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RP

BURN MODE ANALYSIS OF HORIZONTAL CABLE TRAY FIRES

Fritz R. Krause*
Willard H. Schmidt

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Systems Safety Technology Division
Sandia National Laboratories
Albuquerque, New Mexico 87185
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*Now at Los Alamos National Laboratory

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ABSTRACT

Electrical cables constitute a serious fire hazard for nuclear power plants because the plastic insulation material is combustible and large quantities of cables are used in the plants. Nuclear power plant fires often continue to burn in the presence of smoke, whereas building fires usually burn in the presence of clear air, since smoke escapes through windows and doors before descending to the fuel. Fire growth classifications (realms) by the National Fire Protection Association (NFPA) thus may not be completely applicable for fire hazards analyses of nuclear power plants.

Electrical cable fire tests have been conducted at the Sandia Fire Research Facility in Albuquerque, New Mexico, in order to evaluate cable tray fire safety criteria for the Nuclear Regulatory Commission. A burn mode concept was developed in order to describe and classify the thermodynamic phenomena which occur in the presence of smoke and to compare the fire growth and recession of different cable types under otherwise unchanged fire test conditions. The importance of deep seated fires in cable trays from the standpoint of propagation, detection, and suppression is emphasized. The cable tray fire tests demonstrate that fire recession and deep seated fires can result from a descending smoke layer and that reignition and secondary fire growth is possible by readmission of fresh air.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

A fire hazards analysis of Light Water Reactor (LWR) nuclear power plants requires a description of fire phenomena that can be verified in independent fire tests. A burn mode classification of fires both for rooms and cables represent initial efforts towards developing such phenomenological descriptions.

The U.S. Nuclear Regulatory Commission has established guidance on fire hazards analysis for nuclear power plants[1] which includes the following analysis tasks:

(a) Simulate fire phenomena from fire introduction, through its development, to propagation into adjoining spaces;

(b) Confirm or modify principles of industrial fire prevention and control;

(c) Indicate the effect of postulated fires on safety-related plant areas, with and without activation of the automatic suppression system.

Heat release rates and room temperature in residential buildings have been used most widely to quantitatively describe and simulate fire phenomena. Heat release rates were chosen since they indicate the size of the fire, the rate of fire growth and the time available for escape or suppression. Room temperature has been used to quantitatively describe fire effects, since it indicates which rooms may block the escape of people as well as the heat loading of equipment and structures in the vicinity of the fire.

Use of such quantitative measures of fire phenomena and fire effects showed that fire phenomena cannot be matched to the fuel load per unit area or other parameters of the fire zone architecture because of the great variability of fires. Fires grow and recede, once flammable gases evolve, in a way that is beyond the forecast capabilities of present deterministic compartment fire models.[2] Measured heat release rates show a great variability even under controlled experimental conditions.[3] Growth and recession of heat release rates have been observed for the same fuel material and fuel load. This indicates that chemistry and fuel area are not the dominant factors once flammable gases have evolved.

The uncertainty of heat release rates is the main reason why fire protection currently represents an art and not an engineering method.[4] The National Fire Protection Association, NFPA, is trying to develop a probabilistic description of fires for developing an engineering method of fire hazards analysis that at least can be applied to residential buildings. Fire phenomena categories called "realms" are defined thermodynamically to match observed fire test phenomena rather than ad hoc design events which describe failures of architectural elements. Fire tests are then used to determine the probability distributions of realm lifetime and realm transitions. The following thermodynamic definitions are used to identify these realms.[5]

TABLE 1

NFPA Classification of Fire Growth Phenomena

Realm	Phenomena	Thermodynamic Definition
1	Pre-burning	No flames
2	Sustained burning	Ignition (including smoldering) has occurred in the room of origin but heat release rate does not exceed 2 kW.
3	Vigorous burning	Heat release rate inside the room of origin is between 2 and 50 kW, but the upper peak room temperature is less than 150°C.
4	Interactive burning	Average upper room temperature is between 150°C and 400°C; causing secondary ignitions beyond the room of origin but with heat release of less than 2 kW.
5	Remote burning	Average temperature in room of origin is greater than 400°C; causing secondary ignitions beyond the room of origin with heat release of less than 2 kW.
6	Full room involvement	Burning beyond the room of origin releasing 2 to 50 kW; secondary fires have reached realm-3 conditions.

The present NFPA classification of fire growth is practical for analyzing residential building codes, since the code already defines a class of similarly constructed fire zones (rooms, corridors) and since no special hazards are anticipated in ordinary buildings. However, the architecture and ventilation of LWR nuclear power plant fire zones cover a much wider range of conditions than rooms of residential buildings. Nuclear power plant fire zones contain electrical cable bundles, electrical equipment, and flammable liquid and materials that are not usually found in residential or commercial buildings. LWR fires also are more likely to burn in the presence of smoke. The application of a building fire hazards analysis to nuclear power plant fire zones is thus uncertain, even if the NFPA should succeed in developing a reliable engineering method of fire hazards analysis for buildings.

The uncertainty of extending NFPA fire hazards analysis to nuclear power plant fire zones can be reduced by development of methods for simulating both the growth of fires and the performance of fire protection systems in a reproducible manner. For fire prevention studies, ad hoc definitions of events based on architectural design should be replaced by thermodynamic definitions of fire events or modes which are common to most building fires and nuclear power plant fires. Such commonality will increase the reproducibility of building and nuclear power plant fire simulation in two ways:

(a) The data base is vastly increased since the same thermodynamic processes are reflected in a myriad of different architectural designs, ventilation systems, and fire suppression systems.

(b) The uncertainty of nuclear power plant fire phenomena is reduced to the statistical deviation between data segments that reflect the same thermodynamic process. These deviations should be much smaller than the deviation between fire test data segments that describe different thermodynamic processes, i.e., uncertainty is reduced.

In addition to developing thermodynamic definitions of fire events or modes for buildings and nuclear power plants, it is possible to develop thermodynamic burn modes, or event modes from the analytical standpoint, for electrical cable bundles in nuclear power plants. It is important to be able to classify and describe the thermodynamic phenomena which occur in cable tray fires because such fires represent a serious singular threat to the safety of all nuclear power plants.

In a nuclear power plant, literally miles of electrical cables are required to provide electrical power and systems controls throughout the facility, and the insulation materials in the cables constitute a very large source of combustible fuel. The potential hazard of an electrical cable fire is probably best demonstrated by the fire at the Browns Ferry nuclear plant in 1975 which caused extensive damage to the facility and forced the plant to be shut down for a period of two years.[6]

At the Sandia Fire Research Facility in Albuquerque, New Mexico, horizontal full scale electrical cable tray fire tests have been conducted in order to observe and evaluate different candidate cable types under realistic conditions. In order to classify the various thermodynamic phenomena observed and measured in these tests, a concept of electrical cable burn modes has been developed.

The burn mode analysis of cable fires has been very useful in revealing the basic processes of fire growth in cable trays. The cable tray tests have demonstrated the importance of air introduced into smoke saturated hot gas environments on flame development and spreading as well as the reignition of deep-seated fires by the readmission of fresh air.

II. PHENOMENOLOGICAL DESCRIPTION OF CABLE FIRE GROWTH

a. General

Horizontal cable tray fire tests at Sandia, and vertical cable tray tests at Underwriter's Laboratory, both showed that jacket or insulation material may melt or form considerable char.

Four volatilization reactions were observed in vertical cable tray fires:[7]

1. Pyrolysis - "Flaming was uniform over outer surface of the cable bundle as well as throughout the cable bundle. The cable region involved in fire grew steadily for the duration of the test."

2. Smoldering Melt - "The jacket and/or insulation material melted and coalesced into a large mass, and flaming occurred principally on the outer surface of the fused mass. Fire involvement was very dependent upon shape and position of the fused mass within the cable tray."

3. Deep-Seated Combustion - "The jacket and/or insulation material formed considerable char, and flaming occurred principally on the outer surface of the cable bundle. Flaming was not continuous or uniform but rather occurred as sporadic bursts of fire. After the surface flaming subsided, a glowing cable region slowly progressed along the cables with sporadic flaming issuing from the region. The glowing region propagated for up to 4 hours before extinguishing."

4. Interior Combustion - "Flaming was uniform over the outer surface as well as throughout the cable bundle. The cable region involved in fire grew steadily and was continuous. After the surface flaming subsided, a glowing region slowly progressed along the cables with sporadic flaming issuing from this region."

Underwriter's Laboratory associated these classifications with particular cable test descriptions. The above four labels were chosen by one of the authors (F. R. Krause) to relate vertical cable tray fire phenomena and horizontal tray fire phenomena.

The above observations, together with those made during cable fire tests at Sandia, illustrate that electrical cable in trays constitutes a porous solid fuel that may develop both deep-seated fires and interior fuel temperatures in excess of the flash point. Cellulose materials in buildings rarely show the above combination of rapid volatilization and deep-seated fire in the same fuel materials. Some reasonable doubt thus exists that fire growth characteristics of building fires are representative of electrical cable tray fires which can occur in nuclear power plants.

b. Stacked Horizontal Cable Trays

NRC Regulatory Guide 1.75 specifies minimum separation distances for areas, where the fire damage potential is limited to fixtures or faults internal to the electrical equipment or circuit.(8) Minimum physical separation distances are based on open ventilated cable trays, as well as flame retardant cable insulation and jacket materials. These minimum separation distances are illustrated in Figure 1. They are designed to prevent fire propagation among cable trays of one safety division and fire spread between safety divisions. Sandia verified these separation criteria in a 17 tray fire test(9) at the Sandia Fire Research Facility that replicated the cable tray arrangement of Figure 1. The following discussion of cable fire growth phenomena is based on temperature records from this test.

Figure 2 shows two stacks of cable trays before the fire test. The seven lower trays are .875 feet apart from each other and from the floor. They represent one safety division according to NRC guide 1.75. An eighth tray located five feet above tray 7 represents the minimum separation between independent safety divisions.(8) Thermocouples are located along the center line of the north stack at the tray centers.

Smoke density prohibited visual flame observations of the upper trays. Insulation in the 4 inch diameter cable conduits under the trays turned to ash without flaming, and the conduits all showed electrical shorts above tray level 3. At 69 minutes into the test the fire department extinguished the fire to safeguard the explosion rated construction of the building. Manual discharge of 75 gallons of water over a 15 minute period was needed to suppress smoke production from the cable trays.

Figure 3 shows selected temperature time histories of the north stack of trays. The temperature profile of tray 4, characterized by a broad peak, denotes the growth and recession of a surface fire. Similar peaks were observed

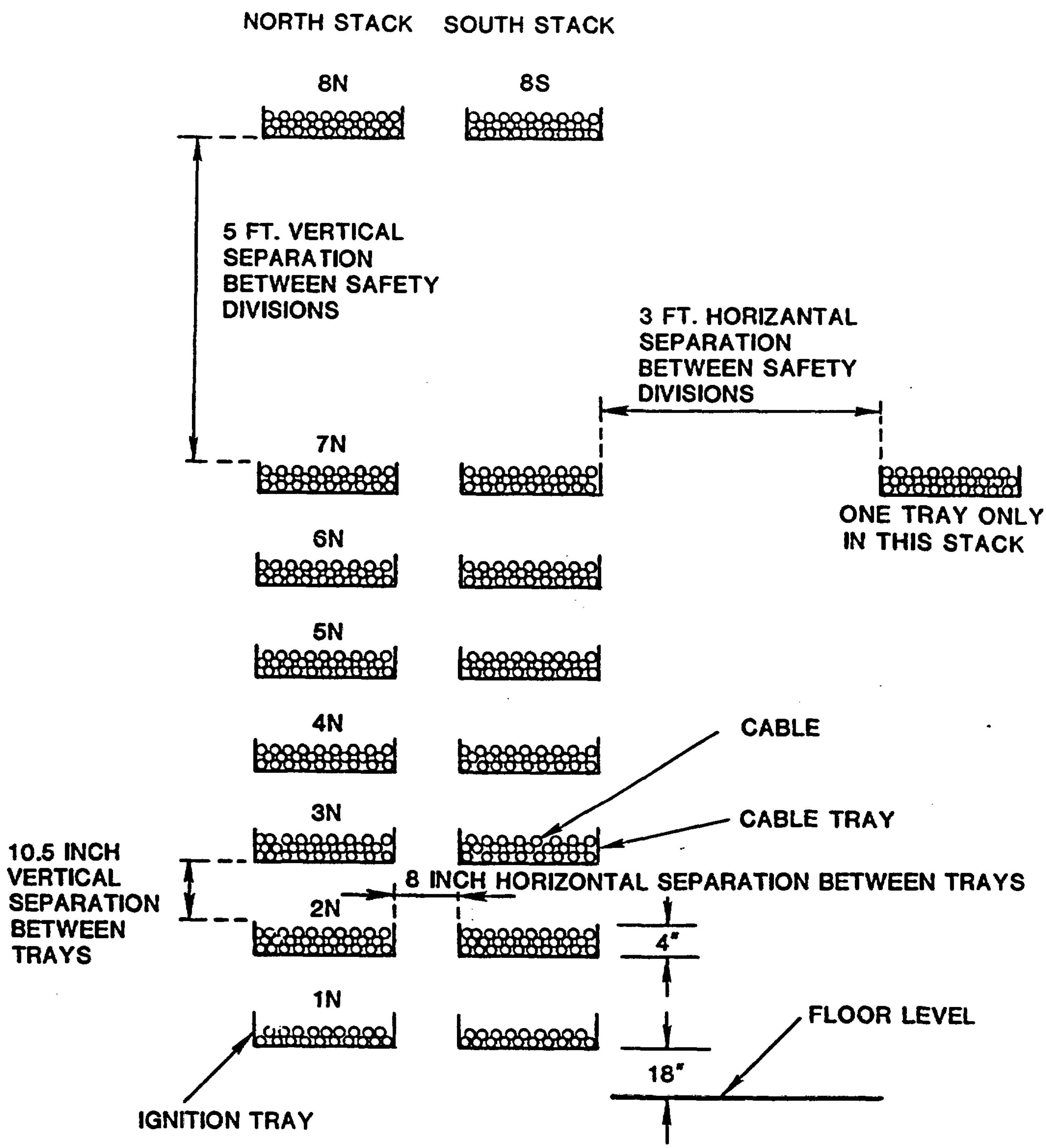

Figure 1. Horizontal Open Space Cable Tray Arrangement

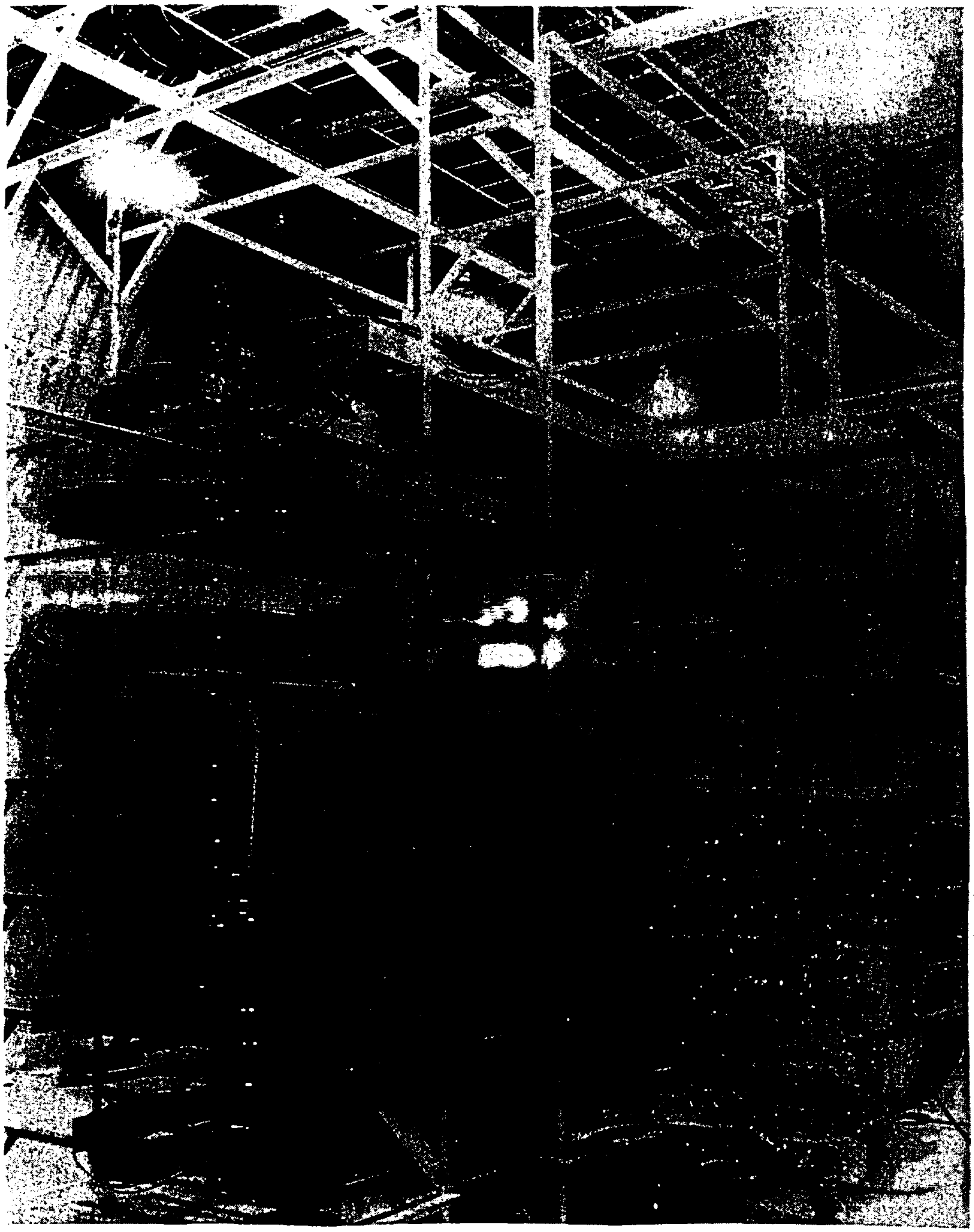

Figure 2. Stacked Cable Trays for Fire Test

for trays 1N, 2N, 3N, and 6N which are not shown in Figure 3. These peaks illustrate the propagation of fire through the north stack. Films of the fire show that this propagation was caused by an unanticipated "leap frog" phenomena, and not by flames from the tray below.

