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Evaluation of Suppression Methods for Electrical Cable Fires

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EVALUATION OF SUPPRESSION METHODS FOR ELECTRICAL CABLE FIRES

J. M. Chavez and L. D. Lambert

October 1986

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for the
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ABSTRACT

The electrical cable fire suppression tests conducted at Sandia National Laboratories were performed to provide confirmatory research for the U.S. Nuclear Regulatory Commission (NRC) on suppression systems effectiveness. This report describes full-scale tests on both horizontally and vertically oriented cable trays, filled with either IEEE-383 qualified cables or unqualified cables, to determine the effectiveness of Halon 1301, water sprinklers, directed water spray, and carbon dioxide fire suppression systems. These four methods of fire suppression were evaluated to determine their effectiveness in suppressing both exposure type and fully developed type cable tray fires. The results show that although all methods of suppression were effective, given sufficient suppressant concentrations, spray durations, and soak times, the water suppression methods were the most effective. Despite their effectiveness in suppressing cable fires, it was observed that both gaseous and water suppressants may cause or permit damage to nonburning cables and equipment. The adverse environments associated with the fire and suppression related activities (e.g., high temperatures, humidity, corrosiveness) could damage cables and equipment and result in immediate or latent damage. Occurrence or likelihood of these failures was not investigated in this test series.

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EXECUTIVE SUMMARY

This report, prepared for the Division of Engineering Technology, U.S. Nuclear Regulatory Commission, provides confirmatory data on fire suppression research. Since the Brown's Ferry fire in 1975, regulatory policy has resulted in what has been called a "defense in depth" approach for nuclear power plant fire protection. This policy has required the use of numerous measures to prevent and control fires, including requirements for automatic suppression.

Thirty-seven full-scale cable tray fire tests were conducted at Sandia National Laboratories to provide confirmatory data on suppression systems. The primary objectives of the testing were to determine the minimum "soak" time (length of time in which no air is exchanged in the room) and/or spray durations necessary to prevent reignition of cable tray fires. The following four (4) suppression systems were evaluated (the codes are National Fire Protection Association (NFPA) standards).

1. Halon 1301 (NFPA-12A)
2. Water Sprinklers (NFPA-13)
3. Directed Water Spray (NFPA-15)
4. Carbon Dioxide (NFPA-12)

In addition to the information on minimum soak times and/or spray duration, the suppression systems were also evaluated for their ability to cool the cables in a cable tray and to cool the room environment.

The test conditions were varied in each of the tests to investigate their effect on the performance of the suppression systems. The conditions varied in the testing were those that appeared to have the most pronounced change on the test, and included:

Cable Type--two types of cable, IEEE-383 qualified cable (XPE/XPE insulation) and unqualified cable (PE/PVC insulation).

Cable Tray Orientations--two orientations, cable trays oriented horizontally or vertically.

Fire Size--two fire sizes, an exposure fire (two cable trays) and fully developed fires (five cable trays).

Instrumentation and measurements included temperature measurements of the enclosure and exhaust temperatures as well as tray and cable temperatures. Also, the concentration of fire gases was monitored with a gas analysis system in each test to determine the concentration levels of the suppression gases and of unburned hydrocarbons.

Results and conclusions pertaining to the extinguishing abilities of the four systems were:

1. All suppression systems were capable of extinguishing cable tray fires. (Soak times are shown in Table 1.)

2. Directed water spray suppression (NFPA-15) was the most effective in extinguishing and preventing reignition of the fires, for all fire sizes, cable types, and tray configurations tested.

3. Water sprinklers (NFPA-13) worked well on the vertical tray configuration, but due to blockage effects by the upper trays in the horizontal configuration, a longer sprinkler duration was necessary to suppress a fire.

4. Both Halon 1301 and carbon dioxide suppression systems worked well in extinguishing all tray configurations and cable types tested with the specified concentrations; 6 percent for Halon 1301 and 50 percent for carbon dioxide, given an adequate soak time. The soak times were approximately the same length.

5. The water sprinklers and directed water spray systems were most effective in cooling the cable surfaces. Halon 1301 and CO_2 also resulted in steady cable temperature decreases after suppression actuation, although at a slower rate.

For the gaseous suppression systems, the key to suppressing the fires was to maintain the specified concentration for the required soak times. For the water systems, a sufficiently long sprinkler or spray time was needed. The directed water spray system was by far the most effective in suppressing the fully developed cable tray fires.

The focus of these tests was on the suppression systems' capabilities in suppressing fires and preventing reignition of the fire. However, in spite of the fact that all types of suppression were found to be effective in suppressing large cable tray fires, the adverse environments associated with fires and suppression activities (e.g., high temperatures, humidity, corrosiveness) could adversely affect nonburning cables and equipment and result in immediate or latent damage. Occurrence or likelihood of these failures was not investigated in this test series.

Table 1

Minimum Soak Time[A] Required to Suppress Fully Developed Cable Tray Fires

Cable Type	Tray Configuration	Type of Suppressant: Halon (6%) NFPA-12A	Water Sprinklers NFPA-13	Water Spray NFPA-15	Carbon Dioxide NFPA-12
IEEE-383 Qualified	Horizontal	15 min	5 min	5 min[B]	15 min
	Vertical	15 min	5 min	5 min[B]	15 min
Un-Qualified	Horizontal	10 min	5 min	5 min[B]	10 min
	Vertical	10 min	5 min	5 min	10 min

Notes:

[A]Length of time the ventilation system was turned off and the exhaust vent was closed.

[B]This is the spray time required during the tests. These tests were performed with the ventilation systems on, thus there was no soak time.

1. INTRODUCTION

1.1 Background

Sandia National Laboratories, Albuquerque (SNLA) has been conducting fire protection research for the U.S. Nuclear Regulatory Commission (NRC) since early 1975. The program was in fact underway before the fire at the Brown's Ferry nuclear power plant, which occurred on March 22, 1975. The original objective was to provide experimental and analytical information to evaluate the adequacy of NRC rules and regulatory guides. All evaluations were to involve the testing of equipment and cable configurations representative of those in operating nuclear power plants. A majority of this work is discussed by Dube.[1]

As a result of the findings of previous test programs, the Sandia Fire Protection Research Program was extended to include the investigation of the effectiveness of fire suppression systems on electrical cable fires. Electrical cables constitute a serious fire threat for nuclear power plants because the jacket and electrical insulation material from numerous control and power cables are combustible. This report describes and presents the results of 37 electrical cable fire suppression tests conducted at the Sandia Fire Research Facility. Fire suppression systems using Halon 1301, water sprinklers, directed water sprays, and carbon dioxide were tested and evaluated for their ability to suppress cable tray fires and prevent reignition of the fire. Twenty-one of these tests were previously reported on in a general overview of the Fire Protection Research Program.[1]

1.2 Previous Work

A literature search has revealed that there has been only a limited amount of testing of suppression system abilities to suppress cable tray fires. However, there have been a number of test programs to evaluate the effectiveness of various suppression systems on other types of fires, primarily fires with paper and room furnishing type materials as the combustibles. In general, these test results are not applicable to suppression of cable tray fires because of the type of material and the size of the fires.

However, one test program performed by Factory Mutual Research Corporation (FMRC) for the Electric Power Research Institute (EPRI),[2] investigated the ability of water sprinkler systems to suppress large cable tray fires. The tests investigated the effects of suppression on up to 15 cable trays in a mixed, horizontal-vertical array, with

different types of cables (IEEE-383 qualified and unqualified) and with different loading methods. All the fires were ignited with 9.1 to 22.7 liters (2 to 5 gallons) of heptane. The relevant conclusions from this test program were:

1. Water sprinklers at the lowest tested "delivered density" of 0.11 $\ell/s \cdot m^2$ (0.16 gpm/ft^2) were sufficient to extinguish all cable tray fires.

2. The higher "delivered density" of 0.31 $\ell/s \cdot m^2$ (0.45 gpm/ft^2) resulted in shorter extinguishment times.

3. Water easily penetrated down through six horizontal layers of trays to the bottom tray.

4. Vertical cable trays may prevent water from reaching horizontal or other vertical cable trays.

These tests were important in showing the effectiveness of water sprinkler systems on large cable tray fires. They are the only such tests on cable tray fires; however, they did not provide some important information on other types of suppression systems or the cooling of the room environment and cables.

1.3 Objectives

The objective of the suppression tests was to determine the minimum soak time and/or spray duration necessary to suppress electrical cable tray fires and prevent reignition of the fire using the following suppression systems and agents:

1. Halon 1301 following NFPA-12A[3] standards;
2. Water; sprinkler systems following NFPA-13,[4] and directed water spray systems following NFPA-15;[5]
3. Carbon d'oxide (CO_2) following NFPA-12[6] standards.

The suppression systems were tested on two fire sizes using electrical cable and tray configurations typical of those found in nuclear power plants.

Soak time is the length of time the ventilation system was turned off and the exhaust vent closed so that no air was exchanged in the room. Spray duration only applies to the water systems; it is the duration of the water sprinkler or nozzle spray--and in some tests may also be combined with a soak time.

1.4 Test Variables

As with all other large test programs there are a number of variables that need to be investigated. Test variables for

the suppression tests that were investigated included the following:

- 2 cable tray orientations
- 2 cable types
- 4 methods of suppression
- 2 fire sizes

Investigating the effects of these variables resulted in 37 tests. The test parameters will be discussed in the following section.

2. TEST METHODOLOGY AND PROCEDURES

2.1 Test Facility and Instrumentation

The Sandia Fire Test Facility is located at Sandia National Laboratories in Albuquerque, NM. In one end of the building is the test chamber itself, while the other end comprises the instrumentation and storage room. The specific physical characteristics of the test facility are as follows: (1) The enclosed volume of the test enclosure is 272 m^3 (9624 ft^3); (2) A ventilation system with six exit ports along each wall near the floor simulates the normal air ventilation and circulation that would be found in a nuclear power plant cable-spreading room. The system was operated during the tests at a ventilation rate of 983 ℓ/s (2083 ft^3/minute), which represents an air exchange rate of approximately one exchange every 4.6 minutes; (3) The test enclosure vent is a 1.22-m (48-in) diameter hatch located in the ceiling, which is furnished with a cover that can be remotely operated to open or close during a test; and (4) A movable 2.4 by 3.0-m (8 by 10-ft) platform with a cable tray mounting fixture is located in the enclosure. A more detailed description of the facility is provided in Appendix A.

