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A Summary of Nuclear Power Plant Fire Safety Research at Sandia National Laboratories, 1975–1987

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ABSTRACT

This report summarizes the results and conclusions generated by the U. S. Nuclear Regulatory Commission sponsored Fire Protection Research Program at Sandia National Laboratories. Efforts conducted from the program's inception in 1975 through 1987 are discussed. The individual efforts are discussed within a framework based on specific areas of investigation. Early efforts are presented in the context of investigations of specific regulatory concerns. Later efforts are presented within the context of an integrated investigation of fire safety issues. This integrated approach considers the fire safety issue in terms of (1) source fire characterization, (2) detection and suppression system effectiveness, (3) room effects, (4) equipment response, and (5) room-to-room fire effects. The report provides a complete bibliography of reports and journal articles generated as a result of these efforts with a cross-reference listing of major reports to specific efforts.

Among the topics investigated by various experimental efforts are the effectiveness of fire retardant cable coatings and cable tray fire barrier systems in the prevention of fire spread and fire induced damage, the effectiveness of suppression methods for cable tray fires, testing of cable penetration seals, transient fuel fire characterization testing, investigation of electrical cabinet and control room fires, equipment damageability testing, and large scale enclosure fire testing for the validation of computer fire simulation codes. Topics investigated as a part of analytical efforts include a review of the fire regulations which bear relevance to nuclear plants, investigation of the standards and strategies invoked in the design of various fire protection subsystems, the modeling of cable fire behavior, the identification of reported transient fuel sources, and the development of a fire occurrence data base.

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The results and conclusions summarized here were generated as a result of several years of research performed by a number of investigators, both within Sandia and at other organizations. Many individuals have contributed to the performance of these efforts. The contributions of each of these individuals are acknowledged as the foundations upon which this work is based.

NOMENCLATURE

ASTM	-	American Society for Testing and Materials
AWG	-	American Wire Gage
BTP	-	Branch Technical Position
CDF	-	Core Damage Frequency
CFR	-	Code of Federal Regulations
EPR	-	Ethylene-propylene Rubber
FMRC	-	Factory Mutual Research Corporation
FPRP	-	Fire Protection Research Program
I&E	-	Inspection and Enforcement
IEEE	-	Institute of Electrical and Electronics Engineers
NBS	-	National Bureau of Standards
NFPA	-	National Fire Protection Association
PE	-	Polyethylene
PMMA	-	Polymethyl-methacrylate
PRA	-	Probabilistic Risk Assessment
PVC	-	Polyvinyl Chloride
RG	-	Regulatory Guideline
RMIEP	-	Risk Methodologies Integration and Evaluation Program
SNL	-	Sandia National Laboratories
TAP-A45	-	Task Action Plan A45
UL	-	Underwriters Laboratories
USNRC	-	United States Nuclear Regulatory Commission
XPE	-	Cross-Linked Polyethylene (also XLPE)

EXECUTIVE SUMMARY

This report presents a consolidation of the results and conclusions generated through numerous individual efforts conducted under the U. S. Nuclear Regulatory Commission (USNRC) sponsored Fire Protection Research Program (FPRP) at Sandia National Laboratories (SNL). This program was initiated in fiscal year 1975 (FY-75) and the report covers efforts from program inception through the termination of efforts as of the end of FY-87. The individual efforts conducted under this program involved both analytical and experimental efforts associated with a broad range of nuclear power plant fire safety issues.

As initially conceived, the early FPRP investigated specific regulatory concerns. These concerns were raised in large part by the cable tray fire at the Browns Ferry Plant in 1975, though the program actually predates that fire by approximately 3 months. As a result of this fire, awareness of the potential impact of fire on the operability of a nuclear power plant increased. The early FPRP investigations focused on the identification of areas of weakness in the fire regulations and on the defintion of a new set of fire protection guidelines.

In more recent years, the focus of the FPRP has shifted towards an integrated investigation of more general fire safety concerns and fire phenomena. The individual efforts performed as a part of this integrated approach to fire safety can be grouped into five areas of investigation. These areas are:

1. Source Fire Characterization,
2. Detection and Suppression System Effectiveness,
3. Room Effects,
4. Equipment Response, and
5. Room-to-room Fire Effects.

Source fire characterization is associated with the identification of potential fire initiation sources and the characterization of the burning behavior of these sources. Detection and suppression system effectiveness includes consideration of the degree of additional safety afforded by such systems, and the adequacy of current guidelines for system implementation in nuclear power plant applications. Room effects issues are associated with the mechanisms for the transport of fire products (heat, smoke, etc.) within the room of fire origin. Equipment response issues are associated with the effects of a fire environment on the operability of plant components. The final area, room-to-room fire effects, is associated with the potential adverse effects of a fire beyond the room of origin. These effects include fire spread through barriers, the management of fire products and fire suppression agents, manual fire brigade accessibility issues, and spurious suppression system operation in uninvolved areas.

A major objective of the more recent investigations has been the support of efforts to assess plant risk due to fires. Each of the five areas of investigation can be associated with one or more of the steps performed in such risk assessments. An adequate understanding of the phenomena involved in a fire is critical to the appropriate modeling of the effects of a fire on plant systems.

Listed below are the specific areas of research conducted under the FPRP. The studies have been grouped to indicate their applicability to either specific regulatory issue investigations, and/or the specific areas of investigation identified as a part of the integrated approach to fire safety. It will be noted that several of these efforts provide insights into more than one area of investigation.

Investigations of Specific Regulatory Concerns:

- 1975 Cable Use Screening Survey
- 1976 Fire Protection Systems Study
- 1979 Fire Protection Subsystems Study
- 1976-81 Cable Tray Fire Testing:
  - 1976 Electrically Initiated Cable Fire Tests
  - 1977 Exposure Fire Cable Fire Tests
  - 1978 Fire Retardant Cable Coating Tests
  - 1978 Cable Tray Fire Barrier Tests
  - 1979 Cable Tray Fire Corner Effects Tests
  - 1981 Cable Radiant and Convective Heating Damage Tests
  - 1981 Burn Mode Analysis of Cable Fires
- 1980 Investigation of Fire Stop Test Parameters
- 1980-83 Fire Suppression System Effectiveness Investigations:
  - 1980 Halon Suppression Effectiveness Tests
  - 1981 Water Sprinkler Suppression Effectiveness Tests
  - 1982 Directed Water Spray Suppression Effectiveness Tests
  - 1983 Carbon Dioxide Suppression Effectiveness Tests
- 1981 Cost Analysis of Fire Protection Systems
- 1982 Detector Siting Criteria Requirements Study
- 1982 Twenty-Foot Separation Adequacy Investigations

Source Fire Characterization Studies:

- 1975 Cable Use Screening Survey
- 1976-81 Cable Tray Fire Testing:
  - 1976 Electrically Initiated Cable Fire Tests
  - 1977 Exposure Fire Cable Fire Tests
  - 1978 Fire Retardant Cable Coating Tests
  - 1978 Cable Tray Fire Barrier Tests
  - 1979 Cable Tray Fire Corner Effects Tests
  - 1981 Burn Mode Analysis of Cable Fires
- 1981 Trash/Pool Fire Correlation Tests
- 1984 Identification and Classification of Transient Fuel Ignition Sources

1985	Review of Fire Characterization Data
1985	Development of Electrical Ignition Apparatus
1985	Transient Fuel Source Fire Tests
1985	Electrical Cabinet and Control Room Fire Tests
1986	Development of Nuclear Power Plant Fire Occurrence Data Base

Detection and Suppression Effectiveness Studies:

1980-83	Fire Suppression System Effectiveness Investigations:
1980	Halon Suppression Effectiveness Tests
1981	Water Sprinkler Suppression Effectiveness Tests
1982	Directed Water Spray Suppression Effectiveness Tests
1983	Carbon Dioxide Suppression Effectiveness Tests
1982	Detector Siting Criteria Requirements Study

Room Effects Studies:

1982	Twenty-Foot Separation Tests
1985	Base Line Validation Enclosure Fire Tests
1985	Electrical Cabinet and Control Room Fire Tests

Equipment Response Studies:

1976-81	Cable Tray Fire Testing:
1978	Fire Retardant Cable Coating Tests
1978	Cable Tray Fire Barrier Tests
1981	Cable Radiant and Convective Heating Damage Tests
1984	Cable Steady State Thermal Damage Tests
1985	Cable Transient Thermal Damage Tests
1985	Equipment Damage Sensitivity Ranking Study
1985	Relay Thermal Damage Tests
1985	Component Testing in Secondary Fire Environments

Room-to-Room Fire Issue Studies:

1979	Fire Protection Subsystems Study
	Fire Barriers
	Ventilation Systems
1980	Investigation of Fire Stop Test Parameters

The results and conclusions of each of these individual efforts are discussed in the chapters which follow. The discussions are presented in a format consistent with the grouping of efforts presented immediately above. The reports, papers, and journal articles generated by the SNL/USNRC FPRP that document the various efforts are listed in Appendix A both in chronological order and with a cross referencing of major reports to specific efforts.

As a result of the investigations undertaken through the FPRP, a number of insights have been gained. Early investigations were intended to address specific regulatory questions and concerns, and as a result, have had a significant impact on the formulation of fire safety guidelines for commercial nuclear reactors. In particular, experimentation under the FPRP demonstrated that the redundant train separation criteria of RG-1.75 were inadequate for the protection of cable trays, even considering the use of low flame spread cables and a variety of passive cable tray protective features. Testing also demonstrated that even the more stringent requirement for redundant train separation stipulated in Appendix R fire regulations is not sufficient in and of itself to prevent redundant train damage due to a single fire. Rather, the degree of safety afforded by such measures will depend on case specific factors involving the magnitude of the fire hazard, the interaction between the fire and the enclosure, and the adequacy of fire detection and suppression systems.

As a result of more recent efforts, a greater overall understanding of fire phenomena and fire risk has developed. Experimentation demonstrated the relative effectiveness of various fire suppression systems, and illustrated potential drawbacks to each system. The behavior of a fire in various transient fuel source packages, and a fire confined to a single electrical control panel were quantitatively evaluated. In an effort to provide data against which to validate computer fire simulation models, a series of 25 large-scale enclosure fire tests was performed. Recent analytical efforts include a review and documentation of the experience base associated with fires in nuclear power plants, a review of available quantitative fire characterization data, the re-analysis of certain past cable fire test efforts, and the support of efforts to estimate the risk of core damage due to fire.

It should also be noted that the efforts described here are related to a number of other efforts associated with the problem of fire safety in nuclear facilities. In particular, the TAP-A45 efforts represented one of the first attempts to quantify nuclear power plant fire risk. More recently, the Risk Methodology Integration and Evaluation Program (RMIEP) and the NUREG-1150 risk analyses have both contributed to the understanding of fire risk and have advanced the methodololgies used in fire risk assessment. Each of these efforts has drawn upon FPRP results as a source of relevant data. In turn, the FPRP has drawn upon these risk studies as a source of insights which have often been used to establish the direction and objectives of new efforts. FPRP efforts have also benefited from and contributed to Department of Energy fire safety investigations both within Sandia and at other national laboratories.

While many insights have been gained through the FPRP efforts, a number of areas remain in which a greater understanding is required. A one year study was initiated at the termination of the FPRP to identify outstanding unaddressed fire safety issues. This study, known as the Fire Risk Scoping Study, identified several areas in which a greater understanding is needed. These issues were examined in the context of fire risk assessment, and many of the issues raised were associated with the adequacy of current fire risk assessment methodologies. However, resolution of many of the unaddressed issues raised will require a greater understanding of fire phenomenology than that currently available.

There are a number of questions associated with the modeling of fire growth and fire effects in nuclear power plant situations which are in need of further understanding. For the fuel types and geometries encountered in nuclear power plants, and in particular cable tray arrays, currently employed analytical models used to predict fire growth behavior have not been validated. While data on the impact of a fire on the environment of a large enclosure was gathered under the FPRP, this data was not fully processed because of the termination of efforts. Hence, this data has not been generally applied in the validation of enclosure fire simulation models. Thus, the accuracy with which analytical predictions of fire growth behavior and the impact of a fire on the surroundings can be made has yet to be demonstrated.

Significant shortcomings also remain in the available base of knowledge regarding the operability of plant equipment in a fire environment. Efforts were initiated to investigate these effects, and certain limited insights were gained. However, very little is known about the mechanisms and thresholds of fire damage for most types of plant equipment. In particular, the data base on cable thermal damageability is quite limited. Also, concerns for the potential impact of smoke on high voltage equipment, the impact of low level thermal exposure and gaseous suppression systems on sensitive control circuitry, and the potential adverse effects of manual fire fighting efforts have not been addressed.

Also not yet investigated are a number of issues associated with the potential adverse effects of a fire and fire products beyond the room of fire origin. These issues include assessment of the reliability of fire barrier systems under actual fire conditions, the investigation of potential mechanisms for the spread of smoke, the effectiveness of fire suppressant management measures, the potential for spurious operation of suppression systems in nonfire areas, and manual fire fighting accessibility issues.

Under the Fire Aging of Electrical Components Program (reference USNRC FIN A-1833), an investigation of plant aging and fire safety has been initiated. The identified issues being investigated include the impact of aging on the fire damageability and flammability of cables and other types of class 1E equipment and the impact of aging on passive fire protection features such as cable wraps and coatings and fire barrier penetration seals.

1.0 INTRODUCTION

1.1 Overview of the Fire Protection Research Program

This report presents a consolidation of the results and conclusions generated through numerous individual efforts conducted under the U. S. Nuclear Regulatory Commission (USNRC) sponsored Fire Protection Research Program (FPRP) at Sandia National Laboratories (SNL). This program was initiated in fiscal year[1] 1975 (FY-75) and the report covers efforts from program inception through termination at the end of FY-87. The individual efforts conducted under this program involved both analytical and experimental efforts associated with a broad range of nuclear power plant fire safety issues.

Since the programs inception in 1975 a number of significant changes in the regulatory approach to the fire safety issue have occurred. With these changes in the regulatory environment came changes in the approach and objectives of the FPRP as well. This section provides a brief overview of the historical development of the fire program. Each of the topics introduced below will be discussed in greater detail in the sections to follow.

On March 22, 1975, shortly after inception of the FPRP program, a severe cable tray fire occurred at the Brown's Ferry nuclear power plant. Largely as a result of this fire a new set of regulations related to fire safety was instituted. This development of new fire regulations began with the release of the first draft of Branch Technical Position (BTP) APCSB 9.5-1 and its associated Appendix A in August of 1976. The main body of this document was intended to cover plants already into the construction phase, while the Appendix was intended to cover plants still in the planning phase. Following a period of review and public comment, these guidelines were modified somewhat and formalized as Appendix R to 10CFR50 which was adopted February 19, 1981. Following adoption of Appendix R, BTP 9.5-1 was reissued as a part of the Standard Review Plan. In this reissue Appendix A to the BTP was eliminated.

During this period from 1975 through 1982 FPRP investigations were designed to address very specific regulatory questions. The emphasis of the FPRP was placed initially on the identification of areas of weakness in the fire regulations. Emphasis later shifted towards the investigation of the technical adequacy of the new guidelines generated. As the regulatory environment for fire protection settled following the institution of Appendix R (to 10CFR50), the fire program underwent a transition to a more integrated, generalized research effort. This difference is clearly reflected in the objectives of efforts conducted under the two approaches.

One of the first efforts performed under the FPRP was a review of the regulations and standards that governed, either explicitly or implicitly,

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1. Fiscal years for USNRC sponsored efforts begin October 1 of the previous calender year and extend through the following September 30.

the implementation of fire protection in nuclear power plants. This review identified explicit guidance documents in the form of regulations and regulatory guidelines (RGs), and implicit documents in the form of a plethora of national fire standards generated by various standards organizations. In general it was concluded that these documents represented a confusing and often contradictory set of guidelines which did not consider certain unique aspects of nuclear power plants.

With the adoption of Appendix R and its supporting documents the USNRC resolved much of the uncertainty and confusion resulting from the existence of contradictory standards by endorsing a specific set of standards for each of the issues of fire protection relevant to the nuclear power situation. These new regulations included consideration of the unique character of the nuclear power plant situation and included general requirements for the protection of certain plant safety features from the damaging effects of fires.

In parallel with these reviews experiments were performed to evaluate the adequacy of the cable separation guidelines of RG-1.75, the then current design guide. This guideline established redundant train minimum separation distances for cable trays of five feet vertically and three feet horizontally. Testing demonstrated that under exposure fire conditions this guide was inadequate to prevent the spread of fire to redundant cable trays, even considering the use of low flame spread cables certified by the IEEE-383-74 flame test. The final test in this series was conducted on July 6, 1977.

As a result, certain additional measures for the protection of cables were experimentally evaluated. These included fire retardant coatings, and protective barriers. While each of these measures resulted in a degree of increased protection, a wide variability in the effectiveness of similar measures developed by various manufacturers was demonstrated. In general, none of these measures was considered adequate to completely insure protection of vital cable trays from exposure fires under the separation criteria of RG-1.75.

One of the principal provisions of BTP 9.5-1, which was also incorporated into the Appendix R guidelines, requires that redundant trains of equipment must maintain a separation of 20 feet horizontally with no intervening combustibles and with inclusion of automatic fire detection and suppression systems. Following release of BTP 9.5-1, an investigation of the adequacy of the 20-foot separation criteria was initiated. In a series of experiments, it was demonstrated that for a small room where hot layer effects could become significant, 20 feet of separation was not in and of itself sufficient to insure that cabling so separated from the source fire would remain undamaged. These tests did not investigate the additional measure of safety afforded by the requirement for the use of automatic fire detection and suppression systems in such situations.

As a result of these findings, additional research was undertaken to further assess the degree of safety afforded by the 20 foot separation criteria. These investigations focused on continuation of the protective coatings and barriers tests for cable trays, and on investigations of the effectiveness of various fire suppression systems when applied to cable fires.

Following the institution of the Appendix R fire safety regulations, investigations shifted towards a more integrated approach to the investigation of fire safety. This shift was partially motivated by a need to support the analysis of fire risk. More recent efforts conducted between 1983 and 1987 were based on five specific areas of concern. These five areas are:

- Source Fire Characterization,
- Detection and Suppression System Effectiveness,
- Room Effects Issues,
- Equipment Response Issues, and
- Room-To-Room Fire Effects Issues.

Characterization of the source fire includes the identification of the anticipated fuel sources and the characterization of ignition and fire growth behavior for these fuel sources. Specific concerns in this area include the rate of release of both heat and combustion products to the environment and the eventual extent of fire growth. Considerations in the effectiveness of detection and suppression include the adequacy, in the context of nuclear power plant applications, of general national and industry guidelines for system design, installation, and maintenance and the effectiveness of common fire suppressants when applied to the combustible fuels found in a power plant, especially cables. Room effects issues are associated with the mechanisms of transport of heat and combustion products within the room of fire origin. Equipment response issues are those associated with the potential damaging effects of fire environments, including the effects of manual or automatic fire suppression efforts, on plant components that may not be directly involved in the fire itself. The final area is concerned with potential room-to-room fire effects including the transport of fire products to remote areas, the spread of fire through fire barrier systems, the spurious actuation of fire suppression systems in remote areas, fire brigade accessibility issues that may compromise barrier integrity, and the management of combustion products and fire suppression agents.

It was during the early stages of this phase of the program that further work was halted through the termination of funding as of the end of FY-87. No new investigations have been initiated under this program since FY-86, and subsequent efforts have been entirely directed at closing out outstanding portions of prior investigations.

Actual investigations performed under this integrated approach focused primarily on source fire characterization, detection and suppression effectiveness, and room effects. Only preliminary and quite limited efforts associated with equipment response and room-to-room issues have been performed. Efforts that have been performed include the characterization of typical fire ignition sources, support of efforts to develop computer models for the prediction of fire behavior and environmental effects, limited cable and component fire environment vulnerability testing, characterization of electrical panel fires, and the development of a fire occurrence data base.

Because these more recent efforts were intended to provide a measure of the degree of safety afforded by the regulations, the work was directed towards providing information useful to PRA analyses. This included the support of efforts to develop analytical fire simulation models for use in risk assessment analyses. In the development and application of such models, an understanding of the phenomenology involved in each of the areas described above is required. Thus, it is often in these models that the various elements of fire research are drawn together. While the actual development of fire simulation models was not undertaken as a part of the Sandia FPRP, the support of such efforts at various other institutions was always a consideration in the formulation of program plans.

The efforts described here are also directly related to a number other efforts associated with the problem of fire safety in nuclear facilities. In particular, the TAP-A45 efforts represented one of the first efforts that quantified nuclear power plant fire risk. More recently, the Risk Methodology Integration and Evaluation Program (RMIEP) and the NUREG-1150 risk analyses have both contributed to the understanding of fire risk and have advanced the methodololgies used in fire risk assessment. Each of these efforts has drawn upon FPRP results as a source of relevant data. In turn, the FPRP has drawn upon these risk studies as a source of insights which have often been used to establish the direction and objectives of new efforts. FPRP efforts have also benefited from and contributed to Department of Energy fire safety investigations both within Sandia and at other national laboratories.

As a result of the FPRP efforts undertaken over the years a list of issues which were unaddressed in the context of a fire PRA and which were perceived to represent potentially significant risk contributors was formulated. Based on this list of issues an effort known as the Fire Risk Scoping Study was undertaken. This effort performed a review of the current perception of fire risk for nuclear power plants and an initial evaluation of the potential significance of six identified unaddressed issues. These issues were:

- Fire Induced Control Systems Interactions,
- The Effectiveness of Manual Fire Fighting, Including the Effectiveness of Smoke Control Measures,
- Equipment Vulnerability in the Total Fire Environment, Including the Adverse Effects of Spurious Suppression System Actuation,
- Seismic/Fire Interactions,
- The Adequacy of Fire Barrier Qualification Standards, and
- The Adequacy of Analytical Tools for Fire.

This effort was completed concurrent with the writing of this report and the findings of that study will be discussed briefly at the close of this report.

1.2 Format for Presentation

The presentation of results and conclusions generated by the various individual analytical and experimental efforts performed under the FPRP has been formulated to conform to the historical development of program objectives. As described above, early efforts in the FPRP were intended to specifically address certain regulatory questions, whereas later efforts were based on a more broadly based, integrated investigation of fire phenomenology. As the primary format for presentation, efforts will be described within these two contexts. For most of the early investigations of specific regulatory questions the results can also be applied within the framework of the integrated fire phenomena investigations. Thus, where appropriate these early efforts will be described both in the context of the investigation of specific regulatory concerns and in the context of the investigations in each of the five areas of interest described above.

Listed below are the specific areas of research conducted under the USNRC/Sandia FPRP. The studies have been segregated indicating their applicability to either specific regulatory issue investigations, and/or the specific areas of investigation identified as a part of the integrated approach to fire safety. Typically, each effort focused on a particular area of investigation, though it will be noted that many of the efforts provide insights into more than one area of investigation.

Investigations of Specific Regulatory Concerns:

- 1975 Cable Use Screening Survey
- 1976 Fire Protection Systems Study
- 1979 Fire Protection Subsystems Study
- 1976-81 Cable Tray Fire Testing:
  - 1976 Electrically Initiated Cable Fire Tests
  - 1977 Exposure Fire Cable Fire Tests
  - 1978 Fire Retardant Cable Coating Tests
  - 1978 Cable Tray Fire Barrier Tests
  - 1979 Cable Tray Fire Corner Effects Tests
  - 1981 Cable Radiant and Convective Heating Damage Tests
  - 1981 Burn Mode Analysis of Cable Fires
- 1980 Investigation of Fire Stop Test Parameters
- 1980-83 Fire Suppression System Effectiveness Investigations:
  - 1980 Halon Suppression Effectiveness Tests
  - 1981 Water Sprinkler Suppression Effectiveness Tests
  - 1982 Directed Water Spray Suppression Effectiveness Tests
  - 1983 Carbon Dioxide Suppression Effectiveness Tests
- 1981 Cost Analysis of Fire Protection Systems
- 1982 Detector Siting Criteria Requirements Study
- 1982 Twenty-Foot Separation Adequacy Investigations

Source Fire Characterization Studies:

- 1975 Cable Use Screening Survey
- 1976-81 Cable Tray Fire Testing:
  - 1976 Electrically Initiated Cable Fire Tests

1977 Exposure Fire Cable Fire Tests
1978 Fire Retardant Cable Coating Tests
1978 Cable Tray Fire Barrier Tests
1979 Cable Tray Fire Corner Effects Tests
1981 Burn Mode Analysis of Cable Fires
1981 Trash/Pool Fire Correlation Tests
1984 Identification and Classification of Transient Fuel Ignition Sources
1985 Review of Fire Characterization Data
1985 Development of Electrical Ignition Apparatus
1985 Transient Fuel Source Fire Tests
1985 Electrical Cabinet and Control Room Fire Tests
1986 Development of Nuclear Power Plant Fire Occurrence Data Base

Detection and Suppression Effectiveness Studies:
1980-83 Fire Suppression System Effectiveness Investigations:
1980 Halon Suppression Effectiveness Tests
1981 Water Sprinkler Suppression Effectiveness Tests
1982 Directed Water Spray Suppression Effectiveness Tests
1983 Carbon Dioxide Suppression Effectiveness Tests
1982 Detector Siting Criteria Requirements Study

Room Effects Studies:
1982 Twenty Foot Separation Tests
1985 Base Line Validation Enclosure Fire Tests
1985 Electrical Cabinet and Control Room Fire Tests

Equipment Response Studies:
1976-81 Cable Tray Fire Testing:
1978 Fire Retardant Cable Coating Tests
1978 Cable Tray Fire Barrier Tests
1981 Cable Radiant and Convective Heating Damage Tests
1984 Cable Steady State Thermal Damage Tests
1985 Cable Transient Thermal Damage Tests
1985 Equipment Damage Sensitivity Ranking Study
1985 Relay Thermal Damage Tests
1985 Component Testing in Secondary Fire Environments

Room-to-Room Fire Issue Studies:
1979 Fire Protection Subsystems Study
Fire Barriers,
Ventilation Systems
1980 Investigation of Fire Stop Test Parameters

The sections that follow provide summary discussions of each of these efforts within the framework presented above. The report focuses on the principal insights and conclusions of each effort as applicable to the particular topic of discussion for each section, as well as the applicability of these insights to fire risk assessment. For a more complete description of a particular effort refer to the reports, papers, and journal articles that document the various efforts. These reports are listed in Appendix A both in chronological order and with a cross referencing of major reports to specific efforts.

2.0 INVESTIGATION OF SPECIFIC REGULATORY CONCERNS

2.1 Scope of This Chapter

Early efforts conducted under the FPRP were primarily intended to address specific regulatory concerns and questions. These efforts are discussed in brief in this chapter. Many of these efforts will also be discussed in following chapters as they also provide insights into the phenomena associated with the five areas of investigation identified as a part of the integrated approach to fire safety research applied in more recent years. The discussions presented in this chapter will focus on the issues of concern that led to each of these early research efforts and the regulatory insights gained as a result. Later chapters will provide more detail on the actual experimental results for these efforts as appropriate.

The studies performed, which were primarily intended to address specific regulatory concerns, are listed below:

1976	Fire Protection Systems Study
1979	Fire Protection Subsystems Study
1976-81	Cable Tray Fire Testing:
1976	Electrically Initiated Cable Fire Tests
1977	Exposure Fire Cable Fire Tests
1978	Fire Retardant Cable Coating Tests
1978	Cable Tray Fire Barrier Tests
1979	Cable Tray Fire Corner Effects Tests
1981	Cable Radiant and Convective Heating Damage Tests
1981	Burn Mode Analysis of Cable Fires
1980	Investigation of Fire Stop Test Parameters
1980-83	Fire Suppression System Effectiveness Investigations:
1980	Halon Suppression Effectiveness Tests
1981	Water Sprinkler Suppression Effectiveness Tests
1982	Directed Water Spray Suppression Effectiveness Tests
1983	Carbon Dioxide Suppression Effectiveness Tests
1981	Cost Analysis of Fire Protection Systems
1982	Detector Siting Criteria Requirements Study
1982	Twenty Foot Separation Adequacy Investigations

Each of these studies is described in turn within this chapter.

2.2 Fire Protection Systems Study

One of the first efforts undertaken as a part of the FPRP was a review of the then current fire protection practices and perceptions.[1] This review investigated a number of aspects of protecting nuclear power plants from the adverse effects of fires. As a part of this review the environment of regulation as embodied in the various national and international regulatory and insurance standards was reviewed. It was concluded that "(t)here exists an abundance of overlapping and often contradictory standards, guides, codes and criteria for nuclear power plants fire protections systems. Additionally, many of the requirements are not founded on adequate experimental and analytical information."

As an additional aspect of this study, the findings and recommendations resulting from investigations of the 1975 Browns Ferry cable fire incident were reviewed. This was coupled to an initial attempt to establish probabilistic fire safety goals and to assess the impact of specific fire protection improvements on overall plant fire safety.

The principal conclusions of the study were that (1) a need existed to establish a consistent set of regulations and guidelines for fire protection in nuclear power applications, and (2) that rather than invoke a number of individual plant fire protective measures, an integrated approach involving the overall identification, quantification, and resolution of the primary plant fire hazards should be undertaken.

2.3 Fire Protection Subsystems Study

As a follow-up to the Fire Protection Systems Study an effort called the Fire Protection Subsystems Study was undertaken. Four specific fire subsystems were identified and relevant information for each subsystem was reviewed and evaluated. The four subsystems investigated were:

- Ventilation Systems
- Fire Detection Systems
- Fire Barriers
- Hazards Analysis

Investigations performed in each of these four areas of study are discussed in turn in the following sections.

2.3.1 Ventilation Subsystems Study

The objective of the ventilation subsystems study was to examine the role of internal plant ventilation systems on fire safety in a nuclear power plant.[2] Under this effort, the standards for the installation of ventilation systems were reviewed. Based on an assessment of the adequacy with which these standards addressed nuclear power plant fire safety issues, the study also developed technical bases for ventilation system functions and performance in fire emergencies. Finally, changes and additions to the guidelines to clarify intent and to define design criteria were recommended.

As a result of these efforts, it was concluded that the standards were generally insufficiently detailed and did not provide for the design of the ventilation system as an integral part of the fire protection system. Four potential fire ventilation strategies were considered. These were (1) smoke removal (smoke purging); (2) smoke control (or containment); (3) fire control (limiting fire intensity by limiting oxygen availability); and (4) temperature control (or heat removal). It was concluded that the most desirable approach to ventilation design for fire emergencies was the temperature control strategy. This approach provides for limited smoke removal and smoke control functions as well. Fire control was considered inappropriate in that this strategy would complicate fire response actions and enclosure accessibility.

It was also recommended that ventilation systems be considered as an integral part of the fire protection system and that appropriate local control capability be provided. This would allow fire fighters to realign ventilation flow under the specific fire conditions to attain the desired configuration.

To the knowledge of the author, these recommendations have not been incorporated into the industry standards and have not been generally incorporated into plant designs. Ventilation system design and installation continues to be governed by essentially the same standards as those considered in the subsystem study.

2.3.2 Fire Detection Subsystems Study

Fire detection subsystems were evaluated from the standpoint of overall plant fire safety considering the technical bases for detection system design, the adequacy of design guidance, and the effectiveness of qualification testing in simulating actual fire performance.[3] It was found that the industry and regulatory guidelines were inconsistent and often provided conflicting requirements. This resulted from an observed inconsistency by which plant areas were identified, and resulted in recommendations for different levels of detector protection for the same plant areas. It was also found that the technical bases upon which choices of detector type and detector siting criteria were determined were inadequate. This resulted from differences in detector qualification standards and from a lack of test methods to evaluate detector siting strategies. Installation and maintenance procedures were also found to have no uniformly applied set of guidelines or procedures.

Certain of these issues, in particular the issue of detector siting, were recognized as being difficult to standardize. It was recommended that a firm technical basis for the selection of detectors be established, that a uniform qualification methodology for different detector types be adopted, and that installation and maintenance standards be developed. To the knowledge of the author, the issues of installation and maintenance have to some degree been addressed by national fire standards organizations. However, different detector types continue to be qualified under different conditions, and detector selection and siting continue to be largely dependent on the use of engineering judgment.

2.3.3 Fire Barrier Subsystems Study

The examination of fire barriers was intended to (1) study and evaluate the standards for the qualification of fire barrier elements, (2) perform thermal analyses of typical three-hour fire barrier systems to determine their response under various conditions, and (3) assess the need for further understanding of barrier performance factors.[4]

The study concluded that the guidelines for the qualification of fire barrier elements provided for an adequate exposure fire intensity and no changes were recommended in this area. Two areas of potential weakness were identified. The first was with respect to the use of a hose stream test as a part of the qualification standards. This test was considered to have poor repeatability, to be imprecise, and to be difficult to control. It was recommended that a more precise methodology be developed for application of tangential loads following fire exposure. The second area was the failure of U.S. standards to incorporate a positive furnace pressure during fire exposure testing of doors and penetration seal systems. This was considered to be an easily corrected shortcoming in the test procedures which, if not corrected, could result in nonconservative estimates of fire barrier endurance under actual exposure conditions. In each of these two areas, no relevant changes have since been made in the national standard tests.

