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Investigation of Twenty-Foot Separation Distance as a Fire Protection Method as Specified in 10 CFR 50, Appendix R

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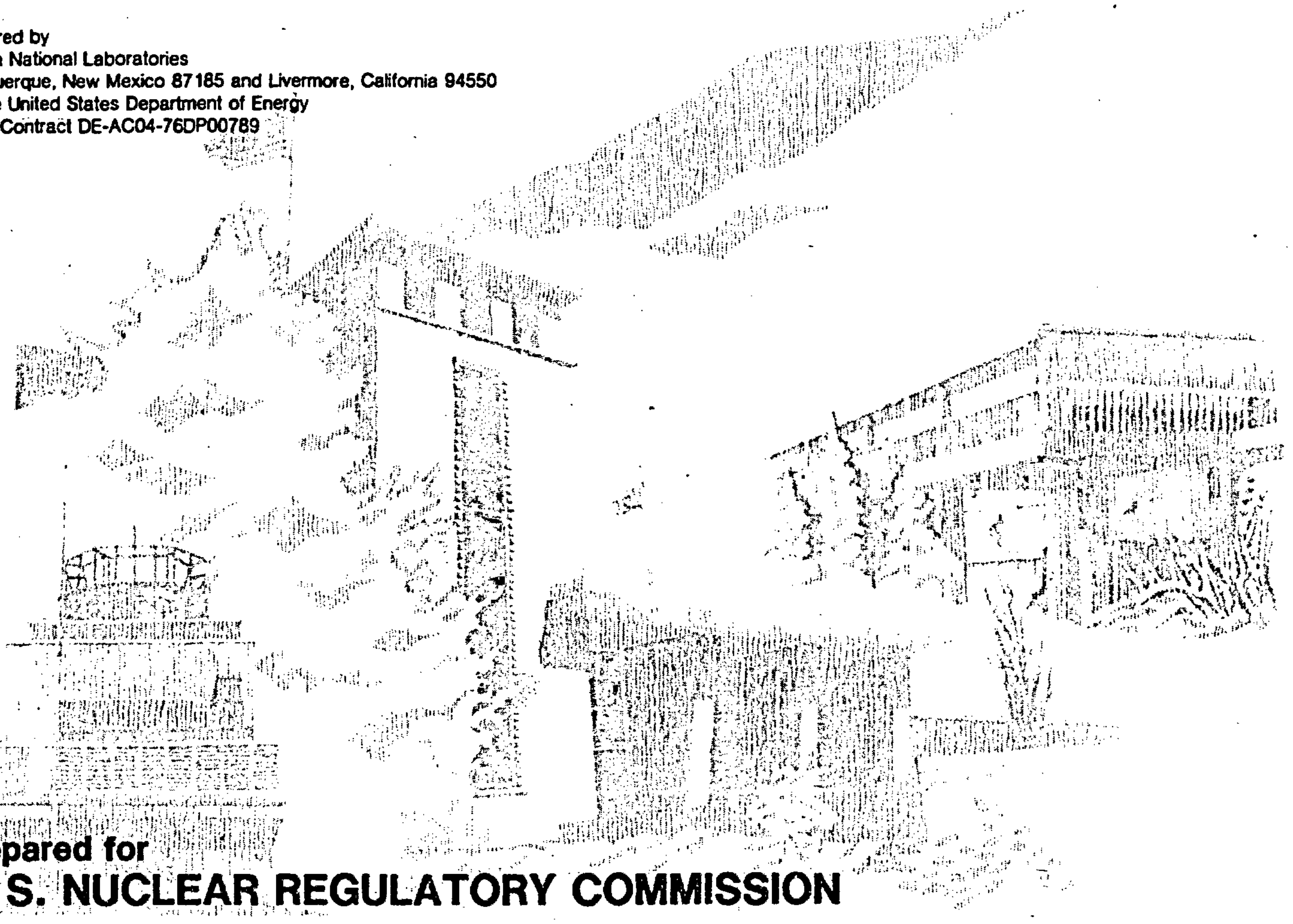

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operated by
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Abstract

A combined experimental/analytical program was conducted to examine the adequacy of the 20-foot separation requirement, one of the requirements set forth in Appendix R of 10 CFR 50 for the fire protection of redundant safety systems that are necessary to achieve hot shutdown in nuclear power plants. Specifically, Sections III.G.2.b and d of Appendix R require separation of the redundant safety systems by a horizontal distance of more than 20 feet with no intervening combustibles or fire hazards. Section III.G.2.b also requires installation of fire detectors and an automatic fire suppression system within fire areas. The experimental investigation consisted of six full-scale fire tests of unqualified and qualified electrical cables separated by 20 feet with (1) no protection, (2) protection with a ceramic fiber blanket and sheet metal covers on the cable trays, and (3) protection with a fire protective coating. For the test conditions investigated, all unqualified cable electrically shorted while qualified cable was found to short only when left unprotected.

Acknowledgments

The efforts of the many people who contributed to the completion of this program are gratefully acknowledged. In particular, at Sandia National Laboratories, the following persons contributed to various stages of the program: Leo Klamerus, Larry Lukens, Donald Dube, Dwight Lambert, Steven Ogan, David Larson, and Nan Bragg, our secretary who graciously prepared the many drafts of this report. Preliminary experiments and full-scale tests were conducted at Underwriters Laboratories, Inc., Northbrook, Illinois, under contract to Sandia. Their support on this project is also gratefully acknowledged—in particular, the special efforts of Leon Przybyla, Thomas Plens, and William Christian.

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Executive Summary

On February 19, 1981, a new "Fire Protection Program for Operating Nuclear Power Plants," (Appendix R to 10 CFR 50) became effective. This action was taken to upgrade fire protection at nuclear power plants licensed for operation prior to January 1, 1979, by requiring resolution of certain contested generic issues in fire protection.

Three sections of Appendix R are retroactive. One of these deals with the specification of certain means to ensure that one of the redundant safety trains required to achieve hot shutdown is free of fire damage. One of the specified methods states that there be "Separation of cables and equipment and associated non-safety circuits of redundant trains by a horizontal distance of more than 20 feet with no intervening combustibles or fire hazards. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area." For noninerted containment, the same requirement is specified except that fire detectors and an automatic fire suppression system are not required. Licensees must either meet these requirements or apply for an exemption that justifies alternatives by a fire hazard analysis.

At the request of the NRC, Sandia National Laboratories developed and conducted a test program to investigate the adequacy of the 20-foot separation criterion.

The program consisted of a combined experimental (both separate-effects tests and full-scale tests) and analytical effort. Scoping analyses were performed to establish important test parameters (e.g., room dimensions, placement of fire, and fuel source). Separate-effects tests were conducted to study the damageability of cables as a function of heat flux and temperature. The results were used to configure four preliminary experiments conducted at Underwriters Laboratories (UL). Ten gallons (38 liters) of heptane were burned in each test to determine the effects of placement of the fuel source and the size of the door opening (ventilation effect).

Initial parameters for the full-scale tests as given by the NRC included: a close grouping of 5 vertical cable trays rising to horizontal cable trays filled (40% volume fill) with unqualified cable; volume of test enclosure as small as possible; exposure fire of 5 gal (18.9 liters)heptane, ceiling height of 15 ft (4.6 m); after 30 min of burning (i.e., the suppression system is considered not to be functional), the temperature in the redundant system (which should contain unqualified cable) should not exceed the maximum temperature rating of the cable for emergency overloads for one hour periods; ventilation system should be off or operate at approximately a few feet per minute. If the unqualified cable fails, the same test should be performed with qualified cable. Although automatic sprinkler protection was not included in the tests, at the request of the NRC, three sprinkler heads were installed and instrumented to record the time of operation of the fusible elements. As a result of the analysis, preliminary experiments, and discussion with the NRC, the original parameters were modified. The test setup was approved by representatives from the NRC.

The parameters chosen for the six full-scale tests were as follows:

Room Geometry:	Length 25 ft (7.6 m), width 14 ft (4.3 m), height 10 ft (3.1 m)
Redundant Safety System:	Two horizontal trays, 20 ft (6.2 m) from the fire and close to the ceiling (1 ft (.3 m) and 2 ft (.6 m) from the ceiling)
Cable Type:	Three conductor, IEEE-383 qualified and unqualified
Cable Protection:	a. None b. Ceramic fiber blanket with steel covers on the cable tray c. Fire retardant coating
Fuel:	5 gal (18.9 liters) heptane, 2 vertical trays, 43 cables/tray (12.5% fill)
Ventilation:	4 ft (1.2 m) × 8 ft (2.4 m) door

The redundant safety system (horizontal cable trays) contained the same cable as the vertical trays and were energized and instrumented to check for electrical integrity during the tests. The cable was protected in the same manner as the cable positioned by the ignition source.

Electrical integrity was used during the preliminary experiments and full-scale tests to monitor the tests results and to define "failures" during the tests.

Although a loss of electrical integrity was selected in the tests as a convenient failure measure, other more stringent criterion (e.g., insulation damage without shorting) may be more appropriate for nuclear power plant applications. However, the selection of a fire damage criteria was beyond the scope of this study.

For the *unqualified cable* (three conductor, No. 12 AWG, polyethylene insulation and polyvinylchloride jacket) all three configurations (cable unprotected, cable protected with a ceramic fiber blanket and metal covers, and cable protected with a fire-retardant coating) failed (electrical short).

For the *IEEE-383 qualified cable* (three conductor, No. 12 AWG, cross-linked polyolefin insulation and jacket) the configurations in which the cable was not protected failed (electrical short), while the other two configurations, as described above, did not short.

In addition, *separate-effects tests* conducted on the same type of electrical cable for an exposure time of 60 min in a convective oven resulted in failure (post-test electrical shorts) at 265°F (130°C) for the unqualified cable and at 480°F (250°C) for the qualified cable.

These full-scale tests demonstrate that for certain conditions a thermal environment exceeding the temperature and/or heat flux limitations of both the qualified and unqualified cables can be reached by a redundant safety system which is 20 ft (6.1 m) from a source fire with a moderate fuel load. Hence, the requirement in Appendix R, 10 CFR 50, for 20-ft separation of the redundant safety equipment required for hot shutdown is *not*, by itself, adequate in all situations tested, even for qualified cable.

Results obtained in this study should be extrapolated with extreme caution. We have determined that the computational state-of-the-art is not, at present, adequate to calculate the effects on the thermal environment of several important parameters. Specifically, the influence of room geometry (particularly ceiling height), fuel load, fuel characteristics, fuel location, ventilation conditions and locations, and cable protection schemes cannot be fully quantified at this time.

Based on the investigation, the following recommendations are made:

1. A combined analytical/experimental program should be initiated to evaluate and further extend the analytical state-of-the-art for predicting the local thermal environment as a result of a fire in a nuclear power plant room. To this end:
    a. Existing experimental data should be compiled.
    b. Fuel loads and fuel types in typical nuclear power plants should be determined.
    c. Fuel types in typical nuclear power plants should be characterized with respect to energy release rate.
    d. Analytical and computational procedures should be developed and compared to all available experimental data.
2. Potential failure modes and conditions of other redundant safety system equipment in addition to cable trays should be identified.
3. The effectiveness of various cable protection systems (e.g., barriers, coatings) should be examined in greater detail.
4. The term "free of fire damage" should be defined.

Investigation of Twenty-Foot Separation Distance as a Fire Protection Method as Specified in 10 CFR 50, Appendix R

1. Introduction

1.1 Background

On October 27, 1980, the US Nuclear Regulatory Commission (NRC) approved Appendix R to 10 CFR 50, "Fire Protection Program for Operating Nuclear Power Plants." The final rule was published in the *Federal Register*, Vol. 45, No. 225, November 19, 1980,[1] and became effective on February 19, 1981. It stated, in part, that "This action is being taken to upgrade fire protection at nuclear power plants licensed to operate prior to January 1, 1979, by requiring resolution of certain contested generic issues in fire protection safety evaluation reports."

Appendix R specifies certain methods for ensuring that one of the redundant safety trains required to achieve hot shutdown is free of fire damage ("free of fire damage" is discussed further by Lukens[2]). Section III.G.2 of Appendix R states that "Except as provided for [*sic*] paragraph G.3 of this section, where cables or equipment including associated non-safety circuits that could prevent operation or cause maloperation due to hot shorts, open circuits, or shorts to ground, or redundant trains of systems necessary to achieve and maintain hot shutdown conditions are located within the same fire area outside of primary containment, one of the following means of ensuring that one of the redundant trains is free of fire damage shall be provided:

a. Separation of cables and equipment and associated non-safety circuits of redundant trains by a fire barrier having a 3-hour rating. Structural steel forming a part of or supporting such fire barriers shall be protected to provide fire resistance equivalent to that required of the barrier;
b. Separation of cables and equipment and associated non-safety circuits of redundant trains by a horizontal distance of more than 20 feet with no intervening combustible or fire hazards. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area; or
c. Enclosure of cable and equipment and associated non-safety circuits of one redundant train in a fire barrier having a 1-hour rating. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area;

Inside noninerted containments one of the fire protection means specified above or one of the following fire protection means shall be provided;

d. Separation of cables and equipment and associated non-safety circuits of redundant trains by a horizontal distance of more than 20 feet with no intervening combustibles or fire hazards;
e. Installation of fire detectors and an automatic fire suppression system in the fire area; or
f. Separation of cables and equipment and associated non-safety circuits of redundant trains by a noncombustible radiant energy shield."

Section III.G.3 states that "Alternative or dedicated shutdown capability and its associated circuits, independent of cables, systems or components in the area, room or zone under consideration, shall be provided:

a. Where the protection of systems whose function is required for hot shutdown does not satisfy the requirement of paragraph G.2 of this section; or
b. Where redundant trains of systems required for hot shutdown located in the same fire area

may be subject to damage from fire suppression activities or from the rupture or inadvertent operation of fire suppression systems.

In addition, fire detection and a fixed fire suppression system shall be installed in the area, room, or zone under consideration."

In addition to the requirement for fire protection of safe shutdown capability, two other requirements (emergency lighting and protection against fires in noninerted containments involving reactor coolant pump lubrication oil) were decided by the Commission to be retroactively applied to all facilities.[1] However, it is also stated that "... the licensee must either meet the requirements of Section III.G of Appendix R or apply for an exemption that justifies alternative by a fire hazard analysis. However, based on present information, the Commission does not expect to be able to approve exemptions for fire-retardant coatings used as fire barriers."[1]

Though as stated in Reference 3 that "The 20 foot separation is considered adequate to provide a safe distance to protect redundant safety divisions exposed to a single, transient exposure fire such as burning 2-5 gal of flammable fluid," the Office of Nuclear Reactor Regulation requested "... that a full-scale fire test program be developed and implemented to determine the adequacy of the 20 foot separation criterion." Sandia National Laboratories developed an experimental program and conducted tests in response to this request. This report documents the results and findings of the investigation. This work was performed for the Electrical Engineering Branch of the Division of Engineering Technology, Office of Nuclear Regulatory Research, NRC.

1.2 Purpose of the Investigation

The purpose of the investigation was to evaluate the effectiveness of the fire protection afforded by the separation of redundant safety related cables by a horizontal distance of 20 ft (6.1 m) with no intervening combustibles or hazards. Both unqualified (not qualified to IEEE-383-1974[4]) and qualified (IEEE-383-1974) cables were to be considered for the following three situations: (a) unprotected, (b) protected with a ceramic fiber blanket and solid metal tray coverings on both sides, and (c) protected with a fire-retardant coating.

An automatic fire suppression system was not included in the investigations at the request of the NRC:[5] "... since the sprinkler may fail to operate, the test will be run without any fire suppression activities so as to simulate failure of the sprinkler system and allow for some reasonable delay in detection and fire brigade response." However, sprinkler heads, without water, were used to detect response times.

This investigation examined the separation of electrical cables and did not examine other safety equipment directly, though the results may be used to infer the response of such equipment.

1.3 Approach

To evaluate the 20-ft separation criterion, Sandia developed a program plan[6] that implemented a combined experimental (separate-effects tests, preliminary experiments, and full-scale tests) and analytical efforts. In brief, the plan used the initial recommendations[3,5,7] of the NRC as a starting point for the program, and as a result of some preliminary analyses, experiments, and discussions with the NRC, developed a final full-scale test configuration. Details are described below.

Since it was impractical to test all possible configurations (e.g., room geometry, fuel load and location), a limited full-scale test program backed with separate-effects tests, preliminary experiments, and analyses was conducted.

Initial parameters for the full-scale tests as given by the NRC[5,7] included: a close grouping of 5 vertical cable trays rising to horizontal cable trays filled (40% volume fill) with unqualified cable; volume of test enclosure as small as possible; exposure fire of 5 gal (18.9 liters)heptane, ceiling height of 15 ft (4.6 m); after 30 min of burning (i.e., the suppression system is considered not functional) the temperature in the redundant system (which should contain unqualified cable) should not exceed the maximum temperature rating of the cable for emergency overloads for 1-hr periods; ventilation system should be off or operate at approximately a few feet per minute. If the unqualified cable fails, the same test should be performed with qualified cable.

Using these guidelines as a starting point, several initial tasks were undertaken by Sandia. These included *scoping calculations* (Section 2) which allowed for the rapid and inexpensive investigation of the test parameters (e.g., room dimensions, placement of fire, and fuel source). The Harvard Fire Code (HFC)[8] was used in this analytical effort. This computer model has been verified by others, but not for the configuration of the planned tests. Nevertheless, the results were useful in scoping the final test configuration. For example, the results showed that 5 vertical and 5 horizontal cable trays plus 5 gal heptane would produce an overly severe fire, and little would be learned from testing this configuration. Also, variations in ceiling height were shown to have a greater effect on the thermal environment than variations in length or width.

Separate-effects tests were conducted at Sandia to study damageability of cables as a function of heat flux and temperature. Test results were used in conjunction with the environmental conditions predicted by the analytical model to estimate the fuel load and room configuration that could lead to cable failure (electrical shorts) conditions. See Section 3 for additional details.

The term "free of fire damage" is not defined in Appendix R; Lukens[2] discusses this point and gives recommendations to resolve this issue.

Preliminary experiments were conducted at Underwriters Laboratories (UL) using two different room configurations (14 ft (4.3 m) wide, 10 ft (3.1 m) high, and 25 ft (7.6 m)and 30 ft (9.1 m) long), with 10 gal (38 liters) heptane as a fuel source (no cables were used as a fuel source) at two different locations, with three different door configurations. A total of four experiments were conducted. Temperatures and heat fluxes within the room, and air velocities at the door, were recorded. On the basis of these experiments, the separate-effects tests, and analytical predictions, the configuration for the full-scale tests was chosen. Details are given in Section 5 and in Appendix A.*

As stated previously, 5 vertical and 5 horizontal cable trays with 40% fill were initially recommended for the full-scale tests. On this basis, an experiment was conducted at Sandia (Appendix C) to determine the *heat release of 5 vertical trays of unqualified cable*. However, during the course of the analytical investigations, it became apparent that a total heat release equivalent to 10 gal heptane would be sufficient to test the adequacy of the separation criterion. The five vertical and five horizontal cable tray fuel load, which is equivalent to about 80 gallons of heptane, was judged to be a threat to the integrity of the test enclosure. Since 5 gal heptane was to be used as the ignition source in the full-scale tests, the results of this heat release experiment were used to determine the amount of cable to be used in the full-scale tests, i.e., the cable should have a total heat release similar to 5 gal heptane. The findings resulted in the recommendation that the cable loading in the full-scale tests be two vertical cable trays with 12.5% fill (43 cables in each tray).

After completing the necessary analyses and preliminary experiments, the *full-scale tests* were conducted by UL (Section 7 and Appendix A). Six tests were conducted with unqualified and qualified cable using (a) no protection on the cable, (b) ceramic fiber blankets and solid metal covers over the cable tray, and (c) fire-retardant coatings on the cable. Five gal heptane was used as the ignition source. The source fire was placed by the vertical cable trays which were filled with 43 lengths of cable (12.5% fill). Temperatures, heat fluxes, air velocities, and electrical integrity of the redundant safety system (horizontal cable trays) were monitored.

The remainder of this report discusses in detail the scoping calculations (Section 2), the cable damageability experiments (Section 3), the ignition source fire characterization (Section 4 and Appendix B), the preliminary experiments conducted at UL (Section 5 and Appendix A), the post-experiment calculations (Section 6), and the full-scale tests conducted at UL (Section 7 and Appendix A). Section 8 presents an overview of results; Section 9, conclusions and recommendations.

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*Appendix A is the full contractor report to Sandia National Laboratories.

1.4 Acceptance Criteria

In References 3 and 7, recommendations regarding unacceptable cable damage are given. These include cable ignition, short circuit, open circuit, or maximum temperature rating of the cable for emergency overloads. This last requirement appeared overly restrictive, since typical values are ~203°F (95°C). Hence, a test program of limited scope (objectives, time, and funding) was conducted to obtain the failure limits for the two types of cables that were to be used in the UL tests. Electrical integrity was used to monitor the test results and to define "failures" during the tests. Failure was defined either as loss of function (i.e., electrical short, either conductor to conductor or conductor to ground) or nonpiloted ignition. Tests were conducted (Section 3 and Reference 2) on two types of unaged cable in a radiant heat facility and in an oven. For the cables tested, electrical shorts occurred at heat flux values less than those required for nonpiloted ignition.

With this information, an acceptance criteria section was written for the program plan.[6] However, this was not used in evaluating the tests conducted by UL. Since the electrical integrity of the cables was monitored in the preliminary experiments and full-scale tests, the occurrence of an electrical short is called a failure in this report.

Although a loss of electrical integrity was selected in the tests as a convenient "failure" measure, other more stringent criterion (e.g., insulation damage without shorting) may be more appropriate for nuclear power plant applications. However, the selection of a fire damage criteria was beyond the scope of this study.

2. Scoping Calculations

Because of the expense of full-scale testing, it was desirable that certain aspects of the 20-ft separation tests be analyzed to identify critical variables which may significantly affect the test results. A sensitivity analysis of these variables helped in developing an economical test plan by reducing the number of tests to be conducted. The severity of a compartment fire can be characterized by a number of variables, the most critical of which are room geometry, fuel load (type and geometry), and ventilation conditions. In preliminary planning for the 20-ft separation tests, both the room geometry and fuel load were specified by the NRC. Natural ventilation (buoyancy induced ventilation) of the fire was provided by an open doorway of standard dimensions.

A variety of analytical techniques have been reported in the literature which can be used to calculate the development of a fire inside an enclosure. Many of these research efforts have been directed toward a description of the fire environment in terms of predefined zones or control volumes.[8-10] The control volumes are coupled through mass and energy balances to provide a set of equations that describe the transient development of the fire environment inside the enclosure. An alternate approach is to describe the fire environment by direct solution of the governing transport equations. An example of this method is described by Ku et al.[11] A particular need of the present test program was the ability to predict the thermal response of a component (e.g., cables) located inside a compartment, given its location relative to an exposure fire. Of the analytical methods surveyed, the Harvard Fire Code (HFC)[8] was found to possess this capability. Therefore, all preliminary calculations performed in support of the 20-ft separation program were conducted with the HFC to provide scoping calculations of the fire environment.

The calculations discussed in the following sections are limited to the preliminary experiments. The reasons for this are twofold. First, the preliminary experiments were conducted to establish the configuration for the full-scale separation tests. Scoping analyses were carried out to help minimize the number of preliminary experiments to be conducted. Second, and more important, the fuel configuration used for the full-scale tests was not amenable to predictive analysis because the time-dependent heat release for the fuel system (two vertical cable trays) was not known *a priori*. The rate of heat release of the burning electrical cables results in a strong transient development of the fire environment (Figure 23). Fuel models available for most analytic methods are structured for constant or quasi-steady heat release fires (i.e., pool fires and gas burners). Suitable models for general fuel sources with highly transient heat release characteristics have yet to be developed.

The time-dependent aspect of the full-scale tests must be considered in any analytical investigation. Efforts are currently under way to improve the analytical models so that these tests may be analyzed.

2.1 Separation of the Redundant Safety Component

The 20-ft separation criterion requires that redundant safety components be separated by a horizontal distance of 20 ft with no intervening combustibles between the two redundant systems. As a preliminary case study, a series of fire simulations were conducted with the HFC to determine the predominant sources of heat transfer to a redundant component located in the immediate vicinity of an exposure fire. The situation analyzed is shown in Figure 1, with the primary fuel source representing the exposure fire and the target object representing the redundant safety component. The primary and target objects were assumed to be circular, with surface area of 21.5 ft^2 (2 m^2) and 10.8 ft^2 (1 m^2), respectively. The properties of each object were specified to be those of cable insulation material as given by Dube.[12]

A general feature of a developing compartment fire is the formation of a zone of hot combustion products and excess air in the upper region of the compartment. As the fire progresses, the hot layer descends toward the floor, spilling out through the upper part of the open door, while cool air is drawn into the compartment through the lower section of the door. In an actual compartment fire the hot layer region is thermally stratified; that is, the temperature varies primarily in the vertical direction across the layer. The numerical solutions provided by the HFC, however, yield only a global mean temperature for the region.

The target in Figure 1 is assumed to be located at the floor level so that its surface is exposed to both the fire plume and the hot layer region near the ceiling. The fire plume, the hot gas layer, and the enclosure walls each provide some component of radiative heat transfer to the target denoted by $\dot{Q}_p$, $\dot{Q}_H$, and $\dot{Q}_w$, respectively. The primary and target system was analyzed with two compartment geometries described in Table 1.

Table 1. Geometry for Separation Case Study

	Room 1		Room 2		Doorway	
	(ft)	(m)	(ft)	(m)	(ft)	(m)
Length	25.0	7.6	50.0	15.2	—	—
Width	20.0	6.1	40.0	12.2	3.0	0.9
Height	8.0	2.4	8.0	2.4	7.0	2.1

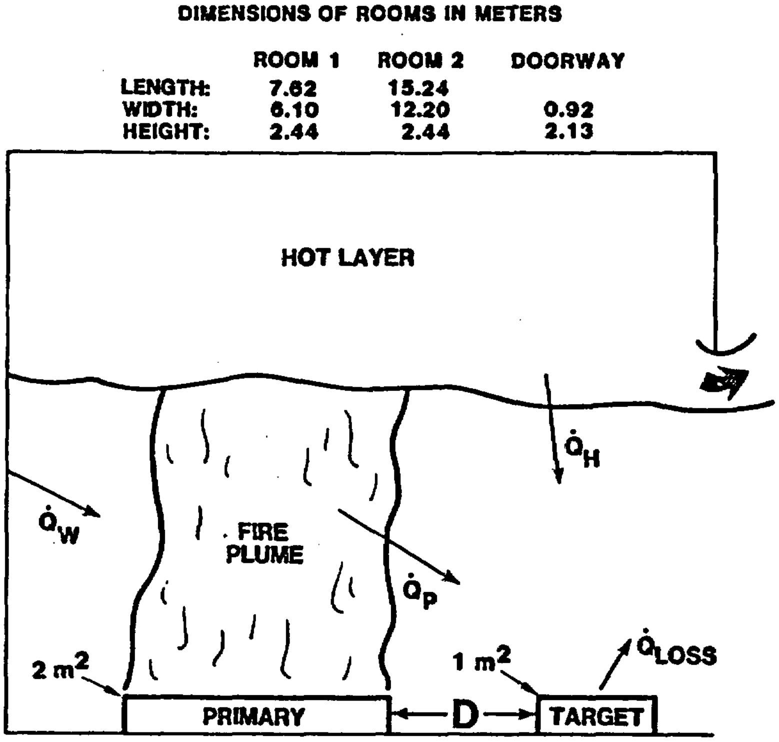


Figure 1. Radiant Heat Transfer to Target Object

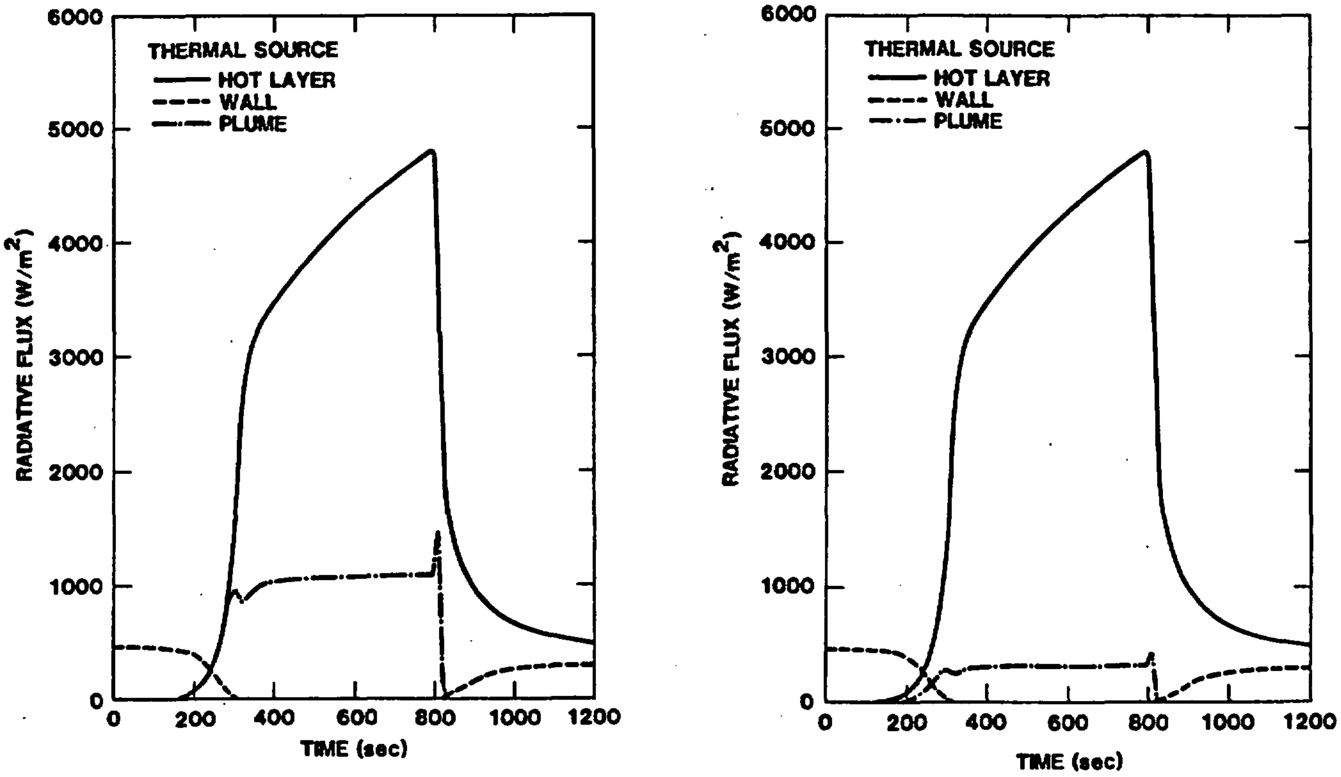


Figure 2a. Room 1, D = 0.2 m

Figure 2b. Room 1, D = 1.0 m

Figure 2. Radiative Flux to Target

The enclosure door, which provided natural ventilation to the fire, and the enclosure height were identical for both rooms. Fire simulations were conducted for each room with the fuel and target located along the centerline of the room and with their properties fixed for all cases. The separation distance denoted by "D" in Figure 1 was varied in each fire simulation as an independent variable.

Typical solution results are shown in Figures 2a and 2b for Room 1. Figure 2a shows the radiant heat transfer rate to the surface of the target from the hot layer, the fire plume, and the walls of the compartment. Note the dominant effect of the hot layer during the period that the fire is fully developed (300 – 800 s). The separation distance in this case was 0.7 ft (0.2 m). In Figure 2b an identical solution is shown; however, in this case the separation distance between the exposure fire and the target source is increased to 3.2 ft (1.0 m). Here it should be noticed that the contribution from the fire plume has been reduced by a factor of ~2 from the case shown in Figure 2a. The contribution of heat transfer from the hot layer region is unchanged from the previous case.

The trends described above may be generalized by examining the rate of heat transfer to the target at a particular time in the fire development, with the separation distance as the independent variable. The time chosen was 300 s, corresponding to the onset of the period during which all of the fires examined were fully developed. Figure 3 shows the effect of separation distance on flux rate to target, with relative contributions of the fire plume and the hot layer region. Note that as the separation distance between the target and the exposure fire increases, the contribution of radiative heat transfer to the target due to the fire plume (denoted by the triangles) decreases. This is the view factor effect where the solid angle through which the target "views" the fire decreases as the separation distance between the two increases. Of even greater importance is the fact that the contribution of heat transfer to the target from the hot layer region is essentially *independent of separation distance* for the two rooms. This trend is clearly shown in Figures 2a and 2b and Figure 3.

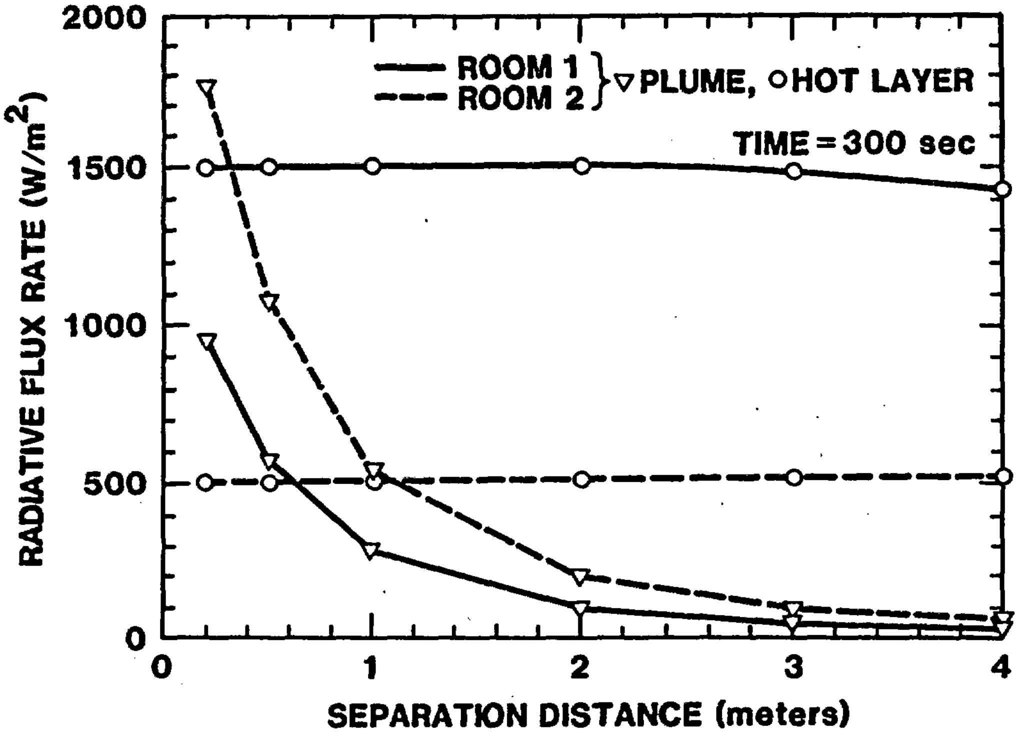


Figure 3. Effect of Separation Distance on Flux Rate to Target

The significance of these results with regard to the 20-ft separation requirement is that for a redundant component separated 20 ft from an exposure fire, the dominant source of heat transfer to the component is *not* from the exposure fire, but from the hot layer region near the ceiling. Since the heat transfer from the fire plume is small, the heat transfer to the component is maximized when the contribution from the hot layer is maximized. Assuming the region to be optically thick and considering convective effects, the heat transfer from the hot layer region to the redundant component is maximized when the component is located near the ceiling and engulfed by the hot layer. This conclusion was later verified in the results obtained from Experiment 1.

2.2 Analytical Fire Model for Preliminary Experiments

For the preliminary experiment configuration shown in Figure 9, a model was developed for the HFC to simulate numerically the transient development of the fire. The configuration for the model is shown in Figure 4. Because of limitations inherent in the code, certain details of the experiment could only be approximated. The rectangular shaped fuel source was modeled as a circular slab with a diameter of 2.52 ft (0.76 m). This diameter equates the surface area of the fuel slab to that of the fuel pan (1 ft × 5 ft) to ensure that energy release rates and total fire duration are matched to those of the actual experiment. The thermal properties of liquid heptane were used to describe the fuel characteristics of the fuel slab. A detailed thermal model of the cable bundles located in the redundant trays (Appendix A, Figure 4) is beyond the scope of the present version of the HFC. However, to simulate the temperature response of the cables during the fire, a short section of the uppermost cable bundle (upper tray in Figure 9) was approximated by a small circular slab (Figure 4). The thermal properties of the target slab were specified to be those of cable insulation material as in the previous case study. The target position was chosen to coincide with the midpoint of the upper cable tray. The upper surface of the slab was oriented parallel to the plane of the ceiling to monitor radiative and convective flux rates from the combustion gases in the upper region of the compartment and the nearby walls and ceiling.

Solutions for the configuration shown in Figure 4 were generated for both a single-width door opening and an alternate door opening to study the effects of increased ventilation to the fire. The two door openings are shown in Figure 5.