Those parameters measured during the cable fire suppression tests included: temperatures (cable, enclosure, and exhaust), heat fluxes, enclosure pressures, gas velocities, and gas concentrations. Instrumentation for acquiring the required data was provided by over 80 channels of data provided by thermocouples, calorimeters, pressure transducers, flow sensors, and gas analyzers. In addition, all tests were videotaped and photographed. Instrumentation output was scanned every 20 seconds by an Accurex Auto-Data Nine data logger and recorded on tape for later data reduction. Additional information on the instrumentation location and type is provided in Appendix A.

2.2 Electrical Cable Arrangement and Type

All cable trays in a power plant are not in a single orientation. However, in order to simplify the test configuration only two cable tray orientations were tested, vertical or horizontal, to assess the effectiveness of suppression systems on each cable tray orientation.

The trays used for both vertical and horizontal tests were 0.46 m (1.5 ft) wide and 3.7 m (12 ft) long, made of galvanized steel, and were the open-ladder type. Separation between trays in all tests was 0.28 m (10.5 in), as specified in Reg. Guide 1.75.

An example of the horizontal, two-tray configuration is shown in Figure 1. The bottom tray was designated the "donor" tray and was ignited by propane burners. The upper tray was designated the "acceptor" tray and, during the ignition phase, was separated from the donor tray by a marinite barrier. This is discussed more fully in Sections 2.4 and 2.5. Above the acceptor tray, an insulating barrier was placed to simulate the reradiative effects of a third tray. In the horizontal five-tray configuration, the marinite barrier and the reradiative insulating barrier were omitted and three loaded cable trays added.

The two-tray and five-tray vertical test configurations were identical to the horizontal configurations except that the long axes of the trays were oriented vertically. A photograph of the five-tray vertical configuration is shown in Figure 2.

Most plants contain both IEEE-383 qualified cable and unqualified cable. The composition of these two types of cables varies depending on the manufacturer and model; however, two cables, one IEEE-383 qualified, the other unqualified, that have been used in previous test programs, were used in the tests.[1] The loading of cables in the trays was based on inspection of actual cable tray loadings and pictures of cable spreading rooms in plants. Specifics of the cables used in the tests are described below.

The IEEE-383 qualified cable was three-conductor, No. 12 AWG, with 0.76-mm (30-mil) cross-linked polyethylene (XPE) insulation, silicon glass tape, and a 1.65-mm (65-mil) cross-linked polyethylene (XPE) jacket, rated at 600 V. This type of cable is designated as "Q" cable in some of the tables and hereafter will be called "qualified cable" in the text, charts, and other tables. The unqualified cable was a three-conductor, No. 12 AWG, with 20/10 polyethylene/polyvinylchloride (PE/PVC) insulation, and a 1.14-mm (45-mil) polyvinylchloride (PVC) jacket. The unqualified cable is designated as "UQ" cable in some of the tables and charts and hereafter will be called "unqualified cable" in the text, charts, and other tables.

Horizontal cable trays were loaded with a single continuous loop of cable laid in the cable tray in the form of a figure eight so that it simulated 90 strands of cable on the tray. The crossover point of the figure eight progressed up and down the tray to level-out the load. This loading pattern yielded a 25 percent fill by cross-sectional area of the cable trays and allowed maximum air passage through the