In the second area, that of the pressure questions, a follow-up study of the effects of positive pressure exposure on cable barrier penetration fire stop systems was undertaken.[5,6] These efforts, which are described below in Section 2.5, confirmed the nonconservative nature of negative pressure test schemes for fire barrier penetration seals.

2.3.4 Fire Hazards Analysis Subsystems Study

In the final area of study, fire hazards analysis, the efforts were limited to a review of the fire hazards analysis methodologies and an assessment of the degree of applicability of those methodologies to the evaluation of nuclear power plants.[7] On the basis of this review, it was concluded that each of the identified methodologies was deficient in meeting at least one of the analysis criteria set forth. It was further concluded that refinements to the existing methodologies were needed. An overall approach was proposed.

Since the performance of this work significant improvements in fire probabilistic risk assessment (PRA) methodologies have been made. Many of the shortcomings identified in the study have been addressed. In a recently completed study, the Fire Risk Scoping Study, the state of the art in fire risk assessment for nuclear power plants was reviewed.[8] This review identified the principal sources of uncertainty in a fire risk analysis, and also investigated the potential risk impact of a number of issues which had been identified subsequent to the performance of several risk analyses. Thus, risk assessment methodologies continue to evolve and mature.

2.4 Cable Tray Fire Testing

In the wake of the 1975 Brown's Ferry cable spreading room fire a number of actions were considered as potential approaches to the reduction of plant fire vulnerability. During the years between 1976 and 1981 a number of efforts were conducted to evaluate the effectiveness of several of these proposed measures. These investigations represented a significant portion of the early fire research efforts. The specific related efforts were:

1975	Cable Use Screening Survey
1976	Electrically Initiated Cable Fire Tests
1977	Exposure Fire Cable Fire Tests
1978	Fire Retardant Cable Coating Tests
1978	Cable Tray Fire Barrier Tests
1979	Cable Tray Fire Corner Effects Tests
1981	Cable Radiant and Convective Heating Damage Tests
1981	Burn Mode Analysis of Cable Fires

One of the first of the potential cable fire mitigation measures evaluated was the adequacy of the newly instituted IEEE-383-74 cable flame spread test standard in reducing the potential for the spread of fire among cable trays.[9,10] Several experiments were conducted in which cable tray arrays which conformed to the then current cable separation criteria of Regulatory Guide 1.75 (RG-1.75) were subjected to fires. These guidelines specify physical separation distances for both single train and redundant train cable tray installations. For single train trays, minimum separation is 10.5 inches vertically and eight inches horizontally. For independent, redundant safety trains, minimum separation distances are five feet vertically and three feet horizontally.

Both electrically initiated and exposure (external fire source) fires were used. It was concluded that while cables which passed the IEEE-383-74 flame test were less likely to propagate electrically initiated fires, exposure fires still posed a threat of redundant train involvement in a single fire. This test series culminated in the test of July 6, 1977, in which full involvement of a large array of trays containing qualified cables, including the involvement of the simulated redundant trays, was observed.

With this determination that RG-1.75 was insufficient to prevent the fire involvement of redundant cable trains, even considering the use of IEEE-383-74 low flame spread cables, other potential protective features were experimentally evaluated. These additional features were the protection of cable trays with insulating wraps and fire retardant coatings, and the use of flame barriers for cable tray arrays.[11-14] While each of these features afforded some additional measure of safety, wide variability between protective features of different types, and even between similar protective features produced by different manufacturers, was observed.[15] In the final analysis, none of the features evaluated was considered sufficient in and of itself to insure fire safety under the separation criteria of RG-1.75.

With the findings described above, it became of increasing interest to provide tools with which one might assess the level of safety provided by various protective features without undertaking extensive testing. This is reflected in the final three efforts, the Cable Tray Fire Corner Effects Tests, the Cable Radiant and Convective Damage Testing, and the Burn Mode Analysis of Cable Fires, which were directed towards providing more broadly based insights into the phenomena involved in cable fire growth and fire induced cable damage. The Corner Effects Tests explored the effects of thermal reradiation from walls and ceilings on the intensity of cable fires.[16] The Cable Radiant and Convective Damage Tests involved initial cable fire environment damageability assessments.[17] The Burn Mode Analysis effort developed a methodology for predicting the mode of burning (i.e. open flaming, smoldering, fire ball behavior, or transitional) based on measurements of a cables surface and internal temperatures.[18] It was in these later cable fire research efforts that a transition to the integrated approach to fire safety research first began to emerge. The results of these efforts are described in more detail in Chapter 3 as a part of the discussions of fire characterization efforts, and in Chapter 6 as a part of the discussion of equipment damageability studies.

2.5 Investigations of Fire Stop Test Parameters

As a part of the Fire Protection Subsystems Study described above (see Section 2.3.3), questions were raised regarding the adequacy of U. S. fire barrier qualification tests. One of the two potential weaknesses identified was that the U.S. standard tests did not address exposure furnace pressure. It is a commonly observed phenomena that enclosure pressures under fire conditions will increase above ambient conditions, particularly for rooms with forced ventilation such as those typical of a nuclear power plant. It was concluded that failure to apply a positive pressure across a barrier element during fire exposure testing could result in nonconservative estimates of the actual fire barrier performance. In practice, barrier elements have often been qualified with negative furnace pressures, which could result in cool air being drawn into the furnace from outside the furnace through air passages in or around a barrier. This could potentially mask a vulnerability of barrier elements to the passage of hot gases from within the furnace, or fire enclosure, out past the barrier to the outside.

As a follow up to these findings, efforts were initiated to examine the standards for the qualification of barrier elements, and to perform a limited number of tests on certain cable penetration fire stops.[5,6] While certain pressure effects were noted for some seal systems resulting in premature failure, the results were not considered sufficient to demonstrate a generic vulnerability for cable penetration seals. This issue was also raised again as a part of the recently completed Fire Risk Scoping Study. Here again it was found that no generic vulnerability has been demonstrated, and recommended actions included a review of actual fire barrier performance.

The question of the significance of pressure on barrier performance continues to be a point of debate within the general fire research community as well. For example, the American Society for Testing and Materials (ASTM) committee responsible for the relevant ASTM standard for fire doors (ASTM E-05.21.2) recently considered and rejected a proposal to modify those standards to include a positive pressure requirement for fire exposure testing, even though scientific evidence that pressure effects have been documented for at least some barrier systems was presented. Of the industrialized nations, only the U.S. and Canada continue to endorse barrier qualification test standards which do not require the imposition of a positive pressure furnace exposure condition.

2.6 Fire Suppression System Effectiveness Investigations

In addition to physical separation of redundant safety trains, Appendix R also requires the use of automatic fire detection and suppression systems where physical separation short of rated three-hour fire barriers is available. It was assumed that provisions for the prompt suppression of a fire would provide an additional measure of safety by limiting the extent of fire damage. For a nuclear power plant, the most common combustible fuel source is cable insulation. This fuel is not typical of fuel loadings in most nonnuclear industry situations for which the existing national standards had been established. Thus, the effectiveness of the commonly available fire suppression systems and of the guidelines for their design and installation had not been demonstrated for the nuclear industry.

During the years 1978-83, a series of experiments was conducted to evaluate the effectiveness of Halon, carbon dioxide, and water based fire suppression systems in suppressing fully developed cable tray fires.[10,19] The individual efforts associated with these investigations were:

1978-80	Halon Suppression Effectiveness Tests
1979-81	Water Sprinkler Suppression Effectiveness Tests
1980-82	Directed Water Spray Suppression Effectiveness Tests
1980-83	Carbon Dioxide Suppression Effectiveness Tests

These tests demonstrated that properly applied suppression system of each type were capable of extinguishing a fully developed cable tray fire. However, proper application for the gaseous systems, Halon and CO_2, required that suppressant concentrations recommended in the design standards must be maintained for up to 15 minutes to insure that deep seated cable fires did not reignite. It was also found that the gaseous systems allowed enclosure temperatures to remain fairly high as compared to water based systems. This resulted from the fact that the gaseous suppressants did not represent as significant a thermal sink as did water. This raised a potential concern for the impact of longer term lower level thermal damage to sensitive equipment. The use of water was also identified as a potential source of damage in that equipment wetting could result if the water is not properly drained, or vulnerable equipment not properly protected.

As a result of these investigations, it was concluded that the general industry design standards for the use of fixed fire suppression systems were adequate for application to nuclear power plants. However, it was recommended that certain additional considerations unique to the nuclear industry should also be factored into system designs. In particular, questions were raised regarding the effects of lower level thermal exposure on particularly sensitive equipment, such as integrated circuits, and over the adequacy with which implementation practices for water suppression systems have provided for the management of the applied water and for the protection of equipment vulnerable to damage due to wetting.

2.7 Cost Analysis of Fire Protection Systems

Following the March 1975 cable fire at the Brown's Ferry plant there was an increased awareness of the importance of fire protection to overall plant safety. As a part of the efforts undertaken in response to this increased awareness, a limited study was undertaken to assess the costs associated with the implementation of certain active and passive fire protective measures.[20] Considerations included the installation of Halon or water spray suppression systems, upgrading of passive barriers to full three-hour rated fire barriers, and the protection of cable trays with one-hour fire barrier systems. In addition, plant areas were examined in order to determine the feasibility of installing fixed fire suppression systems, and in order to develop cost estimates for installation of fire detection systems where fixed fire suppression systems were not feasible.

It was concluded that a number of factors contributed to the cost of fire protection system installations. These factors included the congestion of equipment, scheduling, seismic considerations, quality assurance considerations, and other special considerations of the working environment (e.g., special protective gear requirements and security considerations). The subjectivity of before the fact assessments of these factors was determined to result in considerable uncertainty in the estimates of final implementation costs.

2.8 Detector Siting Criteria Requirements Study

Consistent with the goal of providing for the prompt suppression of plant fires as a method for minimizing the extent of fire damage, the proposed Appendix R regulations included requirements that automatic fire detection systems be provided for areas housing redundant trains of safety equipment. As with the case fixed suppression systems, the USNRC was largely dependant on existing general industry guidelines for the selection, installation, and maintenance of fire detection systems. However, as with suppression systems, the adequacy of the general industry detector guidelines in the context of a nuclear power plant had not been assessed. Thus, an effort was performed to review the relevant guidelines and practices, and to identify potential shortcomings in these guidelines as applied to the nuclear industry.[21]

It was found that, in practice, the selection and siting of fire detectors was based largely on engineering judgement. It was also concluded that general industry guidelines did not realistically take into account a number of environmental and plant safety requirements that are unique to nuclear facilities. In particular, shortcomings were identified in that fuller accountability was required for (1) environmental factors such as ventilation, congestion, and background radiation, (2) the flammability characteristics of power plant combustibles, particularly cables, and (3) the need to limit fire damage to assure continued plant operability.

It was recognized that these factors would be difficult to incorporate into standard test procedures. In particular, it was concluded that very little technical basis existed upon which appropriate test criteria might be selected. Since the performance of this review, very little change in the national guidelines has been made. The selection and siting of fire detectors continues to be heavily dependent on engineering judgment.

2.9 Twenty-Foot Separation Adequacy Investigations

One of the principal provisions set forth in BTP 9.5.1, and later in Appendix R to 10CFR50, requires that redundant trains of equipment, including cables, be separated by 20 feet of horizontal space with no intervening combustibles. The regulations also specify that in situations were such separation is employed, automatic fixed fire detection and suppression systems must also be installed.

In an effort to assess the effectiveness of the twenty-foot separation criteria, a series of ten full-scale fire tests was performed.[42] In these tests a pair of cable trays was used to simulate each of two redundant equipment trains. One pair of cable trays was subjected to an exposure fire and the other pair, separated from the source fire by 20 feet, was monitored for electrical integrity. No suppression of the test fires was employed.

In a number of these tests, damage to the simulated redundant equipment train was observed. For older style cables that would not pass the IEEE-383-74 flame spread test, even fire retardant coatings and passive insulating fire barrier systems were not sufficient to prevent fire induced electrical failure. For the newer IEEE-383-74 certified low flame spread cables, electrical failure was observed in unprotected cables, though for those tests in which both cable trains were protected by cable coatings or cable wraps, no electrical failures were observed.

These results demonstrated that even for cables which passed the IEEE-383-74 flame test, damage to the redundant, non-fire-involved cables could result from hot layer effects alone. Thus, it was concluded that 20 feet of horizontal separation was not, in and of itself, sufficient to insure the continued operation of redundant equipment trains during a fire. This places more reliance on the additional provisions for the inclusion of automatic fire detection and fire suppression systems in such situations. In a deterministic sense the Appendix R requirements will proclude fire induced redundant train damage under most fire conditions. However, these deterministic criteria do not address the residual risk associated with the potential for very large fires or fire suppression system failure.

3.0 FIRE CHARACTERIZATION STUDIES

3.1 Introduction

One of the fundamental questions associated with the assessment of fire safety or fire risk is the question of defining the fire threat itself. This definition requires an identification of anticipated ignition sources and the combustible fuel types, loadings, and geometries present. It also requires an analysis of the fundamental fire behavior of those combustible fuels of concern including the frequency of fire initiation, the fire growth and development behavior of the end configuration of these fuel sources, and the intensity of the input, in terms of heat and combustion products, to the surrounding environment. Each of these questions falls within the scope of fire characterization investigations.

A number of FPRP efforts have focused on the characterization of fires on both an analytical and an experimental basis. These efforts have involved generalized reviews of fire characterization information including the nuclear plant operating experience, the evaluation of transient fuel fire sources, characterization of both self-ignited and exposure cable tray fires, and the examination of fires in electrical control panels. The specific efforts that will be discussed in this chapter are:

General Studies and Experience Base Reviews:

- 1985 Review of Fire Characterization Data
- 1984 Identification and Classification of Transient Fuel Ignition Sources
- 1986 Development of Nuclear Power Plant Fire Occurrence Data Base

Transient Fuel Source Fire Characterization Efforts:

- 1981 Trash/Pool Fire Correlation Tests
- 1984 Identification and Classification of Transient Fuel Ignition Sources
- 1985 Transient Fuel Source Fire Tests

Cable Fire Characterization Efforts:

- 1975 Cable Use Screening Survey
- 1976 Electrically Initiated Cable Fire Tests
- 1977 Exposure Fire Cable Fire Tests
- 1978 Cable Tray Fire Retardant Coatings Tests
- 1978 Cable Tray Barrier Tests
- 1979 Cable Tray Corner Effects Tests
- 1981 Burn Mode Analysis of Cable Fires

Electrical Panel Fire Investigations:

- 1985 Development of Electrical Ignition Apparatus
- 1985 Cabinet and Control Room Fire Tests

3.2 General Studies and Experience Base Reviews

Three FPRP studies have focused on a general investigation of nuclear power plant fire characterization, including reviews of the nuclear plant operating experience base.

3.2.1 Review of Fire Characterization Data

In a review of fire characterization data, the knowledge base of quantitative data on the fire behavior of typical nuclear power plant combustibles was examined.[23] This review identified the available data on the full range of nuclear power plant fuels including various transient fuel sources, liquid fuel pool fires, and cable insulation. A fairly large data base in many areas was identified. In particular, liquid fuel pool fires and trash fires have been explored quite extensively. However, certain critical areas of shortcoming were also identified.

The most significant shortcoming with respect to the nuclear industry is that the quantitative data base on cable fire behavior was identified as inadequate. A large base of data gathered from small-scale tests (i.e., samples on the order of several square inches only) does exist. However, the applicability of this small-scale data to the behavior of a large-scale cable fire has not been demonstrated. While a significant number of large-scale cable fire tests have been performed, both within and outside the FPRP, the principal objectives of these tests have not been to explore fire growth behavior. Hence, detailed fire characterization data was not typically gathered, and the available data is not appropriate to the validation of small-scale cable flammability test results.

The dependency of fire risk analyses on the ability to accurately predict cable fire growth behavior makes this shortcoming particularly important. Typically, many of the most significant fire scenarios center on the potential for fire spread and fire induced damage in arrays of cable trays. Enclosure fire simulation model predictions used in the analysis of nuclear plant fire scenarios depend heavily on the predicted growth rate of the fire source. As not enough is known about full-scale cable fires to a-priori establish the expected fire growth behavior, predictive models of this growth behavior are often employed. These fire growth models are, in turn, dependant on the availability of the type of data generated by small-scale tests. This data includes ignition parameters, heat of combustion, mass loss rate as a function of exposure intensity, and combustion products yield rates. A lack of adequate large-scale test data, coupled with uncertainties as to the applicability of small-scale test results to full scale conditions has prevented the validation of currently employed cable fire simulation correlations.

3.2.2 Identification and Classification of Transient Combustible Fuel Sources

Fuel sources in a nuclear power plant are generally divided into transient and in-situ fuels. In-situ fuels are those combustible fuel sources which exist within a plant as a result of as designed plant systems and structures. These fuels can be well defined for particular plant areas based on inspections of the areas in question. The transient fuel sources are those combustible materials that exist within a plant on a shorter term basis. These materials are often associated with such activities as plant construction, house keeping, and plant maintenance. As these fuels come and go in a plant it is much more difficult to quantify the transient fuel source threat for most plant areas.

In an attempt to overcome this difficulty, the experiences of USNRC plant inspectors was reviewed through both interviews and examination of Inspection and Enforcement (I&E) reports. The objective was to characterize the classes and quantities of transient fuel sources which have been encountered in nuclear power plants. This work was performed in conjunction with the USNRC sponsored Risk Methodologies Integration and Evaluation Program (RMIEP).[2]

It was found that the I&E reports were not adequate to accurately quantify the amounts of various types of combustible materials found at plants. These reports also often did not identify the specific area of the plant in which a particular item was found. In addition, 35 I&E inspectors were polled and several responses were received. Based on this review five general categories of transient fuels were identified. Based on the inspector responses the typical quantities of material found for each of the five categories are as follows:

Oil:	1 to 5 gallons
Solvents:	1 gallon
Paint:	1 gallon
Untreated Wood:	From 10 pounds up
Paper/Trash:	30 to 55 gallon containers

These results must be considered subjective as they are based on an individual's recall, and as such may be biased. For four of these five fuel types, histograms were developed to identify the frequency with which a given quantity of the fuel was reported as a "typical" inspection finding. These histograms are presented in Figure 3.1. For the category of untreated lumber no typical quantity could be established. In addition, for each of the five fuel types, similar histograms were developed for the upper and lower bounds of reported fuel quantities. These histograms are presented in Figure 3.2.

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2. This work has not been previously published, though has been documented in a letter report to the USNRC dated June 29, 1984.

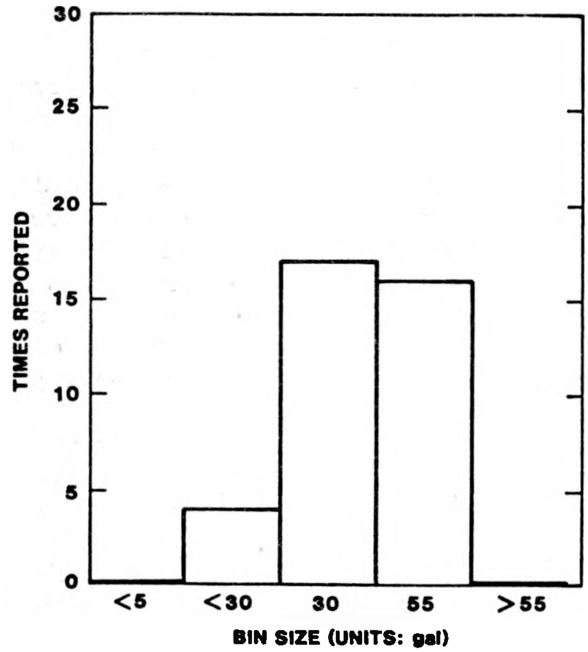

Figure 3.1a: Paper/Trash

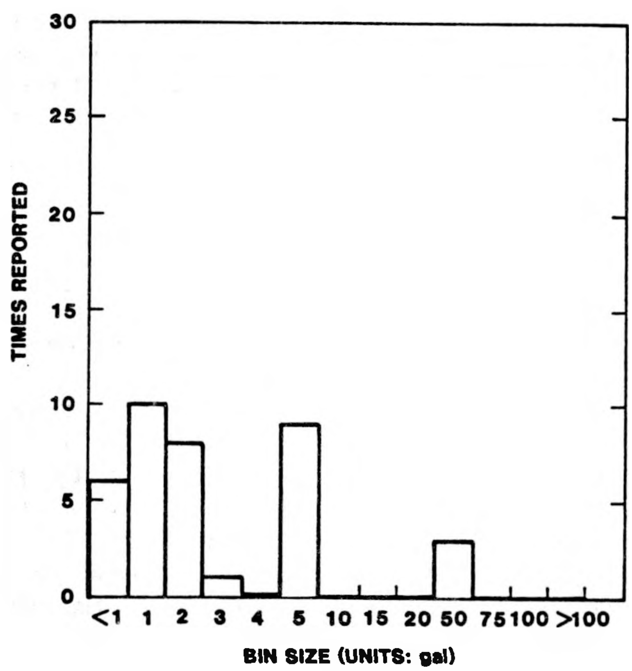

Figure 3.1b: Oil

Figure 3.1: Typical Quantity Transient Fuel Source Histograms

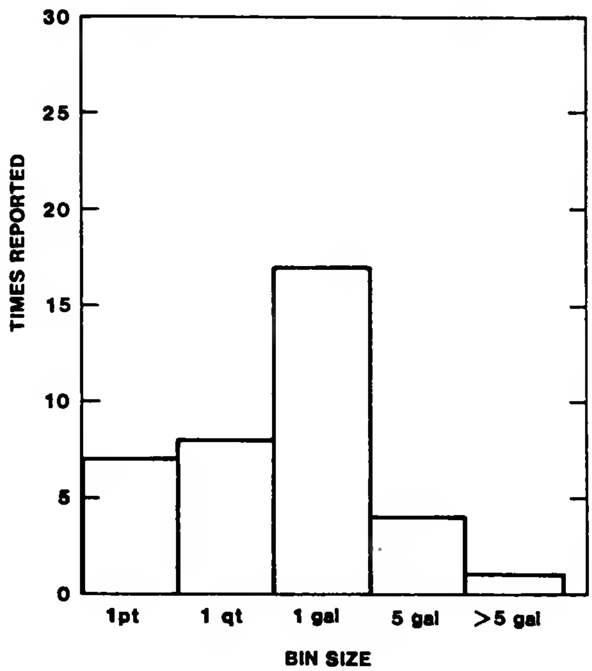

Figure 3.1c: Solvents

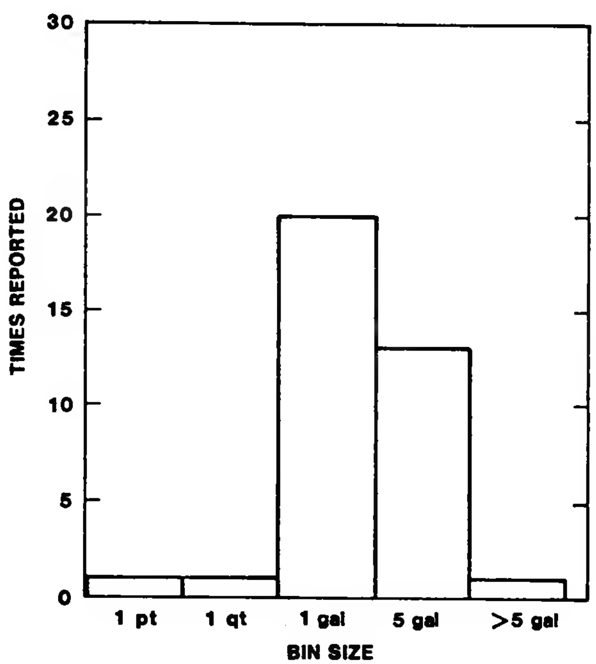

Figure 3.1d: Paint

Figure 3.1: Typical Quantity Transient Fuel Source Histograms (cont).

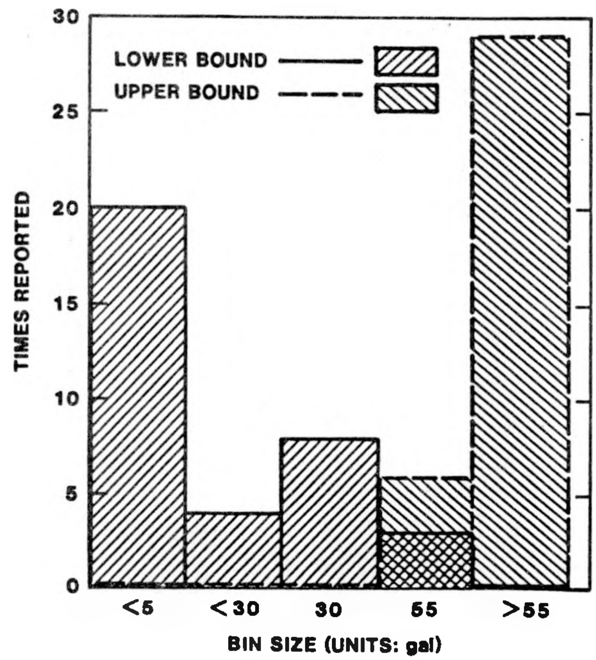

Figure 3.2a: Paper/Trash

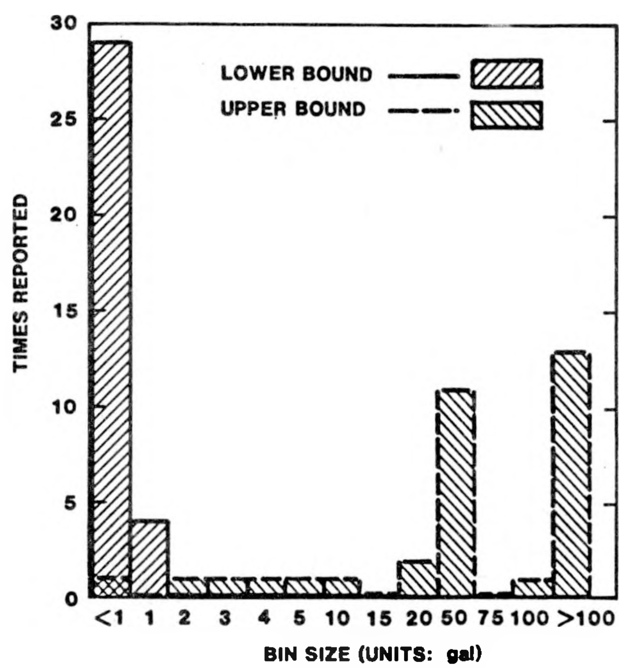

Figure 3.2b: Oil

Figure 3.2: Upper and Lover Bound Quantity Transient Fuel Source Histograms

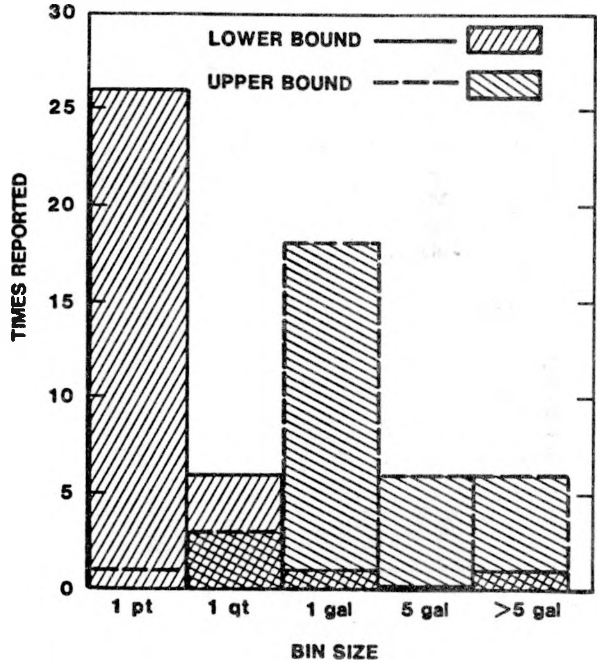

Figure 3.2c: Solvents

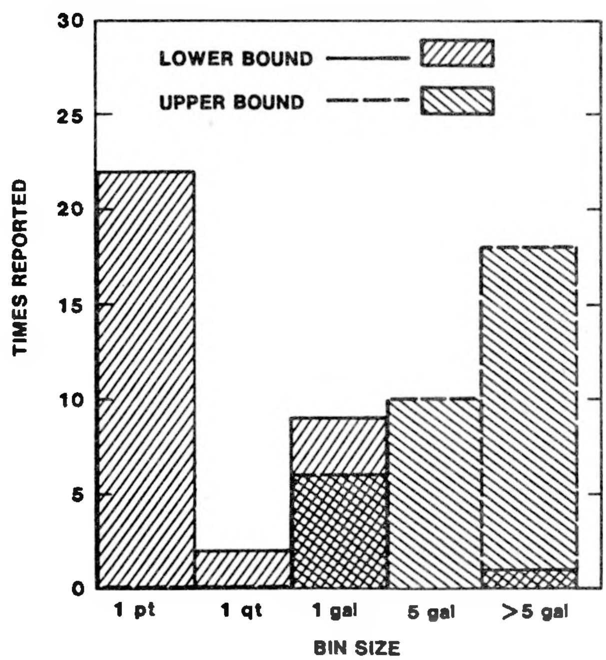

Figure 3.2d: Paint

Figure 3.2: Upper and Lover Bound Quantity
Transient Fuel Source Histograms (cont)

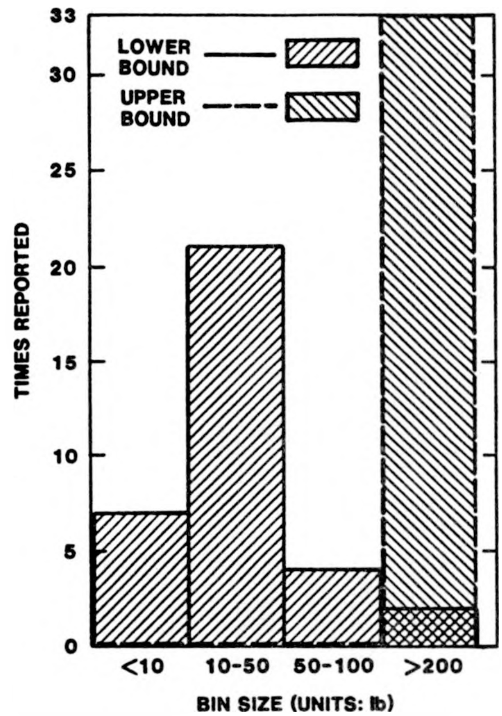

Figure 3.2e: Untreated Wood

Figure 3.2: Upper and Lover Bound Quantity
Transient Fuel Source Histograms (cont)

3.2.3 Development of Nuclear Power Plant Fire Occurrence Data Base

One of the most valuable sources of information on the frequency of fires, the sources of fire initiation, the eventual extent of fire involvement, and the extent of impact of fires on plant operations is the nuclear power plant operating experience base itself. At the time of this work commercial nuclear reactors in the U.S. had logged several hundred years of combined operating experience. In an effort to characterize the actual history of fires in nuclear power plants, a review of the past experience base in this regards was performed in conjunction with the RMIEP study. The results of this review were utilized as the basis for the development of a data base of U.S. nuclear power plant fire occurrences.[24]

This review of fire incidents included fires from as early as 1965 through June of 1985. Incidents were identified through both the USNRC incident reporting system and certain insurance industry data bases. A total of 364 events are identified in the data base. To the extent possible, incident reports include identification of the source of the fire, the extent of fire growth, the extent of fire damage, the impact on plant systems, fire detection and suppression methods and times, as well as several other factors.

One of the difficulties encountered in the formulation of this data base was that fire reports are quite inconsistent in the level of detail provided. Reports can vary in detail from a mere few words stating that a fire occurred, to quite complete descriptions of a fire event. This inconsistency is reflected in differences in the level of detail provided for each fire event.

The data base itself has been designed to be accessed using a standard International Business Machines (IBM) Personal Computer (PC) or compatible systems with commercially available software. The data base files are contained on three 360 kbyte 5¼-inch floppy diskettes available in the public domain. This ready availability and ease of application have made the data base a quite useful tool in the assessment of plant fire risk. It is routinely utilized to estimate fire ignition frequencies for specific plant areas, to classify anticipated fire initiation sources, and to assess the anticipated effectiveness of detection and suppression efforts. The data base also provides some limited insights into the types of equipment most vulnerable to fire initiation and to fire damage.