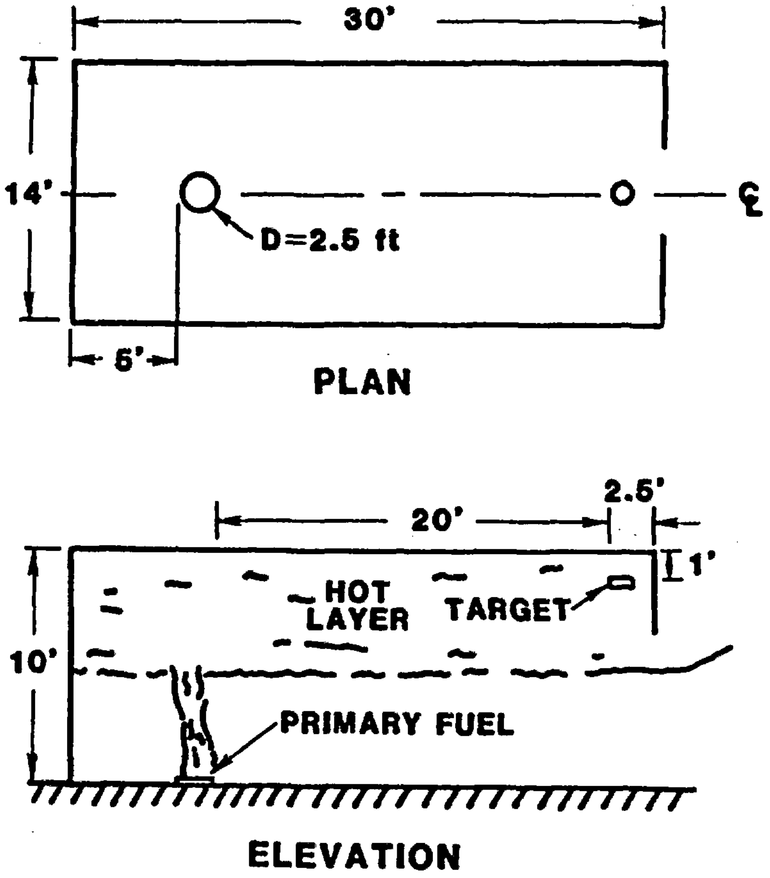


Figure 4. Compartment Configuration for Fire Simulations

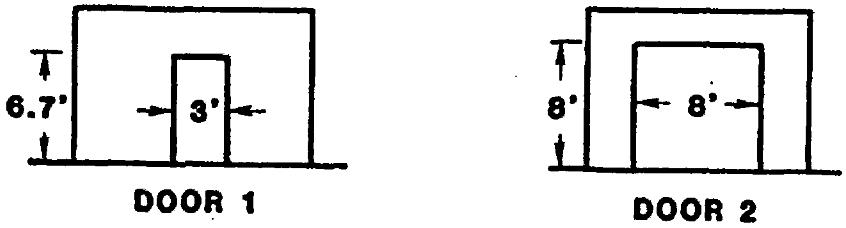


Figure 5. Door Openings for Ventilation Analysis

2.3 Effect of Door Opening on Fire Severity

Before discussing results, it is relevant to examine the concept of fire severity in terms of how the compartment door opening may affect the thermal response of a component located inside the compartment.

As noted by Harmathy,[13] the flow rate of air into the compartment is as important as the specific fuel load in determining fire severity. For small fires (small compared to the total floor area), the rate at which air enters the compartment is more than sufficient for stoichiometric combustion of the fuel volatiles. Consequently, the energy released in the compartment is proportional to the fuel pyrolyzation rate. More typically, however, a fire burning inside a compartment is controlled by the rate of ventilation into the compartment. The physical processes by which this control occurs depends largely upon the type of fuel being burned. For liquid fuels (or any noncharring fuel), the fuel pyrolyzation rate, $\dot{m}_p$, is traditionally assumed to be thermally controlled and may be described by the equation

$$\dot{m}_p = \frac{q''(T)A_p}{L} \tag{1}$$

where A_p is the surface area of the pool and L is the total enthalpy required to generate a unit mass of pyrolysis products. For ventilation-controlled fires, the net heat transfer to the pool, $q''(T)$, is influenced indirectly by the compartment ventilation (door size) by controlling the gas-phase oxidation reactions in the burning plume. As ventilation increases, the amount of fuel volatiles that undergo combustion also increases, thereby leading to an increase in the overall temperature inside the compartment. Because of the coupling effect between the fuel and the compartment, the hot gas and walls of the compartment (at their elevated temperature) radiate more effectively back to the fuel source (thermal feedback). This increased temperature produces an increase in the fuel pyrolyzation rate and a corresponding reduction in the duration of the fire.

When the fire is ventilation controlled, the principal effect of increasing the door opening is to produce a shorter duration fire with an increase in the compartment temperature. Therefore, if the severity of a fire is defined in terms of its ability to damage the compartment (and its contents), it is reasonable to consider that increasing ventilation in this case increases the fire severity as a result of the enhanced combustion within the compartment. This leads to a higher hot layer temperature and a corresponding increase in the rate of heat transfer to a component or object located in the enclosure. A reduction in ventilation lessens the fire damage potential since a significant fraction of the volatiles produced through pyrolyzation of the fuel remain uncombusted because of insufficient oxygen. The unburned volatiles will emerge from the doorway of the compartment along with other combustion products.

When the fire is fuel controlled, the energy release rate is determined by the rate of fuel pyrolysis, and all volatiles produced from the fuel undergo combustion within the compartment. In the fuel-controlled regime, small changes in door opening have a relatively small effect on the temperature response of a component or object located in the room. With larger door openings, excess air will be entrained by the fire plume, reducing the environment temperature by diluting the combustion products.

From this discussion, it is evident that the development of the fire environment and its ability to damage a component or system may be significantly influenced by the rate of ventilation into the compartment.

2.4 Pre-experiment Predictions for UL Experiment 1

For the Experiment 1 simulation, solutions were generated to examine the effect of two different door sizes on the fire environment. Figure 5 shows the two door openings, the size of a standard single-width door and a standard double-width door as found in many power plant installations.

Solutions for the important variables which characterize the development of the fire were obtained for a total duration of 10 min. The time step for the code integration routine was 0.25 s with each simulation requiring ~45 s of CPU time on a CDC-7600. The cost to perform each simulation is therefore not expensive.

Solutions for the hot layer temperature for each simulation are shown in Figure 6. The two solutions are nearly identical, indicating (1) that the development of the fire environment is insensitive to the changes in door size and (2) that the total fire duration is unaffected as well. Thus the calculations indicate the 5 ft^2 (0.46 m^2) pool fire used in Experiment 1 is not ventilation limited for the configurations considered. Sufficient air is drawn through each door opening to burn all available fuel volatiles.

Figure 7 shows the depth of the hot layer for the two different doors. The smaller door opening can be seen to produce a slightly deeper layer as measured from the ceiling. Since the hot layer temperatures were found to be essentially identical (Figure 6), the temperature response of the target is the same regardless of door size. This result is verified in the solution for the target temperature shown in Figure 8.

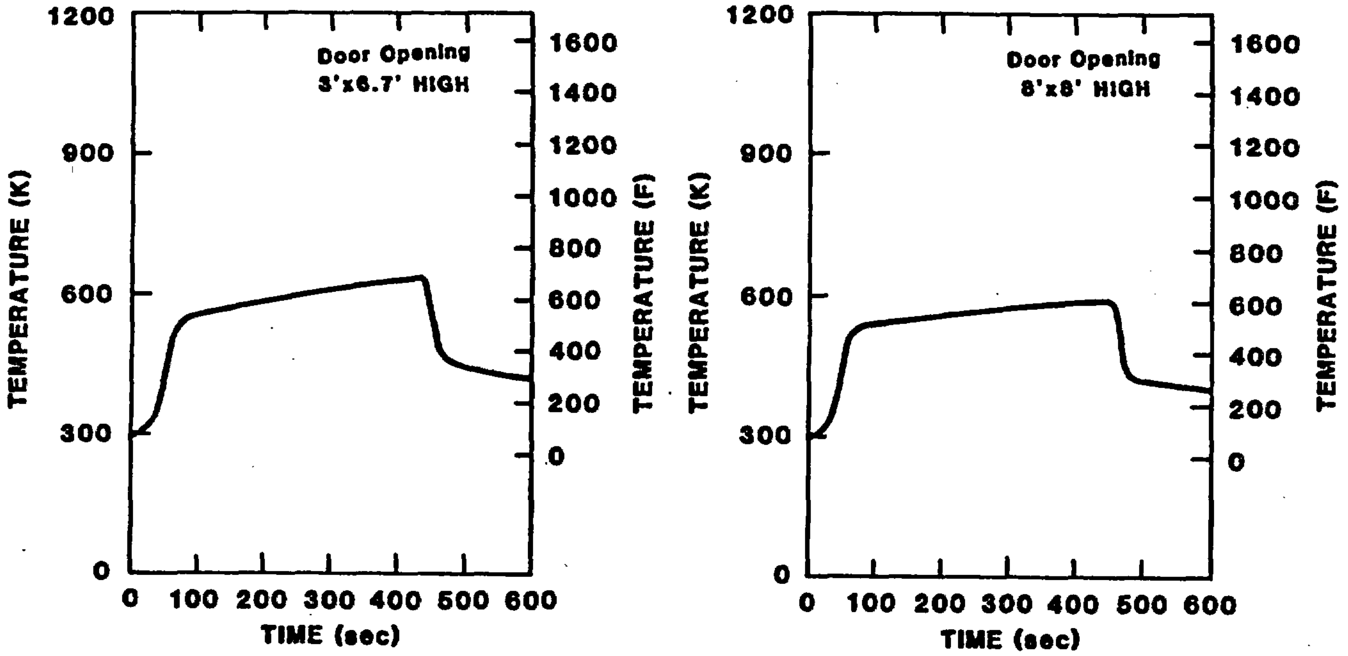


Figure 6. Comparison of Hot Layer Temperature: 5 ft^2 Pool

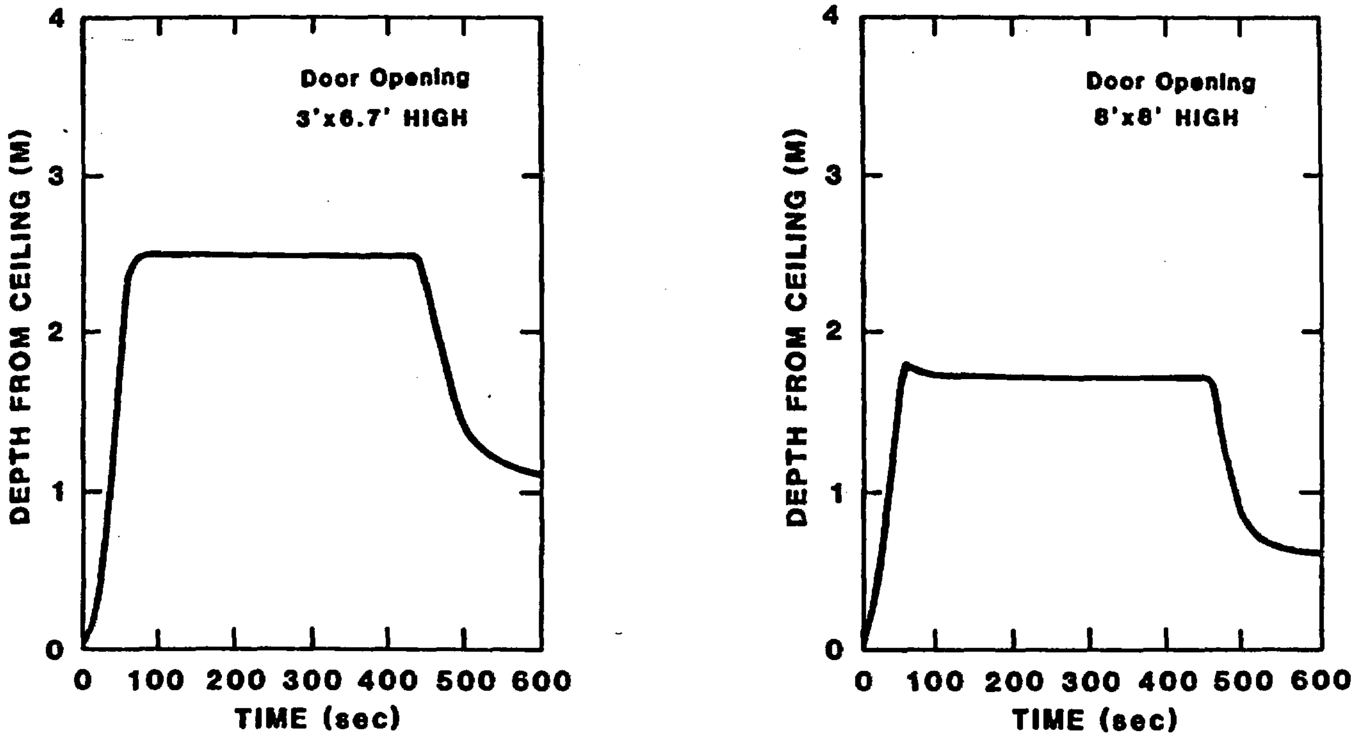


Figure 7. Predicted Depth of Hot Layer in Compartment: 5 ft^2 Pool

Maximum values for the pertinent variables characterizing the fire environment, as predicted for Experiment 1, are provided in Table 2.

The convective component of the total heat flux is calculated from an empirical correlation for an effective heat transfer coefficient. Approximately 50% of the total heat flux may be attributed to convective effects according to the HFC analysis.

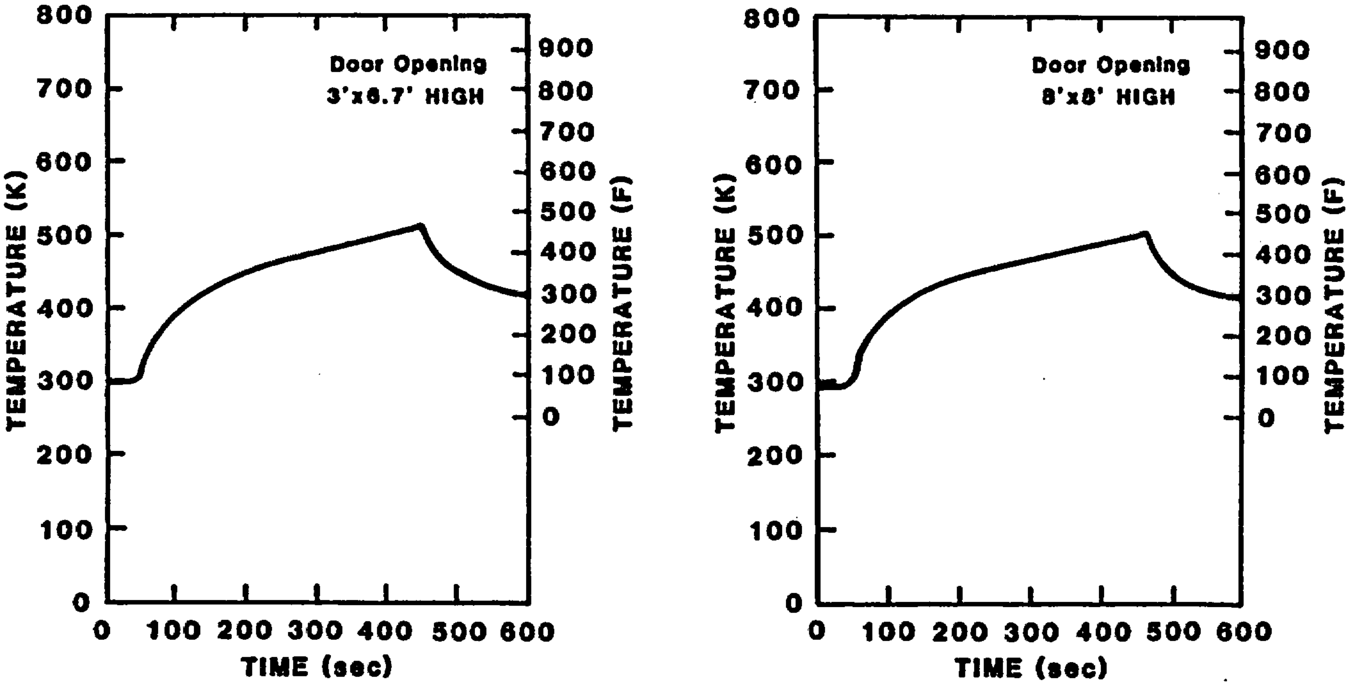


Figure 8. Predicted Temperature Response of Target Object: 5 ft^2 Pool

Table 2. Maximum Values for Predictions of Experiment 1

	Door size	
	3.0 ft × 6.7 ft	8.0 ft × 8.0 ft
Hot Layer Temp (°F)	678	606
Total Heat Flux to Target (kW/M^2)	11.6	10.5
Target Temperature (°F)	464	444
Fire Duration (s)	482	498

3. Cable Damageability Experiments

Appendix R states that the redundant safety system shall be "free of fire damage"; however, the term is not defined in Appendix R. For the purposes of this investigation, the ability to maintain electrical integrity was considered to be "free of fire damage" (i.e., the cables remained functional). Consequently, two sets of experiments were conducted to determine the threshold level of failure for the cables to be used in the UL tests. While the tests at UL did monitor for circuit integrity, they did not establish threshold damageability values. These results are important when conducting analyses to predict whether a failure would or would not occur. They are also useful as input to the planning of full-scale tests. By having some idea of the temperatures or heat fluxes at which cable damage occurs, analyses can be made using fire models to estimate approximate fuel loads and fuel burning rates which are likely to cause critical temperatures or heat fluxes in the vicinity of redundant test cabling.

Two types of experiments were performed on the same kinds of qualified and unqualified cable which were to be used in the UL tests. The first set of experiments was performed in a radiant heat facility at constant heat flux levels, while the second set was conducted in an oven at constant temperature.[2] Thermal aging and radiation exposure effects were not included in the investigation. Both of these aging characteristics as well as other conditions not investigated (e.g., suppressant damage, corrosive vapor damage), may detrimentally affect the performance of electrical cables. However, an investigation of these effects was beyond the scope of this study. Discussion of this topic can be found in References 14 – 17.

In the radiant heat experiments, the critical heat flux at which cable damage in the form of electrical failure (short from conductor to tray) or nonpiloted ignition was determined. The critical flux for electrical failure was determined to be ~8 kW/m^2 for the unqualified cable and ~18 kW/m^2 for the qualified cable. The critical flux for nonpiloted ignition was determined to be ~22 kW/m^2 for the unqualified cable and ~28 kW/m^2 for the qualified cable. In the second set of experiments the temperatures at which electrical failure (short from conductor to conductor) occurs were determined by exposing cables to a constant temperature in an oven. For the unqualified cable an exposure of >265°F (130°C) for a period of 60 min, or for qualified cable an exposure of >480°F (250°C) for a period of 60 min resulted in electrical shorts. Full details are given by Lukens.[2]

As pointed out, Appendix R does not define "free of fire damage." Lukens[2] states, "The properties of electrical cables and threshold values for electrical cable damage identified in this report should not be interpreted as an acceptance criterion for electrical cables exposed to a fire environment. The meaning of the term 'free of fire damage' and, more specifically, what properties should be used to determine electrical cable functionability have not currently been defined by the NRC. The identification of the properties and their corresponding levels, which determine cable functionability, should be the first step in the establishment of an acceptance criterion. With the properties and levels identified, the types of thermal or fire environments which could cause cable damage can be quantified. An acceptance criterion can then be established in terms of both electrical cable properties and thermal exposure levels. This information is necessary for the proper design and interpretation of tests and experiments such as those..." described in this report, ". . . and is also necessary in the development of analytical tools to predict electrical cable damage in a potential fire environment. It is therefore recommended that the NRC take steps to define the properties and their respective levels, which will be used to determine cable functionability after exposure to a fire environment." In addition, it should be noted that, as stated by Lukens,[2] the values quoted above ". . . should not be interpreted as an acceptance criterion for electrical cables exposed to a fire environment. They are applicable to two particular types of unaged electrical cable . . . " tested and ". . . would need to be evaluated for any other type of electrical cable." Also, the values are based on a very limited quantity of test data.

4. Ignition-Source Fire Characterization

Sandia National Laboratories conducted a series of ignition-source fire experiments to evaluate the relationship between the heptane ignition-source fires used in the Underwriters Laboratories 20-ft separation tests and ignition-source fires consisting of several types of combustible power plant refuse. A full description of these experiments is given in Appendix B.

Twelve experiments were conducted at the Sandia Fire Test Facility, in which 6 different fuels were evaluated as the ignition source. Fuel type and quantity as well as the number of experiments conducted for each fuel are shown in Table 3. Duplicate experiments were run to determine the replicability of results. The tests using 5 gal heptane were used as a baseline; the other tests were compared against them to determine the difference in potential heat of combustion, heat fluxes, room temperatures, and fire severity. In the final test, one vertical cable tray with qualified cable was placed behind the ignition-source fuel of 30 lbs of computer paper in two plastic trash cans. The purpose of this test was to determine whether a transient fuel was capable of igniting an in-situ fuel such as qualified electrical cable.

Table 3 shows that the 5 gal heptane ignition-source fires (Experiments 1 and 2) produce higher peak enclosure temperatures (490°F (255°C)), greater oxygen depletion (17.8%), and higher peak emissive powers (104 kW/m^2) than the other ignition-source fire experiments. Also, the duration of the high heat fluxes in Experiments 1 and 2 was longer than in the other experiments.

In Experiments 5 and 10, 30 lbs of computer paper in two plastic trash cans produced the highest peak fire temperature, 1790°F (980°C) (Appendix B). These ignition-source experiments also produced a peak emissive power only 10% less (92 kW/m^2) than the 5 gal heptane experiments. A major difference between the two experiments is that the heptane fire reached its peak heat flux in 2 min and held that peak for ~18 min. The solid fuels (computer paper and plastic trash cans), on the other hand, took 18 min to reach peak heat flux. Also, as soon as the peak was reached, the temperature started to drop. The other experiments did not produce comparably severe fire environments. The heptane ignition-source fires produce a quicker and more uniform energy release rate than the solid fuel (transient) ignition-source fires.

In Experiment 12, a vertical cable tray containing 12.5% fill of IEEE-383 qualified electrical cable was placed next to the ignition-source fire material of 30 lbs of computer paper in two 16.5-lb (7.5-kg) plastic trash cans. This solid fuel "trash" was capable of igniting the cables to produce a self-sustained cable tray fire within 12 min after ignition of the fuel. Therefore, the heptane ignition-source fires used in the 20-ft separation tests at UL do not appear to be more likely to cause ignition of secondary sources than some conceivable trash-type ignition-source fires.

Table 3. Ignition-Source Fire Experiment Matrix

Experiment[a]	Fuel Source	Max Room Temp[b] (°F)	Min Exhaust Oxygen Content[c] (%)	Max Peak Emissive Power[b] $\left(\frac{kW}{m^2}\right)$
1, 2[d]	5 gal (18.9 liters) heptane	493	17.8	104
3	20 lb (9.1 kg) computer paper	280	19.8	33
4, 11	68 lb (31 kg) simulated plant trash	246	19.7	44
5, 10	30 lb (13.6 kg) computer paper in two 16.5-lb (7.5 kg) plastic trash cans	279	19.8	92
6, 7, 8[d]	1 gal (3.8 liter) heptane	318	19.7	88
9	80 lb (36.4 kg) computer paper	185	20.5	31
12[e]	30 lb (13.6 kg) computer paper in two 16.5-lb (7.5 kg) plastic trash cans plus one vertical cable tray with 43 cables (12.5% fill)	394	19.1	—

NOTES:
[a] All fires were ignited with ½ cup alcohol and an electric match.
[b] These values represent the maximum of that value, for the experiments of that type.
[c] These values represent the minimum, for the experiments of that type.
[d] The heptane was burned in a 1-ft × 5-ft pan, similar to that used in the UL experiments and tests
[e] The trash fire ignited the cables in 12 min.

5. Preliminary Experiments Conducted at Underwriters Laboratories

Underwriters Laboratories under contract to Sandia conducted four preliminary experiments and six full-scale tests to simulate the thermal environment created by an exposure fire inside an enclosure. The purpose of the preliminary experiments was to develop data on the effect of changes in room size, fire location, and ventilation conditions so that a conservative configuration could be used for the full-scale tests. The variation of these parameters was made in conjunction with results from the scoping calculations discussed in Section 2. Each experiment investigated a different configuration through simple modification of the test enclosure. Before the experiments were conducted, a test plan[6] was written by Sandia. Further information on the preliminary experiments, including full details of the instrumentation and its location in the test compartment, is provided in Appendix A.

5.1 Preliminary Experiment Configurations

The compartment, both for the experiments and for the full-scale tests, had a simple parallelepiped geometry. In all experiments, the width of the room was 14 ft and the ceiling height was 10 ft. In Experiment 1, the overall room length was 30 ft, while in Experiments 2 – 4, the length was reduced to 25 ft by construction of a secondary wall at the rear of the enclosure. The effects of changing ventilation conditions in the enclosure were investigated by considering three different door openings in the test series. In Experiments 1 and 2 the door opening was 8 ft × 8 ft (2.4 m × 2.4 m), while in Experiment 3 the door width was reduced to 4 ft × 8 ft (1.2 m × 2.4 m). In Experiment 4 the door opening was closed by placing inorganic boards against the opening. No gaskets or sealing materials were used to close gaps between the boards and the exterior of the enclosure. The room configurations for the four preliminary experiments are shown in Figures 9 and 10.

The fuel source for all four experiments was 10 gal heptane contained in a rectangular steel pan, 1 ft by 5 ft by 1 ft deep (.3 m × 1.5 m × .3 m). The pan was filled with water to a depth of 4 in.(.1 m), and the heptane, being less dense than water, was floated on top. This procedure aided in cooling the pan and prevented pan failure caused by thermal expansion effects. In Experiment 1, the pan containing the heptane was 6.5 ft (2 m) from the wall opposite the door opening (i.e., the rear wall); in the other experiments the pan was positioned against the rear wall. There were no cables or trays to simulate a safety system under immediate fire threat or to add to the fuel load; however, there were two horizontal cable trays located a nominal distance of 20 ft from the heptane fire to simulate the redundant safety system. These trays were placed 1 ft (.1 m) and 2 ft (.2 m) from the ceiling, parallel with and nearest to the wall with the ventilation opening. This positioning of the redundant trays was in accordance with HFC calculations that indicated the trays would be engulfed by the hot gas layer at this location. In Experiment 1, bundles of unqualified cables 1 ft long were placed in both trays; in Experiments 2 – 4, bundles of unqualified and/or qualified cable were placed in the top tray only. In these experiments the lower tray contained two continuous loops of cable energized to monitor for the occurrence of electrical shorts. In Experiment 1, an additional tray 3 ft from the floor contained bundles of unqualified cable.

The cables used in the testing program were of the same type used by Sandia in conducting prior fire research experiments. The unqualified cable was 3 conductor, No. 12 AWG, polyethylene insulation with polyvinylchloride jacket. The qualified cable was also 3 conductor, No. 12 AWG, but had a cross-linked polyolefin insulation and jacket. The terms qualified and unqualified refer to whether the cable met the flame test requirements of IEEE-383-1974.

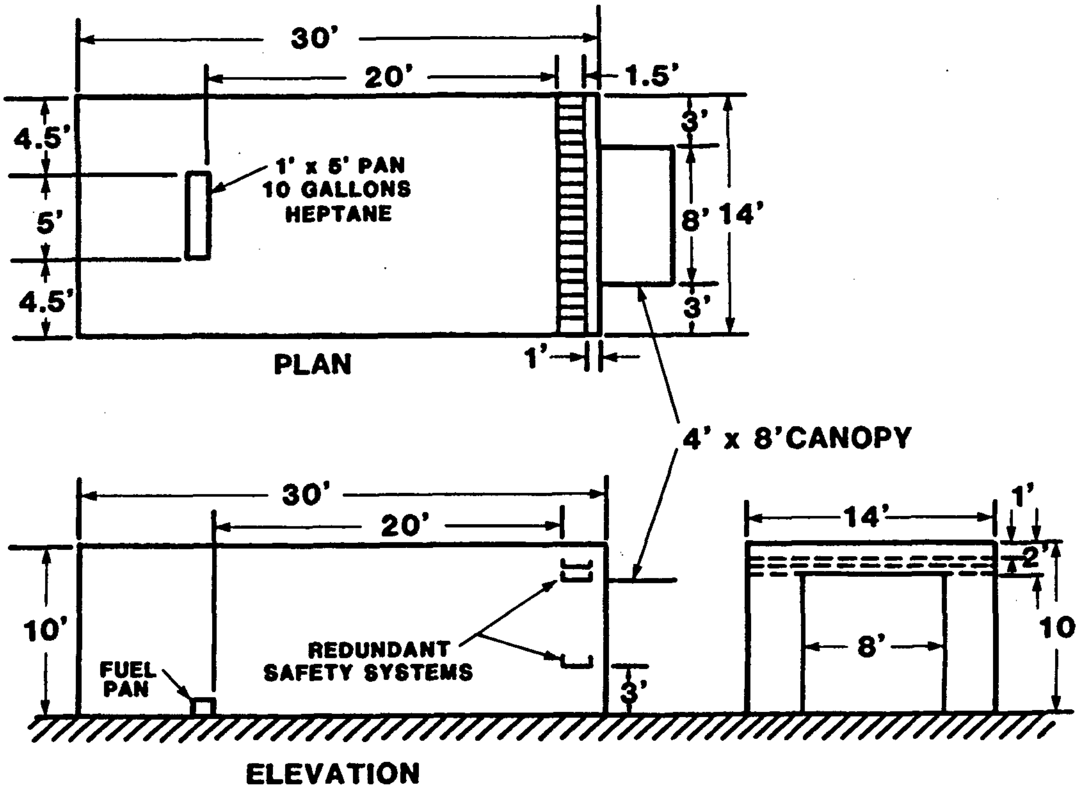


Figure 9. Enclosure Detail: Preliminary Fire Experiment 1

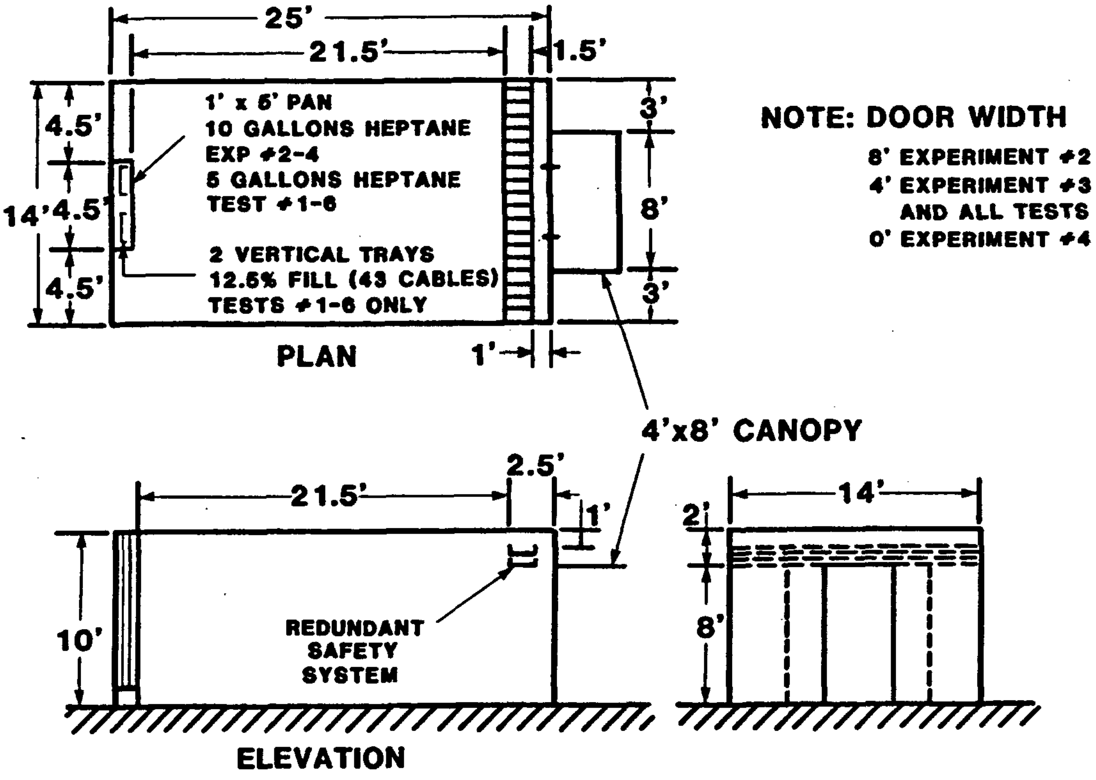


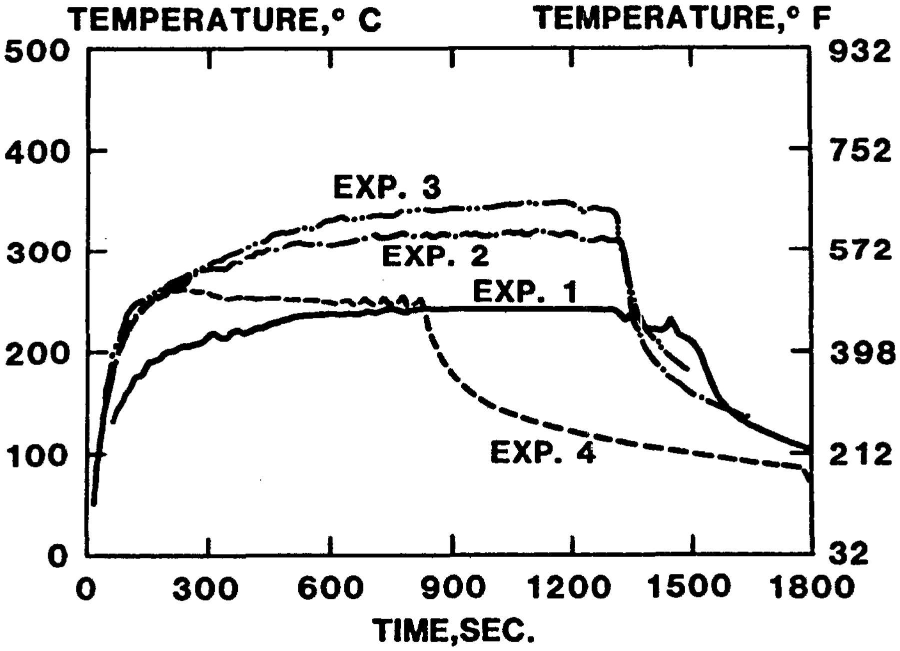
Figure 10. Enclosure Details: Preliminary Fire Experiments 2, 3, 4, and Full-Scale Tests 1 – 6

5.2 Instrumentation

To assess the severity of the thermal environment inside the enclosure, extensive measurements of both temperature and heat flux were made in all preliminary experiments and full-scale tests. Thermocouples were located throughout the enclosure to obtain the temperature distribution within the room, particularly in the region near the ceiling occupied by the hot gas layer. Other thermocouples were placed to record temperatures on the walls and ceiling, as well as temperatures within the sample cable bundles and the energized cable loops. Calorimeters and radiometers were located at key locations in the test compartment and in the redundant safety trays to monitor the levels of local heat flux. Pressure probes were used at three locations in the plane of the door opening to estimate the flow velocity of both the incoming air and the exiting smoke layer. In addition, circuit integrity within the energized cable loops was monitored. Further details on the instrumentation may be found in Appendix A.

5.3 Fire Environment

To begin each experiment, the heptane was ignited with an electric match placed near the fuel surface. Flames from the heptane fire were luminous and uniform across the pan area. In Experiment 1, the maximum flame height was ~9 ft (2. 7 m); in Experiments 2 – 4 (with fuel pan adjacent to the wall) the flames impinged on the ceiling and were deflected outward along the ceiling ~2 ft. The hot gas layer developed rapidly in all experiments, requiring ~60 s to appear fully developed. The redundant cables near the ceiling were therefore engulfed by the layer soon after ignition of the heptane. The lower boundary of the hot layer was smooth and level and maintained a stable position throughout each experiment. The bottom of the hot layer was ~3 ft (.9 m) above the floor in Experiment 1; 4.7 ft in Experiment 2; 4 ft in Experiment 3; and 8 in. in Experiment 4. The depth of the hot gas layer in Experiment 4 was caused by the closed opening preventing the smoke from leaving the compartment. The average temperature vs time of the three thermocouples located 1 ft below the ceiling and 2 ft in front of the redundant horizontal tray are shown in Figure 11. The temperature increase was relatively uniform for the four experiments and remained "flat" until either the fuel was consumed (Experiments 1 – 3) or "oxygen starvation" occurred (Experiment 4). In this latter case, the fire continued to burn until the oxygen content of the surrounding environment was insufficient to sustain combustion.

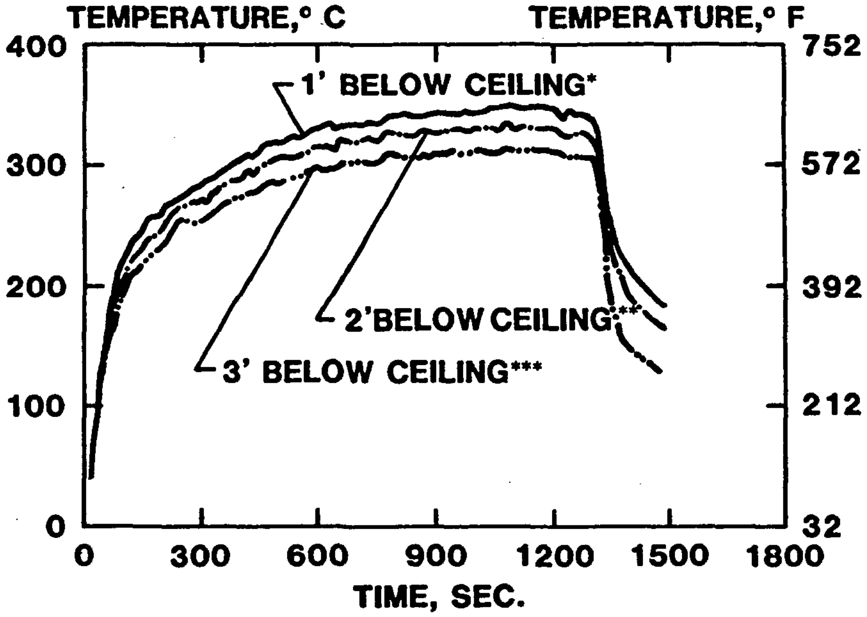


TEMPERATURES ARE THE AVERAGE OF THERMOCOUPLES 69, 73, AND 77. (1 FT. BELOW CEILING AND 2 FT. FROM THE TRAY)

Figure 11. Average Ceiling Temperature Near Horizontal Trays During the Experiments

The recorded maximum average atmospheric temperature occurred in Experiment 3 and was ~660°F (350°C) near the horizontal trays (Figure 11). The variation of temperature within the hot gas layer as a function of the distance below the ceiling is shown for this experiment in Figure 12. Thermal stratification in the hot gas layer is clearly evident in these measurements. The maximum difference is ~70°F (45°C) over the 2 ft vertical distance.

Figure 13 shows the variation of atmospheric temperature with lateral direction for a set of four thermocouples 4 ft and 20 ft from the fire source as occurred in Experiment 3. The relatively small variation in temperature with lateral separation distance should be noted. Also shown in the figure is the variation of temperature with the vertical direction at the two thermocouple stations. The greater vertical temperature variation near the fire source is likely due to plume effects, particularly at the 1 ft location (TC 110).