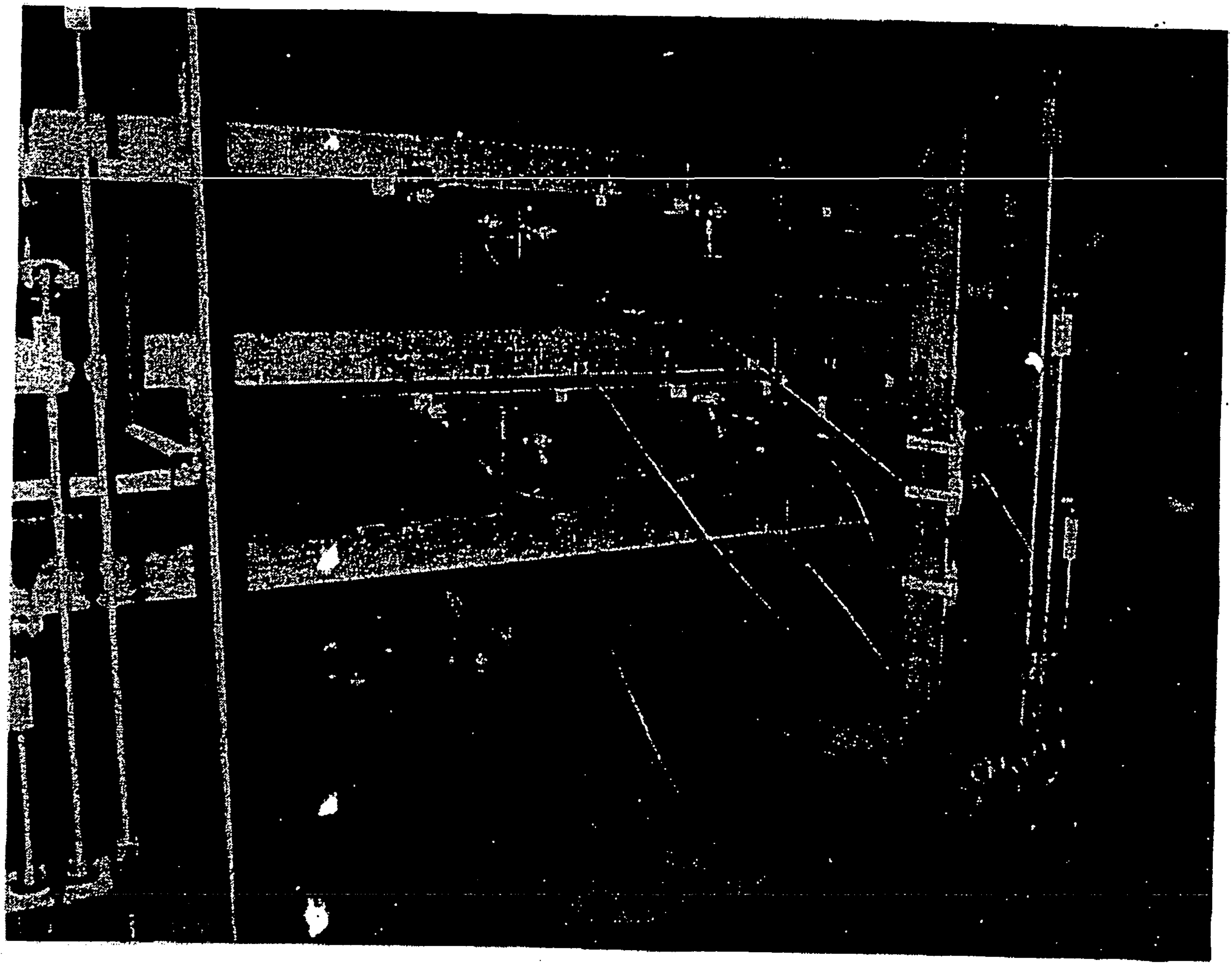


Figure 1. Photograph of the Horizontal Two-Tray Configuration

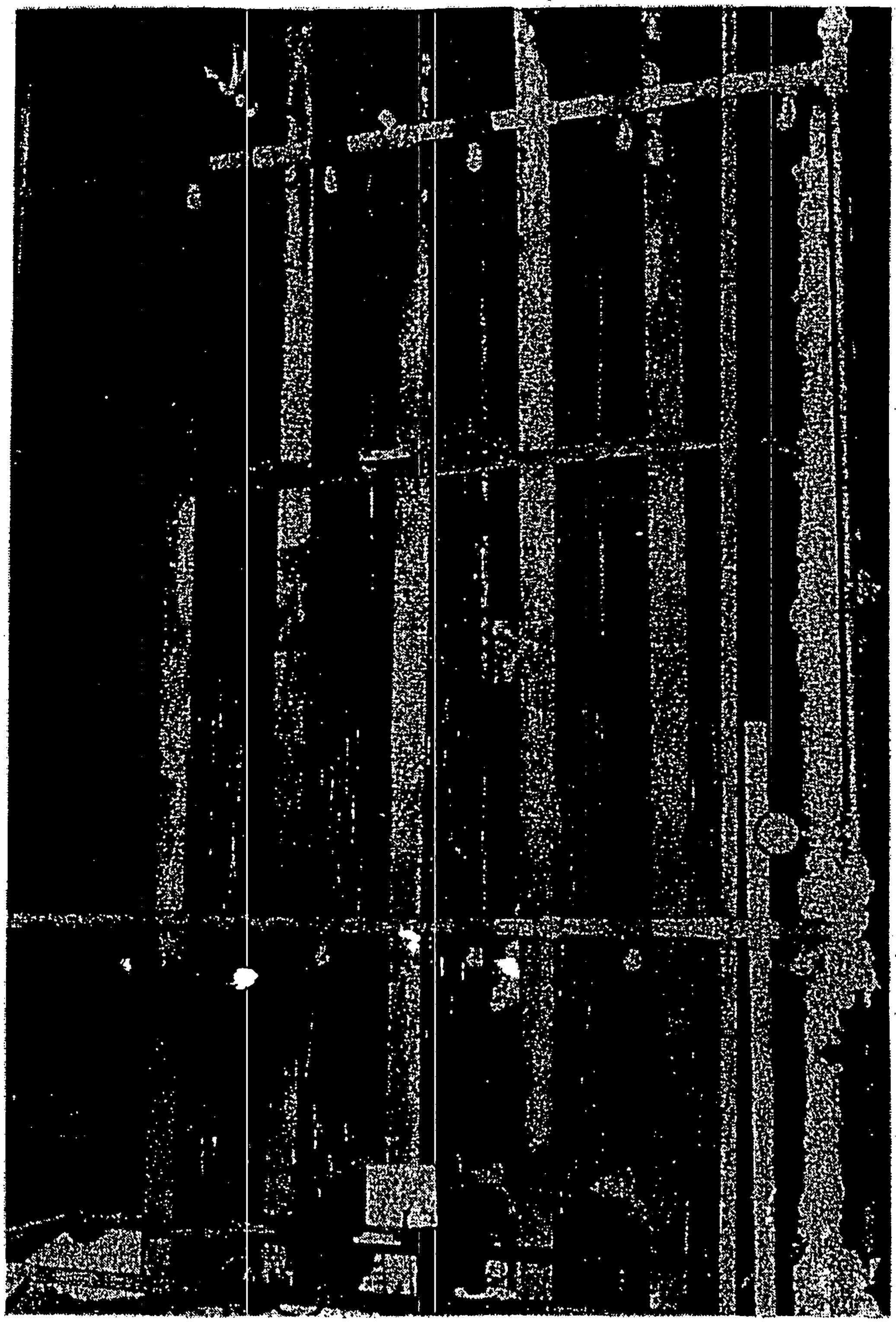


Figure 2. Photograph of the Vertical Five-Tray Configuration

cable tray. This is shown in more detail in Appendix A. The percent loading was representative of the fill found in nuclear power plants, and the method of loading represents a "worst case" method since it allows for maximum air passage. The cable fuel loading in the horizontal trays represented a total potential heat of combustion of approximately 4.18 x 10^6 KJ/tray (3.96 x 10^6 Btu/tray) for qualified cable and approximately 2.97 x 10^6 KJ/tray (2.81 x 10^6 Btu/tray) for the unqualified cable. Assuming that only 50 percent of the fuel would be consumed and a 50 percent combustion efficiency, a total heat release per tray of 1.05 x 10^6 KJ (9.91 x 10^5 Btu) for qualified cable and 7.41 x 10^5 KJ (7.02 x 10^5 Btu) for unqualified cable was expected in the horizontal cable tray fires.

Vertical cable trays were loaded with 13 bundles of cable, each bundle containing 8 cable strands. Seven bundles were placed next to the tray rungs, and the remaining six bundles outside the first seven bundles. This arrangement gave a 28 percent fill by cross-sectional area. Since there were 14 more strands of cable per tray in the vertical orientation vs. the horizontal orientation (because the cables were not looped in a figure eight pattern), the fuel loading was higher. The approximate heat of combustion for qualified cable and unqualified cable was 4.80 x 10^6 KJ/tray and 3.14 x 10^6 KJ/tray (4.55 x 10^6 Btu/tray and 2.98 x 10^6 Btu/tray) respectively. Again, assuming a 50 percent combustion efficiency and that approximately 50 percent of the fuel would be consumed, the expected heat release per tray is 1.20 x 10^6 KJ and 7.78 x 10^5 KJ (1.14 x 10^6 Btu and 7.46 x 10^5 Btu) for qualified and unqualified cables respectively.

2.3 Description of Suppression Systems

In this section suppression systems used in the tests will be briefly described. For a more detailed description of the systems, refer to Appendix B. A general arrangement drawing of the suppression systems showing locations of nozzles, cable trays, and the general layout of the room is shown in Figure 3.

The Halon 1301 suppression system was designed and manufactured to provide 6 percent to 25 percent volumetric room concentrations of Halon 1301 (chemical formula $CBrF_3$) and to comply with NFPA-12A.[3] The system consisted of the Halon storage tanks, associated piping, and two spray nozzles (nozzle diameter of 1.27-cm (1/2 inch)), located on opposite walls, 2.7 m (9 ft) above the burn room floor. The system required 92 kg (202 lb) of Halon 1301 to maintain a volumetric room concentration of 6 percent.

202# for 9624 ft³ is 0.0210# which is the flood factor for 155°F 6.2 n 5% @60°F

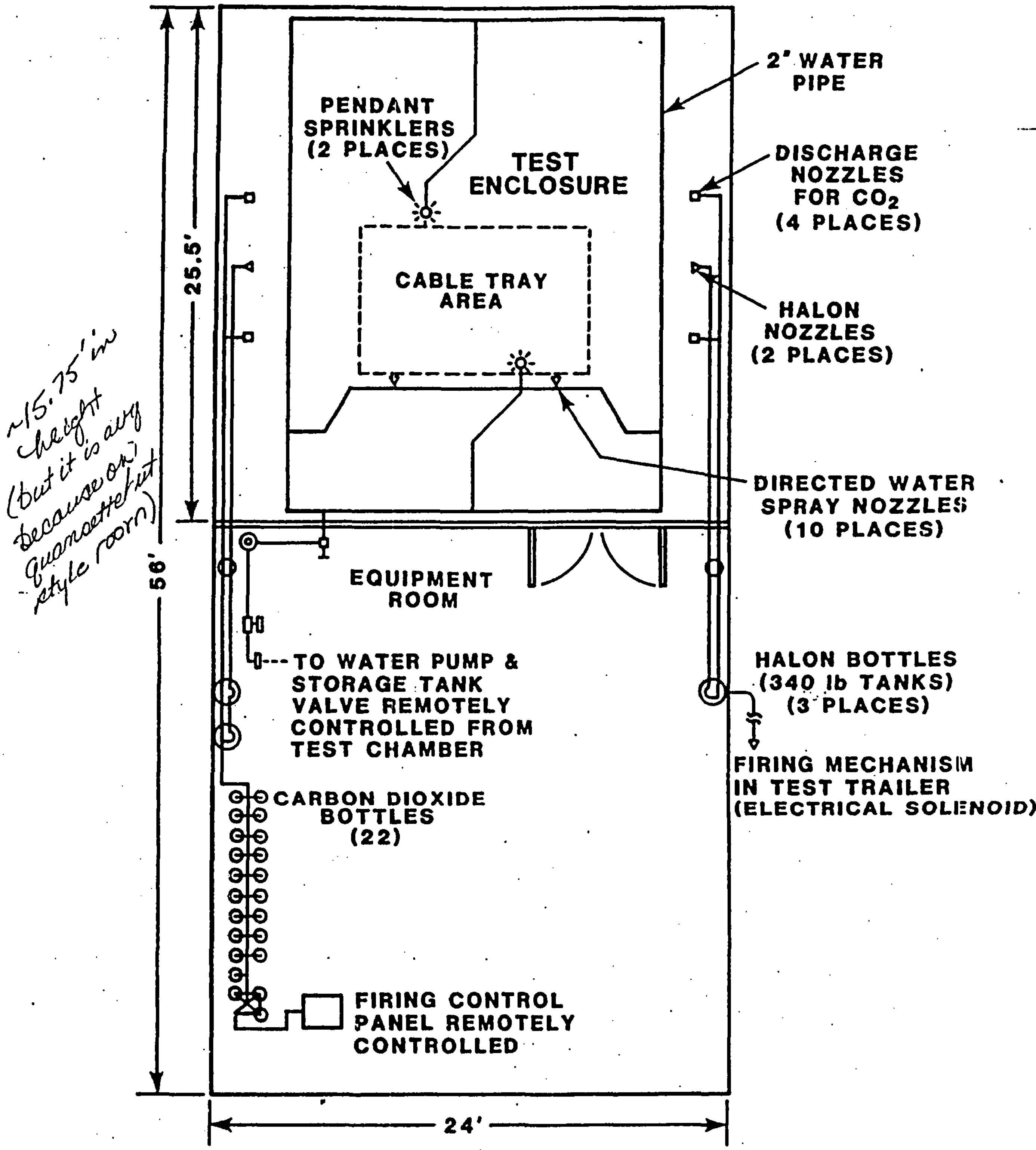


Figure 3. Fire Suppression System Arrangement

Water sprinkler tests were performed with a system that was designed to comply with NFPA-13.[4] This system consisted of two open-head pendant-type sprinklers located 3.8 m (12.5 ft) above the burn room floor, separated horizontally by 3.7 m (12 ft), and offset from the cable trays. The design prescribed a flow rate of 4.5 ℓ/s (71 gpm) at an open head pressure of 241 kPa (35 psig) for a sprinkler orifice diameter of 1.27 cm (1/2 in). The water was drawn from a 13600-ℓ (3000-gal) tank located at the site.

The directed water spray system was designed to provide suppression in accordance with NFPA-15[5] standards. Ten flat, fan-type spray nozzles, diameter 0.28 cm (7/64 in), provided a uniform spray pattern over an angle of 100°. The flow was 0.17 ℓ/s (2.7 gpm) at a static pressure of 558 kPa (81 psig), or a flow density of 12.2 ℓ/minute•m^2 (0.3 gpm/ft^2) of surface area. The 10 nozzles were located, 5 each, on 2 stands adjacent to the cable trays, with 2 nozzles pointing into each tray.

The carbon dioxide fire suppression system met the standards in NFPA-12[6] and provided a volumetric room concentration of 50 percent. The system was comprised of 22 carbon dioxide tanks, associated piping and valves, and 4 nozzles. The 0.64-cm (1/4-in) diameter nozzles were located 2.95 m (9.67 ft) above the floor with two each on opposite walls in the room. To maintain a volumetric room concentration of 50 percent, approximately 374 kg (825 lb) of carbon dioxide was necessary.

All suppression systems were manually activated from a control/instrumentation trailer located near the burn facility.

2.4 Test Procedures

In setting up the tray configuration, cables were loaded into the trays after which thermocouples were placed inside and around the cable jackets. The trays were then moved into the test chamber and positioned in the support fixture which held the tray, and maintained correct tray separation.

no tray pens just pipe pens & vent pens

Prior to each test, a soak time and/or spray time was specified depending on the type of suppression, type of cable, the test configuration, and previous suppression tests. This soak time included the time during which the fire suppression system operated. The soak time will also be referred to as having the room "closed up." For gaseous suppression systems, the gas concentration level was maintained during this period.