Based on this listing of fire experiences, a given nuclear power plant can expect to encounter a significant fire, on average, once every 6-10 years of operation. In this context, a significant fire is one which can or will result in the degradation of one or more safety systems. Further, the U. S. nuclear industry as a whole experiences on the order of 10-15 reportable fires each calender year. The yearly history of fire occurrences documented in the data base is illustrated in Figure 3.3. Based on an informal collection of more recent fire incident reports this

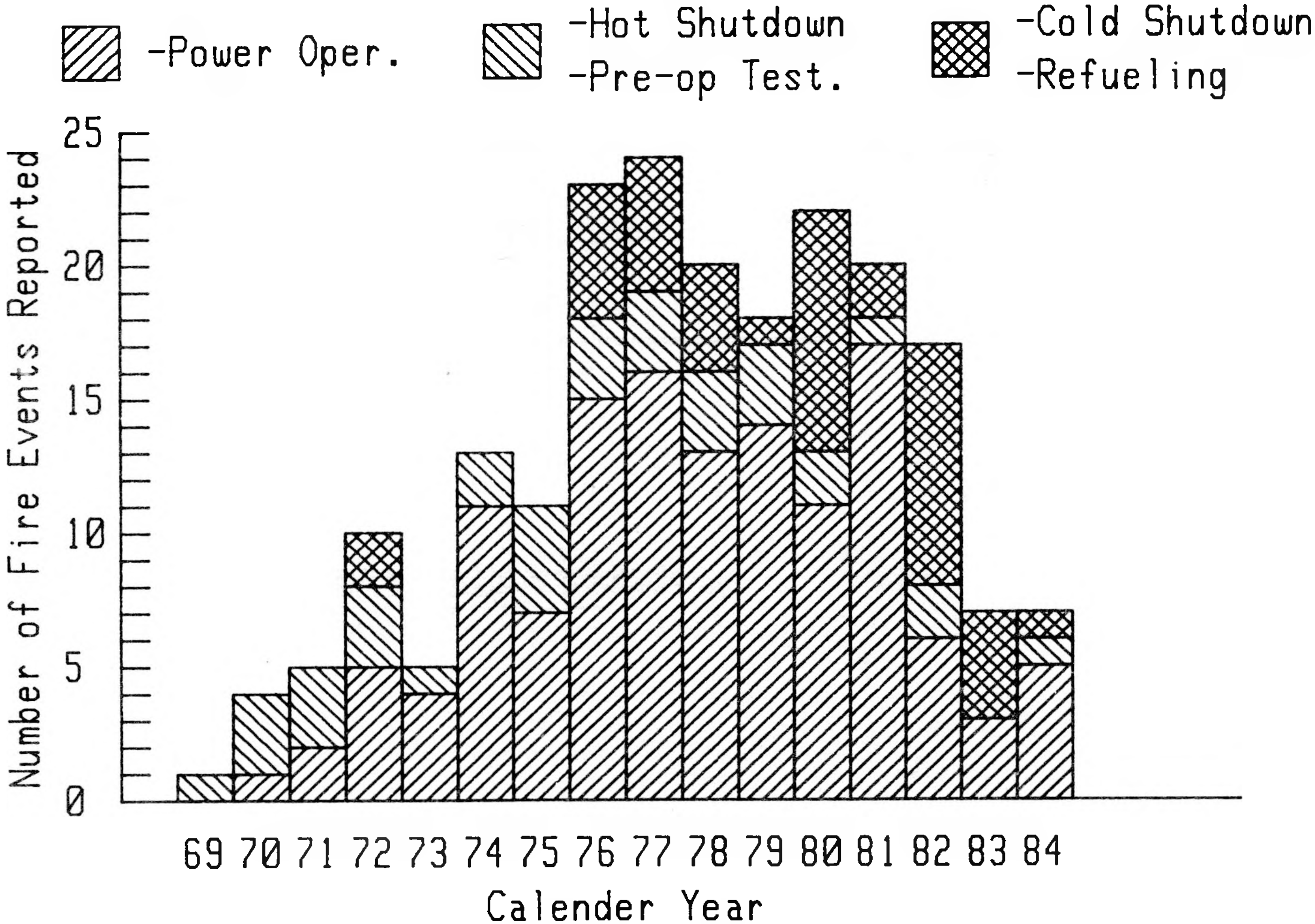

Figure 3.3 Yearly History of Fire Events as Documented in the SNL Data Base

rate of fire occurrences appears to be continuing at approximately the same rate in more recent years.

As a part of the recently completed Fire Risk Scoping Study [8], those incidents within this data base for which asuppression time is reported were utilized as the basis for the development of a suppression probability distribution. A total of 69 such events were identified. These results are described in more detail in Chapter 4 of this report, which describes fire detection and suppression system effectiveness related efforts.

3.3 Transient Fuel Source Fire Characterization Efforts

A transient fuel source is any combustible fuel source that is not a part of the as-designed plant systems and structures. Thus this definition includes such items as trash, construction and maintenance materials, and spills of liquid fuels such as oil and solvents. Two experimental efforts conducted as a part of the FPRP provide direct insights into phenomena of interest in the definition of the fire threat, which certain of these potential fire sources represents. These are:

1981 Trash/Pool Fire Correlation Tests
1985 Transient Fuel Source Fire Tests

3.3.1 Trash/Pool Fire Correlation Tests

The Trash/Pool Fire Correlation Tests were performed during the early stages of the FPRP during which specific regulatory concerns were being investigated.[22] It was considered desirable to establish an equivalency between a liquid fuel pool fire and other transient fuel packages, and in particular trash fires. The investigation of these two transient fuel sources was motivated by two factors. First, in experimental fire work there is a great deal of uncertainty in the anticipated behavior of a particular fuel package because the repeatability observed in many fuel packages is quite poor. Liquid fuel pool fires have been observed to represent one of the most repeatable fire sources. The second factor was the capability of existing fire simulation models to predict the behavior of liquid fuel pool fires based on certain fundamental fuel properties (for example see Reference 25), whereas, such predictions can not be accurately and reliably made for a fuel package made up of trash.

In an attempt to establish a basis for equivalency, the assessment of several experimental fires involving both simulated trash and liquid fuel pools was undertaken. The fire characteristic considered of primary interest was the rate of thermal radiation heat flux emitted by the fire source. This parameter was assumed to most nearly represent the degree of threat a given fuel package represented as an exposure fire source. In each test the rate of thermal heat flux received at certain locations near the fire was monitored, along with several other parameters characterizing the severity of the resulting enclosure environment.

As a result of these tests, it was concluded that a liquid fuel pool fire involving 5 gallons of heptane burned in a 5 square foot fuel pan did not appear to be more likely to cause ignition of secondary fuel sources than certain of the trash-fueled fires tested. (This heptane fuel source had been previously used as a cable tray fire exposure source.) It was also concluded that no true equivalency could be established between the trash fires and the liquid fuel pool fires. This resulted from observed differences between the highly transient behavior of the solid fuel packages and the relatively steady burning in the liquid fuel packages. Some basis for comparison was established, though no true one-to-one correspondence could be demonstrated in all aspects simultaneously. It was also confirmed that the transient fire behavior of the solid fuel packages would be hard to predict without first characterizing fuel behavior through experimentation.

3.3.2 Transient Fuel Source Fire Tests

In a subsequent effort a number of "typical" transient fuel fire sources were experimentally evaluated to determine the rate of heat release observed for each fuel package.[26] Five fuel packages were tested ranging from a small bucket with cleaning solvent and paper rags to a single large plastic trash container filled with paper and cotton rags. The selection of the fuel packages tested was based in part on the results of the transient fuels experience base review described above in Section 3.2.2.

Peak heat release rates observed during testing ranged from 12 to 145 kW. Typical heat release rates were in the range from 20 to 50 kW. It was also found that fires were quite long lasting with open flaming continuing for as long as 65 minutes. Flame heights ranged from as little as 10 inches to as high as 3 feet, with transient bursts as high as 8 feet. Plume temperatures, measured with bare bead thermocouples, at approximately 3 feet above the base of the fire peaked in the range of 250 to 800°C. At a height of six feet above the base of the fire typical plume temperatures ranged from 40 to 100°C. The highest measured plume temperature at six feet was approximately 250°C for a test involving a cardboard box and cleaning solvent.

Comparison of these FPRP tests to tests previously conducted by other investigators [27] involving similar fuel packages also provided useful insights. In these previous tests, the trash fuel configuration used included a highly flammable waxed paper fuel configured in a manner such that fire growth rates would be maximized. In these previous tests peak heat release rates of as high as 600 kW had been recorded. In the FPRP, tests a similarly sized fuel package involving plain paper and cotton rags displayed a peak heat release of only 145 kW. As a result, the previously tested fuel packages were concluded to represent worst case configurations for such fuel packages. The FPRP packages were considered to represent more realistic best estimate configurations.

3.4 Investigation of Cable Tray Fire Behavior

As has been stated above, cable insulation dominates the combustible fuel loading in most nuclear power plant areas. Most of this cable insulation is present in the form of cables routed in extensive cable tray arrays. Thus, the characterization of the fire behavior of cables in tray arrays and of the role of various passive fire protective features in preventing fire spread is of critical importance to the overall understanding of the problem of fires in nuclear facilities.

This critical role of cable insulation as the primary fuel source of interest is further amplified when one considers the results of past fire risk assessments. For many such assessments, the dominant fire scenarios focus on plant areas where power, control, and instrumentation cabling for redundant trains of safety equipment are routed through single fire areas and can thus represent single point multiple system fire vulnerabilities.[8] For these scenarios the rate of fire growth predicted for the cable tray arrays effectively competes with the probability of fire suppression within a given time frame to determine the significance of the given scenario in the overall risk perspective.

In actuality, relatively little fundamental research on the fire behavior of cable tray installations has been performed. As a part of the early work conducted under the FPRP, a number of experimental efforts associated with the investigation of various cable tray fire safety issues were performed. The primary objectives of these efforts were to address specific regulatory questions and concerns, as has been described in Chapter 2 of this report. However, these efforts also provide insights into the general behavior of cables under fire conditions as well. It is these more broadly based insights which will be discussed here.

The specific experimental efforts of interest in this context are:

1975	Cable Use Screening Survey
1976	Electrically Initiated Cable Fire Tests
1977	Exposure Fire Cable Fire Tests
1978	Cable Tray Fire Retardant Coatings Tests
1978	Cable Tray Barrier Tests
1979	Cable Tray Corner Effects Tests

In more recent years, initial efforts to utilize the broader insights gained as a result of these cable tray fire tests in the formulation of cable fire growth simulation models were undertaken. These efforts met with only limited success as the narrow scope of these early cable fire tests resulted in only limited quantitative data being gathered. The particular study of interest in this context is:

1981	Burn Mode Analysis of Cable Fires

3.4.1 Cable Use Screening Survey

As an initial step in the performance of cable fire testing, a survey was conducted in 1975 to determine the commercial nuclear industry design practices regarding the selection of cable insulation materials. This review was not intended to determine the characteristics of cables in existing plants, but rather, to obtain an indication of the characteristics of cables in new installations and for existing plant cable upgrade and replacement activities.

Responses to the survey were obtained from 13 architect-engineering firms, 13 utility companies, and 13 cable manufacturers. The respondents identified 20 different cable types which were being considered for use. The most popularly cited cable types were cross-linked polyethylene (XPE or XLPE) with or without some jacketing material (34% of the respondents), ethylene-propylene rubber (EPR) with a Hypalon jacket (23%), and EPR with a Neoprene jacket (19%).

On the basis of this survey, five cable types were selected for initial screening. All five types were #12 AWG single or multi-conductor cables. This size selection was based in part on the anticipation of the Electrically Initiated Cable Fire Tests (described immediately below) and an understanding that the electrical initiation of fires experimentally would be difficult to achieve. As cable size increases, the power requirements to initiate combustion also increase. Cables of the #12 AWG size were considered an appropriate selection as these are generally the smallest power cables found outside of containment in most power plants. The five cable types selected are described in Table 3.1.

3.4.2 Electrically Initiated Cable Fire Tests

Electrical faults represent one potential source for the initiation of cable fires. As a part of early fire research efforts, an examination of the potential for the development of electrically initiated fires in IEEE-383-74 rated low flame spread cables was performed. As a result several, insights were gained.

It was found that for the #12 AWG cables tested, currents of from 120 to 130 amperes were required to induce open flaming. This compared favorably to pretest analytical predictions that currents in the range of 100-120 amperes would be required to initiate combustion. In full-scale testing, the intense period of fire activity persisted for between 40 and 240 seconds after which rapid reduction to self-extinguishment of the fire was observed.

Also included as a part of these tests was an examination of the adequacy of RG 1.75 cable tray separation criteria in preventing the spread of an electrically initiated cable tray fire. In no case involving electrically initiated fires in rated low flame spread cables was propagation of the fire beyond the tray of fire origin observed. Thus, RG 1.75 was judged adequate to prevent the spread of electrically initiated fires involving IEEE-383-74 rated low flame spread cables. (As will be discussed immediately below, RG 1.75 was judged inadequate when the threat of exposure fires was considered.)

Table 3.1: Cable Types Selected for Initial Cable Fire Testing

Cable #1	Single Conductor #12 AWG, 45 mil (1.14 mm) EPR, 30 mil (0.76 mm) Hypalon jacket, 600 V.
Cable #2	Single Conductor #12 AWG, 47 mil (1.19 mm) chlorinated rubber (proprietary), 47 mil (1.19 mm) chlorinated polymer (proprietary) jacket, 600 V.
Cable #3	Single Conductor #12 AWG, 47 mil (1.19 mm) EPR, 15 mil (0.38 mm) Neoprene jacket, 600 V.
Cable #4	Single Conductor #12 AWG, 30 mil (0.76 mm) XPE, no jacket, 600 V.
Cable #5	Three Conductor #12 AWG, 30 mil (0.76 mm) XPE, silicone glass tape, 65 mil (1.65 mm) XPE jacket, 600 V.

Note: Cables 4 and 5, though similar, were supplied by different manufacturers.

3.4.3 Cable Tray Exposure Fire Testing

In subsequent testing, two of the cables evaluated in the electrical ignition study were tested under exposure fire conditions. The cable types selected for this subsequent testing were those considered to be the least flame resistant of those evaluated previously. These two cable types were both of the XPE type and are those designated as cables #4 and #5 in Table 3.1.

The fire source used in the first series of exposure tests was comprised of two propane ribbon burners, each identical to those used in the IEEE-383-74 flame spread test, placed under the horizontal cable trays. These ribbon burners were each driven at the fuel rates specified for the IEEE-383-74 test burner. Note that the IEEE-383-74 test specifies the use of a single burner so that the total exposure fire source intensity was twice that of the standard test. This increase in exposure intensity was intended to compensate for the horizontal configuration of the cable trays used in the exposure tests, as compared to the vertical tray configuration of the standard test. In a horizontal configuration, self sustaining cable tray fires are more difficult to induce.

It was observed that under this exposure the XPE cables tested required a minimum exposure time of approximately 300 seconds to establish self sustaining combustion in a single cable tray. Note that the IEEE-383-74 standard burner intensity is 70,000 BTU/Hr (20.5 kW). The use of two such burners produces a fire equivalent in intensity to a small, low intensity trash fire or to a heptane pool fire approximately ten inches (0.26 m) in diameter.

The final test in this series of exposure fire tests was conducted on July 6, 1977.[10] In this test one division of safety related cables was simulated using 14 filled horizontal cable trays in a two tray wide by seven tray high array. The lower trays were filled with the single conductor XPE cable described in Table 3.1 as Cable #4, while the upper trays were filled with the three conductor XPE cable described in Table 3.1 as Cable #5. These 14 cable trays were separated by eight inches horizontally and by 10.5 inches vertically, as allowed by RG 1.75. A second, redundant train of safety related cables was simulated by two filled cable trays each located five feet above the highest of the simulated division one cable trays, again consistent with the RG 1.75 guidance. Figure 3.4 provides a photograph of the pre-test configuration. This particular test provides a number of insights into the growth behavior of a cable tray array fire.

A five minute exposure to two standard IEEE-383-74 ribbon burners under one of the lowest two trays produced a fully developed fire within this one cable tray. During this initial five minute period, a barrier was used to shield the remaining trays from the fire. The propane burners then were extinguished and the barrier was removed. The fire eventually propagated through not only the closely stacked division one cable trays, but the simulated redundant division cables as well.

It was also noted, based on infrared thermography, that the fire grew primarily in an upward direction, spreading horizontally only as it progressed from level to level. The rate of fire spread was observed to accelerate as the fire progressed. The angle of this horizontal spread from level to level was estimated at 35° to either side of the vertical. Very little horizontal flame spread in any given tray beyond this angle of flame progression was noted.

Due to the build-up of a dense layer of smoke in the test enclosure, visual observation of the test fire was very difficult. Based on thermocouple measurements, and on a review of infrared thermovision images taken during the fire, the progress of the flames has been estimated. The exposed tray on the first level was observed to be burning intensely, though in a very localized region, after the five minute burner exposure. Within approximately five minutes of removal of the barrier, the second and third level trays appeared to be involved in the fire. Within ten minutes of the barrier removal, the fourth level trays were also involved. The sixth level of cable trays was involved

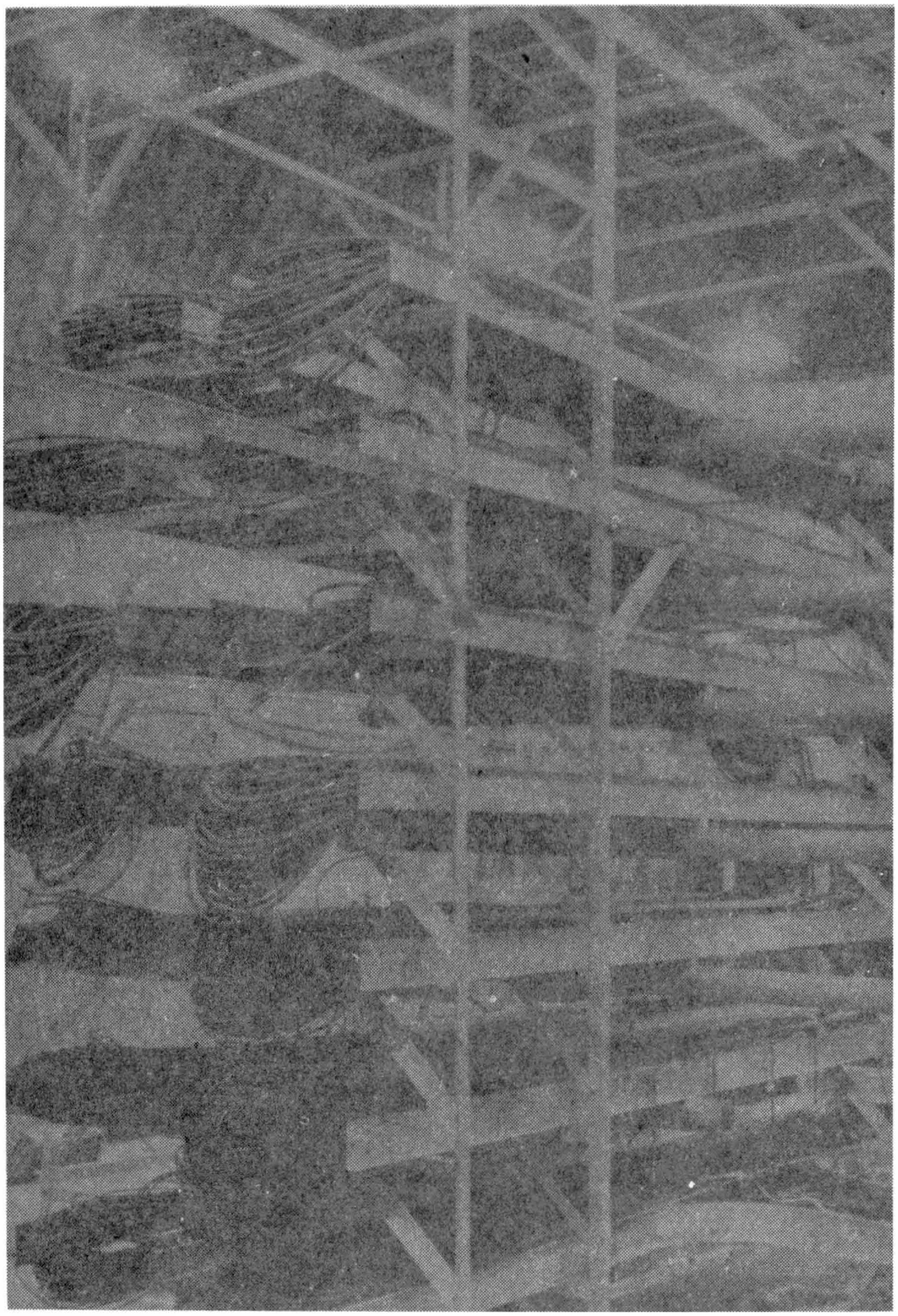

Figure 3.4 Pretest Cable Tray Configuration Used in July 6, 1977, RG-1.75 Separation Criteria Adequacy Test

within 18 minutes of barrier removal. The simulated redundant cable train was observed to be burning within 22 minutes of the removal of the fire barrier.

It is interesting to note that probabilistic risk assessment activities for fire have resulted in the development of a fire suppression probability distribution based on historical experiences of nuclear power plant fires in the U.S.[8] This suppression probability distribution is described in detail in Chapter 4 as a part of the discussion of detection and suppression system effectiveness investigations. Based on this distribution, the median probability that the July 6, 1977, test fire would have been suppressed prior to the involvement of the redundant cable trays would have been estimated at only 58 percent (including credit for the five minute burner exposure).

At approximately 34 minutes into the test, seven minutes after ignition of the simulated redundant train cables, the cable tray array collapsed. This collapse was attributed to the melting of aluminum structures which had been used to support the steel cable trays. The aluminum used in the support structure had an estimated melting point of 1220°F (660°C). Peak temperatures in the vicinity of the cable tray array were measured at up to 1600°F (871°C). The peak temperature measured near the ceiling of the test enclosure approximately six feet (1.8 m) above the highest of the cable trays was approximately 1300°F (704°C).

For all of the cable tray fire tests performed, the height of a cable tray flame was found to be strongly dependant on the nature and intensity of the fire source. For the electrically initiated fires, the flames observed during the peak of fire intensity fluctuated rapidly in heights from 4 to 10 inches. For tests involving exposure of a single cable tray to a propane gas burner, the flames were observed to fluctuate from 10 to 12 inches in height. When a single tray was exposed to a liquid fuel pool fire, cable tray flame heights fluctuated between 30 and 50 inches in height. In the July 6, 1977, test flame heights in the cable tray array were difficult to judge, though as the fire grew in intensity the flame heights also increased. Indications were that the flames from the lower array of division one cables bridged the five foot vertical gap to ignite the division two cables.

Significant differences were also noted in the heat transfer processes observed for self-ignited and for exposure fire conditions. In all cases the flame temperature was roughly 1900°F (1027°C). However, the luminous flame zone for the electrically initiated fires was optically thin with an apparent emissivity on the order of 0.1 measured. This is quite low in comparison to typical values for larger fires, and implies a correspondingly lower intensity thermal radiation output from such fires. It was noted that the transfer of heat to immersed objects was convection dominated in the electrically initiated fires and radiation dominated in the larger exposure fires.

Estimates of the upward velocity of gases in the region of the flame were made by tracking the progress of small luminous eddies shed from the flames. On this basis it was estimated that the average upward gas velocity in the area of the flames was from 3 to 4 feet per second. Variations from this range were quite small, even over a large number of measurements made in different tests.

3.4.4 Cable Tray Fire Retardant Coatings Tests

As a result of the July 6, 1977 test's demonstration that RG 1.75 cable tray separation criteria were insufficient to insure the protection of redundant train cable trays under exposure fire conditions, the investigation of additional fire protective features for cable trays was initiated. These protective features included fire retardant coatings for cable trays. A series of tests was performed to evaluate the effectiveness of a variety of coatings features in (1) reducing material flammability, (2) preventing the spread of fire and (3) preventing fire induced cable failures.

For the fire retardant coatings, tests on both a small- and large-scale were conducted. The small-scale tests evaluated certain fundamental flammability characteristics while the large-scale tests evaluated the effects of the coatings on the spread of fire and on preventing or delaying fire induced damage. (For the purposes of this section, the discussion of the large scale tests will focus on the flammability and fire spread results. Damageability results from these tests will be discussed in Chapter 6, which describes FPRP equipment damageability studies.) In all, a total of seven different coatings were evaluated. These coatings were identified in the test reports only by a letter designation. Thus the coatings are referred to only as coatings 'A' through 'G'. The names of the actual manufacturers of these coatings have not previously been published, and will not be published here. The full matrix of tests performed is presented in Table 3.2.

In the small-scale tests the effects on the flammability of small sections of cable resulting from application of cable fire retardant coatings produced by six of the seven different manufacturers were investigated. These small-scale tests used two types of rated low flame spread cables which are described as cables #4 and #5 in Table 3.1. The flammability of the samples was evaluated through measurements of the time to ignition of the cables themselves, time to maximum heat release rate, and cumulative heat release at given times after initiation of exposure. Each of these parameters was measured at each of four exposure heat flux levels ranging from 1.0 to 4.0 W/cm^2.

As a result, it was found that the coatings were all effective at reducing the materials flammability. However, the effectiveness observed for the different coatings varied dramatically. For example, at an exposure heat flux of 4.0 W/cm^2 with the unprotected cables open flaming was observed within 0.8 minutes and the peak heat release rate was measured after 6.0 minutes of exposure. For the coated samples at this same exposure flux, the time to observed open flaming of the cables themselves varied from a low of 5.0 minutes to a high of 24 minutes. It

Table 3.2: Matrix of Cable Fire Retardant Coatings Tests.

Coating	Small-Scale Tests, 383-Rated Cables, Single Cond.	Small-Scale Tests, 383-Rated Cables, Three Cond.	Single Tray Tests, Gas Burners, 383-Rated, Single Cond.	Single Tray Tests, Gas Burners, 383-Rated, Three Cond.	Single Tray Tests, Gas Burners, Non-383, Three Cond.	Two Tray Tests, Gas Burners, 383-Rated	Two Tray Tests, Gas Burners, Non-383	Two Tray Tests, Oil Pool, Non-383
None	X	X	X	X	X	X	X	
A	X	X	X	X		X	X	X
B			X	X		X	X	X
C	X	X	X	X		X	X	X
D	X	X	X	X		X		
E	X	X	X	X		X	X	X
F	X	X						
G	X	X	X	X		X	X	X

should be noted that, in certain cases, open burning of the coating materials was observed in significantly shorter times. The time to maximum heat release similarly varied from a low of 12 minutes to a high of 34 minutes. (Note that for these two parameters a longer time indicates lesser flammability.)

In terms of the cumulative heat release, significant variations were also noted. For the unprotected cables at an exposure of 4.0 W/cm^2, the cumulative heat release after 15 minutes of exposure was 78.0 MJ/m^2. For the coated cables, this parameter varied from a low of only 8.1 MJ/m^2 to a high of 60.4 MJ/m^2. (In this case, higher cumulative heat releases indicate a higher flammability.)

While in overall terms the small-scale test results were relatively self consistent, certain inconsistencies did appear. For example, the best delayer of cable ignition was the coating identified in the tests as coating E, which delayed cable ignition to 24 minutes. The next best performer in this sense was coating D which delayed ignition to 14 minutes. However, in terms of cumulative heat release after 15 minutes of exposure coating E allowed 22.5 MJ/m^2 while coating D allowed only 8.1 MJ/m^2.

It is also of interest to note that for both of these samples no open flaming of the cables had been observed for most or all of this 15 minute period. Thus, the released heat is presumably accounted for as (1) combustion of the coating itself, and (2) smoldering combustion in the cables prior to open flaming. This observation of smoldering combustion also implies that even though open flaming may be delayed or prevented, significant cable degradation, and possibly electrical failure, may be observed. Thus, these small-scale tests demonstrated that no one single parameter should be used to judge the effectiveness of a given coating.

The full-scale cable coatings tests were performed using cable trays loaded with either IEEE-383-74 rated low flame spread cables or with a nonrated cable. The rated cable used was the three conductor XPE cable used in previous testing and described as Cable #5 in Table 3.1. The nonrated cable used was a 12 AWG three conductor cable with a 20/10 PVC/PE insulation and a PVC jacket. A total of 33 tests on five of the seven coatings was performed. Fifteen of these 33 tests involved the exposure of a single cable tray to a gas burner fire. Thirteen tests involved the exposure of a two tray stack to a gas burner. In all of the gas burner exposure fire tests two of the standard IEEE-383-74 propane ribbon burners were used as in previous RG-1.75 cable fire tests described above. For the coatings tests repeated burner cycles of five minutes on and five minutes off up to a maximum test duration of 60 minutes (six full cycles) or until ignition of the cable samples was observed were utilized. The final five tests involved the exposure of a two tray stack to a diesel fuel liquid pool fire.

Table 3.3 summarizes some of the principal results of the single tray gas burner cable coatings tests. Note that the time to ignition for uncoated, low flame spread cables was 5 minutes. (That is to say, ignition occurred during the first burner cycle.) For the coated cables, ignition times varied from 5 minutes (coating C) to no observed ignition within 60 minutes (coatings D and E). The times to electrical failure of the coated cable were also significantly affected in most cases. Several of the coatings prevented electrical failure entirely. These results are discussed further in Chapter 6 as a part of the discussion of equipment damageability investigations.

Table 3.3: Summary of Principal Single Tray Gas Burner Cable Fire Retardant Coatings Test Results.

Cable Type: Coating	Time to Ignition (min)	Burn Duration (min)	Burn Length (in)
3-Conductor, IEEE-383-74 Rated Cables:			
None	5	13	27
A	10	15	30
B	15	7	40
C	5	40	43
D	No	0	0
E	No	0	0
1-Conductor, IEEE-383-74 Rated Cables:			
None	5	10	34
A	10	6	35
B	20	7	43
C	10	15	58
D	No	0	0
E	No	0	0

One result of particular interest is the effect of the coating 'C' on the duration of burning after ignition, and the length of the burned area. For the uncoated low flame spread cables, burn durations for the 3-conductor and 1-conductor cables were 13 and 10 minutes respectively. The corresponding burn distances were 27 and 34 inches respectively. For the coating designated 'C' the burn durations for the 3-conductor and 1-conductor cables actually increased to 40 and 15 minutes respectively. Similarly, the length of the burned area increased to 43 and 58 inches respectively. Thus, for this coating, while the times to electrical shorting were delayed somewhat, the duration of burning and extent of fire spread were both increased significantly.

For the two tray gas burner coatings tests, both rated and nonrated cables were used. The primary result of interest from these tests is the effects of the fire on the upper of the two trays. The only case in which propagation of the fire to the upper tray was observed involved coating 'C' with unqualified cables. In no case was propagation of the fire to the upper tray observed for coated low flame spread cables. It should be noted that, as in previous tests, an insulating barrier was placed between the two trays during the times when the gas burners were on. This barrier was removed during cycle periods when the burners were off. This limited the effects of the exposure fire on the upper tray to that produced by the burning of the lower tray only.

The two tray diesel fuel coatings tests differed from the gas burner tests in three important respects. First, the exposure fire involving the diesel fuel pool was more intense than that involving the gas burners. Second, no barrier was placed between the two trays during the burning of the diesel fuel exposure fire. Third, the diesel fuel pool fire burned continuously for approximately 13 minutes as opposed to the use of 5 minute on, 5 minute off burner cycles. The diesel fuel fire tests are indicative of the actual response of a coated two tray stack to a relatively severe exposure fire situation. Only five of the seven coatings were evaluated in this configuration.

All of the diesel fuel pool fire coatings test involved the use of the nonrated PE/PVC 3-conductor cable. The results of these tests are summarized in Table 3.4. Note that the times to electrical failure varied from 3-11 minutes for the lower tray, and from 7-19 minutes for the upper tray. Three of the five coatings evaluated, coatings 'A', 'B', and 'E', prevented the propagation of fire to the second upper tray even under these fairly severe conditions. For the other two coatings tested in this series, significant fire spread within the upper tray was observed.

In summary, the Cable Tray Fire Retardant Coatings Tests demonstrated a wide variability in the effectiveness of the different cable coatings evaluated. This variability was noted in virtually every parameter investigated including (1) the delay in the onset of cable burning, (2) the delaying or prevention of fire induced electrical failure, and (3) the rate and extent of fire spread. Certain of the cable coatings performed very well under all of the conditions evaluated. The coating identified as 'E' would be judged the overall best performer. The coatings identified as 'A' and 'B' also performed well in that they prevented the propagation of fire to the upper cable tray under the relatively severe exposure conditions of the two-tray diesel fuel fire tests. The coating identified as 'C' would be judged the poorest performer. In some instances, this coating actually resulted in more severe fire conditions than did uncoated cables.

Table 3.4: Summary of Principal Two Tray Diesel Fuel Fire Cable Fire Retardant Coatings Tests Involving Nonrated 3-Conductor Cables.

Coating	Time to Ignition (min)	Burn Duration (min)	Burn Length (in)
Lower Tray Response:			
A	13	42	72
B	13	31	20
C	12	37	84
E	No	0	36
G	12	42	66
Upper Tray Response:			
A	No	0	72
B	No	0	72
C	12	43	96
E	No	0	0
G	12	46	84

However, these tests also demonstrated that the use of any of the fire retardant coatings evaluated would not prevent the onset of electrical failure under the diesel fire exposure conditions. Thus, the use of such coatings can not be, in and of itself, considered sufficient to prevent fire induced cable degradation.

