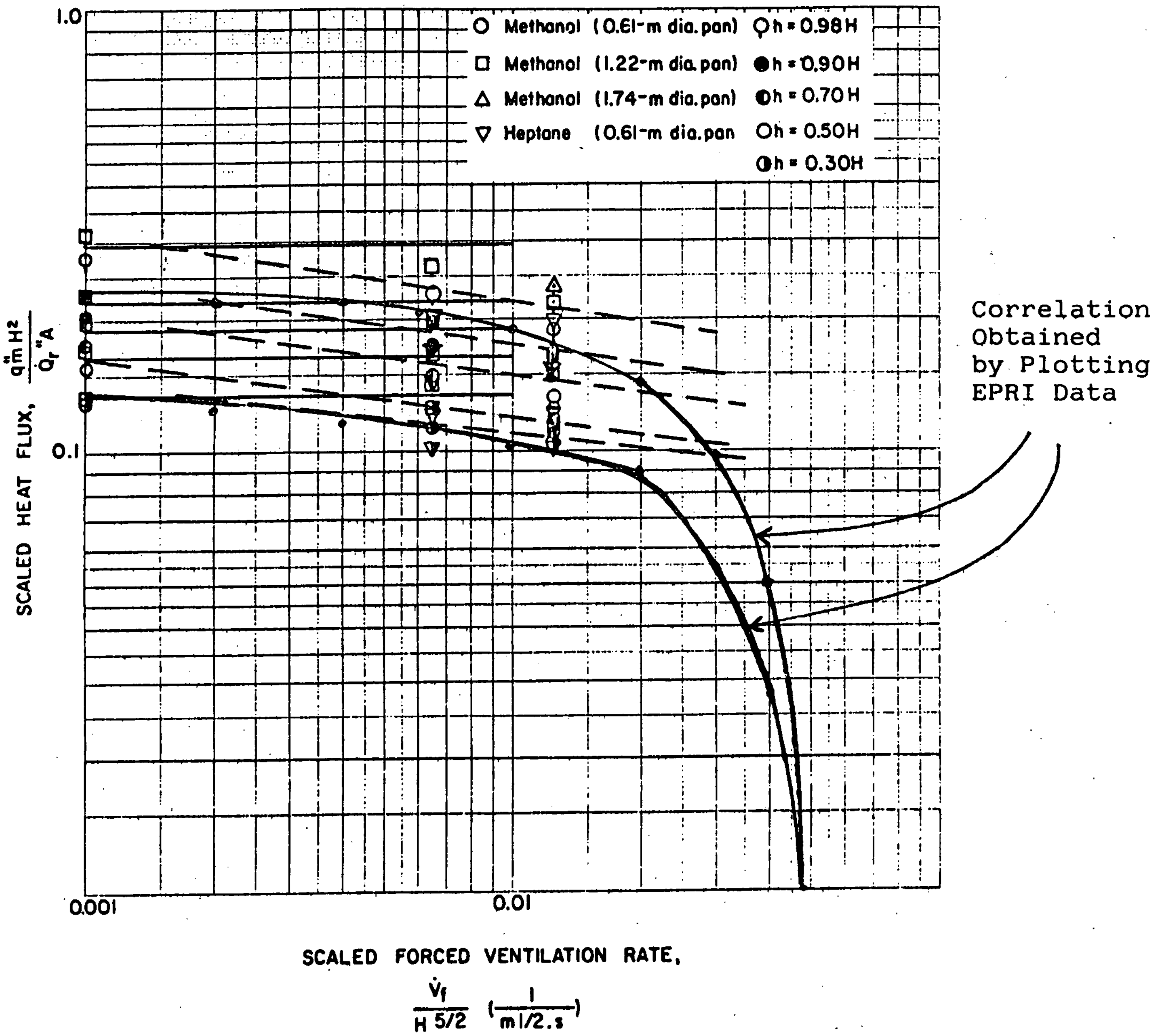
Reproduced from Newman, J.S. and Hill, J.P., "Assessment of Exposure Fire Hazards to Cable Trays", EPRI-NP-1675, Electric Power Research Institute, Palo Alto, CA, January, 1981



Heat flux and gas temperature at ceiling (Station 4) versus time from ignition for Test EP008

Figure B-1

Reproduced from Newman, J.S. and Hill, J.P., "Assessment of Exposure Fire Hazards to Cable Trays", EPRI-NP-1675, Electric Power Research Institute, Palo Alto, CA, January 1981.



Scaled Heat Flux versus Scaled Forced Ventilation Rate

Figure B-2

Reproduced from Newman, J.S. and Hill, J.P., "Assessment of Exposure Fire Hazards to Cable Trays", EPRI-NP-1675, Electric Power Research Institute, Palo Alto, CA, January 1981.

APPENDIX C

Diffusion Plumes

A low-level fire in an enclosure develops a turbulent, buoyant, diffusion plume which flows upward towards the ceiling or the first horizontal surface. Driving the upward flow of hot gases are the gravitational forces acting on the difference in density between the plume and its ambient environment, a condition which poses a problem for the analyst to consider. An understanding of the physics of such plumes is esential to the modeling of the effects of such plumes on immersed materials and components. Fortunately, recent developments as discussed in the literature allow for the prediction of the effects of such plumes.

The history of the modeling of turbulent buoyant diffusion plumes is fairly recent. An early description of the flow of buoyant plumes published in 1941 is attributable to Schmidt (1). In a series of experiments involving convective plumes of air above small sources, Schmidt noted the tendency of buoyant plumes to exhibit conical patterns in turbulent vertical flow. Assuming symmetry conditions existed, Schmidt generated velocity and temperature profiles for constant ambient temperatures involving point and line sources and verified their accuracy against experimental data.