During the two-tray tests, 41-kW (140,000-Btu/hr) propane burners were used in 5-minute on-and-off burn cycles until a "well-developed" fire was started in the donor tray. At this point, the marinite barrier separating the donor and acceptor cable trays (with the exception of Test 78 which had no barrier) was removed. In the exposure fires the marinite barrier was used to prevent burning of the acceptor tray until the fire in the donor tray was well developed. This way the effectiveness of the suppression system in preventing ignition of the cable tray could be evaluated. After a 1-minute freeburn (which was used to confirm that the fire was well developed and self sustained), the ventilation system was turned off and the exhaust stack cover closed. The suppression system was then energized, and the test enclosure remained closed during the predetermined soak time. The exposure fire is explained more fully in Section 2.5.

The procedure for the five-tray tests called for the constant use of the propane burners until a self-sustaining "fully developed" fire was maintained in the first four of the five trays and the temperature in the cables in tray 4 was approximately 600°C (1112°F). With a fire of this size, the fire was deep seated in the cables and produced a fire severe enough to challenge the suppression systems. The burners were then turned off and the fire was allowed to freeburn for 1 minute before the room was closed up and the suppression system activated. The fully developed fires are explained more fully in Section 2.5.

2.5 Discussion of Fire Size and Type

Two fire sizes and types were used to test the cables and suppression systems. It was not the purpose of this test program to defend or justify the types and sizes of fires the suppression systems should be tested against, rather it was to evaluate suppression effectiveness on credible yet challenging fires. However, in this section a discussion is presented of the basis used in selecting the two test fire sizes.

2.5.1 Exposure Cable Tray Fires

Initially, the suppression test program was designed to test the suppression systems on smaller initiating-type fires, designated as "exposure fires." The exposure fires were defined as self-sustaining fires in a single cable tray that were allowed to free burn for 1 minute before the suppression system was actuated. All "exposure fire" tests involved two cable trays. A decision was made that these "exposure fires" were indicative of a fire starting in a single tray either electrically or by some transient fuel. The purpose of these exposure fire tests was to evaluate the

suppression systems' ability to extinguish a relatively small cable fire and prevent damage to an exposed cable tray above the fire.

The time required for the propane burner to establish the self-sustaining exposure fire in the donor tray for both horizontal and vertical two-tray configurations and for both qualified and unqualified cable is shown in Table 2. It is clear from Table 2 that the fire-retardant additives used in the qualified cable effectively increased the time required to establish the exposure fire in comparison to the unqualified cable, which contained no fire-retardant additives. There is, however, no significant time difference between the horizontal and vertical configurations in the time required to establish an exposure fire for either qualified or unqualified cable. A sequence of events for Test 71 is shown in the photographs in Figure 4.

Table 2

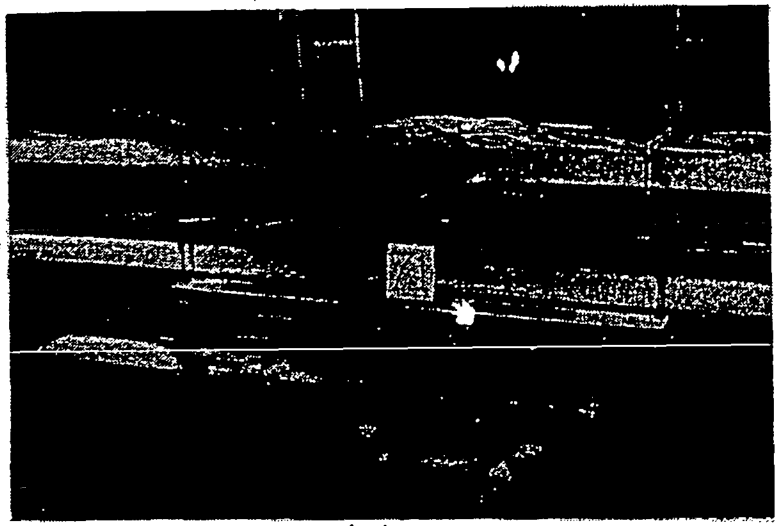
Initiation Fire Duration, Two-Tray "Exposure-Fire" Tests

Tray Configuration	Cable Type	
	IEEE-383 Qualified	Unqualified
Horizontal	TWO--5-minute burn cycles (Total - 10-minute burn)	3.5 to 5 minutes
Vertical	TWO--5-minute burn cycles (Total - 10-minute Burn)	3 to 4 minutes

Exposure fires in the vertical configuration were much less severe in that the ribbon burner was placed under only the donor tray. As in the horizontal configuration, the acceptor tray was covered by a marinite board just before the 1-minute free burn. As a result of the tray being in the vertical orientation, all the heat went up the donor tray and the acceptor tray was virtually unaffected by the fire in the donor tray.

2.5.2 Fully Developed Cable Tray Fires

The suppression test program was later expanded to include testing the suppression systems on larger "fully developed"



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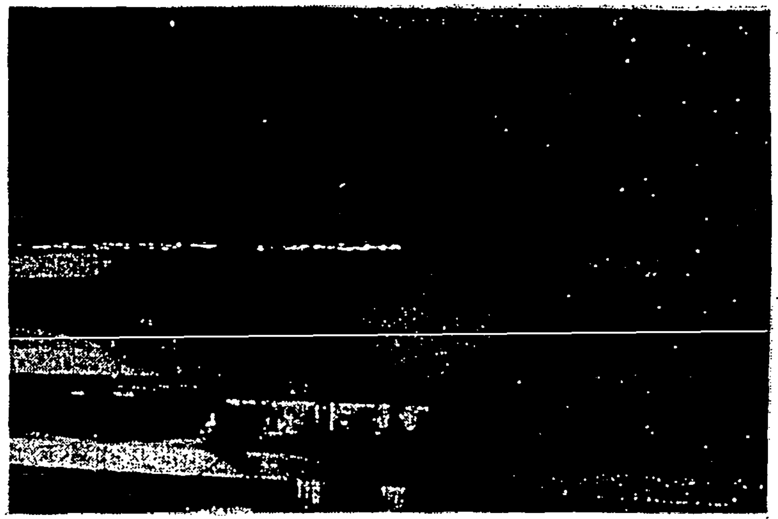

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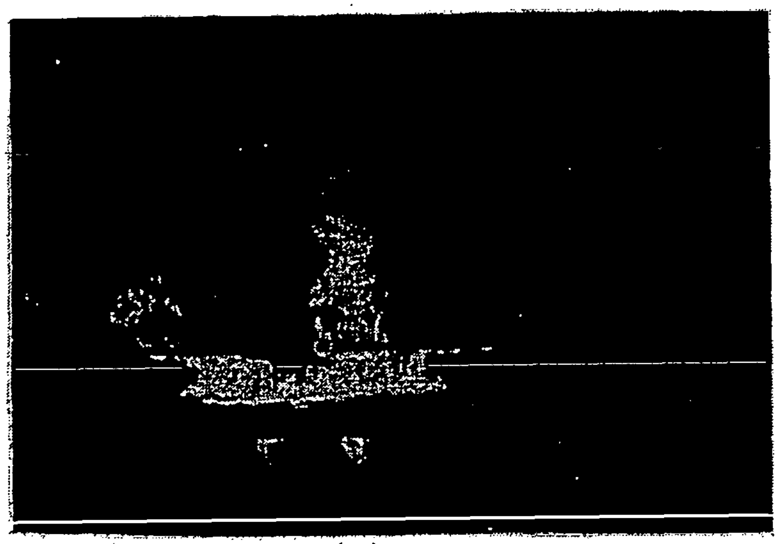

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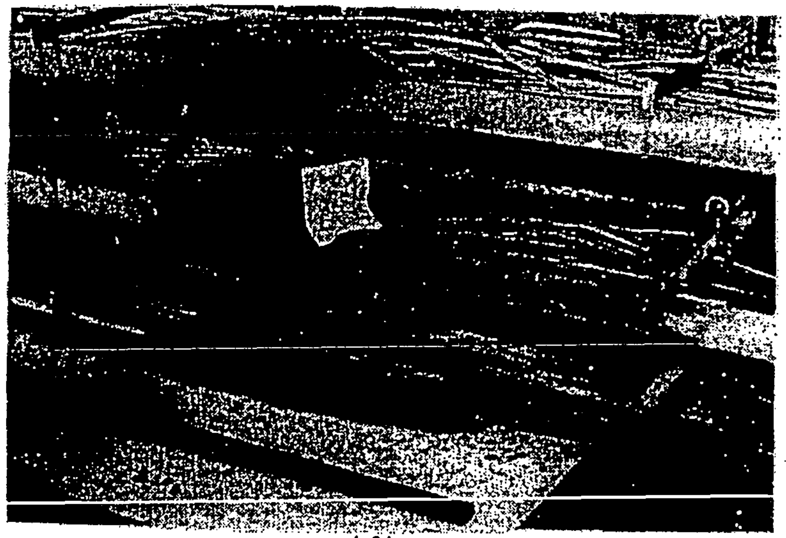


(d)

Figure 4. Sequence of Events During Fire Development for a Horizontal Exposure Fire

cable tray fires. The initiative behind evaluating the suppression system effectiveness on "fully developed" fires was that although the probability of a "fully developed" fire occurring is small, the suppression systems were designed to handle these larger fires, and hence, should be tested under these conditions. The "fully developed" cable tray fires were defined as fires that involved four of five cable trays. This represented a fire that had been burning for some time. Four burning cable trays represent a significant fuel loading.