*AVERAGE TEMPERATURES OF THERMOCOUPLES 69, 73, AND 77
**AVERAGE TEMPERATURES OF THERMOCOUPLES 70, 74, AND 78
***AVERAGE TEMPERATURES OF THERMOCOUPLES 71, 75, AND 79
(THERMOCOUPLES ARE 2 FT. IN FRONT OF HORIZONTAL TRAY)

Figure 12. Temperatures at Several Levels Within the Gas Layer During Experiment 3

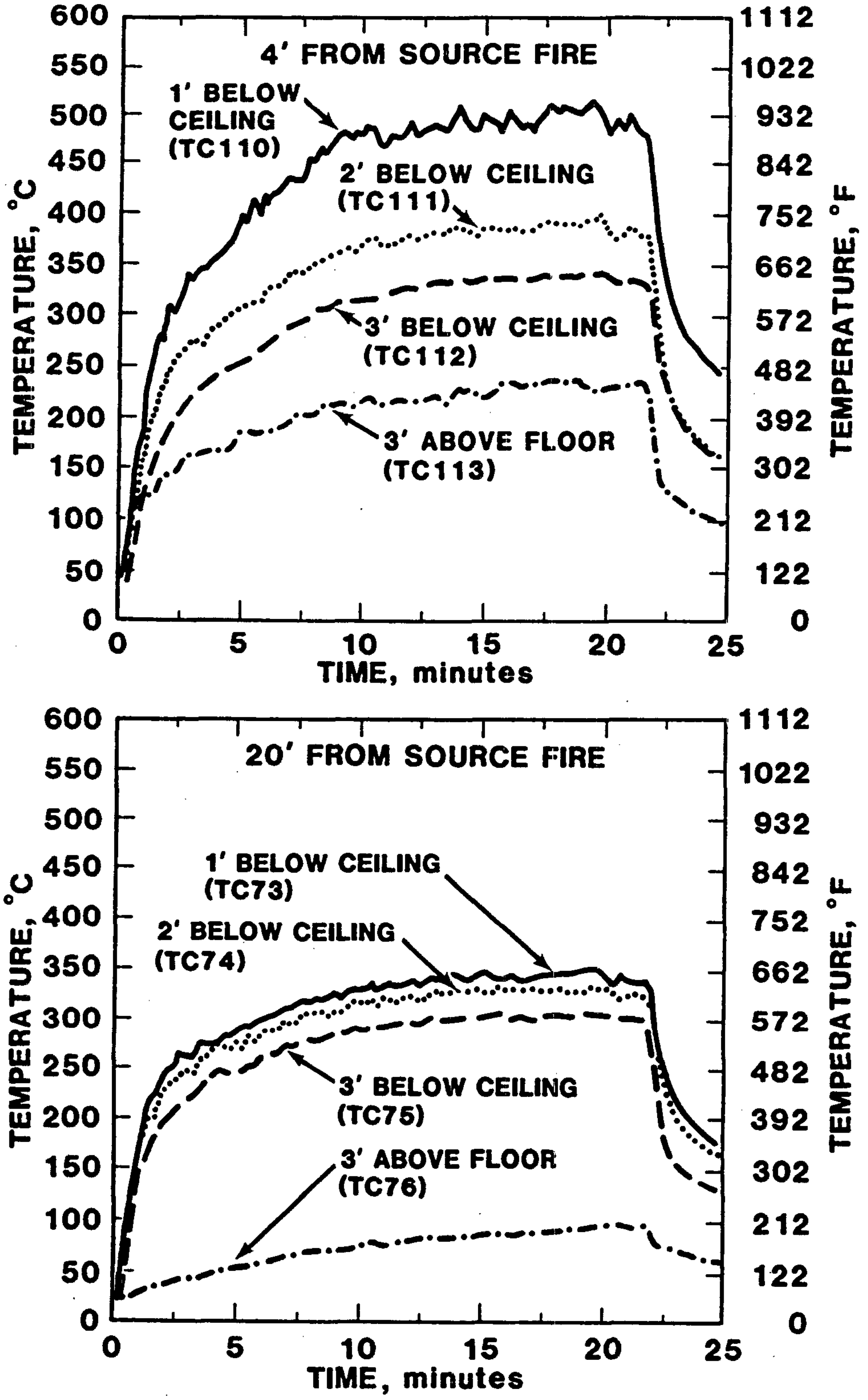


Figure 13. Variation in Atmospheric Temperatures With Lateral Direction

5.4 Effects of the Fire Environment on the Redundant System

Since the redundant cable trays were engulfed by the hot gas layer in each of the four experiments, they were subjected to locally severe thermal environments as evidenced by the temperature trends shown previously in Figure 11. The total heat transfer rates measured at the lower horizontal tray for each experiment are shown in Figure 14. Since the hot layer has some velocity relative to the trays, it may be inferred that the total heat transfer is due to both radiative and convective sources. No attempt has been made to distinguish between these two components of heat transfer in the data reduction to date. The maximum total heat flux for all four experiments was recorded in Experiment 3 at the lower horizontal tray and was 13 kW/m^2.

The cables in the lower horizontal tray were energized in Experiments 2 – 4 to check for cable integrity. In Experiments 2 and 4, a conductor to tray (ground) short occurred in the unqualified cables at 10.23 min and 12.25 min, respectively. The qualified cable in Experiments 3 and 4 maintained electrical integrity for the duration of the tests. The cable jacket temperatures for the energized cable loops were recorded in Experiments 2 – 4. Depending on the location of the thermocouple within the cable, there can be large variations in the recorded temperature. Therefore, the local temperature measured by the thermocouple imbedded in the cable may not necessarily correspond to the location of failure; thus, care must be taken in interpreting the data.

5.5 Observations and Results

As stated, the purpose of the preliminary experiments was to aid in defining a conservative room and fuel configuration in which to conduct the six full-scale tests. The effect of moving the fire against the rear wall was to increase the severity (temperature) of the thermal environment surrounding the redundant cables (both temperatures and heat fluxes were higher in Experiment 2 than in Experiment 1). There was also an increase in severity of the environment when the door opening was decreased from 8 ft × 8 ft (Experiment 2) to 4 ft × 8 ft (Experiment 3). Blocking the opening to the compartment in Experiment 4 not only decreased the severity of the local environment, but also decreased the total fire duration in comparison to Experiments 2 and 3. Based on these observations and on discussion with the NRC, the Experiment 3 configuration was selected as the most conservative for the full-scale tests.

A summary of the results from the four preliminary experiments is given in Table 4.

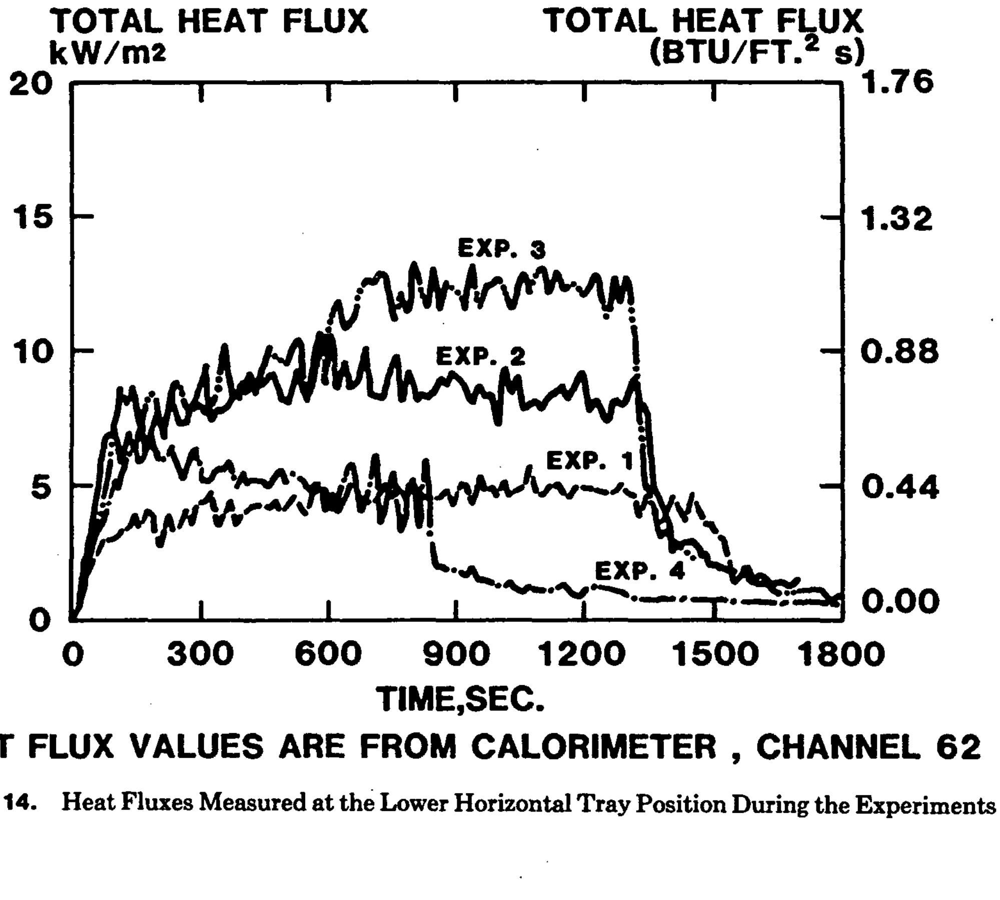


Figure 14. Heat Fluxes Measured at the Lower Horizontal Tray Position During the Experiments

Table 4. Summary of Experiments

	Experiment No.			
	1	2	3	4
Door Opening Size, ft	8 × 8	8 × 8	4 × 8	No Door
Room Length, ft	30	25	25	25
Fire Location	FF	AW	AW	AW
Approx Duration of Fire, min	25.4	22.5	21.9	14
Approx Max Recorded Temp in Hot Gas Layer Near Cable Trays, °F	470	620	660	500
Approx Max Recorded Heat Flux at Lower Cable Trays, kW/m²	5.5	10.0	13.0	8.0
Approx Max Recorded Cable Temp, °F:				
Upper Tray, Avg Temp:				
Qualified Cable Bundle	NT	460	420	220
Unqualified Cable Bundle	390	370	520	340
Lower Tray:				
Energized Cable	NT	570(UQ)	580(Q)	430(Q, UQ)
Nonenergized Cable	NT	500(UQ)	570(Q)	NT
Unqualified Cable Bundle	320	NT	NT	NT
Time to Short Circuit, min	NT	10.23 (UQ)	None	12.25 (UQ)
Approx Max Air Velocity, ft/sec:				
2 ft Below Top of Door	2.85	4.40	5.61	NR
2 ft Above Floor	1.31	1.57	2.99	NR

NOTE: 10 gal heptane used in a 1-ft × 5-ft pan
Room, height 10 ft, width 14 ft
AW = Against wall
FF = Away from wall
NR = No reading
NT = Not tested
Q = Qualified cable
UQ = Unqualified cable

6. Post-experiment Calculations

Post-experiment calculations were carried out to help identify the key parameters and variables that controlled the development of the fire environment. These calculations also helped establish a technical basis for efficient interpretation of experimental results, allowing a beneficial impact on the full-scale separation tests.

6.1 Post-experiment Results and Analysis: UL Experiment 1

Data obtained from Experiment 1 may be directly compared to the pre-test predictions shown in Table 2. Maximum values for the pertinent thermal variables measured in Experiment 1 are presented in Table 5.

Table 5. Maximum Values Measured During Experiment 1

Door Size (ft)	8.0 × 8.0
Hot Layer Temperature, TC 73 (°F)	470
Total Heat Flux to Upper Cable (kW/m^2)	5.5
Upper Cable Temperature, TC 108 (°F)	390
Fire Duration (s)	1525

Comparison of these results with those in Table 2 indicates the pre-test predictions overestimate the maximum temperature of the hot gas region; consequently, the maximum temperature predicted for the redundant cable is also overestimated. The primary source of this discrepancy is the failure of the pre-test calculation to predict adequately the duration of the fire. Because of this, the energy release rate for the HFC analysis is greater than that in the actual test, thereby producing a higher hot layer temperature. The source of the differences in the energy release rate is difficult to ascertain. One explanation lies in the use of a rectangular fuel pan (1 ft × 5 ft) in the UL experiments. This pan geometry alters the flame profile and therefore alters the rate of fuel pyrolyzation caused by radiative feedback from the fire. The pre-experiment calculations, which assume a circular fuel pan geometry, predict a pyrolyzation rate, using Equation (1), approximately three times greater than actual test conditions. In addition to pyrolyzation rate discrepancies, the nondimensional HFC cannot handle hydrodynamic effects which are functions of the fire and room on a three-dimensional scale. Because of this, differences between Experiment 1 and the HFC analysis include vertical temperature variations in the compartment (thermal stratification) and the relative importance of local convective heat transfer. Each of these effects may be important to predict the cable temperature response although physical models for these phenomena do not exist in the present version of the Harvard Fire Code.

The following section describes a typical post-experiment calculation for Experiment 3. The burn rate algorithm in the HFC was modified to account for the longer duration of the fire. No post-test calculations were conducted for the full-scale tests (described in Section 7) because there was no adequate physical model for describing the transient rate of heat release of the cable configurations burned during that phase of the separation test program.

6.2 Post-experiment Analysis: UL Experiment 3

Examination of the data obtained from the four preliminary experiments revealed that the most severe fire environment was achieved with the configuration used in Experiment 3. Analysis of the Experiment 3 data demonstrated the effects of compartment geometry on the severity of the fire environment.

The baseline compartment configuration for Experiment 3 is shown in Figure 10. The source fire consisted of 10 gal liquid heptane confined to a 1-ft by 5-ft pan. The fuel pan was positioned lengthwise along the back wall of the compartment, limiting the amount of air entrained by the fire plume and resulting in an extended flame zone that traveled along the back wall and impinged on the ceiling.

Data from Experiment 3 are presented in Figures 15 and 16. The hot layer temperature measurements are those obtained from thermocouple No. 73, located along the centerline of the room, 2 ft forward of the cable trays and 1 ft below the ceiling (Appendix A, Figure A2). The target temperature response shown is the temperature measured in the qualified cable bundle by thermocouple No. 106, located in the uppermost tray at the top of the cable bundle (Appendix A, Figure A4, Section H).

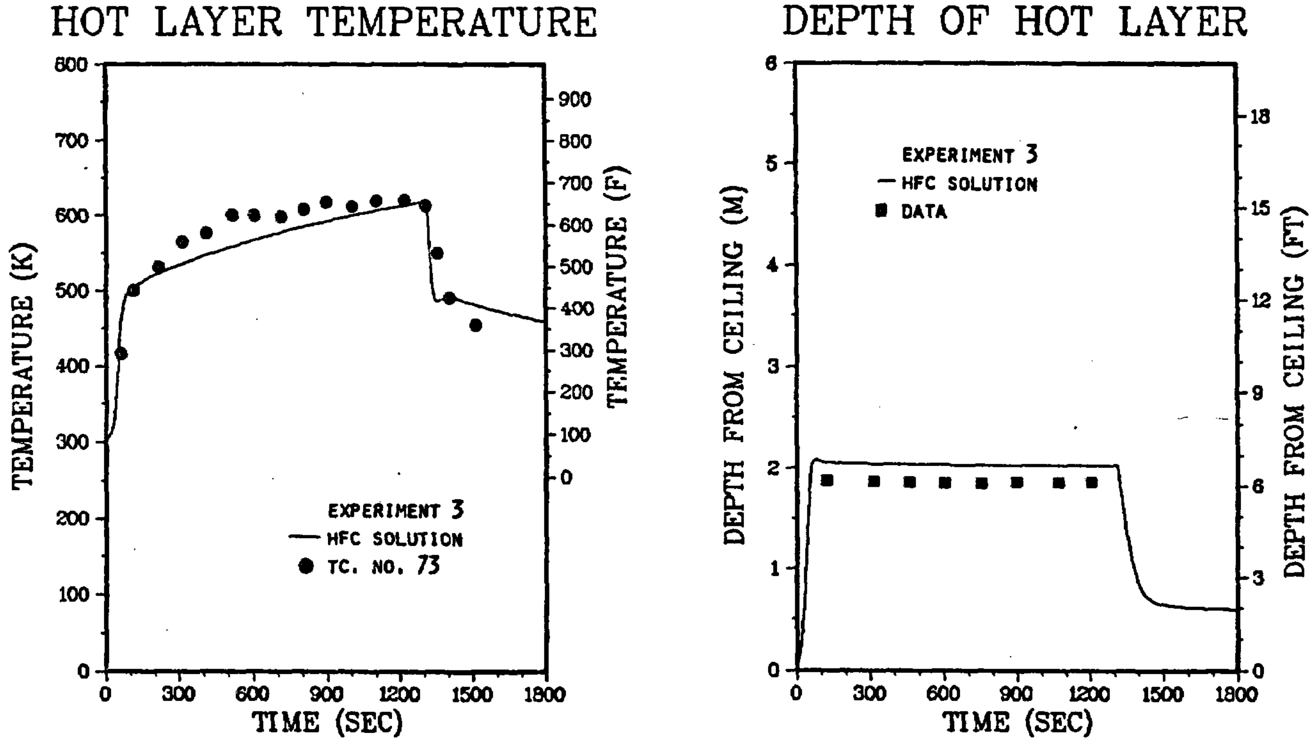


Figure 15. Comparison of HFC Solution and Experiment 3: Hot Layer Temperature and Depth

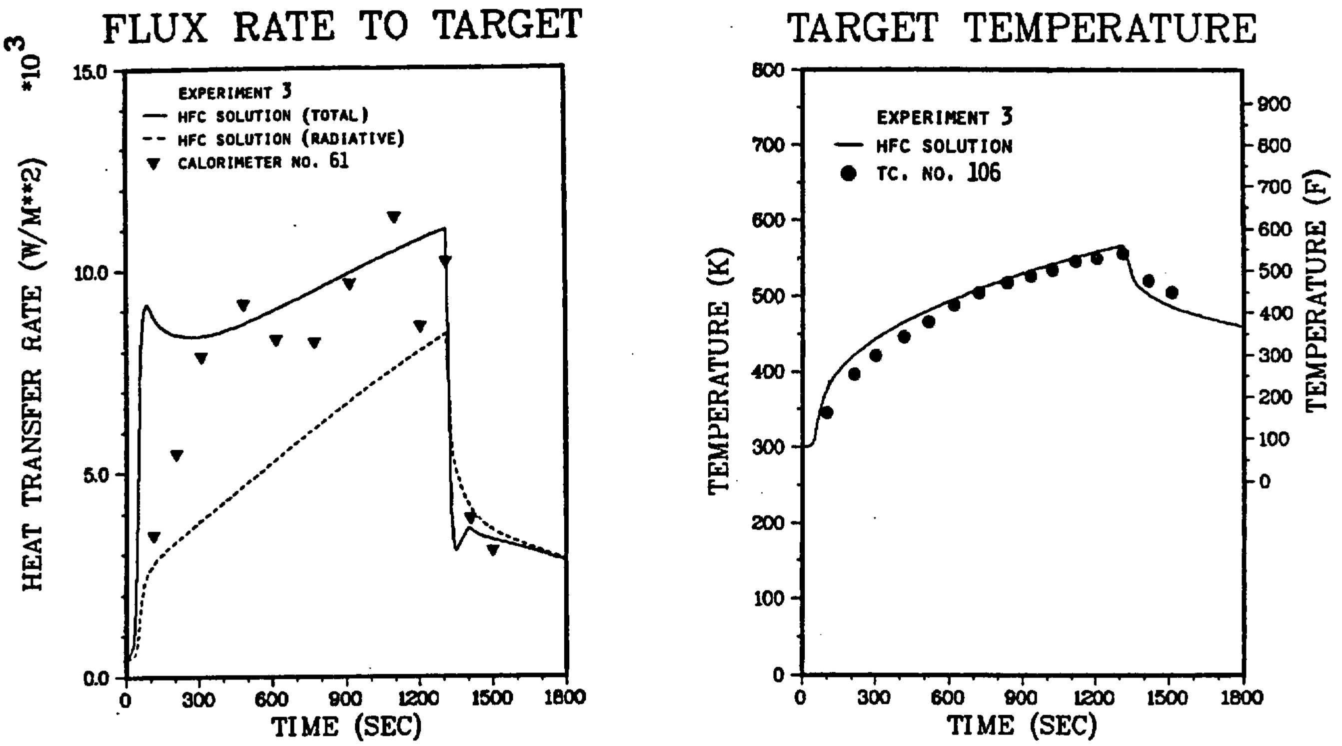


Figure 16. Comparison of HFC Solution and Experiment 3: Flux Rate to Target and Target Temperature

The theoretical solutions (solid line) shown in Figures 15 and 16 were generated with the HFC in which the experiment was modeled as previously described. To match the local hot layer temperature, two adjustments in the fuel source model were made. First, to match the duration of the fire, the thermal feedback to the fuel source was reduced because the pre-experiment solutions, previously shown in Table 2, underpredict the duration of the fire. Second, the heat of combustion of the heptane fuel source was increased from its normal value of 47 KJ/g to an artificial value of 70 KJ/g. This change was necessary because a hydrodynamic model for the hot layer is lacking in the present version of the HFC. Analysis of the data reveals that the hot layer region was vertically stratified ~45°F/ft (82°C/m) during the test, whereas the Harvard model for the hot layer considers this region to be well-mixed and thermally homogeneous. The present model also assumes all combustion in the fire plume ceases at the hot layer interface. Laboratory experiments conducted by Zukoski et al[18] demonstrate that the fire plume does indeed extend into the layer. It is assumed, however, that matching the uppermost (highest temperature) thermocouple data conservatively characterizes the thermal environment inside the compartment. The fact that the predicted target temperature closely follows the measured temperature response of the electrical cable (as a result of matching the local hot layer temperature) provides a degree of confidence in the simple slab model used to represent the cable tray nearest the ceiling. The predicted layer depth and total heat flux rate to the redundant cables are also seen to be in relatively good agreement with the experimental data. The total heat flux data are taken from calorimeter No. 61, in the uppermost horizontal tray (Appendix A, Figure A2). Note that at early times (>100 s), the HFC analysis predicts convective effects to be the predominant mode of heat transfer to the redundant system, whereas at later times, it predicts thermal radiation to be the predominant mode.

6.3 Compartment Geometry Analysis

A parametric study of the effects of room size was conducted by independently varying the baseline room dimensions (length, width, and height in Figure 10). Solutions were generated for each baseline dimension increased by factors of 1.5 and 2. The fuel source-target configuration was kept constant: the fuel source was positioned along the back wall, with the target (cable model) separated 20 ft from the source fire and 1 ft *below the ceiling*. The values for length, width, and height shown in Table 6 summarize the compartment geometries that were studied.

Table 6. Compartment Length × Width × Height (Baseline = 25 × 14 × 10)

	1.5 × Baseline (ft)	2 × Baseline (ft)
Length	38 × 14 × 10	50 × 14 × 10
Width	25 × 21 × 10	25 × 28 × 10
Height	25 × 14 × 15	25 × 14 × 20
General	38 × 21 × 15	50 × 28 × 20

The "general" values represent a case study in which all three dimensions were simultaneously increased by the appropriate factor.

6.4 Discussion of Results

Numerical solutions showing the effect of compartment length are provided in Figure 17. The solid line solutions (as well as all subsequent solutions) represent the results for the baseline compartment configuration (see Figure 15). The dashed and broken-line solutions are the results for the baseline length multiplied by factors of 1.5 and 2, respectively. Notice that the larger sized compartments produce a lower (less severe) hot layer temperature. The amount of heat transfer to the target cable model is reduced accordingly. Solutions for which the compartment width was varied exhibit similar trends, as shown in Figure 18.

The effect of changing the baseline ceiling height is shown in Figure 19. Again it is apparent that increasing room volume reduces the severity of the thermal environment for a fixed energy release rate from the source fire. Because thermal stratification is most likely to change with the vertical dimensions of the compartment (as opposed to its lateral dimensions), the results presented in Figure 19 are more questionable than the two previous cases when length and width were varied.

For the final case investigated, all three dimensions of the compartment were simultaneously increased. The numerical solutions generated by the HFC analysis are shown in Figure 20. The temperature reduction in the hot layer region from the baseline solution is substantial. However, even for the largest compartment (50 ft × 28 ft × 20 ft) (15.2 m × 8.5 m × 6.1 m), with a source fire of 10 gallons of liquid heptane, the hot layer attains a mean temperature of 280°F(140°C) at the termination of the fire. It should be reemphasized that vertical temperature variations in the hot layer are *not* considered in this analysis. When thermal stratification effects are considered, the local temperature in the vicinity of the component (i.e., near the ceiling) may be higher.

Increasing compartment size has two primary effects on the hot layer temperature. As the compartment dimensions are increased, the wall areas for convective and radiative losses also increase, leading to a reduction in the net heat transfer into the hot layer region. An increase in the size of the compartment causes the hot layer to occupy a larger volume. The increased thermal capacitance of the layer in conjunction with the increased thermal losses to the walls contribute to produce a lower environment temperature for a fixed rate of heat release from the fire.

From the compartment geometry analyses it may be concluded that the most severe (highest temperature) thermal environment was produced with the baseline UL configuration. Alternate compartments of larger dimension produced lower temperature environments and consequently lower temperatures in the simulated cable tray.

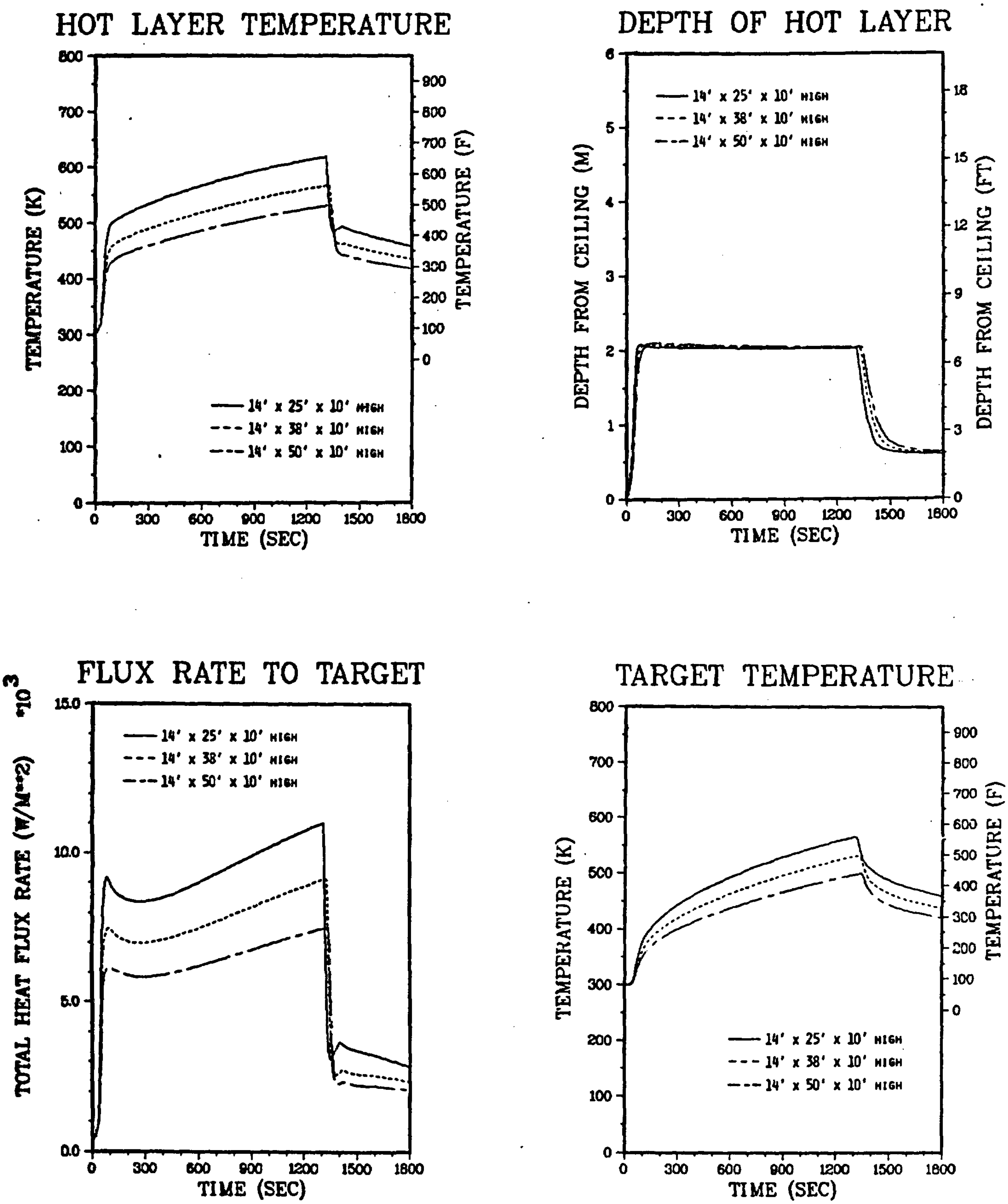


Figure 17. Solutions for Variation in Compartment Length

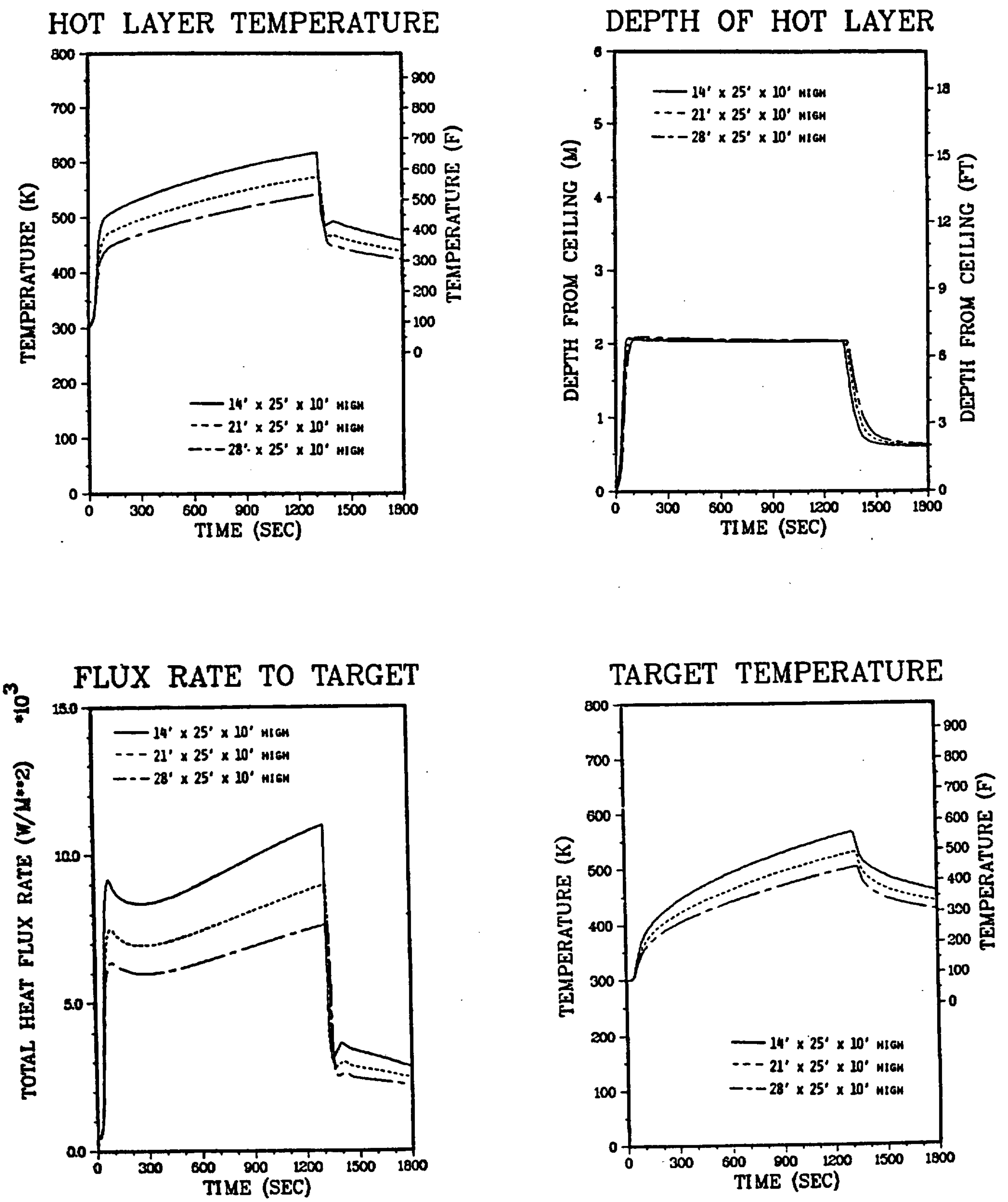


Figure 18. Solutions for Variation in Compartment Width

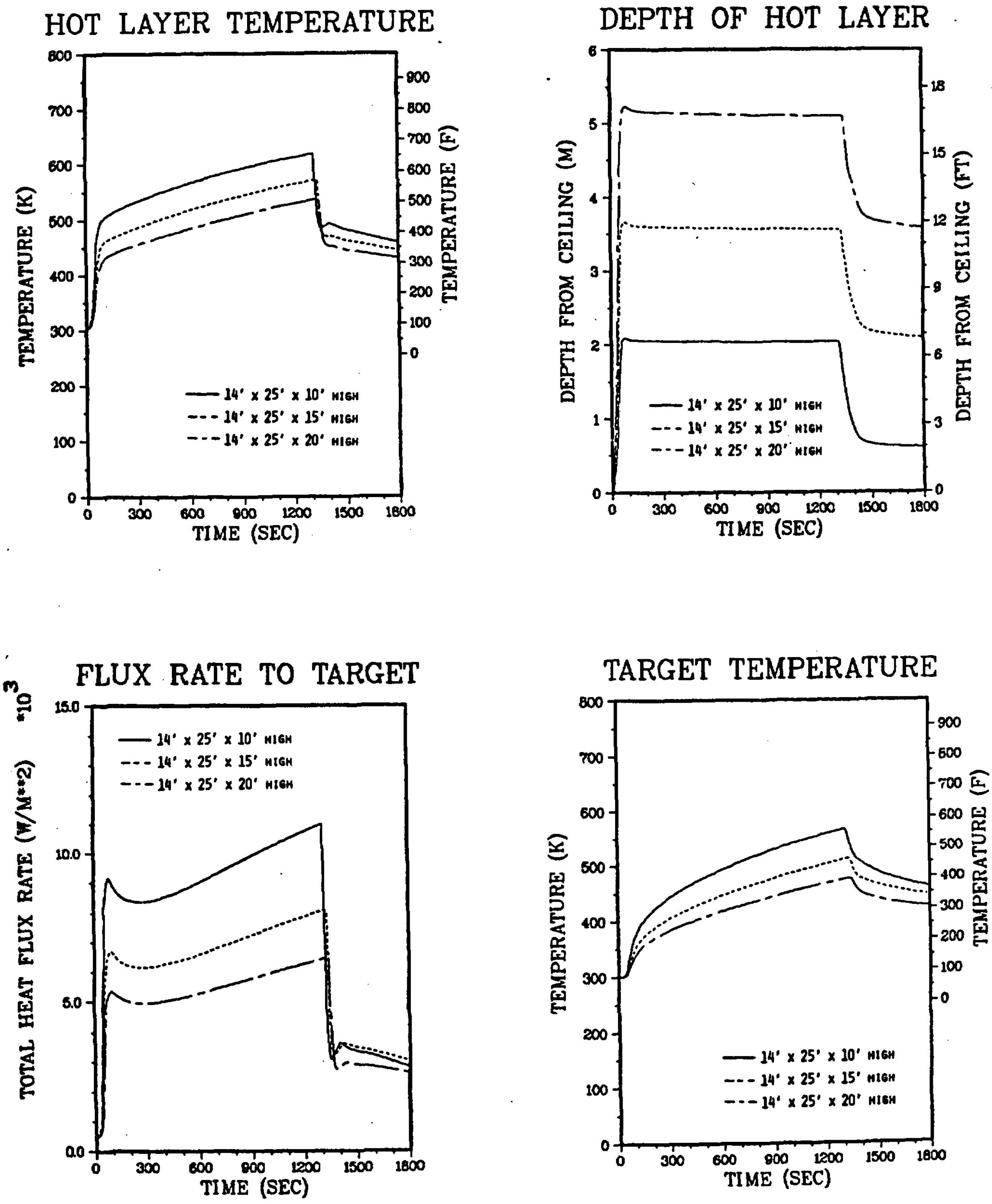


Figure 19. Solutions for Variation in Ceiling Height

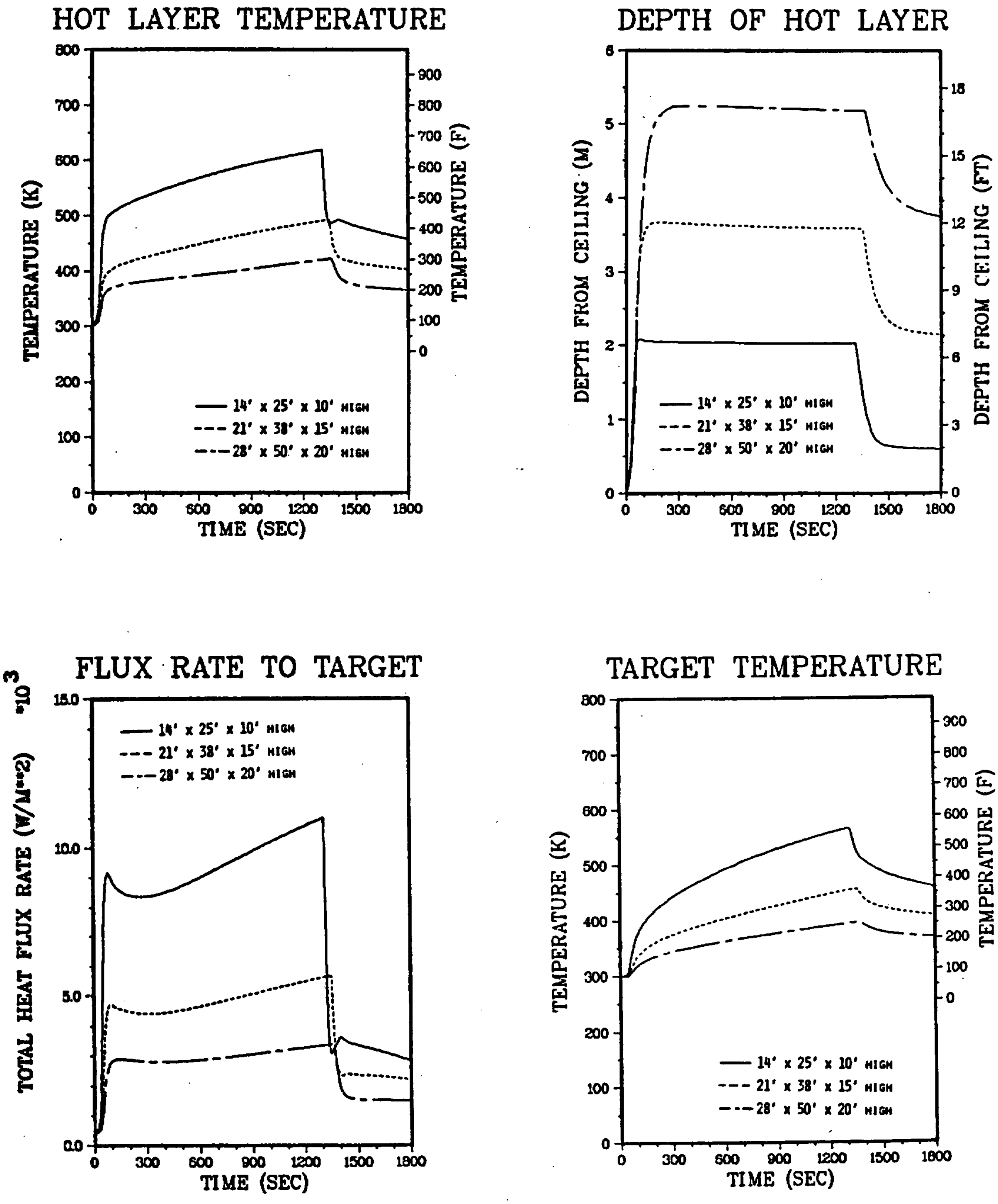


Figure 20. Solutions for General Compartment Dimensions

7. Full-Scale Tests Conducted at Underwriters Laboratories

The scoping calculations and preliminary experiments were used to aid in configuring the room for the six full-scale tests conducted at Underwriters Laboratories. In these tests, only the type of cables and cable protection in both the source fuel and in the redundant safety train were varied; all other parameters remained fixed. The full-scale tests were conducted to evaluate the survivability of the redundant safety train in order to assess the adequacy of the 20-ft separation criterion. The details of the test instrumentation and observations for the six full-scale tests are given in Appendix A.