One should also note that these tests did not address certain other aspects of the use of such coatings on cable performance which should be considered in the practical application of such measures. In particular, no investigation was performed of the impact of application of such coatings on the ampacity rating of the cables, or of the potential degradation of these coatings due to aging or other effects. Nor were the coatings examined for material composition. In these tests, all coatings were applied to thickness recommended by the individual manufacturers. These recommended thicknesses varied considerably from a light coating to quite thick, trowel on coatings. This thickness almost certainly would play a role in the effectiveness of all aspects of the coating performance. The effects of either increasing or decreasing the recommended thickness was not investigated.

3.4.5 Cable Tray Fire Barrier Tests

As a second potential method for reducing the severity of cable tray fires, and for reducing the likelihood of fire induced damage, the use of protective passive fire barrier systems for cable trays was experimentally investigated. These tests were conducted in a manner identical to that used in the single tray and two tray gas burner cable coatings tests described immediately above. The same cable types and the same gas burner exposure fire source were used. Five potential fire barrier systems were tested. These were:

1 - ceramic wool blanket wrap,
2 - solid tray bottom covers,
3 - solid tray top cover with no vents,
4 - solid tray bottom cover with vented top cover, and
5 - 1-inch insulating barrier between cable trays.

The matrix of cable tray fire barrier tests is presented in Table 3.5. The barrier system identifiers in this table are those number codes given immediately above.

Table 3.5: Matrix of Cable Tray Fire Barrier Tests.

Barrier System Identifier*	Single Tray Tests 383-Rated Single Cond.	 Three Cond.	 Non-383 Three Cond.	Two Tray Tests Non-383 Three Cond.
1			X	X
2	X	X	X	X
3			X	X
4	X	X	X	X
5				X

* Defined in text.

The most telling of these tests are the two tray gas burner tests as all five of the barrier systems were evaluated using a consistent fire exposure. These tests can also be compared to the previously reported case in which a two tray configuration of unprotected nonrated cables was exposed to the same ignition source. The results of these tests are summarized in Table 3.6.

Table 3.6: Summary of Principal Two Tray Gas Burner Cable Tray Fire Barrier Tests Involving Nonrated 3-Conductor PE/PVC Cables.

Barrier System Identifier*	Time to Ignition (min)	Burn Duration (min)	Burn Length (in)
Lower Tray Response:			
None	5	39	67
1	15	45	108
2	20	4	43
3	10	68	120
4	10	55	66
5	5	42	120
Upper Tray Response:			
None	3	59	84
1	No	0	0
2	No	0	0
3	No	0	0
4	No	0	0
5	No	0	0

* Defined in Text.

In all cases, the propagation of fire to the upper tray was prevented. In only two cases were electrical faults in the upper tray observed, and in one of these two cases (involving barrier system #5), the fault resulted from fire propagating in the lower tray beyond the end of the insulating fire barrier placed below the upper tray. However, in no case was electrical failure prevented in the lower of the two trays. In fact, the barriers (with the exception of barrier system #2) generally increased both the duration and eventual extent of fire development in the lower tray.

3.4.6 Cable Tray Fire Corner Effects Tests

In a fire, the intensity of the thermal feedback delivered to a fuel element can dramatically affect that fuel elements burning rate and fire growth rate. Sources of thermal feedback include hot layer effects, heat transfer from other burning fuel elements, and the re-radiation of heat from enclosure surfaces. In cable fire testing, it has often been observed that the presence or absence of thermal feedback can determine whether or not a fire will self extinguish or continue to burn and grow. This is illustrated by the observation that while it is difficult to establish self-sustaining combustion in a single strand of cable, cables laid up in a cable tray array or placed in a cabinet configuration burn much more easily, and much more intensely. In these latter cases, the presence of other combustible fuel sources, and/or the proximity of the cables to a surface contribute to the intensity of combustion.

Under the FPRP, an effort was conducted to investigate the effects of proximity to enclosure surfaces on the burning of a cable tray. In these tests, known as the Corner Effects Tests, a room ceiling-wall corner was simulated using insulating wallboard panels. In a series of six tests, pairs of cable trays were positioned at various distances from the simulated corner and then subjected to a gas burner exposure fire. The distance from the cable tray to the simulated corner was varied from 12 inches (5 inches horizontal and 10.5 inches vertical) to 134 inches (60 inches horizontal and 120 inches vertical). These tests involved both an IEEE-383-74 rated low flame spread cable and a nonrated cable (identical to those used in the fire retardant coatings tests described above). The gas burner exposure fire source used was physically identical to that used in previous tests described above. As in the previous tests a burner operation time of five minutes was used, though in the corner effects tests repeated burner cycles were not used. During the cycle period in which the burners were on, the upper tray was shielded from the gas burner fire. After five minutes the gas burner was extinguished and the barrier removed, exposing the upper tray to only the fire established in the lower tray.

As a result of these tests, a pronounced effect on the fire behavior was observed. One of the parameters measured was the total weight loss for the cables in the upper of the two trays. The nonrated cables experienced a 62% increase in total weight loss, from approximately 30.5 to 49.5 pounds, as the distance between the upper tray and the corner was decreased from 134 to 12 inches. For the rated cables an even more pronounced increase was observed with upper tray weight loss increasing from 3.75 to 39.75 pounds, or an equivalent increase of more than 960% of base value.

A second parameter measured was the average rate of mass loss for the upper tray. In the case of the nonrated cables this mass loss rate increased from 0.78 to 0.92 lbs/min as the distance from the upper tray to the corner decreased from 134 to 12 inches. For the rated cables the increase in upper tray mass loss rate was from 0.15 to 1.99 lbs/min for this same change in distance from the upper tray to the corner.

A third parameter measured was the total length of fire involvement for the upper cable tray. For the nonrated cables at a distance between the upper tray and the corner of 134 inches the length of fire involvement prior to self extinguishment was 96 inches. At distances of both 21 and 12 inches full tray fire involvement was observed (total tray length was 144 inches). For the rated cables at a distance of 134 inches, only 16 inches of the upper tray burned prior to self extinguishment. When the distance to the corner was decreased to 21 inches, the length of involvement increased to 72 inches. At a distance of 12 inches to the corner the length of fire involvement increased to 120 inches.

These results are summarized in Table 3.7. It is clear from these tests that thermal feedback will profoundly impact the development of a cable fire. In particular, for the rated low flame spread cables while in a relatively open condition away from the surfaces, combustion conditions were marginal with very little spread of fire in the second tray. However, when the thermal feedback was increased through proximity to the surfaces, self-sustaining combustion continued much longer and the fire progressed much farther along the upper cable tray. (Similar marginal combustion conditions for rated cables were also noted in the fire testing of control panel cable configurations as described in Section 3.5 below. Here again the presence or absence of significant thermal feedback was sufficient to determine whether the fire would grow or self extinguish in low flame spread cables.) For the cables not rated as low flame spread, combustion was much more vigorous in an open configuration than was that involving rated cables. Even so, thermal feedback contributions to increased fire severity are apparent.

3.4.7 Burn Mode Analysis of Cable Fires

As a result of the insights gained from the various cable tray fire tests, an effort to formulate an empirical correlation between certain characteristic cable thermal parameters and the mode of cable combustion was performed. Under this approach, a cable's surface and subsurface temperatures were used to predict the mode of cable combustion. The combustion modes considered were (1) continuous use range, (2) accelerated aging, (3) pyrolosis, (4) deep seated or smoldering fire, (5) interior gas combustion, (6) surface fire, (8) fire ball flaming, (9) deflagration, and (10) flashover. Each of these modes was associated with a given combination of interior and surface temperature for a given fuel element or cable type.

Using these fire mode definitions the progression of certain of the cable fires observed in past testing were plotted. The data was taken from the cable tray fire retardant coatings and fire barrier tests described above. Two fire tests had been conducted using unprotected cables in order to establish a base line for cable fire behavior. One of these tests involved an IEEE-383-74 rated low flame spread cable, while the other involved an nonrated cable. Figure 3.5 and 3.6 provide examples of the fire development observed for these two different cable types based on experimental measurements of the cable temperatures, and on observations of the actual fire burning mode.

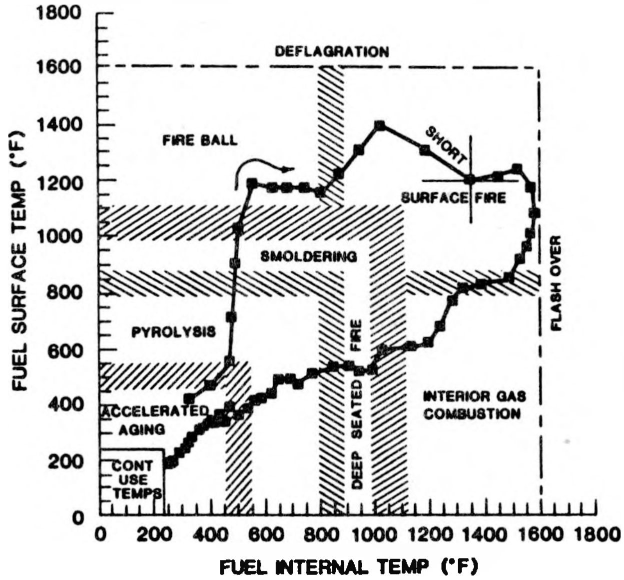

Figure 3.5: Burn Mode Analysis of Non-Rated Cable Fire

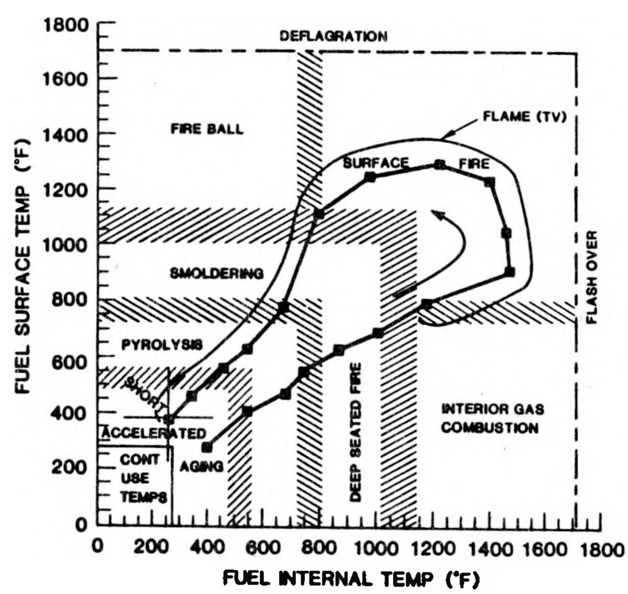

Figure 3.6: Burn Mode Analysis of Rated Low Flame Spread Cable Fire.

Table 3.7: Summary of Corner Effects Test Results for Upper of Two Cable Trays.

Cable Type/ Distance to Surfaces (in.)	Total Weight Loss (lbs)	Average Mass Loss Rate (lbs/min)	Length of Fire Area (inches)
IEEE-383-74 Cables:			
Side = 5.0 Top = 10.5	39.75	1.99	120
Side = 10.5 Top = 18.0	29.5	1.23	72
Side = 60.0 Top = 120.	3.75	0.15	16
Nonrated Cables:			
Side = 5.0 Top = 10.5	49.5	0.92	144*
Side = 10.5 Top = 18.0	44.75	0.89	144*
Side = 60.0 Top = 120.	30.5	0.78	96

* Total length of cable tray.

The development of this burn mode analysis technique was limited in that only cable fire data available from previously conducted tests was used. No further confirmatory testing was undertaken. The available data had been gathered in pursuit of quite different objectives, and hence, was not ideally suited for use in this analysis methodology. However, the technique did display a potential for addressing cable fire growth modeling limitations by providing a basis for the prediction of cable fire burning modes, and hence, cable fire growth modes.

The modeling of cable fire growth behavior remains a source of considerable uncertainty in the modeling of nuclear power plant fire scenarios, and in the analysis of fire risk. Should further experimental investigations of cable tray fire behavior be undertaken, it would be of utility to provide for the investigation of the adequacy of the burn mode analysis technique as a part of these investigations. The technique, if adequately validated, is well suited to incorporation into fire simulation models as it depends only on a prediction of the fuel surface and subsurface temperatures. Such predictions could be generated by a simulation model by using one-dimensional or composite transient thermal targets as fuel models rather than using lumped parameter element models as are typically employed in current models.

3.5 <u>Investigations of Electrical Control Panel Fires</u>

In recent years an investigation of electrical control cabinet fires was performed. There are two aspects of this work relevant to the issues of source fire characterization. First, an apparatus for electrically initiating fires through the simulation of a faulty electrical connection was developed. Second, the effects of various cabinet parameters on the development of a cabinet fire were investigated. Each of these two aspects of the cabinet fire investigations are discussed in turn in the two sections which follow.

3.5.1 Development of an Electrical Fire Initiation Apparatus

Historically, a large number of electrical control panel fires have occurred in commercial U. S. reactors. The Sandia Fire Occurrence Data Base [24] includes 39 reported cabinet fire incidents occurring between 12/16/72 and 8/2/84.[8] Nearly all of these fires resulted from self-generated electrical faults within the panel. The remainder resulted from electrical faults generated by an external source (e.g., rodents, water, etc.). Thus, in the experimental investigation of electrical panel fires it was of interest to investigate the behavior of an electrically initiated fire. However, as was found in previous tests involving cable trays, described above, the experimental inducement of an electrically initiated fire is quite difficult to achieve.

As a part of the cabinet fire investigations an apparatus was developed which could reliably and repeatably induce a self-sustaining fire in nonrated (i.e., not qualified by the IEEE-383-74 flame spread qualification test) cables in a control panel configuration.[28] The criteria for the development of this apparatus included the restriction that the fault should not be detectable by a 15 ampere fault current breaker.

The apparatus developed simulates a faulty terminal block connection. Ignition of nonrated electrical cables was achieved using a power source of less than 200 watts. In full scale cabinet fire tests this apparatus was used to initiate fires in cable arrays within actual electrical control panels. With the unqualified cables, propagation was observed which eventually resulted in the complete involvement of the subject cabinet. The most intense of the electrically initiated fires grew to a peak intensity of 1.3 MW within approximately 10 minutes of ignition. These tests are described in more detail below.

One of the concerns which was raised by these tests was that in practice cables in electrical control panels are often stripped of their protective outer jacket. In the IEEE-383-74 flame spread test cables are tested with the cable jacketing intact. The standard test does include a requirement for the flammability testing of the individual conductors, though this requirement is significantly less stringent than the testing for the full cable configuration. It was of potential concern that if a qualified cable were stripped of its jacket it may be more susceptible to fire than initial qualification testing might indicate.

Attempts were initiated to electrically induce ignition and propagation of fire in IEEE-383-74 rated low flame spread cables. These efforts were terminated before conclusive results were obtained. While the qualified cables appeared more resistant to the development of a self-sustained fire, ignition of the cables was achieved readily, and it was the impression of the investigators that under the proper conditions a self sustaining fire would result. Efforts to investigate this potential were terminated in the early stages as a result of the termination of the Fire Protection Research Program and the Cabinet Fire Testing Program.

3.5.2 Experimental Evaluation of Electrical Panel Fires

The experimental evaluation of electrical panel fires investigated two aspects of the cabinet fire question. First, the program investigated the effects of a number of cabinet parameters on the development of a fire within a single control panel.[29] Second, the program investigated the environmental impact of a fire confined to a single control panel on a very large, near control room sized enclosure.[30] For the purposes of the discussion of fire characterization efforts being presented here, only the first of these two aspects is of direct interest. Results of the investigation of the impact of a cabinet fire on the environment of an enclosure will be deferred to the discussion of room effects issues presented in Chapter 5.

In the first series of tests the effects of cabinet parameters including the style of cabinet (i.e., benchboard versus vertical cabinets), the fuel loading density, the fuel configuration, cable type, open versus closed cabinet doors, the presence of ventilation grills, the presence of internal cabinet partitions, and the intensity of the ignition source on the rate and eventual extent of fire growth were investigated. In all, 22 cabinet effects tests were conducted, of which six involved fully fuel loaded full-scale cabinet fire tests. The remaining 16 tests involved partially fuel loaded, or nonfuel loaded cabinet fire tests investigating very specific fire growth questions. The conclusions resulting from these 22 cabinet effects tests are summarized as follows:

1. Cabinet fires can be ignited and will propagate in either qualified or unqualified electric cables. It was found that it was much more difficult to establish a self-sustaining fire in the qualified cables, though in certain configurations, quite intense fires in qualified cables were observed.

2. Once ignited, the cabinet fires observed often developed quite rapidly, growing from fire ignition to peak fire intensities of up to 1.3 MW in as little as 5-8 minutes. The electrically initiated fires involved significant pre-ignition heating times, and it is suspected that <u>in-cabinet</u> smoke detectors

would have detected these faults prior to ignition, though no tests were performed to confirm this suspicion.

3. The observed rapid fire growth rates are expected to make the suppression of cabinet fires by plant personnel using hand-held extinguishers quite difficult. Such suppression activities cannot be expected to be effective under most circumstances if suppression activity is not initiated within approximately five minutes of ignition.

3. The propagation of a fire from cabinet to cabinet under the conditions tested was considered unlikely. These conditions were comprised of a solid steel, double wall barrier with no through penetrations. No conclusions can be drawn regarding the effectiveness of other barrier systems in preventing the spread of fire.

4. Adjacent cabinet temperatures, while below those expected to result in nonpiloted ignition, may be severe enough to cause failure and/or calibration shifts in electronic components.

It is important to note that in all the cases tested the fire was confined to a single control panel. A number of questions remain unanswered regarding the potential for a cabinet fire to spread beyond the cabinet of origin. Potential fire spread mechanisms not investigated include the effectiveness of single wall steel fire barriers, the reliability of cable penetration seals, and the spread of fire to either overhead or below cabinet cable trays and raceways. The only fire barrier system which was evaluated was the effectiveness of a solid, double wall steel barrier with no through penetrations such as that between two stand-alone fully enclosed cabinets. This configuration was found to be quite effective in reducing the adjacent cabinet temperatures below those expected to cause nonpiloted ignition of the cabinet fuel materials. The temperatures observed may, however, cause failure and/or calibration shifts in electronic components for these adjacent cabinets.

Another aspect of this issue not yet investigated is the effectiveness of fire suppression systems when applied to a burning cabinet. General room area fire suppression systems may be inhibited by the presence of the cabinet walls, especially water sprinkler systems. Also unresolved are questions associated with the use of in-cabinet gaseous suppression systems. The use of such systems could compromise the operability of electronic equipment housed in the cabinet.

4.0 DETECTION AND SUPPRESSION SYSTEM EFFECTIVENESS STUDIES

4.1 Introduction

As a part of the guidance provided in 10CFR50 Appendix R, the USNRC has endorsed a variety of national fire standards. Among those standards are several associated with the design and installation of fire detection and fire suppression systems. However, during the formulation of the Appendix R guidelines it was recognized that these standards had been developed for application to typical industrial, occupancy, and storage facilities. It was concluded that the applicability of these national standards to the circumstances of a nuclear power plant had not been demonstrated. Two factors of particular concern were identified. The first was the applicability of detector system selection and installation guidelines given the congestion of equipment, ventilation ducts, and cable trays typical of nuclear power plants. Second, the effectiveness of the various fire suppressants when applied to deep seated cable fires had not been investigated.

As a result of these concerns, investigations into certain aspects of fire detection and fire suppression systems were performed as a part of the USNRC/Sandia FPRP. The specific studies of interest in this context are:

Fire Detection Systems Investigations:

1979	Fire Protections Subsystems Study; Fire Detection
1982	Detector Siting Criteria Requirements Study

Fire Suppression System Effectiveness Investigations:

1980	Halon Suppression Effectiveness Tests
1981	Water Sprinkler Suppression Effectiveness Tests
1982	Directed Water Spray Suppression Effectiveness Tests
1983	Carbon Dioxide Suppression Effectiveness Tests

In addition, as a result of the development of the Fire Occurrence Data Base, certain insights have been gained based on the historical experience with respect to the detection and suppression of actual fires.

4.2 Fire Detection Systems Investigations

4.2.1 Fire Protection Subsystems Study; Fire Detection

One of the four subsystems investigated as a part of the Fire Protection Subsystems Study was fire detection systems. The regulatory implications of this study have been discussed in Chapter 2 above. The discussion presented here will focus on the technical aspects of the work performed, and the principal conclusions generated.

The Fire Detection Subsystems Study [3] examined the adequacy of fire detection in the context of nuclear power plant applications. The specific aspects of fire detection systems considered were (1) establishing area detection requirements, (2) selecting specific detector types, (3) locating and spacing detectors, and (4) performing installation tests and maintenance.

The study found that the traditional approach to the design and installation of fire detection systems included the use of a combination of fire codes (regulations), test standards, fire consultant recommendations, insurance agency requests, and detector vendor suggestions as inputs to the design process. This approach had been developed as a result of installation experiences primarily gained through fire detection implementation in residential and general commercial applications. In a nuclear power plant a number of factors are present which were identified as somewhat unique, and hence, not necessarily accounted for in this traditional design approach. These factors are ventilation conditions, ceiling heights, ceiling construction, and the types of combustibles present.

The first step in the detection system design process is the determination of area fire detection requirements. That is to say, one must establish which areas within a plant require the installation of an automatic fire detection system. Seven criteria were set forth upon which such assessments should be made:

1. Importance of the area to overall plant safety,
2. Susceptibility of the area to surrounding fire hazards,
3. Degree of fire hazard within the area,
4. Potential of fire spreading to other areas,
5. Type of available fire suppression (e.g., manual or automatic, inert gas or water),
6. Cost of added fire detection capability, and
7. Normal occupancy of the area.

It was found that in practice, it is not always possible to assess all of these factors objectively for each area of a power plant. As a result, detector requirements have generally been established on the basis of the importance of an area to plant safety, regardless of the level of associated fire risk.

The standards and guidelines for the determination of area fire detection needs were identified as providing confusing, and often contradictory requirements. This resulted from (1) differences in the principal concerns of the standards organizations (e.g., plant safety versus property protection) and (2) inconsistency in the terminology used to identify specific plant areas (e.g., remote shutdown rooms versus auxiliary panel rooms, or emergency/standby cooling equipment versus safety related pump room).

The second step in the design of detection systems is the selection of specific detector types, or combinations of detector types, for use in a given area. Five types of fire detectors were considered in this study. These five types represented the selection of devices with a proven record of operability outside the laboratory environment. These five types are:

1. Area heat detectors,
2. Continuous line heat detectors,
3. Ionization products of combustion detectors,
4. Photoelectric smoke detectors, and
5. Ultraviolet flame detectors.

Although other types of detectors were being developed, none had been proven outside the laboratory environment. To a large extent this remains true, and the five detector types cited above remain the most popularly selected fire detector types.

It was found that the available fire detection system design standards provided very little guidance upon which to base fire detector type selections. Eight factors were identified which should be considered in the selection of detector types. These factors are:

1. Anticipated nature of the combustion products to be developed by the fuels in the area of concern,
2. Anticipated rate of development of a fire in the area of concern and the acceptable ultimate extent of fire involvement,
3. Characteristics of the area's ventilation system,
4. Room congestion which may reduce "visibility" of the fire or combustion products,
5. Room geometry factors, and in particular, ceiling height,
6. Operational activities expected for the area which may compromise the effectiveness or spuriously actuate the fire detection system,
7. Detector maintenance requirements, and
8. The cost of detector system implementation.

The next step in the design process is to determine the appropriate placement and spacing of fire detectors within the area of concern. Here again, it was found that the standards for the design and installation of detector systems provided very little guidance. Five factors were identified as important to the placement of fire detectors. These five factors are:

1. Ventilation conditions,
2. Ceiling height,
3. Ceiling construction factors such as solid joists and sloping surfaces,
4. Room congestion, and
5. Detector zoning.

The consideration of these factors was recognized as requiring the extensive use of engineering judgment.

The final step in the design and installation of fire detection systems is the performance of installation tests and maintenance. This step was identified as particularly important as actual applications seldom resemble the conditions used in the qualification testing of detectors. Furthermore, the subjective nature of the design process leaves considerable uncertainty as to the actual effectiveness to be expected of the installed system. Four factors were identified as criteria upon which installation testing should be performed. These four factors are:

1. Visual inspection to insure detectors are installed as designed,
2. Verification of the proper wiring and operation of each individual detector,
3. Monitoring of the stability of the detector system over a period of several weeks, and
4. The evaluation of the detector system response to an actual test fire under typical conditions of operation.

With respect to maintenance activity, three criteria were set forth. These are:

1. Periodic testing of the operability of each individual detector,
2. Periodic cleaning of detectors, and
3. Restoration of detector operation promptly upon completion of periodic testing and cleaning.

In summary, the study found that the design and installation of fire detection systems was based largely on the use of engineering judgment. Furthermore, the available standards for detection systems provided inadequate guidance upon which to base decisions associated with a number of important and fundamental design and implementation factors. A number of design, installation, testing, and maintenance criteria were identified. It was concluded that the fire detection operating principles and qualification tests did not permit the prediction of detector response characteristics. Furthermore, it was considered doubtful that any theory would be developed and proven in the near future to describe the complex interaction of each physical parameter affecting detector operation. It was recommended that the best approach to solving the uncertainties associated with the design and installation process would be the implementation of in-place testing of detector response under environmental conditions anticipated to occur normally in each area being protected.

4.2.2 Detector Siting Criteria Requirements Study

The Detector Siting Criteria Requirements Study [21] performed a review of relevant research associated with the implementation of fire detection in a nuclear power plant. Of particular concern to the study was research on the characteristics of cable tray fires which had been performed at a number of organizations, and the implications of that research to the problem of fire detection for a nuclear power plant. The study cited and reviewed work performed at Factory Mutual Research Corporation (FMRC), the National Bureau of Standards (NBS), and efforts sponsored by Underwriters Laboratory (UL).

The principal finding of the study was that the evaluation of a cable fire situation is a complex problem requiring the use of many types of inter-related data. It was found that the various studies each provided considerable and significant insights. However, it was concluded that further experimental evaluations of cable fires would be required in order to bring together the various pieces of the cable fire problem. In particular, the state of knowledge regarding the behavior of cable fires was insufficient to provide for the determination of fire detector siting requirements. It was recommended that an effort be initiated to establish criteria for the determination of fire detection system effectiveness as a part of the design process. It should be noted that such efforts have not, to date, been undertaken.

4.3 Investigations of the Effectiveness of Fire Suppression Systems

As stated above, the guidelines for the implementation of fire protection in nuclear power plants include provisions for the installation of fire suppression systems under certain conditions. It is intended that such provisions would limit the extent of damage from a single fire through the prompt suppression of the fire itself. However, it was recognized that the standards upon which the design and installation of suppression systems were based had been developed as a result of experience in the application of such systems to residential and general commercial installations. Thus, the adequacy of the common suppression systems as applied to the nuclear power plant situation had not been assessed. In particular, the effectiveness of these systems in suppressing a deep seated cable tray fire had not been demonstrated.

As a part of the FPRP, efforts were performed to evaluate the effectiveness of the most common of the fire suppression systems in suppressing a fully developed cable tray fire.[19] Four fire suppression systems were evaluated. These four systems are:

1. Halon[3] 1301 room flooding gaseous suppression systems,
2. Carbon dioxide room flooding gaseous suppression systems,
3. Water sprinkler suppression systems, and
4. Directed water spray suppression systems.

Each of these systems was evaluated in a configuration consistent with the design and installation guidelines provided in the relevant National Fire Protection Association (NFPA) fire standards. In all, 37 full-scale cable tray fire tests were performed. The primary objective of these tests was, for the gaseous systems, to determine the minimum "soak time" required to suppress a fully developed cable fire at the suppressant

3. Halon is a registered trademark of the DuPont Corporation.

concentrations recommended in the relevant design standards. The "soak time" is that length of time in which suppressant concentration must be maintained in order to insure that the fire would not reignite upon the reintroduction of oxygen or the dilution of the suppressant. For the water based systems, the objective was to determine the minimum spray time required to fully suppress the test fires.

In these tests both IEEE-383-74 rated low flame spread cables and nonrated cables were used. Cable trays were arranged in both vertical and horizontal configurations. Each test fire involved either two or five cable trays. In each case sufficient fire growth time was allowed to insure that a fully developed, deep seated fire resulted.

Table 4.1 summarizes the findings of these tests. The soak times or spray times required to extinguish a cable tray fire involving either vertical or horizontal cable trays and either rated or nonrated cables are reported for each type of suppression system investigated. The most effective of the systems evaluated was the directed water spray system. The sprinkler system was also quite effective for vertical cable trays. However, for horizontal trays the blockage of lower trays by the upper trays meant that somewhat longer spray times were required. Both the Halon and carbon dioxide systems were effective at extinguishing the cable tray fires when concentrations of 7% and 50% by volume respectively were used. However, soak times of up to 15 minutes were required to prevent reignition.

One observation made was that while the rated low flame spread cables were more difficult to ignite, and fires grew more slowly than in the case of the nonrated cable, once a fully developed fire is present the rated cables are mcre difficult to extinguish than are the nonrated cables. This is reflected in the increased soak time required for the gaseous systems to extinguish, and prevent reignition, of fires involving the rated cables.

Water was more effective as a suppressant than were either of the two gaseous systems tested. With the application of water, a significant heat sink is introduced which quickly acts to cool both the burning cables and the general enclosure environment. With the gaseous systems this heat sink is not as great, and consequently, both the cables and the room air can remain at elevated temperatures for extended periods of time. While the gaseous systems eventually extinguished the test fires, if concentrations were not maintained for fairly long periods, up to 15 minutes, then reignition of the fire was likely upon the reintroduction of oxygen (in the case of carbon dioxide) or the dilution of the suppressant (in the case of Halon). This results from the failure of the gaseous systems to quench the smoldering combustion process typical of deep seated cable fires.

4.4 Detection and Suppression Insights Based on Actual Experience

In conjunction with the Risk Methodologies Integration and Evaluation Program (RMIEP), a data base was compiled documenting the history of

Table 4.1: Summary of Fire Suppression System Effectiveness Study Results. (This table provides the minimum gaseous system soak times and water based system spray times required to suppress a fully developed cable tray fire and prevent reignition.)

Cable Type	Tray Orientation	Fire Suppression System			
		Halon (6%) NFPA-12A	Carbon Dioxide NFPA-12	Sprinklers NFPA-13	Directed Spray NFPA-15
IEEE-383 Rated Low	Horizontal	15 min	15 min	5 min	5 min
Flame Spread	Vertical	15 min	15 min	5 min	5 min
Nonrated	Horizontal	10 min	10 min	5 min	5 min
	Vertical	10 min	10 min	5 min	5 min

reported fire events for commercial nuclear reactors in the U.S.[24] The data base included incidents reported both under the reporting reuqirements of the USNRC, and incidents reported to certain of the nuclear industry insurance interests. While the level of detail provided in the original incident reports varies considerably, for many of the incident reports the method of fire detection and fire suppression is identified. Also included in this data base are 69 incidents in which the actual time required to suppress the fire was included. These incident reports have provided a number of insights into actual circumstances of fire detection and suppression under actual fire conditions.

For those incidents for which the method of detection and suppression is reported, the vast majority involved both manual detection and manual suppression of the subject fire. Only a few fires, the remainder of those events which include such information, have been automatically detected and automatically suppressed. The time required to suppress those fires for which a suppression time is reported ranged from two minutes to over seven hours. These 69 suppression time data points are well represented by a lognormal probability distribution curve. The parameters of this curve, based on a least-squares fit to the linearized log-normal data, are a mean suppression time of 42 minutes, a median suppression time of 20 minutes, a 5th percentile value of 3 minutes, and a 95th percentile value of 150 minutes. The data and the fitted log-normal curve are presented in Figure 4.1 in cumulative probability versus time form.

It should be noted that this suppression probability curve lumps all of the reported incidents into a single curve. This presentation does not include consideration of a number of factors which will influence actual fire detection and suppression times. Among others, these factors include the presence of automatic fire detection and suppression systems in the fire area, the level of training received by the manual fire team, the type of fire source, the location of the fire, and the level of activity associated with the fire area. Such factors can be expected to play a significant role in the actual fire response times to be expected in a given situation. However, there is insufficient data available upon which to base an assessment of the actual impact of these, and other, factors on the probability of fire suppression within any given time frame. This derives largely from the observation, noted above, that most of the fires included in the formulation of this suppression model were manually detected and suppressed. In the performance of a fire risk assessment, one is largely dependent on the use of judgment in the evaluation of such factors.