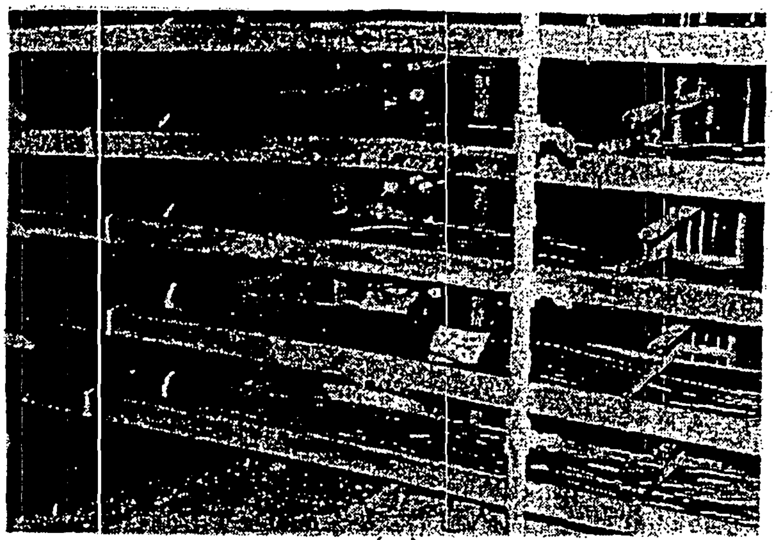
During the ignition phase for the "fully developed" cable fires using the five-tray configuration, the propane ribbon burners were burned continuously until a self-sustaining, fully developed fire involving four of the five trays was established, and the temperature in tray 4 (Figure 5) reached approximately 600°C (1112°F). The times required for the propane burner to establish a fully developed fire are shown in Table 3. The superior fire resistance of the qualified cable in comparison to the unqualified cable is shown even more clearly in these tests than in the two-tray tests. The unqualified cable required approximately the same ignition time in both the horizontal and vertical configurations. The qualified cable generally required a longer ignition time in the vertical configuration than in the horizontal configuration, but this was not a consistent observation. At the end of the propane burn there was still sufficient fuel remaining to support a self-sustaining fire in the cable trays. The sequence for a fully developed fire is shown in Figure 5.

Table 3

Initiation Fire Duration, Five-Tray "Fully Developed" Fire Tests

Tray Configuration	Cable Type	
	IEEE-383 Qualified	Unqualified
Horizontal	17 to 19.5 minutes	5 to 7 minutes
Vertical	17 - 25 minutes	5 minutes

In the five-tray vertical configuration, a propane ribbon burner (with a flame as wide as the tray) was aligned at the base of each of the first four trays (see Figure 2). Tray 5



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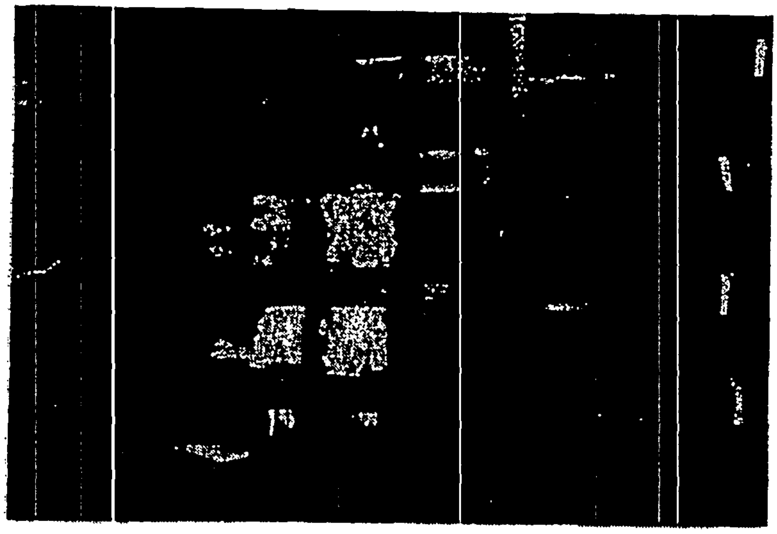

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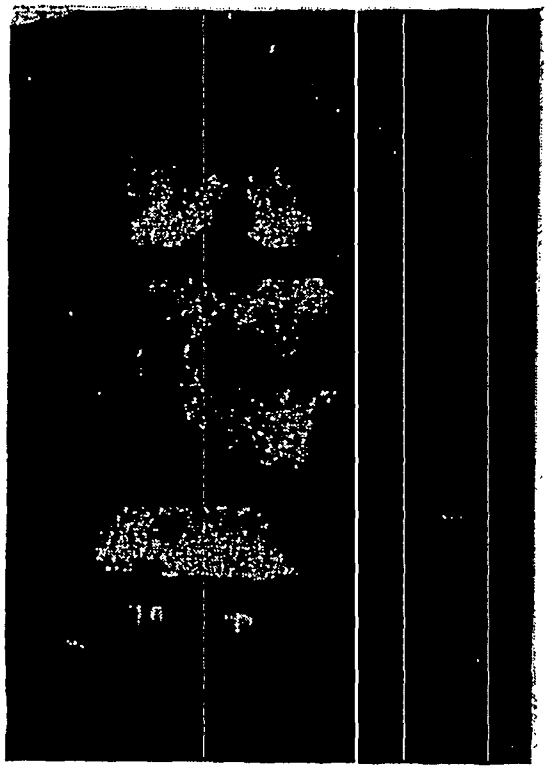

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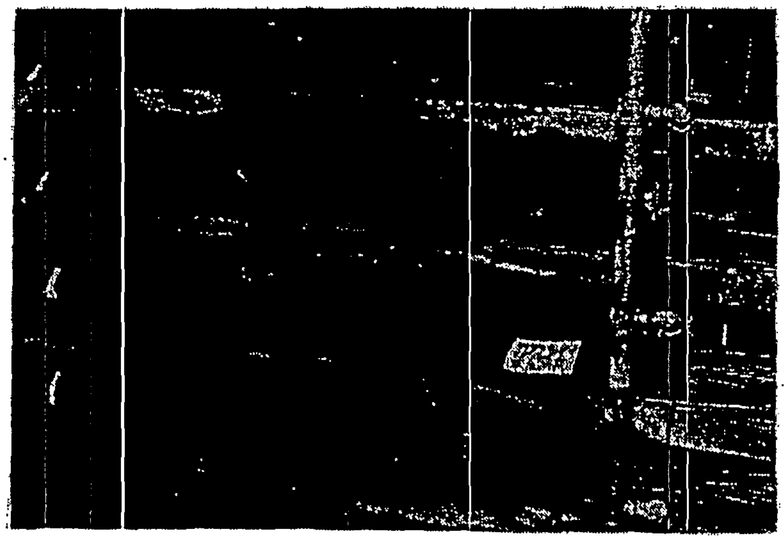

(d)

Figure 5. Sequence of Events During Fire Development for a Horizontal Fully Developed Fire

did not have a propane burner. The flames spread up each of the first four trays but did not spread to tray 5 or even visibly affect it. The feedback effect between trays was not as significant for the vertical configuration as for the horizontal configuration and the qualified cable generally took longer to ignite.

2.5.3 Discussion of Fire Sizes

Based on discussions with the NRC and on previous experience[1] and data[8] on "real" fires, the two fire sizes, previously discussed, were selected as being feasible and representative fires for testing the suppression systems. At first glance, the initiating fire burn duration (before the 1-minute free burn) may seem overly long, particularly for the "fully developed" qualified cable. However, it was not the length of the initiating fire duration that was considered a critical parameter; it was the actual size of the fire that was deemed important to challenge the suppression systems' capabilities.

It could be argued that the detectors and/or automatic suppression systems would have activated long before the 10 minutes required to ignite a qualified cable "exposure" fire and certainly before the 20 minutes required to ignite the qualified cable "fully developed" fire. However, the ignition fire durations do not seem unreasonable if the detection system was out for some reason (i.e., maintenance) or the detection system failed, allowing the fire to burn for some time. Also, some plants have only manually actuated suppression systems in certain plant areas. For these situations, it would take plant personnel "...from a few minutes (personnel present in area using portable extinguishers or local hose station) to about 15 minutes..."[7] to extinguish the fire. Furthermore, an EPRI report on fire loss data[8] reveals that of the fires reported with duration times, approximately 70 percent lasted longer than 15 minutes and approximately 57 percent lasted longer than 20 minutes. Consequently, it is not unreasonable to assume that an "exposure" fire could last 10 to 15 minutes or a "fully developed" fire could last 20 to 25 minutes.

2.6 Test Evaluation Criteria

Originally, criteria for judging suppression system effectiveness were based on the two-tray, exposure-fire tests, which required that there be no self-sustained flames and no flammable gas concentrations after suppression. However, when the tests were redesigned to test suppression systems in a more severe-type fire (fully developed, five trays), the criteria were reevaluated. It should be noted that the objective of the tests was to determine the minimum soak times for gaseous suppression systems and the minimum soak

time or spray duration for water suppression systems, necessary to suppress and prevent reignition of the fire. The following criteria were only used in evaluating the relative effectiveness of the different suppression systems. The criteria used in evaluating all 37 suppression tests, both the two tray and the five tray, were as follows:

1. Ability of the suppression system to suppress the fire--no reignition of the fire after oxygen is reintroduced into the test enclosure (soak time and/or spray duration required).

2. Effectiveness of the suppression systems' ability:

   - to cool the room environment
   - to cool the cables, both on the surface and its interior

3. For gaseous systems--ability to maintain specified concentrations for the required soak time.

Each of the suppression systems was evaluated independently, and then the results compared to the other suppression systems.

This is extinguishment not suppression

3. TEST DETAILS AND RESULTS

3.1 General Discussion

A total of 37 cable tray fire suppression tests were conducted. These tests are summarized in the matrix shown in Table 4. The tests and results will be described more completely in the following sections.

All tests using either of the two water suppression systems had both a soak time and spray duration specified prior to the start of a test. In most cases, except those noted on Table 4, and later in Section 3.2, 3.4, and 3.5, the soak times were the same as the spray durations. Therefore, for consistency, soak time will be used in the text and in the tables when discussing a test unless the spray duration is different from the soak time, in which case both will be discussed.