Batchelor (2) extended Schmidt's results to both stratified and uniform environments in a manner similar to Rouse et al. (3). These classical relationships are reproduced below:

$$U = F_a^{1/3} z^{-1/3} f_1\left(\frac{r}{z}\right)$$

$$g' = F_a^{1/3} z^{-5/3} f_2\left(\frac{r}{z}\right)$$

$$d = \lambda z$$

where $F_a \equiv$ buoyancy/unit time $\Big|_{\text{source}}$

$$= 2\pi \int_0^\infty U\, g' r dr$$

$g' \equiv$ buoyancy $= g \dfrac{\Delta\rho}{\rho_a}$

$z \equiv$ height above source

$r \equiv$ radial distance from plume axis or centerline

$g =$ acceleration of gravity

$\Delta\rho =$ density difference between local and ambient gas

$\rho_a =$ ambient density

$U =$ mean vertical velocity in plume

$d =$ plume radius

$\lambda =$ dimensionless constant

In defining these relationships, the forms of $f_1(r/z)$ and $f_2(r/z)$ were initially undetermined although it may be apparent that boundary conditions require that they be at once continuous and well-behaved. This consideration was confirmed through a series of experiments involving hot air in a large room by Rouse et al. (3) where it was demonstrated that both the mean temperature and the velocity profiles were essentially Gaussian. On this basis, Batchelor's relationships become:

$$U = 4.7F_a^{1/3}z^{-1/3}e^{-(\frac{96r^2}{z^2})}$$

$$g' = 11F_a^{1/3}z^{-5/3}e^{-(\frac{71r^2}{z^2})}$$

At this point, the development of a theory for buoyant diffusion plumes is limited by the mixing length theories which form the basis for the similarity solution approach taken by Batchelor (2). These assumptions imply a loss of generality of Batchelor's functions for plumes diffusing into non-uniform gas temperatures. However, this difficulty is overcome through the use of an entrainment assumption attributable to Taylor (4) for air blast phenomena associated with nuclear detonations. This very fundamental assumption relates the mean inflow velocity across a plume edge to the local mean vertical velocity primarily through entrainment. Morton et al. (5) applied this asumption to the study of convection currents.

As reported in Stavrianidis (6), three principal assumptions are made by Morton et al. (5).

(1) The largest local variations of density in the field of motion are small in comparison to some chosen reference density.

(2) The mechanics of entrainment can be represented fully by taking a mean radial inflow velocity across some suitably defined "mean outer boundary" as proportional to the mean vertical velocity on the plume axis at that height. Equivalently,

$$V = E_o U_o$$

where E_o = 0.1 from Stavrianidis (6) and Turner (2)

U_o = mean vertical velocity on plume centerline

(3) The mean profiles of longitudinal velocity, temperature and density are similar in shape at all elevations in the plume.

These relationships apply to weakly buoyant plumes. Extension of the theory to strongly buoyant plumes initially leads to a redefinition of the local entrainment function due to Morton (8):

$$E = \left(\frac{\rho}{\rho_a}\right)^{\frac{1}{2}} E_o$$

With this modification for the local entrainment function, solution of the general plume conservation equations for the case of the strongly buoyant plume was shown by Morton to be essentially equivalent to that of the weakly buoyant plume with larger convective heat release rates. Heskestad (9) subsequently confirmed this generality inside the flame envelope in a series of experiments.

With this background, it is apparent that turbulent, buoyant, diffusion plumes could be described mathematically in terms of convective heat release rates and position above the source. Stavrianidis (6) extended this basis in a series of experiments involving large scale hydrocarbon fires which measured the actual heat release rate in the plume. The redefined plume laws correlated to Stavrianidis' data yield, independent of fuel type:

$$\overline{\Delta T} = 0.092 Q_c^{2/3} (z - z_o)^{-5/3} \; e^{-\left(\frac{71 r^2}{z^2}\right)}$$

$$U = 1.20 Q_c^{1/3} (z - z_o)^{-1/3} \; e^{-\left(\frac{96 r^2}{z^2}\right)}$$

where $\overline{\Delta T}$ = normalized excess temperature on plume centerline

$$= \frac{T - T_a}{T_a}$$

T = mean plume temperature

T_a = ambient temperature

Q_c = actual convective heat release rate

z = height above physical source

z_o = height of virtual source above physical source

Stavrianidis demonstrated the validity of these correlations well into the flame envelope to a point of divergence noted for plume gas temperatures. The data reveals a constant maximum value for temperature of 1235°K for heptane, methanol, and silicone oil fires. The point of divergence is defined as the critical height, a function solely of the convective heat release rate, and given by:

$$z_c = 0.13Q_c^{2/5} + z_o$$

The determination of the height of the vertical source is given by:

$$z_o = 7.54F^{1/5}\left(\frac{\dot{m}^2S^3}{\alpha_c H_c}\right)^{1/5} - 0.15Q_c^{2/5}$$

where $F = \dfrac{c_p T_a}{\rho_a^2 g}$

$\dot{m}$ = fuel vaporization rate

$\alpha_c = \dfrac{Q_c}{\dot{m}H_T}$

H_c = convective heat of combustion

H_T = theoretical heat of combustion

S = stoichiometric fuel-oxygen ratio

With these experimentally derived relationships, it is possible to calculate a number of parameters of interest relative to the exposure fire problem, in particular:

(1) Plume temperatures above a pool fire,

(2) Gas velocities above a pool fire,

(3) Heat flux delivered to a point above a pool fire,

(4) Radiative heat flux associated with luminous flames.

Each of these calculations is of value in the quantitative fire hazards analysis contained in this report. This appendix will cover those aspects related to the heat flux associated with diffusion plumes.

The problem of plume impingement is treated in this analysis in three distinct approaches:

(1) Stagnation heat flux associated with direct plume impingement on a horizontal surface.

(2) Cross flow heat flux to a cylinder (cable) associated with immersion in a turbulent buoyant plume.

(3) Parallel flow along a plate associated with immersion in a turbulent buoyant plume.

Axisymmetric fire-induced flow beneath a flat horizontal surface such as a ceiling has been discussed in the literature for some time. Early work includes that of Pickard et al. (10) and Thomas (11). The theory, however, did not progress to the level of generality until Alpert (12) developed a basis for the accurate prediction of turbulent ceiling jets as a function of the heat release rate and distance to the ceiling. Alpert's analytical work, which was verified through experiments, demonstrated the validity of using small-scale models to predict the behavior of large-scale ceiling jets.

The basis for Alpert's work includes the top-hat source profiles of Morton et al. (5) and the Gaussian temperature/velocity profiles of Rouse et al. (3). Alpert's model views the ceiling jet as a boundary layer divided into two regions: an outer region where entrainment occurs as a result of turbulent mixing and a viscous essentially laminar sublayer at the horizontal surface. Data taken in Alpert's experiments indicates a decline in entrainment by an order of magnitude 3-4 ceiling heights from the fire axis. A significant decline in ceiling temperature as well as an increase in jet thickness is also noted 3-5 ceiling heights from the fire axis. Finally, the stagnation region is considered to extend radially outward to a distance of approximately 20% of the ceiling height prior to transitioning to a uniform stratified layer. Semi-Gaussian profiles are assumed for the transition or turning region.