After a surface fire is sustained in tray number one, a fire ball forms at the bottom of the third tray up the stack. This fire ball grows and subsequently touches down on the second tray. The fire ball is then replaced by a surface fire, that starts at the top surface of the tray and not at the flame exposed bottom surface. The whole propagation sequence then repeats itself for next higher level of the stack. The surface fires grow slightly in area with higher peak fuel temperatures at each higher level. Based on these observations, which show that fires are not propagated from tray to tray due to direct flame exposure, we feel that Regulatory Guide 1.75 separation requirements are adequate to prohibit such propagation. However, physical separation by itself obviously does not necessarily inhibit other mechanisms of fire propagation.

Tray 5N shows an extreme temperature rise at 32 minutes and this temperature exceeded typical peak values of 1500 to 1600°F recorded in all other trays. Peak temperatures could not be recorded since the thermocouples stopped operating around 2300°F. The most likely explanation for the sharp temperature rise is a sudden flash of a fuel vapor engulfing tray 5.

Flashover is a common means of fire propagation among physically separated fuel elements in a room. In the case of the above cable tray fire, however, flashover occurred too late to play such a role. Ceiling tray 8N already had reached flame temperatures of 1200°F before the flash occurred. Oxygen starvation by engulfing fuel vapor probably prohibited surface fire development in tray 5N.

Tray 7N behaved abnormally by not developing a peak temperature that is characteristic for the growth and recession of a surface fire. One explanation is that descending smoke and/or fuel vapor accumulation prevented a surface fire by oxygen starvation. Even the flashover of tray 5N did not succeed in igniting a surface fire on tray 7N. Tray 7N temperatures, however, rose slowly and steadily. Water spray halted the temperature rise, but did not cool the tray. The temperature appeared to rise again after the water spray stopped. The most likely explanation for this is a deep-seated fire. Observations for trays 1N, 2N, 3N, and 6N which are not shown in Figure 3. These peaks illustrate the propagation of fire through the north stack. Films of the fire show that this propagation was caused by an unanticipated "leap frog" phenomena, and not by flames from the tray below.

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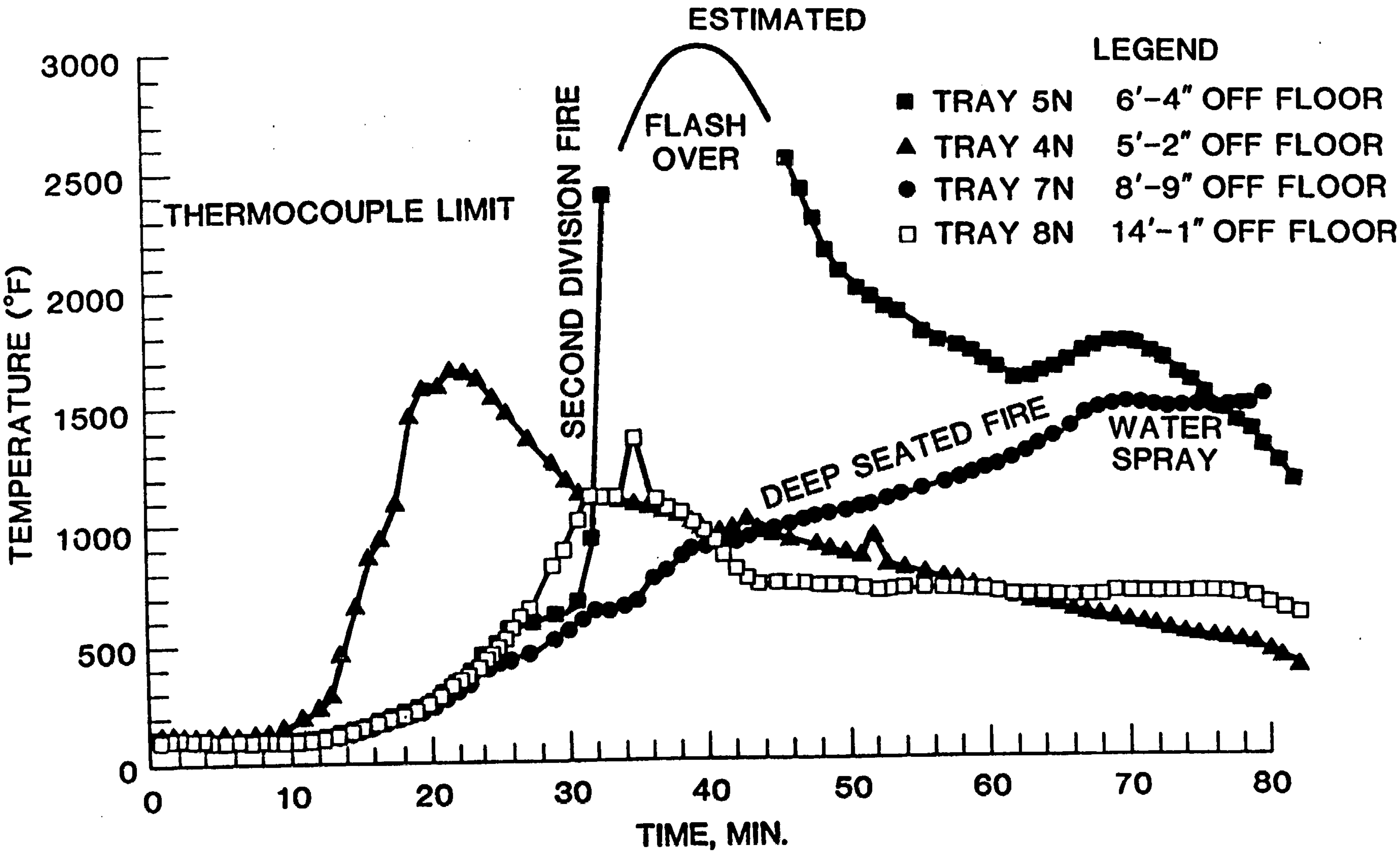


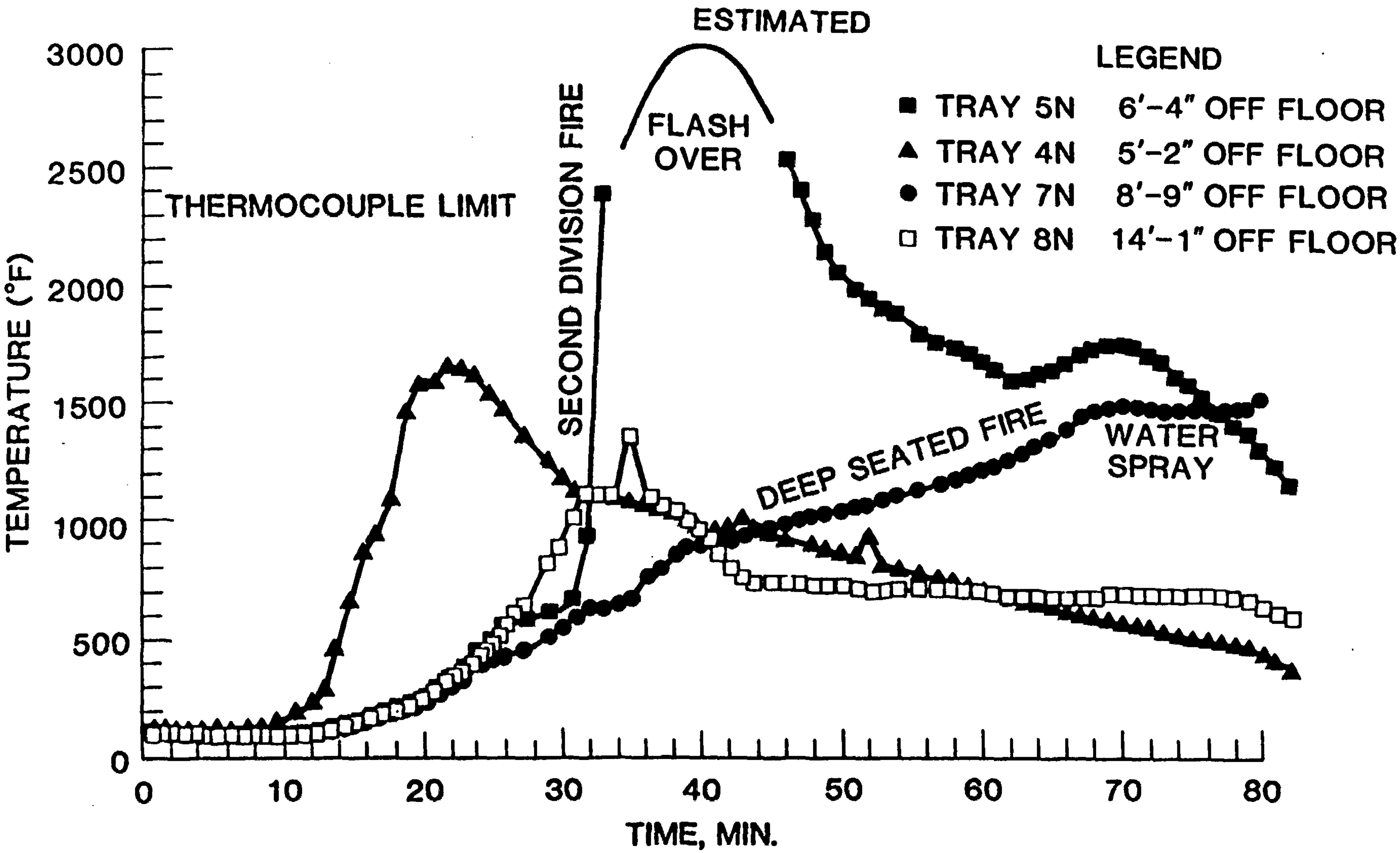
Figure 3. Burn Room Temperatures vs. Time

A comparison of test data for trays 5N and 7N indicates that fuel temperature transients provide an important basis for distinguishing between deep-seated and surface fires. (See Figure 3). Figure 4 shows three vertical temperature stratifications along the north stack center line: a) just before the hydrocarbon flash (32 minutes), b) after the flashover (35 minutes), and c) when post flashover cooling slowed down (48 minutes). The data shows that the flash was created by the interaction of multiple fires that is not present in single tray tests and may not occur in two tray tests. At 32 minutes tray 5N had reached a temperature just below the autoignition threshold. The absence of thermal transients in this temperature range shows that fuel vapor was accumulating inside the tray. Burn room ceiling temperatures in excess of 1000°F indicate a layer of burned gas above tray 5N that may have helped to confine a hydrocarbon cloud about the tray. The cloud was heated by the hot trays 4 and 6 from above and below. Flashover occurred a short time later, when the temperature reached the autoignition threshold.

Conditions between 32 and 35 minutes can be compared to the NFPA building classifications. The average room temperature is 700°F (371°C). The heat release of fire may be estimated crudely by multiplying the air mass in the room (334 lb) with the specific heat of air (.240 BTU/lb °F) and the ceiling temperature rise rate (80°F/min). This gives a heat release of 113 kW. According to the NFPA classifications in Table 1, the fire phenomena should be characterized by interactive burning, (heat release in excess of 50 kW) that is close to remote burning, i.e., average room temperatures greater than 400°C.

The NFPA classification thus indicates that a sudden transition to remote burning could occur. Such a transition did occur, however, remote burning of tray 8N was already fully developed some 12 minutes earlier. See Figure 3.

The NFPA classification, therefore, is uncertain for the type of cable fire that burns in the presence of smoke. Remote burning of cables may occur at temperatures and heat rates which would, in the absence of smoke, only support interactive burning. In Chapter V we will describe an extension of the NFPA classification to fires that burn in the presence of smoke.



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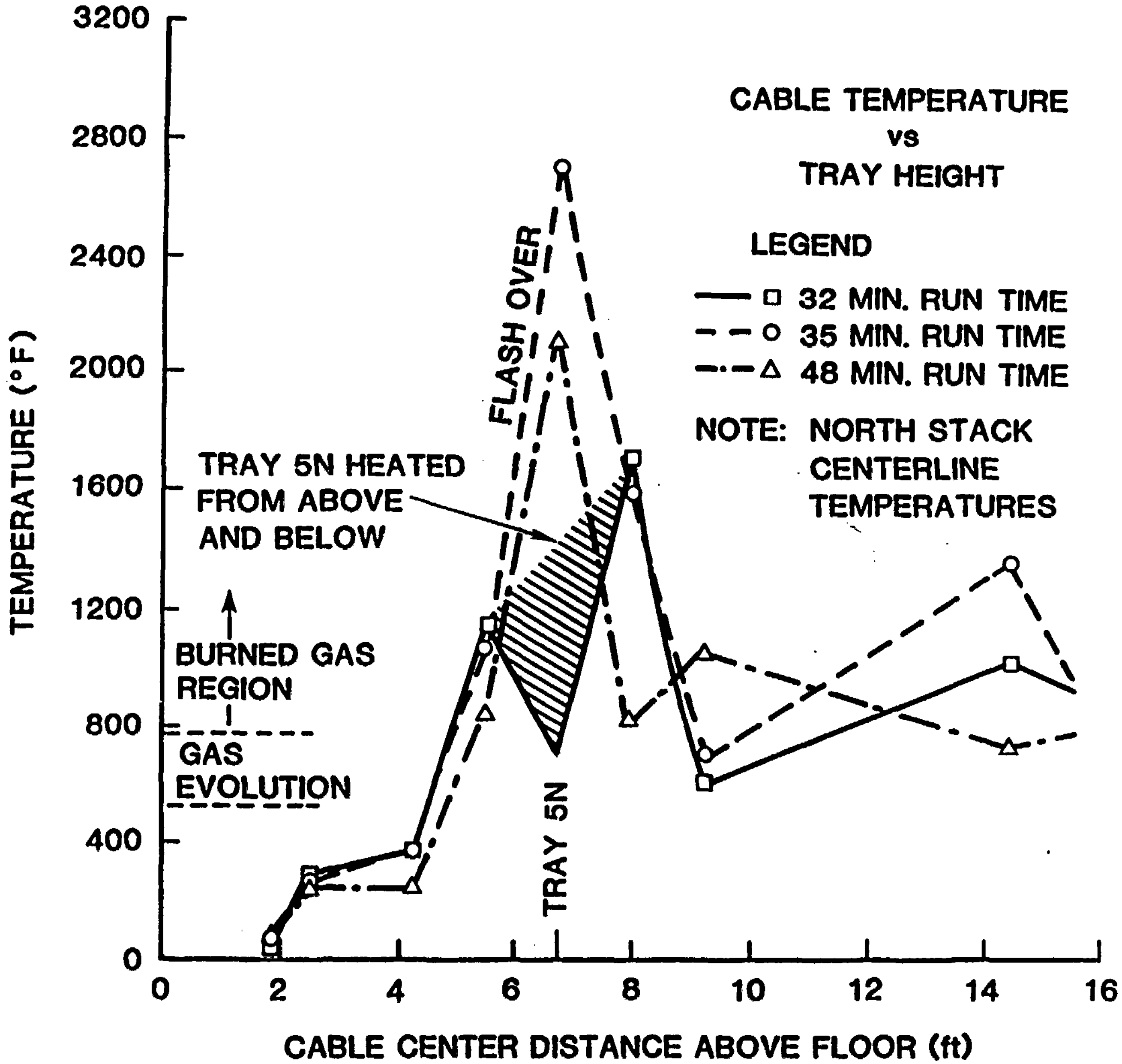


Figure 4. Cable Temperature vs. Tray Height

III. BURN MODE ANALYSIS OF FIRE TEST RESULTS

During the course of an electrical cable fire a number of different thermodynamic phenomena are produced. They can be observed, measured, recorded, and classified. These phenomena are the result of the generation of flammable gases due to the initial heating of the cables and combustion of the gases. Heat release due to combustion causes a further temperature rise and the process continues to accelerate. The availability of oxygen, the cable temperature, and the type of combustible material in the cables are all fundamental in determining the limits for fire growth.