In the following sections a term "cool down rate" will be used to describe the rate with which the suppression system effectively cools either the enclosure or cables. The cool down rate will be given for a specified period of time which will be noted. In all cases the enclosure cool down rate will be given for the soak time and/or spray duration and an average cool down rate, for each type of suppression system will be given based on the soak times and/or spray duration. It is not practical to determine an average cool down rate for cables because it is dependent on too many variables (i.e., thermocouple location, tray orientation, etc.) whereas enclosure cool down rate is dependent only on one thermocouple. Therefore, cable cool down rates will be given for individual tests discussed and for the location indicated; however, no "average" cool down rate will be given for cables.

In addition to the suppression tests, there were two oxygen deprivation tests (58 and 59) performed using the two-tray horizontal configuration. The purpose of these tests was to bound the soak times required for suppression systems by determining the time required for the fire to either burn itself out due to total consumption of fuel or because of a lack of oxygen. After the required ignition cycle, removal of the marinite barrier, and 1-minute free burn, the room was sealed for a specified time. No fire suppressant was introduced. In Test 58 , the enclosure was "closed up" with no ventilation for 45 minutes; however, the fire burned out in 30 minutes, apparently due to total consumption of fuel in the donor tray. The enclosure was "closed up" for 10 minutes in Test 59; however, the fire was still burning when the ventilation was restarted. These two tests bounded the possible soak times that would be required for the suppression systems.

Shouldn't min soak be 10 min then?

Table 4

Matrix of Cable Tray Fire Suppression Tests

Test[a] Number	Number of Trays	Orientation of Trays	Type of Cable	Suppression Method	Soak[b] Time (min)	Test Outcome
56	2	H	Q	Halon, 6% conc.	45	NR
57	2	H	Q	Halon, 6% conc.	10	NR
58	2	H	Q	Oxygen deprivation	45	NR
59	2	H	Q	Oxygen deprivation	10	R
60	2	H	Q	Halon, 6% conc.	4	R
61	2	H	U	Halon, 6% conc.	16	NR
62	2	V	U	Halon, 6% conc.	5	NR
63	2	V	Q	Halon, 6% conc.	4	NR
64	2	V	Q	Halon, 6% conc.	0	NR
65	2	V	Q	Sprinkler, 75 GPM	7[c]	NR
66	2	V	Q	Sprinkler, 75 GPM	0[c]	NR
67	2	V	U	Sprinkler, 75 GPM	5	NR
68	2	H	Q	Sprinkler, 75 GPM	15	NR
69	2	H	Q	Sprinkler, 75 GPM	10	NR
70	2	H	Q	Sprinkler, 75 GPM	5	NR
71	2	H	U	Sprinkler, 75 GPM	16	NR
72	5	H	Q	Spray, 0.3 GMP/ft^2	5	NR
73	5	H	Q	Spray, 0.3 GMP/ft^2	0[c]	NR
74	5	H	U	Spray, 0.3 GMP/ft^2	0[c]	NR
75	5	V	Q	Spray, 0.3 GMP/ft^2	0[c]	NR
76	5	V	U	None, test aborted	--	--
77	5	V	U	Spray, 0.3 GPM/ft^2	5	NR
78	2	V	Q	None, test aborted	--	--
79	5	V	Q	Sprinkler, 75 GPM	5	NR
80	5	V	U	Sprinkler, 75 GPM	5	NR
81	5	H	Q	Sprinkler, 75 GPM	5	R
82	5	H	U	Sprinkler, 75 GPM	5	NR
83	5	H	Q	CO_2	10	R
84	5	H	Q	CO_2	15	NR
85	5	H	U	CO_2	10	NR
86	5	H	U	Halon, 6% conc.	10	NR
87	5	H	Q	Halon, 6% conc.	15	NR
88	5	V	Q	CO_2	15	NR
89	5	V	Q	None, test aborted	--	--
90	5	V	Q	Halon, 6% conc.	15	NR
91	5	V	U	CO_2	10	NR
92	5	V	U	Halon, 6% conc.	10	NR

Legend: H – Horizontal cable trays; V – Vertical cable trays; Q – Qualified IEEE-383 cable; U – Unqualified cable; NR – No reignition after soak time; R – Reignition after soak time

[a]Tests 1-55 were performed under a previous NRC-sponsored test program.

[b]Length of time that the ventilation system was turned off and the damper closed. Zero soak time = continuous ventilation with stack cover open during suppression activity.

[c]In these water suppression tests, the soak time and spray durations were not the same. For all other tests with water suppression systems, the soak time and spray durations were the same.

Furthermore, the effectiveness of Halon 1301, water sprinkler, and directed water spray fire suppression systems were tested with "no soak time" (with the enclosure "closed up" and the ventilation system running) using the two-tray horizontal and vertical configuration. Tests with carbon dioxide suppression were not conducted with "no soak time" because only tests on the large, fully developed fires were run with carbon dioxide suppression and these fires were judged too large to suppress with carbon dioxide or Halon suppression with the ventilation system on. These tests are listed in Table 4 as Tests 64, 66, 73, 74, and 75. For each of these tests, the fire suppression system was discharged after the 1-minute free burn but the stack cover remained open and ventilation of the room continued. The purpose of these tests was to demonstrate the importance (or insignificance) of sealing the room. The results of these tests are discussed in Sections 3.2 through 3.7.

Three of the suppression tests (76, 78, and 89) were aborted either because of equipment malfunctions or because the cables did not maintain a self-sustaining fire.

3.2 Exposure Fire Cable Tray Suppression Tests (Two-Tray)

As part of this test series, a total of 14, two-cable tray exposure fire suppression tests were performed, shown in Table 5. Seven tests each with Halon 1301 and water sprinklers were performed. It was after this series of tests that the program was changed to test suppression systems on larger fires. Therefore, there are no tests with either directed water spray or carbon dioxide suppression on the exposure fires. However, both types of cable, qualified and unqualified, and both cable orientations, horizontal and vertical, were tested. In the subsections of Section 3.2 both Halon 1301 and Water Sprinkler tests will be discussed. Due to the similarity of data for many of the tests the following discussion of the exposure fire suppression tests will not refer to results of all the tests. Specifically Tests 57, 60, 61 and 62 will be discussed for the Halon suppression tests. In discussing the water sprinkler suppression results, Tests 67 and 68 will be employed.

3.2.1 Environment Temperature Response

Enclosure temperature is an indicator of a suppression system's capability in that the thermal response of the room can be a measure of how effective the suppression system is in extinguishing a fire. The environment response was based on the exhaust gas temperatures measured by thermocouples located in the exhaust vent of the enclosure, which gave a reasonable indication of the average air temperature in the upper part of the enclosure; this will be called the enclosure temperature. In general the enclosure temperatures for

Table 5

Exposure Fire Tests Matrix

Test Number	Type of Suppression	Number of Trays	Orientation of Trays	Type of Cable	Sprinkler Duration (min)	Soak[a] Time (min)	Test Outcome
56	Halon	2	H	Q	N/A	45	No reignition after ventilation
57	Halon	2	H	Q	N/A	10	No reignition after ventilation
60	Halon	2	H	Q	N/A	4	Reignited when ventilated
61	Halon	2	H	U	N/A	16	No reignition after ventilation
62	Halon	2	V	U	N/A	5	No reignition after ventilation
63	Halon	2	V	Q	N/A	4	No reignition after ventilation
64	Halon	2	V	Q	N/A	0	No reignition
65	Sprinkler	2	V	Q	4	7	No reignition after ventilation
66	Sprinkler	2	V	Q	4	0	No reignition, some smoking
67	Sprinkler	2	V	U	5	5	No reignition after ventilation
68	Sprinkler	2	H	Q	15	15	No reignition after ventilation
69	Sprinkler	2	H	Q	10	10	No reignition after ventilation
70	Sprinkler	2	H	Q	5	5	No reignition after ventilation
71	Sprinkler	2	H	U	16	16	No reignition after ventilation

Legend:
H - Horizontal cable trays
V - Vertical cable trays
Q - Qualified IEEE-383 cable
U - Unqualified cable

[a]Length of time that propane burners are on.

[b]Length of time that the ventilation system is turned off and the damper closed. Zero soak time = continuous ventilation with damper open during suppression dump.

the exposure fire tests did not peak at greater than 110°C, and most were below 70°C.

First, the environment temperature in the Halon tests will be discussed. The enclosure temperature in Test 57 (qualified cable, horizontal orientation) peaked at 52°C and decreased to 40°C during the soak time, a temperature decline rate of 1.2°C/minute, as shown in Figure 6. The temperature rise at ~46 minutes is a result of the ventilation being restarted, exhausting hot gases. The cooling rate in this test was not significant, and the temperatures were not high enough to result in damage to other cables. In Figure 7, Test 62 (unqualified cable, vertical orientation), the temperature dropped 14°C during the 5-minute soak time, a temperature decline rate of 2.8°C/minute, and decreased rapidly after ventilation was resumed and the hot gases in the enclosure were exhausted. Exposure fires suppressed with Halon 1301 experienced an average cooling rate of 2°C/minute, with a cooling rate ranging from 1°C/minute to 4°C/minute.

In this paragraph the effects of water sprinklers in cooling the environment will be discussed. The environment temperature response for the water sprinklers was much more pronounced. A plot of the room temperature for Test 67 (unqualified cable, vertical orientation), Figure 8, shows a rapid cooling of the room temperature when the sprinklers were turned on. The temperature dropped from 110°C to 40°C during the 5-minute soak period, a temperature decline rate of 14°C/minute, and continued to drop after ventilation was started. The average room cooling rate for the sprinkler system on exposure fires was ~12°C/minute, with a range of 18°C/minute and 9°C/minute.

Based on the enclosure temperatures, it should be noted that in most cases the exposure fires did not produce fires severe enough to have resulted in damage to other cables in the room, particularly after suppression.

3.2.2 Cable Temperature Response

Another indication of the effectiveness of a suppression system is its ability to cool cables. The cable cooling rate can demonstrate the presence of combustion and smoldering combustion that could result in reignition of the cables after a soak time.