7.1 Full-Scale Test Configuration

The same compartment geometry used in preliminary experiment 3 (i.e., a 25-ft long × 14-ft wide × 10-ft high enclosure with a 4-ft × 8-ft door opening) was used for all six full-scale tests (Figure 10). The calculations and preliminary experiments showed that, of the room geometries tested, the one just described would yield the most conservative results for the fuel load tested. The initial source fire was provided by 5 gal heptane in the 1-ft × 5-ft steel pan placed against the back wall of the compartment. In addition, two vertical trays with cables were placed 5 in. from the wall directly above the pan of heptane. In Tests 1, 3, and 5, unqualified cable was used along with the heptane as the source fire, while in Tests 2, 4, and 6, qualified cable and heptane were used. In Tests 1 and 2, no external protection was used on the cables. In Tests 3 and 4, a ceramic fiber blanket was placed over the cables on the non-rung side of the cable tray; then the trays were covered on both sides by 0.059-in.-thick sheet steel. In Tests 5 and 6, a flame retardant coating (⅛-in. wet thickness) was applied to the cables on the trays. In each test, the redundant cable system (two horizontal cable trays 20 ft from the fire) had the same protection as the vertical (source fuel) trays.

The two vertical trays above the pan of heptane each contained 43 lengths of cable (12.5% fill). This amount of cable was chosen as the source fuel to equal 5 gal heptane in total heat release. A special test, described in Appendix C, was conducted at Sandia to obtain an approximate value of the heat release for unqualified cable. This "equivalent" amount of cable, i.e., 43 lengths, was used in all six tests.

Additional cables could have been placed in the trays. An early NRC recommendation was to use 5 fully filled vertical trays and 5 filled horizontal trays in conjunction with the 5 gal heptane. However, pretest calculations indicated a fuel load that large would threaten the structural integrity of the room and potentially exceed the venting capacity of the UL facility. In addition, results of the preliminary experiments (heptane fuel only) indicated that the two 12.5% filled vertical trays with 5 gal heptane would be sufficient to pose a threat to the redundant system. The tests confirmed that expectation. As shown by the following calculations, the fuel load used is not a conservative or "upper limit" fuel load.

A traditional method for predicting the severity of a fire has been to calculate the fuel load in the room per unit floor area. This is referred to by Berry and Minor[19] as the "barrier analysis method." Using the total heat release for unqualified cable and heptane found in Appendix C, the approximate fuel load of the preliminary experiments and full-scale tests at UL can be calculated. For preliminary experiments 2 – 4 with 10 gal heptane only, in a room with 350 ft^2 (32.5 m^2) of floor area, the fuel load is ~2103 BTU/ft^2. The calculated fuel load for the full-scale tests with unqualified cables, assuming the source fuel of 5 gal heptane and two vertical cable trays with 43 cables per tray (12.5% fill), is ~2114 BTU/ft^2. This traditional technique then compares the calculated fuel load to a linear fire duration scale in which a fuel load of 80 000 BTU/ft^2 corresponds to a 1-hr-duration fire. This method was first proposed by the National Bureau of Standards; its shortcomings are discussed by Berry and Minor.[19] Nevertheless, a comparison of these fuel loads with a 1-hr fire duration (80 000 BTU/ft^2) does show that the fuel load used in these tests is very small.

In the two horizontal trays, used to simulate the redundant safety system, a single continuous cable was placed in a coil pattern and looped back and forth until 43 single lengths were in place. The ends of the cable were passed through the wall and were energized to monitor for electrical continuity.

The type of cables used in the full-scale tests was the same as in the preliminary experiments. (See Section 5.1)

7.2 Instrumentation

The instrumentation employed in the six full-scale tests was the same as that used in Experiments 2 - 4, described in Section 5.2 (Appendix A, Figure A2). In addition, three sprinkler heads were installed 9.5 in. below the ceiling along the centerline of the room. The sprinkler heads were of pendant type and had a temperature setting of 165°F (74°C) in Tests 1, 3, and 5 and 212°F (100°C) in Tests 2, 4, and 6. The heads were not connected to piping, but were monitored to record the time when the links fused, indicating that they had been activated. The NRC had requested that the tests be conducted without active sprinklers, i.e., without any fire suppression activity.[5]

7.3 Fire Environment

In each test, after the heptane was ignited with an electric match, the cables in the vertical trays became engulfed in the flames and quickly ignited. The time of maximum flaming varied according to cable type and protection.

As in the preliminary experiments, a smoke layer formed early (within 60 s) and descended to about 4 ft above the floor, remaining smooth and stable throughout the tests.

The rapid formation of the hot layer caused the thermal environment to develop very quickly. The average hot layer gas temperature versus time of three thermocouples located 1 ft below the ceiling and 2 ft in front of the horizontal trays is shown in Figure 21. The shape of the curves is similar for the common conditions, that is, for Tests 1 and 2, Tests 3 and 4, Tests 5 and 6 (in each set of tests, the cable was protected in the same manner). Also, maximum temperature is almost the same for the test sets (i.e., taken two at a time) even though each pair of tests was run with qualified and unqualified cable. The maximum temperature difference is ~90°F (70°C). The odd-numbered tests were with unqualified cable, and the even-numbered tests were with qualified cable. The temperature should also be compared to that obtained for Experiment 3 (10 gal heptane only) given in Figure 11. The difference in magnitude and shape, particularly for Tests 1 and 2, is due to the simultaneous burning of the solid fuel (cables) and liquid (5 gal heptane), while in the preliminary experiments only a liquid pool fire burned (10 gal heptane). The liquid pool fire has a uniform burn, i.e., energy release rate, while the cable fire tends to have a nonuniform burn. Thus, the difference between Experiment 3 and the tests is the greatest in Tests 1 and 2, since the cables ignited early and the fire spread rapidly up the unprotected cables. In the other tests, the ignition of the vertical cables was delayed, and the rate of fire spread was slowed because of the protection on the cables. The room temperature was hottest in Tests 1 and 2 and attained maximum temperature in the shortest time for the reasons just stated.

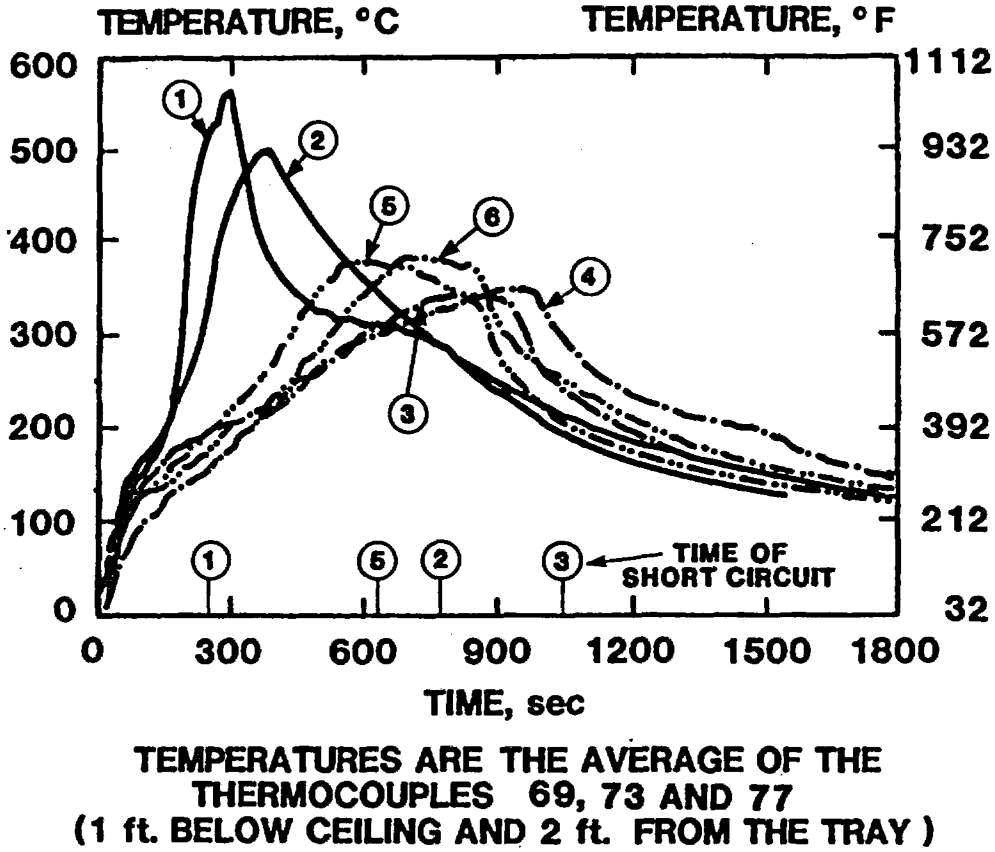
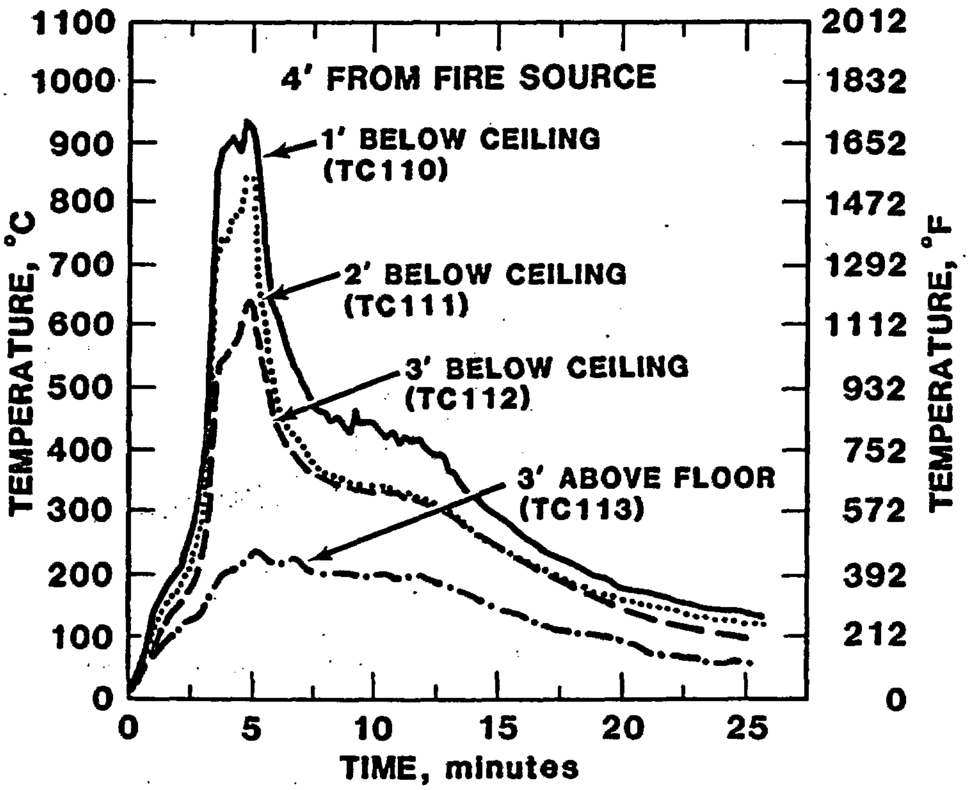


Figure 21. Average Atmospheric Temperatures Near Horizontal Trays During Tests

Examination of the magnitude of the thermal response shows that in Tests 1, 2, 5, and 6, the average atmospheric temperature (thermocouples 69, 73, and 77) exceeded that recorded in the preliminary experiments; in Tests 3 and 4, the maximum temperature was about the same as recorded in preliminary experiments 2 and 3.

Figure 22 shows the variation of atmospheric temperatures with lateral direction for a set of four thermocouples 4 ft and 20 ft from the fire source (Test 1). The lateral variations in the full-scale tests are large compared to those in the preliminary experiments (Figure 13). Also shown in each figure is the variation of temperature with the vertical direction.



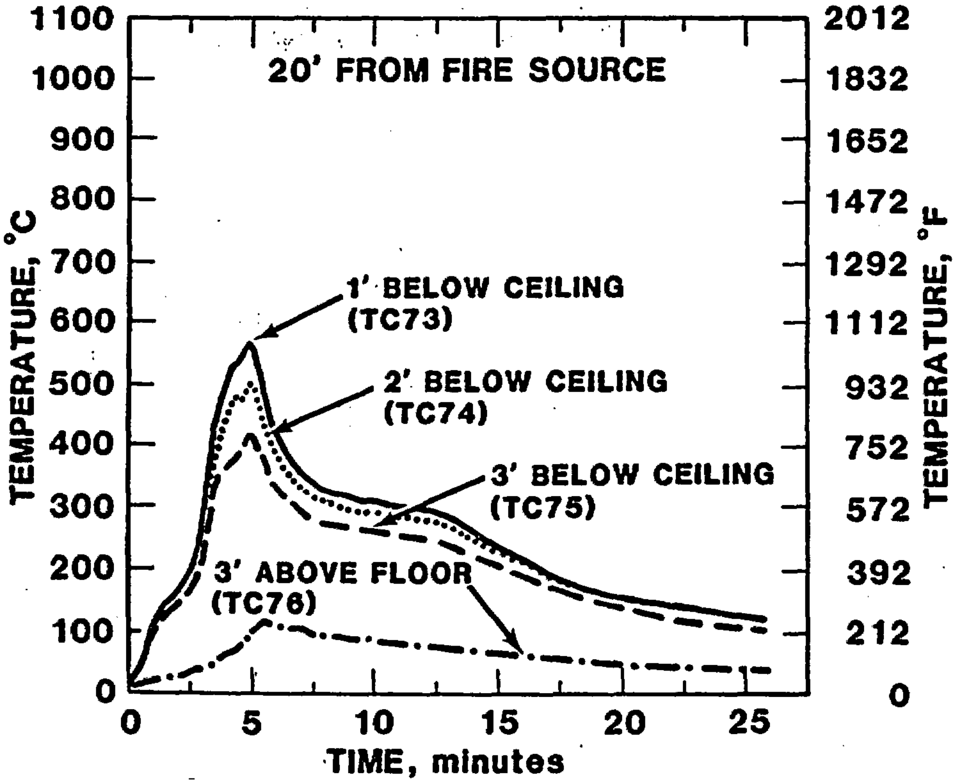


Figure 22. Variation in Atmospheric Temperatures With Lateral Direction: Full-Scale Test 1

7.4 Effects of the Fire Environment on the Redundant System

Cables in the redundant safety system, 20 ft away and near the ceiling, were subject to a locally severe thermal environment because of the surrounding hot layer. The heat flux as a function of time for the six tests is shown in Figure 23. The readings are for a calorimeter, mounted in the lower horizontal tray, with a viewing angle of 180°, facing the fire. As in the experiments, the shape of the heat flux curves resembles the thermal response curves (Figure 21); however, there is a more rapid decrease in the heat flux curves.

Also shown in Figure 23 is the threshold level of heat flux that caused an electrical failure in the separate-effects test (Section 3, Cable Damageability Experiments). However, these values were not used in evaluating the performance of the redundant system since the electrical continuity was monitored.

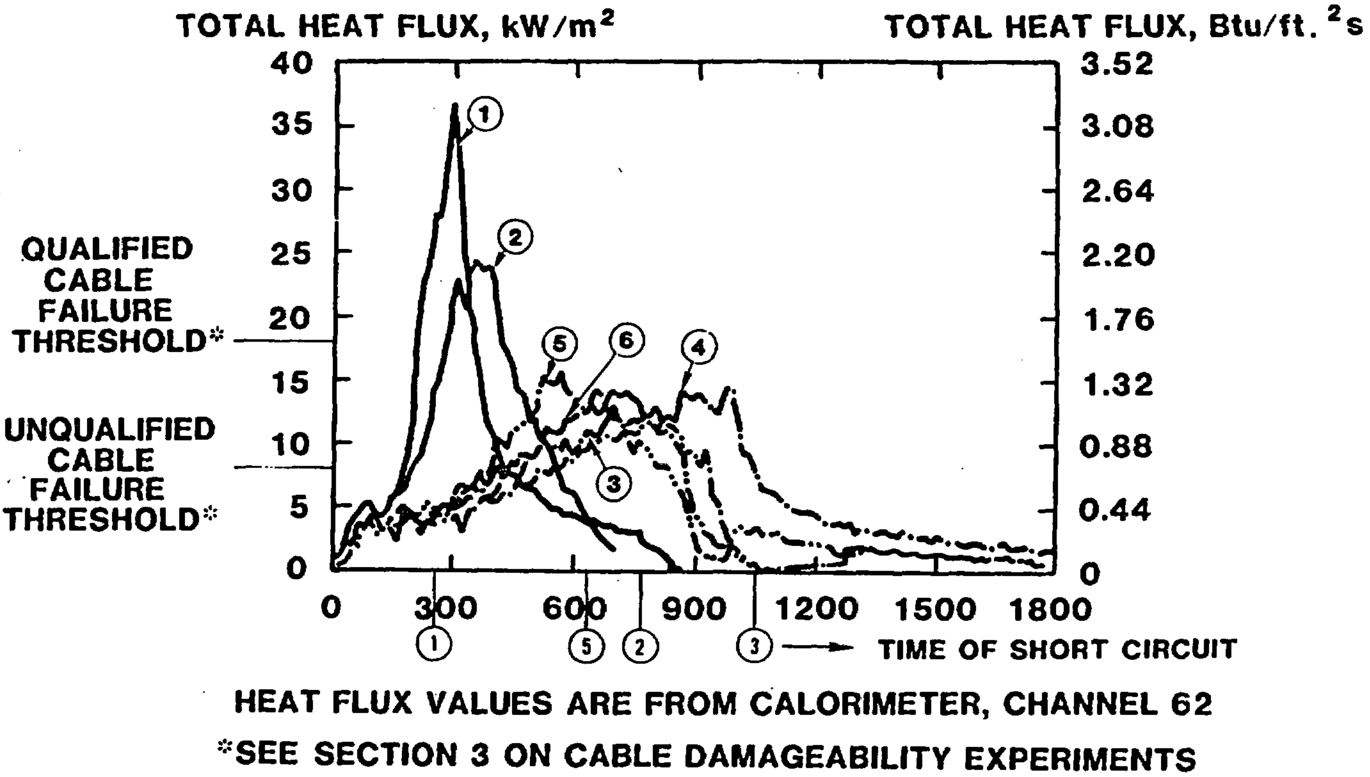
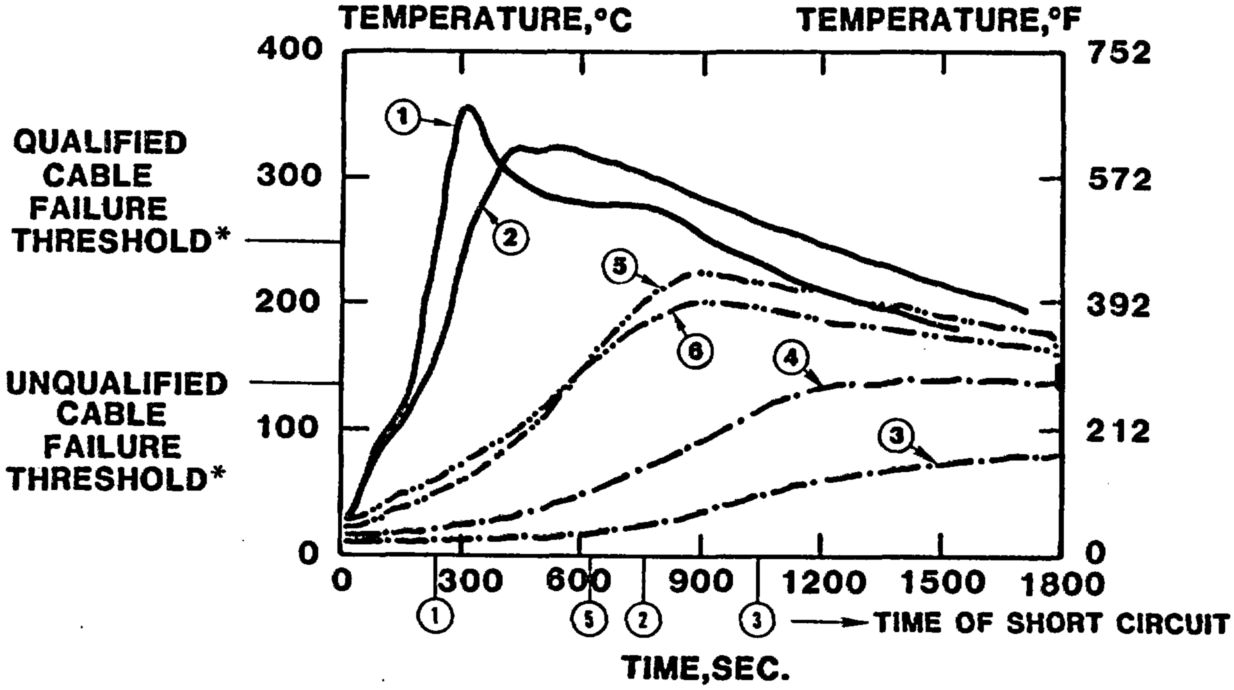


Figure 23. Heat Flux at Lower Horizontal Trays During Tests

The average temperatures recorded for a group of thermocouples embedded about 1/32 in. (.08 cm) in the top of the outside cable jacket in the upper horizontal tray is shown in Figure 24. Exact locations are given in Appendix A. Also shown in Figures 21, 23, and 24 are the four failure times (described below) for those tests where a failure did occur. It should be noted that the recorded readings are the average of a group of thermocouples; because of local variations, it is not likely that the reading is a true local maximum for the cables. For example, heating of the cable occurs through the heating of the atmosphere and also by local conduction when the cable is in intimate contact with either the cable tray rung or the side rail of the cable tray. Hence, even though the average cable jacket thermal response for Test 3 would not, by itself, indicate failure, the cable did fail. The threshold value for the temperature that caused an electrical failure in the separate-effects tests is also shown in Figure 24 (Section 3). However, these values were not used in evaluating the performance of the redundant system since the electrical continuity was monitored.



FOR TESTS 1&2 AVERAGE OF THERMOCOUPLES 118-122 (UPPER TRAY)
FOR TEST 3 AVERAGE OF THERMOCOUPLES 118-120 (LOWER TRAY)
FOR TESTS 4-6 AVERAGE OF THERMOCOUPLES 124-128 (UPPER TRAY)
*SEE SECTION 3, ON CABLE DAMAGEABILITY EXPERIMENTS

Figure 24. Cable Jacket Temperatures During Tests

The significant difference in the cable jacket temperatures of Tests 3 (unqualified cable) and 4 (qualified cable) is an anomaly, without satisfactory explanation at this time. The average atmospheric temperature (Figure 21) would indicate that the cable jacket temperature response in Tests 3 and 4 should have been very close (that of Test 3 was significantly lower than that of Test 4).

The electrical integrity of the cables in the horizontal trays was monitored to determine if and when short circuits occurred. The following results were obtained:

	Time (sec) and Type of Short Circuit	
Test No.	Upper Tray	Lower Tray
1	244 G	262 G
2	775 C	None
3	None	1043 C
4	None	None
5	642 C	776 C
6	None	None

G = Conductor to tray short
C = Conductor to conductor short

7.5 Sprinkler Head Response Times

The response time of the sprinkler heads was monitored to determine when fire suppression would have been activated. No water was supplied to the sprinklers in these tests. The following observations were recorded:

	Response Time (sec)		
Test No.	Head 1 (4 ft from wall)	Head 2 (12.5 ft from wall)	Head 3 (21 ft from wall)
1	58	88	112
2	70	120	200
3	105	152	169
4	126	151	181
5	*	*	121
6	86	129	194

NOTES:
*Link fused during test, but recording equipment malfunctioned. In Tests 1, 3, and 5, the head rating was 165°; in Tests 2, 4, and 6 the head rating was 212°F.

All response times occurred before any short circuits.

The sprinkler heads were located along the centerline; the distance given is from the wall by the ignition source.

7.6 Additional Post-tests

Two additional sets of tests were conducted on the cables after the full-scale fire test.

The first group of tests subjected samples from Tests 2 – 6 to the voltage withstand tests in accordance with IEEE-383-1974, paragraph 2.3.4. Eight samples of cables from each test were used. The results are as follows:

Test No.	No. of Samples Passed
2*	6
3*	8 (All)
4	8 (All)
5*	3
6	8 (All)

---

*Failure (short) occurred in Full-Scale Fire Test

For a description of the failure, see Appendix A.

The second group of tests were conducted only on samples from Test 4 and on samples of the same cable which had not been subjected to the thermal environment. Both tensile strength and elongation were determined in accordance with paragraph 34 of UL 83, "Thermophysical-Insulated Wires and Cables." Tensile strength was essentially unchanged, and tensile elongation was decreased only slightly. This testing showed that even though some of the cables shorted (failed), they were still capable of passing various standard tests.

7.7 Post-test Cable Observations

The following visual observations of cable conditions in the horizontal trays were made after each test.

Test No.	Observations
1*	Cable jacket melted and flowed, coalesced on cooling.
2*	Cable jacket discolored and hard, with crack near bends.
3*	Cable jacket melted at tray side rail facing the fire.
4	Cable jacket less flexible, no cracking or discoloration.
5*	Cable jacket melted, flowed through cracks in the coating, then solidified into small puddles on the coating surface.
6	Cable jacket did not melt; discoloration or hardness change not determined, since coating could not be easily removed without damaging cable.

---

*Failure (short) occurred

7.8 Results

The results of the full-scale tests show that the redundant safety system cables failed (short circuited) in four of the six tests, varying only the types and protection of the cables, in the room configuration used. A summary of the results of the six full-scale tests is given in Table 7. A detailed overview and interpretation of the results follow in Section 8.

Table 7. Summary of Full-Scale Tests

	Test No.					
	1	2	3	4	5	6
Cable Protection	none	none	ceramic fiber blanket with 0.059-in. steel covers	same as 3	flame retardant coating, ⅛-in. thick (wet)	same as 5
Cable Type	UQ	Q	UQ	Q	UQ	Q
Max Recorded Air Temp in Hot Gas Layer Near Cable Trays, ~°F	1050	950	660	670	710	740
Max Recorded Heat Flux at Lower Cable Trays ~kW/m²	36	23	12	14	15	14
Max Recorded Cable Temp, ~°F	860	720	215	390	420	500
Time to Short Circuit, min, Upper Tray	4.07	12.92	none	none	10.70	none
Lower Tray	4.37	none	17.38	none	12.93	none
Sprinkler Head Response Time Near Cable Tray, min	1.87	3.33	2.82	3.02	2.02	3.23
Approx Max Air Velocity at Doorway, ft/sec						
2 ft below top of door	7.35	6.69	5.61	5.97	5.71	5.51
2 ft above floor	2.89	1.16	2.82	2.26	3.67	3.97

NOTES:
1. 5 gal heptane used in all tests with 43 cables (12.5% fill) in vertical cable trays
2. Room Size: Length 25 ft, width 14 ft, height 10 ft
3. Door Opening: 4 ft × 8 ft
4. UQ = Unqualified Cable
5. Q = Qualified Cable

8. Overview of Results

Ten compartment fire tests were conducted at UL to provide a data base with which to evaluate the adequacy of the 20-ft separation requirement as specified in 10 CFR 50, Appendix R. In the preliminary experiments, geometrical characteristics of the test configuration were varied to establish the compartment configuration for the six full-scale tests. Selection of the test configuration for the full-scale tests was based on results from Experiment 3, which produced the most severe temperature extremes in the vicinity of the redundant cable trays for the conditions considered (e.g., room size, fuel source). The primary variables in the full-scale tests were the type of cable (qualified and unqualified) and the level of protection for each cable configuration (no protection, ceramic fiber blanket with covers, and fire retardant coating).

The results of the six full-scale tests cannot be used to assess the adequacy of the 20-ft separation requirement for all situations. The large variation of enclosure geometries, fuel loads, and ventilation conditions in nuclear power plants make it extremely difficult to infer the outcome of a particular fire scenario from results of a limited test series. A systematic investigation of all possible variables has yet to be conducted; therefore, the adequacy of the 20-ft separation requirement cannot be completely assessed for all situations. It is correct to state, however, that 20-ft separation as a fire protection method is not adequate, by itself, for some of the particular room and fuel configurations tested. Additional insight into the adequacy of the 20-ft separation criterion for other configurations can be gained by careful interpretation of both the preliminary experiments and the full-scale test results. Important aspects of these results and their significance to the 20-ft separation requirement are discussed in the following sections.

8.1 Hot Layer Temperature

The local environment temperature must be known in order to characterize the thermal response of components and/or systems engulfed by the hot layer. A brief overview of the temperature variations in both the preliminary experiments and the full-scale tests follows.

8.1.1 Preliminary Experiments (Heptane)

Development of the hot gas layer near the ceiling is controlled primarily by the heat release rate of the fuel source and the geometry of the enclosure, including the location of vents and doorways. In the preliminary experiments, the heat release rate of the heptane fire was constant. Thus, following an initial transient, the time rate of change of the hot layer temperature was relatively small in all four experiments (Figure 11). The time interval associated with the early transient reflects the time required for the interior walls of the enclosure to come into thermal equilibrium with the hot gases. At later times, the energy influx to the layer by the fire is approximately equal to the energy lost by the layer as it exits through the compartment door.

Of importance to the issue of 20-ft separation is the lateral variation of temperature in the test compartment. For the preliminary experiments, Figure 25 shows the temperature along the centerline of the room with time at 1 ft, 2 ft, and 3 ft below the ceiling. The series of curves represent the temperature at increasing separation distance from the source fire. The variation in temperature with lateral separation distance is small, particularly at the lower levels in the layer. This result indicates that a component or critical system immersed in the smoke layer, and not engulfed by the fire plume, would be subjected to the same thermal environment regardless of its horizontal separation distance from the source fire for this test configuration.

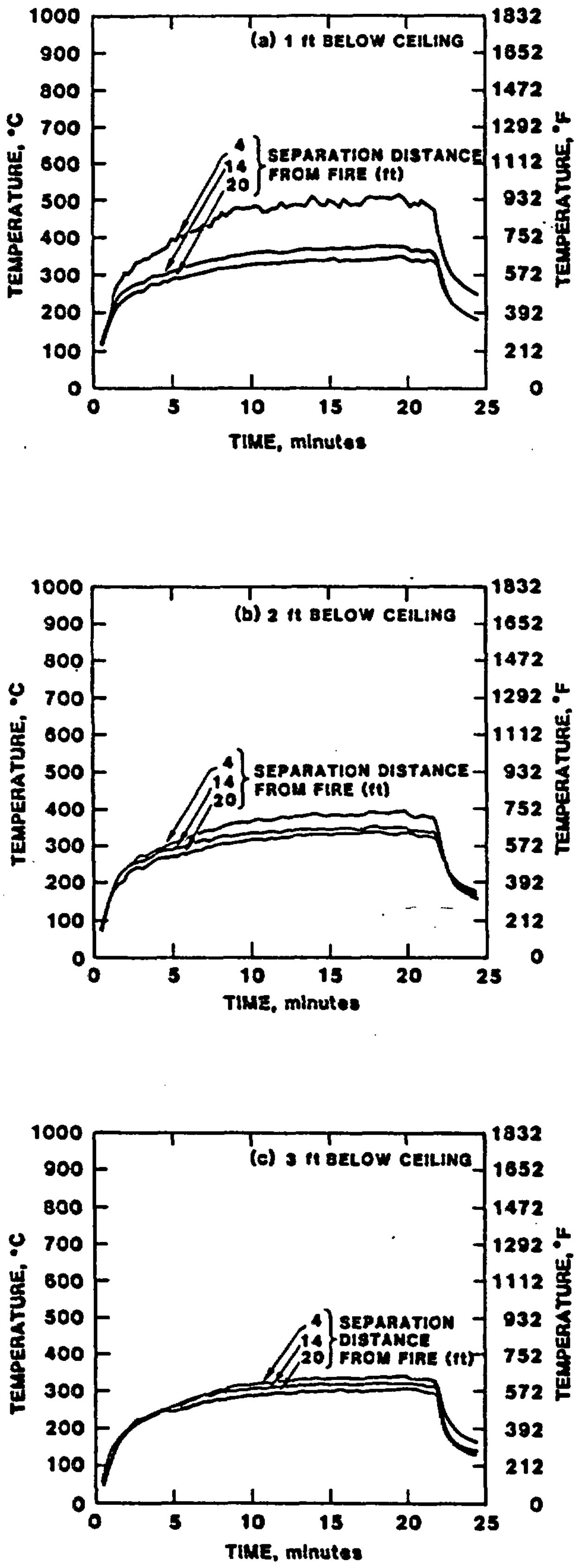


Figure 25. Lateral Variation in Atmospheric Temperatures: Experiment 3

8.1.2 Full-Scale Tests (Heptane With Cable Trays)

For the six full-scale tests, development of the ceiling layer temperature exhibits a strong time dependency because of the time-dependent heat release of the burning electrical cables. This is evident in the temperature trends from Test 1 as shown in Figure 22. The period of peak fire development (from 2 min to 8 min) in Test 1 corresponds to the time during which the electrical cables experienced vigorous pyrolyzation and combustion.

The lateral variation of temperature with time for Test 1 is shown in Figure 26. As in Figure 25, the temperature trends are shown for the centerline of the room at 1 ft, 2 ft, and 3 ft below the ceiling. Unlike the results from the experiments, the temperature in the hot gas layer varies with the horizontal separation distance from the fire. Note that the period of greatest variation in temperature occurs during the period of peak fire development. Considering the vertical variation in temperature shown in Figure 22, it may be concluded that the hot layer temperature varies significantly not only with time, but also with the lateral and vertical directions in the compartment. This time and spatial variation in temperature is consistent throughout all six full-scale tests and is the principal reason that the full-scale tests were not amenable to analyses with present capabilities as discussed at the beginning of Section 2.

8.2 Compartment Geometry

The effects of compartment geometry cannot be quantified solely on the test results since a fixed geometry was maintained for all full-scale tests. The compartment length was shortened 5 ft (1.5 m) in Experiment 2; however, the source fire was also moved adjacent to the back wall, making it difficult to discern the effects of changing compartment length alone. Analyses conducted with the HFC (described in Section 6.3)indicate that increasing compartment dimensions reduces the temperature severity of the thermal environment in the hot layer for a fixed rate of heat release from the source fire. This result assumes the hot layer region to be well mixed (thermally homogeneous) and does not consider the effects of thermal stratification, which occurred in all ten tests. Additional analyses are required to determine the effects of compartment geometry on the local thermal environment in an enclosure.

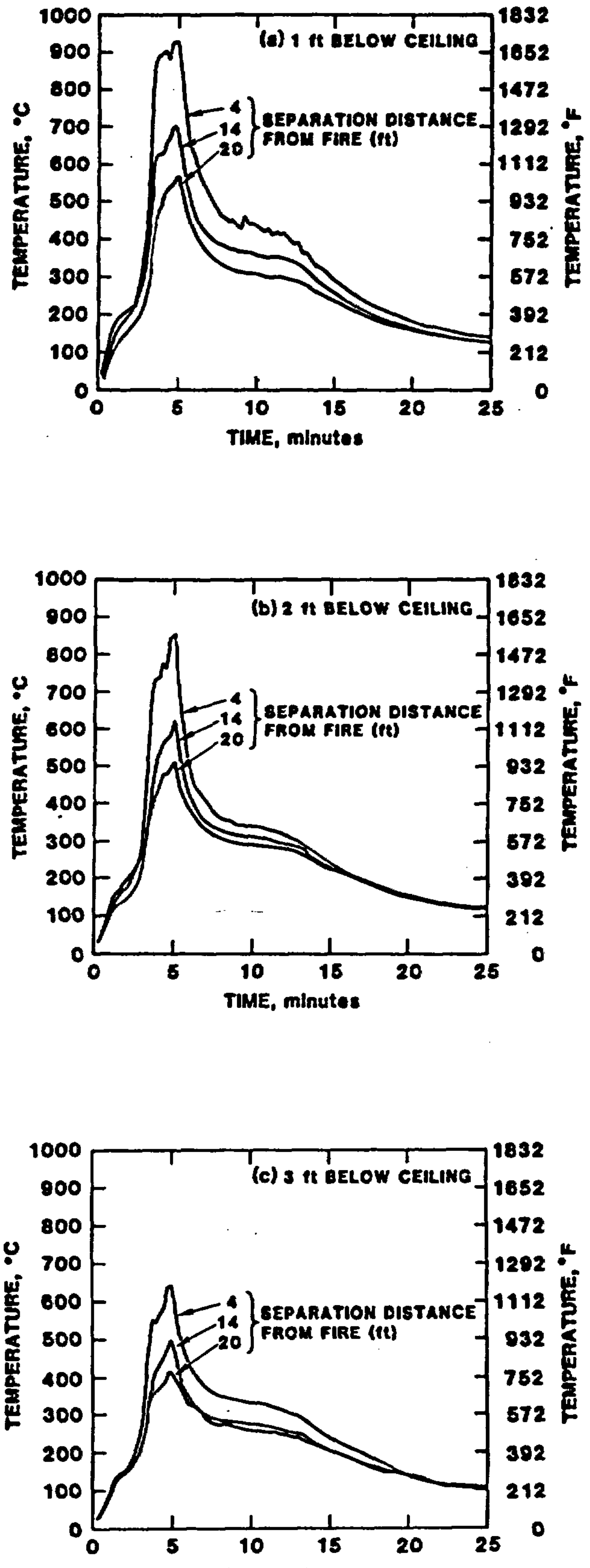


Figure 26. Lateral Variation in Atmospheric Temperature: Full-Scale Test 1

8.3 Ventilation

Quantifying the effect of ventilation on the severity of the UL test environment is difficult, particularly for the six full-scale tests. For the preliminary experiments, calculations performed with the HFC indicated the heptane fire was not ventilation-limited. That is, more air was drawn into the compartment than that required for stoichiometric combustion of the fuel volatiles. The vertical cable trays in the six full-scale tests became partially engulfed by the smoke layer as it descended toward the floor. The degree of combustion of the cables in the layer is difficult to assess. Post-test observations of the vertical cable trays revealed that all portions of the electrical cables appeared equally consumed, indicating the fire plume extended along the cable trays and into the ceiling layer.