You and Faeth (13) extend Alpert's work and determine a heat flux within the stagnation region ($r/h < 0.2$) as a function of gas properties and the fire's heat release rate:

$$\frac{\dot{q}'' H^2}{\dot{Q}} = 31.2 Pr^{-3/5} Ra^{-1/6}$$

when Pr = Prandtl number (~0.7)

Ra = Rayleigh number

$$= \frac{g \beta \dot{Q} H^2}{\rho C_p \nu^3} \quad (10^9 < Ra < 10^{14})$$

$$\frac{H_f}{H} < 1.5$$

H = ceiling height

H_f = free flame height

g = gravitational constant

β = coefficient of columetric expansion

ρ = density

ν = ceiling radial velocity for the jet

$\dot{q}''$ = heat flux

c_p = heat capacity

$$\frac{\dot{q}''H^2}{\dot{Q}} = 0.04 \left(\frac{r}{H}\right)^{-1/3}$$

for $10^{10} < Ra < 2 \times 10^{13}$

$Pr \sim 0.7$

$\frac{H_f}{H} < 0.6$

References:

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APPENDIX D

Cable Failure Criteria

A concept of an electrical cable damage criterion with a sound technical basis is essential to the modeling of the effects of fire. The approach utilized in this report focuses on the flammability properties of the materials of concern and the effects of incident heat flux on the ability of the cable to function properly.

Electrical cables consist of several individual insulated cables bounded within a jacket designed to protect the cables from external hazards while ensuring adequate cooling under normal conditions. Generally, both the insulation and the jacket are manufactured from polymeric materials. Typical of such macromolecules is polyethylene, a long molecule based on the ethylene monomer $(-CH_2CH_2-)_n$ chain. Polymerization of vinyl monomers with chloride as the pendant group yields polyvinylchloride, a jacket material found in electric cables in older nuclear units.

Thermal decomposition of polymeric materials (pyrolysis) results in the physical degradation of a cable's insulation and produces combustible gases that may ignite in the presence of an ignition source. The process of pyrolysis requires a minimum heat flux exposure and may be measured in terms of the insulation and jacket mass loss rate. Higher mass loss rates at a particular heat flux exposure suggest that more rapid combustion and higher overall heat release rates are possible with the material.

The detailed study of material flammability properties and an understanding of the pyrolysis/combustion process requires the use of a calorimeter capable of measuring mass loss rates, analyzing gaseous products, and determining heat release rates under varying incident fluxes. Such an apparatus has been in use for several years at Factory Mutual Research Corporation as described by Tewarson and Pion (1). This apparatus presents results for ignition, mass pyrolysis/burning rate, product mass generation rates, heat release rates, optical transmission through the products, and material thermal inertia. Experimental data for common polymeric solids and liquid hydrocarbons is presented in Tewarson (2) and Tewarson et al. (3).

With the objective of understanding the physical processes underlying electrical cable flammability, the Electric Power Research Institute funded research at Factory Mutual Research Corporation utilizing the Tewarson apparatus. Initial results were reported in Tewarson et al. (4) for twenty (20) different cable specimens which included a number of IEEE-383 qualified cables [IEEE (5)]. Cables evaluated in this program are listed in Table D-1. This program was the most comprehensive study of electrical cable flammability then in existence. With the Tewarson work as a basis, the transition from a fundamental and comprehensive understanding of the electrical cable flammability parameters to a damageability criteria is not especially difficult. Before making that transition, however, it is important to discuss the relationship of the flammability parameters to the IEEE-383 fire test and the meaning of the standard itself.

The criteria given for the IEEE-383 flame test is as follows:

(1) The fire test should demonstrate that the cable does not propagate fire even if its outer covering and insulation have been destroyed in the area of flame impingement.

(2) The fire test should approximate installed conditions and should provide consistent results.

This test is essentially a "go/no-go" test which is generally considered appropriate for all cable arrangement conditions. Tewarson et al. (4) demonstrated the validity of the intuitive notion, however, that cable flammability is actually dependent on multiple parameters. In that series of tests it was demonstrated that some electrical cables which were not qualified according to IEEE-383 exhibited flammability characteristics more desirable than those of the qualified cables tested. In fact, the only statement that Tewarson could make concerning the IEEE-383 tested cables was that the actual heat release rates were less than about 350 kW/m^2 for an external heat flux of 60 kW/m^2. This is not to suggest that IEEE-383 cable does not demonstrate good fire resistance qualities but rather to illustrate the complex phenomenon associated with fire and to highlight the fact that some unqualified IEEE-383 cables exhibited equally desirable performance characteristics.

The value of controlled laboratory experiments in categorizing cable flammability has been clearly demonstrated. As thermal conditions vary with a fire, different electrical cables undergo physical and chemical changes depending upon their chemical composition. In this context the concept of damageability must be related to the thermal conditions which cause impairment to the cable's function.

This concept of damageability was examined by Lee (6) using data presented by Tewarson et al. (4). Four basic phenomena were examined and are presented below in increasing magnitude of damage.

- Insulation degradation--the onset of jacket mass loss from a cable.
- Electrical failure under piloted conditions--the onset of short circuit between conductors for a 70 VDC signal under piloted conditions.
- Piloted ignition--the onset of ignition in the presence of a small pilot flame.
- Auto-ignition--the onset of self ignition.

For each cable, Lee plotted the external heat flux incident of the specimen against the inverse of the time to failure. These plots yielded the following information for each specimen:

(1) Critical heat flux--that incident heat flux above which the cable damage process is expected to occur.

(2) Critical energy--that amount of energy exposure necessary to cause cable failure to occur given a heat flux at or above the critical value.

The critical heat flux is obtained through the linear extrapolation of a regression curve to the heat flux intercept as the time to failure approaches infinity. The critical energy is defined as the inverse slope of the regression curve on the heat flux-inverse time to failure (x-y) axis. Figures D-1, D-2, and D-3 illustrate the case of cross-linked polyethylene cables with neoprene jackets for the four criteria defined.