The different tray heating phenomena which take place during the lifetime of a cable fire can be considered events from an analytical standpoint, and event tree analysis can be performed to obtain burning characteristics for different cable types. The thermodynamic events which denote sudden transitions between cable tray temperatures can be classified and these are called burn modes.

Burn modes are studied for a generic classification of fire growth phenomena that can be used for comparing building fires, electrical equipment fires, and flammable liquid fires. The following classification was restricted to the use of temperature measurements, since temperature is the only parameter that has been recorded in full-scale compartment fire tests of both building materials and electric equipment.

The purpose of a burn mode classification is to subdivide a raw data record into segments such that the segments of one class reflect a generic chemical process. Recognition of volatilization and combustion reactions requires a temperature signature of individual reactions. Thermogravimetric laboratory tests use the concept of a weight loss activation temperature to characterize volatilization of polymers. In the case of flammable liquids, this weight loss activation temperature is simply the boiling point. We have introduced the concept of a heat release activation temperature to characterize not only volatilization reactions but also combustion reactions. Using heat release in lieu of weight loss is more in line with the above NFPA definition of fire phenomena and permits correlation of reactions with the location of individual thermocouples. Such space resolution is absent in global measurements of fire weight loss.

The introduction of heat release activation temperatures makes it possible to divide the burn mode classification of raw data records into three basic tasks:

1. Retrieval of heat release activation temperatures,

2. Grouping of raw data records into burn mode dedicated data segments,

3. Analysis of classified data segments.

A preliminary approach to these basic test data reduction tasks is described in the remainder of this chapter.

III.1 Heat Release Activation Temperatures

Following the qualitative discussion of the 17 tray fire test, we use the rate of fuel temperature rise above the temperature of the ambient atmosphere as a qualitative indicator of local heat release. Heat release activation temperatures are retrieved by plotting the temperature rise rate against the fuel temperature as shown in Figure 5. Experience with the 17 tray fire test data also showed that temperature rise rates in excess of 160°F/min indicate flaming combustion near the tray. The peak level of the temperature rise rate can therefore be used to separate surface fires above the instrumented fuel section from other heat release reactions. Any temperature excursion found is then traced back to the preceding minimum of the temperature rise rate. The associated fuel temperatures are then identified with a heat release activation temperature according to the following screening criteria:

1. <u>Flammable gas evolution</u>

   The minimum temperature rise rate indicates a reversal of a sharp cooling trend which was caused by shutting down the burner and which dropped through the 160° F/min threshold from above.

2. <u>Autoignition</u>

   The minimum temperature rise rate indicates a reversal of a cooling trend that was independent from the burn shut down. The subsequent excursion is steep and reaches peak temperature rise rates that are comparable to burner shut down values.

The third type of heat release activation temperature is associated with the maximum of the fuel temperature. This maximum is interpreted as char oxidation. T. E. Harmathy introduced the concept of fuel volatilization by a slowly propagating char oxidation front[10] while analyzing over 250 full-scale building fires.

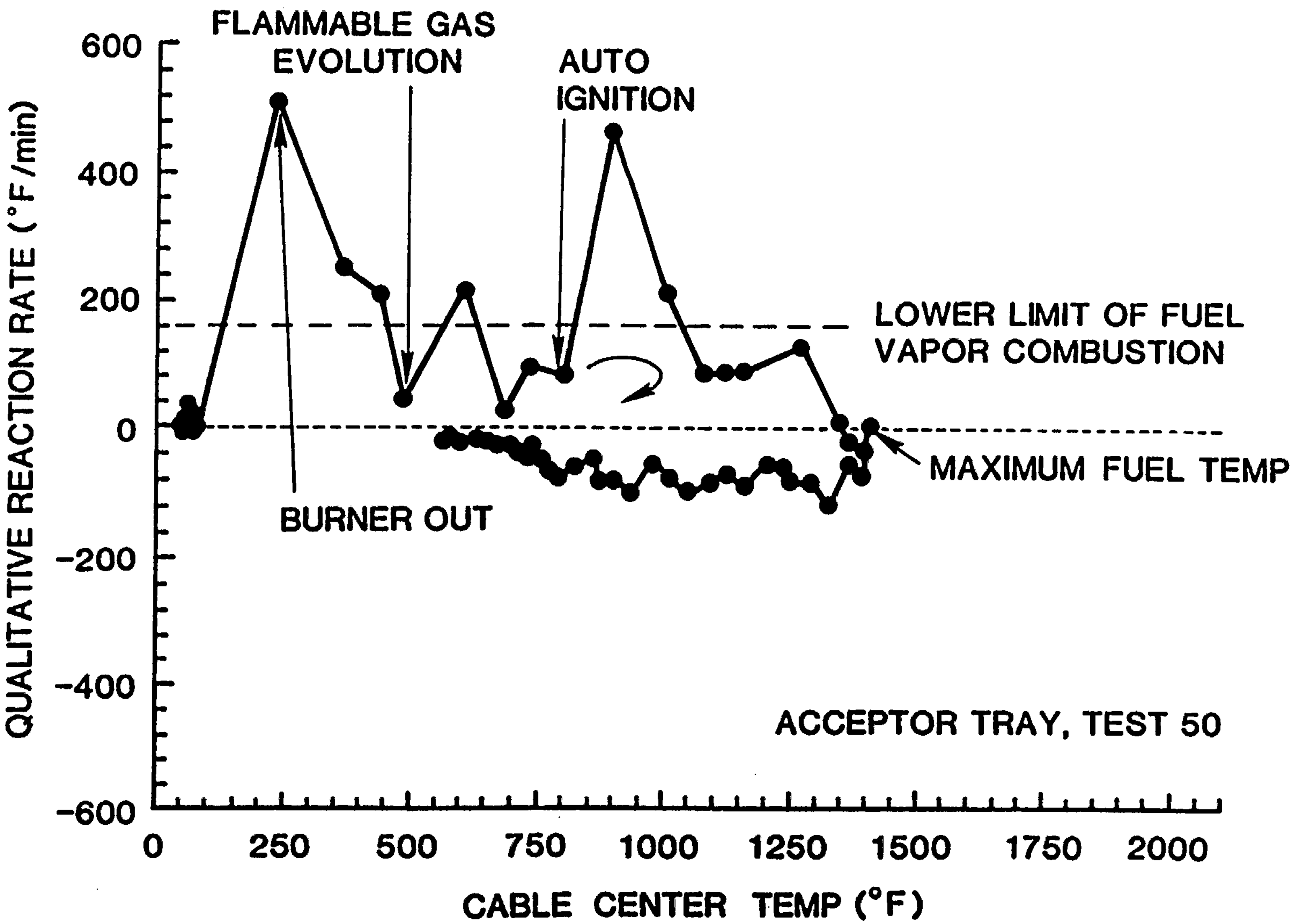


Figure 5. Qualitative Reaction Rate Profile

Flammable gas evolution temperatures, autoignition temperatures and char oxidation temperatures were retrieved from a series of 21 special effects electrical cable tests. The selection of these tests was based on the condition that an electrical short occurred in the burning tray. The tests differed in material composition and cable design as shown in Figure 6. The tests also differed in using four different cable arrangements:

1. Single tray with three conductor cables in center of room,[11] duplicating geometry for tray 1N of Figure 1.

2. Two tray stack with three conductor cables in bottom tray and single conductor cables in top tray in center of open room,[12] duplicating tray geometry 1N and 2N of Figure 1.

3. Single tray as in (1) above in corner of a metal enclosure.[13]

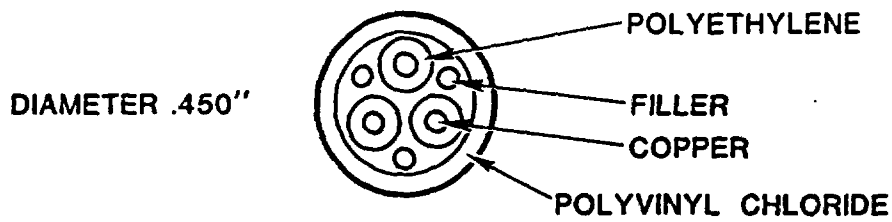
4. Two tray stack as in (2) above in corner of metal enclosure.[13]

The single and two-tray arrangements were covered by a permanent barrier on top to crudely simulate the radiation exchange within a tray stack as in the 17 tray fire (see Figure 7).

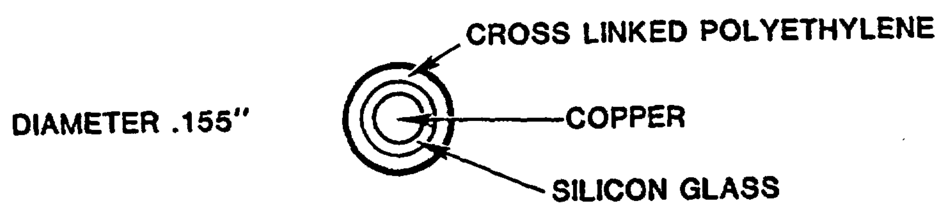
Retrieving heat release activation temperatures from these special effects tests produced the results given in Table 2. The following chemical classification was used:

1. Pre-383 cables
2. IEEE 383 qualified cables
3. IEEE 383 qualified cables with coating "C."

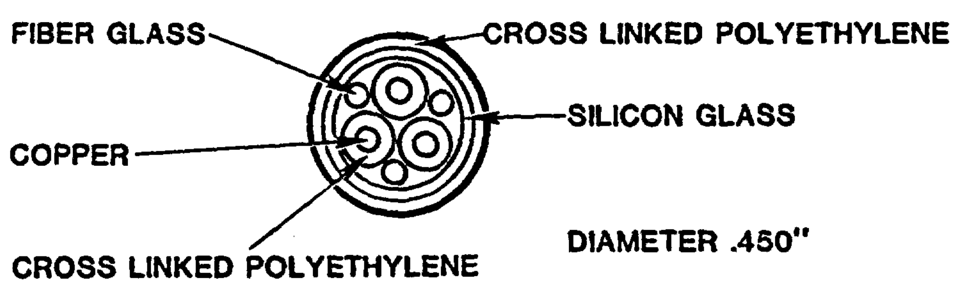
These classes represent an increasing amount of flame retardant materials. However, each class still includes both single and 3-conductor cables and both single tray and two tray test configurations. Classes 1 and 2 also include corner test arrangements.



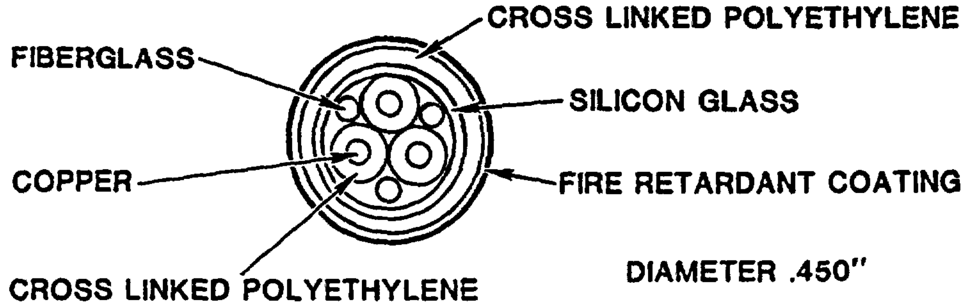
PRE-383 3 CONDUCTOR CABLE



IEEE-383 SINGLE CONDUCTOR CABLE



IEEE-383 3 CONDUCTOR CABLE



IEEE-383 CABLE WITH FIRE RETARDANT COATING

Figure 6. Electrical Cable Cross Sections

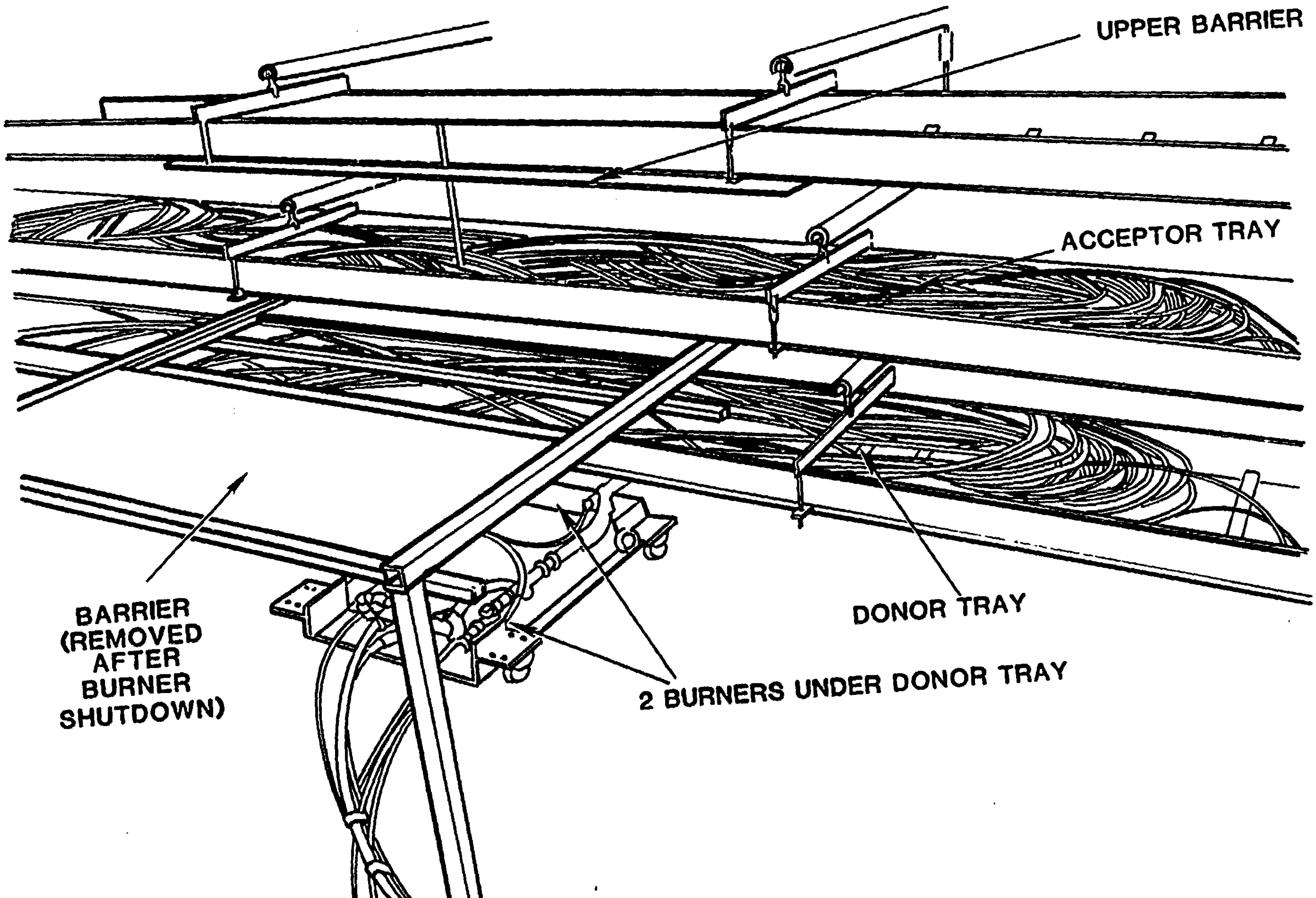


Figure 7. Two Tray Cable Fire Test Arrangement

The results indicate that all cable tray burns include at least two different combustion reactions which are triggered at different autoignition temperatures. The difference between the first autoignition temperatures for the different cable types may be statistically significant and indicates that the low temperature combustion reactions are affected by flame retardant components of the cable surface. The effect of the IEEE qualification is counter-intuitive; it lowers the autoignition temperature. The high temperature combustion reactions on pre-383 and 383 qualified cables are ignited at very similar temperatures that exceed most flammable gas flash points. Coating an IEEE-qualified cable raises both autoignition temperatures but lowers the char oxidation temperature threshold.

TABLE 2

Heat Release Activation Temperatures

Cable Type	Maximum Cont. Use Temp. (F°)	Flammable Gas Evolution Begins (F°)	1st Auto Ignition (F°)	2nd Auto Ignition (F°)	Char Oxidation Temp. (F°)
Pre-383	235	505 ± 45	835 ± 45	1045 ± 60	1415 ± 130
383	275	525 ± 40	765 ± 55	1070 ± 65	1380 ± 115
"C"-coated 383	275	325 to 490	880 ± 50	1300 ± 50	1262 ± 75

Flammability handbooks for plastics(14) list the following weight loss activation temperatures.