8.4 Fuel Source

The time-dependent heat release of a fuel source in an enclosure depends upon a number of factors including fuel type, fuel load and its geometry, flame spread characteristics, ventilation conditions, and the location of the fuel inside the enclosure. Altering any one of these factors may significantly affect the transient development of the fire environment. Indeed, the UL test results demonstrate the importance of the ignition and burning of secondary fuel sources (e.g., cable trays) to the development of the fire environment in an enclosure.

Generally for a fixed enclosure geometry, an increase in the rate of heat release of the fuel will increase the severity of the thermal environment inside the enclosure. Components and/or systems exposed to this environment will very likely be damaged by increased temperature extremes or by corrosive effects of the combustion products. It should be emphasized that the two vertical cable trays (12.5% fill) used for the six full-scale tests represent only a modest fuel load for this room configuration (Section 7.1).

8.5 Cable Protection Methods

Two types of cable protection schemes were investigated in the full-scale tests: Both the source trays and the redundant trays were protected by either (1) a ceramic fiber blanket with steel covers on the trays or (2) a fire retardant coating. The effects of these protection methods on the source fire and redundant system are described as follows.

8.5.1 Cable Protection on Source Trays

The two vertical cable trays were burned with either no protection, steel covers and ceramic blankets, or coatings for qualified and unqualified cable. For each level of protection, the qualified and unqualified cables burned essentially the same, producing similar thermal environments near the redundant trays as shown in Figure 21. With the approximation that the heat release rate of the source fire is proportional to the time rate of change of the environment temperature, it can be seen in Figure 21 that the heat release rate of the source trays is relatively unaffected by the use of qualified or unqualified cable for the three methods of protection.

Comparison of environment temperatures in Figure 21 for protected and unprotected cable trays reveals that peak temperatures are reduced when a protection method is used. This reduction is caused by the mitigating effects of the cable protection on the rate of production of fuel volatiles from the cable. The amount of temperature reduction is nearly identical for both the covered trays and the coatings. This result indicates that the two levels of protection are approximately equal from the standpoint of reducing the severity of the thermal environment inside the test compartment.

8.5.2 Cable Protection on Redundant Trays

The level of protection applied to the redundant cable trays was identical to that of the source trays in each test. Cable jacket temperatures in the redundant trays are shown in Figure 24. The jacket temperatures for the covered trays are somewhat lower than those for the coated cables. This temperature difference shows the greater insulating effect of the steel covers and ceramic blankets since, as previously described, the local thermal environments for the protected cable tests (Tests 3 – 6) were approximately the same. It is not correct to infer the insulating effect of the protection methods by comparing jacket temperatures from Tests 1 and 2 to Tests 3 – 6 because the thermal environments for the unprotected cable fires were significantly more severe.

For tests using unqualified cable with protection (Tests 3 and 5), electrical shorts in the redundant system occurred at the times shown in Figure 24. For tests involving qualified cable with protection (Tests 4 and 6), no electrical shorts occurred. In all tests and experiments, no ignition or flaming of the redundant electrical cables was observed. Failure of the redundant system occurred as a result of exposure to a locally severe thermal environment. In Test 1 the magnitude of the total heat flux to the redundant system did exceed the critical flux level required for ignition; however, the duration of the exposure was relatively short (~2 min). Furthermore, it is doubtful that nonpiloted ignition of redundant cables could occur under the present test conditions because of the reduced oxygen content of the surrounding smoke layer.

Since the severity of the local thermal environments was approximately the same for these four tests, the ability of the redundant system to withstand temperature extremes is determined by the threshold level of failure for the particular type of cable. That is, despite identical protection methods and similar thermal environments, the redundant system with qualified cable did not fail because it had a higher failure threshold.

8.6 Limitations and Extrapolation

As in any experimental program, the present full-scale tests were conducted over a limited range of conditions in order to develop a test plan that was both feasible and economical. Extrapolation of the test results to conditions other than those specifically tested should be performed with extreme caution. A review of the pertinent literature indicates that the phenomenological understanding of fire behavior as well as the computational state-of-the-art is not, at present, adequate to account for many important physical processes that may influence the development of the fire environment. Specifically, the influence of room geometry (particularly ceiling height), fuel load, fuel characteristics, fuel location, ventilation conditions and locations, and cable protection schemes cannot be fully quantified at this time.

In addition to these factors, the uncertainty concerning damageability of cables and other safety-related equipment cannot be assessed at this time.

9. Conclusions and Recommendations

The following results were obtained for the configurations investigated, namely, a room with a length of 25 ft, height of 10 ft, and width of 14 ft; a door opening of 4 ft by 8 ft with a 4 ft by 8 ft canopy outside the room over the door opening; and a fuel load of 5 gal heptane with two vertical trays, each containing 43 cables (12.5% full), and horizontal trays containing the redundant safety system near the ceiling by the doorway (20 ft from the source fire).

For the *unqualified cable* (3 conductor, No. 12 AWG, polyethylene insulation and polyvinylchloride jacket), all three configurations (cable unprotected, cable protected with a ceramic fiber blanket and metal covers, and cable protection with a fire-retardant coating) failed (electrical short).

For the *IEEE-383 qualified cable* (3 conductor, No. 12 AWG, cross-linked polyolefin insulation and jacket), the configuration with unprotected cable failed (electrical short); in the other two configurations, described above, the cable did not short.

These full-scale tests demonstrate that, for certain conditions, a thermal environment exceeding the temperature and/or heat flux limitations of both the qualified and unqualified cables tested can be reached by a redundant safety system which is 20 ft from a source fire with a very moderate fuel load. Hence, the requirement in Appendix R, 10 CFR 50, for 20-ft separation of the redundant safety equipment required for hot shutdown is *not*, by itself, adequate in all situations, even for qualified cable.

Note that an active fire suppression system was not used in the tests, although three sprinkler heads were installed and instrumented to record the time of operation of the fusible elements.

On the basis of our investigations, the following recommendations are made:

- A combined analytical/experimental program be initiated to evaluate and extend the analytical state-of-the-art for predicting the local thermal environment as a result of a fire in a nuclear power plant room. To this end, the following steps should be undertaken:
  - —Existing experimental data should be compiled.
  - —Fuel loads and fuel types in typical nuclear power plants should be determined.
  - —Fuel types in typical nuclear power plants should be characterized as to energy release rate.
  - —Analytical and computational procedures should be developed and compared to all available experimental data.
- Potential failure modes and conditions of other redundant safety system equipment in addition to cables should be identified.
- The effectiveness of various cable protection systems should be examined in greater detail.
- The term "free of fire damage" should be defined.

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APPENDIX A

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FIRE TEST INVESTIGATION OF TWENTY-FOOT SEPARATION

TOPICAL REPORT

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ABSTRACT

Experiments and tests were conducted to provide data for use in evaluating the twenty-foot separation specification contained in the US Nuclear Regulatory Commission Appendix R to 10 CFR 50. Four preliminary fire experiments were conducted to determine the room size, fire location and ventilation conditions to be used for the fire tests. Six fire tests were conducted to evaluate fire performance within a room configuration with circuits in vertical trays and circuits in horizontal trays that were separated by a horizontal distance of at least 6.1 m (20 ft). The circuits were either unprotected or protected with either insulation and tray covers or a flame retardant coating. Two different cable constructions were used; one that met the IEEE 383-1974 flame test requirements and one that did not. The data indicated that when the cables were unprotected, short circuits developed and the cable was damaged in both the vertical and horizontal trays, regardless of the cable construction used. When the cables were protected, cables were damaged in the vertical trays, while short circuits and cable damage occurred in the horizontal trays for only one of the two cable constructions. Voltage withstand tests and physical property tests were conducted on some of the cable sections which had been exposed in the fire tests. These tests provided data which permitted visually observed cable damage to be quantified.

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PREFACE

A fire research program is being conducted by Sandia National Laboratories (SNL) for the US Nuclear Regulatory Commission (NRC) to evaluate the adequacy of the twenty-foot separation specification included in Appendix R to 10 CFR 50.[1] The research program consists of full-scale fire tests, separate effects experiments and analysis. The tests and experiments described in this Report are one task of this program.

These tests and experiments were conducted at Underwriters Laboratories' facility in Northbrook, Illinois.

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FIRE TEST INVESTIGATION OF TWENTY-FOOT SEPARATION

TOPICAL REPORT

1. Introduction

Background

Sandia National Laboratories (SNL) is conducting a fire research program to evaluate the adequacy of the twenty-foot separation specification contained in the Nuclear Regulatory Commission rule on fire protection, Appendix R to 10 CFR 50.[1] Section III.G of Appendix R specifies the requirements concerning fire protection of safe shutdown capability. One of the methods specified with the intent to ensure that one of the redundant trains is free of fire damage is stated in the regulations as follows:

"...b. Separation of cables and equipment and associated nonsafety circuits of redundant trains by a horizontal distance of more than 20 ft with no intervening combustible or fire hazards. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area; ..."[1]

The SNL fire research program of the twenty-foot separation specification consists of several tasks involving fire experiments, full-scale fire tests, separate effects tests and mathematical analyses.[2] This Report describes some of the tests and experiments that are one task of this program.

This task was intended to provide data for evaluating the fire protection afforded by the separation of redundant safety-related cables by a horizontal distance of twenty feet without fire detectors and an automatic fire suppression system in operation. The task reported here consisted of several series of tests. These included: conducting four preliminary fire experiments, six full-scale fire tests and several supplemental tests.

Preliminary Fire Experiments

The preliminary fire experiments involved a series of pool fires (flammable liquid confined to a pan) conducted within a room with one opening to simulate a doorway. In these experiments, fire location, room length and ventilation conditions were varied. The fire was located either against the rear wall of the room or about 1.98* m (6.5 ft) from the rear wall. The room was either 9.14 m (30 ft) or 7.62 m (25 ft) in length. Three ventilation conditions were used, involving either limited air movement from a room without openings or free convective movement through a doorway opening of either 2.44 m by 2.44 m (8 ft by 8 ft) or 1.22 m by 2.44 m (4 ft by 8 ft) located in the front wall. To provide information relative to cable damage, trays with cable were installed 0.305 m (1 ft) from the front wall and between 0.305 m (1 ft) and 0.509 m (1.66 ft) from the ceiling. These experiments were intended to:

- Identify the room size, fire location and ventilation conditions for the full-scale fire tests;
- Provide supplemental information on the temperature, cable damage and circuit integrity of the cable constructions to be used in the fire tests;
- Provide data on atmospheric temperatures, heat fluxes, cable jacket temperatures and gas velocities for use in mathematical analyses of the fire experiments (to be conducted in another task of the research program).

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* In this Report, SI units may only be approximate values of English units.

Full-Scale Fire Tests

The full-scale fire tests were conducted within the same room with the length, fire location and ventilation as identified by the preliminary fire experiments. Two sets of cable trays with cables were installed within the room. Two trays were installed vertically, 0.127 m (5 in.) from and near the center of the rear wall and two trays were installed horizontally, 0.305 m (1 ft) from the front wall and 0.305 m (1 ft) and 0.509 m (1.66 ft) from the ceiling. The horizontal distance was about 6.55 m (21.5 ft) between the horizontal and vertical trays. Each test was conducted with either of two different cable constructions and with the cables either unprotected or protected with different systems. The cable constructions used had the same number and size of conductors, but differed in that one met the flame test requirements per IEEE Standard 383-1974,[3] Paragraph 2.5 (qualified) while the other did not (unqualified). In two tests the cables were protected by steel tray covers and insulation. In two tests a flame retardant coating was applied to the cables. In the other tests the cables were left exposed.

These full-scale fire tests were intended to:

- Provide data useful in analyzing the effectiveness of a twenty foot separation between cables in cable trays;
- Provide data with respect to operation times of sprinkler fusible links in the specific environment;
- Provide data on atmospheric temperatures, heat fluxes, cable jacket temperatures and gas velocities for use in mathematical analyses of the fire tests, (to be conducted in another task of the research program).

Supplemental Tests

For the supplemental tests, both new cable and samples of cable taken from the fire tests were subjected to tensile strength and elongation tests on the cable jacket material and voltage withstand tests in accordance with IEEE 383-1974[3], Paragraph 2.3.3.4. These tests were intended to provide data which permitted visually observed cable damage to be quantified.

Facility

The preliminary fire experiments and full-scale fire tests were conducted on a configuration consisting of cables in trays located within a concrete block room. The room was 4.27 m (14 ft) wide either 9.14 m (30 ft) or 7.62 m (25 ft) long, and 3.05 m (10 ft) high (Figures 1-3). There was a 2.44 m by 2.44 m (8 ft by 8 ft) opening in the front wall to simulate a doorway. The room was located within a test building was 20.44 m (67 ft) long, 11.28 m (37 ft) wide and 6.40 m (21 ft) high.

Instrumentation and Equipment

Various instrumentation were used to record the data. They consisted of thermocouples, heat flux gauges, pressure probes and electronic barometers. Data were recorded using a Digital Data Acquisition System. Ammeters and a circuit integrity device were used to monitor circuit integrity of the cables. An events recorder was used to record the time when the links of the sprinkler heads fused. The experiments and tests were recorded in color on video tape and with 35 mm slide and print film. The instrumentation and their locations and the equipment are described in the Appendix.

2. Preliminary Experiments

General

Four preliminary fire experiments were conducted to develop data on the effect of changes in room size, fire location and ventilation conditions. Each experiment was conducted to investigate a different condition.

> Preliminary Fire Experiment 1 was conducted to provide data on temperature and fluxes developed with a pan of burning heptane at the north-south centerline of the room and 1.37 m (4.5 ft) from the rear wall. The door opening was 2.44 m by 2.44 m (8 ft by 8 ft), at the center of front wall.
>
> Preliminary Fire Experiment 2 was conducted to provide data on temperatures and fluxes developed with a pan of burning heptane placed against the rear wall and the room size of 7.62 m (25 ft) long by 4.27 m (14 ft) wide by 3.05 m (10 ft) high. The door opening was 2.44 m by 2.44 m (8 ft by 8 ft), at the center of the front wall.
>
> Preliminary Fire Experiment 3 was conducted to provide data on temperatures and fluxes developed with the room configuration of Experiment 2, except that the door opening was 1.22 m by 2.44 m (4 ft by 8 ft).
>
> Preliminary Fire Experiment 4 was conducted to provide data on temperatures and fluxes developed with the room configuration of Experiment 2, except that the door opening was covered with boards that were not sealed so that air leakage could occur.

A summary of the experimental plan is given in Table 1.

Facility

The experimental configuration consisted of a room with two horizontal cable trays and a pan to contain the heptane.

Room

The room was 4.27 m (14 ft) wide, either 9.14 m (30 ft) or 7.62 m (25 ft) long and 3.05 m (10 ft) high (Figures 1 and 2). The walls of the room were constructed with nominal 0.20 m by 0.20 m by 0.40 m (8 by 8 by 16 in.) hollow core concrete blocks laid up with mortar. The ceiling consisted of cellular steel floor and form units that were nominal 80 mm (3 in.) deep, 0.76 m (30 in.) wide and fabricated from galvanized steel. Mineral fiber insulation was placed between the concrete block walls and steel form units as a compressible seal. Pieces of nominal 12 mm (1/2 in.) thick inorganic board with a density of 769 kg/m^3 (48 lb/ft^3) were fastened with screws to the flat plate of the cellular units at two locations (Figures 1 and 2). A cementitious mixture was sprayed over the surface of the boards to about a 6 mm (1/4 in.) thickness and sprayed over the remaining ceiling surface of the cellular units to about a 19 mm (3/4 in.) thickness. The cementitious mixture was a proprietary mixture of predominantly inorganic dry ingredients that were mixed with water just prior to spray application.

Three 0.20 m by 0.20 m by 0.40 m (8 in. by 8 in. by 16 in.) openings were constructed in the east wall and located as shown in Figures 1 and 2. A piece of transparent plastic or mineral fiber insulation was placed over each opening, except in Experiment 4 in which each opening was filled with mineral fiber. At the centerline of the north wall, a 2.44 m by 2.44 m (8 ft by 8 ft) opening was constructed (Figures 1 and 2). A canopy of structural steel angles and inorganic boards was located above this opening outside of the room.

In Experiment 3, one-half the width of a 1.22 m by 2.44 m by 12 mm thick (4 ft by 8 ft by 1/2 in.) inorganic board was placed along each side of the opening in the north wall. The resulting opening area was then 1.22 m by 2.44 m (4 ft by 8 ft) at the middle of the north wall (Figure 2). In Experiment 4, boards were laid full width across the opening in the north wall. The boards were placed over the opening without gaskets or sealing materials.

Cable Trays

In each experiment, two 4.27 m (14 ft) long cable trays were installed horizontally 0.305 m (1 ft) from the north wall and 0.305 m (1 ft) and 0.509 m (1.66 ft) from the ceiling. The trays were clamped to steel angles that were bolted to the east and west walls. In Experiment 1, one additional 0.915 m (3 ft) tray was located on a steel rack, 0.915 m (3 ft) above the floor under the other trays and at the center of the north wall. All trays were open ladder type, nominal 0.46 m (18 in.) wide by 0.10 m (4 in.) deep and made from 1.6 mm (0.065 in.) thick galvanized steel with a maximum loading depth of 76 mm (3 in.). The side rails were constructed with 19 mm (3/4 in.) flanges facing outward from the center of the tray. The rungs were 25 mm (1 in.) deep, 25 mm (1 in.) wide and spaced 0.22 m (9 in.). The trays were located as shown in Figures 1 and 2.

Cables

Cables were installed in the horizontal trays. Two different cable constructions were used (Table 2). One construction met the flame test requirements of IEEE 383-1974 (qualified) while the other did not (unqualified).

Bundles of 0.305 m (1 ft) long cable segments were installed in all the trays in Preliminary Fire Experiment 1, and in the upper tray in the remaining experiments. Each bundle consisted of eight cable segments fastened together with steel tie wires except for Experiment 1 in which the segments were fastened with plastic ties.

In Preliminary Fire Experiment 1, fourteen bundles of unqualified cable were installed in two layers at the center and quarter points of the two upper trays and at the center of the lower tray. In the upper horizontal tray in Preliminary Fire Experiments 2, 3 and 4, fourteen bundles of unqualified cable were installed in two layers at 1.68 m (5.5 ft) west of the east wall and fourteen bundles of qualified cable were installed in two layers at 1.68 m (5.5 ft) east of the west wall (Figure 4).

In Preliminary Fire Experiments 2-4, two continuous 9.14 m (30 ft) long cables were placed in the lower tray starting at the east wall, running to the west wall, looping and running back to the east wall (Figure 5). The ends of one looped cable in Experiments 2 and 3, and the ends of both cables in Experiment 4, were passed through access holes in the east wall. The cables were placed parallel to each other without touching. The cables were fastened to the tray rungs near the west and east walls with steel ties. Unqualified cables were used in Preliminary Fire Experiment 2, while qualified cables were used in Preliminary Fire Experiment 3. In Preliminary Fire Experiment 4, one qualified and one unqualified cable were used. In addition to the looped cables in Preliminary Fire Experiment 3, a single 0.914 m (3 ft) length of unqualified cable was placed in the center of the tray.

Instrumentation

Various instrumentation were used. Thermocouples were used to measure atmospheric, wall, roof/ceiling and cable jacket temperatures. Calorimeters and radiometers were used to measure heat fluxes. Probes with electronic barometers were used to measure atmospheric pressures. Descriptions and locations of these instruments are in the Appendix.

Procedure

A pan that was 0.3 m (1 ft) wide by 1.52 m (5 ft) long and 0.3 m (1 ft) deep formed from 6 mm (0.025 in.) thick steel was used to contain the heptane for each experiment.

The center of the pan was located on the north-south centerline of the room and with the south side of the pan either against the south wall in Experiments 2-4 or 1.98 m (6.5 ft) away from the south wall in Experiment 1.

In Experiments 2 and 3, one of the looped cables in the lower tray was energized at 120 V ac with one conductor at 9A and one conductor at 4.5A. The remaining conductor was neutral (ground) (Figure 6). In Experiment 4, both looped cables were energized in the same manner.

The pan was filled with water to a level of about 0.10 m (4 in.). At about 180 s before the start, 0.038 m^3 (10 gal) of heptane was poured into the pan.

The heptane was ignited by spark or by match to start the experiment. During the experiment, observations were recorded as to the character and development of the fire. The experiments were continued until the flames from the burning heptane had subsided or until 1800 s. All temperatures, fluxes and pressures were recorded and the ammeters for the energized cables were monitored continuously for short circuits.

Data

Identification of room size, fire location and ventilation conditions for the full-scale fire tests was conducted by analysis of the appearance of the flames, atmospheric temperatures and total heat fluxes near the horizontal trays. Supplemental information was obtained on the cable performance from the cable jacket temperatures, cable damage and electrical integrity of the conductor circuits.

Observations During Experiments

Flames from the heptane fire were luminous and uniform across the pan area. In Experiment 1, the maximum flame height of the heptane fire was about 2.7 m (9 ft). In Experiments 2-4, the flames from the heptane fire impinged on the ceiling (3.05 m (10 ft) high) and were deflected along the ceiling surface about 0.6 m (2 ft).

In each experiment a smoke layer formed at the ceiling, and had a lower boundary that was smooth and level. The height of the bottom of the layer was about 1.24 m (4 ft, 8 in.) in Experiment 2 and 1.22 m (4 ft) in Experiment 3. In Experiment 4, the smoke layer descended to 0.20 m (8 in.) above the floor.

The appearances of the fire in Experiment 1 and Experiment 3 are shown in Figures 7 and 8, respectively.

Atmospheric Temperatures

The average atmospheric temperatures near the upper horizontal tray, 0.305 m (1 ft) below the ceiling are shown in Figure 9.

The maximum average atmospheric temperatures that occurred during the four experiments was about 340 °C (644 °F) and occurred in Experiment 3 (Figure 9).

The average atmospheric temperatures near the upper horizontal tray for Experiment 3 at 0.305 m (1 ft), 0.610 m (2 ft) and 0.915 m (3 ft) from the ceiling are shown in Figure 10.

Heat Fluxes

The total heat fluxes at the lower horizontal tray for each experiment are shown in Figure 11. The maximum heat flux measured at the lower horizontal tray was 13 kW/m^2 (1.14 Btu/ft^2·s) which occurred in Experiment 3.

Cable Jacket Temperatures

For Experiment 3, the average cable jacket temperatures of the qualified cable installed in a bundle in the upper tray and the cable jacket temperatures of the qualified cable that was energized in the lower tray are shown in Figure 12. For Experiment 3, the average atmospheric temperatures near the horizontal lower tray at 0.610 m (2 ft) below the ceiling and the cable jacket temperature of the energized cable in the lower tray are shown in Figure 13.

Circuit Integrity

A short circuit developed in the looped unqualified cable in the lower tray at 614 s in Experiment 2 and at 735 s in Experiment 4. The looped qualified cable in the lower tray maintained electrical integrity during Experiments 3 and 4. A summary of the times when short circuits occurred is given in Table 3.

Observations After Experiments

The cable jacket and insulation material of unqualified cable bundles had coalesced into a single mass. The single unqualified cable jacket was irregular shaped from melted material which solidified upon cooling. The jacket material of the qualified cable installed singly and in bundles was cracked and the cable had become less flexible.

Findings

Based upon these data, the room length, fire location and ventilation conditions in Experiment 3 were selected for the full-scale fire tests since:

- the flame height from the burning heptane impinged on the ceiling (3.05 m (10 ft) high and were deflected along the ceiling surface about 0.6 m (2 ft); and
- the maximum average atmospheric temperatures near the horizontal trays that occurred during the four experiments was about 340 °C (644 °F) and occurred in Experiment 3; and
- the maximum total heat flux that was measured at the lower horizontal tray during all the experiments was 13 kW/m^2 (1.14 Btu/ft^2·s) and occurred in Experiment 3.

3. Full-Scale Fire Tests

General

Six full-scale fire tests were conducted to provide data for use in evaluating twenty-foot separation for protecting cable circuits. Each test was conducted with a different cable construction or cable protection system.

> In Test 1, unqualified cable was used, installed without protection.
>
> In Test 2, qualified cable was used, installed without protection.
>
> In Test 3, unqualified cable was used, installed with a system composed of a layer of insulation and steel tray covers.
>
> In Test 4, qualified cable was used, installed with a system composed of a layer of insulation and steel tray covers.
>
> In Test 5, unqualified cable was used, installed with a flame retardant coating.
>
> In Test 6, qualified cable was used, installed with a flame retardant coating.

A summary of the test plan is given in Table 5.

Facility

The experimental configuration consisted of the room used in the preliminary fire experiments with two sets of cable trays that were separated by a horizontal distance of about 6.55 m (21.5 ft) and a pan to contain the heptane.

Room

The tests were conducted within the room using the same conditions as in Preliminary Fire Experiment 3 [7.62 m (25 ft) long, 4.27 m (14 ft) wide and 3.05 m (10 ft) high with the door opening at the centerline of the north wall that was 1.22 m by 2.44 m (4 ft by 8 ft), Figure 3].

Cable Trays

In each test, two nominally 4.27 m (14 ft) long cable trays were installed horizontally in the east-west direction, 0.305 m (1 ft) from the north wall and 0.305 m (1 ft) and 0.509 m (1.66 ft) from the ceiling and two nominally 3.05 m (10 ft) long cable trays were installed vertically, 0.127 m (5 in.) from the south wall and 0.229 m (9 in.) from the north-south centerline of the room (Figure 3). The horizontal trays were supported at the east and west walls by steel angles while the vertical trays were welded to bracing angles that were bolted to the south wall.

The horizontal trays in Tests 1-4 were open ladder type, nominal 0.46 m (18 in.) wide by 0.10 m (4 in.) deep and made from 1.6 mm (0.065 in.) thick galvanized steel with a maximum loading depth of 76 mm (3 in.). The side rails were constructed with 19 mm (3/4 in.) flanges facing outward from the center of the tray. The rungs were 25 mm (1 in.) deep, 25 mm (1 in.) wide and spaced 0.22 m (9 in.). The vertical trays and the horizontal trays in Tests 5 and 6 were open ladder type, nominal 0.46 m (18 in.) wide by 0.10 m (4 in.) deep and made from 1.5 mm (0.059 in.) thick galvanized steel with a maximum loading depth of 95 mm (3-3/4 in.). The side rails were constructed with 19 mm (3/4 in.) flanges facing in toward the center of the tray. The rungs were flared, 16 mm (5/8 in.) deep, 25 mm (1 in.) wide and spaced 0.127 m (5 in.) OC.

Cables

The same two cable constructions used in the preliminary fire experiments were used in the full-scale fire tests.

In each vertical tray forty-three, 3.05 m (10 ft) lengths of cable were installed. Except for Test 1, the top end of each cable length was bent and hooked over the top run of the tray and fastened to the rungs near the center, top and bottom of the trays with steel tie wires (Figure 14).

In the horizontal trays, a single continuous cable was laid in the tray into a coil pattern that was made by running the cable to the end of the tray and then looping the cable back several times until forty-two, 4.27 m (14 ft) single lengths of cables were simulated. The ends of the cable were passed through small access holes in the east wall. The cable was fastened to the rungs near the end of each tray with steel tie wires (Figure 14).

In Tests 1, 3 and 5, unqualified cable was installed. In Tests 2, 4 and 6, qualified cable was installed.

Cable Insulation

A layer of insulation was placed on top of the cables (nonrung side) in each tray for Tests 3 and 4. The insulation was a ceramic fiber blanket that was nominally 12 mm (1/2 in.) thick with a density of 128 kg/m³ (8 lb/ft³) and cut to an 0.48 m (19 in.) width and installed in a continuous piece of 3.05 m (10 ft) or 4.27 m (14 ft) long dependent upon tray length. The insulation was also tore into small pieces and stuffed at both ends of the horizontal trays and the top end of the vertical trays in Tests 3 and 4 (Figure 15).

Tray Covers

Solid tray covers were installed on the vertical and horizontal trays in Tests 3 and 4. The covers were formed from 1.5 mm (0.059 in.) thick steel and with one flange that was 25 mm (1 in.) long. The covers were either 0.46 m (18-3/16 in.) wide or 0.50 m (19-3/4 in.) wide dependent upon the cable tray used. The covers were either 3.05 m (10 ft) or 1.32 m (4.33 ft) in length. The covers were fastened to the tray side rails with sheet metal screws, 305 mm (1 ft) OC (Figure 15).

Cable Coating

A flame retardant cable coating was applied to the cables in the horizontal and vertical trays in Tests 5 and 6. The coating was applied by an industrial applicator recommended by the coating material manufacturer. The material was applied in accordance with the manufacturer's application instructions and in accordance with the applicator's quality control procedure. The material was applied to a 3 mm (1/8 in.) wet thickness and about a 1.39 mg/m³ (87 lb/ft³) wet density. The material had reached moisture equilibrium prior to test as determined by coating samples having reached constant weight.

Sprinkler Heads

Three sprinkler heads were installed 241 mm (9.5 in.) below the ceiling along the north-south centerline of the room as shown in Figure 3. The sprinkler heads were pendent type with standard 12 mm (1/2 in.) orifice. The temperature rating for the sprinkler heads in Tests 1, 3 and 5 was 74 °C (165 °F) while the rating was 100 °C (212 °F) for the heads in Tests 2, 4 and 6. The sprinkler heads were not connected to piping, but the links were connected to electrical circuits for recording the time when the links fused.

Instrumentation

Various instrumentation were used. Thermocouples were used to measure atmospheric, wall, roof/ceiling and cable jacket temperatures. Calorimeters and radiometers were used to measure heat fluxes. Probes with an electronic barometer were used to measure atmospheric pressures. Descriptions and locations of these instruments are in the Appendix.

Procedure

The same pan used in the preliminary fire experiments was used in these tests. The center of the pan was located on the north-south centerline of the room and with its side against the south wall. For Tests 1 and 2, the 2.82 m (9.25 ft) long vertical trays extended 76 mm (3 in.) into the pan. For the remaining tests, the 3.05 m (10 ft) long trays were in contact with the bottom of the pan.

In Tests 3 and 4, an approximate 1.5 m (1/16 in.) thick coating of refractory type mortar was applied over the side joints of the tray covers at the bottom of the two vertical trays for a distance of about 0.30 m (12 in.) from the base.

The continuous cable in the lower horizontal tray was energized at 120 V ac during each test. One conductor was at 9.0A; one conductor was at 4.5A; and the remaining conductor was neutral (ground) (Figure 6).

In the upper horizontal tray, the continuous cable was connected to a circuit integrity device for detecting if shorts occurred between conductor or between a conductor and ground (Figure 6).

The pan was filled with water to a level of about 0.14 m (5-1/2 in.). At about 180 s before the start, 0.019 m^3 (5 gal) of heptane was poured into the pan.

The heptane was ignited by spark or by match to start the test. During the test, observations were recorded as to the character and development of the fire. The tests were conducted until fire activity subsided or 1800 s (30 min). All temperatures, fluxes and pressures were recorded, cable circuits monitored for shorts and sprinkler links monitored for the time when they fused.

Data

The data of interest for this Report were observations during the tests, atmospheric temperatures and total heat fluxes near the horizontal trays, cable jacket temperatures, observations after the tests, the electrical integrity of the cable circuits and operation times of the sprinkler heads.

Observations During The Tests

After ignition of the heptane, the cables ignited in the vertical trays in each test. In Tests 1 and 2, the cable became involved in flames with the maximum area of cable involved and maximum flaming from the cables and heptane occurred between 120 s to 300 s. In the remaining tests, the maximum area of cable involved and maximum flaming from the cables and heptane occurred between 480 s to 720 s for Tests 5 and 6 and at 900 s for Tests 3 and 4.

A smoke layer formed in each test prior to 60 s. The layer gradually descended to about 1.22 m (4 ft) from the floor. The smoke layer was optically dense and appeared stable and homogenous. As each test continued, smoke accumulated in the test building, and eventually was entrained in the air that entered the test building below the smoke layer. The color and density of this accumulated smoke was different for each test. Examples of the appearances of the fire in Tests 1 and 4 are shown in Figures 16 and 17, respectively.

Atmospheric Temperatures

The average atmospheric temperatures near the upper horizontal tray at 0.305 m (1 ft) below the ceiling are shown in Figure 18. As shown, the maximum average atmospheric temperature was 560 °C (1040 °F) and occurred at 300 s in Test 1.

Heat Fluxes

The heat fluxes at the lower horizontal tray are shown in Figure 19. As shown, the maximum heat flux of 37 kW/m^2 (3.2 $Btu/ft^2/s$) occurred in Test 1.

Cable Jacket Temperatures

The average cable jacket temperatures for the cable in the upper tray are shown in Figure 20. As shown, the maximum average cable jacket temperature was 356 °C (673 °F) which occurred at 315 s in Test 1.

Observations After Test

In the vertical trays, all cable insulation and jacket materials were consumed by the fire with only the conductors and ash that remained.

In the horizontal trays different cable damage were observed. In Test 1, it appeared that the cable jacket had melted and flowed during the fire and then coalesced into a single mass upon cooling. Some charring and some areas of exposed conductors were observed. In Test 3, most of the cable was free from damage. The only damage was melted cable jacket at several places near the tray side rail facing the fire. Along this side, at each location where the cable was in contact with the south tray side rail or with the tray rung, there was some damage. In Test 5, the cable jacket material had melted and flowed through cracks in the coating during the fire and then solidified into small puddles on the coating surface. In Test 2, the cable jacket material had become discolored and hard with cracks near each bend. In Test 4, the cable jacket became less flexible but was not cracked or discolored. In Test 6, cable material did not flow through the coating during the test as it did in Test 5. Observations of the color and hardness of the jacket were not obtained since the coating could not be easily removed without damaging the cable.

A summary of the cable damage is given in Table 4. Appearances of the cable damage is shown in Figure 21.

Electrical Integrity

In Tests 1, 2, 3 and 5 shorts occurred. The earliest time at which a short circuit occurred was in Test 1 at 244 s. The latest time at which a short circuit occurred was in Test 3 at 1043 s. A summary of the electrical integrity for all the tests is shown in Table 3.

Response Times Of Sprinkler Heads

The head closest to the south wall operated earliest in Test 1 (58 s) and the latest in Test 4 (126 s). The head closest to the north wall operated the earliest in Test 1 (112 s) and the latest in Test 2 (200 s). A summary of the sprinkler operation times is given in Table 6.

4. Supplemental Tests

General

Physical property tests and voltage withstand tests were conducted to provide data which permitted visually observed cable damage to be quantified. Voltage withstand tests were conducted on samples from Tests 2-6. Physical properties tests were conducted only on samples from Test 4. Control tests were conducted on samples of new cable for comparison of physical properties.

Procedure

Samples for the voltage withstand tests were 3.05 m (10 ft) long and obtained from four general locations within the horizontal trays (Figure 14). Two samples were from the ends of the tray where the cable was looped. One sample was from near the south tray side rail and one sample was from the center of the tray.

The voltage withstand tests were conducted in general accordance with IEEE 383-1974, Paragraph 2.3.3.4.[3] Each 3.05 m (10 ft) sample was coiled about an 0.458 m (18 in.) diameter mandrel and immersed in tap water at room temperature. While the cable was immersed, a voltage of 2400 V/ac was applied to qualified cable samples and 1600 V/ac applied to unqualified cable samples.

Samples for the physical property tests were from 3.05 m (10 ft) lengths of cable obtained from the reel and from the center and along the side rail of the tray from Test 4.

The physical property tests were conducted in accordance with Paragraph 34 of UL 83 "Thermoplastic-Insulated Wires And Cables."[4] The samples were pulled until rupture. Elongation was measured as the distance between the bench marks divided by the original bench-mark length.

Data

The voltage withstand test data indicated that same samples from Tests 2 and 5 did not hold the applied voltage, while samples from Tests 3, 4 and 6 did. A summary of the data is given in Table 7.

The physical property test data indicated that the samples from Test 4 compared to samples from the reel had a decrease in the average elongation from 330 to 300 percent and an increase in tensile strength from 17.32 to 17.55 mPa (2512 to 2545 psi). A summary of the data is given in Table 8.

5. References

1. "Nuclear Regulatory Commission, 10 CFR 50, Fire Protection Program for Operating Nuclear Power Plants," pp. 76602-76616 Federal Register, Vol. 45, No. 225, Wednesday, November 19, 1980.
2. L. J. Klamerus, L. L. Lukens, D. D. Cline, D. A. Dube, "Program Plan For Evaluation of Twenty-Foot Separation Distance, 10 CFR 50, Appendix R," prepared for NRC by Sandia National Laboratories, March 10, 1982.
3. "IEEE Standard for Type Test of Class IE Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations," IEEE Standard 383-1974.
4. "Standard For Thermoplastic-Insulated Wires And Cables," UL 83, Eighth Edition.