It should be emphasized at this point that the data presented for each cable represents fundamental properties of the cable without taking credit for the mitigating effects associated with the use of cable trays. Such effects include and are not necessarily limited to self-shielding and conductive cooling. Thus, these values should be considered to be conservative in the usual sense and offer the unique advantage of understanding relative performance characteristics independent of qualification. This point is especially meaningful when evaluating the relative fire resistance of electrical cables installed in nuclear power plants prior to the implementation of IEEE-383.

The fire hazards analysis utilizes this concept for electric cable failure criteria when modeling the effects of exposure fires on safe shutdown equipment. In general, the more limiting criterion of electrical failure is considered unless otherwise specified. The use of electrical failure as a criterion rather than cable ignition is also useful in that it focuses on the loss of function aspect of the fire protection issue. In cases where cable tray fires are postulated, their ignition is investigated using the piloted ignition criteria for cable flammability defined by parameters developed in Tewarson et al. (4). Thus, issues related to variation in the ignition criteria associated with fully developed fires are moot.

References:

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TABLE D-1

CABLE SAMPLES USED IN THE STUDY

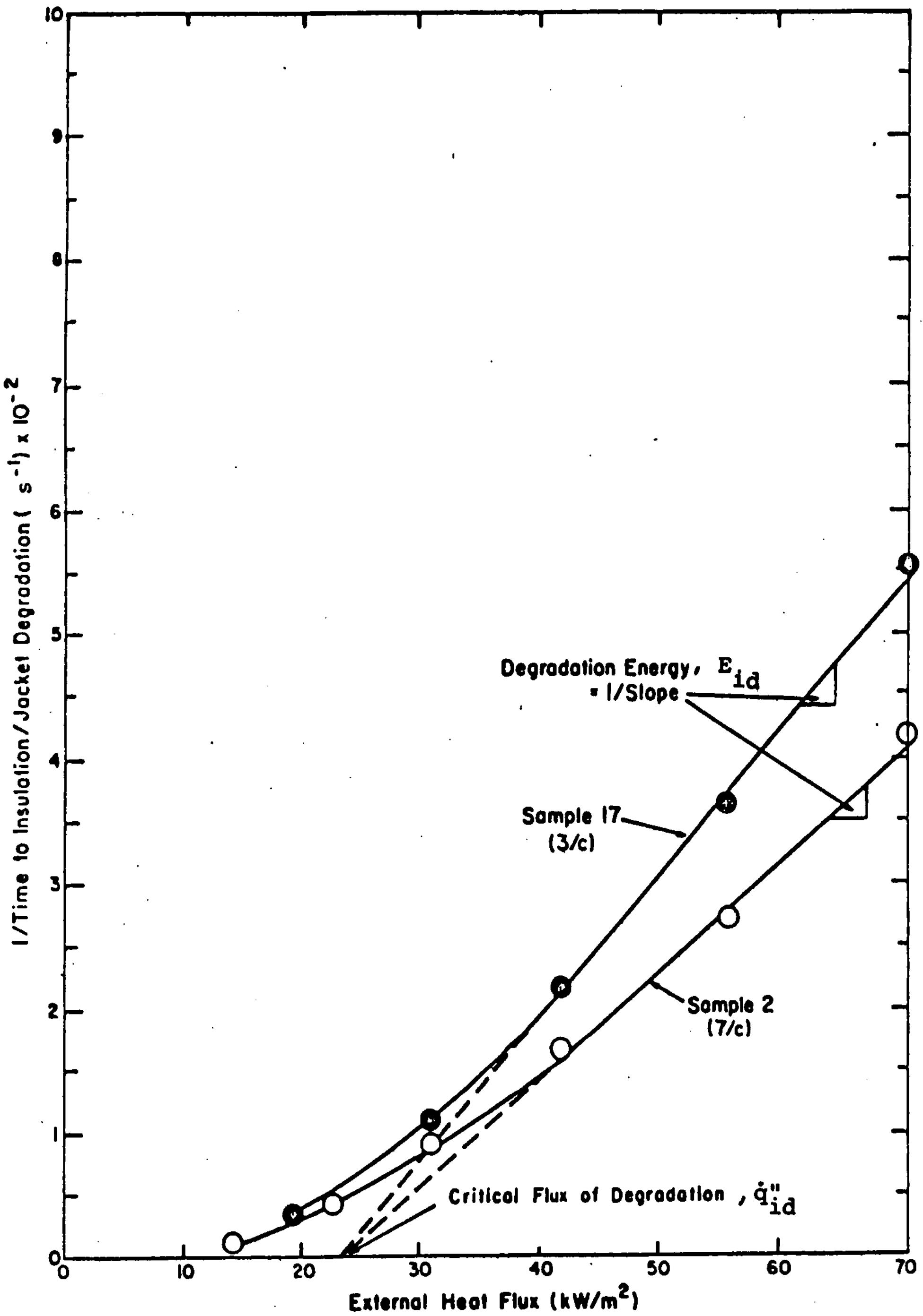
Number	Insulation/Jacket Materials[a]	Conductor No.	Conductor Size (AWG)	Outer Cable Diameter in. (m)	Insulation/Jacket Materials (% of total cable weight	Insulation Jacket Materials remaining as char (% of initial wt. of insulation/jacket materials)	IEEE-383 Rating
	Polyethylene (PE)/No Jacket						
1	Low density PE (ℓdPE), no jacket	1	14	0.128(0.003)	23.9	0.10	-
	Polyethylene/Polyvinyl chloride (PE/PVC)						
3	PE/PVC	1	-	0.945(0.024)	15.6	21.9	
4	PE/PVC	1	12	0.164(0.004)	26.5	0.6	Fail
5	PE/PVC	3	-	0.438(0.011)	49.9	20.8	Fail
6	PE/PVC	5	-	0.748(0.019)	51.0	25.6	
7	PE/PVC	12	-	1.000(0.025)	57.8	24.4	
	Polyethylene, Polypropylene/Chlorosulfonated Polyethylene (PE, PP/Cℓ·S·PE)						
8	PE,PP/Cℓ·S·PE (silicone coating)	1	-	0.445(0.011)	23.2	41.6	Pass
9	PE,PP/FRCℓ·S·PE[b]	1	6	0.368(0.009)	40.2	46.4	Pass
10	PE,PP/Cℓ·S·PE	1	12	0.192(0.005)	42.9	45.6	Pass
11	PE,PP/Cℓ·S·PE	5	14	0.668(0.017)	77.1	48.3	Pass
12	PE,PP/Cℓ·S·PE	2	16	0.426(0.011)	77.4	40.5	Pass
	Cross-Linked Polyethylene/Cross-Linked Poyethylene (XPE/XPE)						
13	XPE/FRXPE[b]	3	12	0.458(0.012)	61.4	44.9	Pass
14	XPE/XPE	2	14	0.377(0.010)	73.5	-	Pass
	Cross-Linked Polyethylene/Chlorosulfonated Polyethylene (XPE/Cℓ·S·PE)						
15	FRXPE/Cℓ·S·PE[b]	4	16	0.368(0.009)	56.2	29.5	Pass
16	XPE/Cℓ·S·PE	4	16	0.442(0.011)	62.1	31.0	Pass
	Cross Linked Polyethylene/Neoprene (XPE/Neo)						
17	XPE/Neo	3	16	0.369(0.009)	73.2	43.9	Pass
2	XPE/Neo	7	12	0.630(0.016)	53.6	-	
	Polyethylene, Nylon/Polyvinyl chloride, Nylon (PE, Ny/PVC, Ny)						
18	PE, Ny/PVC, Ny	7	12	0.526(0.013)	39.9	-	
19	PE, Ny/PVC, Ny	7	12	0.520(0.013)	43.5	-	
	Teflon						
20	Teflon	34	-	0.516(0.013)	48.9	3.9	Pass
	Silicone						
21	Silicone, glass braid	1	-	0.363(0.009)	34.0	-	
22	Silicone, glass braid/asbestos	9	14	0.875(0.022)	70.5	59.4	Pass