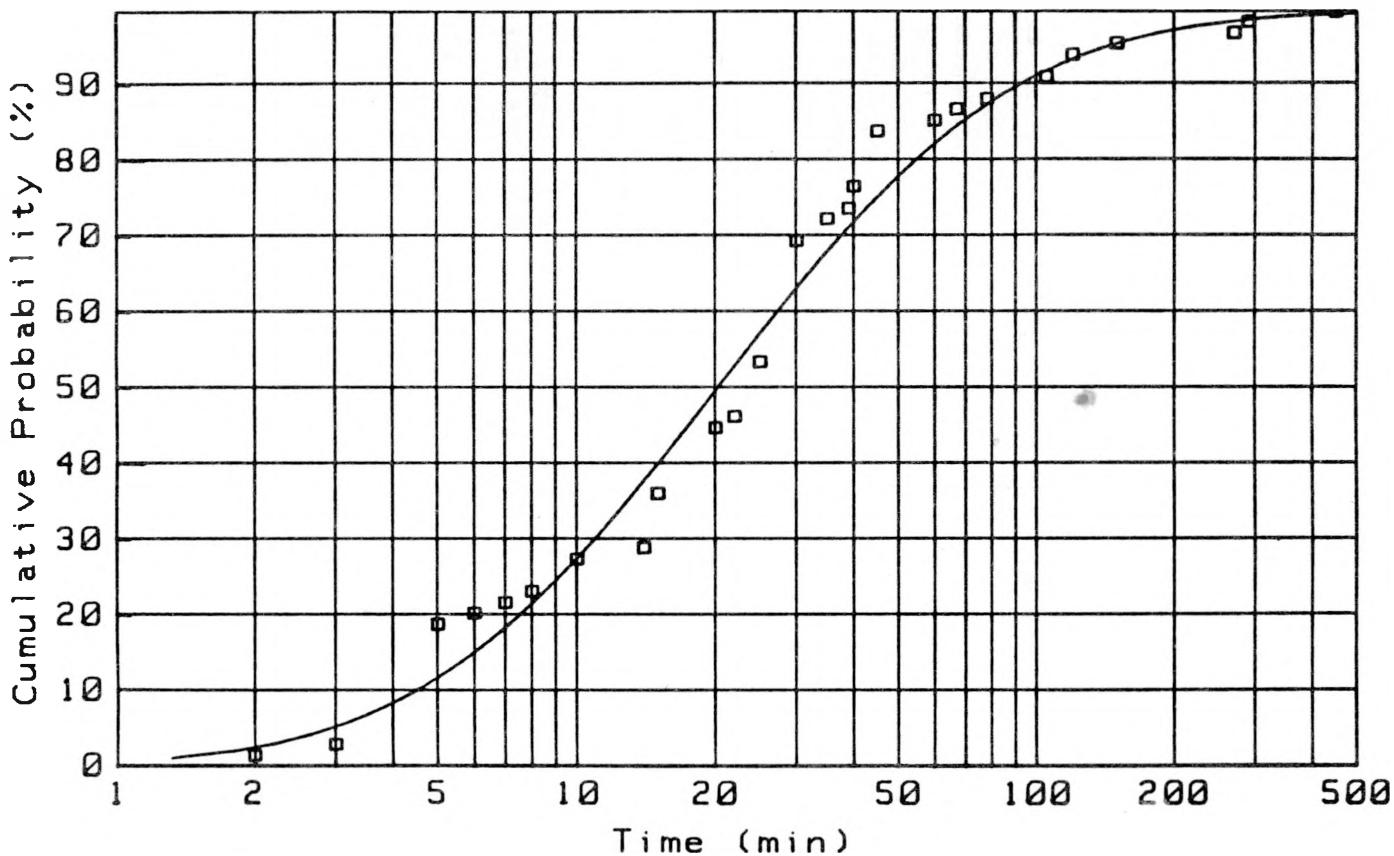

Figure 4.1 Fire Suppression Probability Curve Based On Incidents In the SNL Fire Occurrence Data Base for Which a Time to Fire Suppression is Reported.

5.0 ROOM EFFECTS STUDIES

5.1 Introduction

The adverse impact of a fire can extend well beyond the area of immediate burning and fuel involvement. A fire represents a source of heat, smoke, toxic and corrosive gases, water vapor, and other combustion products. Once released, these products will disperse within the enclosure in which the fire occurs. (These products can also be distributed to other nearby enclosures, though this aspect of the fire problem will be addressed in Chapter 7 of this report.) The various fire products can, in turn, induce damage in equipment not directly involved in the fire. Traditional concerns have focused on the problem of heat, though equipment damage concerns extend to the potential adverse impact of the other combustion products as well.

An understanding of the damaging impact of a fire on equipment operability will be dependant on two factors. First is the behavior of the combustion products in distributing themselves within (and outside) the fire enclosure, and second is the susceptibility of the equipment to damage. This chapter focuses on efforts associated with the characterization of the behavior of fire products in distributing themselves about the fire enclosure. Expressed somewhat differently, this chapter focuses on efforts to characterize the impact of a fire on the environment within the fire enclosure. The investigation of equipment vulnerability issues is discussed separately in Chapter 6.

Three FPRP efforts have, either directly or indirectly, addressed the characterization of enclosure environments during a fire. These three efforts are:

1982	Twenty-Foot Separation Tests
1985	Base Line Validation Enclosure Fire Tests
1985	Electrical Cabinet and Control Room Fire Tests

The principal insights associated with the characterization of enclosure fire environments resulting from each of these three efforts are discussed in turn in the sections which follow.

It should be noted that enclosure fire environment characterization testing is closely linked to efforts to numerically simulate fire environments through the application of computer models. The validation of a fire simulation model is entirely dependant on the availability of appropriate test data. The actual development of fire simulation models has not been a part of the past Sandia FPRP. However, the USNRC did support efforts to develop a complex, three-dimensional, finite difference type "field" model for the evaluation of fire. These efforts were conducted under an independent contract between the USNRC and Brookhaven National

Laboratories. The role of the Sandia FPRP in this code development effort was one of experimental support for code validation. In particular, the Base Line Validation Tests, described below, were performed primarily to provide validation data for use in benchmarking this, and other, fire models. For a further description of the model development effort refer to Reference 31.

5.2 Twenty-Foot Separation Tests

The Twenty-Foot Separation Tests were performed during the early stages of the FPRP in which the primary focus was placed on the investigation of specific regulatory concerns. One of the principal provisions of the BTP 9.5-1, and later of the Appendix R fire protection regulations, requires that equipment associated with redundant safety trains must be separated by a minimum of 20 feet of horizontal space with no intervening combustibles. In addition, under such circumstances, automatic fire detection and suppression systems must be employed as an additional measure of protection. (Exceptions to this regulation are considered on a case by case basis.) A total of 10 large-scale enclosure fire tests were performed in order to assess the adequacy of 20 feet of spatial separation as a fire protection measure.

The regulatory implications of these tests have been discussed in detail in Chapter 2 of this report. The findings of these tests related to the damageability of cables due to hot layer effects are discussed in Chapter 6 below. The discussions which are presented here will focus on the technical aspects of the data gathered as related to the problem of enclosure fire environment characterization.

A test enclosure constructed of concrete block and measuring 25x14x10 feet (LxWxH) with an open door of variable size was used in all tests. (This is with exception to experiment 1, in which the room length was 30 feet, and experiment 4, in which the door was closed.) Four preliminary "Experiments" were performed in order to provide base line information on the enclosure environments to be expected. The source fire in these "Experiments" was comprised of a liquid fuel pool fire measuring 1x5 feet and filled with ten gallons of heptane. Six "Tests" were then performed to evaluate the effectiveness of 20 feet of spatial separation as a means of protecting cables from fire induced damage.

In each of Tests 1-6 two vertical cable trays (representing one of two trains of equipment) were exposed to the same liquid fuel pool fire described above, except that only five rather than ten gallons of fuel were used. A second pair of cables (representing a second equipment train) was located above the door at the opposite end of the test enclosure. These second train cables were not involved in actual combustion.

Testing involved the use of both rated low flame spread and nonrated cables. Each of the two cable types used were tested in each of three modes of cable protection. These three modes of protection were (1) no passive cable protection, (2) protection of the cables with a fire retardant coating, and (3) protection of the cables with an insulating wrap and solid tray covers. In each case both simulated trains of cable were similarly protected.

An extensive array of instrumentation was placed within the test enclosure. Measurements included air temperatures, enclosure surface temperatures, doorway air flow conditions, and heat flux conditions. Figure 5.1 illustrates the placement of instrumentation within the test enclosure.

Table 5.1 summarizes the principal enclosure fire environment severity results for Experiments 1-4. Table 5.2 summarizes these same results for Tests 1-6. Figure 5.2 illustrates the average near ceiling air temperatures measured near the simulated redundant cable trays during Experiments 1-4. Figure 5.3 provides similar information for Tests 1-6. For Experiments 1-4 the maximum recorded air temperatures in the vicinity of the redundant cable trays ranged from 470°F to 660°F (243-349°C). For Tests 1-6 the source fires were somewhat more intense as a result of the additional involvement of the two cable trays simulating the first equipment train. Maximum hot layer temperatures in the vicinity of the simulated redundant cable trays during Tests 1-6 ranged from 660°F to 1050°F (349-566°C).

During the original experiments, no instrumentation was provided for the measurement of the fire heat release rates. However, in the utilization of many enclosure fire simulation models, the heat release rate of the source fire is required as an input. Developers of certain of the fire simulation models had expressed a desire to utilize the data from these tests in the validation of their enclosure fire response models as the enclosure environment characterization data gathered was somewhat unique. This uniqueness results from the construction of the test enclosure, the inclusion of cable trays as a part of the fire source, and the extent of instrumentation included within the enclosure.

In order to facilitate these validation efforts, posttest data analysis was performed to estimate the rate of heat release for certain of the experimental fires. This analysis considered the rates of energy loss from the test enclosure based on measurements of the doorway air flow conditions and the enclosure surface response data in the formulation of an overall enclosure energy balance. In all, data from Experiments 2 and 3, and Tests 1 and 2 was reprocessed.[4]

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4. This is an account of previously unpublished work which has been documented in a letter report to the USNRC dated May 8, 1984.

Table 5.1: Summary of Principal Environment Characterization Results for Experiments 1-4 of the 20-Ft Separation Tests.

	Experiment Number 1	2	3	4
Door Size (WxH, ft)	8x8	8x8	4x8	no door
Room Length (ft)	30	25	25	25
App. Fire Duration (min)	25.4	22.5	21.9	14.0
App. Max Near Cable Tray** Hot Layer Temperature (F)	470	620	660	500
App. Max Lower Cable Tray** Heat Flux (kW/m^2)	5.5	10.0	13.0	8.0
Time to Short Circuit** (min)	NT	10.2*	NF	12.3*
App. Max Doorway Air Velocity				
2 ft Below Top (ft/sec):	2.9	4.4	5.6	NT
2 ft Above Bottom (ft/sec):	1.3	1.6	3.0	NT

* - Failures in Non-IEEE-383 rated cables
** - Refers to Simulated Redundant Trays Above Doorway
NT - Data Not Taken
NF - No Failure Noted

Table 5.2: Summary of Principal Environment Characterization Results for Tests 1-6 of the 20-Ft Separation Tests.

	Test Number					
	1	2	3	4	5	6
Cable Protection*	None	None	Sys 2	Sys 2	Sys 3	Sys 3
Cable Type	UQ	Q	UQ	Q	UQ	Q
App. Max Near Cable Tray** Hot Layer Temperature (F)	1050	850	660	670	710	740
App. Max Lower Cable Tray** Heat Flux (kW/m^2)	36	23	12	14	15	14
Time to Short Circuit (min)**						
Upper Tray:	4.1	12.9	NF	NF	10.7	NF
Lower Tray:	4.4	NF	17.4	NF	12.9	NF
Sprinkler Head Response Time (min):	1.9	3.3	2.8	3.0	2.0	3.2
App. Max Doorway Air Velocity						
2 ft Below Top (ft/sec):	7.4	6.7	5.6	6.0	5.7	5.5
2 ft Above Bottom (ft/sec):	2.9	1.2	2.8	2.3	3.7	4.0

* - Cable Protection Systems Described in Text
** - Refers to Simulated Redundant Trays Above Doorway
NF - No Failure Noted
UQ - Cable Not Qualified by IEEE-383-74
Q - Cable Qualified by IEEE-383-74

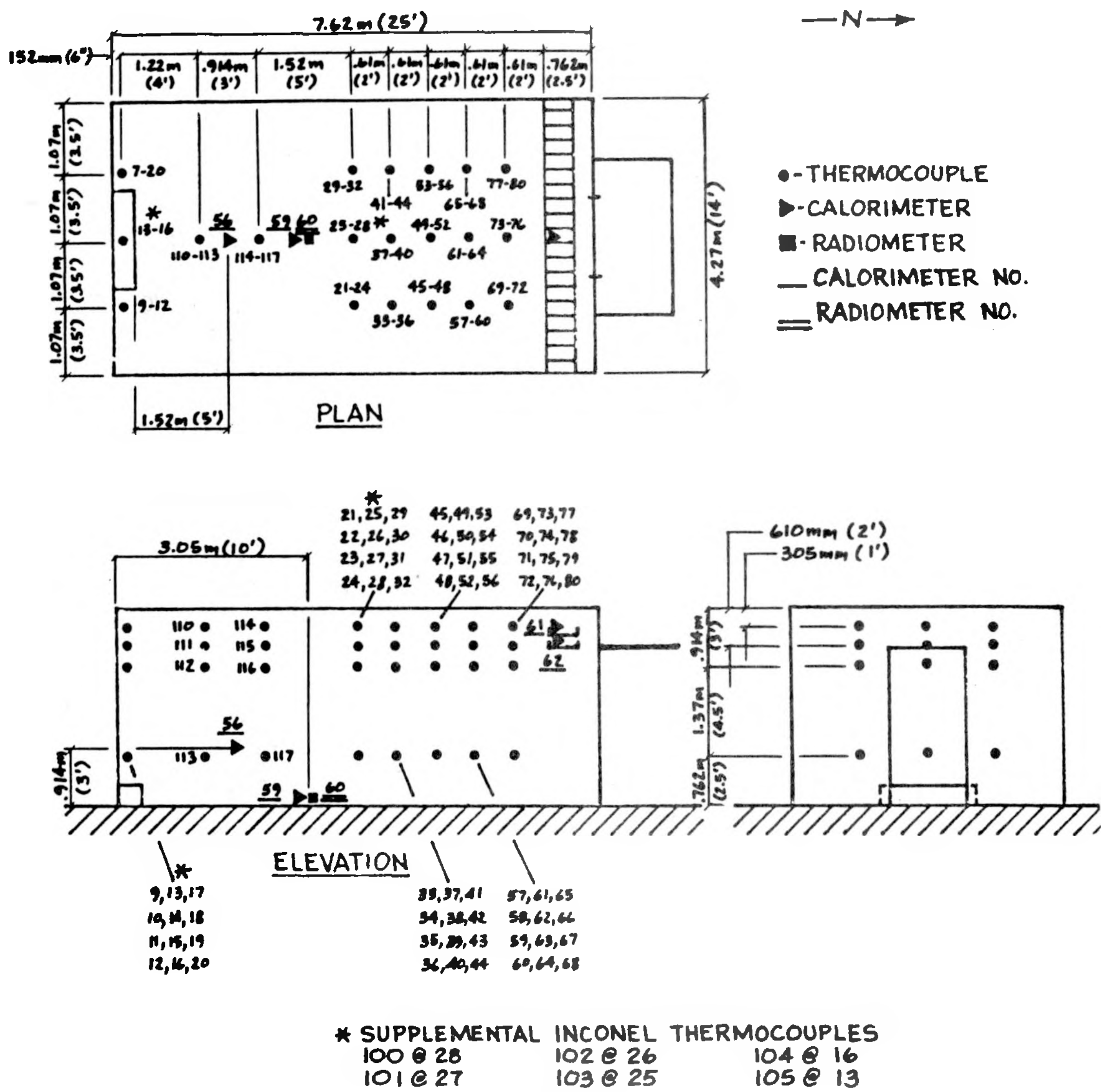

Figure 5.1a Free Standing Instrumentation

Figure 5.1 Instrumentation Placement Used in the Twenty-Foot Tests

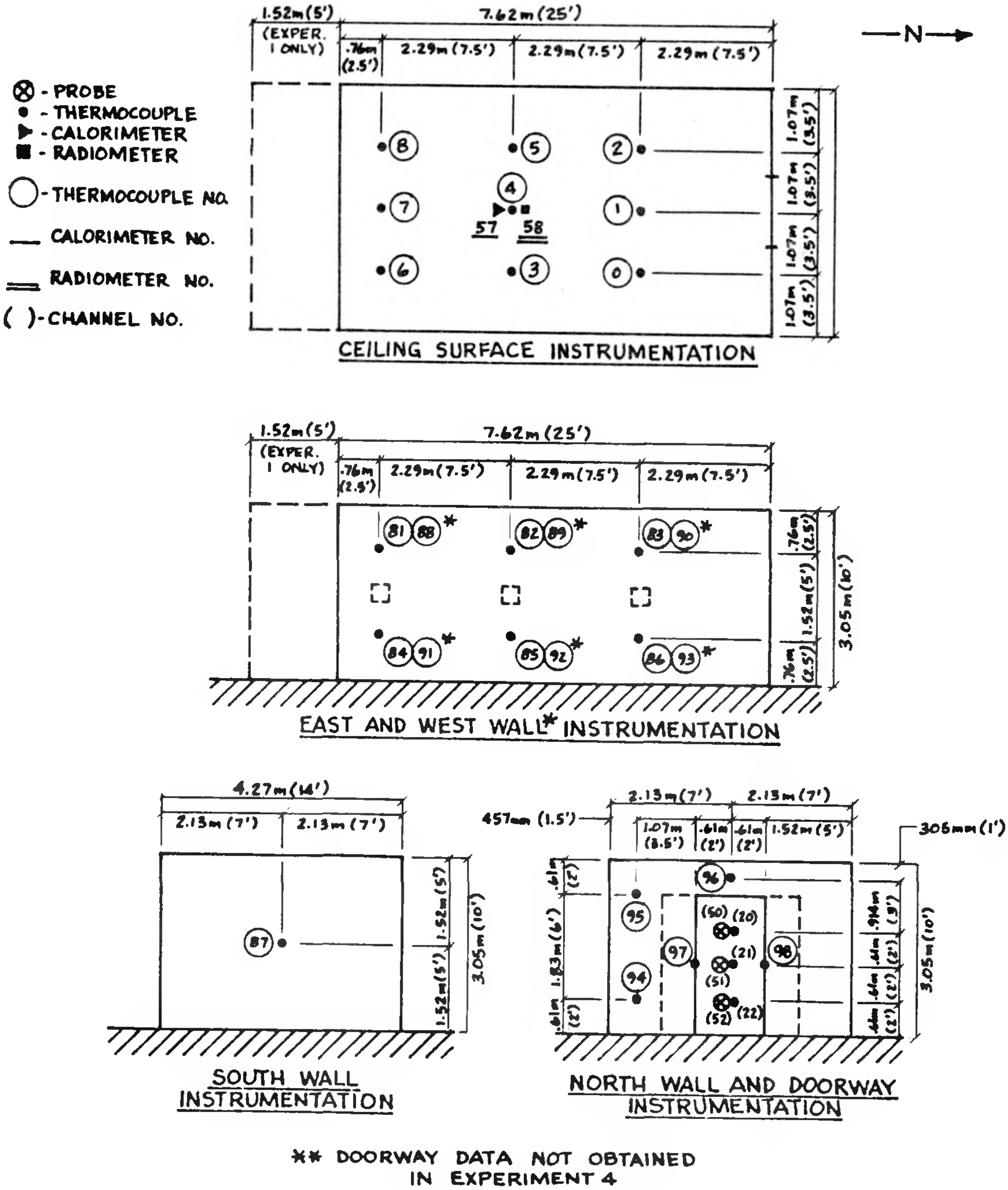

Figure 5.1b Surface Mounted Instrumentation

Figure 5.1 Instrumentation Placement Used in the Twenty-Foot Tests (cont)

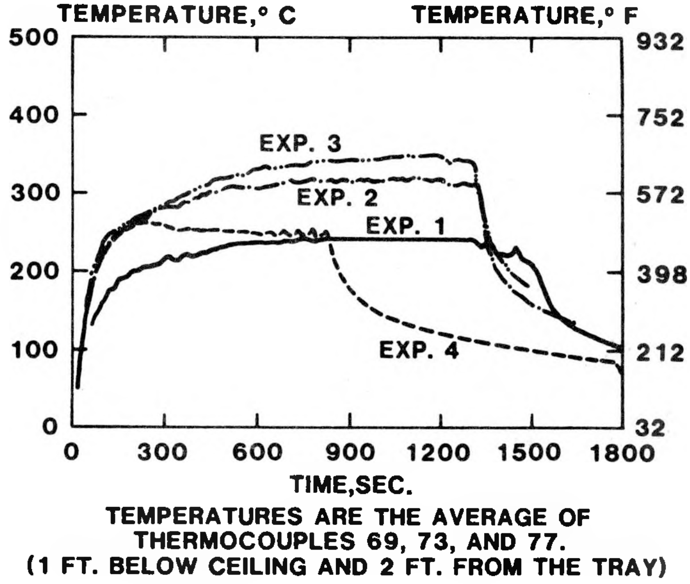

Figure 5.2 Average Temperatures Measured Near the Redundant Train Cable Trays During Experiments 1-4 of the Twenty-Foot Separation Tests

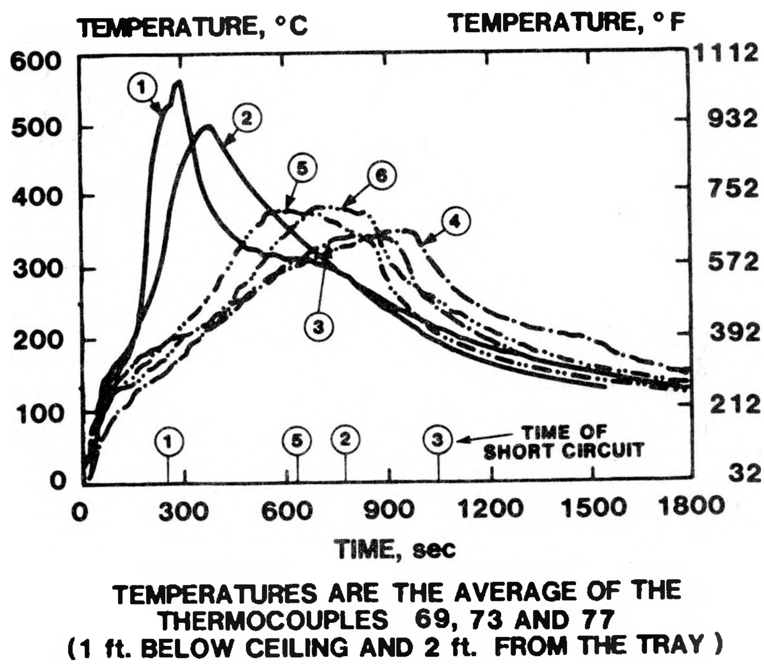

Figure 5.3 Average Temperatures Measured Near the Redundant Train Cable Trays During Tests 1-6 of the Twenty-Foot Separation Tests

Figure 5.4 provides plots of the estimated heat release rates for Experiments 2 and 3, and for Tests 1 and 2. The estimated heat release rates for Experiments 1 and 2 were approximately 550 to 600 kW. As these experiments involved only the liquid fuel pool fire, the heat release rates were relatively constant. The results of the energy balance analysis for these simple liquid fuel pool fires compared well with both analytical predictions of the anticipated pool fire intensity (using the methodology presented in Reference 25), and with separate pool fire tests involving the same fuel source, but for which the actual heat release rates were measured. These results lent confidence to the overall validity of the energy balance method, and to the specific formulation developed.

For Tests 2 and 3, which included the additional fire involvement of two vertical trays of nonrated and rated low flame spread cables respectively, peak heat release rates were estimated to be approximately 850 to 900 kW. Relatively little difference in fire behavior was noted between Test 1, involving nonrated cables, and Test 2, involving rated low flame spread cables. In fact, contrary to what one might expect, the fire in Test 2 grew at nearly the same rate, peaked at a higher intensity, and released more heat overall than did the fire in Test 1. This result reiterates other test results (e.g. the suppression effectiveness tests, and cabinet fire tests described above) in which it has been observed that while more difficult to ignite, once a fire is established in the rated cables, that fire is often more intense, and more difficult to extinguish than a similar fire in nonrated cables.

These tests represent a rather unique data set regarding nuclear power plant enclosure fire behavior. However, the results are limited in several respects. First, heat release rate estimates are available for only four of the ten experimental fires. Second, the room size is typical of only the smallest of enclosures encountered in a power plant. Third, all of the tests were conducted under conditions of natural ventilation (i.e. and open doorway) whereas in a power plant forced ventilation conditions are nearly universal. Each of these limitations was resolved in the performance of the Base Line Validation Tests, which are described immediately below.

5.3 <u>Base Line Validation Enclosure Fire Tests</u>

As a part of the FPRP a series of large-scale enclosure fire tests was performed to provide enclosure fire environment characterization results for use in the validation of computer fire simulation models. These tests differed from previous tests performed, both within and outside the FPRP, in several important respects. First, the test enclosure utilized was considerably larger than any previously used fire test enclosure for which extensive environment characterization information had been gathered. This test enclosure measured 60x40x20 feet (LxWxH) (18.3x12.2x6.1m). Second, all of the tests utilized conditions of forced ventilation typical of those encountered in nuclear power plant enclosures. These ventilation

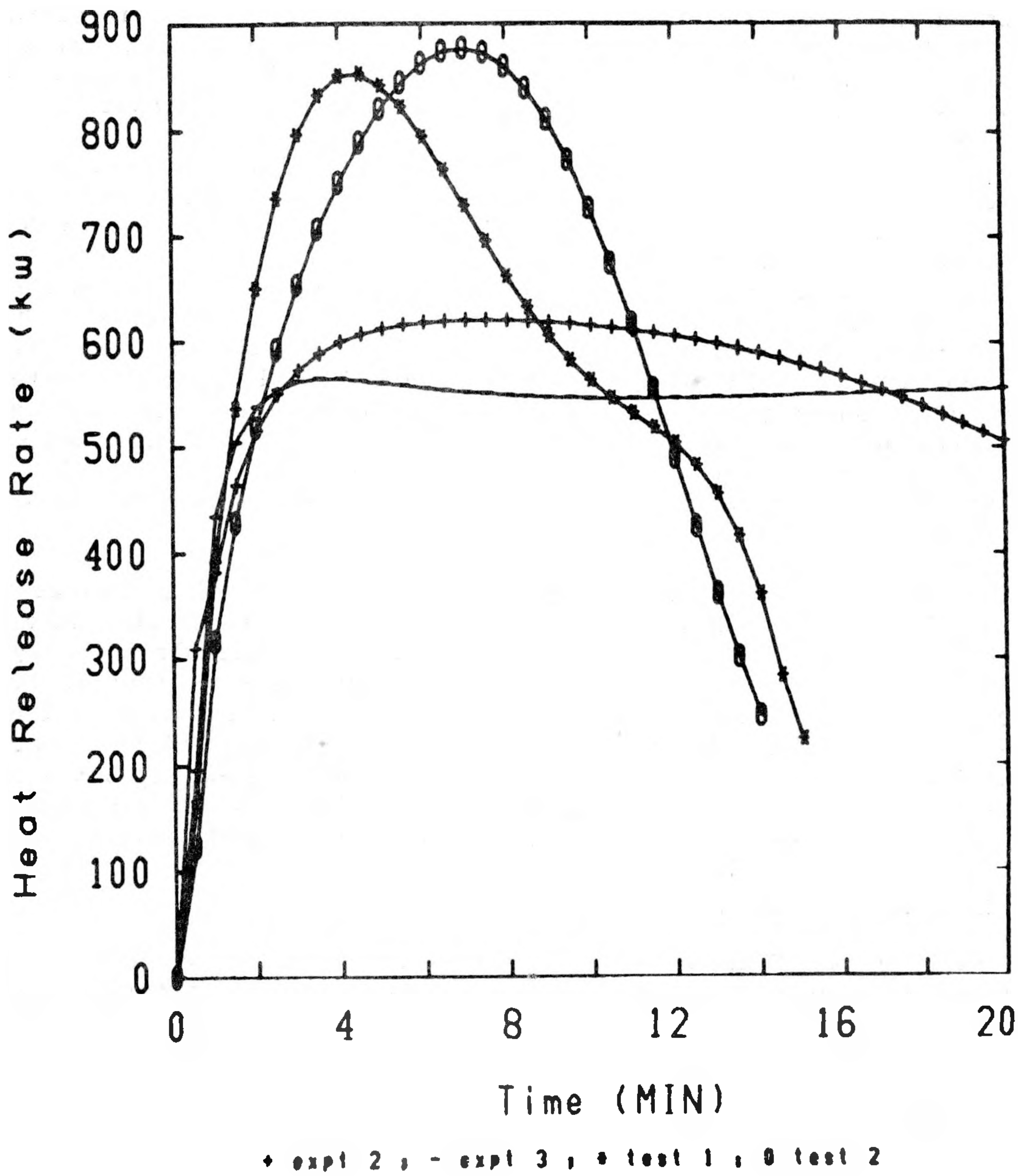

Figure 5.4 Estimated Heat Release Rates for Experiments 2 and 3, and for Tests 1 and 2 of the Twenty-Foot Separation Tests

conditions were varied during testing, and simulated conditions including those typical of control room smoke purging ventilation rates. Third, the tests included the use of a full-scale control room mock-up physical configuration to investigate the effects of internal room partitioning on the room environment. Fourth, the density and variety of instrumentation included as a part of the test program was significantly greater than previously performed fire tests had utilized. This instrumentation density was intended to provide adequate data upon which to base the validation of even the most complex, three-dimensional fire simulations models being developed. Finally, the source fires included a variety of fuels ranging from quite simple liquid fuel pool fires and gas burners to simulated electrical control panels loaded with cable insulation.

Figure 5.5 illustrates the placement of instrumentation within the test enclosure. Measurements included air temperatures based on both bare-bead and aspirated thermocouples, slug calorimeter heat fluxes, concentrations of carbon dioxide, oxygen, carbon monoxide, and total hydrocarbons both within the enclosure and in the exhaust gases, smoke optical densities, and enclosure inner and outer surface temperatures. In all a total of over 300 channels of data were installed. The data for each channel was logged at five second intervals for periods from fire initiation, through natural fire extinguishment, and including a period of post fire cool-down.

A total of 20 Base Line Validation Tests involving simple fuel fire sources were performed. (As will be described below an additional five tests involving a fire source located within a control room panel were also conducted.) Table 5.3 provides a matrix of the simple fuel fire tests performed as a part of the Base Line Validation test effort. Parameters varied during testing were the rate of enclosure ventilation, the intensity of the source fire, the type of fire source, location of the fire source, and the presence or absence of the control room panels.

These tests were performed in the later stages of the FPRP. As a result of the termination of FPRP efforts shortly after the completion of these tests, full processing of the test data has not, to date, been undertaken. Data processing routines have been developed and certain limited data processing has been performed. Table 5.4 provides a summary of certain of the principal results obtained from the limited data processing which has been completed. In addition to these general results, three tests, Tests 4, 5, and 21, have been examined in some detail.[32]

The temperature measurements made within the enclosure illustrate a significant degree of vertical thermal stratification as shown in Figures 5.6 and 5.7. No true hot layer effect was observed in these tests in that the vertical stratification presented a relatively smooth transition from high ceiling temperatures to lower floor temperatures, rather than a near discontinuous jump from the hot to cold layer. This is believed to be at least in part due to the presence and configuration of the forced

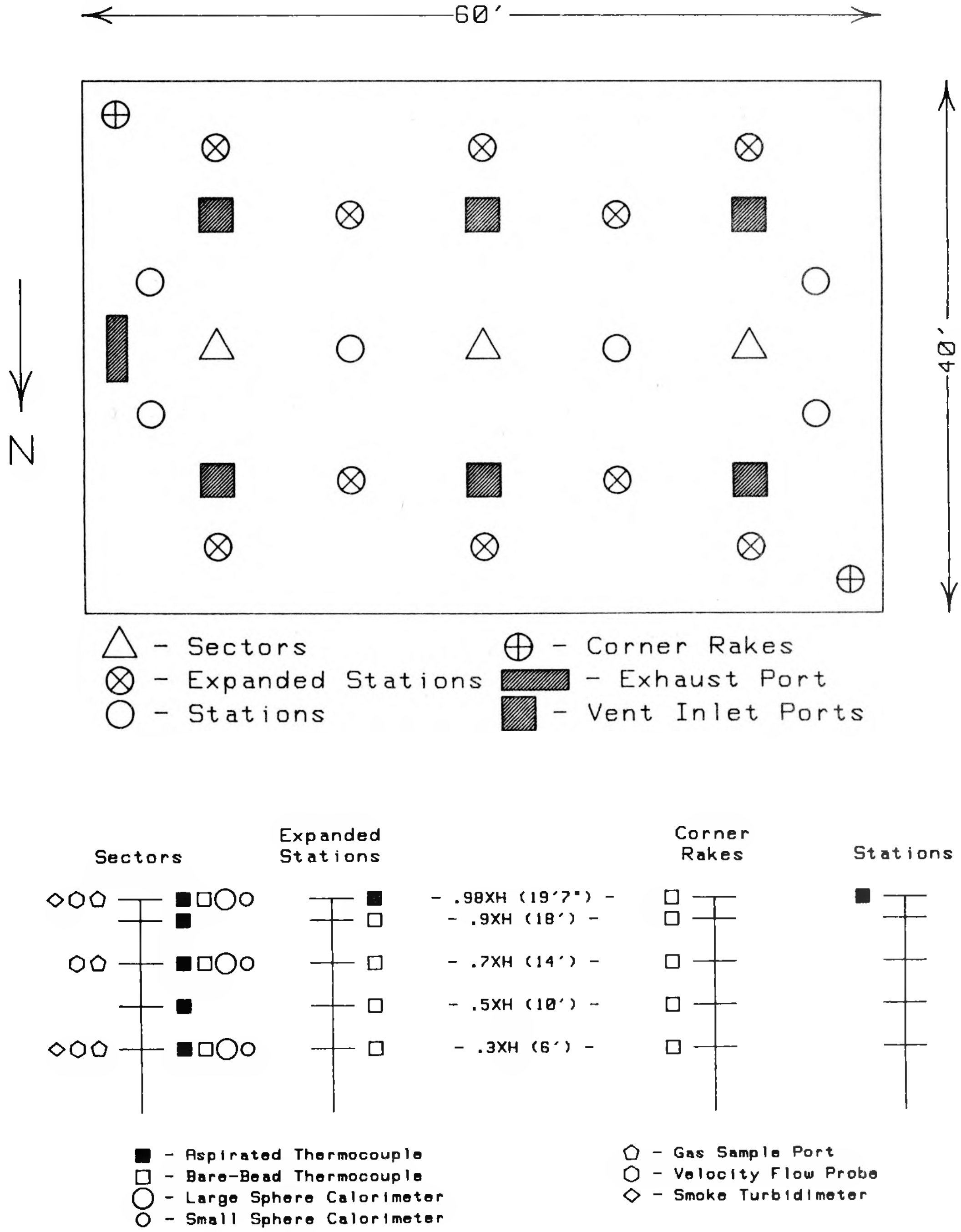

Figure 5.5: Instrumentation Placement Used in the Base Line Validation Tests

Table 5.3: Matrix of Simple Fuel Base Line Validation Tests.