TABLE 1

Experimental Plan

	Conditions		
Experiment	Fire Location	Room Length, m (ft)	Doorway, m x m (ft x ft)
1	Middle of Room	9.15 (30)	2.44 x 2.44 (8 x 8)
2	Against Wall	7.62 (25)	2.44 x 2.44 (8 x 8)
3	Against Wall	7.62 (25)	1.22 x 2.44 (4 x 8)
4	Against Wall	7.62 (25)	Closed

TABLE 2

Cable Constructions

	Conductors		Insulation		Insulation Covering		Cable Jacket		
Reference	No.	Size, AWG	Material	Thickness* mm (in.)	Material	Thickness* mm (in.)	Material	Thickness* mm (in.)	Diameter* mm (in.)
NQ	3	12	Polyethylene	0.9 (0.037)	Polyvinyl Chloride	0.3 (0.013)	Polyvinyl Chloride	1.6 (0.063)	11.1 (0.440)
Q	3	12	Cross Linked Polyolefin	1.2 (0.047)	-	-	Cross Linked Polyolefin	2.0 (0.078)	11.6 (0.460)

Notes:

NQ - Cable did not meet flame test requirements of IEEE 383-1974

Q - Cable met flame test requirements of IEEE 383-1974

* - Approximate

All conductors were stranded copper

TABLE 3

Electrical Integrity of Circuits

Test (T) Or Experiment (E)	Time and Type of Short Circuit					
	Upper Tray			Lower Tray		
	Cable	Time (s)	Type	Cable	Time (s)	Type
E1	XX	XX	XX	XX	XX	XX
E2	XX	XX	XX	NQ	614	G
E4	XX	XX	XX	NQ	735	G
				Q	N	-
E3	XX	XX	XX	Q	N	-
T1	NQ	244	G	NQ	262	G
T5	NQ	642	C	NQ	776	C
T3	NQ	N	-	NQ	1043	C
T2	Q	775	G	Q	N	-
T4	Q	N	-	Q	N	-
T6	Q	N	-	Q	N	-

Notes:

XX - Cable circuits not energized.

NQ - Cable that did not meet IEEE 383 flame test requirements.

Q - Cable that met IEEE 383 flame test requirements.

N - Cable remained functional and short circuit did not occur.

G - Conductor to tray (ground) short.

C - Conductor to conductor short.

TABLE 4

Cable Damage

Experiment (E) Or Test (T)	Vertical Trays	Horizontal Trays
E1	Trays not installed.	Cable jacket material melted and fused together.
E2	Trays not installed.	Cable jacket material melted.
E3	Trays not installed.	Cable jacket material deformed at rungs.
E4	Trays not installed.	Q Cable - Cable jacket material deformed at rungs. NQ Cable - Cable jacket material melted.
T1	Material consumed; ash and conductors remain.	Cable jacket melted and fused together along length.
T2	Material consumed; ash and conductors remain.	Cable jacket hard, cracks in jacket near bends.
T3	Material consumed; ash and conductors remain.	Cable near south tray rail melted and fused to rail and tray rungs. Remaining cable appeared unchanged.
T4	Material consumed; ash and conductors remain.	Cable jacket is harder than new cable, but is not cracked or deformed.
T5	Coating remains intact; cable material under coating consumed; ash and conductors remain.	Several puddles of solidified cable jacket material along cracks of coating.
T6	Coating remains intact; cable material under coating consumed; ash and conductors remain.	No apparent change to coating.

TABLE 5

Test Plan

Test	Parameters Cable	 Protection	 Sprinkler Rating, °C (°F)
1	NQ	None	74 (165)
2	Q	None	100 (212)
3	NQ	Insulation/Covers	74 (165)
4	Q	Insulation/Covers	100 (212)
5	NQ	Coating	74 (165)
6	Q	Coating	100 (212)

NQ - Cable that did not meet IEEE 383 flame test requirements.

Q - Cable that met IEEE 383 flame test requirements.

TABLE 6

Sprinkler Operation Times

Test	Head Rating °C (°F)	Operation Time (s) Head 1	Head 2	Head 3
1	74 (165)	58	88	112
5	74 (165)	*	*	121
3	74 (165)	105	152	169
2	100 (212)	70	120	200
6	100 (212)	86	129	194
4	100 (212)	126	151	181

* - Recording equipment malfunction and time at which link operated was not obtained. Link did fuse during test.

TABLE 7

Voltage Withstand Data

Test	Upper Tray				Lower Tray			
	Sample Number							
	1	2	3	4	5	6	7	8
2	WI	WI	WI	A	WI	WI	WI	B
4	WI	WI	WI	WI	WI	WI	WI	WI
6	WI	WI	WI	WI	WI	WI	WI	WI
3	WII	WII	WII	WII	WII	WII	WII	WII
5	WII	C,D	E	F,G	WII	H	WII	J,K

WI = Withheld 2400 V ac for 300 s, Q cable.
WII = Withheld 1600 V ac for 300 s, NQ cable.
A = Breakdown at 880 V ac between conductor and ground.
B = Breakdown at 2400 V ac at 2 s between conductor and ground.
C = Breakdown at 100 V ac between conductors.
D = Breakdown at 980 V ac between conductor and ground.
E = Breakdown at 400 V ac between conductors.
F = Breakdown at 500 V ac between conductors.
G = Breakdown at 1420 V ac between conductor and ground.
H = Breakdown at 800 V ac between conductors.
J = Breakdown at 200 V ac between conductors.
K = Breakdown at 1600 V ac at 26 s between conductor and ground.

TABLE 8

Physical Property Data

	Tensile Strength, mPa (psi)			
	Sample			
	1	2	3	Average
Reel Samples	15.81 (2293)	17.70 (2567)	18.46 (2678)	17.32 (2512)
Test 4 - Samples	18.38 (2666)	17.06 (2475)	17.21 (2496)	17.55 (2545)

	Elongation, Percent			
	Sample			
	1	2	3	Average
Reel Samples	330	330	330	330
Test 4-Samples	340	280	280	300

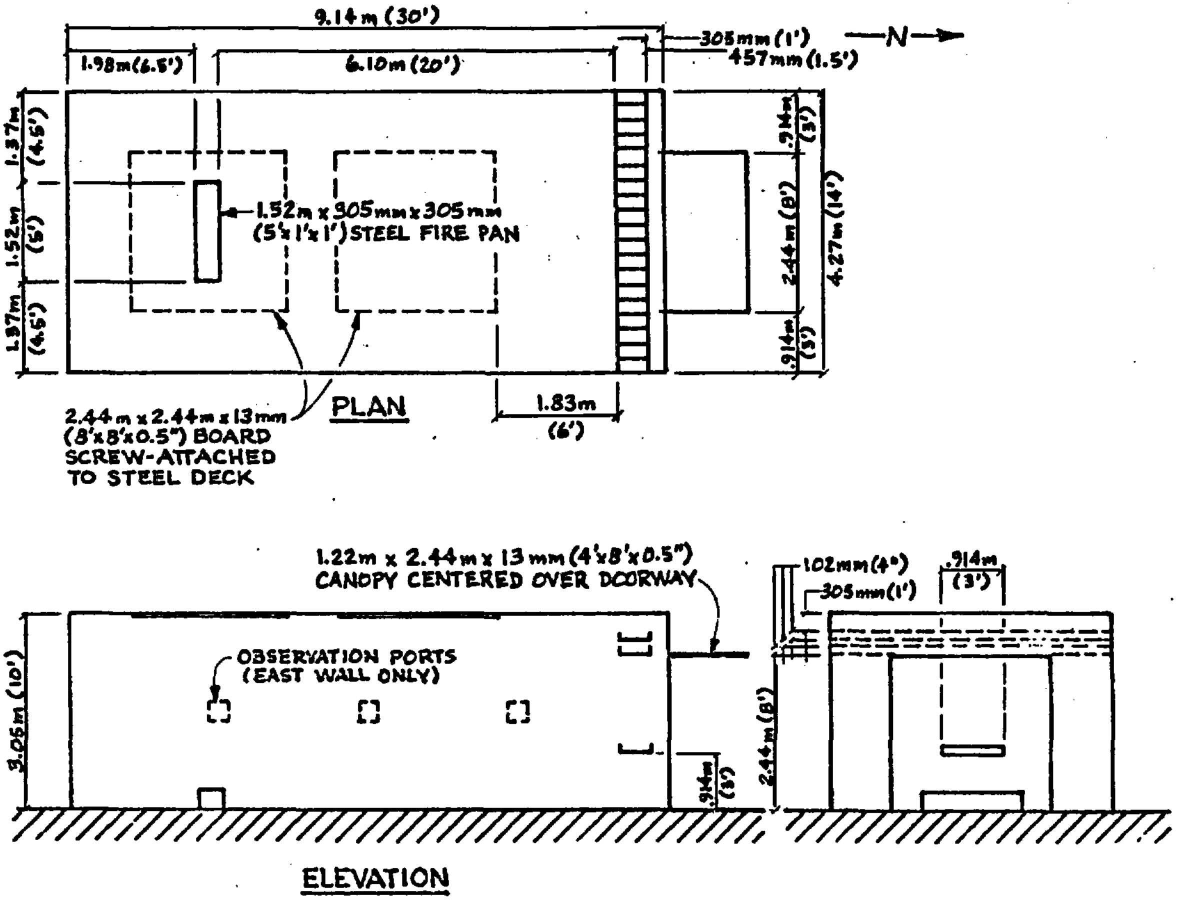
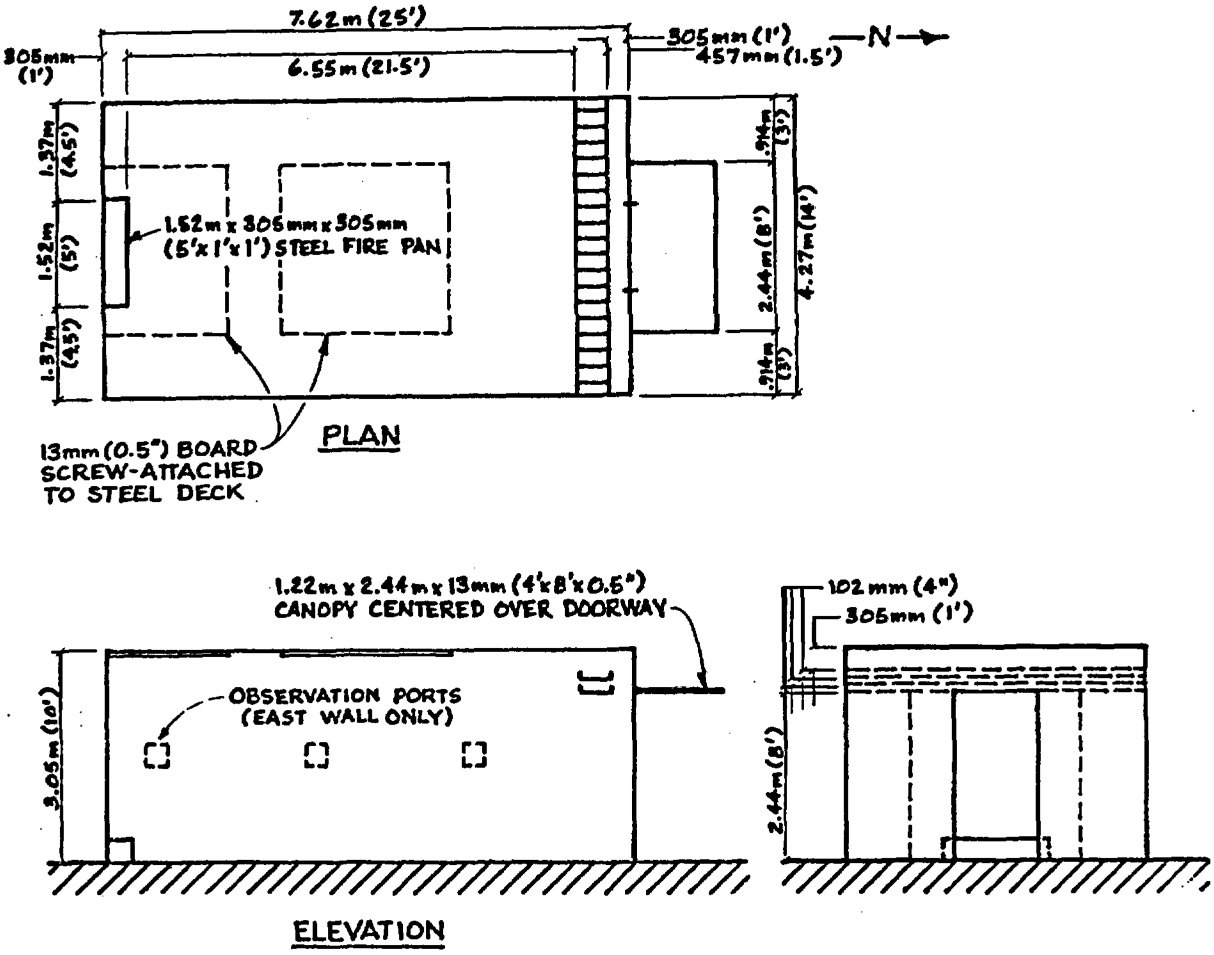
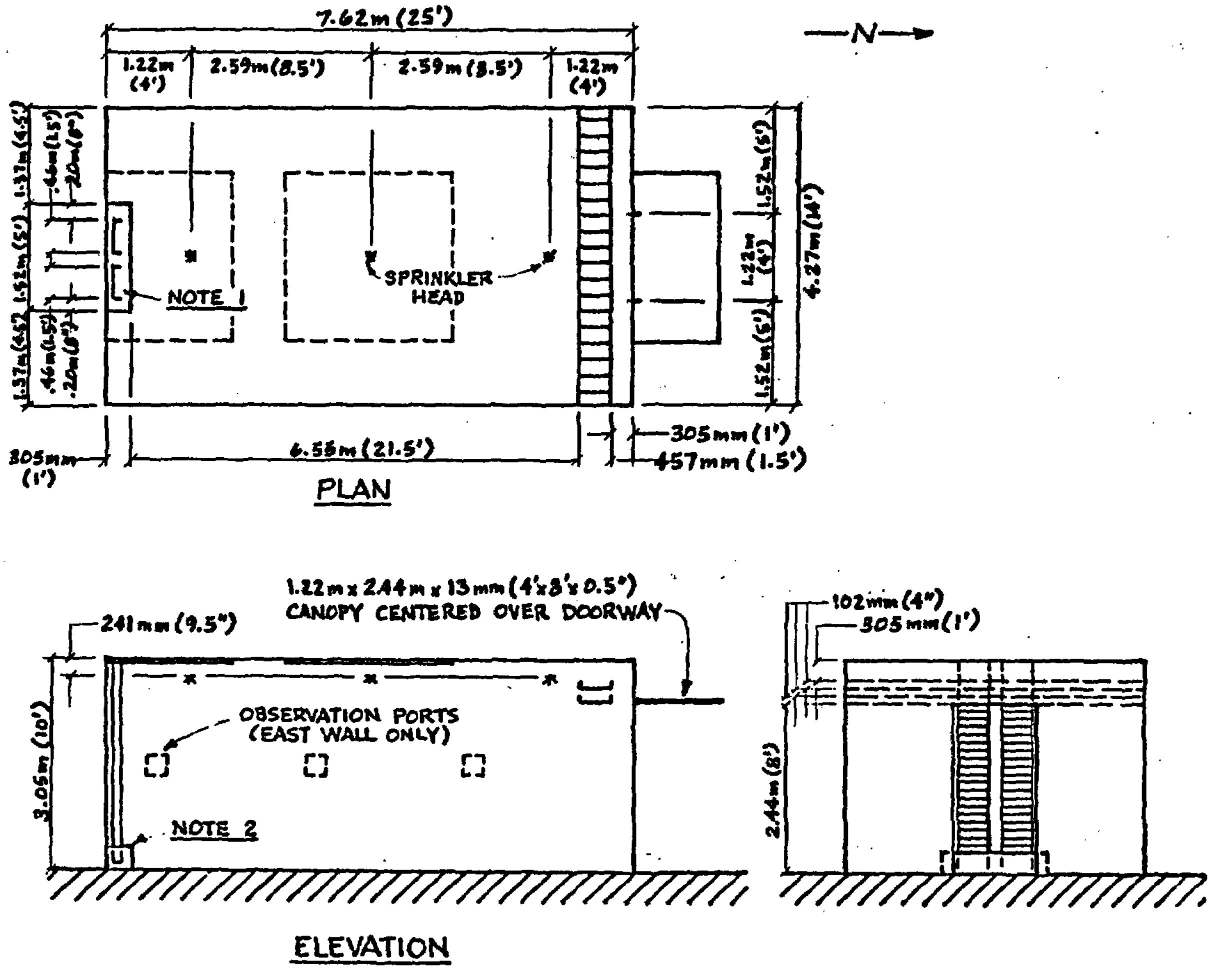


Figure 1 - Configuration For Experiment 1



FOR EXP. 2, THE DOORWAY WAS 2.44m (8') WIDE BY 2.44m (8') HIGH.
FOR EXP. 3, THE DOORWAY WAS 1.22m (4') WIDE BY 2.44m (8') HIGH.
FOR EXP. 4, THE DOORWAY WAS SEALED CLOSED.

Figure 2 - Configuration for Experiment 2 Through 4

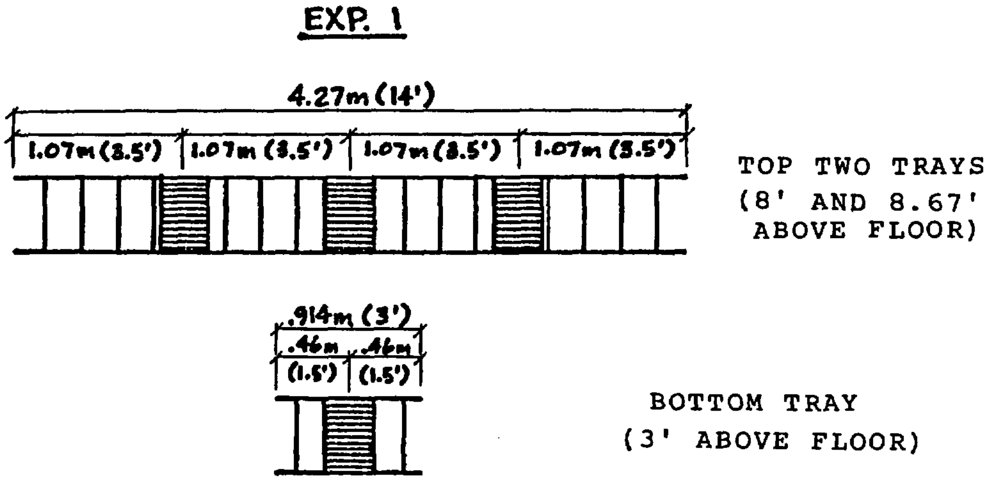


NOTE 1 : 102mm (4") FROM TRAY TO PAN; 127mm (5") FROM TRAY TO WALL.

NOTE 2 : FOR TESTS 1&2, TRAYS EXTEND 76mm (3") INTO FIRE PAN (51mm (2") ABOVE WATER/HEPTANE). FOR TESTS 3,4,5&6, TRAYS EXTEND TO BOTTOM OF FIRE PAN. BOTTOM 305mm (1') OF TRAYS AND STEEL COVER PLATES IN TESTS 3&4 COATED WITH REFRACTORY MATERIAL ALONG JOINTS TO SEAL HEPTANE FROM INTERIOR OF TRAY ASSEMBLY.

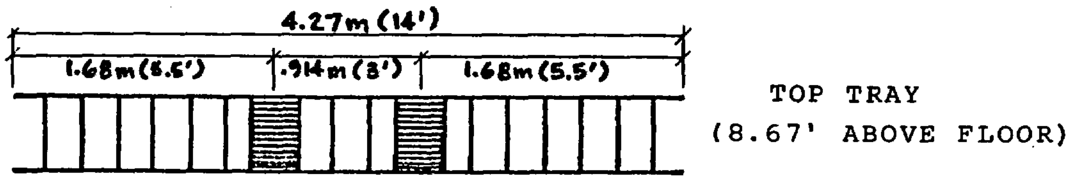
Figure 3 - Configuration For Tests 1 Through 6

EXP. 1



FOURTEEN BUNDLES (8 CABLES/BUNDLE) OF NQ CABLE AT EACH LOCATION IN UPPER AND LOWER 4.27m (14') TRAYS AND IN CENTER OF 0.914m (3') TRAY.

EXP. 2,3&4

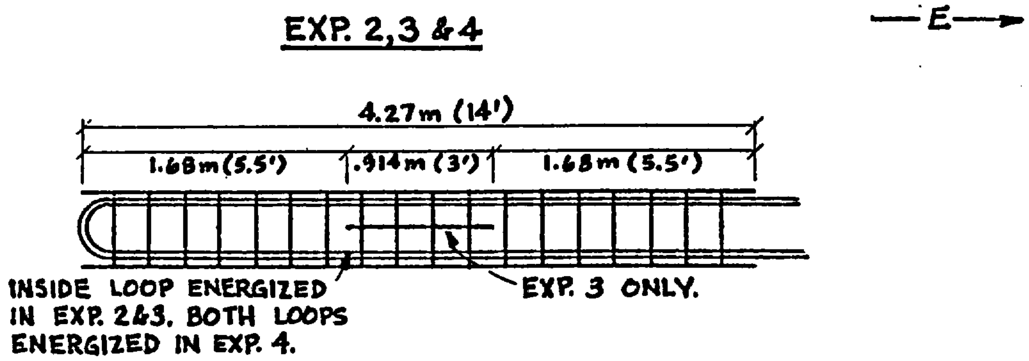


FOURTEEN BUNDLES (8 CABLES/BUNDLE) OF Q AND NQ CABLE PLACED IN UPPER HORIZONTAL TRAY. Q CABLE INSTALLED WEST OF TRAY CENTERLINE, NQ CABLE INSTALLED EAST OF TRAY CENTERLINE.

Q - QUALIFIED CABLE

NQ- UNQUALIFIED CABLE

Figure 4 - Cable Bundle Installation



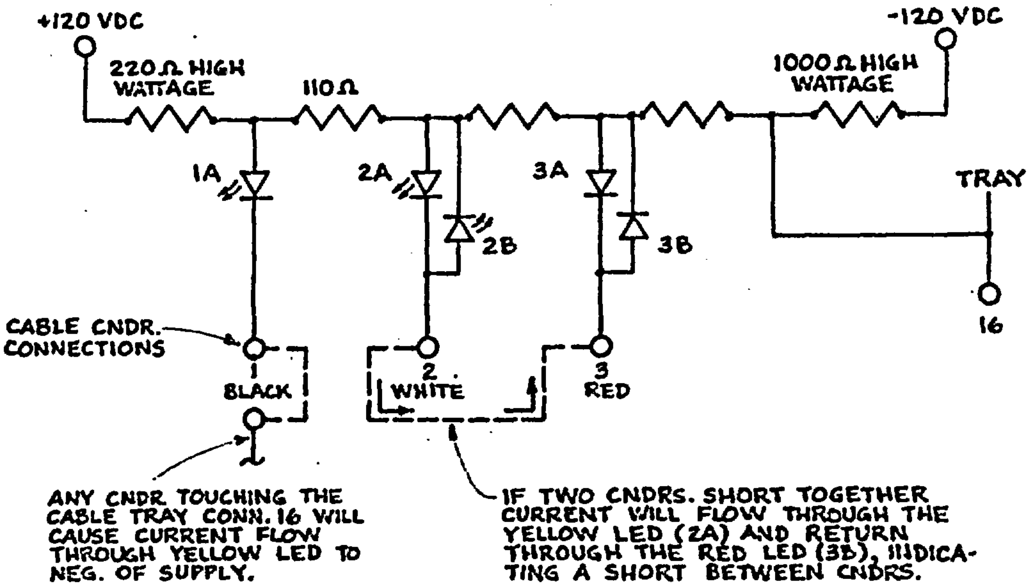
TWO 9.14m (30') LONG CABLES PLACED IN LOWER HORIZONTAL TRAY, LOOPED AT WEST END AND EXITING THROUGH EAST WALL. CABLE LENGTHS PLACED PARALLEL TO EACH OTHER WITHOUT TOUCHING.

FOR EXP. 3, A 0.914m (3') LENGTH OF NQ CABLE WAS PLACED IN THE CENTER OF THE TRAY.

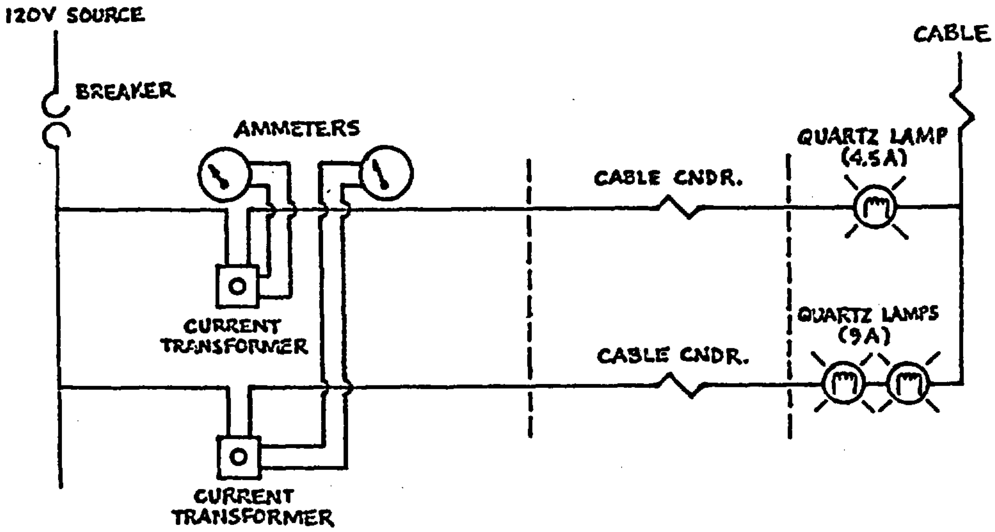
Q - QUALIFIED CABLE

NQ - UNQUALIFIED CABLE

Figure 5 - Single Loop Cable Installation

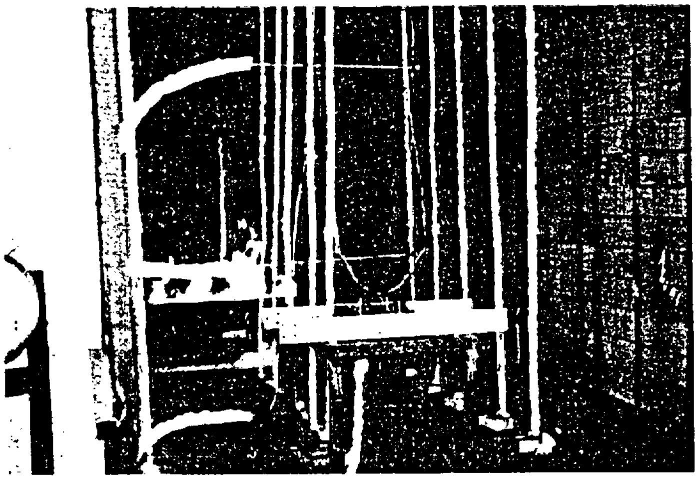


CIRCUIT INTEGRITY DEVICE

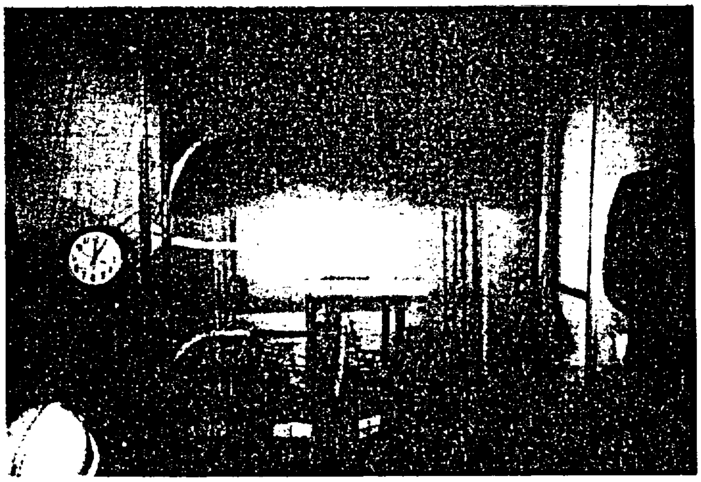


ENERGIZED CABLE

Figure 6 - Circuit Integrity Device And Energized Cable



At ignition



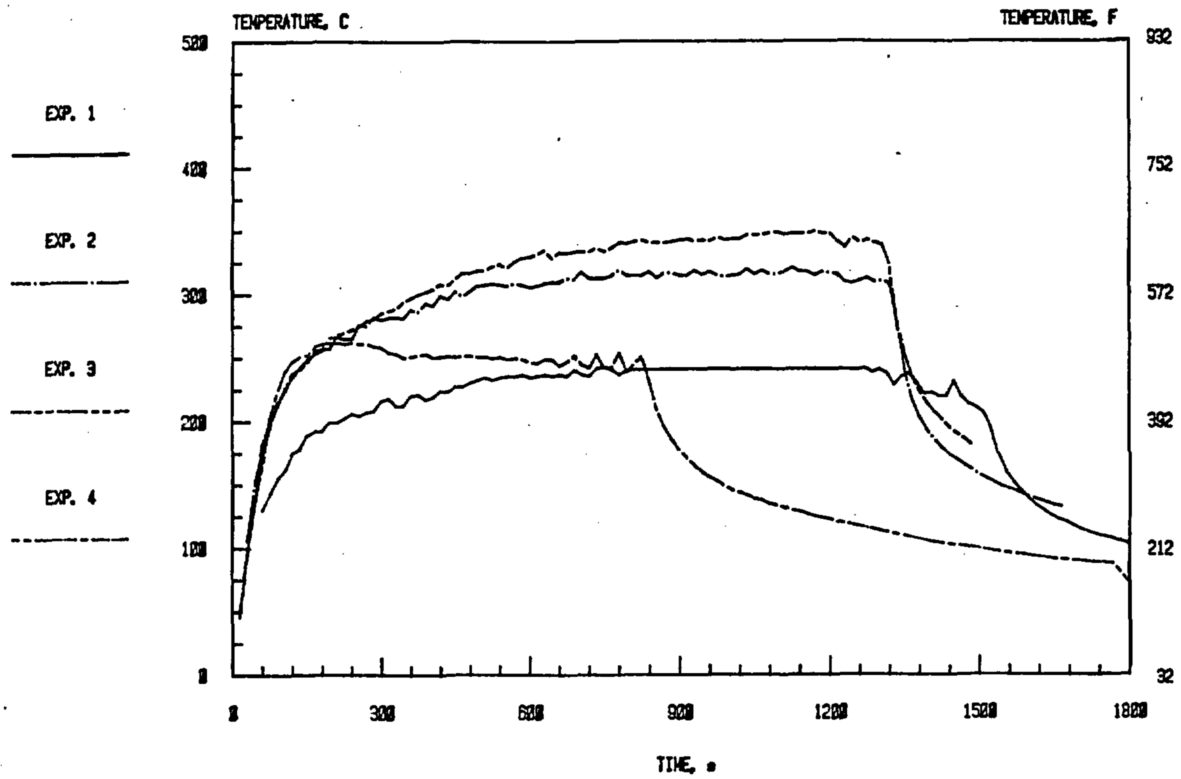
At 288 s

Figure 7 - Appearance of Fire During Experiment 1

At ignition

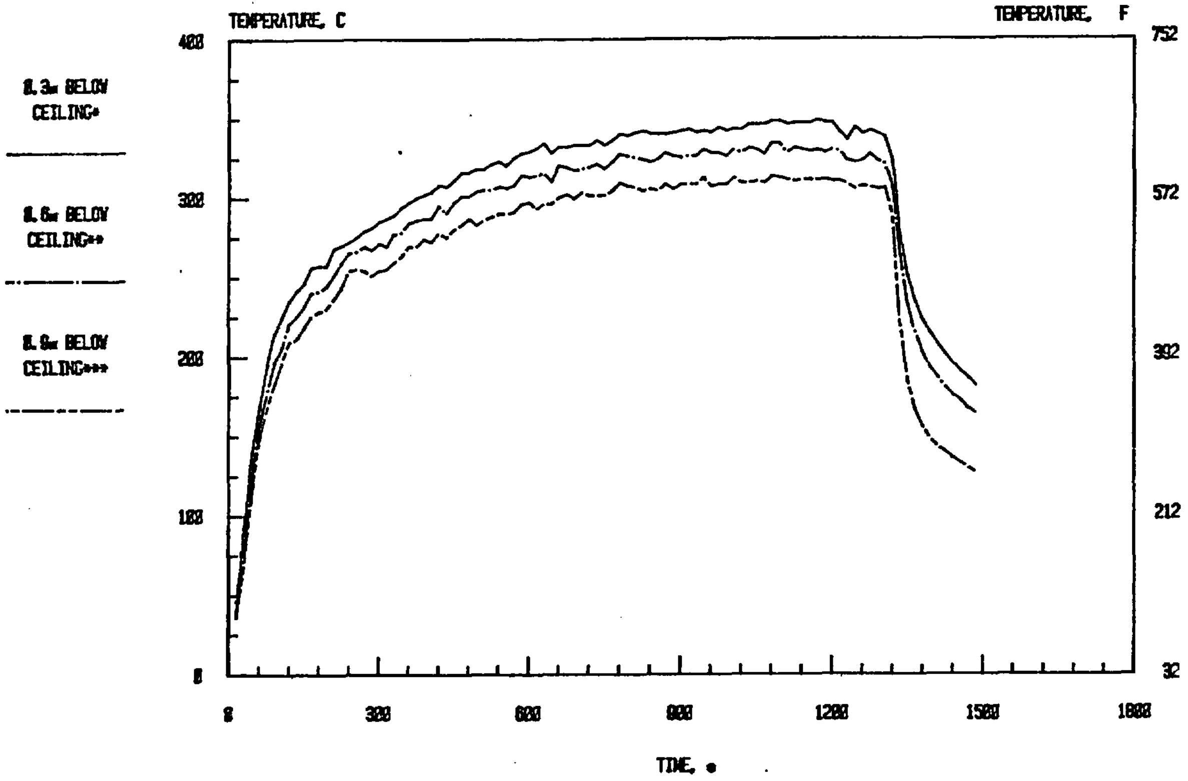
At 333 s

Figure 8 - Appearance of Fire During Experiment 3



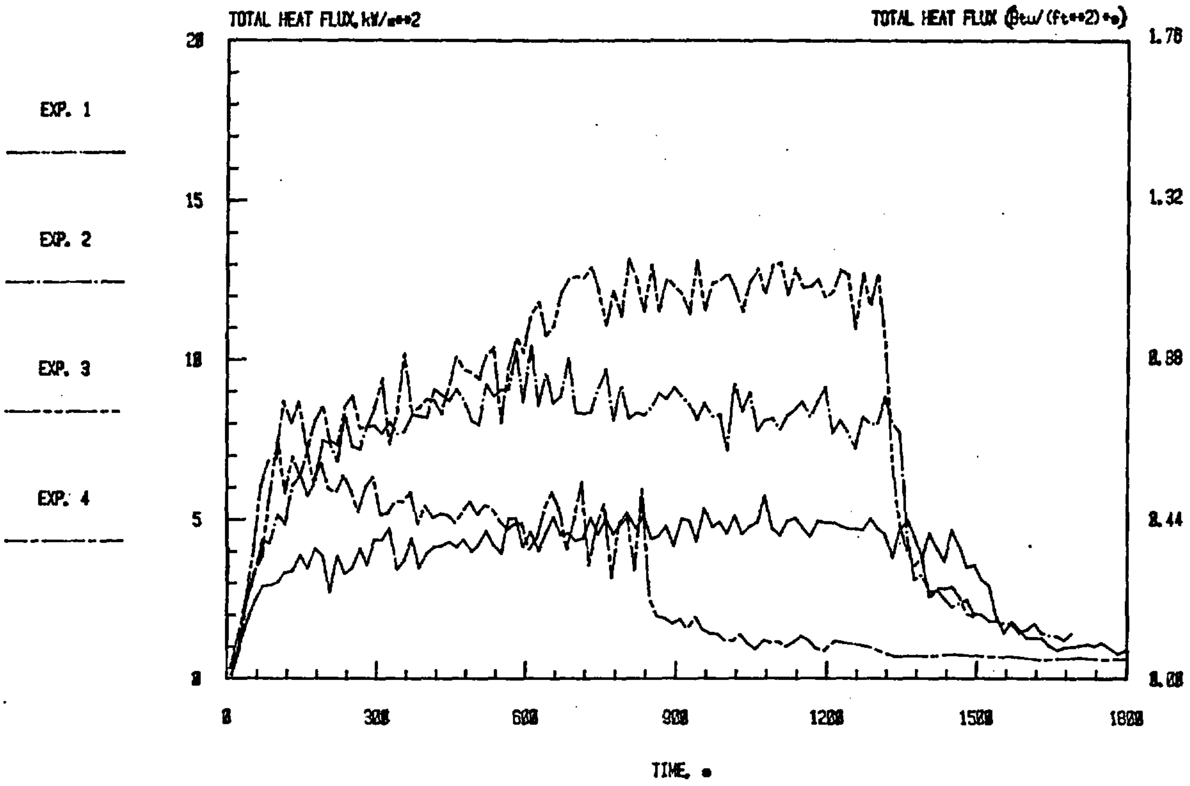
Temperatures are the average of thermocouples 69, 73 and 77

Figure 9 - Average Atmospheric Temperatures Near Horizontal Trays During the Experiments