[a] Generic class as given by the suppliers. Cable samples belonging to similar generic class may not be similar because of different types and amounts of unknown additives in the cable samples.

[b] FR - with fire retardant chemical

(Reproduced from A. Tewarson, J. L. Lee, and R. F. Pion, "Categorization of Cable Flammability Part 1: Laboratory Evaluation of Cable Flammability Parameters", EPRI-NP-1200, Part 1, Electric Power Research Institute, Palo Alto, CA, October, 1979.)

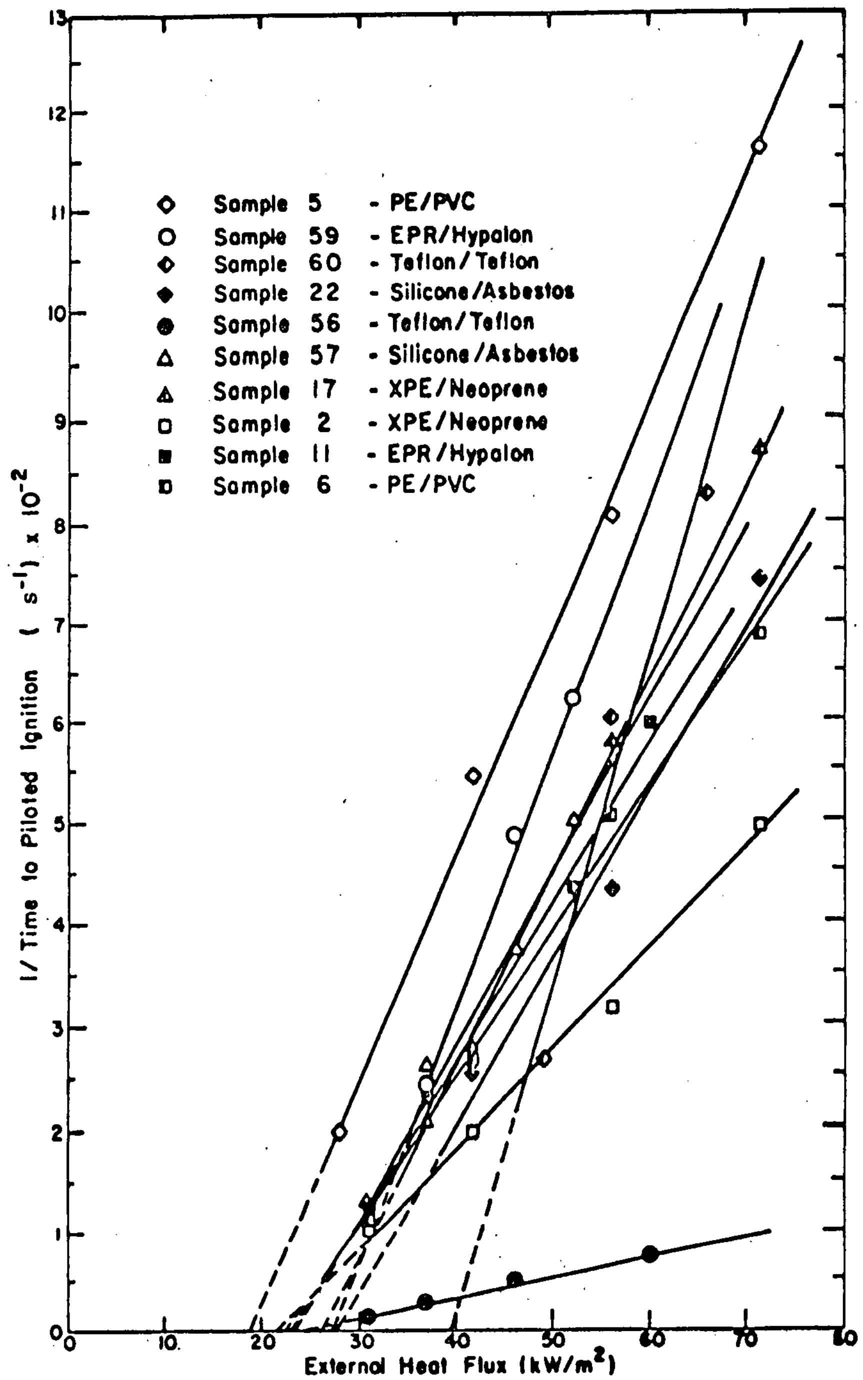
FIGURE D-1



Thermal Degradation of XPE/Neoprene Cables

(Reproduced from J. L. Lee, "A Study of Damageability of Electrical Cables in Simulated Fire Environments", EPRI-NP-1767, Electric Power Research Institute, Palo Alto, CA, March, 1981.)