In order to show the difference between a successful and an unsuccessful suppression test for Halon 1301 on horizontal cable trays, Tests 57 and 60 will be compared. Tests 57 and 60 were identical except for the soak times, which were 10 and 4 minutes, respectively. Cable surface temperatures, as recorded by thermocouples wrapped around cables in the donor and acceptor trays, are shown in Figures 9 (Test 57, 10-minute soak) and 10 (Test 60, 4-minute soak). These tests

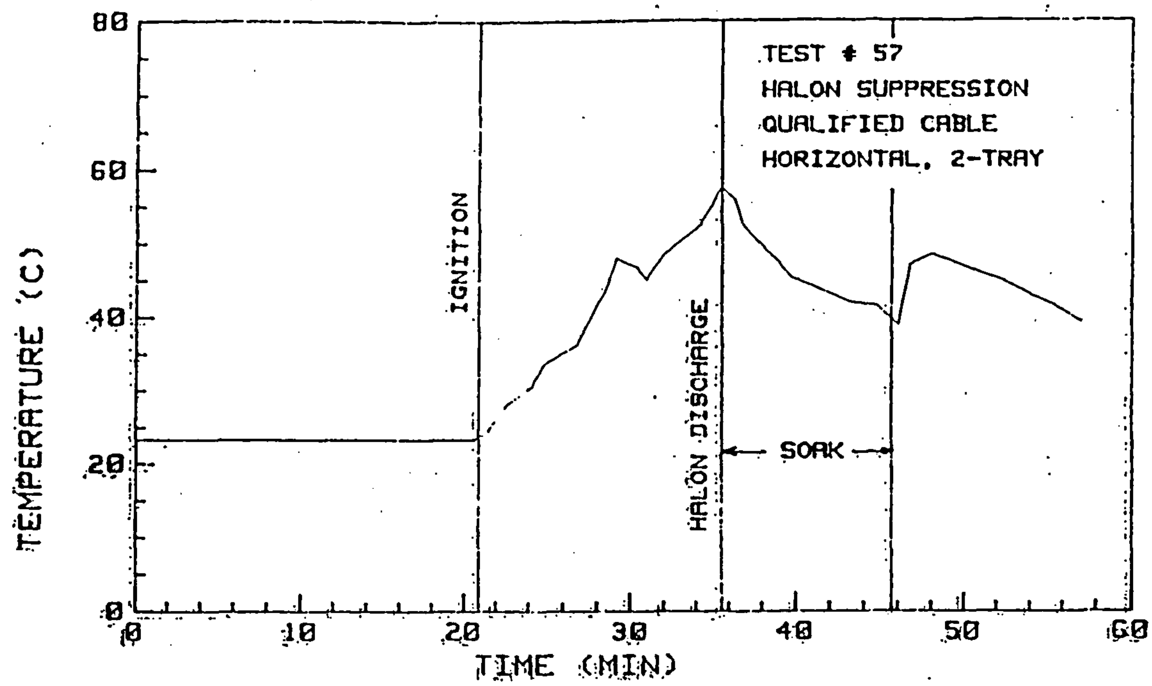

Figure 6. Enclosure Temperature, Test 57

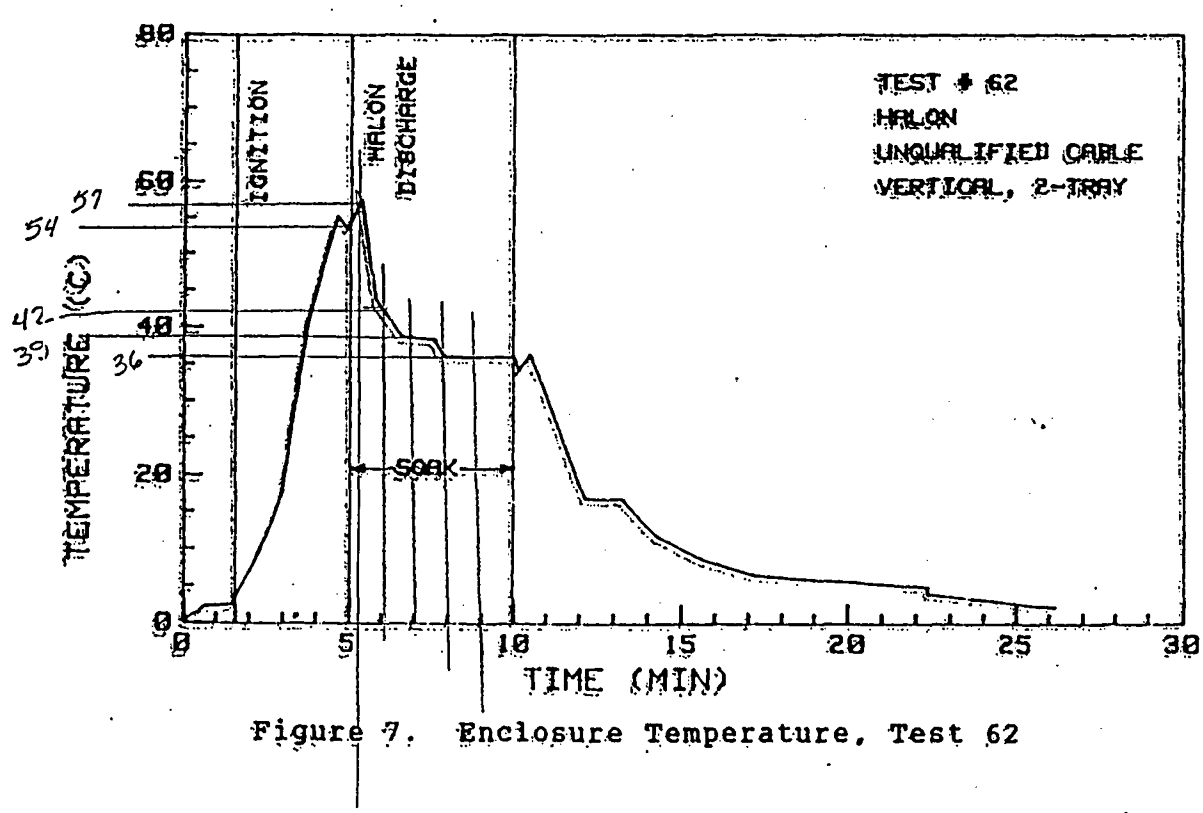

Figure 7. Enclosure Temperature, Test 62

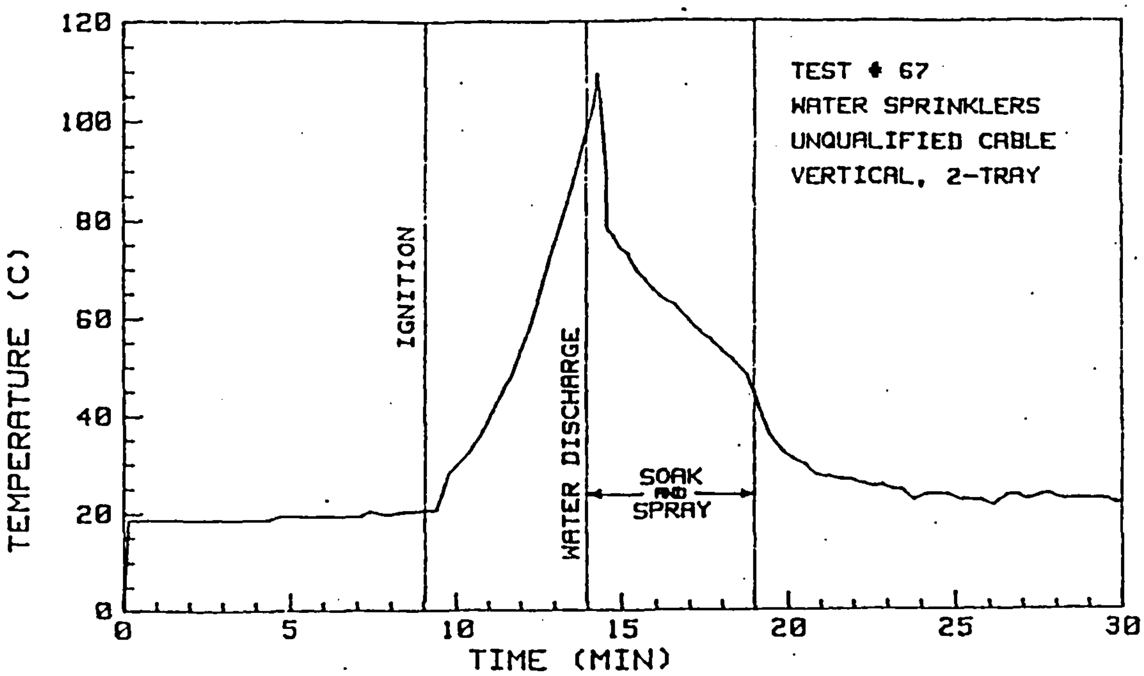

Figure 8. Enclosure Temperature, Test 67

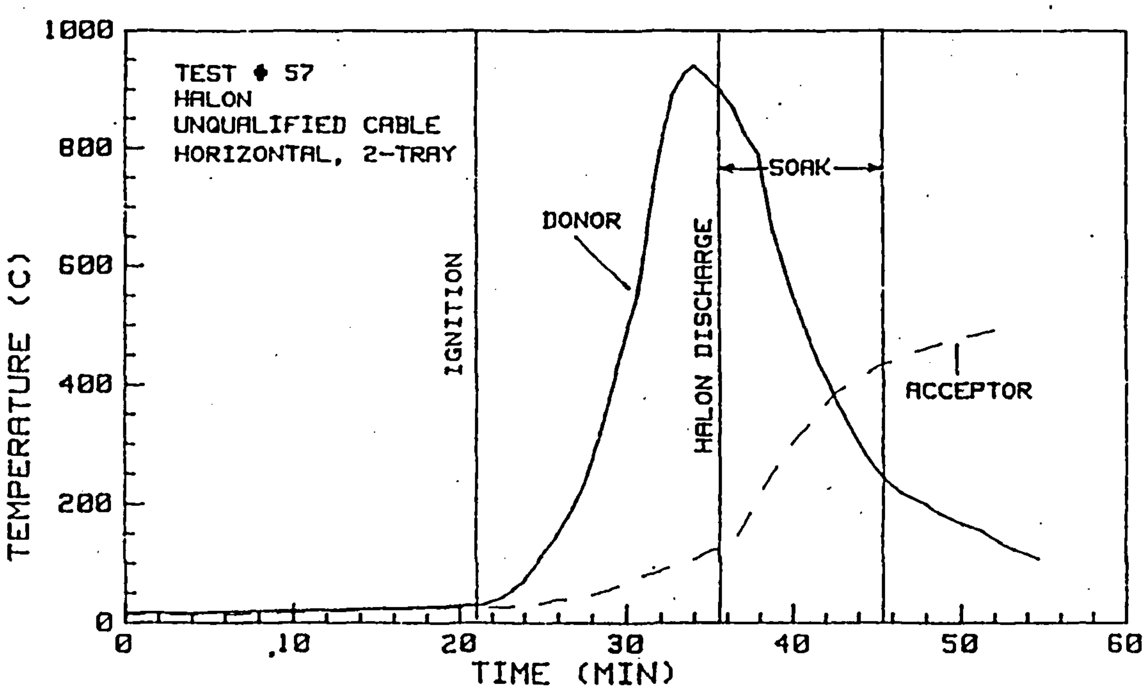

Figure 9. Cable Surface Temperature, Center of Donor and Acceptor Trays, Test 57

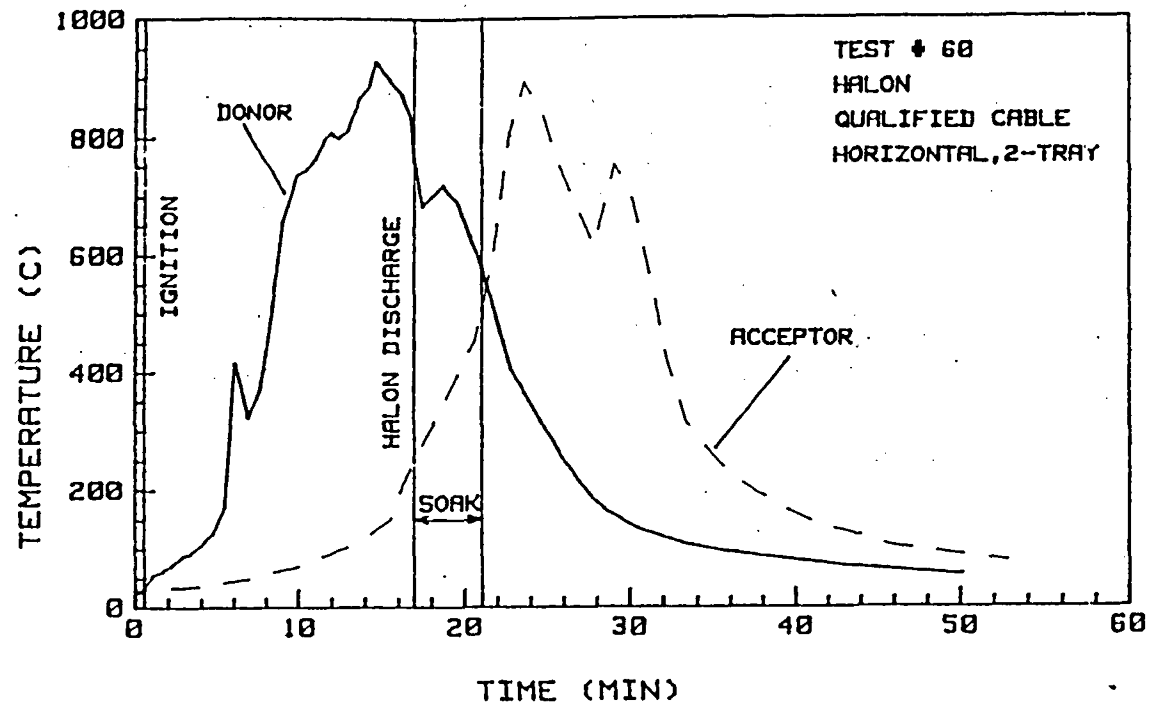

Figure 10. Cable Surface Temperature, Center of Donor and Acceptor Trays, Test 60

show similar cable surface temperature decline rates in the donor tray of approximately 60°C/minute during their soak times.

Temperatures for the acceptor trays for these same two tests show a continued increase after suppression and the specified soak time, even though the cable did not appear to reignite. In Test 57, shown in Figure 9, this rise is due to hot gases rising from the donor tray and possibly to smoldering combustion in a localized area near the thermocouple, confirming that qualified cables tend to char and smolder. The temperature in the acceptor tray peaked at 493°C for Test 57 (10-minute soak, Figure 9) which is near the cable ignition temperature, indicating continued smoldering of the cable although no ignition. However, for the 4-minute soak in Test 60, Figure 10, the temperature in the acceptor cable tray increased sharply to a maximum of approximately 900°C, indicating combustion of the cable and failure of the suppression system to prevent reignition.

Test 62, with Halon suppression, was a test with unqualified cable in the two-tray vertical configuration. Figure 11 shows the temperatures in the center of the donor and acceptor trays. The maximum temperature in the donor tray as shown in Figure 11 was approximately 500°C as compared to the 900°C for the qualified cable in Test 60. Based on previous tests it appears that this difference is due to the type of cable used, not