Commercial grade polymer	Pyrolysis in Absence of Oxygen (°F)	Ignition in Presence of Flame (°F)
Polyvinylcloride, PVC	392 to 572	536 to 604
High density polyethylene, PE	635 to 842	740 to 811

Comparing these values with Table 2 suggests that flammable gas evolution of pre-383 cables is associated with decomposition of the PVC jacket. Flammable gas evolution of IEEE-qualified cables probably reflects volatilization of a plasticizer or fire retardant. First stage autoignition of both 383 and pre-383 cables probably denotes the combustion of polyethelene decomposition products. The second autoignition threshold is characteristic of spontaneous ignition[15] of surface heated cellulose materials (930 to 1200°F) and plastics (1200°F).

The results of Table 2 support our belief that heat release activation temperatures are common to a diverse range of fuel element construction, fuel element arrangements, and fire zone architecture. The generic aspect of heat release activation temperatures is demonstrated by the following observations:

(a) A crude chemical classification of the combustible material allowed reproducible heat release activation temperatures with 4 to 9 cable tray burns in spite of significant variations within each class of element construction (1 versus 3 conductors), element arrangement (single tray, two trays), and architecture (open room, corner of enclosure).

(b) The results of special effects tests (chemical class 2) agree closely with full scale replication of LWR fire zones that used 7 tray stacks.

(c) First autoignition temperatures agree with the handbook values of polythylene ignition in the absence of flames, and second autoignition temperatures agree with handbook values of spontaneous surface ignitions.

III.2 Burn Mode Classification

The qualitative discussion of cable fire growth indicated two fundamentally different types of combustion reactions: flammable vapor combustion and char oxidation. The ignition of the first type is controlled by the temperature of the fire zone atmosphere and the ignition of the second by the interior temperature of the fuel. Fuel vapor reactions can be subdivided into additional generic subclasses according to observed phenomena which occur at simultaneously recorded temperatures of the ambient atmosphere and interior fuel temperatures.

Computerized raw data records from Sandia's cable fire tests were used for a preliminary burn mode classification based on temperature alone. Additional information on these tests and the test data is given in Appendix A. The burn room geometry is illustrated in Appendix B.

Thermocouples were cemented to the cable insulation and not the copper conductor. The measured temperatures are thus uncertain, whenever:

(a) The insulation has burned away from the original thermocouple junction, or

(b) Heat deformation of cables has caused deviation from the vertical separation distance between thermocouple locations in the cable bundle.

Consequently, depending on test conditions, the thermocouples measured the temperature of the gas near the cable, a char surface, or the temperature of the copper conductor. This uncertainty permits a general classification of test results, but the data may not be sufficiently definitive for deterministic modeling of heat transfer near a reaction zone.

The preliminary classifications of the raw data records are derived from two thermocouple positions. The first screening temperature, called fuel internal temperature, T_f, represents the temperature in the cable tray center between the two ribbon burners. It was calculated by taking the arithmetic mean of thermocouples 2 and 4 (see Figure A1). The second screening temperature, T_a, called fuel surface temperature, represents the measured output of thermocouple 3. This thermocouple was cemented to one cable at the top of the filled tray facing downwards.

Burn modes were identified by subdividing the above two independent temperature records into intervals that are determined by the heat release activation temperature thresholds (see Table 2). This postulation of burn modes is illustrated graphically in Figure 8. The shaded bars in Figure 8 represent the experimental uncertainty of the heat release activation temperatures. The blank inner spaces are labeled burn modes according to the phenomenological descriptions of volatilization and combustion reactions that were discussed in the last section.

PRE-IEEE-383 CABLE THRESHOLDS

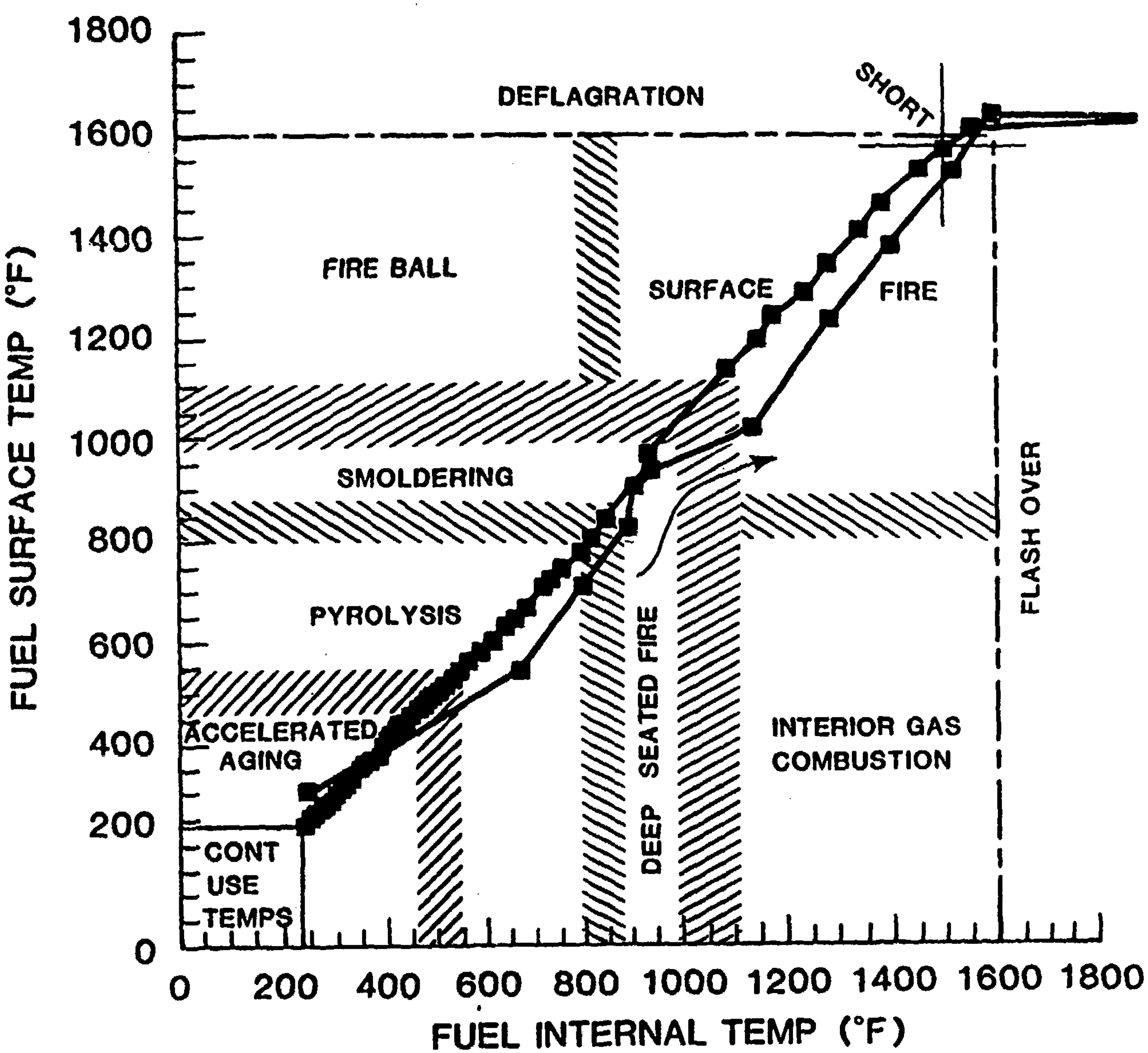


Figure 8. Temperature Profile, Acceptor

Electrical engineering handbooks list a continuous use temperature that assures electrical resistance and dielectric properties of insulation materials for 20,000 to 100,000 hours of operation.[16] Maximum continuous run temperature ratings are:

PVC, flexible, filled:	130 to 150°F
PE, .91 to .925 g/cm^3:	180 to 212°F
PE, .92 to .94 g/cm^3:	220 to 250°F
PE, .941 to .965 g/cm^3:	250°F
PE, cross linked	275°F

These continuous use temperatures thus give the lowest temperature at which volatilization can occur. The range between continuous use and pyrolysis temperature denotes accelerated aging. The range between pyrolysis and lower autoignition temperature denotes pyrolysis of highly volatile fuel components that are characterized by low energy chemical bonds.

Volatilization reaction rates are known to follow the Arrhenius law[17] i.e., they grow exponentially with temperature. Volatilization reactions, then, are not independent from combustion reactions. The coupling of volatilization and combustion reactions is typical for nonflaming combustion. The temperature range between the first and second autoignition temperature thresholds will sustain combustion of flammable gases in the absence of flames if we assume that the second ignition threshold denotes the spontaneous ignition temperature of gases from a cable tray surface (see discussion following Table 2). In Figure 8, the area between these two ignition threshold temperatures denotes nonflaming combustion or smoldering. Friedman[15] describes smoldering as follows:

> "It may propagate by a 'front' or 'wave' which involves air oxidation generally combined with pyrolysis. It may be self-sustaining, or it may require assistance from an adjacent energy source. It occurs in bulk porous material which may be in contact with a heat sink as long as the porous material is thicker than the critical value. Flexible polyurethane foams, even if fire retardant, can smolder in a self-sustained mode."

Summarizing common observations of smoldering, Friedman also notes that smoldering generates an aerosol of condensed, high molecular weight species formed by pyrolysis in or near the smoldering zone, which is combustible. However no visible products may emerge until the smoldering zone reaches the surface because of self-absorption of products within the bed.

Self-sustained smoldering can create a local hot zone inside a porous material, while the surface temperature is still cool. This is a deep-seated fire. We hereby propose to define a deep-seated fire as a subclass of smoldering with the following conditions (see Figure 8):

- Fuel interior temperature is between the fuel vapor and surface autoignition temperatures of the fuel

and

- Fuel surface temperature is below the upper or surface autoignition temperature.

This is a quantitative definition of deep-seated fires that can be used to monitor deep-seated fires on line. Figure 8 illustrates such monitoring. Realizing that data points are 30 seconds apart, we find that a deep-seated fire developed in the acceptor tray of corner test 49 (Pre-383 cable) a couple of minutes after the burner was shut down. The deep-seated fire lasted about 1.5 minutes and then started a surface fire. We have thus clearly identified the segment of the test 49 data record, where a deep-seated fire occurred.

A subdivision of the smoldering zone into self-sustained combustion (deep-seated fire) and externally heated combustion (henceforth called smoldering) is justified, in our opinion, due to the extreme importance of the deep-seated fire phenomena relative to fire protection. A deep-seated fire is very difficult to suppress since fire suppressing agents cannot easily get to the seat of the fire, and it is also difficult to detect since combustion is primarily under the cooler surface. The NFPA thus requires (NFPA-12A) or strongly recommends (NFPA 12, NFPA 15) the verification of suppression agent discharge requirements by test. However, a formal a priori definition of deep-seated fire so far does not exist and no suppression verification test method is presently available. We hope that the concept of burn modes will help fill this gap.

Fuel elements can sustain flames, once the fuel temperature exceeds the upper autoignition threshold. We distinguish two burn modes. Interior gas combustion denotes a fuel with a surface temperature too cool to allow external surface fires. External surface fires should occur if both fuel interior and fuel surface temperature are between the upper (spontaneous) autoignition temperature and the char oxidation temperature. Fire balls are characterized by hot combustible gases with temperatures in excess of the upper ignition threshold but with a fuel surface too cool for ignition of surface flames.

To achieve fuel interior temperatures beyond the char oxidation temperature requires intense external heating. Figures 3 and 8 show two such observations. The discussion of Figure 3 associated flashover with such extensive heating. The flashover region is designated in Figure 8.

We did not observe excursions of the char oxidation temperatures. Labeling the remaining area in Figure 8 as "deflagration" is thus speculative. Our main motivation was that temperature of unburned gas in excess of the char oxidation temperature can probably be achieved only by compression heating of the gas and this is the definition of a deflagration.

III.3 Results From Test Data

All of the data used to classify and describe the thermodynamic phenomena associated with electrical cable fires in this report came from the thermocouple records of the 21 tests mentioned previously. From these data we were able to determine the thermodynamic burn classifications or modes given in the previous section of this report, and their respective temperature limits for the three cable types tested as indicated in Table 2. The thermodynamic history of each of the cable fire tests is given by temperature profiles as illustrated in Figures 9 through 14. These are plots of the cable bundle internal temperatures (fuel internal temperatures) vs. fuel surface temperatures imposed on a burn mode matrix for each of the three types of cables. The data points are at 30 second time intervals.