	Test #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Fuel Type	Propylene Burners	X	X	X	X	X		X	X	X									
	Heptane Pool						X				X		X	X		X	X	X	
	Methanol Pool											X			X				
	PMMA Solid Slabs																		X
Nominal Peak Fire Intensity	500 kW	X	X		X	X	X	X				X			X		X	X	
	1000 kW								X	X	X					X			X
	2000 kW			X									X	X					
Fire Location	Room Center	X	X	X	X	X		X	X	X									
	South Wall						X				X	X	X	X	X	X			X
	S-W Corner																X	X	
Nominal Enclosure Ventilation Rate	1 ch/hr (800 CFM)				X		X	X	X						X	X	X		X
	4.4 ch/hr (3500 CFM)										X	X	X						
	8 ch/hr (6400 CFM)									X				X					
	10 ch/hr (8000 CFM)	X	X	X		X												X	
Burner Fire Mode	Steady State Mode	X	X	X				X											
	Growing Fire Mode				X	X			X	X									

Table 5.4: Summary of Principal Results for the Base Line Validation Tests

Test #	Fuel Type *	Vent Rate (ch/hr)	Peak HRR (kW) T = Transient	Peak Non-Flame Temperature (C)	Time For Smoke To Reach The 6' Level (min)
1	P	10	500	120	3.0
2	P	10	500	123	3.0
3	P	10	2000	368	3.0
4	P	1	500 T	133	7.5
5	P	10	500 T	115	6.0
6	H	1	500	106	5.5
7	P	1	500	146	4.5
8	P	1	1000 T	290	8.0
9	P	8	1000 T	229	7.0
10	H	4.4	1000	210	6.5
11	M	4.4	500	121	–
12	H	4.4	2000	332	3.0
13	H	8	2000	304	2.5
14	M	1	500	140	–
15	H	1	1000	121	6.0
16	H	1	500	114	5.5
17	H	10	500	95	4.5
18	S	1	1000 T	130	–
19	H	1	1000	206	3.0
20	H	8	1000	245	3.0
21	P	1	500 T	146	6.2
22	P	1	1000 T	164	7.2
23	C	1	1250 T	262	7.0
24	C	1	1350 T	237	5.0
25	C	8	800 T	82	5.0

* – P = Propylene Burner
H = Heptane Pool
M = Methanol Pool
S = PMMA Solid Slabs
C = Cable Loaded Cabinet

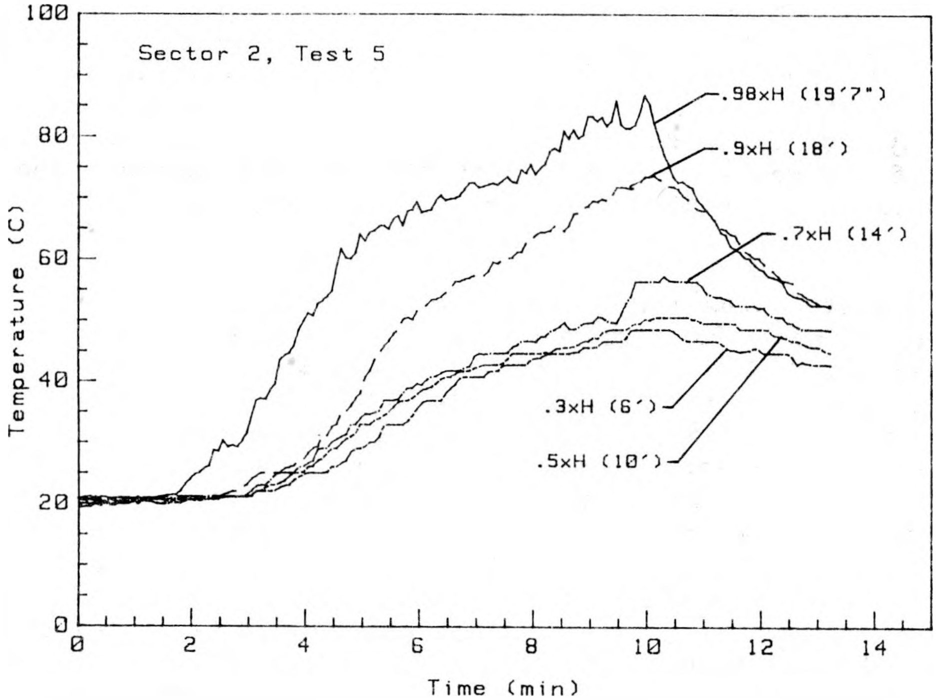

Figure 5.6 Temperature Versus Time with Elevations as the Curve Parameter at the Room Center Instrument Tree (Sector 2) During Base Line Validation Test 5

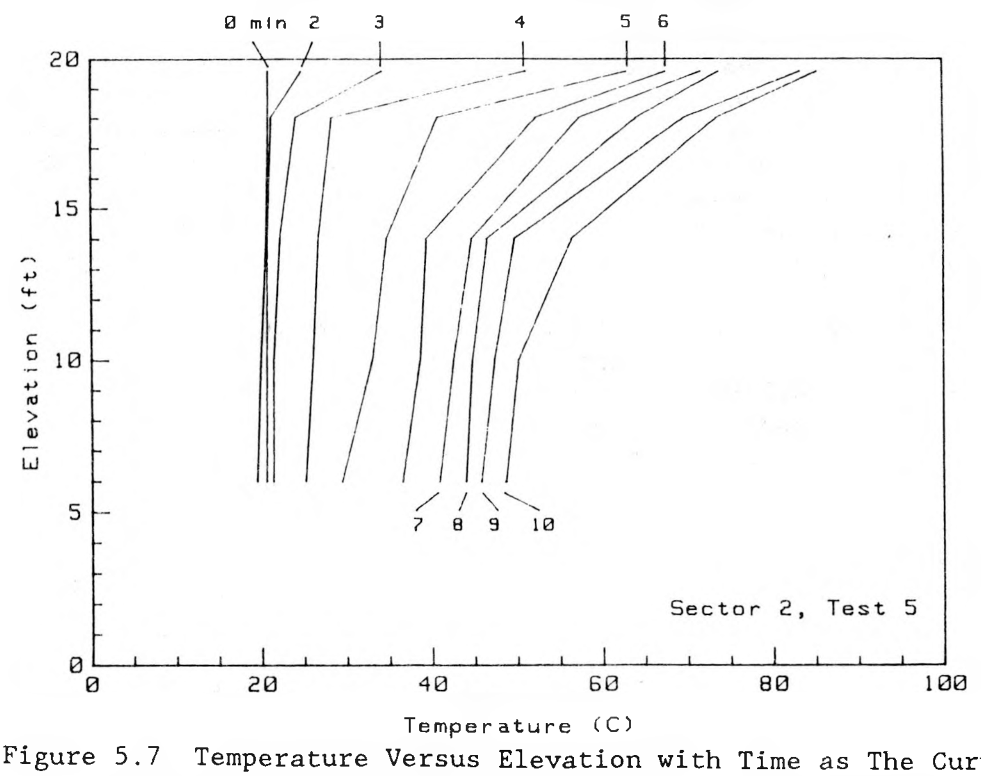

Figure 5.7 Temperature Versus Elevation with Time as The Curve Parameter at the Room Center Instrument Tree (Sector 2) During Base Line Validation Test 5

ventilation system, which presumably enhanced the level of mixing within the enclosure. Furthermore, it was observed that the level of the ventilation inlets represented somewhat of a physical layer boundary in that temperatures above the level of the ventilation inlet ports were significantly higher than those below the inlets as shown in Figures 5.6 and 5.7. This observation would tend to imply that in the application of zone or layered fire models, it might be more accurate to provide for a dividing of the hot layer itself into two separate layers. The level of this division would be determined by the configuration of the ventilation system.

A second important observation was that in virtually all of the tests, a dense layer of smoke was observed to fill the test enclosure from floor to ceiling within 5-15 minutes of fire initiation. This smoke layer completely obscured any visibility in the room. Even the fire could not be seen once this smoke layer had descended, and in some cases the fire source was as little as 12 feet from an observation window. Forced ventilation rates as high as 10 room air changes per hour were not sufficient to maintain visibility in the test enclosure. These conditions can be expected to severely hamper manual fire fighting efforts, as well as limit the ability to perform plant operations (either in the control room or in remote fire areas) even given that a self contained breathing apparatus is available. (The only tests in which a smoke layer did not form were those involving a methanol pool or the PMMA[5] solid, both of which are very clean burning fuels.)

Processing of the data from these tests has also led to the development of an extension to the traditionally employed carbon dioxide calorimetry heat release rate calculation methodology. The rate of heat release is one of the most important characteristics of a fire. In experimentation the rate of carbon dioxide generation by a fire has been used extensively to provide an estimate of the rate of heat release based on a thermal balance for the exothermic conversion of a carbon chain to carbon dioxide. However, the large size of the test enclosure used in these tests introduces unique difficulties in the application of carbon dioxide generation calorimetry techniques. The technique requires that one accurately estimate the time dependant rate of carbon dioxide generation. Under most typical test conditions, this rate is estimated based on measurements of the composition of the gases exiting the test enclosure. However, with the large test enclosure utilized here, accumulation of fire products within the room would result in the underestimation of fire intensity by as much as 60% under this simplistic approach.

As a part of the data processing, a methodology was developed in which the measurement of gas concentrations made at nine locations within the test enclosure were utilized to estimate the time dependent rate of fire

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5. Poly-methyl-methacrylate, or more commonly, plexiglass.

products accumulation within the test enclosure. The heat release rates of the test fires can then be estimated based on both the outflow gas conditions, and the rate of enclosure accumulation. Figure 5.8, described below, illustrates the results obtained using this enhanced methodology. The enhanced carbon dioxide generation based calculations follow closely the expected burner profile during both the transient and steady state periods of combustion. Of particular interest is the accuracy with which the sudden cut off of the gas burner is reflected in the carbon dioxide calorimetry based intensity estimates. One should also note that the methodology developed would be equally applicable to estimation of heat release rates by oxygen consumption calorimetry as well.

The data available from these tests represents a truly unique data set. No other large-scale enclosure fire experimental effort, either within or outside the FPRP, has provided the level of instrumentation in an enclosure of the size used in these tests, nor explored the variety of nuclear power plant enclosure fire issues which were investigated here. The available data could go a long way towards resolving many of the uncertainties currently associated with the simulation of nuclear power plant fire enclosure fire effects. However, a number of enclosure fire questions would still remain unaddressed. These include room to room spread of fire and/or smoke though ventilation connections and open doorways, the effects of room partitioning and ceiling soffits on the fire environment, the effectiveness of dedicated smoke removal and smoke control systems (such systems are not currently employed in U.S. reactors), the impact of smoke on operator and fire brigade performance, and the responsiveness of fire detection and suppression systems in very large enclosures.

5.4 Cabinet and Control Room Fire Tests

The cabinet fire test program was conducted in two phases. The tests conducted under the first phase investigated the effects of various cabinet parameters on the development of an electrical control panel fire (reference A-56). These tests were conducted at the SNL Fire Test Facility, which measures 24x25x18 feet (7.3x7.6x5.5 meters) (LxWxH). In the second phase of the cabinet fire test program [30] a series of five electrical control panel fire tests were conducted using the same test enclosure and test instrumentation as that described in Section 5.3 above in conjunction with the Base Line Validation Tests. The enclosure used for these second phase tests was quite large, measuring 60x40x20 feet (18.3x12.2x6.1 meters).

Of particular interest to the present discussion is the data associated with characterization of the enclosure environment which was gathered during these tests. The discussions which follow will focus on the second phase tests for several reasons. First, the density and variety of enclosure instrumentation provided in the second phase tests was much more extensive than that of the first phase tests. Second, the test enclosure for the second phase tests was much larger than that used in the first phase tests, and was more typical of nuclear power plant enclosure dimensions. Third, the second phase tests were conducted with a full-scale control room panel physical mock-up in place in the test enclosure. Fourth, the ventilation configuration used in the second phase tests was more typical of that found in a nuclear power plant. It was, in fact, the specific objective of the second phase tests to explore the impact of a cabinet fire on the environment of a typical nuclear power plant enclosure.

Five cabinet fire tests were conducted as a part of the second phase tests. Two of these five tests, Tests 21 and 22, involved the use of a gas burner placed within a cabinet shell. The gas burners were controlled with a pre-programmed burning rate. The remaining three tests involved the burning of an electrical control panel loaded with cable. Two of these three cable tests utilized a benchboard cabinet, Test 23 involving IEEE-383-74 rated low flame spread cables, and Test 24 involving nonrated cables. The third cable test, Test 25, involved nonrated cables in a vertical cabinet. In both of the nonrated cable fire tests, the fire was electrically initiated using the apparatus described in Section 3.5.1. (This apparatus simulates a faulty terminal block connection generating 200 watts of heat at less than 15 amperes.) The single test involving rated low flame spread cables was initiated using a simulated transient fuel source comprised of a small plastic bucket, laboratory wipes, and one quart of acetone. The experimental conditions for each of these five cabinet fire tests are summarized in Table 5.5. Figures 5.9 through 5.13 illustrate the measured rate of heat release for each of the five cabinet fire tests.

The findings with respect to the enclosure environment observed during the second phase cabinet fire tests can be summarized as follows:

1. Peak temperatures at the ceiling of the enclosure directly above the cabinet fire were observed to reach as high as 262°C (504°F).

2. Outside of the immediate vicinity of the fire plume enclosure temperatures for a fire confined to a single cabinet were observed to reach no higher than 150°C in this large test enclosure. (Caution must be exercised in extrapolating these results to smaller enclosures, or to situations in which electrical panels form the equivalent of a smaller enclosure through internal room partitioning often employed as a part of ventilation system design).

3. The build-up of smoke in the test enclosure was in all cases found to be a significant problem. Typically, within 6-15 minutes smoke had totally obscured visibility throughout the test enclosure from ceiling to floor. Smoke purge ventilation rates as high as 10 room air changes per hour were ineffective at maintaining even minimal visibility.

Table 5.5: Matrix of Control Room Fire Tests.

	Test #	19	20	21	22	23	24	25
Fuel Type	Propylene Burner			X	X			
	Heptane Pool	X	X					
	Cable Loaded Cabinet					X	X	X
Nominal Peak Fire Intensity	500 kW			X				
	800 kW							X
	1000 kW	X	X		X			
	1300 kW					X	X	
Fire Location	Room Center	X						
	South-West Corner		X					
	Benchboard Cabinet 'A'			X	X	X	X	
	Vertical Cabinet 'C'							X
Nominal Enclosure Ventilation Rate	1 ch/hr (800 CFM)	X		X	X	X	X	
	8 ch/hr (6400 CFM)		X					X
Gas Burner Fire Mode	Steady State Mode							
	Growing Fire Mode			X	X			

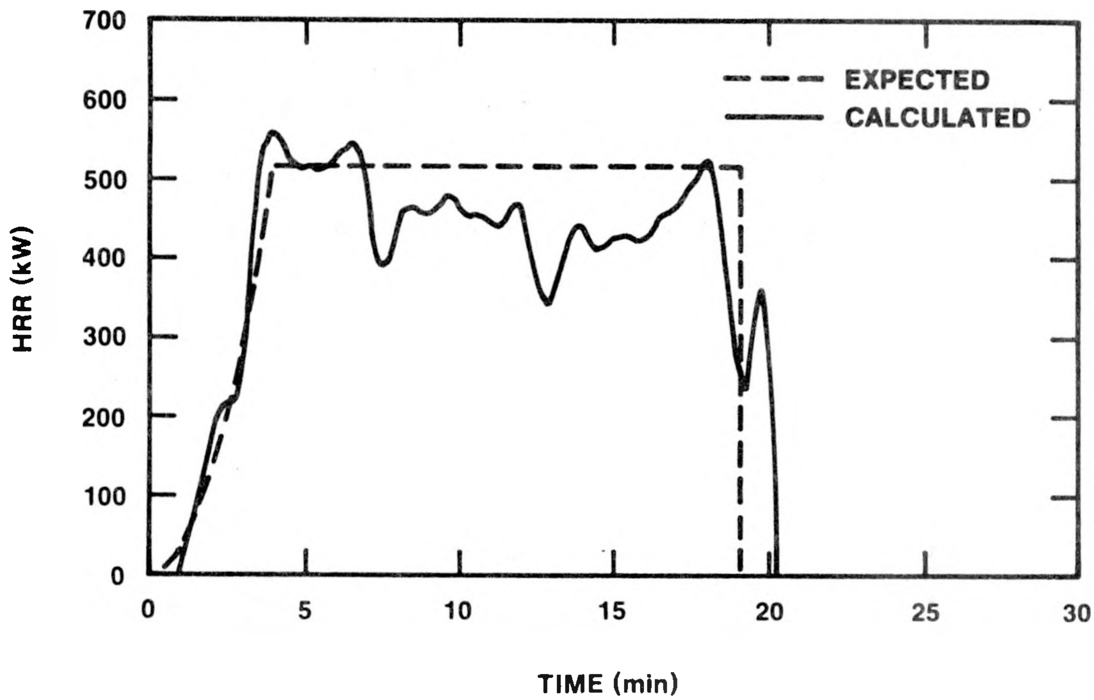

Figure 5.8 Heat Release Rate for Control Room Fire Test 21

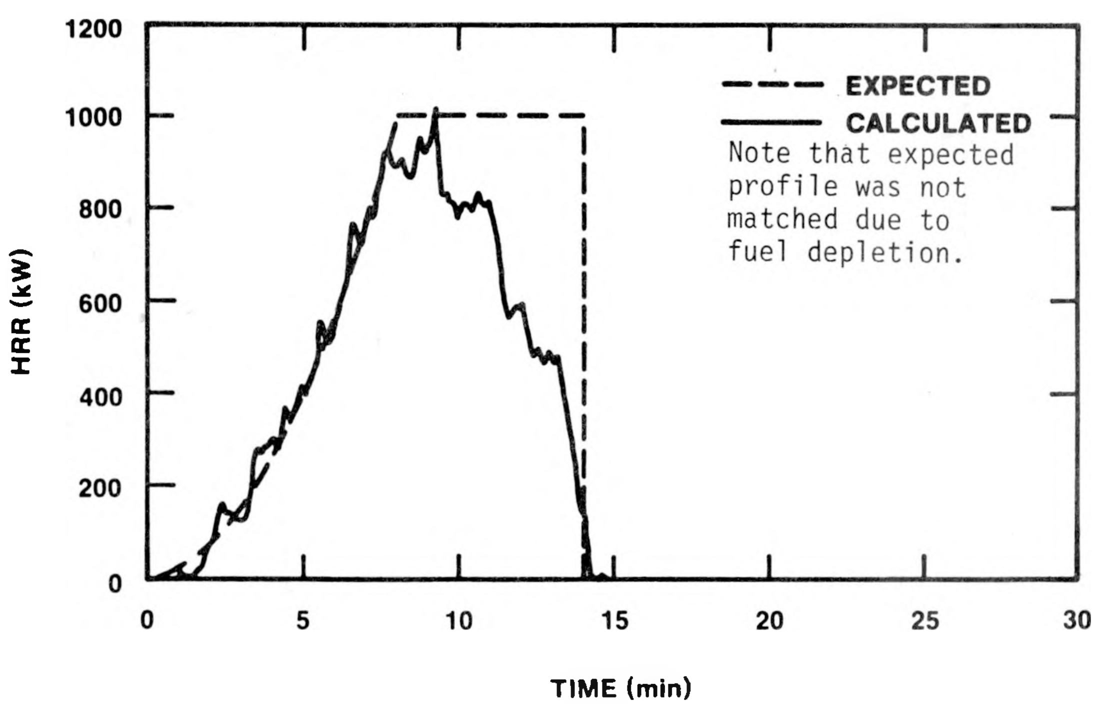

Figure 5.9 Heat Release Rate for Control Room Fire Test 22

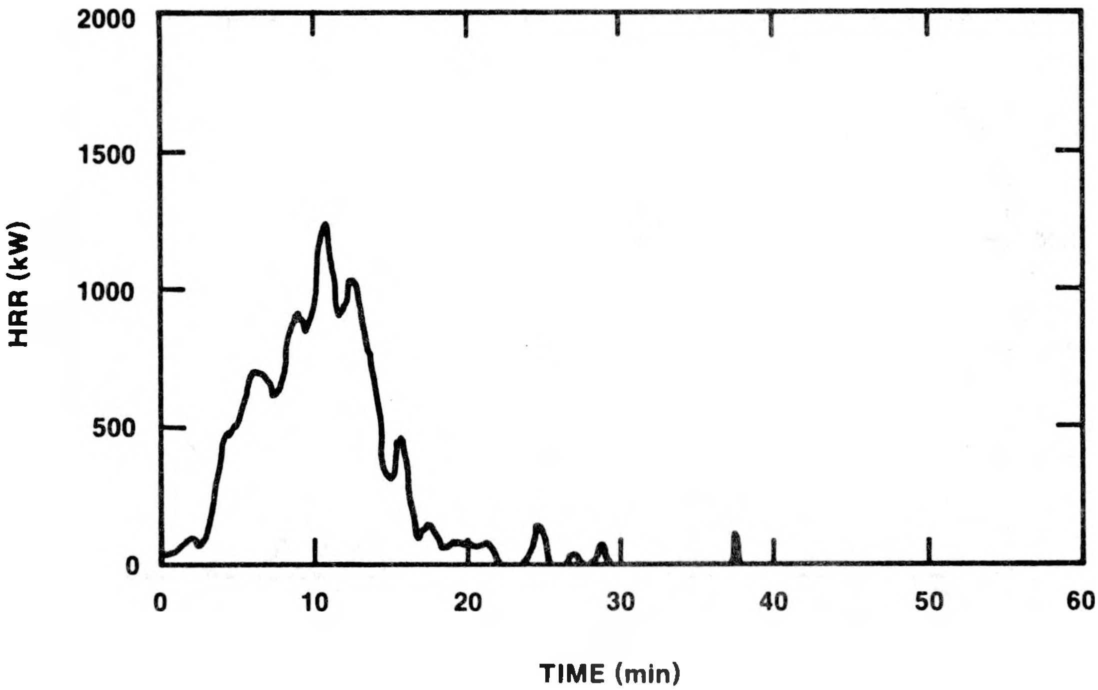

Figure 5.10 Heat Release Rate for Control Room Fire Test 23

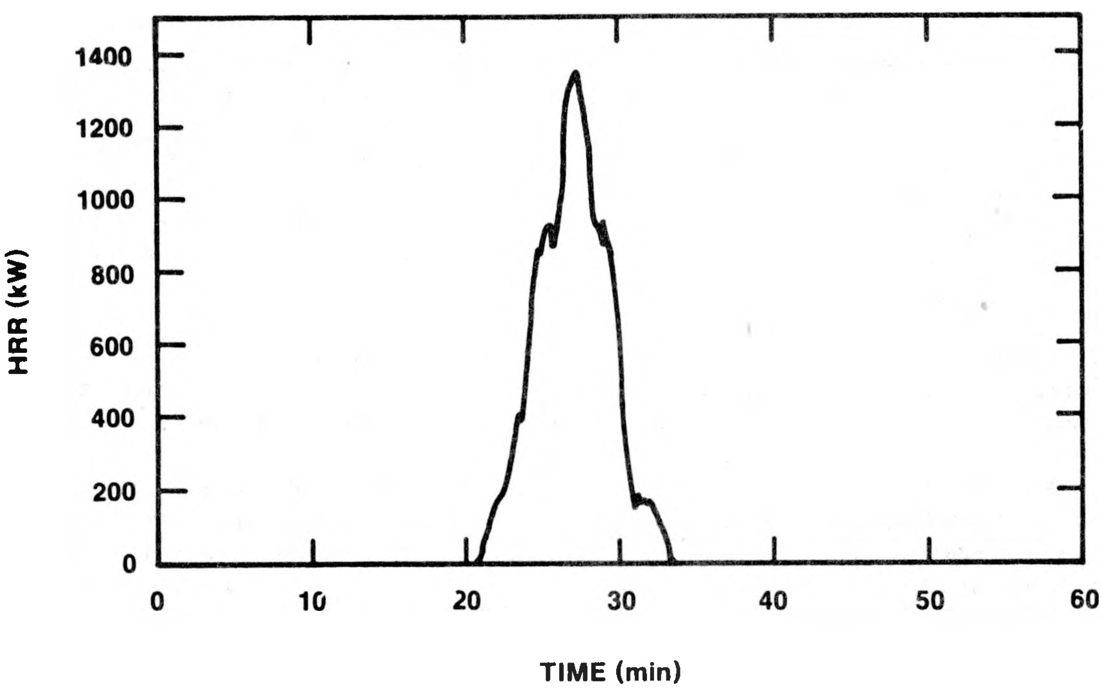

Figure 5.11 Heat Release Rate for Control Room Fire Test 24

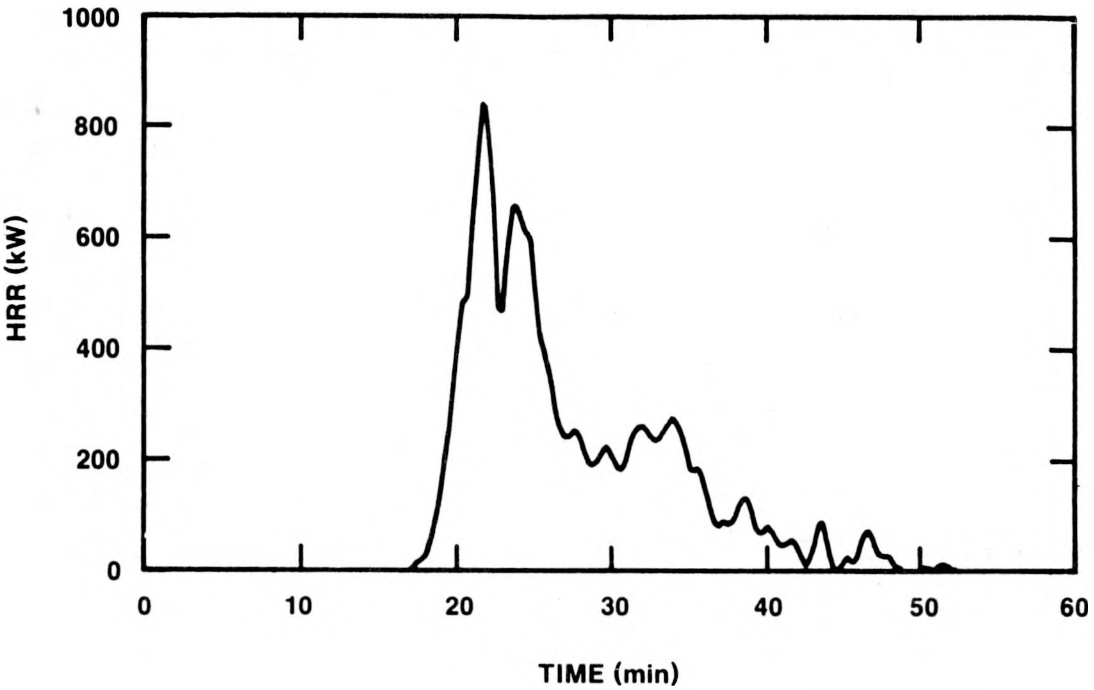

Figure 5.12 Heat Release Rate for Control Room Fire Test 25

4. Heavy depositions of soot were observed throughout the test enclosure, including within closed cabinets not involved directly in the fire. In the case of fires involving polyvinyl chloride (PVC) cables, this soot was found to be heavily laden with chlorides. If the soot deposits are wetted, possibly by suppression water, equipment could be exposed to a conductive, and highly corrosive solution. (This is discussed in more detail in Chapter 6 below.)

These tests explored the impact of a fire confined to a single cabinet on the environment of a large enclosure. In general it was found that the enclosure environments experienced would not represent a thermal threat to most types of plant equipment, with the possible exception of sensitive electronic equipment. However, other adverse environmental effects were noted. In particular, smoke buildup and deposition within the enclosure was quite severe. These tests did not explore the potential for the spread of fire to more than a single cabinet, nor to cable trays either above or below a burning cabinet. The presence of such fire spread paths may be likely, and hence, a cabinet fire may grow well beyond the bounds to which the fires in these tests were confined. Such fire growth would result in fire environments much more severe than those encountered here.

The available data from the Cabinet and Control Room Fire Tests is of equal quality and completeness to that gathered during the Base Line Validation Tests. Thus, this data represents a unique source of enclosure fire environment characterization information. The Cabinet and Control Room Fire Tests, in particular, provide data on the response of a large forced ventilated enclosure to a fire which is confined within a metal cabinet, and hence, produces relatively little radiative thermal input into the fire environment. Three out of the five cabinet tests involved the uncontrolled burning of actual lengths of insulated cables and can be considered characteristic of the behavior to be expected of an actual cabinet fire, which remains confined to a single cabinet. The level of instrumentation employed in these tests has provided for the accurate estimation of the actual heat release rates experienced during these tests. The availability of this heat release rate information will provide for the minimization of actual fire growth and fire intensity modeling uncertainties. This will allow fire modelers to focus on the other aspects of the fire model, such as the distribution of heat within the enclosure and the modeling of hot layer effects, somewhat independent of the estimation of fire intensity.

6.0 EQUIPMENT RESPONSE STUDIES

6.1 Introduction

The concerns of fire safety in a nuclear power plant extend beyond the actuarial and life safety concerns which dominate traditional applications. For a nuclear power plant the ability to maintain safe operation or to achieve and maintain safe shut down of the reactor itself is of paramount concern. This operational ability will be dependant on the availability of undamaged plant equipment and systems during and after a fire event. Thus, in the consideration of fire protection measures, and in the analysis of fire risk, an understanding of the impact of a fire on the operability of plant equipment is needed. From this perspective, a fire represents a source of adverse environmental effects which may degrade the operability of plant equipment. Equipment operability concerns are broader in context and extent than the traditionally considered issues of material ignitability and flammability. The impact of secondary fire effects (e.g., heat, smoke, corrosive products, suppression effects) are also of potential concern. These secondary effects hold the potential to render plant equipment inoperable, even though that equipment may not actually burn.

As a part of the FPRP, only limited equipment vulnerability investigations have been undertaken. Many of the early investigations do provide certain limited insights into equipment vulnerability, though this was not typically the primary concern of these early, i.e., regulatory issues, investigations. As a part of more recent efforts, initial attempts were undertaken to investigate equipment vulnerability issues. The specific efforts which provide such insights, and which will be discussed in the sections which follow, are:

1976-81	Cable Tray Fire Testing:
	Fire Retardant Cable Coating Tests
	Cable Tray Fire Barrier Tests
1981	Cable Radiant and Convective Heating Damage Tests
1982	Twenty-Foot Separation Tests
1984	Cable Steady State Thermal Damage Tests
1985	Cable Transient Thermal Damage Tests
1985	Equipment Damage Sensitivity Ranking Study
1985	Relay Thermal Damage Tests
1985	Component Testing in Secondary Fire Environments

6.2 Investigation of Cable Fire Vulnerability

Data on the thermal damageability of cables represents the majority of information which has been gathered with regards to the vulnerability of equipment to fire induced damage. This holds true for both efforts conducted within and outside the SNL/USNRC FPRP. Cables have been the focus of research for a number of reasons. Two to the most significant of these reasons are (1) the high level of interest in the overall problem of fire safety for cable installations which developed in the wake of the 1975 cable fire at the Browns Ferry Reactor site, and (2) the fact that fire vulnerabilities at cable pinch points such as the cable spreading room or cable tunnel often represent significant contributors to fire risk and to overall plant risk.