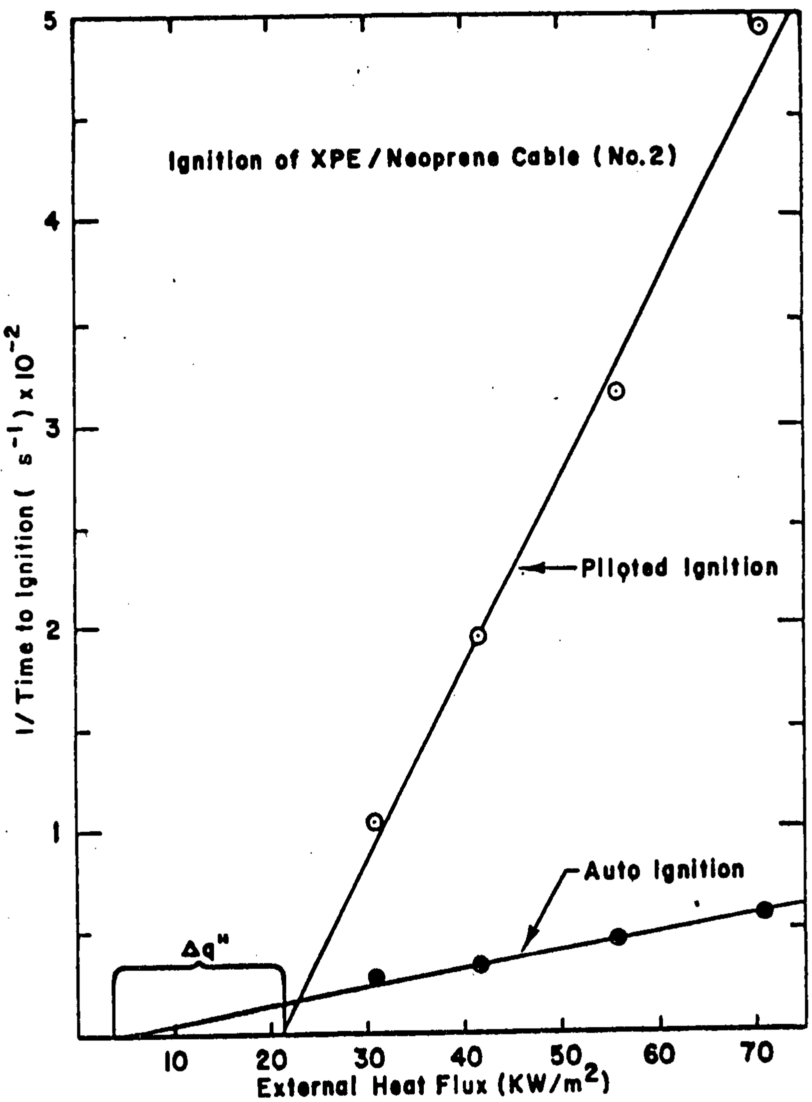
FIGURE D-2



Piloted Ignition of Cables Under Various External Heat Flux

(Reproduced from J. L. Lee, "A Study of Damageability of Electrical Cables in Simulated Fire Environments", EPRI-NP-1767, Electric Power Research Institute, Palo Alto, CA, March, 1981.)

FIGURE D-3



Auto and Piloted Ignition of XPE/Neoprene Cable (#2) at Various External Heat Flux. $\Delta\dot{q}''$ is the difference between the critical flux of piloted ignition and that of non-piloted ignition.

(Reproduced from J. L. Lee, "A Study of Damageability of Electrical Cables in Simulated Fire Environments", EPRI-NP-1767, Electric Power Research Institute, Palo Alto, CA, March, 1981.)

APPENDIX E

Radiation

Radiation can be a significant contributor to the overall heat flux produced as a result of a fire and must be accounted for in properly modeling exposure fires in nuclear power plants. This appendix discusses the approach taken in this report for modeling the effects of radiation from such fires.

The combustion of organic materials such as liquid hydrocarbons is an exothermic reaction. The energy released as a result of such reactions leads to the generation of a high temperature turbulent buoyant diffusion-plume consisting of both gaseous byproducts of combustion and soot particles. The energy contained within this plume is transferred to the environment through two processes: (1) convection associated with momentum of the plume and (2) radiation from the plume.

Molecules in an excited state transfer energy via radiation principally through band emission. For the fundamental products of combustion, i.e., CO_2, CO, H_2O and soot, such emission tends to be concentrated in the visible and infrared regions typically less than 15μ (1). The energy transferred by radiation over these wavelengths depends on a number of parameters including average temperature of the source and its constancy.

Historically, fire models and the discipline of fire protection engineering have addressed radiation in considering the effects of an initial exposure fire. Radiant heating has been found to be a dominant mechanism in the development of largscale conflagrations. This focus is inherently reflected in the use of temperature as a standard of measurement in tests determining fire resistance. Typical of this genre are the standards published by the National Fire Protection Association for qualifying barriers and doors for commercial structures and the E-152 Test issued by the American Society for Testing and Materials (2, 3). These tests are essentially oven tests employing radiant heaters in an attempt to model the dominant heat transfer process in large scale conflagrations involving residential and commercial structures consisting of and containing high densities of combustible material.

The early application of classical radiative heat transfer techniques to the problem of determining safe horizontal separation distances for building fires is documented in reports issued in the post-war period by British and Japanese investigators (4, 5). These and later reports published in the 1950s and 1960s retained the concept of horizontal separation as a principal means of protecting adjacent combustible material (i.e., neighboring buildings) from the intensive effects of major building fires where radiant heat transfer in the open air is the dominant mechanism for damage. During this period, applications of principles for modeling radiant heating, well known in other scientific disciplines, were also made to such distinct problems as the effects of fire-induced flows through windows and doors on adjacent structures, effects of wind on flames, the sensitivity of radiant energy to different flame temperatures and the impact of various wall materials. The conclusions from such studies tended to emphasize the difficulty of developing generalized empirical relationships independent of scientifically based theory and the importance of understanding the effects of material flammability parameters in modeling the radiative effects of fire.