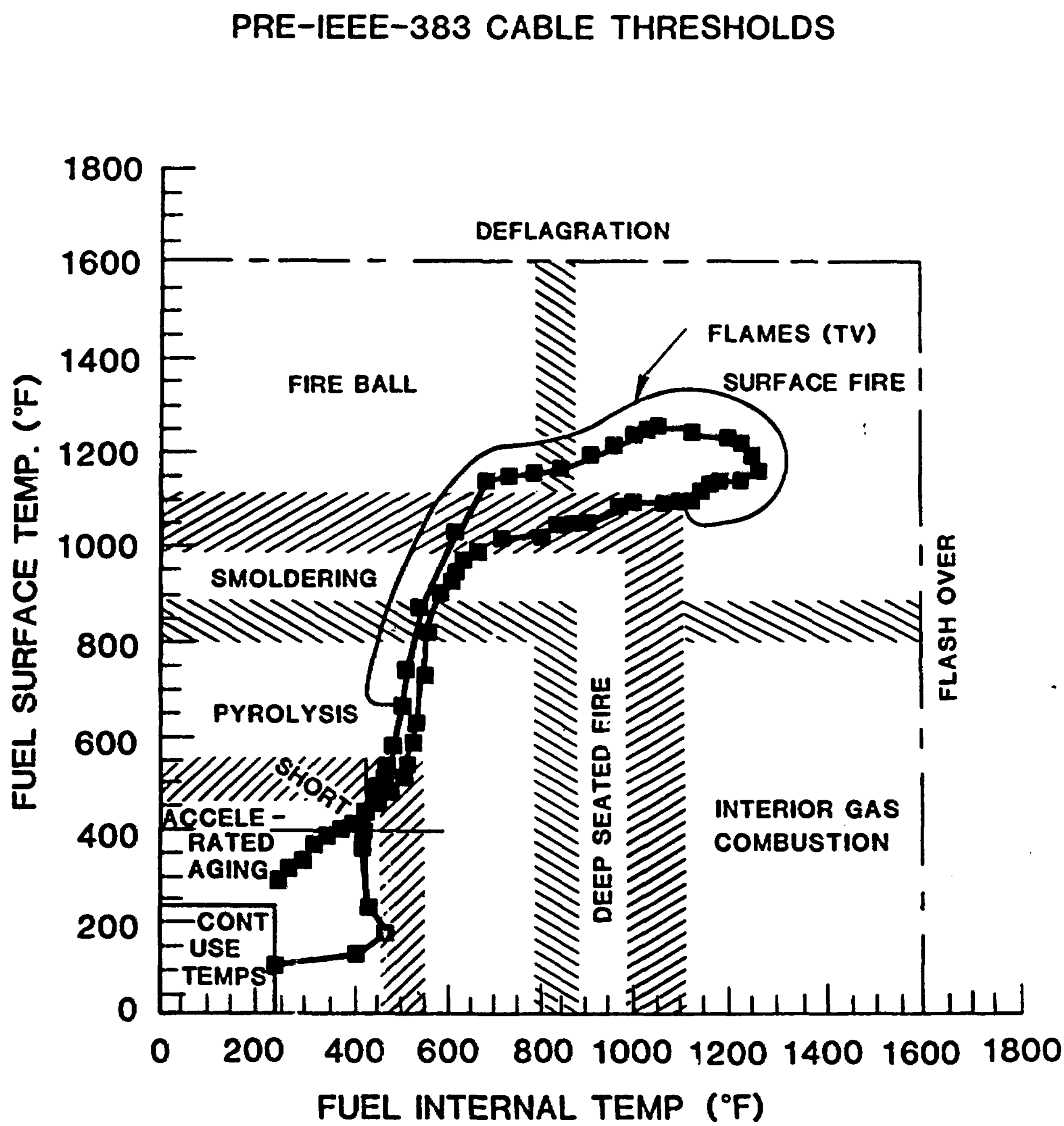


Figure 9. Temperature Profile, Donor Tray, Test 21

PRE-IEEE-383 CABLE THRESHOLDS

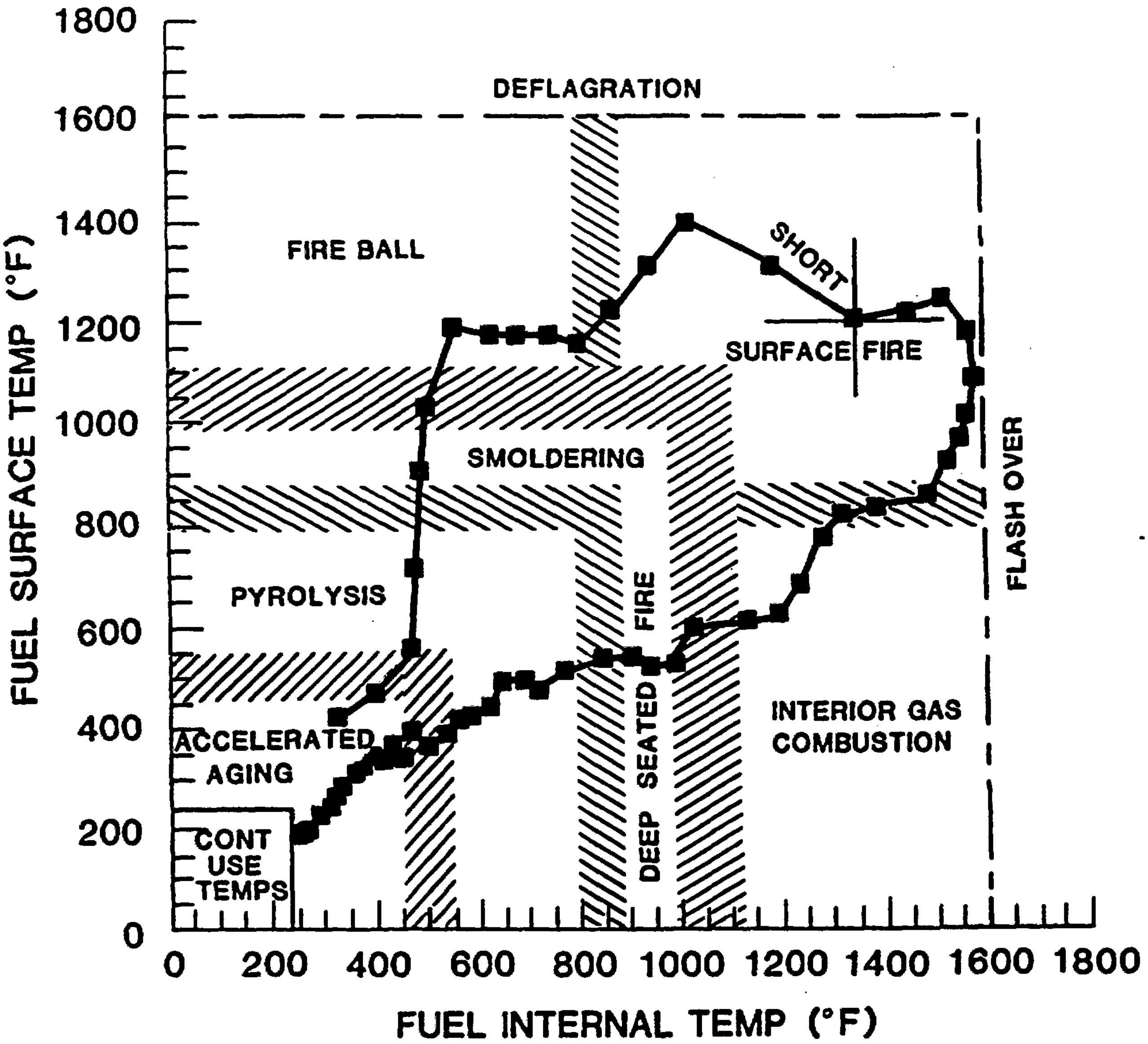


Figure 10. Temperature Profile, Acceptor Tray, Test 21

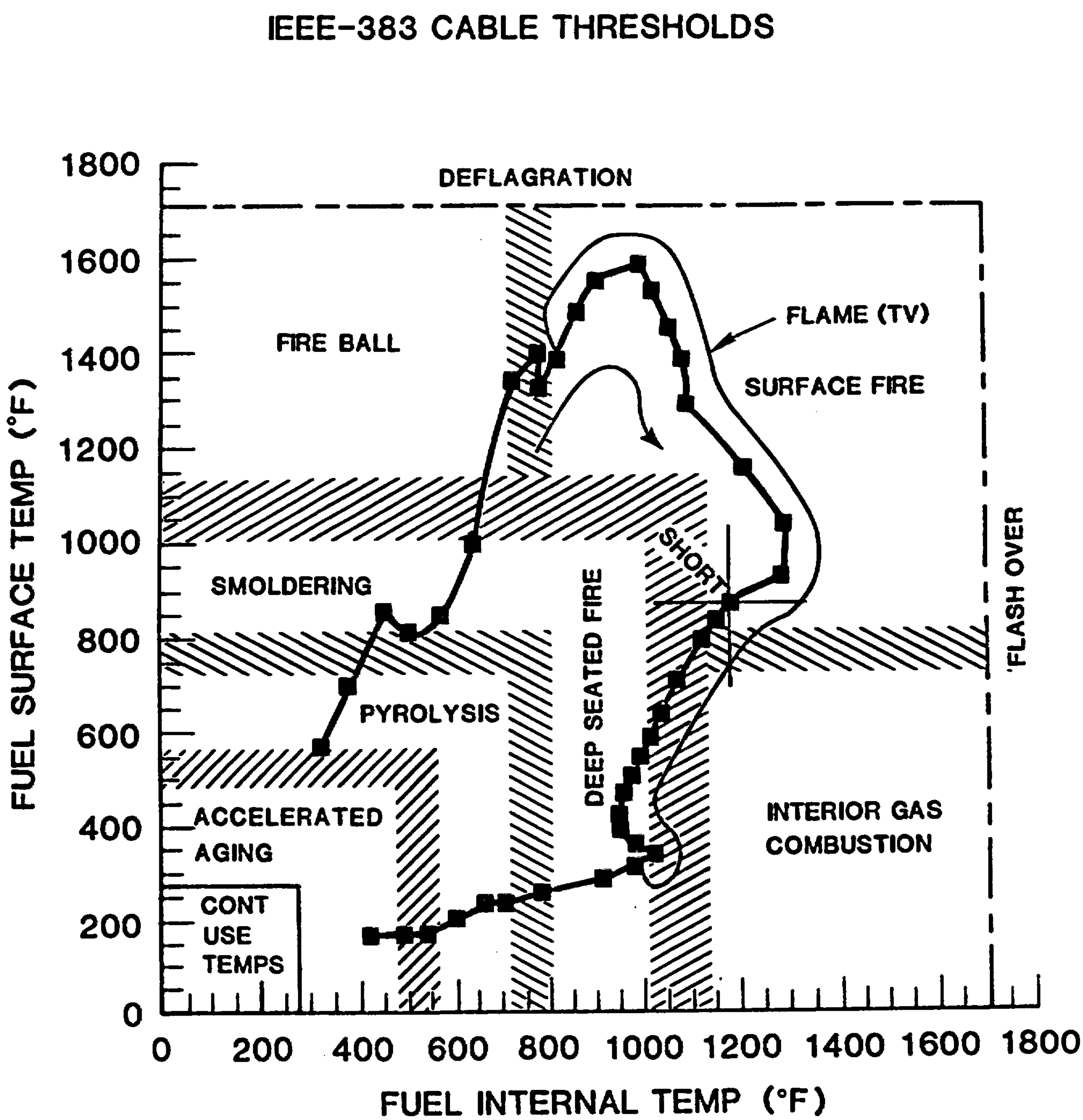


Figure 11. Temperature Profile, Donor Tray, Test 20

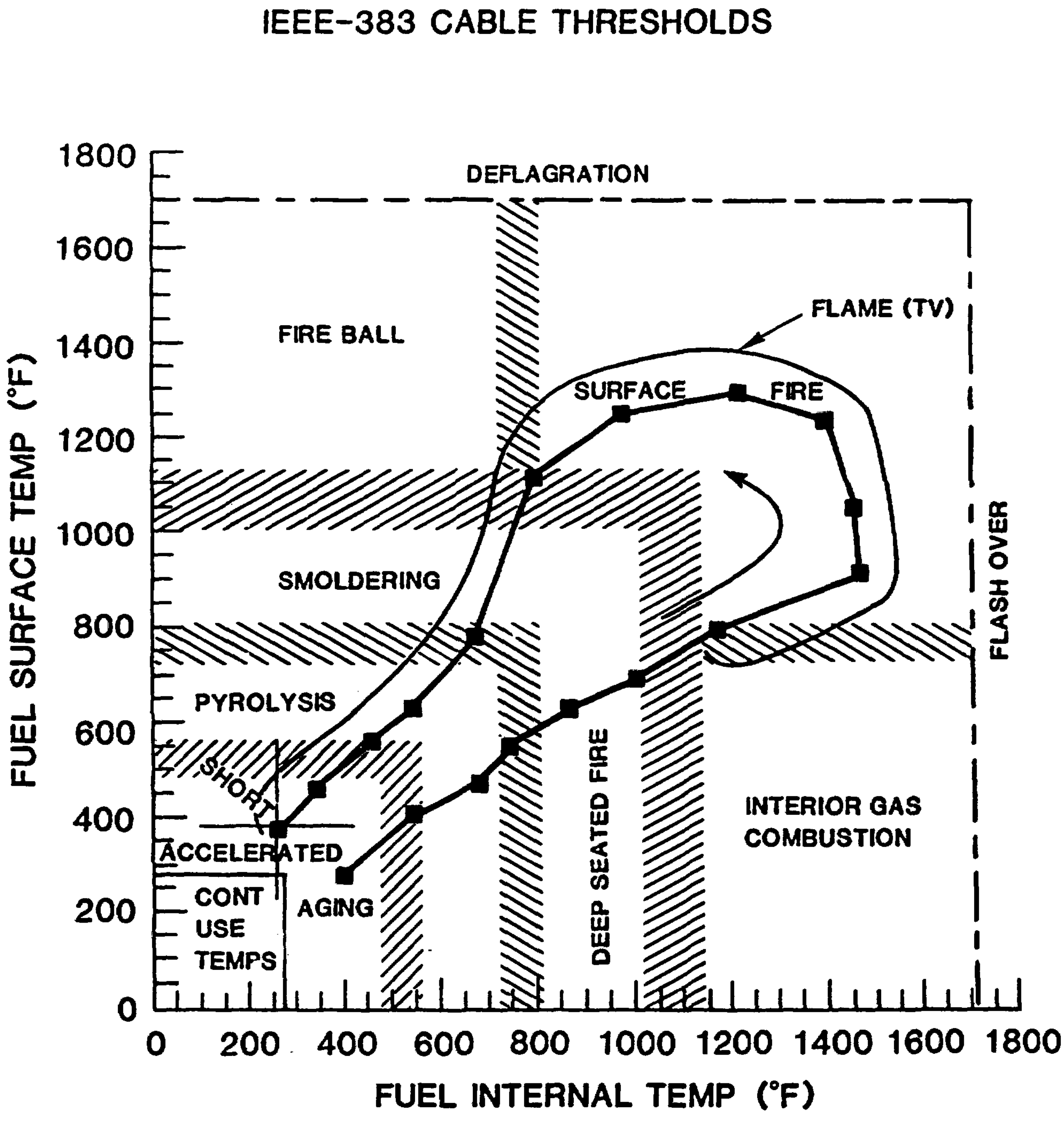


Figure 12. Temperature Profile, Acceptor Tray, Test 20

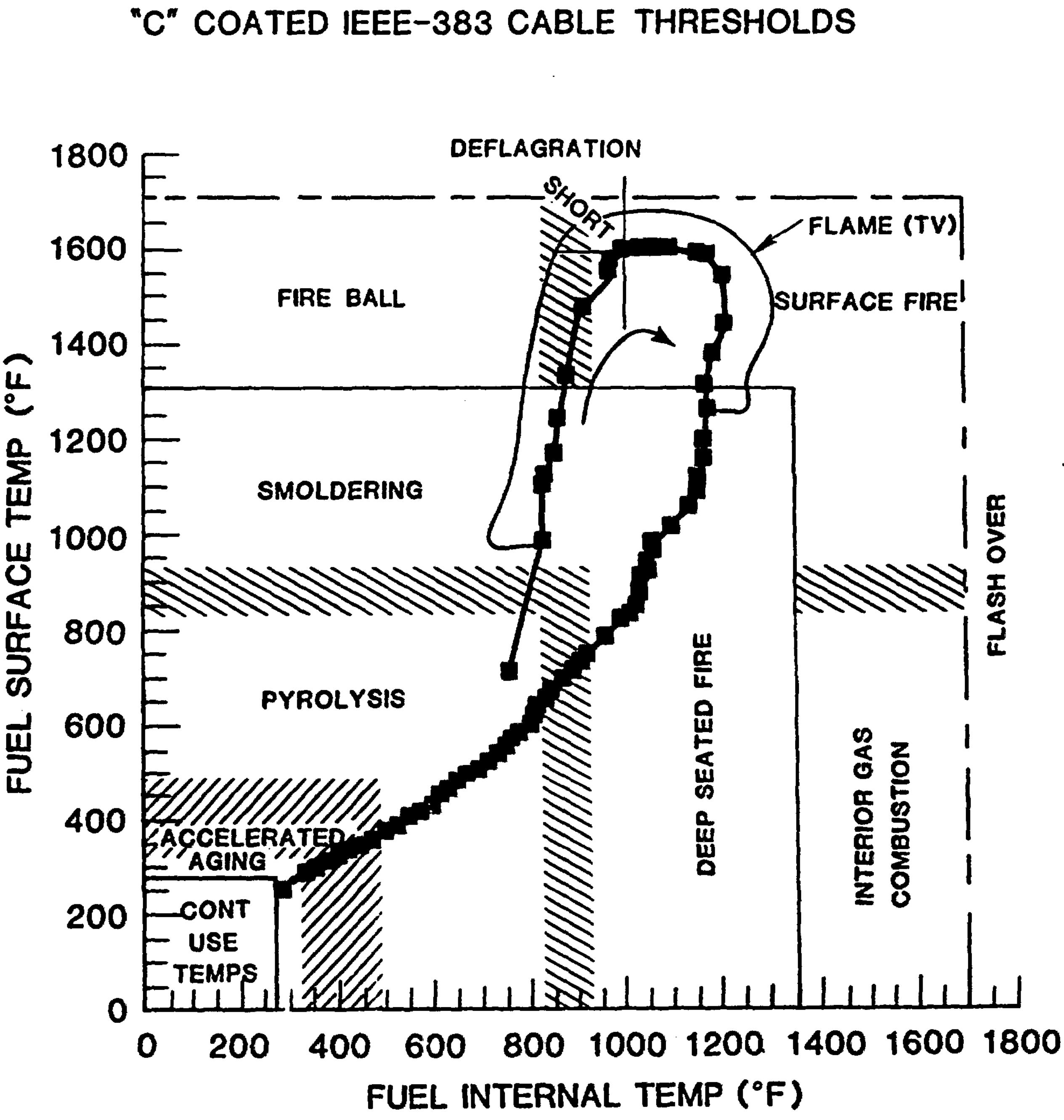


Figure 13. Temperature Profile, Donor Tray, Test 17

"C" COATED IEEE-383 CABLE THRESHOLDS

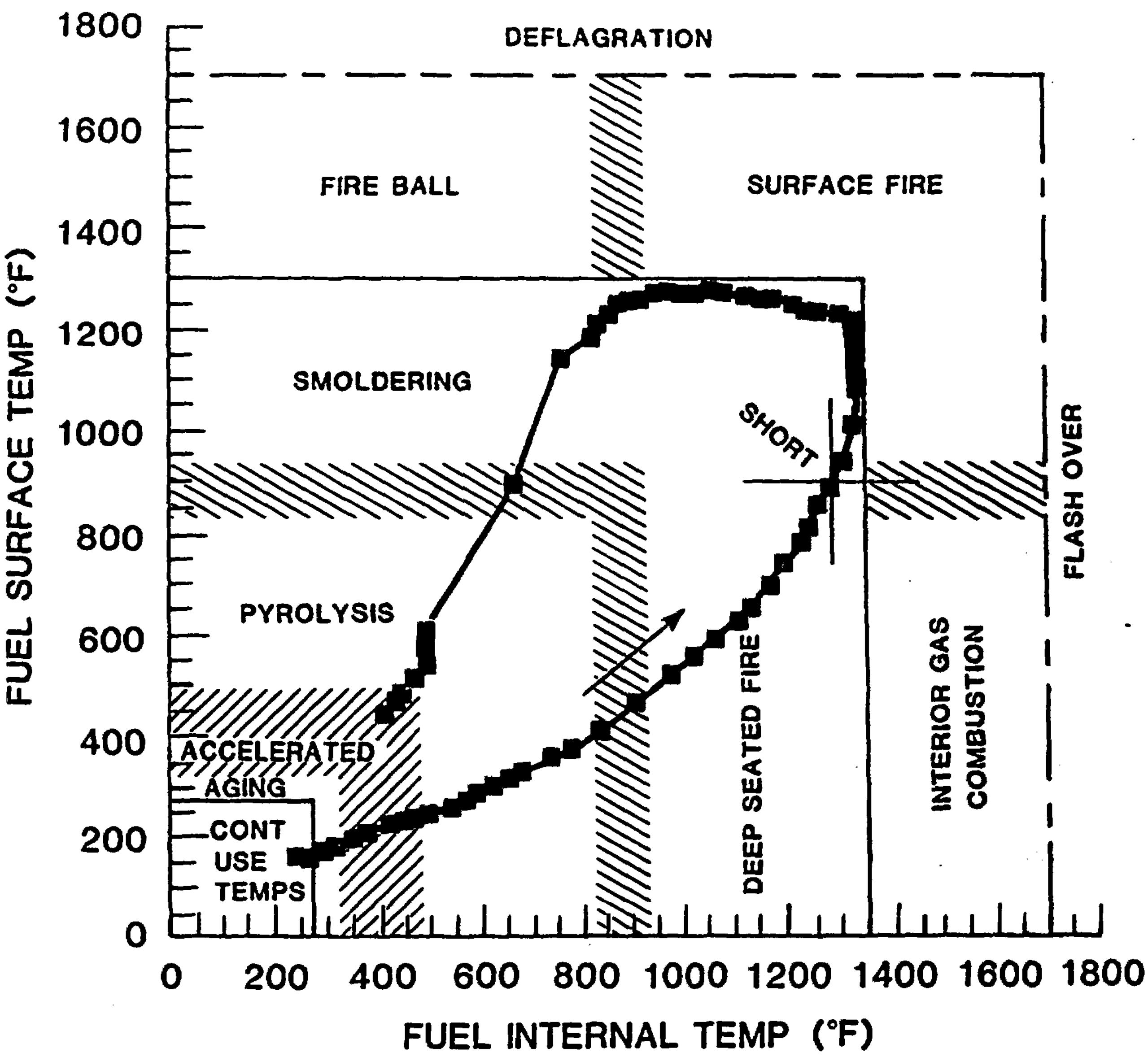


Figure 14. Temperature Profile , Acceptor Tray, Test 17

Each of the temperature test profiles is characterized by a curve which rises and falls as the respective surface and internal temperatures increase and cool. Each of the profiles, therefore, has a heating cycle and a cooling cycle. The burn modes which are activated during a fire test can be determined readily from the temperature profile plots, and the length of time which each mode is activated can be determined by counting the data points (which are separated by 30 second time intervals). A summary of modal life fractions from fire test data for those types of cables tested is given in Table 3.

The modal lifetime fraction data given in Table 3 includes results from all of the 21 special effects electrical cable fire tests. These tests include the four different cable arrangements and the three different chemical classifications (cable types). The data has been separated into these three classifications in order to reduce the uncertainty of the results as indicated by the standard deviations. However, because the number of tests is so low, the data was not separated according to the different cable tray arrangements.

In any case it is clear that there is a large spread of data insofar as modal lifetimes for cable types is concerned. This indicates that fires of the same fuel configurations and chemical composition grown and recede in a non-reproducible manner. Nevertheless, the activation of certain burn modes provides valuable information for understanding and controlling critical burn modes that initiate fire growth, and this is addressed in the next section of this report.

TABLE 3

Summary of Modal Life Fractions From Cable
Fire Test Data

Pre-IEEE-383 Cables

BURN MODES

Test	Pyrolysis		Smoldering		Deep Seated Fire		Fire Ball		Surface Fire		Interior Gas Combustion		Deflagration		Flashover		Total
Cycle	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	
51D	.15	.10	.13	----	----	.025	----	----	.41	.19	----	----	----	----	----	----	1.0
51A	.29	.076	----	.038	.13	----	----	----	.24	.16	.063	----	----	----	----	----	1.0
53D	.29	.089	----	.036	----	.13	----	----	.32	.14	----	----	----	----	----	----	1.0
13D	.21	.026	----	----	.13	.11	----	----	.32	.21	----	----	----	----	----	----	1.0
21D	.13	.075	.15	.038	----	----	----	.057	.42	.15	----	----	----	----	----	----	1.0
21A	.24	.043	----	.065	.087	----	----	.11	.28	.043	.13	----	----	----	----	----	1.0
53A	.30	.11	.14	.11	----	----	----	----	.20	.14	----	----	----	----	----	----	1.0
49A	.35	.046	----	----	.12	.070	----	----	.23	.12	----	----	----	----	----	.067	1.0
49D	.23	.058	.10	----	----	.029	----	----	.19	.38	----	.014	----	----	----	----	1.0
Active Mode Average	.24	.069	.13	.057	.12	.073	----	.084	.29	.17	.097	.014	----	----	----	.067	
σ	.072	.028	.021	.032	.021	.047	----	.027	.085	.092	.034	0.	----	----	----	0.	

Cycles C and H refer to cooling and heating cycles, respectively
Test numbers with D and A pertain to donor and acceptor trays, respectively
The symbol σ refers to the standard deviation

IV. BURN MODE DESCRIPTION OF FIRE GROWTH

Burn modes describe local reactions in the vicinity of the thermocouples. They do not, by themselves, describe fire growth. Such growth can only be described by the interaction of physically separated burn modes.