Under the FPRP, data on cable thermal damageability has been gathered, either directly or indirectly, as a part of several efforts. These efforts are:

1976-81	Cable Tray Fire Testing:
	Fire Retardant Cable Coating Tests
	Cable Tray Fire Barrier Tests
1981	Cable Radiant and Convective Heating Damage Tests
1982	Twenty-Foot Separation Tests
1984	Cable Steady State Thermal Damage Tests
1985	Cable Transient Thermal Damage Tests

The 1976-81 Cable Tray Fire Tests were conducted during the early stages of the FPRP during which specific regulatory concerns were being investigated. As a part of these tests some information on the limits of thermal operability for a limited selection of cable types was gathered. This is also true of the Twenty-Foot Separation Tests. The 1981 Cable Radiant and Convective Heating Damage Tests were the first FPRP effort to specifically investigate the operability limits of cables. The 1984 Steady State Thermal Damage Tests were conducted as a part of more recent FPRP efforts, and investigated the limits of thermal damage under constant temperature exposure conditions. The final effort, the 1985 Cable Transient Thermal Damage Tests, were performed in an attempt to reproduce, in a simulation chamber, the damage conditions which had been observed in the Twenty-Foot Separation Tests. These tests also assessed the impact that initiation of fire suppression would have had on the observed damage had active suppression been employed.

6.2.1 Cable Tray Fire Testing

As originally conceived, the FPRP investigated a variety of regulatory questions associated with nuclear power plant fire safety. Many of the questions raised were associated with the general problem of fire safety for cable tray installations. As a part of certain of these early cable tray fire test efforts, the vulnerability of cables to fire induced damage was also investigated. It should be noted that the damageability aspect of these tests was only a secondary concern. These tests were primarily concerned with issues of fire initiation and fire growth in cable tray installations. However, certain insights were gained from the limited damageability information which was gathered. Those cable tray fire efforts which did include some investigation of fire induced cable damage were the Fire Retardant Cable Coating Tests, and the Cable Tray Fire Barrier Tests.

Testing under each of these two programs involved the use of three cable types. The first was an XPE insulated IEEE-383-74 rated low flame spread cable (described as cable #5 in Table 3.1 above). The second was a PE/PVC insulated cable which was nonrated (described in Section 3.4.4 above). Both of these cables were 12AWG 3-conductor power cables. The third cable was a single conductor 12AWG XPE insulated rated low flame spread power cable (described as cable #4 in Table 3.1 above).

Of the Fire Retardant Cable Coatings Tests conducted, those of interest here are the single tray gas burner exposure tests and the two tray diesel fuel fire exposure tests. In the single tray gas burner tests, a single horizontal loaded cable tray was exposed to an external fire source comprised of a pair of IEEE-383 type standard gas burners. These two burners were cycled in five minute on-five minute off burner cycles until a sustained fire was established in the exposed cable tray. In the two tray diesel fuel fire tests, a stack of two horizontal loaded cable trays was exposed to an external fire source comprised of a diesel fuel pool fire. These fire exposure conditions have been described previously (see Chapter 3).

Of the fire barrier tests, those of interest here are the single tray gas burner exposure fire tests. These tests were performed in essentially the same manner as the single tray fire retardant coatings tests. However, rather than fire retardant coatings, five types of passive fire protective barrier systems were evaluated.

The two tray gas burner fire retardant coatings and barrier tests performed are of limited interest to the current discussions due to the constraints placed on the fire exposure of the upper tray (as described in Chapter 3 above). In these tests the upper tray was protected from exposure to the external fire source by a nonflammable barrier during the repeated gas burner fire cycles. It was intended that this limitation to the upper tray exposure would simulate the conditions of a self-ignited cable tray fire, rather than exposure fire conditions. As a result of this limitation to upper tray exposure, only one case of electrical faulting was observed.

Tables 6.1, 6.2, and 6.3 summarize the damageability results for the single tray gas burner fire retardant coatings tests, the two tray diesel fuel fire retardant coatings tests, and the single tray fire barrier tests, respectively. Presented are the times to observed electrical failure for each test, and in the case of the two tray tests, for each cable tray. These results illustrate that the various passive fire protective measures employed did delay the onset of electrical damage. This is with the exception of the nonrated cable tests involving the various fire barrier systems in which no delaying of electrical failure was noted. The effectiveness of the different measures varied significantly. Even for a given measure, e.g. coatings, different products performed differently. For the less severe gas burner exposure tests, many of the protective measures successfully prevented electrical faulting completely. However, as illustrated by the diesel fuel fire tests, none of the measures can be expected to prevent electrical faulting under more severe exposure fire conditions.

Table 6.1: Summary of Single Tray Gas Burner Cable Fire Retardant Coatings Test Results. (Note that these tests used 3 different types of cables as described in text.)

Cable Type: Coating Designator	Failure Time* (min)
IEEE-383 Rated XPE 3-Conductor:	
No Coating	9
Coating A	26
Coating B	NF
Coating C	15
Coating D	NF
Coating E	NF
IEEE-383 Rate XPE Single Conductor:	
No Coating	5
Coating A	NF
Coating B	NF
Coating C	24
Coating D	NF
Coating E	NF
Nonrated PE/PVC 3-Conductor:	
No Coating	6

* 'NF' Indicates no failure observed within 60 minutes.

These tests illustrate that some measure of operability protection can be gained for cable tray installations through the application of passive fire protective features. However, these measures do not entirely eliminate the problem of potential electrical damage for cable tray installations. The testing clearly demonstrates the variability between various protective features, and the continued potential for damage even when passive protection is employed. These tests did not consider such factors as coating thickness, ampacity, durability, aging, asbestos content, potential chemical interactions with the cable materials, ease of application, and cost. In practical applications all of these factors must be considered.

Table 6.2: Summary of Two Tray Diesel Fuel Cable Fire Retardant Coatings Test Results. (Note that these tests used a nonrated PE/PVC 3-conductor cable.)

Coating: Tray:	Failure Time (min)
Coating A:	
Lower Tray:	10
Upper Tray:	11
Coating B:	
Lower Tray:	6
Upper Tray:	11
Coating C:	
Lower Tray:	3
Upper Tray:	7
Coating E:	
Lower Tray:	10
Upper Tray:	19
Coating G:	
Lower Tray:	11
Upper Tray:	11

Table 6.3: Summary of Single Tray Gas Burner Cable Fire Barrier Test Results. (Note that these tests used three different types of cables as described in text.)

Cable Type: Barrier Designator*	Failure Time** (min)
IEEE-383 Rated XPE 3-Conductor:	
No Barrier***	9
Barrier 2	NF
Barrier 4	NF
IEEE-383 Rate XPE Single Conductor:	
No Barrier***	5
Barrier 2	NF
Barrier 4	NF
Nonrated PE/PVC 3-Conductor:	
No Barrier***	6
Barrier 1	2
Barrier 2	4
Barrier 3	3
Barrier 4	5

* Barrier designators correspond to the following:
1 - Ceramic wool blanket over open ladder tray,
2 - Solid tray bottom with no cover,
3 - Solid tray cover with no bottom,
4 - Vented tray cover and solid tray bottom,

** "NF" Indicates no failure observed within 60 minutes.

***Reported previously in Table 6.1, reproduced here for reference.

6.2.2 Twenty-Foot Separation Tests

The objective of the Twenty-Foot Separation Tests was to determine the technical adequacy of the proposed USNRC Twenty-Foot separation criteria. This criteria required that equipment associated with redundant safety trains must maintain a horizontal separation of Twenty-Foot with no intervening combustibles. It was intended that spatial separation would minimize the likelihood of fire damage to redundant equipment trains. The adequacy of this criteria as a means of fire protection was assessed through the performance of a series of enclosure fire tests. In each test, the continued operability of a simulated redundant train of cables separated from a source fire in accordance with Appendix R was monitored, and electrical faults noted.

This effort involved the performance of four preliminary "Experiments" and six "Tests." In the four preliminary "Experiments" the fire source was comprised of only a liquid heptane fueled pool fire. This pool consisted of ten gallons of heptane in a five-by-one foot fuel pan. In each case the fire was located along the rear wall of the compartment. Two horizontal cable trays were located above the doorway at the front of the compartment. In Experiments 2 and 4, only, energized cables were monitored for electrical failure.

In the six "Tests" two trains of equipment were each simulated by two loaded cable trays separated by the mandated Twenty-Foot. One of the simulated trains of equipment was located at the back of the test enclosure and subjected to a liquid fuel pool, the same as that described above though using only five gallons of heptane, as an exposure fire source. The second train was located above and just inside of an open doorway at the front of the test enclosure. Certain of the cables within this simulated second train were monitored for electrical integrity throughout the test.

In several cases, electrical failure was observed in the second train cables (those located above the doorway). The damage observed was attributed entirely to hot layer effects. The simulated redundant cables were not subjected to either direct flame or fire plume impingement. Heating of the cables was entirely due to the flow of hot gases across the room and out the open doorway. In no case was ignition of the second train of cables observed.

Two types of cabling were utilized in these tests. The first was a three conductor, 12AWG, polyethylene (PE) insulated and jacketed cable. This cable was <u>not</u> an IEEE-383 rated low flame spread cable. The second cable was a three conductor, 12AWG, cross-linked polyolefin insulated and jacked cable. This second cable was a rated low flame spread cable.

For each of these two cable types, three cable protection configurations were evaluated. These were (1) no protection of the cables, (2) protection with a ceramic blanket wrap and solid tray covers, and (3) protection with a fire retardant coating. (In each test both of the simulated trains of cable received identical protection.) For the nonrated PE cable, damage was observed in all three of the cable protection configurations tested. For the rated low flame spread cable, failure was observed only in the case in which no cable protection was employed.

Table 6.4 summarizes the test conditions utilized in each of the four "Experiments" and six "Tests." Figure 5.2, presented above, illustrates the temperature profiles measured in the vicinity of the cable trays near the doorway for Experiments 1-4. Figure 5.3, presented above, illustrates the same information during Tests 1-6. The time at which electrical failure was observed is also indicated on these figures for each of the tests in which such failures were observed. (As stated above, no damage information was gathered during experiments 1 and 3.)

These results are of limited quantitative value as measurements of the thermal conditions of the cables at the time of failure were not considered reliable. Also, as the temperature profiles observed are highly transient, it is difficult to extrapolate these results to other fire situations. However, these tests did dramatically illustrate the potential impact of indirect fire effects on the operability of cables in particular, and plant equipment in general. The tests also indicated that in some cases, longer term failures may be observed even though the most severe part of a fire's growth history may have passed. This is illustrated by the failure time observed in Tests 2 and 3. In both of these cases electrical failure was observed well after the time at which the peak air temperatures were reached. In Test 2 temperatures had dropped from the peak value of approximately 500°C at 6 minutes, to a value of approximately 300°C by the observed time of electrical failure at 13 minutes. Later analyses showed that the fire in Test 2 had essentially self-extinguished due to the consumption of the available fuel by the time electrical damage was observed. This "delayed" failure illustrates that damage may occur following the peak intensity, or possibly even the extinguishment, of the fire itself.

6.2.3 Cable Radiant and Convective Heating Damage Tests

In conjunction with the Twenty-Foot Separation Tests described immediately above, a series of independent cable damageability tests was conducted (reference A-37). These tests investigated the damageability limits of the two cable types used in the Twenty-Foot tests (the PE and polyolefin cables described above) under conditions of either convective or radiative heating.

Table 6.4: Summary of Experimental Conditions Varied in Each of the Twenty-Foot Separation Tests. (Note that the ten tests are identified as Experiments 1-4 and Tests 1-6.)

Experiments 1-4:*

Experiment Number	Room Length: (w=14ft, h=10ft)	Door Size (w x h)
1	30 ft	8ft x 8ft
2	25	8 x 8
3	25	4 x 8
4	25	Closed

Tests 1-6:**

Test #	Cable Type:	Cable Tray Protection:
1	Nonrated	None
2	Rated	None
3	Nonrated	Ceramic Blanket and Steel Covers
4	Rated	Ceramic Blanket and Steel Covers
5	Nonrated	Fire Retardant Coating, 1/8 inch
6	Rated	Fire Retardant Coating, 1/8 inch

* All experiments used a 1x5 ft. pan with 10 gal. of heptane, only, as the fire source.

** All tests used the 25 ft. length room with a 4x8 ft door. The fire source was a 5 gallon heptane pool plus two vertical cable trays, protected as indicated, simulating one of two equipment trains.

In the convective heating tests, samples of each of the two cable types were subjected to an elevated, steady temperature in a convective oven. The cables were exposed using four different cable configurations as described below:

1. Cable segments placed on a metal mesh shelf (12 tests),
2. Cable segments placed on a cable tray with a downward 90° bend over one rung of the tray and a weight hung from the end of this downward section (to simulate additional cable) (12 tests),
3. Cable segments placed in a cable tray with a distributed weight placed on top of the cable (to simulate the bottom cable in a loaded tray) (2 tests), and
4. Cable segments wrapped around an 18 inch (46 cm) aluminum mandrel (3 tests).

Cables in each of these configurations were exposed to a variety of elevated temperatures ranging from 130°C to 450°C for a predetermined length of time ranging from 10 to 60 minutes. Following exposure the cable samples were removed from the oven and allowed to cool. They were then tested for the presence of conductor to conductor shorts and open conductors. A total of 29 tests were performed.

It should be noted at the outset that this methodology can allow for the masking of actual failures. In subsequent testing, described below, it has been found that monitoring of a cable during the exposure period is critical to the accurate identification of cable failures. It has been observed that cables which develop shorts during exposure will often "heal" once cooled. This healing has been observed up to the point were actual ignition of the cable insulation occurs. It has also been noted that for energized cables a short will often act as a fire ignition source as well, and that the resulting fire will often completely consume all cable insulation and jacketing materials near the location of the fault. Thus, a lack of post exposure shorting in the tests described here can not be considered conclusive evidence that the subject cables would actually survive the exposures without shorting.

With the cables in the first configuration, no cases of electrical shorting were observed. In many tests the cable jacketing and insulation materials suffered severe discoloration, embrittlement, and shrinkage. With the cables in the second configuration, the weighted bend, nonrated cable shorting was observed at exposure temperatures as low as 150°C. At temperatures of 170°C, shorting was observed after as little as 30 minutes of exposure. No shorting was observed in the rated low flame spread cable following 60 minute exposures at 250°C. In the third configuration, distributed weighting, shorting of the nonrated cable was observed after a 60 minute exposure at 170°C. No samples of the rated low flame spread cable were tested in this configuration. In the final configuration, mandrel wrapped, following a 60 minute exposure at 275°C the rated low flame spread cable would not pass a voltage withstand test. (This is a more stringent failure criteria than that used for the previous configurations.) Based on these results, the threshold of thermal damage for the two cable types were estimated to be 130°C for the nonrated cable and 250°C for the rated cable.

As an independent part of this test program, a number of radiative heating cable tray tests were also performed. These tests utilized three banks of quartz heaters to expose a loaded cable tray to predetermined heat flux conditions. These heat flux levels varied from 5 to 40 kW/m^2. In each test the subject cables were energized to 320 VDC and powered to 5 amperes AC. The failure criteria used was the presence of a cable to cable tray short as indicated by the presence of a cable to cable tray current. No monitoring of conductor to conductor shorts was performed.

A total of 10 experiments, 5 each on the rated and nonrated cables, was performed. The observed times to electrical failure, and the observed times to nonpiloted ignition, versus the exposure heat flux level were analyzed using a methodology developed at Factory Mutual Research Center (FMRC).[33,34] Under this methodology the inverse time to electrical failure, or ignition, is plotted as a linear function of the exposure heat flux. Recently, the adequacy of this critical flux methodology has been questioned.[8] While this correlation works fairly well for higher heat flux levels, as one approaches the threshold values, the correlation breaks down. Thus, the extrapolation of this data back to the abscissa, and the interpretation of the extrapolated value as a critical heat flux for damage, or for ignition, is inappropriate.

Figures 6.1 and 6.2 illustrate the results obtained for the onset of cable to tray shorts and nonpiloted ignition of the cable samples, respectively. In the original test report extrapolation of this data to the abscissa was performed, and critical heat flux values were reported. However, as described above, the more recent information indicates that the interpretation of these values as threshold exposure values was inappropriate. Thus, these results have not been reproduced here.

6.2.4 Cable Steady State Thermal Damage Tests

In a more recent effort an additional series of convective thermal exposure cable damageability tests was performed. Two types of cabling were exposed to steady state elevated temperature environments in a convective oven. One of the cable types tested was a non-low-flame-spread, 3 conductor, 12AWG, 20/10 PE/PVC insulated, PVC jacketed cable rated to 600V. The second cable was an IEEE-383-74 rated low flame spread, 3 conductor, 12AWG, cross-linked polyethylene (XPE or XLPE) insulated and jacketed cable.[6]

6. This is an account of previously unpublished work which has been documented in a letter report to the USNRC dated July 14, 1984.

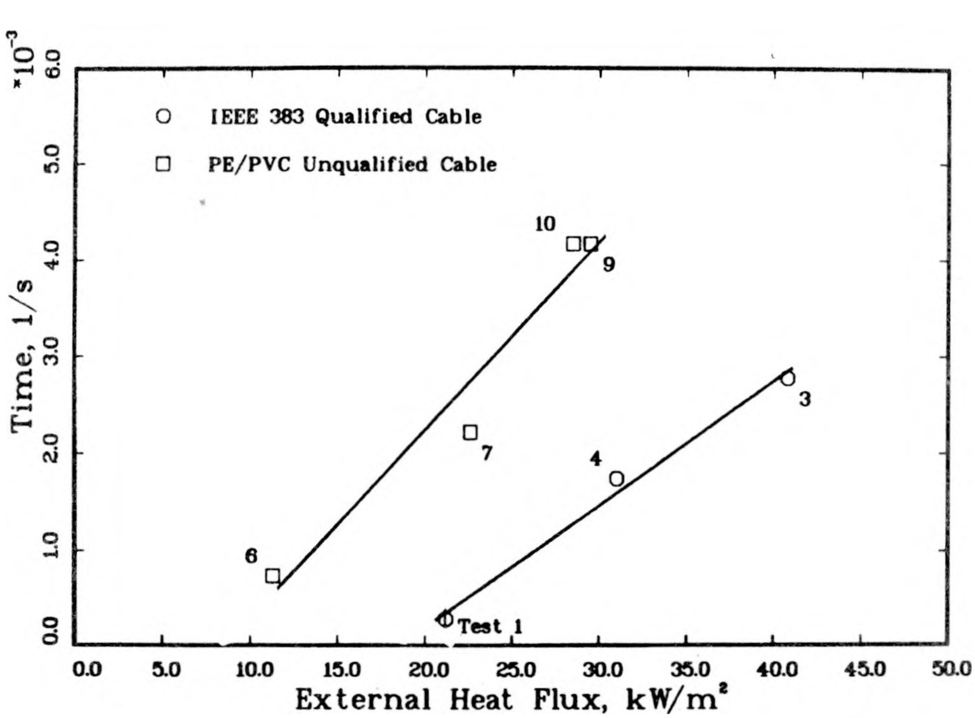

Figure 6.1 Radiant Thermal Heating Cable Tray Damageability Test Results

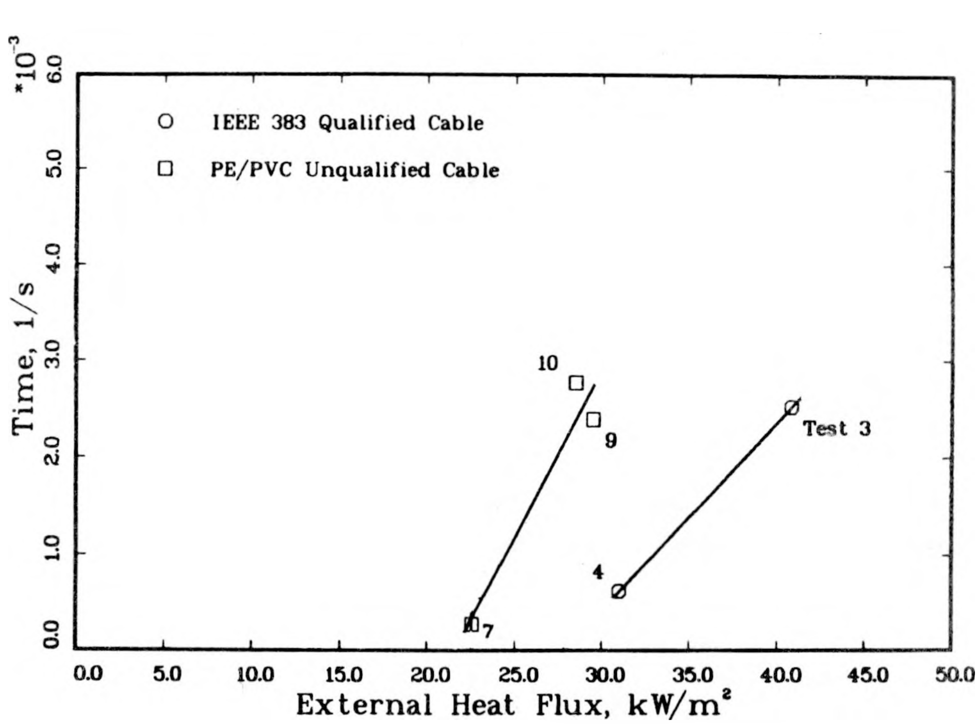

Figure 6.2 Radiant Thermal Heating Cable Non-Piloted Ignition Test Results

These tests differed from the previous tests, described immediately above, in two important respects. First, conductor to conductor shorts were monitored throughout the period of exposure, not just following the exposure. Second, in certain respects the cable configuration was less severe than that used previously. In these tests a segment of cable was routed into the oven onto a cable tray and back out of the oven. In the previous tests, cable configurations included weighted bends, the use of distributed weights pressing down on the samples, and mandrel bends. The configuration used in these tests is most similar to the first configuration used in the previous tests in which cable segments were simply placed on a mesh shelf.

The results of these tests provided data, for each cable type, on both the threshold of thermal damageability, and the time to damage versus exposure temperature at higher temperatures. For the rated cable, electrical shorting was observed within approximately 40 minutes at temperatures as low as 270°C. Failures in the nonrated cables were observed at temperatures as low as 250°C. The time to failure versus exposure temperature data are presented in Figures 6.3 and 6.4.

These tests provide an important first step in the quantitative evaluation of cable vulnerability in a convective environment. The ability to analytically predict cable failures under convective conditions can play a significant role in the evaluation of fire risk as many fire risk scenarios involve the exposure of cables to hot layer conditions in which convection is the dominant mode of heat transfer. The recording of time to failure versus the steady state exposure temperatures provides information of use in the analytical prediction of time to electrical failure for transient thermal exposures as well. The use of a simple threshold exposure temperature value may not be appropriate as a criteria for cable failure. Short term exposures at much higher temperatures will not necessarily result in electrical failure. These tests also demonstrated that in the performance of experiments, the monitoring of a cable during the exposure period is important as "healing" of electrical faults was in some cases observed. These tests represent only an initial step towards the analysis of cable failure. Only two types of cables were tested, and only under a limited range of thermal exposures. Also, no criteria for the onset of cable electrical failure has yet been demonstrated.

6.2.5 Cable Transient Thermal Damage Tests

In the Twenty-Foot Separation Tests it was demonstrated that 20 feet of horizontal separation was not, in and of itself, sufficient to insure the safety of redundant equipment trains. However, the Appendix R fire regulations require that in addition to 20 feet of separation with no intervening combustibles, one must also provide automatic fire detection and suppression systems in plant areas were such separation is employed as a protective measure. In the Twenty-Foot Separation Tests active

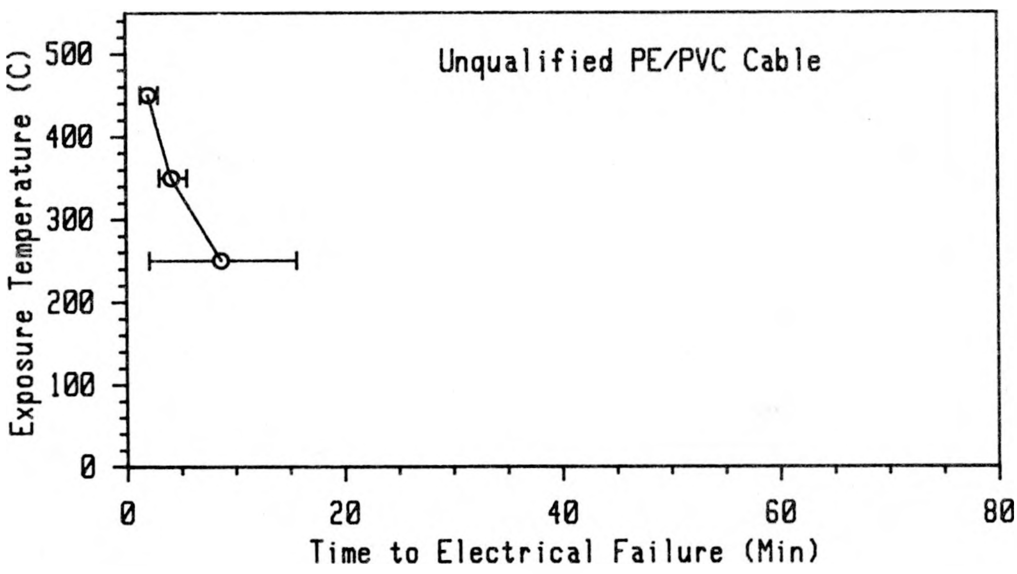

Figure 6.3 Cable Steady State Thermal Damageability Results for a Non-Rated PE/PVC 3-Conductor Power Cable

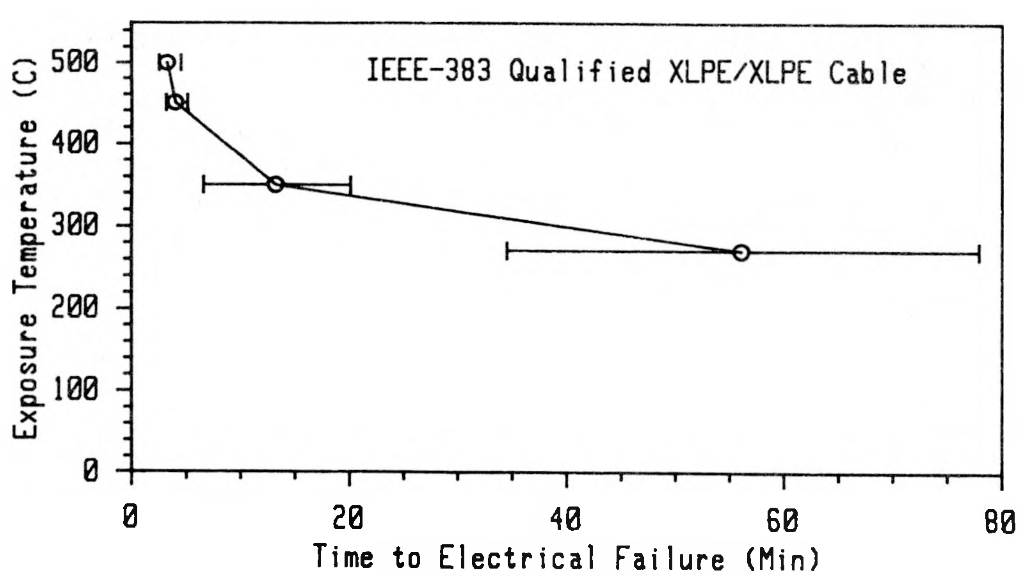

Figure 6.4 Cable Steady State Thermal Damageability Results for a Rated Low Flame Spread XPE 3-Conductor Power Cable

suppression of the test fire was not employed. Nonpressurized sprinkler heads were placed within the test enclosure and were monitored for activation of the fusible link. The Cable Transient Thermal Damage Tests investigated the possibility that the actuation of the sprinkler system and active suppression of the test fires might have prevented the observed cable failures.[35]

The observed exposure temperature profiles which, during the Twenty-Foot tests, had resulted in the failure of the unprotected rated and nonrated cables were experimentally reproduced in a transient thermal exposure chamber. These profiles were those observed during Tests 1 and 2, which have been described previously. In each of these two tests the cables were not protected by any passive coating or barrier system. Test 1 involved the nonrated cable and Test 2 involved an IEEE-383-74 rated low flame spread cable. The observed temperature profiles in the vicinity of the cables for each test were reproduced in full to simulate the actual test conditions, and in part to simulate the onset of active fire suppression and the resultant cooling of the enclosure environment. This simulation of the cooling effects of suppression system activation was achieved through interruption of the transient temperature profile at the observed time of sprinkler head actuation. As a result a number of insights were gained.

It was found that cables with unprotected terminations in the test chamber were much more susceptible to damage than were those which did not terminate in the chamber. This was attributed to the fact that the insulation materials would shrink upon heating, thus exposing unprotected conductor. Careful measures needed to be taken in order to insure that the presence of a cable termination did not in itself induce a premature cable failure. It was also found that the geometry of the cable samples played an important role in the time to observed damage. Shielding of a monitored sample by other cables, as in a simulated loaded cable tray, delayed, and often prevented the onset of electrical damage. Convection was also found to significantly effect cable damage times. In single cable tests the level of visible damage (e.g. cracking, blistering, discoloration) was directly related to the magnitude of the velocities near the cable, and hence the magnitude of the convective heat transfer coefficient. This clearly indicates that convective, as well as radiative, damage mechanisms must be considered, both in testing and in analytical fire modeling.

In the tests involving the simulation of fire suppression it was found that damage was, in fact, prevented. However, in the case of the nonrated cable in particular, significant cracking, and blistering of the jacket and insulation material was still observed. This raises a potential concern in that if suppression with water were actually employed, high humidity environments and wetting of the cables would result. Thus, the presence of significant cracks and blisters in the insulation could allow water to induce shorting. It was intended that a second phase of this effort would be initiated to investigate this potential. These second phase tests were, however, not undertaken due to the termination of FPRP efforts.

6.3 Equipment Damage Sensitivity Ranking Study

As a lead-in to anticipated component fire environment damageability testing, a study was performed to rank the fire damage significance of safety-related nuclear power plant equipment. This ranking considered 33 types of plant equipment. In the initial screening the performance requirements and potential sensitivity to fire induced damage were considered. This screening resulted in the identification of the following list of plant equipment as the highest ranking equipment in terms of the decreasing sensitivity to fire damage:

Recorders
Logic Equipment
Controllers
Power Supplies
Meters
Relays (solid state and electrical/mechanical)
Hand Switches

As a second screening step equipment was further examined based on system significance, relative prevalence, and potential for affecting the loss of a complete safety function. The LaSalle Nuclear Power Plant was used as the basis for evaluation of these criteria. This screening found that at LaSalle the prevalence of each type of equipment throughout the plant was as follows:

	Total Number	Number in LaSalle Front Line Systems
Recorders	25	3
Logic Equipment	114	33
Controllers	93	1
Power Supplies	40	10
Meters	127	102
Relays	771	524
Hand Switches	446	322

As can be seen, relays and hand switches are much more prevalent, both in the plant in general and in front line safety systems, than are the other types of equipment identified as potentially the most sensitive to fire damage. On this basis relays and hand switches were identified as the first choices for the performance of fire damageability testing. Other likely candidates identified include logic equipment, power supplies, transmitters, and motor control centers.

6.4 Relay Thermal Damage Tests

As described immediately above, relays were identified as the first candidate for fire damageability testing based on both the vulnerability to fire damage and on the prevalence of relays in front line safety systems. Thus, as an initial step in the performance of damageability testing on equipment other than cables, two types of relays were tested to thermal failure (reference A-49).

The two relays tested were the Agastat GPI relay and the General Electric HMA relay (model 12HMA111B9). In each test a single relay was powered and placed inside of a controlled environment thermal exposure chamber. The initial temperature in the chamber was typically 50°C, and was increased in incremental steps of 10°C every ten minutes until failure of the relay to function was observed.

The Agastat relay uses an external socket connector. Two types of connectors are available, and one relay was tested with each of the two sockets. Failures in the Agastat relay were observed between 160°C and 210°C. Failure modes included shorts in the sockets, open circuits between the relay terminals and the socket, apparent shorting of the external socket connection screws to the metal base plate, and melting of a contact support internal to the relay. Severe warping of the relay socket was observed, and many of the failures are attributed to this warping.

The General Electric relay used direct connections rather than a socket. Failure of the relay system was observed above 350°C. However, this failure was caused by the initiation of a fire in the coil lead wires resulting from two of the lead wires shorting together. The relay itself was still functional at the time of cable failure. The resulting fire badly damaged the relay.