At a more fundamental level, the effects of radiation may be tied to the gaseous dynamics associated with the fire plume itself. With its dominant contributions in both the visible and infrared regions of the electromagnetic spectra, the natural focus for a radiation model therefore becomes one based on the material flammability parameters and, in particular, the height of the visible portion of the turbulent buoyant diffusion plume. In this regard, F.R. Steward's work, (1970), assumes an important role in providing a comprehensive statement of the dynamics of fire plumes for subsequent researchers (6).

Later work by Dayan and Tien (1974) builds on Steward's research in developing a radiant heat flux model which offers excellent agreement with experimental data (7). This model assumes good mixing associated with combustion conditions in the burning zone so as to provide an essentially uniform gaseous temperature and chemical species concentration in a cylindrical form. The use of cylindrical form does not appear to suffer a loss of generality relative to some other shape such as one which is either conical or hyperbolic and, in fact, may well be a more accurate representative of average fire conditions. Of greater significance than fire shape in the modeling of radiant heating is that of soot and gaseous temperature.

Soot and gaseous temperature directly affect the emissivity associated with the luminous flames of a fire. This effect is seen in the following form of the Stefan-Boltzmann law:

$$\dot{Q} = \varepsilon \sigma T^4$$

where $\dot{Q}$ = radiant energy transfer rate

ε = emissivity (dimensionless)

σ = Stefan-Boltzmann constant

T = absolute blackbody temperature

The emissivity of a flame essentially determines the proportion of energy released in the form of radiant energy. The individual components of the total emissivity may be broken up as follows:

$$\varepsilon = \varepsilon_g + \varepsilon_s$$

where ε = total emissivity associated with the fire

ε_g = emissivity of the hot gas within the burning zone

ε_s = emissivity of the luminous soot within the burning zone

Felske and Tien (1973) provide an analytical basis supported by experimental data for understanding the parametric relationships of gaseous and soot emissivity (1). This understanding is a further development of an earlier description provided by Hottel and Sarofim (8). In particular, the relationship of emissivity to spectral wavelength is given for the dominant emission species of water vapor, carbon dioxide and soot. This relationship is strongly affected by the partial pressures of the products of combustion. As in the case of other, well-behaved spectral functions, the use of an effective value for emissivity is supported by the data and may be provided over the range of sensitivity. This range occurs at wavelengths shorter than the 15μ and for infrared band and contains over 96 per cent of the total black body radiation emitted in a fire.

Focusing on gaseous emissivity for the moment, with the assumption of near-optimal fluid mixing and thermal conditions in a fire, combustion may be assumed to involve the following typical reaction:

$$(CH_2)_X + (\tfrac{3}{2})\ X\ O_2 \rightarrow X\ CO_2 + X\ H_2O$$

Under ideal conditions, the partial pressure of CO_2 is 0.131 atm, given a standard environment where the partial pressure of oxygen is 0.21 atm and the partial pressure of nitrogen-argon is 0.79 atm. From Hottel and Sarofim (8) and Hadvig (10), the gaseous emissivity is described by:

$$\varepsilon_g T_g = 600.0\ (P_{CO_2} L_m)^{0.412}$$

where L_m = mean beam length

T_g = gaseous temperature

P_{CO_2} = partial pressure of CO_2

For the case of an essentially infinite cylinder (i.e., an electrical cable):

$$L_m = 0.94D$$

where D = cylinder diameter

This yields the following for the emissivity of a hot gas:

$$\varepsilon_g = \frac{[600][(0.131)(0.94D)]}{T_g}$$

The gaseous temperature is assumed to be a uniform 1255°K (1800°F) based on the work of Stavrianidis (1980) using pool fires consisting of heptane and acetone as fuel (9).

As in the case of gaseous emissivity, the contribution of soot to total emissivity may also be characterized by effectively a single value. Here again, Felske and Tien (1) develop a view consistent with earlier work by Hottel and Sarofim (8). This view suggests that the mainstream of conditions involving the burning of liquid hydrocarbons, i.e., generally lower gaseous temperatures and longer volume of reaction path lengths associated with fairly efficient (energetic) combustion, the emissivity of soot may be bounded for the majority of cases. In these circumstances, a value of 0.1 for the soot emissivity becomes limiting.

With this perspective, a cylindrical fire model is utilized to analyze the effects of radiant heating on the material of interest. The burning zone is described by a more current analytical model for turbulent buoyant diffusion plumes strongly supported by excellent correlations with experimental data obtained under controlled conditions involving fairly large scale acetone and heptane fires (9). This model is described in more detail in the appendix covering diffusion plumes.

The radiant heat flux to an electrical cable from a postulated fire is therefore given by:

$$\dot{q}'' = (5.67 \times 10^{-12} T_g{}^4 + \frac{1.435 \times 10^{-8} D^{0.412}}{T_g} T_g{}^4) F_{21}$$

where $\dot{q}''$ = radiant heat flux incident on a cable

D = cable diameter

T_g = gaseous temperature = 1200°K (1800°F)

F_{21} = configuration factor describing the fraction of heat flux delivered to a point by a radiant right cylinder

This expression is accurate to within 5% for a gaseous temperature range of 1000°K-1600°K.

References:

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APPENDIX F

Thermal Shields

This appendix presents an analytical treatment of the efficacy of baffles when used as thermal shields for the purpose of diverting hot fire gases from direct impingement upon electrical cable. The results of this analysis provide a basis for determining the size such baffles need to be in order to protect a vertical stack of trays from convective heating associated with transient combustible exposure fires.

In fire protection reviews performed subsequent to the Browns Ferry fire, licensees considered the guidelines of BTP APCSB 9.5-1 Appendix A. This document assumes a flexible and multi-layered approach to backfitting fire protection measures to operating power plants. Such measures include the use of flame retardant coatings, suppression and baffles used as thermal shields. As a result of this process many operating plants upgraded their overall fire protection capability as documented in the safety evaluation report (SER) issued by the NRC Staff.