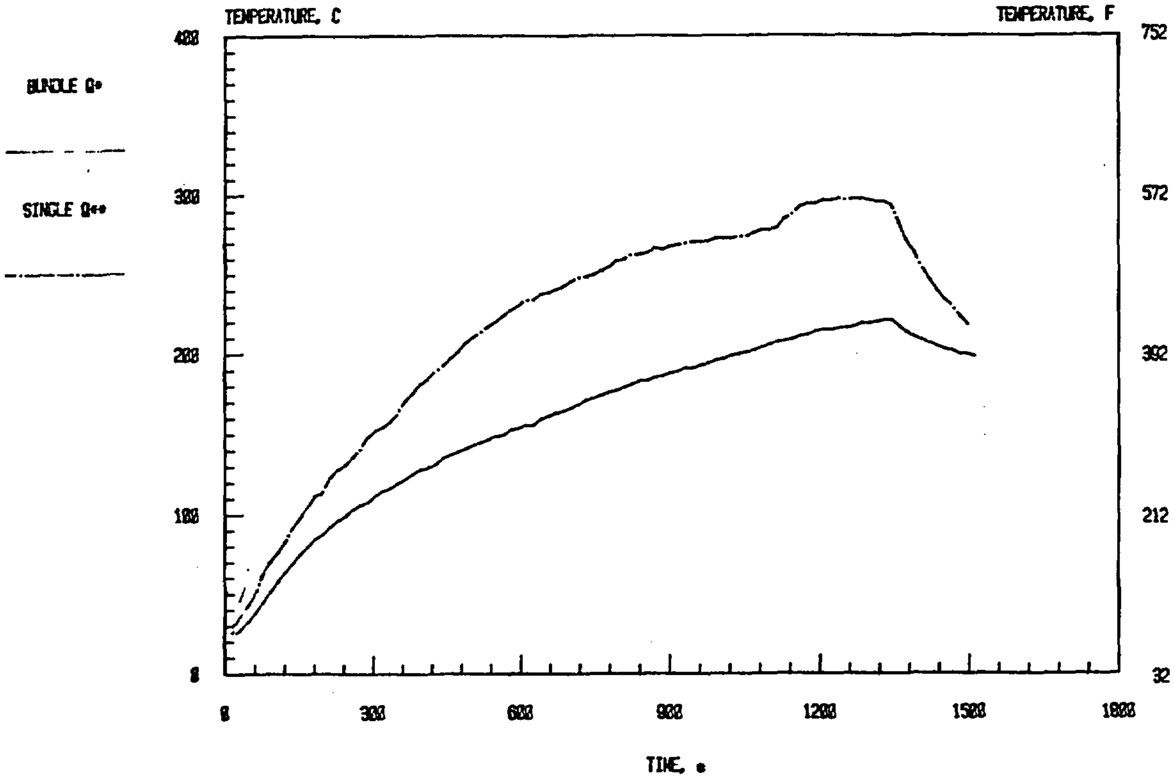
*Average temperatures of thermocouples 69, 73 and 77
**Average temperatures of thermocouples 70, 74 and 78
***Average temperatures of thermocouples 71, 75 and 79

Figure 10 - Temperatures at Several Levels Within the Gas Layer During Experiment 3



Heat flux values are from calorimeter, channel 62

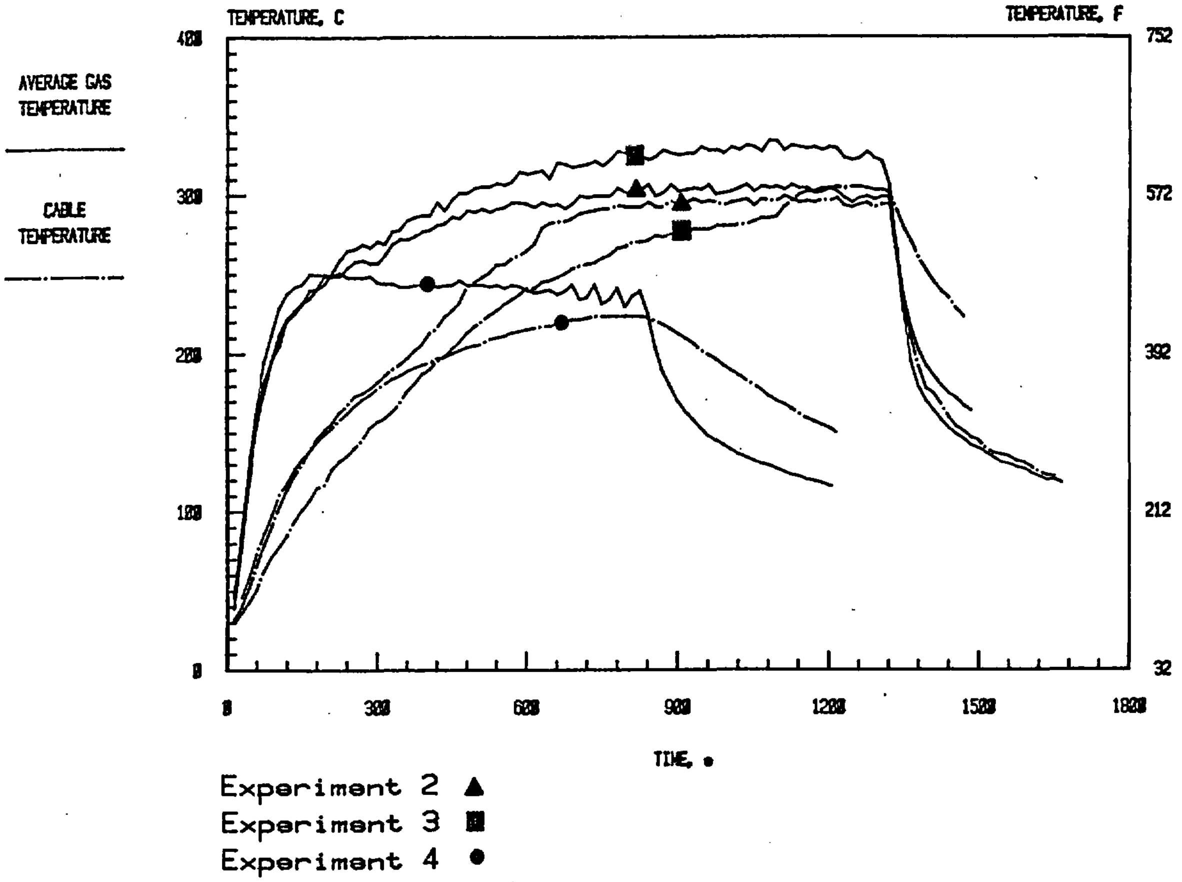
Figure 11 - Heat Fluxes at Lower Horizontal Tray During the Experiments



* Experiment 3, thermocouples 106 & 107
** Experiment 3, thermocouple 118

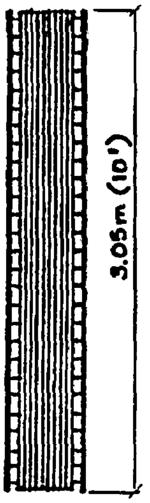
NQ- cable that did not meet IEEE flame test requirements
Q- cable that met IEEE flame test requirements

Figure 12 - Cable Jacket Temperatures During Experiment 3

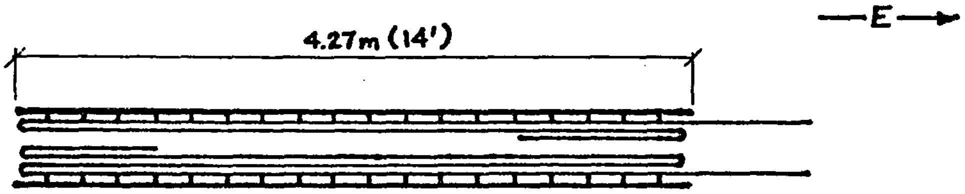


Thermocouples 70, 74 & 78 used for average gas temperatures. Thermocouple 118 used for cable jacket temperatures in Experiments 2 & 3. Thermocouples 118, 119 & 120 used for cable jacket temperatures in Experiment 4.

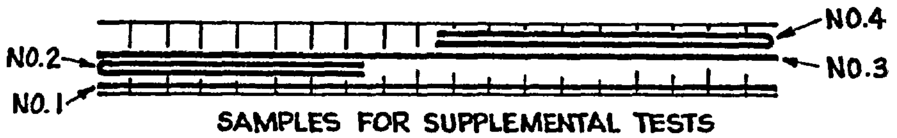
Figure 13 - Atmospheric and Cable Jacket Temperatures During Experiments 2 Through 4



43 SEPARATE SEGMENTS OF CABLE PLACED IN EACH VERTICAL TRAY. CABLE SEGMENTS HOOKED OVER TOP RUNG (EXCEPT TEST 1) AND SECURED TO TRAY RUNGS WITH STEEL WIRE TIES APPROX. 0.914 m (3') ON CENTER. NQ CABLE USED IN TESTS 1,3 & 5. Q CABLE USED IN TESTS 2,4 & 6. CABLES UNPROTECTED IN TESTS 1 & 2. CABLES IN TESTS 3 & 4 PROTECTED WITH CERAMIC FIBER BLANKET AND STEEL CABLE TRAY COVERS. CABLES IN TESTS 5 & 6 PROTECTED WITH A 3mm (1/8") WET THICKNESS OF CABLE COATING.

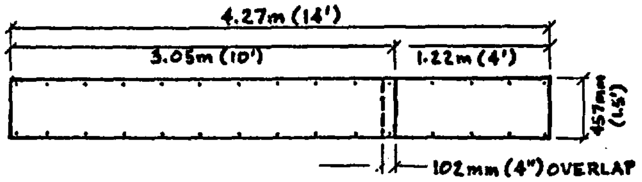


SINGLE CONTINUOUS CABLE LOOPED BACK-AND-FORTH TO SIMULATE 42 CABLE SEGMENTS IN EACH HORIZONTAL TRAY. ENDS OF CABLE EXIT COMPARTMENT THROUGH EAST WALL. CABLE SECURED TO TRAY RUNGS WITH STEEL WIRE TIES AT BOTH ENDS. NQ CABLE USED IN TESTS 1,3 & 5. Q CABLE USED IN TESTS 2,4 & 6. CABLE UNPROTECTED IN TESTS 1 & 2. CABLE IN TESTS 3 & 4 PROTECTED WITH CERAMIC FIBER BLANKET AND STEEL CABLE TRAY COVERS. CABLE IN TESTS 5 & 6 PROTECTED WITH A 3mm (1/8") WET THICKNESS OF CABLE COATING.

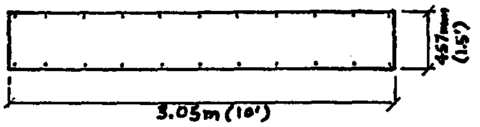


SAMPLES FOR SUPPLEMENTAL TESTS

Figure 14 - Cable Segment and Multiple Loop Cable Installation



COVER DETAIL-HORIZ. TRAYS



COVER DETAIL-VERT. TRAYS

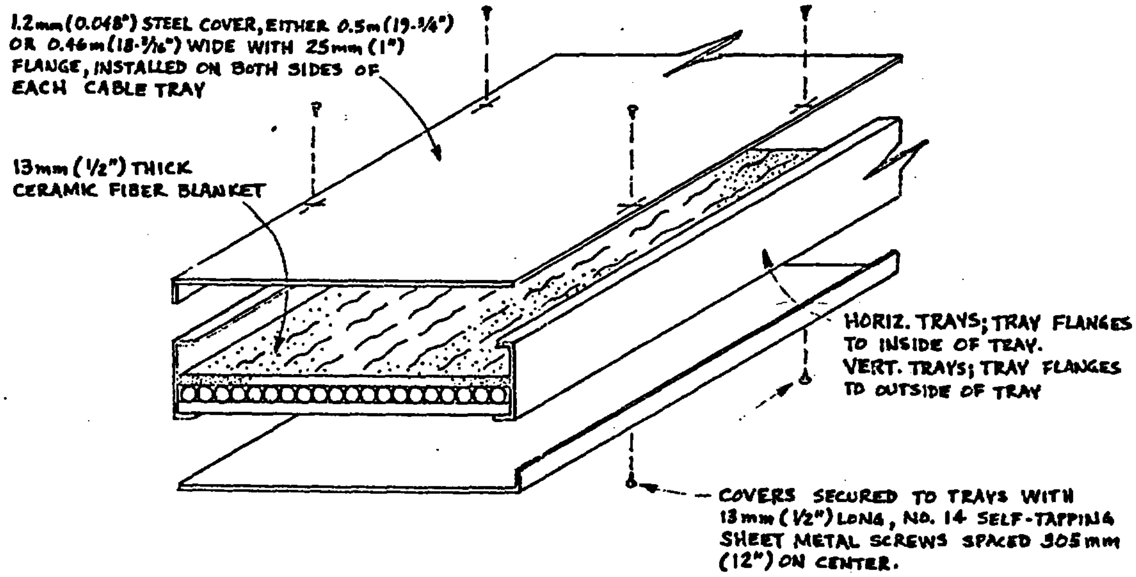


Figure 15 - Cable Tray Cover and Insulation Installation

At ignition

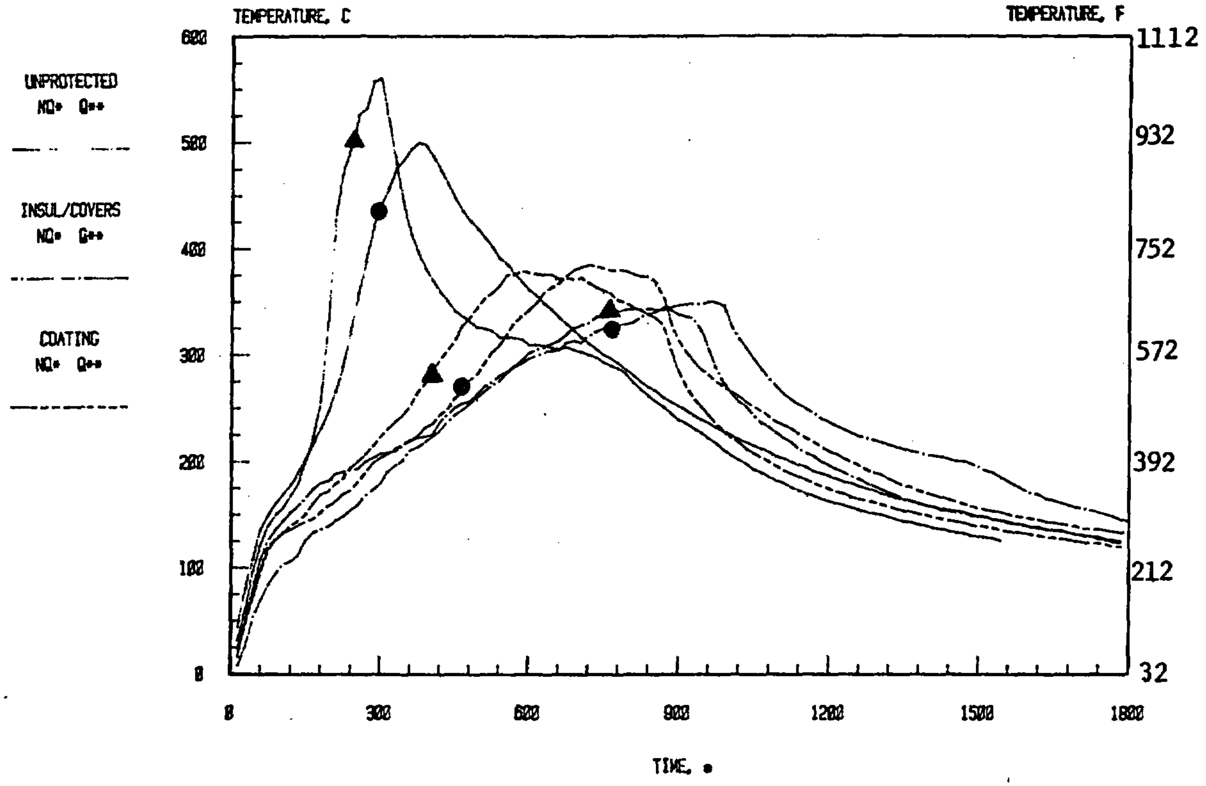
At 220 s

Figure 16 - Appearance of Fire During Test 1

At ignition

At 462 s

Figure 17 - Appearance of Fire During Test 4

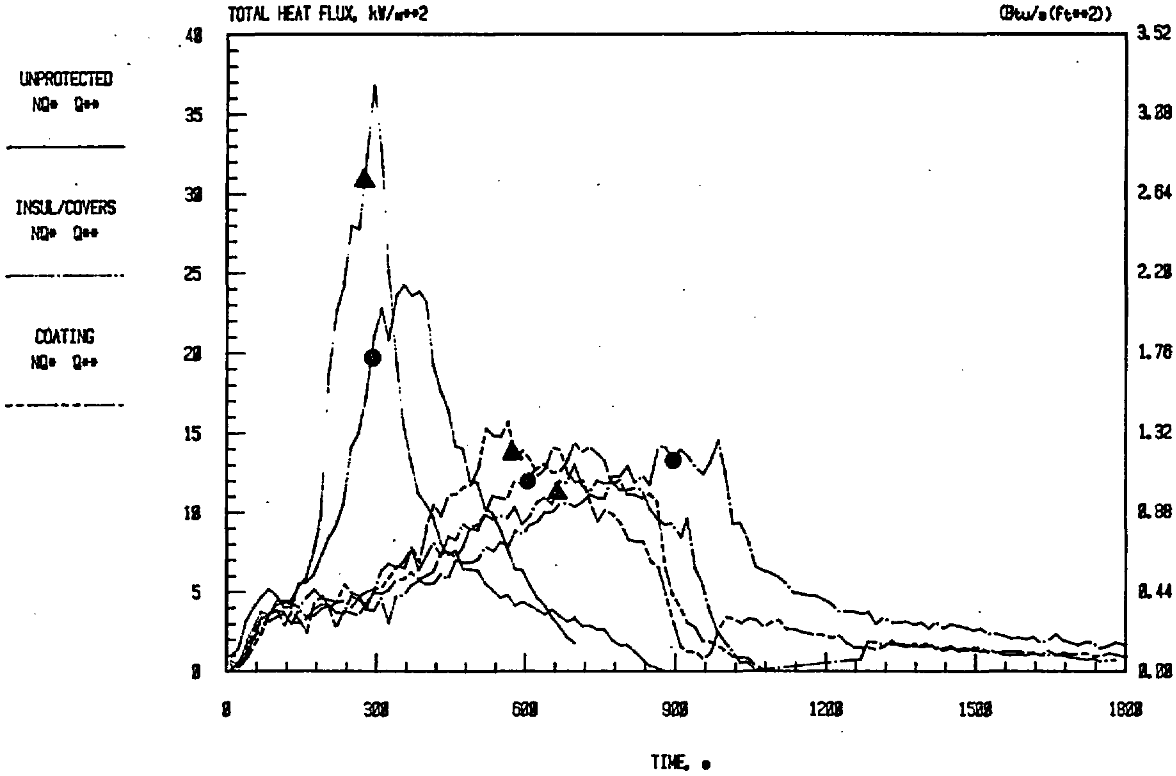


* Unqualified cable – ▲

** Qualified cable – ●

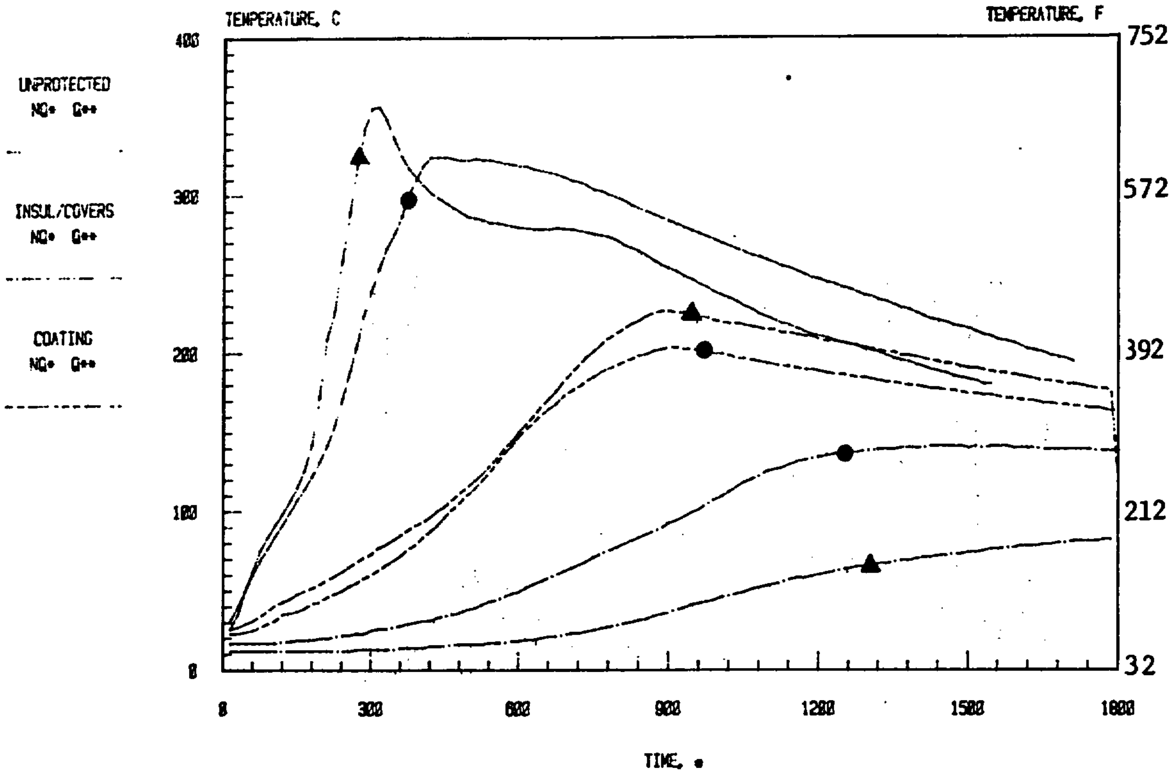
Temperatures are the average of thermocouples 69, 73 and 77

Figure 18 – Average Atmospheric Temperatures Near Horizontal Trays During Tests



Heat flux values are from calorimeter, channel 62
▲-NQ*-Cable that did not meet the IEEE flame test requirements
●-Q*-Cable that met the IEEE flame test reqiurements

Figure 19 - Heat Flux at Lower Horizontal Tray During Tests



* Unqualified cable –▲
** Qulified cable –●
For Tests 1–3 average of thermocouples 118–122
For Tests 4–6 average of thermocouples 118–120

Figure 20 – Cable Jacket Temperatures
During Tests

Looking south at vertical trays

Looking up at horizontal trays

Figure 21 - Appearance of Cable Damage

APPENDIX

Instrumentation and Equipment

LIST OF FIGURES

Instrumentation

Thermocouples

Thermocouples were installed at various locations (Figures A1-A3) to measure atmospheric, wall, roof/ceiling and cable jacket temperatures. Thermocouple assemblies, used to measure temperatures within the room at the level of the roof/ceiling, were 28 gauge chromel-alumel wire enclosed within and grounded to an 0.0625 in. (1.6 mm) inconel sheath. Thermocouples for the remaining locations were 24 gauge, glass wrapped and braided, bare chromel-alumel assemblies.

Heat Flux Gauges

HyCal calorimeters and radiometers were used to measure the heat flux within the room configuration for all experiments (Figures A1-A3). The calorimeters had a viewing angle of 180° with a flat black surface. The body material was comprised of OFHC copper. The full-scale range of the calorimeters was 170 kW/m^2 (15 Btu/ft^2-s) at 10 mV. To prevent condensation of water vapor from product gases on the sensing foil, water, approximately 75 °F (24 °C), was circulated in copper cooling tubes on the body.

The radiometers had a viewing angle of 150° with a high emissivity graphitic coating on the active sensor face. The body material was comprised of OFHC copper. The full-scale of the radiometers was 170 kW/m^2 (15 Btu/ft^2-s) at 10 mV. To prevent condensation on the radiant heat flux sensor the same method as for the calorimeters was used. The window of the radiometer was purged with nitrogen to reduce soot accumulation.

Probes and Barometers

Differential pressure probes for use in the measurement of atmospheric pressures were placed in the vertical center plane of the doorway opening as shown in Figure A3. The probes consisted of horizontal 14 mm (0.56 in.) diameter stainless steel cylinders, 32 mm (1.25 in.) long, divided symmetrically into upstream facing and downstream facing halves by an internal barrier. The pressure difference between these cylinder halves was measured by electronic barometers. The velocity was calculated using the temperature at the probe and pressure.

Equipment

Circuit Integrity Device And Energized Cable System

A device to monitor circuit integrity was connected to the cable conductors in the upper horizontal tray in each test. The device (Figure 6) was designed to indicate if a short occurred between any conductor and the tray or if a short occurred between conductors. In the lower tray, the conductors were energized at 120 V ac with different amperage+ (Figure 6). The amperage was monitored continuously by ammeters during the tests and experiments.

Digital Data Acquisition System

The voltage outputs from the thermocouples, heat flux gauges, and electronic barometers were connected to an Accurex Autodata 9 or 10 data logger. The data channels were continuously scanned at a rate of 2.5 lines per second* for the Autodata 9 and 6 lines per second for the Autodata 10. All data were recorded on 9 channel magnetic tapes for subsequent processing.

Sprinkler Events Recorder

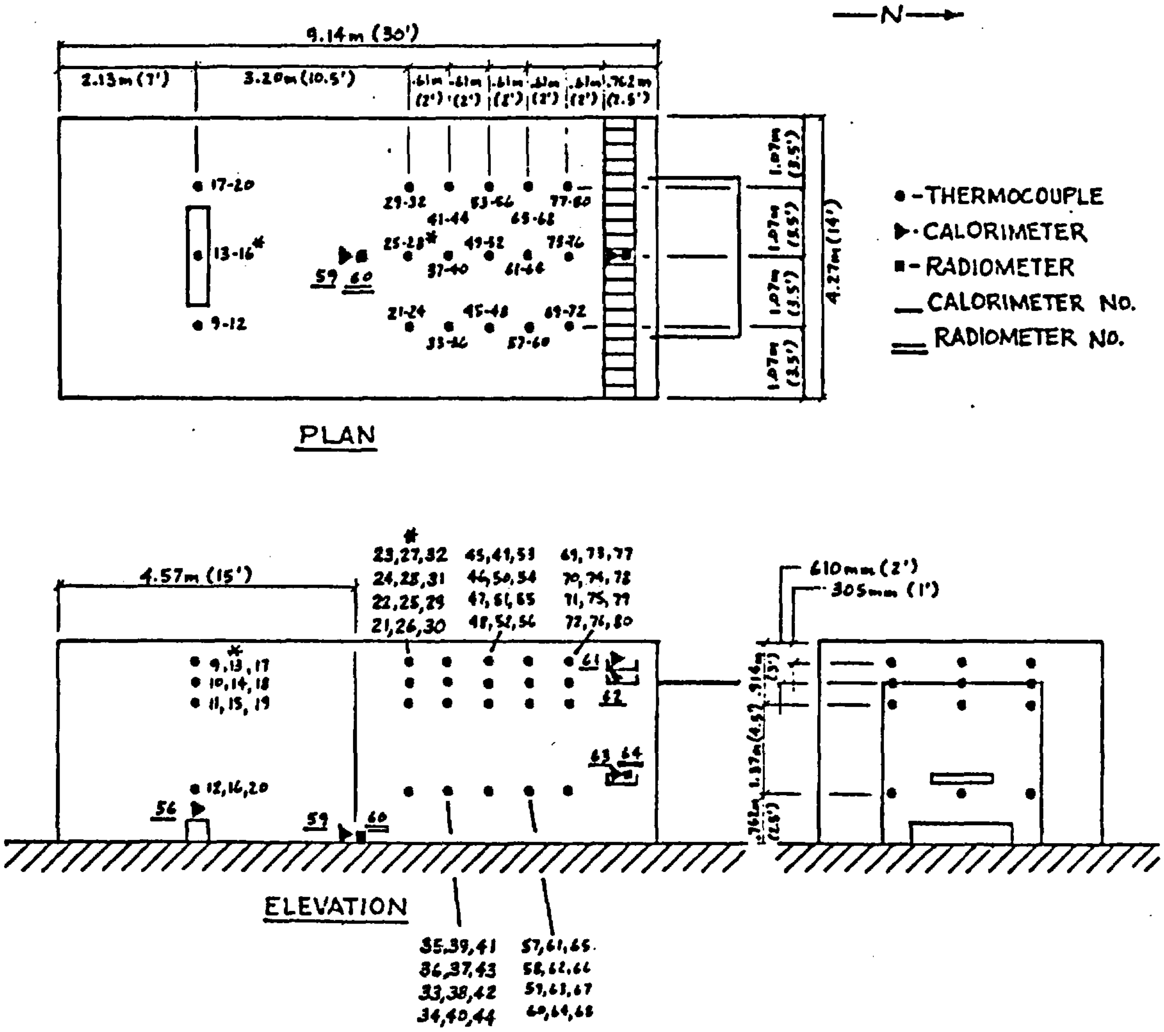
The fusible link of each sprinkler head was part of an electrical circuit that was connected to an events recorder to record the time when the links fused.

Photography and Video Recording

All of the experiments were recorded with intermittent 35 mm color slides and with continuous color video tape. These were taken through the viewing windows centered along the east wall of the configuration and through the doorway. The 35 mm slide camera was an Olympus OM-2 with a 50 mm f 1.8 lens. The color video camera was a Sony DXC-1600 with an F2.5, 13 mm to 108 mm zoom lens and connected to a Sony VO-2800 video tape recorder. Instant replay was available on a Sony CVM-1750 color monitor.

+ One conductor to ground, one conductor at 4.5 amps and one conductor at 9.0 amps.

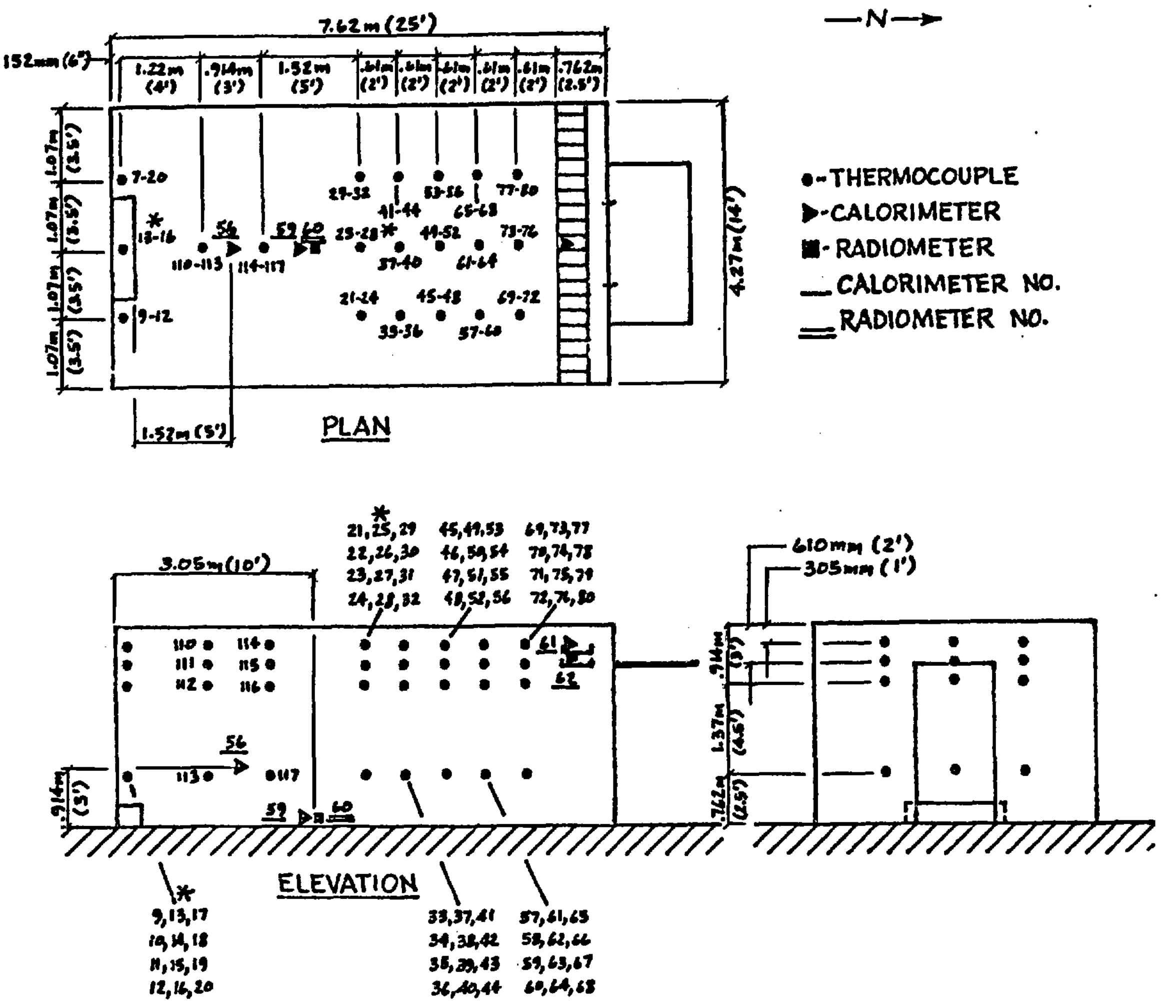
* 15 seconds per point.



* SUPPLEMENTAL INCONEL THERMOCOUPLES

100 @ 28	102 @ 26	104 @ 16
101 @ 27	103 @ 25	105 @ 13

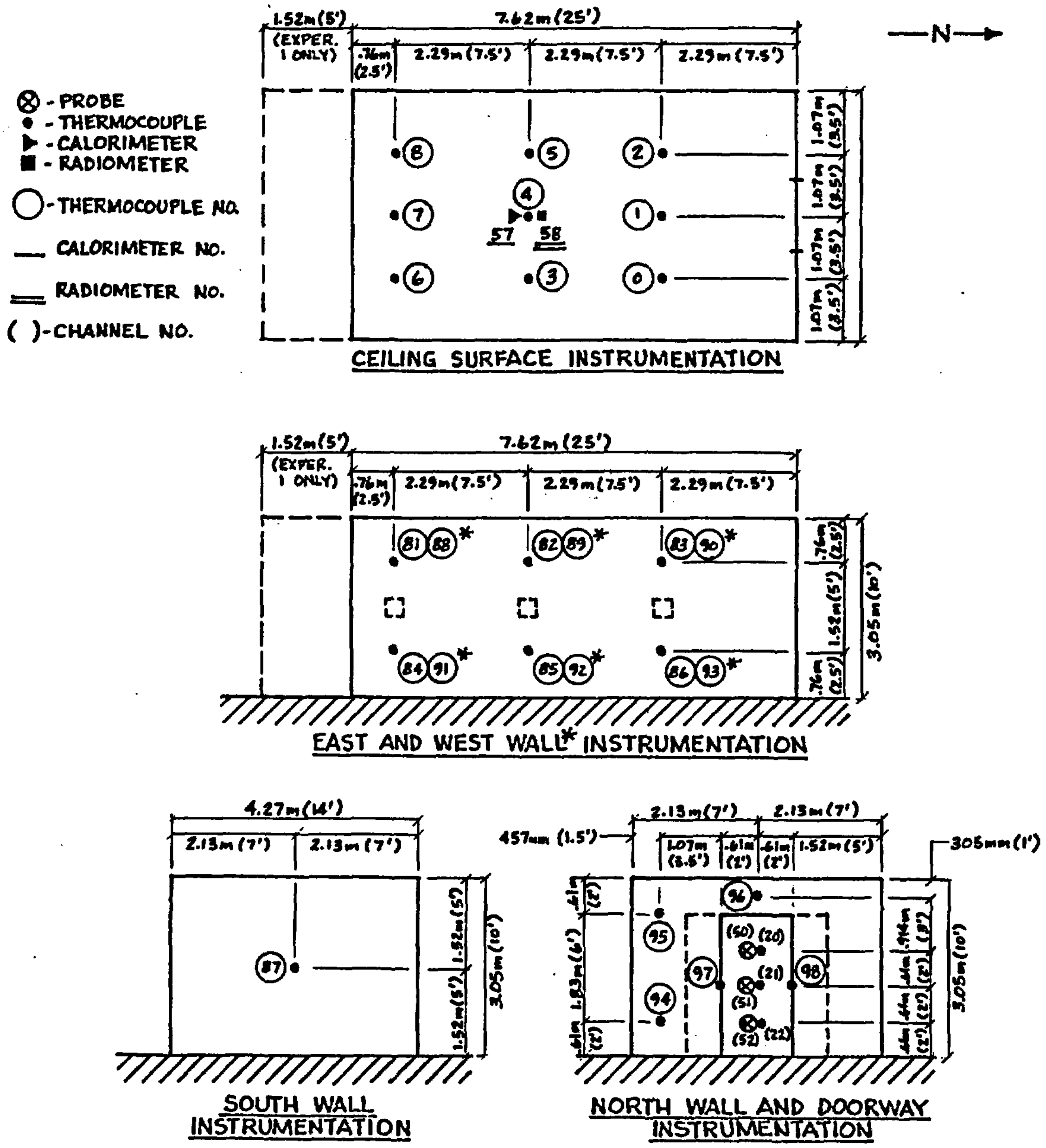
Figure A1 - Instrumentation Within Compartment, Experiment 1



* SUPPLEMENTAL INCONEL THERMOCOUPLES

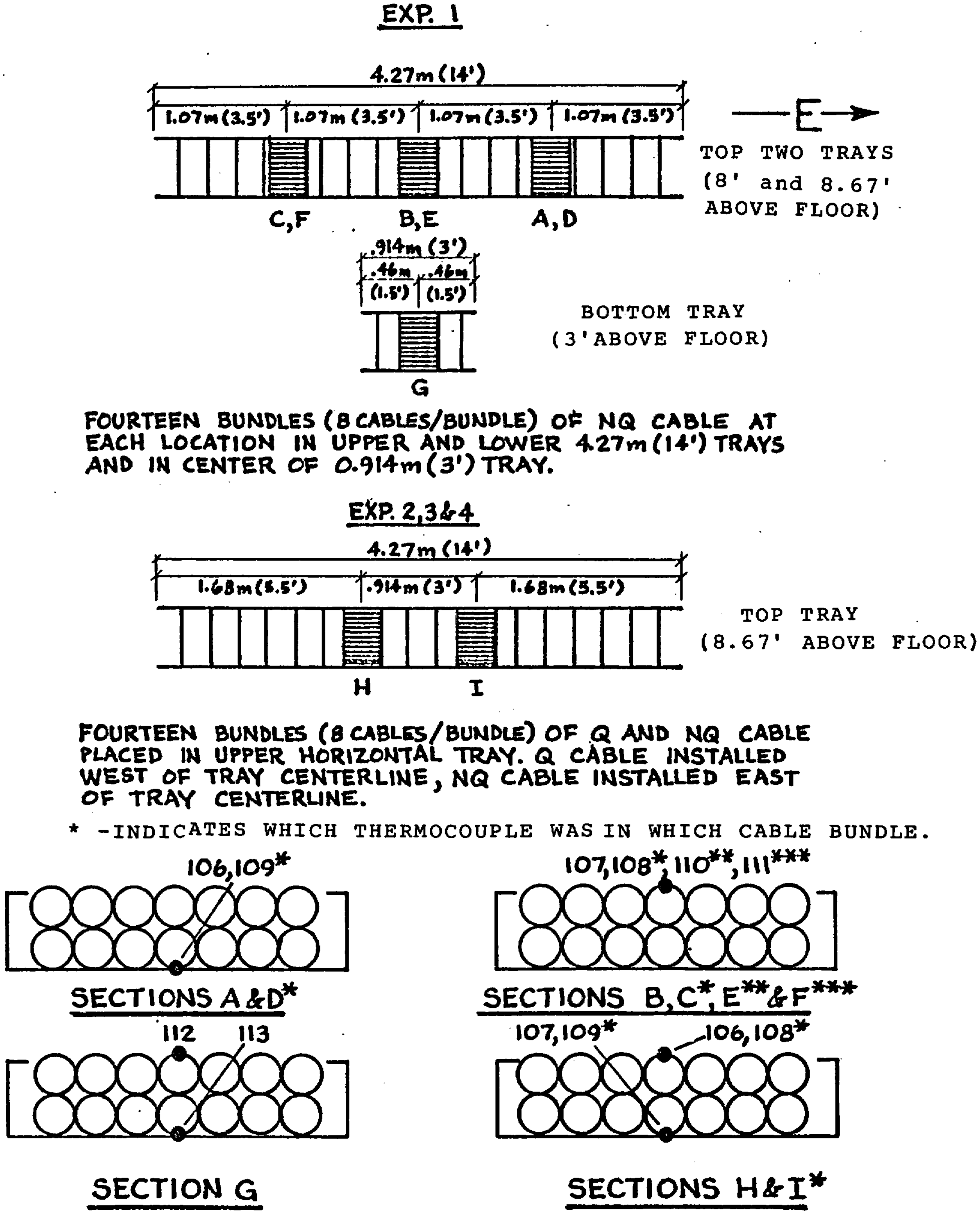
100 @ 28
101 @ 27
102 @ 26
103 @ 25
104 @ 16
105 @ 13

Figure A2 - Instrumentation Within Compartment, Experiments 2 Through 4 and Tests 1 Through 6



** DOORWAY DATA NOT OBTAINED IN EXPERIMENT 4

Figure A3 - Instrumentation For Compartment Ceiling, Wall and Doorway

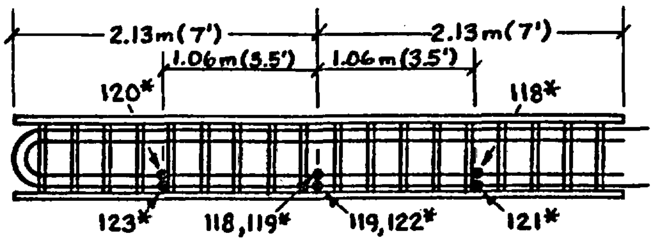


FOURTEEN BUNDLES (8 CABLES/BUNDLE) OF NQ CABLE AT EACH LOCATION IN UPPER AND LOWER 4.27m (14') TRAYS AND IN CENTER OF 0.914m (3') TRAY.