These tests clearly demonstrated that even equipment of a similar nature, i.e. relays, can exhibit significantly different failure thresholds and modes. The failure temperatures for the Agastat relay were near or below those typically assumed for even unqualified cables. Thus, the consideration of damage to equipment other than cables, and in particular in the analysis of a control room, may play a significant role in the analysis of fire risk. These tests demonstrated that the vulnerability of such equipment will be dependant on many factors.

6.5 Component Testing in Secondary Fire Environments

In an attempt to explore the impact of an actual fire environment on the operability of plant equipment, a series of component exposure tests were performed in conjunction with the Cabinet Fire Tests described above.

During cabinet fire testing a number of components were placed at various locations within the test enclosure. These components were subjected to the uncontrolled environment which developed during the tests. Component exposures were performed during both the first phase Cabinet Effects Tests, and the second phase Room Effects Tests. These two phases differed primary in that the first phase tests were performed in a 10,000 cubic foot enclosure while the second phase tests were performed in a 48,000 cubic foot enclosure.

Qualified nuclear power plant components subjected to these uncontrolled fire environments included switches, meters, relays, and chart recorders. In addition, certain other equipment which was not typical of that used in a nuclear power plant were also tested. These were electronic counters, a power supply, and an oscilloscope amplifier. These components do represent equipment of a similar nature to other types of electronic equipment. Many of these components were powered, and certain of the components were monitored for operability. In all, components were included in five of the cabinet fire tests. All five of these fire tests involved the burning of cables within a control panel. In most cases the components were positioned such that they were not involved in the actual fire itself. Thus, the environments are described as secondary fire environments, and did not include such effects as flame impingement or actual component burning. As a result of these experiments a number of insights were gained regarding the potential modes of failure one might expect for the various types of equipment tested.

Switches were tested in various orientations with some panel mounted in a cabinet with an open back, some mounted on their sides, and some placed upright on a horizontal surface. None of the switches tested experienced any gross failure due to secondary fire effects. In several cases the switches did experience moderate to heavy depositions of soot on the working parts and contact surfaces. In one case, a switch which was closed during exposure had a contact resistance of approximately 100 kohm. The application of a 15VAC stress across contact points was sufficient to reduce the contact resistance to essentially that measured prior to exposure (in the milli-ohm range). During two of these tests, one switch was powered and monitored. The peak temperatures experienced by these switches were approximately 60°C and 30°C respectively. These two switches continued to carry their load currents without apparent difficulty. No detectable leakage currents were experienced (0.25 mA AC sensitivity).

Two of the exposed switches were subsequently placed in a 27°C, 70% relative humidity environment for 12 days. These switches were not cleaned and the soot deposits were left intact. Following this humidity exposure, one of the two switches displayed visible evidence of fairly extensive corrosion. This switch, when first closed, displayed a high contact resistance. This condition was quickly corrected by the application of a low DC voltage stress across the contact points. Neither of the switches experienced any gross adverse functionality effects.

Samples of the same type of relays which had been tested to failure previously, as described immediately above, were also used in this effort. The maximum thermal environments experienced by the relays were approximately 60°C. Other than slight corrosion on the metal surfaces of relays whose covers had been removed during exposure, no adverse impact on the functionality of the relays was noted. As with the switches, several of the relays experienced moderate to heavy deposition of smoke particulate. One relay placed in a 27°C, 70% relative humidity environment for 12 days following exposure also showed no adverse functionality impact.

A total of 13 meters of different types were also tested. These meters were not powered during exposure, though pre- and post-exposure calibrations were performed. None of the meters experienced any apparent damage due to this exposure, with the exception of two meters which became involved in the fire and were destroyed. The most severe environment experienced, short of fire involvement, reached a peak temperature of approximately 100°C.

Two strip chart recorders were also tested. In the first case, the recorder's front cover was removed and the recorder was placed on a surface in the enclosure approximately 8 feet from the burning cabinet. In the second case, the recorder's cover was left intact and the recorder was panel mounted in an open backed cabinet not involved in the fire. In the first case, heavy deposition of soot on the strip chart pen sliders completely blocked pen movement. Attempts to clean this deposition and restore functionality were unsuccessful. In the second case, only a light deposition of soot was noted. This soot prevented one of the three recording pens from traveling over its full range under the input of a slowly changing voltage source as one would expect during normal operation. This failure was successfully cleared by applying a sudden step change in voltage.

Two solid state electronic counters were tested. In the most severe exposure, one of the two counters experienced a peak temperature of 167°C with temperatures remaining above 150°C for about five minutes. This counter was not powered nor monitored during exposure, though post-exposure evaluation showed the counter to be working normally. A heavy deposition of soot was found on the circuit board. This counter was subsequently powered and placed, without cleaning, into an environment of 32°C and 90% relative humidity for 5.5 hours. The environment was then modified to a 95% relative humidity and the exposure continued. After 17.5 hours of this exposure the counter was found with the front display deactivated and the its power supply fuse blown. The counter was removed from the chamber, the fuse replaced, and before the mode of failure could be diagnosed counter function returned to normal. The counter was again placed in the humidity chamber at 40°C and 95% relative humidity for an additional 18 hours. At the end of this period the counter was again found with the same failure symptoms. In this case the failure was traced to the build-up of a conductive medium which allowed excessive leakage currents near the power supply transistor. This medium was removed, and counter function returned. The counter was again checked, some hours later, and was found to have malfunctioned as a result of another problem. This problem was eventually traced to corrosion related bridging of a series of four closely spaced current paths on the printed circuit board.

One final piece of equipment tested for which an interesting result was observed was an oscilloscope amplifier. This amplifier was fed a nominal one volt input, set to a factor of 5 amplification, and the output monitored. The environment in the vicinity of the amplifier reached a peak temperature of 110°C, and included a direct exposure to the thermal radiation from the back of the open fire cabinet. During the exposure a severe calibration drift in the output signal was noted. Eventually the output signal was lost entirely. This loss of output was attributed to the actuation of a thermal cut-out protection breaker which was set to 58°C. Once this cut-out was reset, and the component cooled, the function returned to normal.

One additional finding which resulted from these tests was that the soot which was deposited throughout the enclosure was found, in the case of burning PVC insulated cables, to be heavily laden with chlorides. It was estimated that the soot deposits were comprised of as much as 33% by weight water soluble chlorides. As much as 60% of the chloride generation expected from the cable fires was accounted for by chloride bound to the soot, rather than airborne chloride gases. These chlorides, when combined with water, can be highly corrosive and conductive. This is considered the most likely cause of both the leakage current and corrosive bridging failures noted in the case of the electronic counter.

These tests have illustrated a number of mechanisms by which various types of electrical/mechanical equipment might be damaged in a fire environment. The results include quantitative assessments of the thermal environment to which the components were subjected. In other respects, the results are relatively qualitative in that no attempt was made to determine damage thresholds, nor to quantitatively evaluated the relative degradation of functionality in the context of a control circuit. This makes it difficult to extrapolate the results to other equipment and other fire environments, except to say that equipment of a similar type to that tested would be expected to display similar vulnerabilities.

The failure mechanisms observed include melting, high temperature electronic failures, thermally induced calibration shifts, leakage currents induced by conductive smoke or smoke and water combinations, leakage currents on open contact pairs, particulate build-up on moving parts, corrosion of moving parts, and high contact resistance. The presence of corrosive and conductive deposits also raises a potential for high voltage breakdown in equipment such as switchgear and motor control centers, though these effects have not been investigated. Other potential damage mechanisms which have not been investigated include the impact of water sprays (either alone or in combination with other fire effects), and the impact of gaseous suppressant application on equipment operability.

7.0 ROOM-TO-ROOM FIRE EFFECTS STUDIES

7.1 Introduction

Room-to-room fire effects involve the potential for a fire or fire products to spread beyond the room of fire origin. The primary mechanisms for fire and fire products spread is the failure of fire barrier elements to contain a fire. Such failures could result from either design inadequacies, inadequate barrier maintenance, barrier aging degradation, or from personnel actions. The spread of fire products, such as smoke and heat, to remote locations may also occur through the plant ventilation system. Fire or fire products spread could induce significant increases in plant risk since the fire barriers form the first and foremost plant feature which is expected to limit the extent of fire damage and protect redundant trains of plant equipment.

As a part of the FPRP, only limited investigations of room-to-room fire effects have been undertaken. The particular studies which provide insights applicable to this aspect of fire safety are:

1979	Fire Protection Subsystems Study; Ventilation Systems
1979	Fire Protection Subsystems Study; Fire Barriers
1980	Investigation of Fire Stop Test Parameters

7.2 Fire Protection Subsystems Study: Ventilation Systems

As a part of the Fire Protection Subsystems Study, a review of the role played by plant ventilation systems in fire protection was performed (reference A-15). The primary focus of this study was a review of the guidelines for the design and installation of ventilation systems as related to fire protection strategies and design. The principal purpose of this study was to formulate recommendations for the modification of these regulations for application to nuclear power plants.

With respect to of room-to-room fire effects, ventilation systems represent a potential conduit for the spread of fire products to nonfire areas. It was found that the guidelines and regulations for the design and installation of ventilation systems were not sufficiently detailed to allow for the design of ventilation systems as an integral part of the fire protection systems. No provisions were included to provide such desirable features as local control and alignment of the ventilation system to meet the needs of fire products control or containment.

In practice, ventilation systems are typically installed with fire dampers at those locations where the ventilation duct work penetrates a rated fire barrier. These dampers are designed to close when either smoke or sufficient heat is detected in the ventilation ductwork. However, these dampers are typically designed to contain the spread of fire and flames rather than smoke or heat. Thus, many damper systems allow significant amounts of heat and smoke to pass even when fully closed. While one would expect that unrealistically large quantities of heat must be passed to represent a threat of fire spread, experimental evidence indicates that even relatively low level heat may cause calibrations shifts in certain types of plant equipment such as integrated circuitry. In addition, while not yet investigated experimentally, it is to be expected that smoke itself will represent a potential source of equipment damage for certain types of plant equipment such as high voltage switchgear.

As the design and installation of ventilation systems continues to be governed by essentially the same guidelines as those considered in this study, ventilation systems continue to represent a potential conduit for the spread of fire products to nonfire areas. To date no experimental investigations of this have been undertaken. Also, as noted in Chapter 6 above, very little is known about the vulnerability of plant equipment to relatively low thermal exposures, nor the impact of smoke on the operability of plant equipment. Thus, the significance of fire products spread to nonfire areas remains largely unassessed.

It should also be noted that the significance of room-to-room fire effects will be dependant on the thresholds of equipment vulnerability to fire induced damage. In particular, it is to be expected that the environments in nonfire locations will be less severe than those in the room of fire origin. Should it be determined that equipment will survive relatively harsh fire enclosure environments, then concerns for room-to-room equipment damage may be limited to suppression system actuation problems. However, to date there is insufficient data upon which to base such suppression induced equipment vulnerability assessments.

7.3 Fire Protection Subsystems Study: Fire Barriers

In the consideration of room-to-room fire effects, fire barrier systems play a key role. In particular, one is dependent on the integrity and durability of seals installed in cable, conduit, ducting, and other fire barrier through penetrations and the integrity and durability of fire doors to prevent the spread of fire and fire products from the room of fire origin. As a part of the Fire Protection Subsystems Study, a review of the regulations governing the qualification of fire barrier elements was conducted.[4]

As a result of this study, two potential weaknesses were identified. The first was the use of a hose stream test as a part of such qualifications. This test was judged to have poor repeatability. The second was the failure of qualification standards in the U.S. to specify the a positive pressure differential across the barrier element during the fire exposure testing. It is this second potential weakness which was considered of greater importance.

In an actual enclosure fire, the heating of the enclosure air will result in an increase in the enclosure pressure. Thus, should a fire barrier element or penetration seal have cracks or gaps which would allow for the passage of air, during an actual enclosure fire the elevated pressure could force hot air, or even flames, out past the barrier element. Such cracks or gaps may result from improper installation, inadequate maintenance, aging effects, or may actually be a part of the as designed barrier element (as in the case of doors). The failure of the U. S. standard tests to impose a positive differential pressure during qualification testing could mask this potential barrier failure mechanism.

This question of pressure effects on barrier elements was investigated further in the Fire Stop Test Parameters investigation. It was also raised as a part of the Fire Risk Scoping Study.[8] The results of these investigations are described in Section 7.4 and in Chapter 8 respectively.

7.4 Investigation of Fire Stop Test Parameters

As a follow up to the Fire Protection Subsystems Study, a limited series of cable tray fire barrier penetration seal positive pressure fire exposure tests were performed.[5] These tests also explored the impact of such factors as the loading density of cable in the penetration, the diameter of the penetrating cables, and the type of conductor (i.e. aluminum or copper) on the response of the seal system to the standard exposure test. This test series was limited in that (1) only a very few penetration seal systems were investigated, and (2) none of the seal systems tested were specifically qualified for use, nor verified to actually be in use, in nuclear power plants.

It was found that for those seal material which remained integral during the test and did not allow a path for gas flow, the effects of changes in pressure differential were not significant. For tests with a pressure differential from 2 to 125 Pa (0.008 to 0.5 inches of water), no significant change in the transmission of heat nor the onset of flaming on the unexposed side were noted. However, for one type of silicone elastomer seal system installed with through opening, a significant degradation in performance was note when the differential pressure in the furnace was made positive. Within 15 minutes of the initiation of the exposure tests, hot gas issuing through the passages was melting the cable insulation materials near these passages. While these cables were already electrically failed due to the fire on the exposure side, the onset of insulation melting is a good indicator that ignition thresholds are being approached. In all probabilility, any type of pilot flame would have been sufficient to ignite these cables. When the standard test was performed for this same penetration type without the pressure imposition, no hot gas passage nor insulation melting was observed.

It was also found that the construction of the fire stop would affect its response to the exposure test. Increasing the number or diameter of the cables or conduits penetrating the seal would result in more rapid increases in the unexposed surface temperature. Different cable insulation materials, and different conductor materials would also affect the seal response.

This investigation provided only a limited and rather qualitative assessment of the effects of various fire stop physical parameters and qualification test parameters on the exposure response. It was recommended that a further study of these effects be undertaken to determine whether the observed effects were significant for typically employed nuclear power plant fire seal systems.

8.0 AN OVERVIEW OF THE FIRE RISK SCOPING STUDY

8.1 Introduction

As a result of the various efforts which were undertaken as a part of the FPRP a list of six issues was developed which represented potential contributors to fire risk, and yet, had not been addressed in previously completed fire risk assessments. In response, an effort known as the Fire Risk Scoping Study was undertaken. It was the purpose of this study to (1) review and update the perspective of fire risk in light of the information developed through the FPRP, and (2) to identify and perform initial investigations of any potential unaddressed issues of fire risk. While performed as a separate and independent project, the findings of this study will be discussed briefly because (1) the efforts were a direct outgrowth of the FPRP, and (2) the study generated a number of conclusions and recommendations which are relevant to any future fire safety research which may be undertaken.

8.2 A Review and Updating of the Fire Risk Perspective

As an initial step in the performance of the Fire Risk Scoping Study, a review of four previously completed fire probabilistic risk assessments (PRAs) was performed. In each PRA the data and information made available as a result of the FPRP since the performance of the original work was used as the basis for requantification of the risk scenarios. In addition, plant modifications made in response to implementation of Appendix R since performance of the original PRA was also incorporated, and risk estimated again re-calculated. The objective of these reassessments was to assess the impact of the updated information, fire modeling techniques, and Appendix R implementation on fire risk.

The four plant fire PRAs which were reviewed were those for Limerick, Indian Point II, Seabrook, and Oconee. In each case only the dominant fire risk areas were re-examined. The requantifications were performed within a limited scope. No reassessment of the fundamental fault scenarios was performed, except in the cases where Appendix R modifications were made. The requantifications were performed following, as closely as possible, the methodology of the original analyses. Finally, judgmental factors used in the quantification process were not revised. The results of the requantification analyses prior to incorporation of Appendix R plant modifications are presented in Table 8.1. Table 8.2 illustrates the impact of identified Appendix R plant modifications on the updated risk estimated.

In each case, fire was found to represent a dominant contributor to plant core damage risk. This had been consistently demonstrated by risk analyses performed by a variety of analysts for a number of commercial reactors, and was not altered by the use of the updated information and modeling techniques. While the results of the NRC fire protection

Table 8.1 Summary of Scenario Requantification Results Prior to the Incorporation of Plant Appendix R Modifications

Plant:	Original CDF	Requantified CDF
Limerick[a]	2.3E-5	1.6E-4
Indian Point 2[b]	6.5E-5	2.0E-4
Oconee[a]	1.3E-5	2.0E-5
Seabrook[b]	2.1E-5	4.6E-5

a - Point Estimate
b - Mean Value Estimate

Table 8.2 Summary of Appendix R Plant Modification Risk Impact*

Plant:	Requantified Without Appendix R Mod's	With Appendix R Modifications
Limerick[a]	1.6E-4	5.9E-5
Indian Point 2[b]	2.0E-4	8.8E-6
Seabrook[b] **	4.6E-5	4.6E-5

* - Oconee Analysis Already Considered Appendix R Changes
** - Seabrook Appendix R Changes Did Not Affect The Dominant Scenarios
a - Point Estimate
b - Mean Value Estimate

research program have reduced fire risk estimate uncertainties, the overall perception of fire as a source of risk was not significantly altered. Even considering the improvements in fire protection which have resulted from the implementation of the Appendix R fire regulations, fire continues to represent a dominant core damage risk contributor. Implementation of Appendix R fire protection guidelines was demonstrated to have reduced fire risk at certain reactors by an order of magnitude. However, for other reactors the implemented plant modifications did not affect the dominant fire risk scenarios.

It was concluded that little or no basis for comparison of risk estimates from analysis-to-analysis existed. This primarily resulted from differences in how five factors, which were identified as the principal sources of fire risk analysis uncertainty, were determined. These are (1) estimation of fire occurrence frequency and fire size, (2) screening methodology differences, (3) modeling of fire detection and suppression, (4) estimation of of equipment damage thresholds, and (5) modeling of fire growth and environment response. It was recommended that standardized methodologies be developed in each of these areas in order to provide a basis for analysis-to-analysis comparison. In addition, the available fire growth models were identified as inadequate, and the adequacy of fire analysis tools in general was further examined as a part of the investigation of unaddressed fire risk issues.

8.3 Identification and Assessment of Unaddressed Fire Risk Issues

The Fire Risk Scoping Study was initiated on the basis of a list of fire risk issues developed as a part of the FPRP. This list was comprised of fire safety issues which had been identified subsequent to the performance of several plant fire PRAs. Using this list as the starting point, a number of plant designers, fire researchers, industry representative, fire protection consultants, and regulators were polled to insure that, to the degree possible, the list of unaddressed risk issues was complete. As a result a final list of six issues was developed. The potential impact of each of these issues on fire risk was assessed. The issues investigated are:

Control Systems Interactions
Total Environment Equipment Survival
Manual Fire Fighting Effectiveness
Fire Modeling Adequacy
Seismic/Fire Interactions
Fire Barrier Reliability

The evaluation of control systems interactions focused on the examination of the LaSalle Station control room. This work was performed in conjunction with the RMIEP analysis of that plant. The risk contribution due to a fire in one section of one control panel in the control room, the electrical distribution panel, was estimated at 8.1E-6/yr. This can be compared to an estimated risk for all internal events of 2.0E-5/yr to 4.0E-5/yr. The design evaluated in this analysis does meet the criteria of Appendix R. However, the deterministic reviews of control system independence performed as a part of Appendix R fire safety reviews can leave probabilisticly significant control systems interaction vulnerabilities unresolved. In the case examined, it was found that the level of indication and control provided on the remote shutdown panel was instrumental in reducing the estimated core damage frequency by an order of magnitude through operator recovery actions. It was recommended that a review of industry practices on the implementation of remote shutdown capability be performed and that control systems be examined on both deterministic and probabilistic bases.

In the evaluation of the importance of manual fire fighting to plant fire risk, two approaches were taken. First, a review of current plant practices was performed. This review found that a wide plant-to-plant variability exists. Fire brigade staffing and training varied from the minimum requirements of Appendix R to training far in excess of the regulations. The study identified a potential weakness in the Appendix R fire regulations in that training for members of manual fire fighting teams need not include training on actual fires. Thus, personnel assigned as fire fighters may never have faced a smoke filled room nor an actual fire.

The second approach involved the variation of assumed manual fire suppression probabilities and the assessment of the impact of this variation on risk estimates. It was found that for many dominant fire risk scenarios, the estimated time to fire induced critical failures is quite short making it unlikely that manual fire fighting efforts will be successful prior to damage. It was also found that relatively small variations in fire suppression times can result in order of magnitude changes in fire risk estimates. It was recommended that a review of manual fire fighting provisions be performed on a plant specific basis and that plant areas for which manual suppression is the only available fire fighting system be reexamined to determine whether predicted fire damage times are consistent with realistic manual brigade response times.

The currently available tools for use in fire analysis were also examined. It was found that these tools are, in general, inadequately validated. This results in large part from a lack of appropriate experimental data for situations typical of nuclear power plants against which to base validation. While many fire tests of various types have been performed, the objectives of these tests has not generally been nuclear power plant fire model validation. One notable exception to this is the Base Line Validation Tests and the Cabinet and Control Room Fire Tests performed under the FPRP. These tests were specifically performed to provide enclosure fire model validation results under conditions typical of nuclear power plant fire situations. However, these tests were performed shortly before the termination of the Fire Protection Research Program and planned efforts to process and make this data available were cancelled.

Another area investigated under this effort was the adequacy of the available data on the vulnerability of plant equipment to fire, or fire suppression induced damage. Very few efforts have been conducted to specifically examine the impact of a fire on the operability of plant equipment. Most of the available data, both from within and outside the FPRP, has focused on cables. However, even for cables, relatively little is known about the mechanisms and thresholds of fire induced damage. In addition, certain of the publicly available cable damageability data was identified as having been extrapolated in a nonconservative manner and is considered inappropriate for use in fire risk assessments. For other types of plant equipment, and for damage mechanisms other than direct thermal heating, very little information is available. It was determined that insufficient data existed upon which to base an assessment of the risk impact of this issue. It was recommended that equipment damageability studies be undertaken. In particular, the impact of fire suppression systems on control circuitry, the damageability of electrical cables, the effects of smoke and/or water on high voltage equipment, and the impact of smoke and/or water on control circuitry were identified as potentially significant equipment damage mechanisms.

Also investigated was the potential impact of seismic/fire interactions on plant risk. While it was determined that risk significant seismic/fire interactions can be identified, it was also concluded that such vulnerabilities will be more easily corrected than quantified. It was recommended that an effort be undertaken to develop guidelines upon which plants could base a comprehensive walkdown to identify and resolve these vulnerabilities.

The final area investigated was the reliability of fire barrier elements. This issue is directly related to the questions raised in past efforts regarding the reliability of fire barriers under actual fire conditions. The study found that there was insufficient data upon which to base actual risk estimates. A simple screening analysis showed that should barrier reliability be on the order of 99%, then no significant risk impact is expected. However, should barrier reliability be on the order of 90% then an order of magnitude increase in fire risk could result. It was recommended that a comprehensive review of fire barrier performance in the U.S. be performed in order to determine whether any fire barrier designs are particularly vulnerable to premature failure. It is anticipated that such a review would demonstrate that most barrier systems function well in actual fires, and hence, no significant risk impact would be expected.

8.4 Summary

The Fire Risk Scoping Study performed a review and requantification of past fire risk scenarios. This review demonstrated that while fire risk estimate uncertainties have been reduced, the overall perception of fire as a significant risk contributor has not changed. Recommendations were made to develop standardized methodologies for the performance of a number of fire risk assessment steps in order to provide a basis for analysis-to-analysis comparison of results.

In addition, six unaddressed fire risk issues were examined. The results of this examination are summarized in Table 8.3. A number of recommendations were made for follow-on efforts associated with these six issues. Of the six risk issues, control systems interactions and manual fire fighting effectiveness are considered the plant issues of the highest importance. Each is estimated to have a potential order of magnitude impact on plant risk. (Note that this impact is not expected to be multiplicative when more than one issue is considered simultaneously.) Also considered important are the issues of the adequacy of fire analysis tools and total environment equipment survival. In each of these two areas, a greater understanding of the phenomena is needed. The issue of barrier reliability is identified as potentially significant; however, it is anticipated that a comprehensive review of fire barrier performance in the U.S. would demonstrate that barrier reliability is adequate. For the final issue, seismic fire interactions, potential vulnerabilities were identified. However, these vulnerabilities are considered to be more easily resolved than quantified.

Table 8.3 Summary Unaddressed Issues Investigation Findings

Issue:	Potential CDF Impact*:	Applicability	Comments:
Control Systems Interactions	O(10)	Generic	Difficult to Quantify, Probabilistic Issue Not Deterministic
Manual Fire Fighting Effectiveness	O(10)	Generic	
Adequacy of Fire Analysis Tools	O(10)	Generic	Not A Plant Issue
Total Environment Equipment Survival			
Fire Induced Effects	Unknown	Generic	Not Quantified, Insufficient Data
Spurious Suppression Effects	Small-O(10)	Plant Specific	Not Quantified, Insufficient Data
Barrier Reliability	Small-O(10)	Generic	Vulnerability Not Assessed, No Data
Seismic/Fire Interactions	Small	Generic	Easily Resolved on Plant Specific Basis

* - O(10) Is a mathematical representation for order of magnitude.
Note: The core damage frequency (CDF) impacts are not expected to display multiplicative character when more than one issue is considered, rather, the effects will be additive.

9.0 SUMMARY

During the years 1975-1987 the Fire Protection Research Program has investigated a variety of issues associated with fire safety in commercial nuclear power plants. The efforts performed have been conducted on both analytical and experimental bases. Investigations of fire ignition, fire growth, fire induced damage, fire detection and suppression, the modelling of fire, and fire risk have been performed. These investigations have led to a better understanding of the adequacy of past and present fire protection regulations, as well as a greater understanding of fire overall. The following lists some of the major results and conclusions which have resulted from these efforts:

- Fire retardant cable insulation, cable coatings, cable tray covers, and other passive cable tray protective measures reduce fire severity. However, such measure do not insure that fire induced damage will not occur and wide variability in relative effectiveness of different systems and products was demonstrated.

- While cables certified by the IEEE-383-74 flame spread test are more difficult to ignite and spread fire more slowly, even these rated low flame spread cables can be ignited, burned, and/or damaged. It has also been observed that once a self-sustaining fire is developed in such cables, these fires tend to be more intense and more difficult to extinguish.

- If properly designed and installed carbon dioxide, and Halon suppression systems will eventually extinguish even deep seated fires such as those encountered with cable tray installations. However, the maintenance of proper concentrations of suppression agents for sufficient periods of time is critical to prevent reignition.

- Gaseous suppression agents applied during a fire permit enclosure temperatures to remain higher than do water based suppression systems. Sensitive control circuitry may experience loss of function and/or calibrations shifts during extended exposures at even relatively temperature elevations.

- Water is the most effective fire suppressant for suppressing even deep seated cable fires. The use of water does, however, produce severe moisture environments which may lead to equipment damage, even beyond the region of immediate fire involvement. The proper management of fire suppression water must also be considered as a part of system design.

- Cable and ducting wall penetration seals can allow hot gases and flame to pass through prematurely under conditions of positive pressure differential if the seal system is such that air passages are incorporated, even though such penetration seal systems may pass standard fire qualification tests.

- Hot gas layers from fires have, during testing, been observed to cause damage to cables spatially separated in accordance with the provisions of the Appendix R fire regulations and not directly involved in the fire. (In these tests no active suppression of the room fires was attempted. Appendix R does specify the use of automatic fire detection and suppression where spatial separation is used as a fire protection measure.)

- Failure mechanisms identified for electrical components include high temperatures melting, calibration shifts due to relatively low elevations in temperature, smoke deposition, moisture, and/or corrosive gases. Thermal cut-out protective features activation has also been observed. Such cut-out may require operator action to restore equipment operability.

- Testing has shown that cables can fail at temperatures well below the nonpiloted ignition temperatures.

- Room environments in control room sized enclosures induced by a fire in a single control cabinet can be severely degraded by the rapid development of thick, toxic, and corrosive smoke. In terms of the thermal environment, for the configurations tested (i.e. a single cabinet burning in a large open room) temperatures remained below those expected to cause damage to most plant equipment including cables.

- Electrical cabinet fires which consumed all of the available combustible materials within approximately 15 minutes of ignition were observed for both IEEE-383-74 rated low flame spread cables and for nonqualified cables.

- For the nonqualified cables, full involvement cabinet fires can be electrically initiated as a result of a low intensity (less than 15 Ampere) simulated electrical fault.

- The deterministic criteria of the Appendix R guidelines do not address the residual risk associated with probabilistic events such as multiple faults, multiple spurious operations, and multiple random equipment failures.

- Manual fire fighting and operator control actions may be severely hampered by smoke from cable fires, even in very large rooms having high forced ventilation rates. Typical ventilation configurations used in practice can not be expected to purge smoke from a fire enclosure adequately to insure either visibility nor habitability.

- Chlorides released during PVC cable insulation fires were observed to become bound to smoke particulate which was subsequently deposited on surfaces throughout a fire enclosure. These chlorides, when combined with water, can form a highly corrosive deposit.

The Fire Protection Research Program has fostered a greater understanding of the behavior of fires, the adequacy of fire related regulations and guidelines, the adequacy of various fire protection measures, and fire risk. Historical evidence indicates that significant plant fires occur, on average, once every seven to ten years of operation. Thus, most plants can expect to experience a number of significant fires during their design life. Fire risk, as estimated by several risk assessments, consistently represents one of the dominant contributors to overall risk even when consideration of Appendix R plant modifications is included. The Appendix R regulations are deterministic in nature and do not address the residual risk associated with probabilistic combinations of multiple fire induced failures and random plant equipment failures.

While the understanding of fire phenomena has significantly improved and the risk due to fire has been reduced by Appendix R implementation, a number of areas remain in which our knowledge base is relatively poor. In particular, fire modeling, equipment vulnerability to fire suppression induced damage, the effects of smoke on high voltage equipment, the impact of fire environments on control circuitry, fire induced control systems interactions, the effectiveness of manual fire fighting efforts, and room-to-room fire effects are all areas in which a greater understanding is needed. These areas are particularly important in that each has a direct impact on the perception of fire as a source of risk.

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APPENDIX A

BIBLIOGRAPHY LISTING OF SNL/USNRC FIRE PROTECTION RESARCH PROGRAM PUBLICATIONS WITH CROSS REFERENCE LISTING OF MAJOR REPRORTS TO SPECIFIC RESEARCH EFFORTS

APPENDIX A-1

LISTING OF FORMAL REPORTS, JOURNAL ARTICLES, AND PUBLISHED CONFERENCE PAPERS GENERATED BY THE USNRC/SNL FIRE PROTECTION RESEARCH PROGRAM BETWEEN THE YEARS 1975 AND 1988

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APPENDIX A-2

CROSS REFERENCE LISTING OF MAJOR REPORTS TO SPECIFIC
FIRE PROTECTION RESEARCH PROGRAM EFFORTS

Experimental Studies:

1976 Electrically Initiated Cable Fire Tests
SAND77-1125C, A-4
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SAND83-0306, NUREG/CR-3192, A-42
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1975 Cable Use Screening Survey
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SAND79-0324, NUREG/CR-0654, A-17

1981 Burn Mode Analysis of Cable Fires
SAND81-0079, NUREG/CR-2431, A-32

1981 Cost Analysis of Fire Protection Systems
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1982 Detector Siting Criteria Requirements Study
SAND81-7168, NUREG/CR-2409, A-34

1984 Identification and Classification of Transient Fuel
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1985 Review of Fire Characterization Data
SAND86-0311, NUREG/CR-4679, A-59

1986 Development of Nuclear Power Plant Fire Occurrence Data Base
SAND86-0300, NUREG/CR-4586, A-51

1985 Equipment Damage Sensitivity Ranking Study
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11. ABSTRACT *(200 words or less)*

This report summarizes the results and conclusions generated by the U. S. Nuclear Regulatory Commission sponsored Fire Protection Research Program at Sandia National Laboratories. Efforts conducted from the program's inception in 1975 through 1987 are discussed. The report provides a complete bibliography of reports and journal articles generated as a result of these efforts with a cross-reference listing of major reports to specific efforts. Among the topics investigated by various experimental efforts are the effectiveness of fire retardant cable coatings and cable tray fire barrier systems in the prevention of fire spread and fire induced damage, the effectiveness of suppression methods for cable tray fires, testing of cable penetration seals, transient fuel fire characterization testing, investigation of electrical cabinet and control room fires, equipment damageability testing, and large scale enclosure fire testing for the validation of computer fire simulation codes. Topics investigated as a part of analytical efforts include a review of the fire regulations which bear relevance to nuclear plants, investigation of the standards and strategies invoked in the design of various fire protection subsystems, the modeling of cable fire behavior, the identification of reported transient fuel sources, and the development of a fire occurrence data base.

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