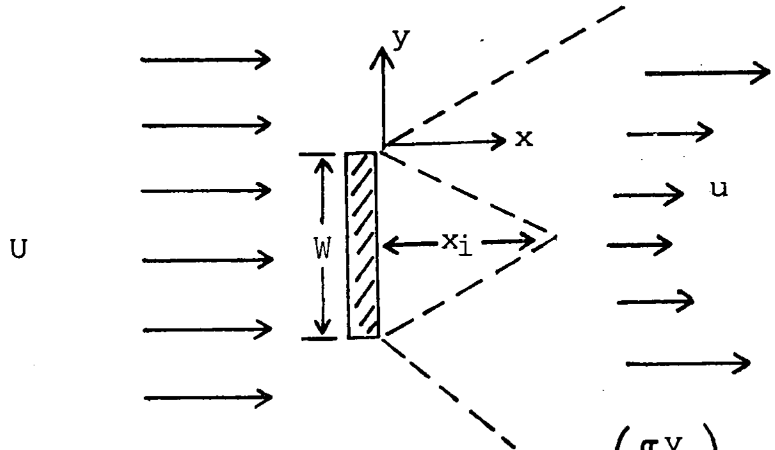
The BTP Appendix A fire hazards analysis led to the implementation of significant modifications at operating plants. The value of such modifications was questioned, however, by the Commission in the issuance of 10CFR50 Appendix R in November 1980. While the Commission explicity highlighted the issue of flame retardant coatings, it may be be inferred that the value of thermal shields was also subject to question. As in the case of coatings, the question turned to the lack of available data.

Phenomenological testing of baffles as thermal shields had been performed at Factory Mutual Research Corporation under the sponsorship of the Electric Power Research Institute [Newman and Hill (1)]. In one test in a series involving the use of sprinklers and baffles, a fire was ignited in a 1.2 meter diameter circular pan containing 17 gallons of #2 fuel oil located 1.8 meters beneath an electrical cable tray protected solely by a 13 mm. (0.5 in.) thick baffle composed of refractory material. Temperatures recorded beneath the baffle were generally in excess of 700°C. After immersion in the 3.7 meter high flames for over 15 minutes before the fire self-extinguished, an examination of the electrical cables showed no visual evidence of charring nor was there a loss of conductor continuity for a 70 Vdc signal at any time during the test.

Physical tests of this type are indicative of the performance of baffles in protecting cable trays against the effects of exposure fires. The process involves the disruption of turbulent flow by a blunt body and may be modeled using standard fluid dynamics computer codes with detailed results available throughout the simulated flow field. This report, however, utilizes a data correlation based on a theoretically coherent approach based on an analysis of the turbulent mixing associated with the wake developed by the baffle. The treatment is by Schlichting (2) who reports on velocity distributions generated in the mixing zones produced by blunt objects. The original data is reported by Tanner (3).

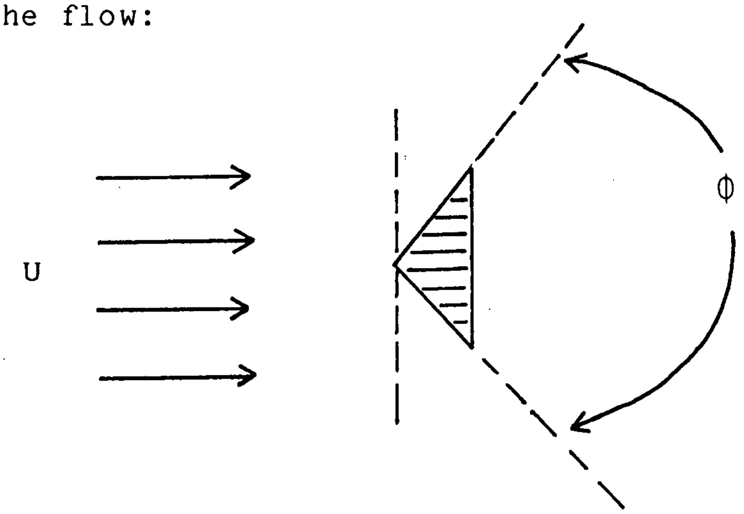
As discussed in Schlichting (2) for a baffle of width, w, located within a flow field characterized by an average velocity, U, the wake velocity at any point in the mixing zone is given by:

$$u = U\left[\frac{1 \pm \mathrm{erf}\left(\frac{\sigma y}{x}\right)}{2}\right]$$



where, $\mathrm{erf}\left(\frac{\sigma y}{x}\right)$ is the error function of $\frac{\sigma y}{x}$

Based on experimental work by Tanner (3), σ is defined to be a function of the angle, ϕ, of the leading edge of the object in the flow:



ϕ	σ
0°	14
30°	10
60°	9
120°	8
180°	7

Therefore, a baffle analysis uses a value for σ equal to 7.

If the protected zone boundary is defined to be bounded by

$$\frac{u}{U} = 0.20$$

the width of the associated baffle in terms of the downstream extent of the protected zone is given by:

$$0.20 = \frac{1 - \operatorname{erf}\left(\frac{7w}{2X_{0.2}}\right)}{2}$$

$$\operatorname{erf}\left(\frac{7w}{2X_{0.2}}\right) = 0.60$$

$$\frac{7w}{2X_{0.2}} = 0.5951$$

$$w = 0.17\ X_{0.2}$$

The choice of $\frac{u}{U} = 0.20$ was based on the assumption that the heat flux will be reduced to 20% of the free stream value, as well as the velocity. Actually, the mixing will further reduce the heat flux by lower fluid temperatures downstream of the baffle. The relationship between w and $X_{0.2}$ identifies the area within which the velocities are below 20% of the free stream velocity. Thus, to create a protected zone around a vertical stack of trays approximately 6 ft. in height, this analysis suggests the installation of a baffle below the lowest tray with a width of at least 13 inches or the width of the tray, whichever is larger. However, the presence of the trays in the wake will lengthen the extent of the protected zone by inhibiting mixing layer growth. Therefore, the baffle width suggested in this analysis will be more than adequate to protect the stack of trays.

It is concluded on this basis that the barrier effect contributed by a vertical stack of closed-sided cable trays combined with the wake effect of a baffle will reduce the convective heat fluxes incident on cables within the trays due to an exposure fire directly beneath the trays, thereby preventing the onset of cable damage.

References

(1) J.S. Newman and J.P. Hill, "Assessment of Exposure Fire Hazards to Cable Trays", NP-1675, Electric Power Research Institute; Palo Alto, CA, January 1981.

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(3) M. Tanner, "Einfluss des Keilwinkels auf den Ähnlichkeitsparameter der turbulenten Vermischungszone in inkompressibler Strömung", Forschg., Ing.-Wes., 39, 121-125 (1973).