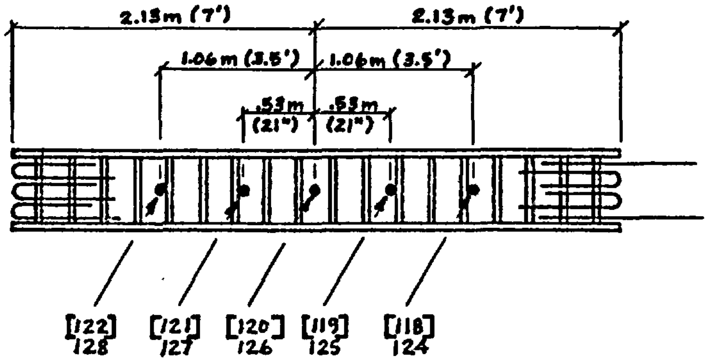
FOURTEEN BUNDLES (8 CABLES/BUNDLE) OF Q AND NQ CABLE PLACED IN UPPER HORIZONTAL TRAY. Q CABLE INSTALLED WEST OF TRAY CENTERLINE, NQ CABLE INSTALLED EAST OF TRAY CENTERLINE.

* -INDICATES WHICH THERMOCOUPLE WAS IN WHICH CABLE BUNDLE.

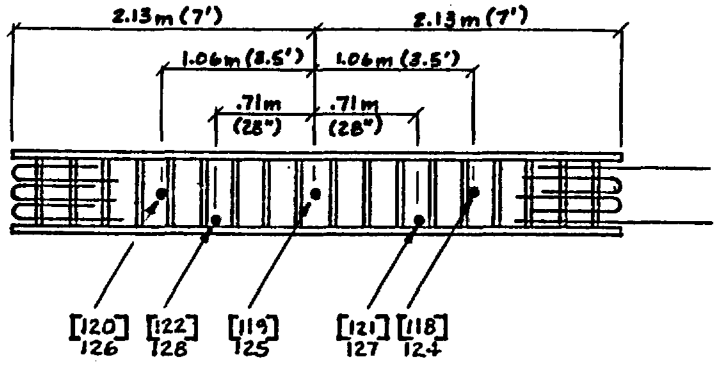
Figure A4 - Thermocouple Locations on Cables



EXP. 2,3&4*



TEST NOS. 1,2&3



TEST NOS.4,5&6

[]-DENOTES THERMOCOUPLES IN UPPER HORIZONTAL TRAY. THERMOCOUPLES EMBEDDED APPROX. 0.8mm (1/32") IN TOP OF OUTSIDE CABLE JACKET.

3-CNDR. CABLE IN UPPER TRAY-MONITORED CABLE INTEGRITY.

3-CNDR. CABLE IN LOWER TRAY-ENERGIZED CABLE. (120 VAC; 9A FOR TWO QUARTZ LAMPS; 4.5A FOR ONE QUARTZ LAMP.)

* -DENOTES THERMOCOUPLES USED ONLY IN EXPERIMENT 4.

Figure A5 - Thermocouple Locations on Cable Bundles

APPENDIX B

IGNITION-SOURCE FIRE CHARACTERIZATION

Introduction

A series of heptane pool fire experiments and solid fuel "trash" fire experiments were conducted at Sandia National Laboratories (SNL). The experiments were designed to provide the NRC with data on the relationship between the heptane ignition source fires used in the Twenty-Foot Separation program and ignition-source fires consisting of several types of combustible refuse similar to what might be found in a nuclear power plant.

Experimental Facility

The ignition-source fire experiments were conducted at the SNL Fire Test Facility. A wall 2.4 m (8 ft) wide by 3.7 m (12 ft) high was constructed on a mobile test platform located near the center of the Fire Test Enclosure. A smaller fire platform was placed adjacent to the wall on the west side. The locations of the test platform, wall, and fire platform in the Fire Test Enclosure are shown in Figure B-1.

The Fire Test Enclosure was instrumented to measure and record the following parameters:

1) Inlet Air

   Temperature;
   Volumetric Flow

2) Exhaust Gas

   Temperature;
   Oxygen Content

3) Enclosure

   Vertical Temperature Profile.

The vertical temperature profile in the enclosure was measured using two sets of thermocouples. A set of eight thermocouples with thermal radiation shields was located near the north wall of the enclosure starting from .2 m (8 in.) above the floor at .6 m (2 ft) intervals. A set of eight thermocouples was located near the east wall of the enclosure starting from .8 m (31 in.) above the floor at .6 m (2 ft) intervals.

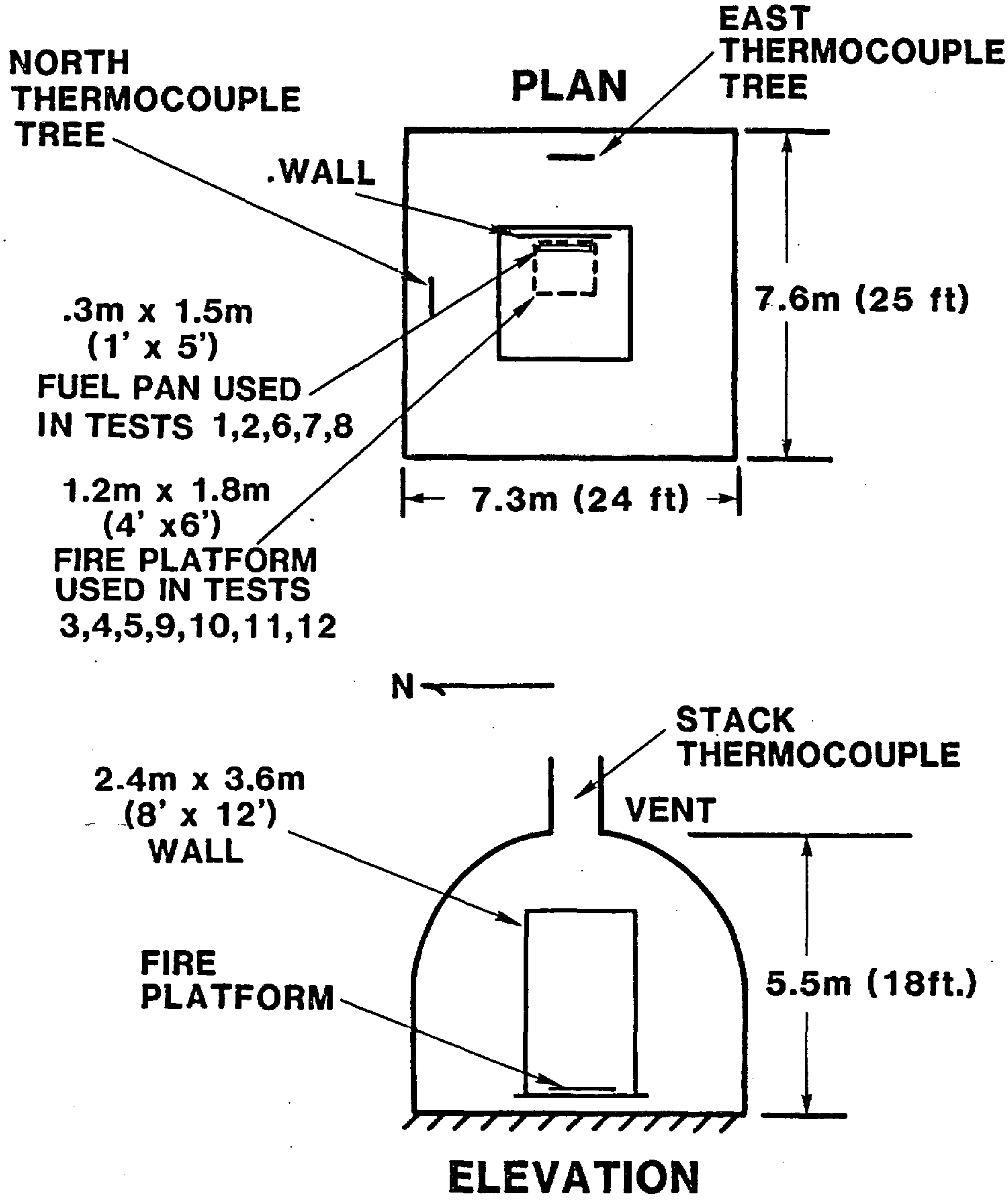


Figure B-1.
Fire Test Enclosure Details
(Dimensions approximate)

The ignition-source fires were instrumented to measure and record fire temperature, heat flux, and fuel mass loss. Fire temperature was measured with 10 thermocouples on the wall adjacent to the fire platform. Heat flux was measured with five calorimeters located to the front and to the side of the fire platform. Fuel mass loss was measured with a load cell located under the fire platform. The locations of the ignition-source fire instrumentation are shown in Figure B-2.

Experimental Procedure

A total of twelve ignition source fire experiments were conducted using several different fuels. The procedure for all twelve experiments was as follows. The fuel was positioned on the fire platform. The instrumentation was checked and the recorder was started. The Fire Test Enclosure ventilation system was set for .71 m^3/s (1500 cfm), this rate allows the fire to burn with sufficient ventilation so as not to become ventilation limited. This represents approximately 9 room changes per hour, which is typical for a power plant room. The fuel was ignited and allowed to burn either until it self-extinguished or for a maximum of 30 minutes. The heptane source fires were ignited with an electric match, all other source fires were ignited with a paper towel saturated with 125 ml (1/2 cup) of alcohol and an electric match. All repetitions of tests were done to evaluate the reproducability of the test results. The fuel sources for the twelve experiments are summarized in Table B-1.

In Experiments 1 and 2 the fuel was 18.9 liters (5 gallons) of heptane. The heptane was contained in a steel pan .3 m (1 ft) wide, 1.5 m (5 ft) long, and .25 m (10 in) deep. The pan was placed on the fire platform adjacent to the wall and filled to a depth of .11 m (4.5 in) with water before adding the heptane. In Experiments 6, 7, and 8 the fuel was 3.8 liters (1 gallon) of heptane, The same pan and the same amount of water used in Experiments 1 and 2 was used in Experiments 6, 7, and 8. The approximate potential heat of combustion for the 18.9 liters (5 gallons) of heptane was calculated to be 613 MJ; for the 3.8 liters (1 gallon), it was calculated to be 123 MJ, these values are shown in Table B-1.

The fuel source in Experiments 4 and 11 was simulated plant trash. The trash consisted of 11.4 kg (25 lb) of rags, 7.7 kg (17 lb) of paper towels, 5.9 kg (13 lb) of plastic products (gloves and tape), and 7.5 liters (2 gallons) (5.9 kg) of methyl alcohol evenly mixed and placed in two plastic trash bags (approximately 40 gallon size). The two bags of simulated plant trash were placed on the fire platform adjacent to the wall. The approximate potential heat of combustion of the simulated plant trash was approximately equal to that of 18.9 liters (5 gallons) of heptane.

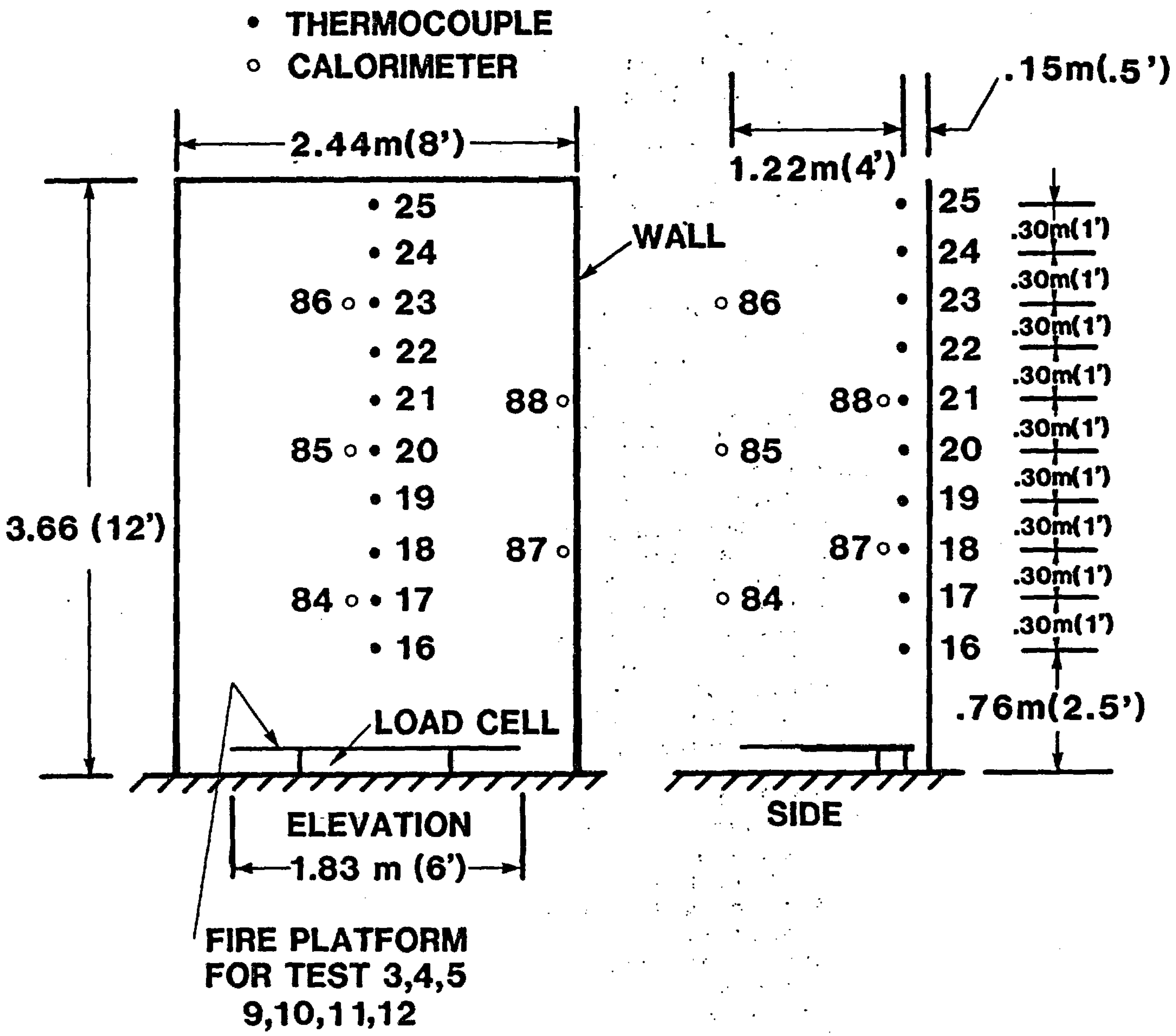


Figure B-2.
Ignition Source Fire Instrumentation

In Experiment 3 the fuel was 9.1 kg (20 lb) of computer paper. The computer paper was crumpled up and divided into two plastic trash bags. The two bags of paper were placed on the fire platform adjacent to the wall. The approximate potential heat of combustion of the computer paper was about equal to 25% that of 18.9 liters (5 gallons) of heptane.

The fuel in Experiment 9 was 36.4 kg (80 lb) of computer paper. The computer paper was divided into two plastic bags with 2.3 kg (5.50 lb) crumpled up and 15.9 kg (34.95 lb) folded in each bag. The two bags of paper were placed on the fire platform adjacent to the wall. The approximate potential heat of combustion of the computer paper was approximately equal to that of 18.9 liters (5 gallons) of heptane.

In Experiments 5, 10, and 12 the fuel was 13.6 kg (30 lb) of computer paper and two large (approximately 50 gallon) plastic trash cans weighing 7.5 kg (16.5 lb) each. The computer paper was crumpled up and divided into the two plastic trash cans. The two plastic trash cans were placed on the fire platform adjacent to the wall. The approximate potential heat of combustion of the computer paper and plastic trash cans was about 75% of that of 18.9 liters (5 gallons) of heptane.

In Experiment 12, two vertical cable trays were placed between one of the trash cans and the wall. The two trays were six inches out from the wall, one with 43 IEEE-383 qualified cables (12.5% fill) (same type as used in the UL 20-ft tests) and the other was empty. One of the trash cans was centered between them. The cable tray was a steel ladder type tray 3 m (10 ft) long, .5 m (18 in) wide, and .1 m (4 in) deep.

Results

The heptane pool fires self-extinguished in less than 30 minutes when the heptane was consumed. Figure B-3 shows the ignition-source fire heat flux as a function of time and also the duration of the fire. The 18 liter (5 gal) heptane fires (Experiment 1 and 2) lasted about 16 minutes. The 3.8 liter (1 gallon) fires, Experiments 6,7, and 8, lasted about 4.5 minutes. The solid fuel "trash" experiments were still burning after 30 minutes when the experiments were terminated.

The highest fire temperatures recorded during these experiments were from the thermocouple directly above the fire platform approximately 15 cm (6 in) out from the wall (see Figure B-1, Channel 16). The peak fire temperature recorded at this location is shown for each experiment in Table B-1. The highest temperature recorded was from Experiment 5 and was approximately 980°C (1790°F).

Table B-1

Summary of Results for Ignition Source Fire Experiments

Experiment Number	Fuel Source	Approximate Heat of Combustion[A] (MJ)	Peak Fire[B] Temperature[D] oC	Peak Room Temperatures[B] Northwall oC	Eastwall oC	Stack oC	Min. Exhaust[B] Gas Oxygen Content(%)
1, 2	18.9 liters (5 gallons) heptane[E]	613	782	195	256	230	17.8
3	9.1 kg (20 lbs) computer paper	153	694	122	138	98	19.8
4, 11	Simulated plant trash (approximately 31 kg) (68 lbs)	613	651	99	119	103	19.7
5, 10	13.6 kg (30 lbs) computer paper and two 7.5 kg (16.5 lbs) 2 plastic trash cans	460	978	116	137	128	19.8
6, 7, 8	3.8 liters (1 gallon) heptane[E]	123	797	135	163	134	19.7
9	36.4 kg (80 lbs) computer paper	613	947	70	85	72	20.5
12	13.6 kg (30 lbs) computer paper and 2 plastic trash cans with one cable tray 12.5% fill IEEE 383 cable	C	880	149	201	182	19.1

A The approximate potential heat of combustion referred to is the product of the total mass of the combustible and the heat of combustion of that material or some similar material as found in [2].
B Maximum or minimum recorded value for the experiments of that type.
C Not calculated.
D Channel 16, see Figure B-2.
E Burned in a 1 ft x 5 ft x 1 ft steel pan, like that used in the UL experiments and tests

The peak enclosure temperatures are also shown for each experiment in Table B-1. In general, the high enclosure temperatures were measured, also had the high measured heat fluxes occurred, these were the heptane experiments and the experiments with computer paper in plastic trash cans.

The amount of oxygen in the exhaust gases at the exhaust stack of the enclosure was recorded during each experiment. The minimum exhaust gas oxygen content was 17.8% from Experiment 1. It was noted in general that the lower the oxygen content the more severe the fire environment.

The highest radiant heat flux levels recorded during these experiments were from the lowest calorimeter facing the wall approximately 1.2 m (4 ft) from the wall (channel 84, see Figure B-2). The radiant heat flux levels are shown versus time in Figure B-3 for six of the twelve experiments, covering the six different fuel sources used. Only the values and plots from the most severe case of each type of fuel source were used, so as not to be redundant. It is obvious in comparing the curves that the radiant heat flux from fires with the 18.9 liter (5 gallons) of heptane is the highest for the longest duration (35 kW/m^2 for 14 minutes). Experiment 5 has a relatively high radiant heat flux for a long period of time (15 kW/m^2 for 14 minutes) but it is slow in attaining the high heat flux. Only Experiment 7, 3.8 liters (1 gallon) heptane, compares with the other two in peak flux but it is for a much shorter duration (30 kW/m^2 for three minutes).

These plots give an indication of the relative intensity of the environment of the individual experiments. However, calorimeter measurements of the radiative flux emitted by burning objects are dependent upon the geometry of the experiment configuration, i.e., the fire size and the position of the calorimeter relative to the fire. Therefore direct comparison of the radiative energy received by the calorimeter is not particularly meaningful when attempting to assess the radiation hazard posed by an ignition-source fire. This is discussed further in the analysis.

In Experiment 12 an ignition-source fire of the type used in Experiments 5 and 10 was used in an attempt to ignite a cable tray containing a 12.5% fill of IEEE-383 qualified cable. The source fire successfully ignited the qualified cable and created a self-sustaining fire which consumed all of the cable insulation. The ignition of the cable took place approximately 12 minutes after the source fire was started.

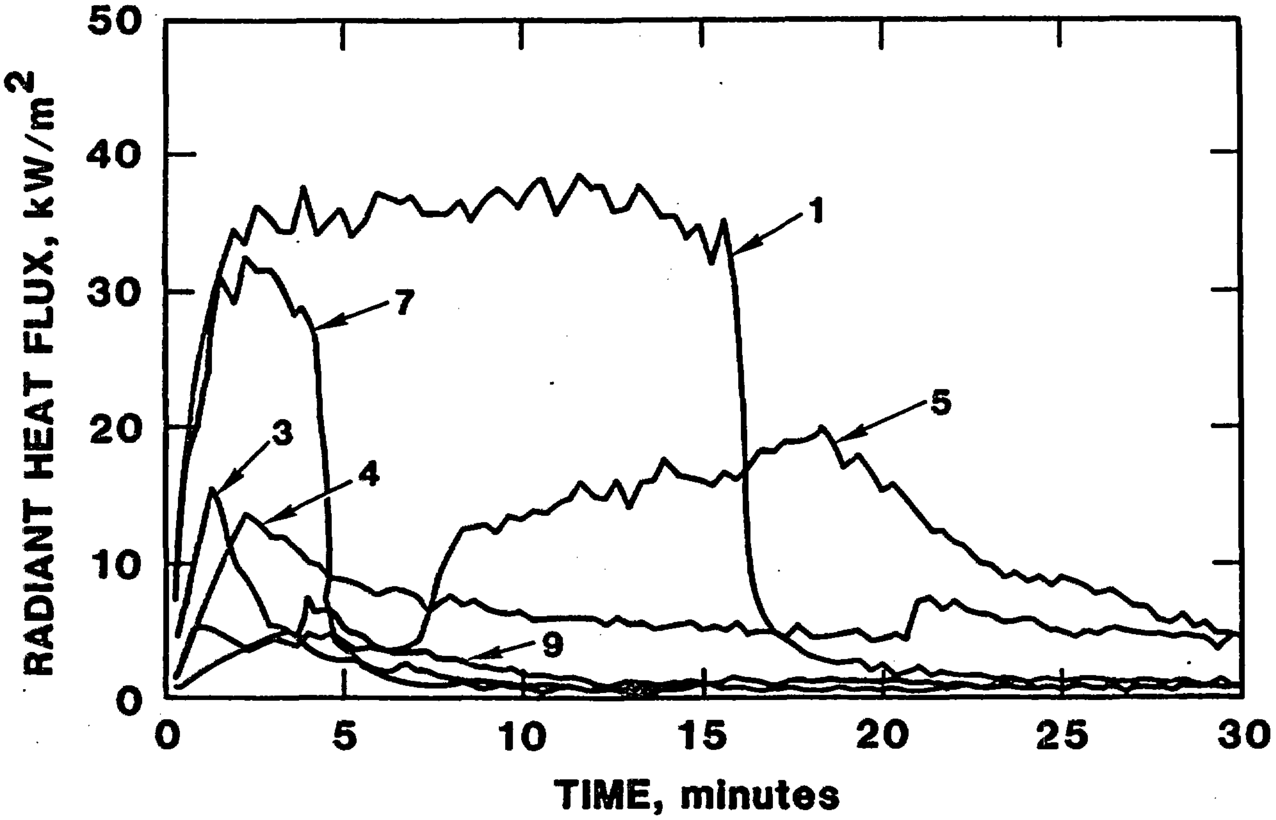


Figure B-3.
Ignition-Source Fire Heat Flux Measurements
Experiments 1, 3, 4, 5, 7, and 9

Analysis

The total radiative energy released by a fire is a function of its emissive power (i.e. energy per unit area) and its size (radiating area). Since the emissive power describes the local radiation, that is, the energy leaving the immediate flame surface, the relative emissive power of the different ignition-source fires is a better measure of the ability of the fire to ignite material in or immediately adjacent to the fire. Thus, calculations were performed to determine the peak emissive power from the measured radiative heat flux.

The calculated peak emissive powers for these experiments are shown in Table B-2. It is worth noting that typical values of emissive power for large turbulent fires range from 90 to 220 kW/m^2 [2]. Also notice that the ignition-source fire from Experiment 5 had a greater peak emissive power than the fire from Experiment 7, even though its peak flux value as measured by the calorimeter was lower (see Table B-2).

With the emissive power of the fire known, the radiant flux received by the calorimeter as a function of separation distance from the fire can be calculated. Results for the six different fuel sources are shown in Figure B-4. As separation distance is increased, the solid angle through which the calorimeter views the fire decreases, resulting in a decrease in the radiative flux received by the calorimeter. It is interesting to compare these results to the Harvard Fire Code Analysis for the radiant heat flux from a fire plume shown in Section 2, Figure 3.

Conclusions

A series of 12 ignition-source fire experiments were conducted at Sandia. The experiments evaluated six different fuel sources including two sizes of heptane pool fires and four types of solid fuel "trash" fires. Ignition-source fire parameters such as fire temperature, enclosure temperature, oxygen depletion, relative intensity during combustion, and emissive power were compared for the 12 experiments.

The ignition-source fires using heptane as a fuel source produce a more uniform release of energy than the ignition source fires examined using solid fuel.

The ignition-source fires using 18.9 liters (5 gallons) of heptane produced higher peak enclosure temperatures, greater oxygen depletion and higher peak emissive powers than any other source fire examined.

Table B-2

Peak Radiant Flux and Peak Emissive Powers of Ignition-Source Fires

Experiment Number		Calculated Peak Emissive Power (kW/m^2)	Peak Radiant Flux (kW/m^2)
1	18.9 liters (5 gallons) heptane	104	38
3	9.1 kg (20 lb.) computer paper	33	16
5	Simulated plant trash (approximately 31 kg) (68 lb.)	44	19
4	13.6 kg (30 lb.) computer paper plus two 7.5 Kg (16.5 lb.) plastic trash cans	92	13
7	3.8 liters (1 gallon) heptane	88	32
9	36.4 kg (80 lb.) computer paper	31	8

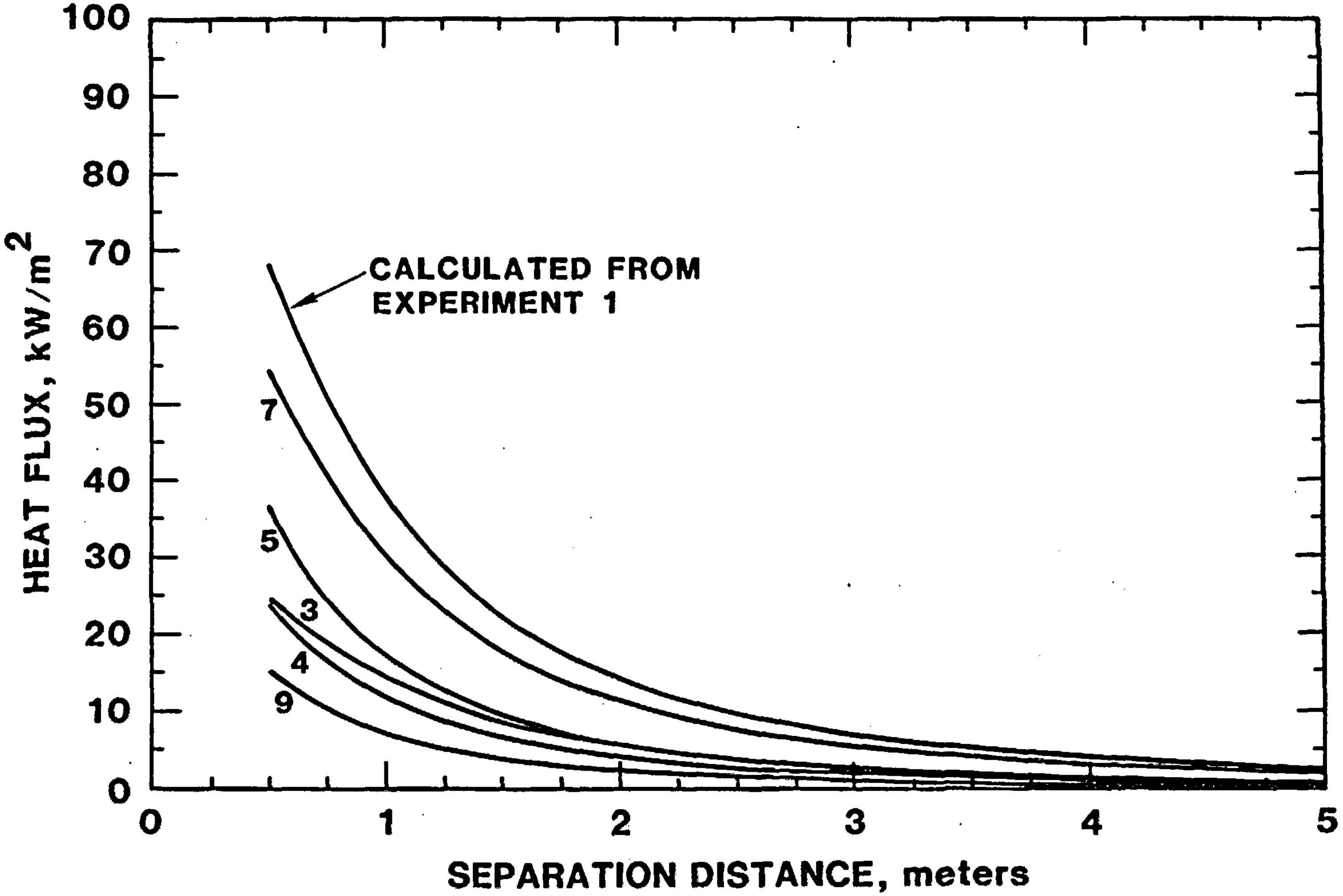


Figure B-4
Heat Flux vs. Separation Distance

The ignition-source fires using 13.7 kg (30 lbs) of computer paper in two plastic trash cans produced higher peak fire temperatures than any of the other source fires examined. These fires also produced peak emissive powers second only to the large heptane fires (5 gallons) by approximately 10%. In addition, an ignition-source fire with this fuel source (Experiment 12) was able to ignite a cable tray containing IEEE-383 qualified electrical cable to a self-sustaining cable fire, within 12 minutes.

It is evident that due to their size the two heptane pool fires (Experiments 1 and 7) present the greatest radiation hazard to objects located external to the fire. However, due to its emissive power, the simulated plant-trash fire is, essentially, a comparable strength ignition source for material located in or immediately adjacent to the fire.

An ignition-source fire using solid fuel (trash) produced peak fire temperatures higher than those of a 18.9 liter (5 gallon) heptane fire (similar to the source fires used in the Twenty Foot Separation tests) and peak emissive powers only 10% lower than those of a 18.9 liter (5 gallons) heptane fire. Therefore, the 18.9 liter (5 gallon) heptane ignition-source fires used in the Twenty Foot Separation tests do not appear to be more likely to cause ignition of secondary fuel sources than some conceivable trash-type ignition-source fires.
It is difficult to develop any kind of "equivalency" between the liquid fuel heptane fires and the solid fuel combustible refuse because the fire and fire environment are controlled by the rate of heat release. The liquid fuel fires have a uniform heat release rate (see Figure B-3) whereas, the solid fuels have a very transient heat release rate. This transient fire development is difficult to model or take into account without having first characterized the heat release rate.

References

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3. Baumeister, T., Avallone, E.A., Baumeister B, T., Marks' Standard Handbook for Mechanical Engineers, 8th edition, McGraw Hill Co., 1978.

APPENDIX C

HEAT RELEASE OF FIVE VERTICAL CABLE TRAYS OF UNQUALIFIED CABLE

It is well known that the rate of heat release of a fire source is the primary factor which controls the development of the fire environment inside an enclosure. The fuel to fuel variation in burning rates, however makes it difficult to characterize and compare different fuel loads in a meaningful, quantifiable manner. To aid in determining the amount of cable to be used in the full-scale tests, results from the UL preliminary experiments were interpreted in terms of an "equivalent" cable loading based on the total heat release expected by the cables. The anticipated heat release by the cables was determined from the test described in this appendix.

In January 1982, a test (test designated as Test No. 76) was conducted at Sandia National Laboratories in which five vertical cable trays, each filled to 25% (90 cables) with unqualified cable (non-qualified to IEEE-383 standards), were burned in the 10,000 ft^3 (283.2 m^3) fire test facility. This test was conducted specifically to determine the heat equivalency of large-scale cable configurations. The configuration of five vertical trays was chosen based on initial recommendations by the NRC for the full-scale tests. Four of the cable trays were ignited with IEEE-383 propane ribbon burners. The ventilation rate was adjusted to 1500 ft^3 (42.5 m^3) of air per minute, approximately the rate expected in the full-scale tests.

The mass of the cable trays was monitored during the test by the use of load cells attached to the cable supports. During the first ten minutes following ignition of the burners, little mass loss from the cable trays was observed. However, following this ten minute period the fire became fully developed and 90% of the total mass loss occurred during the next 5 to 6 minutes. At this point in the test, the smoke layer had descended sufficiently to engulf the trays. Combustion proceeded very slowly until the test was ended 30 minutes from the start. During the test all five trays burned.

Measurements of weight were taken for each cable tray before and after the test. Neglecting the high and low values and adjusting for unburned residue on the floor, an average of 57.4 lb (26.1 kg) of mass was lost per tray. Using 13,000 BTU/lb (30.2 kJ/g) as the heat of combustion of the PE/PVC cable insulation and assuming 50% combustion efficiency yields a net actual heat of combustion of 6500 BTU/lb (15.1 kJ/g). This lies in the range of 3960 (9.2) to 13,259 BTU/lb (30.8 kJ/g) given for the actual heat of combustion reported by Tewarson, Lee, and Pion [1]. Considering that these tests were laboratory scale samples of cable insulation, the value of 6500 BTU/lb (15.1 kJ/g) is quite reasonable. For the five trays in this test this yields a total heat release of 1.86 x 10^6BTU (1.97 x 10^6 kJ).

Tewarson et al., [1] also gives an actual heat of combustion of 13,259 BTU/lb (30.8 kJ/g) for liquid heptane fuel (compared to 19,199 BTU/lb (44.6 kJ/g) for complete combustion), which is equivalent to 73,600 BTU/gal of heptane. Hence the heat released during the 30 minute test of the five vertical cable trays is approximately equivalent to 25 gallons of heptane ("equivalent" in terms of total heat release). This may be considered to be a median value and due to the variability in combustion efficiency of both the cables and heptane, the deviation could be large.

Following completion of this test, analysis and preliminary experiment results showed that the five vertical trays of unqualified cable would likely produce an overly severe thermal environment inside the UL test enclosure. The total fuel load for the full-scale tests was reduced accordingly. Determining the amount of cable reduction was simplified through application of the data obtained in this test.

Reference

1. A. Tewarson, J. L. Lee, R. F. Pion, "Categorization of Cable Flammability Part 1: Laboratory Evaluation of Cable Flammability Parameters," NP-1200, Part 1, by Factory Mutual Research Institute, for Electric Power Research Institute Palo Alto, CA, October 1978.

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A combined experimental/analytical program was conducted to examine the adequacy of the 20-foot separation requirement, one of the requirements set forth in Appendix R of 10 CFR 50 for the fire protection of redundant safety systems that are necessary to achieve hot shutdown in nuclear power plants. Specifically, Sections III.G.2.b and d of Appendix R require separation of the redundant safety systems by a horizontal distance of more than 20 feet with no intervening combustibles or fire hazards. Section III.G.2.b also requires installation of fire detectors and an automatic fire suppression system within fire areas. The experimental investigation consisted of six full-scale fire tests of unqualifed and qualified electrical cables separated by 20 feet with (1) no protection, (2) protection with a ceramic fiber blanket and sheet metal covers on the cable trays, and (3) protection with a fire protective coating. For the test conditions investigated, all unqualifed cable electrically shorted, while qualified cable was found to short only when left unprotected.

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