We propose to extend the current NFPA classification of fire growth stages (realms) from building fires to cable fires, by correlating heat release rate and ceiling temperature signatures with burn mode signatures.

A preliminary burn mode classification of fire growth phenomena is given in Table 4. The potential value of such a classification is illustrated by applying it to selected two-stack-tray fires. The results are given in Figures 15 and 16. Both figures clearly show recession followed by growth and recession of cable fires. They also demonstrate that the duration of individual fire growth stages (realms) and the sequence of such stages is dominated by plant-specific, special effects such as use of fire retardant coatings and the proximity of a corner. Clearly, fire growth history is very fire-zone and fuel-specific, although the underlying burn mode classification is not.

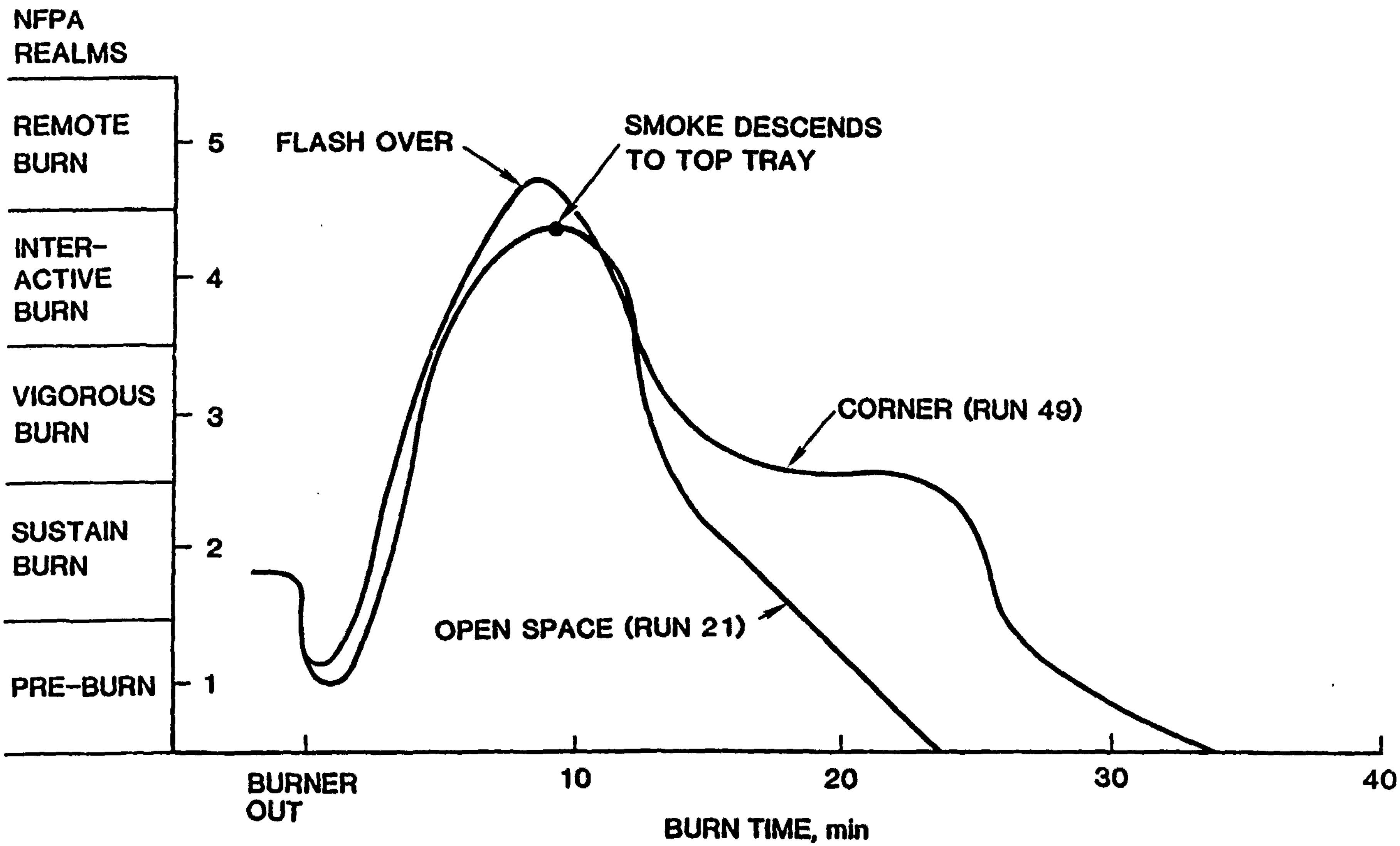


Figure 15. Fire Histories of Two-Tray Stacks, Pre 383 Cables

TABLE 3 (Continued)

Summary of Modal Life Fractions From Cable Fire Test Data

IEEE-383 Cables

BURN MODES

Test	Pyrolysis		Smoldering		Deep Seated Fire		Fire Ball		Surface Fire		Interior Gas Combustion		Deflagration		Flashover		Total
Cycle	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	
9D	.22	.027	.22	.14	----	----	----	----	.19	.22	----	----	----	----	----	----	1.0
50A	.24	.059	----	.078	.25	----	----	----	.24	.14	----	----	----	----	----	----	1.0
50D	.10	.23	----	.025	.17	----	----	----	.35	.12	----	----	----	----	----	----	1.0
20D	.10	.050	----	.10	.33	----	----	.025	.25	.15	----	----	----	----	----	----	1.0
20A	.13	.13	.066	----	----	.20	----	----	.13	.33	----	----	----	----	----	----	1.0
48A	.10	.19	----	----	.21	.10	----	----	.14	.26	----	----	----	----	----	----	1.0
48D	.079	----	.18	----	----	.29	.21	.10	----	.032	----	.13	----	----	----	----	1.0
Active Mode Average	.14	.11	.16	.086	.24	.20	.21	.063	.22	.18	----	.13	----	----	----	----	
σ	.065	.083	.080	.0023	.068	.095	0.0	.038	.082	.079	----	0.0	----	----	----	----	

TABLE 3 (Continued)

Summary of Modal Life Fractions From Cable Fire Test Data

"C" Coated IEEE-383 Cables

BURN MODES

Test	Pyrolysis		Smoldering		Deep Seated Fire		Fire Ball		Surface Fire		Interior Gas Combustion		Deflagration		Flashover		Total
Cycle	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	
2D	.097	.18	.17	.15	.21	----	.024	.11	.061	----	----	----	----	----	----	----	1.0
35D	.27	.20	.21	.11	----	----	.12	----	----	.078	----	----	----	----	----	----	1.0
17D	.36	.014	----	.067	.32	----	----	----	.11	.12	----	----	----	----	----	----	1.0
17A	.11	.21	.079	----	.11	.49	----	----	----	----	----	----	----	----	----	----	1.0
Active Mode Average	.21	.15	.15	.11	.21	.49	.072	.11	.086	.099	----	----	----	----	----	----	
σ	.13	.092	.067	.042	.11	0.0	.048	0.0	.025	.021	----	----	----	----	----	----	

Cycles C and H refer to cooling and heating cycles, respectively
Test numbers with D or A suffix pertain to donor and acceptor trays, respectively
The symbol σ refers to the standard deviation

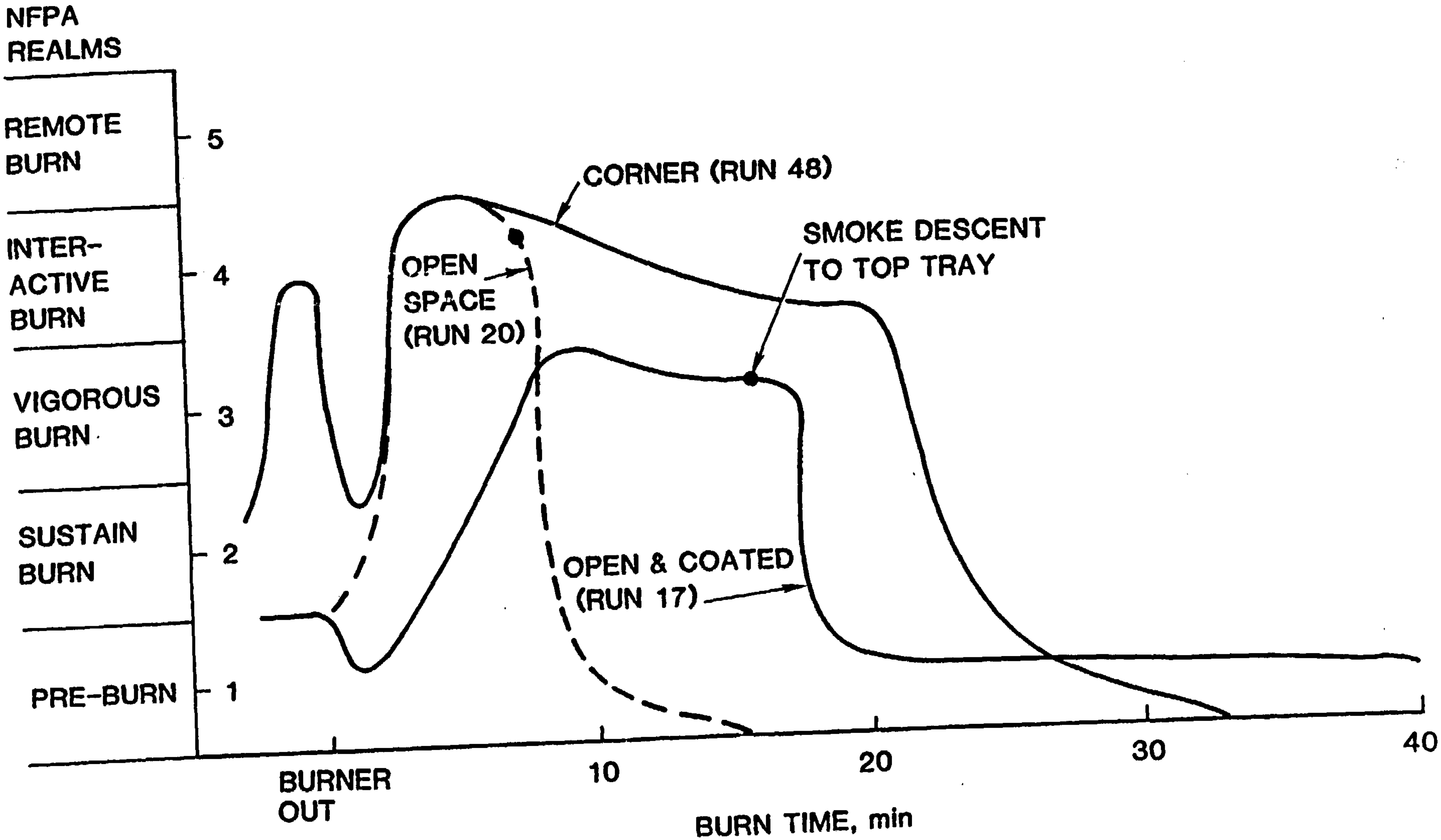


Figure 16. Fire Histories of Two-Tray Stacks, IEEE-383 Cables

TABLE 4

Match of Electrical Cable and Building Fire Phenomena

NFPA Definition		Extension to Cable Fires
Realm	Name	
1	Preburning	Fuel decomposition in the absence of a surface fire by any one of the following reactions: Pyrolysis, smoldering, deep-seated fire, interior gas combustion.
2	Sustained Burning	Single external reaction (surface fire or fire ball) with decomposition linked to one fuel package.
3	Vigorous Burning	Single external reaction with multiple fuel package decomposition.
4	Interactive Burning	Multiple external reactions with ambient temperature below upper autoignition threshold.
5	Remote Burning	Multiple external reaction with ambient temperature above upper autoignition threshold.

In spite of the uncertainty of the overall fire growth cycle, some common aspects of fire growth might exist for building and cable tray fires. We hypothesize that the following generic aspects dominate the observed fire growth cycles:

- Fire recession is caused by descending smoke.
- Fire growth is caused by readmission of fresh air to deep-seated fires.

Based on this hypothesis, Figures 15 and 16 provide the following insight into cable fire growth.

Pre-383 cables develop smoke rapidly and the smoke is trapped under the upper tray barrier at the time the burner is shut off. The trapped smoke blocks the oxygen supply and makes fires on both the upper and lower trays recede or become deep-seated. The rate of smoke release is then diminished such that updraft from the hot fuel suffices to clear the trapped smoke. The associated readmission of fresh air ignites intense surface fires and smoke release rates are increased enough to repeat the cycle.

In the center of the burn room, smoke descends sufficiently fast to prevent development of self-sustained fires (Run 21). Readmission of fresh air does not reignite surface fires in the absence of deep-seated fires. In the corner test smoke is trapped and hovers near the acceptor tray surface, and small flames (Run 49) flicker on and off according to short repetition of the smoke descent and readmission cycle until the deep-seated fire is terminated by the overall cooling of the acceptor tray.

IEEE qualified cables behave differently, as shown in Figure 16. The open ladder tray in the center of a room (Run 20) shows the same recession/growth/recession as the equivalent pre-383 cable (Run 21). However, when the stack is placed in a corner (Run 48) the use of flame retardant materials combined with a heavy smoke release is sufficient to prevent a surface fire, and the burner generates instead a deep-seated fire. This fire reignites as soon as the burner exhaust no longer blocks the updraft of fresh air. The associated surface fire is maintained by the deep-seated fire until the deep-seated fire is terminated by tray cooling. Cooling periods are very similar for 383 (Run 48) and pre-383 (Run 49), as both deep-seated fires terminate approximately 25 minutes after burner shutdown.

Coated cable in the open ladder tray provides a dramatically different fire (Run 17 versus Run 20). Readmission of fresh air at burner shutdown does not immediately rekindle the deep-seated donor fire. The deep-seated fire has to burn for another 3 minutes before flames develop above the donor tray. The subsequent donor fire releases smoke at a lower rate, such that little smoke is trapped temporarily at the upper barrier. A deep-seated fire develops in the upper tray only after the smoke blanket has descended from the ceiling to the tray. This fire does not ignite since the smoke blanket prevents the readmission of fresh air. The donor fire is terminated 2 minutes later by the still descending smoke. However, contrary to the uncoated tray, the deep-seated acceptor fire persists to the end of the run.

The above interpretations of Figures 15 and 16 illustrate how the observed variety of fire growth and recession can be explained by only two common factors namely, smoke descent and admission of fresh air. The above descriptions of possible events were deliberately designed to fit the observed facts to the hypothesis. Other explanations are conceivable and burn mode analysis of many more tests is needed to confirm or ammend the hypothesis.

The above hypothesis, based on the effects of smoke and fresh air on fire growth, can be used to design and evaluate fire confinement and fire suppression requirements including the role of ventilation systems, if substantiated by experiments. A fire protection strategy could be to prohibit the development of deep-seated fires that last one minute or longer. Fire growth would then be prevented in all electrical equipment configurations that meet Regulatory Guide 1.75 requirements for physical separation.

Some additional evidence is already available from post-test observation of char formation and from current unpublished fire suppression tests. Figures 15 and 16 indicate that the rate of smoke development is highest in pre-383 cables, somewhat lower in 383 qualified cables, and considerably lower in coated cables. It is reasonable to expect that the diminished rate of smoke release manifests itself in a higher rate of char formation. Pre-383 cables should then show the least amount of char on the burned section of cable trays. IEEE-383 cable should show somewhat more and coated cables should show much more char. This is confirmed by all post-fire cable tray inspections.

Evidence from Figure 3 and Figure 16 also shows that deep-seated fires, which are due to the descending smoke blanket, last much longer than deep-seated fires that are generated by temporary fire ball touchdown. The duration of a deep-seated fire is related to the area and the duration of burned gas exposure. This is demonstrated by the Halon cable tray fire suppression tests in which a strong deep-seated fire was generated by holding the descending smoke blanket at the top of the acceptor tray.(18) This deep-seated fire grew into the strongest surface fire ever observed as soon as fresh air was readmitted after 10 minutes. A 4 minute soak with 6% Halon 1301 was not sufficient to terminate this fire. A ten minute Halon soak was required to prevent reignition upon fresh air admission. The suppression tests provide additional evidence that cable fire propagation can be started by readmission of air to deep-seated fires and that deep-seated fires are sustained by a hovering layer of burned gas.

V. SUMMARY AND CONCLUSIONS

Quantitative temperature records from 21 fire tests of horizontal cable trays were reduced to thermodynamically defined burn modes in order to develop a physical classification of fire phenomena which meets NRC Regulatory Guide 1.170 requirements for fire hazards analysis. This data base is neither statistically significant nor extensive enough to cover the wide range of architecture, ventilation, and fire protection design parameters encountered in LWR plants. The tests do, however, provide important insight as to how a suitable classification of fire phenomena might be developed, especially for electrical cables.

Burn modes describe local volatilization and combustion reactions which have been observed in many porous fuel and flammable liquid fires. A preliminary classification method was developed which identifies such reactions using only the time history of fuel internal and surface temperatures.

The classification of raw data records from 21 special effects cable fire tests into data segments, which reflect one burn mode each, confirmed flame aspects of the generic burn mode reactions with independent observations of flames and post-test inspection of charred surfaces. There was good correlation between the phenomena indicated by burn mode analysis with flame and char observations from tests for which TV films were available. These tests covered three different types of fire retardant materials, two different cable combinations and four different tray stack geometries as well as a full scale 17 tray replication of an LWR fire zone. This partial verification of burn modes encourages us to think that our preliminary test record classifications might indeed give generic descriptions of fire phenomena that are applicable for a wider range of architectural fire zone parameters as well as for a wider range of ventilation and fire suppression system operations. Further verification of the generic nature of burn modes is warranted.

The following conclusions are tentative, since they are based on the 21 test data base which is considered meager as mentioned above. They are nevertheless given to illustrate the insight which burn mode analysis can provide for confirmation or modification of fire protection requirements.

1. The cable fire burn modes reflect volatilization reactions and oxygen consumption modes, that have been observed previously in full scale compartment fire tests. This commonality should provide a

technical basis for confirming or modifying principles of industrial fire prevention and control for LWR plants.

2. Duration of burn modes and transitions between burn modes depend on fuel chemistry, fuel arrangement and smoke descent. A reproducible simulation of entire fire life cycles is unlikely since many different patterns of fire growth and recession can develop from the same fuel configuration once the fuel is volatized.

3. Burn mode analysis provides a new physical definition of deep-seated fires that allows monitoring on-line. The screening method of this paper illustrates the principles for such monitoring, and also reveals that both propagation and reignition of cable fires are frequently preceded by a deep-seated fire in excess of 1 minute duration. The temperature criteria for deep-seated fires thus represent a direct indicator of fire growth potential that has been derived from a cable fire replication test and 21 associated special effects tests.

4. Burn mode analysis of fire confinement and fire suppression verification tests is needed to confirm that prevention of deep-seated fires will prevent fire propagation between fuel elements that meet Regulatory Guide 1.75 separation requirements. With this information NRC fire protection requirements could possibly be verified in special effects tests without replicating full-scale LWR fire zones and/or protection system operations.

5. Deep-seated fires were generated in the electrical cable tests by a hovering layer of burned gas. In horizontal cable trays such hovering was caused by a descending fire ball and/or by a descending smoke blanket. Consideration should thus be given to inspecting existing porous fuel arrangements for previously unknown fire propagation hazards associated with trapping of burned gas.

6. The use of fire retardant materials (IEEE-383 cable qualifications, cable tray coatings) tend to increase the duration of deep-seated cable fires. A reasonable doubt thus exists that industrial experience with IEEE cable qualification and fire retardant coatings applies fully to multiple cable tray arrangements.

The use of fire retardant materials does significantly reduce the probability of self-sustained surface fires, but associated longer-lasting deep-seated fires might increase the probability of propagating surface fires once started.

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VII. APPENDIX A

Notes On Fire Test Data

Thermocouple placements for single tray tests are shown in Figure A1. In the case of two tray tests the acceptor tray has the same instrumentation as shown for the donor tray. The observed interior cable bundle temperatures were interpolated to the position of the stack center line by averaging the corresponding thermocouple readings on each side of the center line.

List of Fire Tests From Which Data Were Taken

IEEE-383 QUALIFIED CABLES

Open Ladder Trays: Tests 9, 20
Shielded Trays: Tests 24, 37, 38
Corner/Open Trays: Tests 48, 50, 52

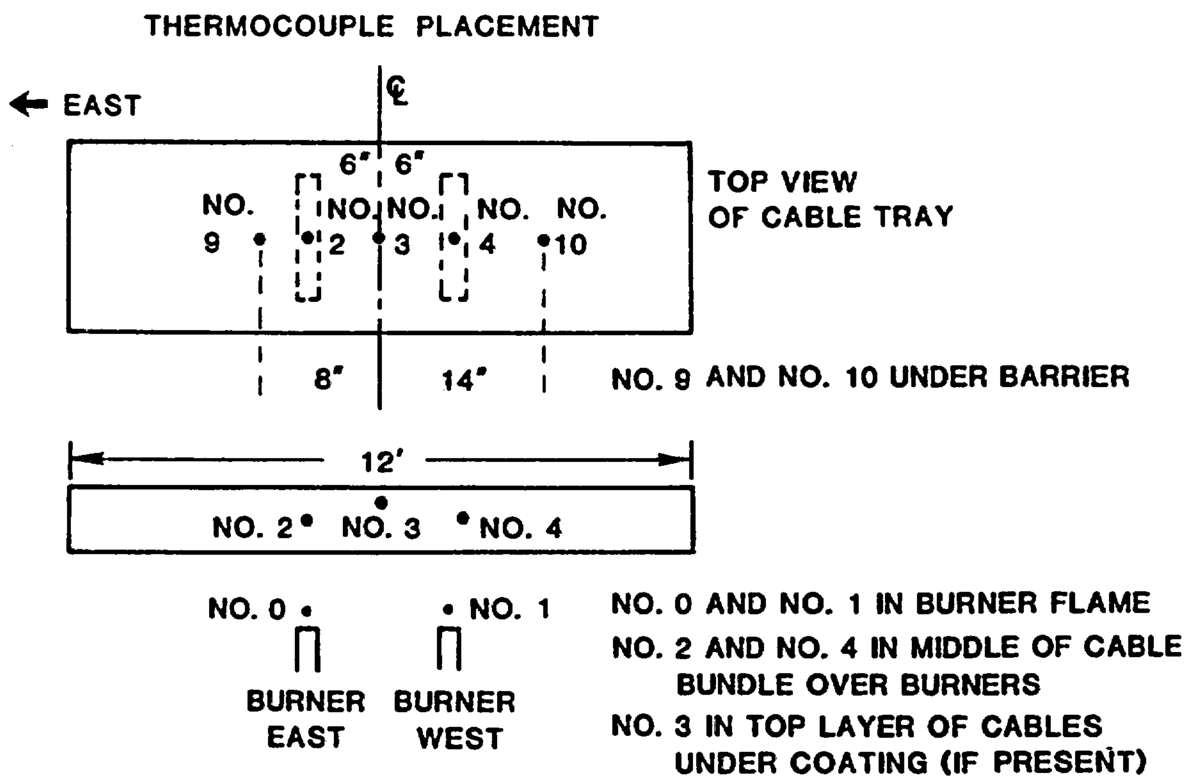
PRE-383 CABLES

Open Ladder Trays: Tests 13, 21
Corner/Open Trays: Tests 49, 51, 53

COATED, OPEN LADDER TRAYS

Cables with Coating C: Tests 2, 17, 35
Cables with Coating G: Tests 27, 29

IEEE 383 qualified cables have crosslinked polyethylene insulation and jackets. Pre-383 cables had linear polyethylene insulation with PVC jackets. Coated cables refer to crosslinked polyethylene insulation and jackets plus fire retardant coatings of 1/8 inch (3.2 mm). The bottom trays were filled with a three conductor cable of 1300 feet length, and the acceptor trays were filled with one conductor cable of 6800 feet length. The inside dimensions of the cable tray were 12' x 18" x 4". Loaded trays weighed between 190 and 220 pounds. The weight of an empty tray is 20 pounds.



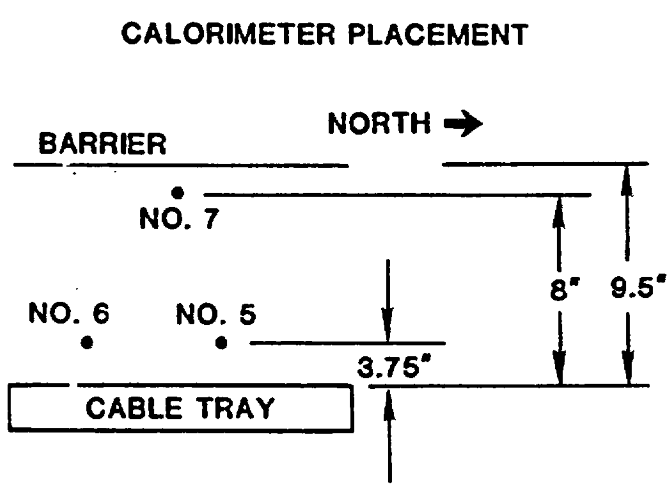


Figure A1. Thermocouple and Calorimeter Placement for Single-Tray Tests

Figures A2 and A3 show representative fire test data histories. Burner shutdown is indicated by a descending exposure fire temperature. The start of test time has been arbitrarily defined as the time when the burner temperature crosses the 900°F level from above. An electrical short is considered to exist when the current to ground exceeds 100 milliAmpere. Burn room temperature profiles as a function of distance from the ceiling are illustrated in Figure A4 for test 20. The extent of the burned gas layer can be inferred from a two layer linear fit of the burn room temperature stratification as shown in Figure A5 for $t = 13$ min, the time of maximum ceiling temperature.

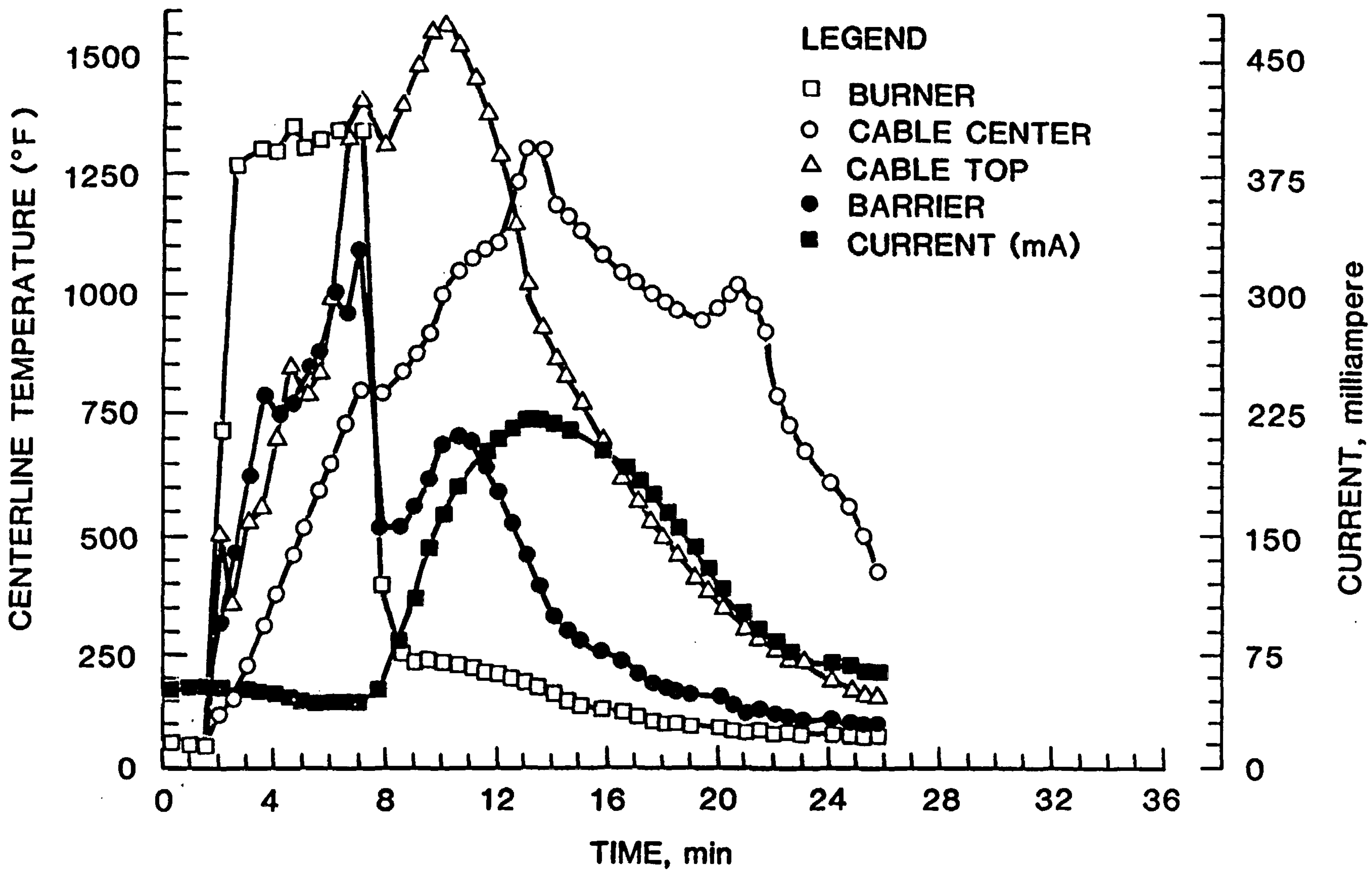


Figure A2. Test Data Histories, Donor Tray, Test 20

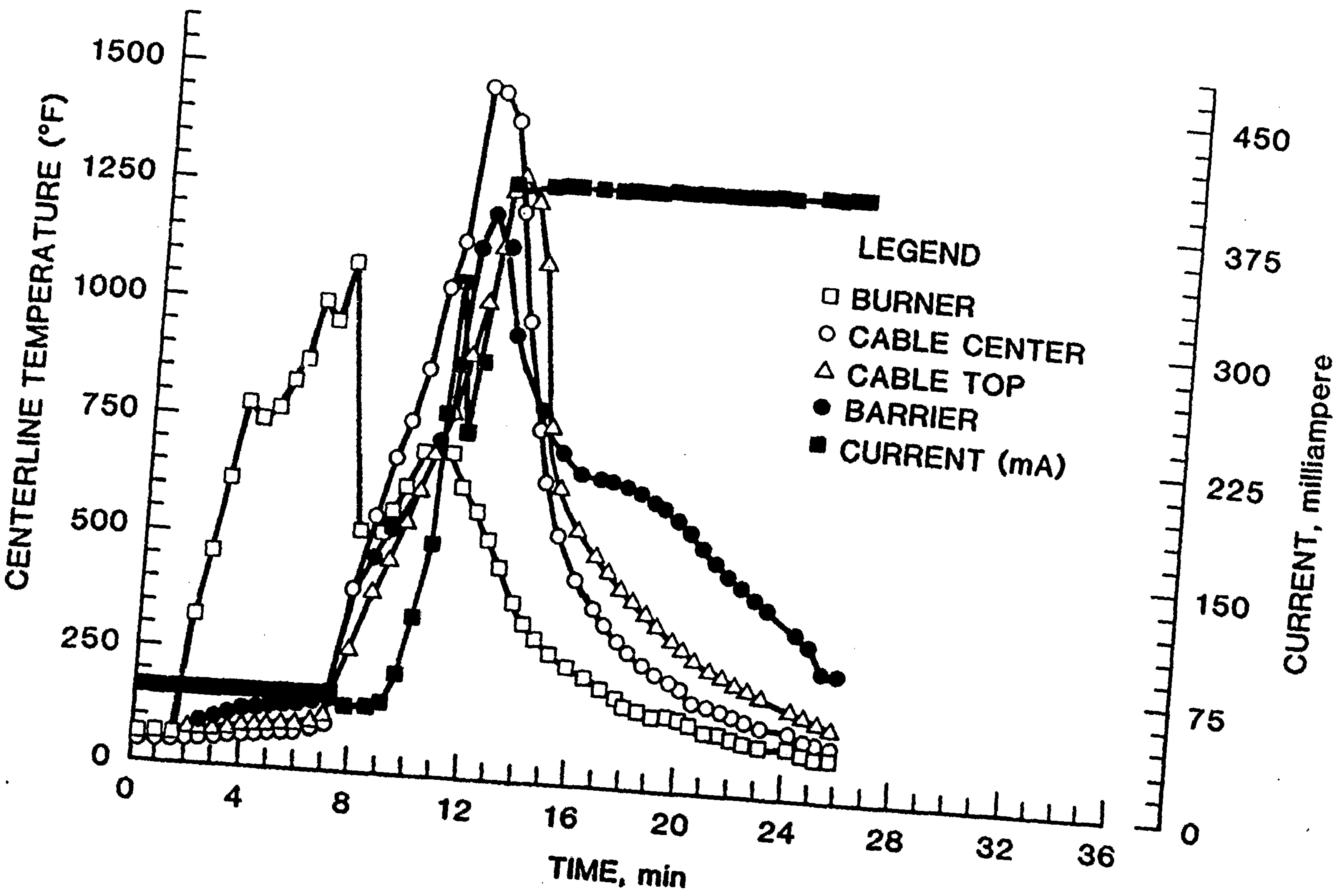


Figure A3. Test Data Histories, Acceptor Tray, Test 20

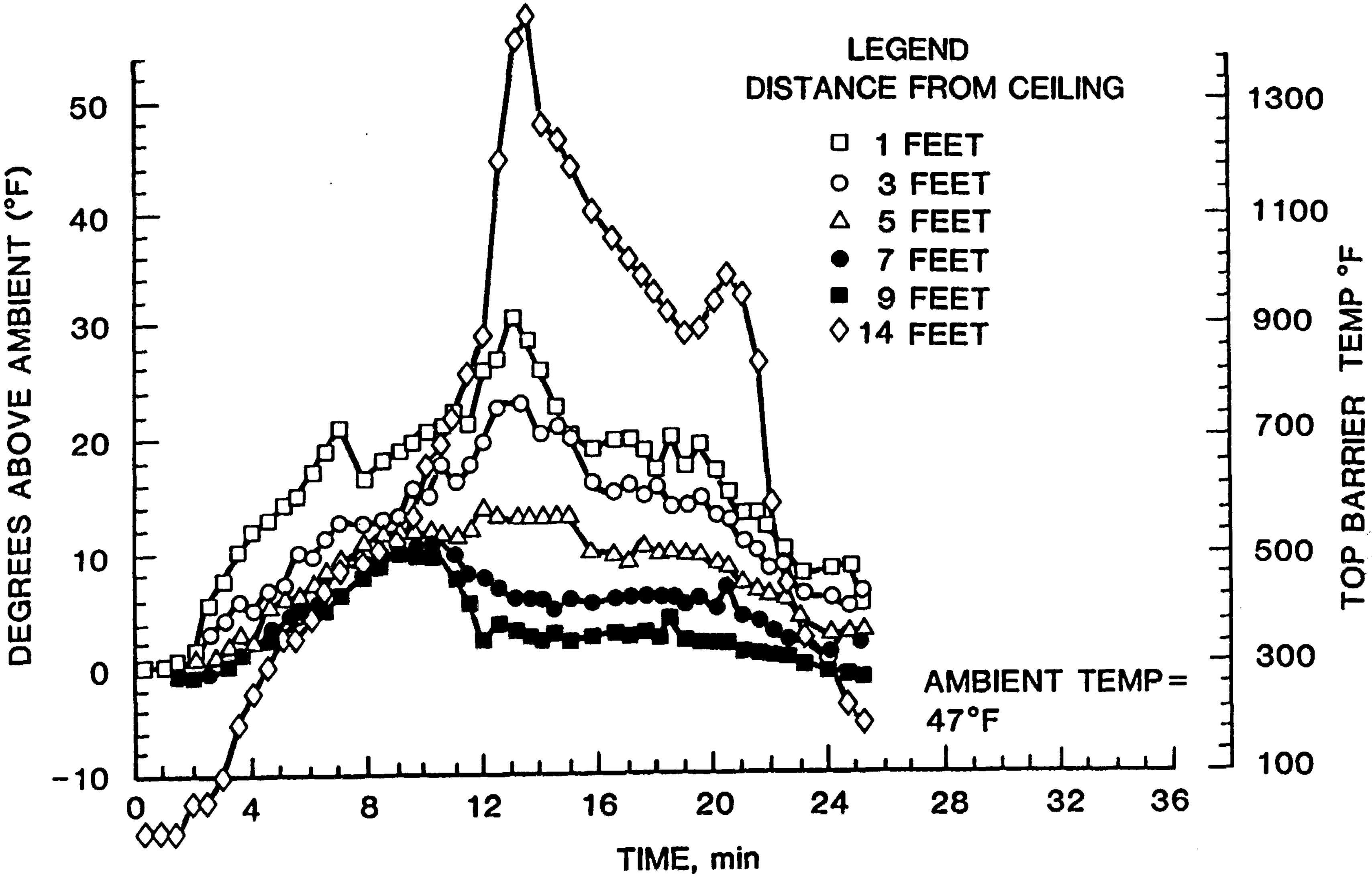


Figure A4. Burn Room Temperature Histories, Test 20

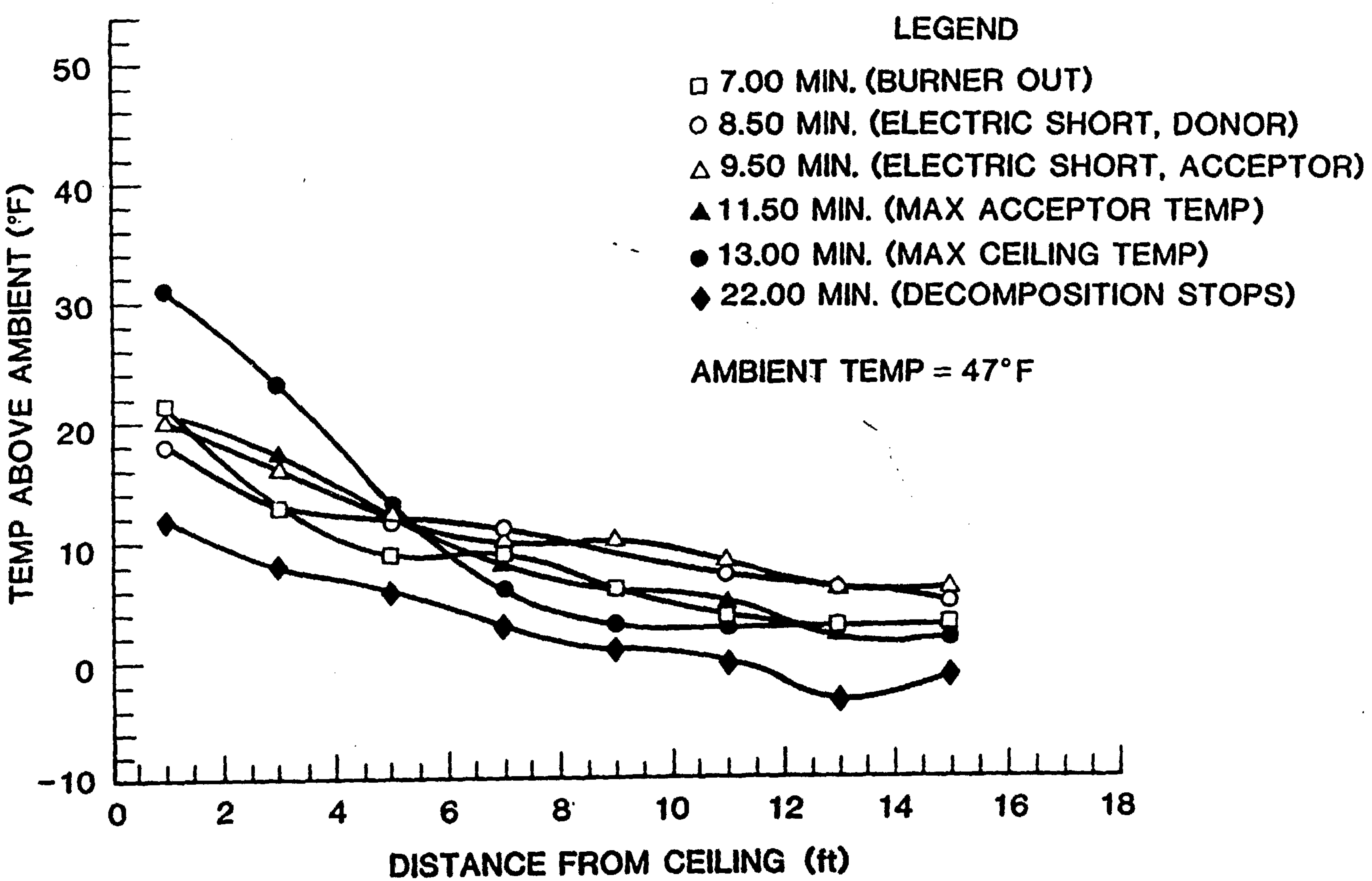


Figure A5. Burn Room Temperatures vs. Distance from Ceiling, Test 20

VIII. APPENDIX B

Burn Room Geometry

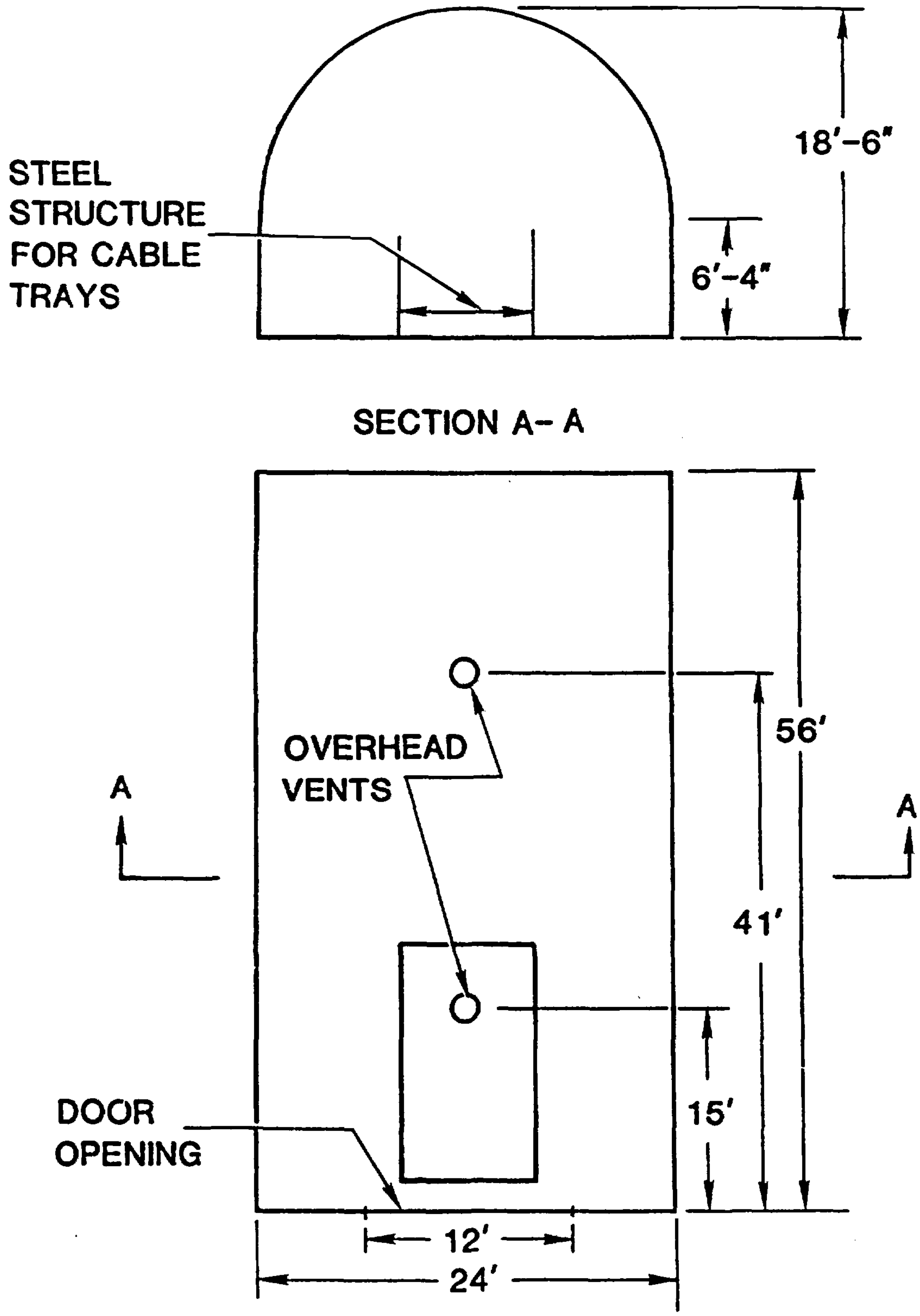


Figure B1. Burn Room Geometry, Sandia Fire Research Facility

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