the difference in orientation. The temperature decreased from 500°C to 125°C immediately after activation of the Halon 1301 suppression system and stayed at 125°C during the remainder of the soak time (a cool down rate of 75°C/ minute). The data indicate that the acceptor tray hardly noticed that the donor tray was on fire; the maximum temperature was less than 60°C. This is because of the blocking effects of the trays in the vertical orientation.

In the next few paragraphs results of the water sprinkler tests will be discussed. The water sprinklers cooled the cables both externally and internally in Test 67 (unqualified cable, vertical orientation, with a soak and sprinker duration of 5 minutes). Figure 12 shows a rapid decrease in the donor cable temperature upon suppression actuation, from ~600°C to 95°C in 1 minute, a cool down rate of 505°C/minute. By the end of the soak time, the temperature had dropped to 45°C, a cool down rate during the soak time of 110°C/minute. The acceptor tray in this test, as in all vertical tests, did not get very hot (<60°C) and did not burn. Figure 13, for Test 68 (qualified cable, horizontal orientation), also shows the effectiveness of sprinklers. The temperature in the donor tray drops from ~730°C to 98°C in the first 10 minutes of the soak time, (a cool down rate of ~63°C/minute). During the length of the soak time, the cool down rate was 47°C/minute.

This is a slower cooling rate than for the vertical cable configuration (Test 67), but that is due to the blocking effects of the acceptor tray in this configuration. Acceptor cable temperatures, Figure 13, also drop rapidly, from 445°C to 55°C (37°C/minute).

3.2.3 Suppression Effectiveness and Summary of Results

Halon 1301 with a 6 percent concentration is easily capable of extinguishing an exposure fire, given a sufficient soak time. An observation made during the tests was that the Halon quickly knocked down the flames and extinguished the fire.

The gas concentration of Halon 1301 in the enclosure during the exposure fire tests was maintained at or above the specified 6 percent in all tests. Figure 14 (Test 62) shows concentrations ranging from 7 to 8 percent during the 5-minute soak time. This is higher than the 6 percent specified;

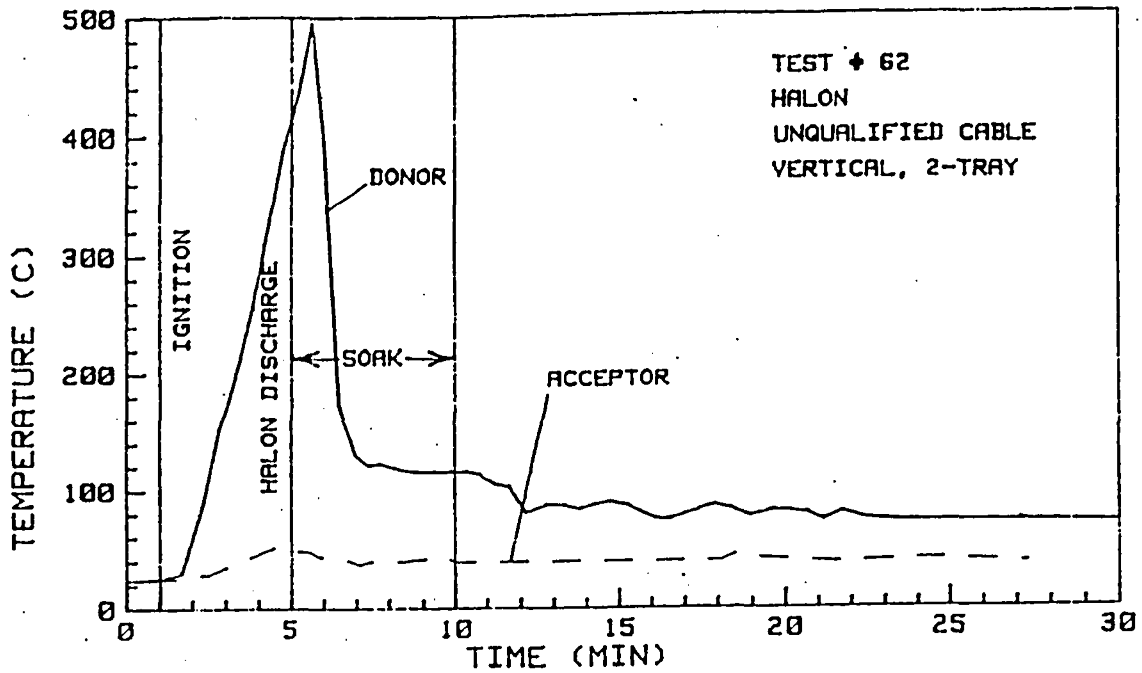

Figure 11. Cable Surface Temperature, Center of Donor and Acceptor Trays, Test 62

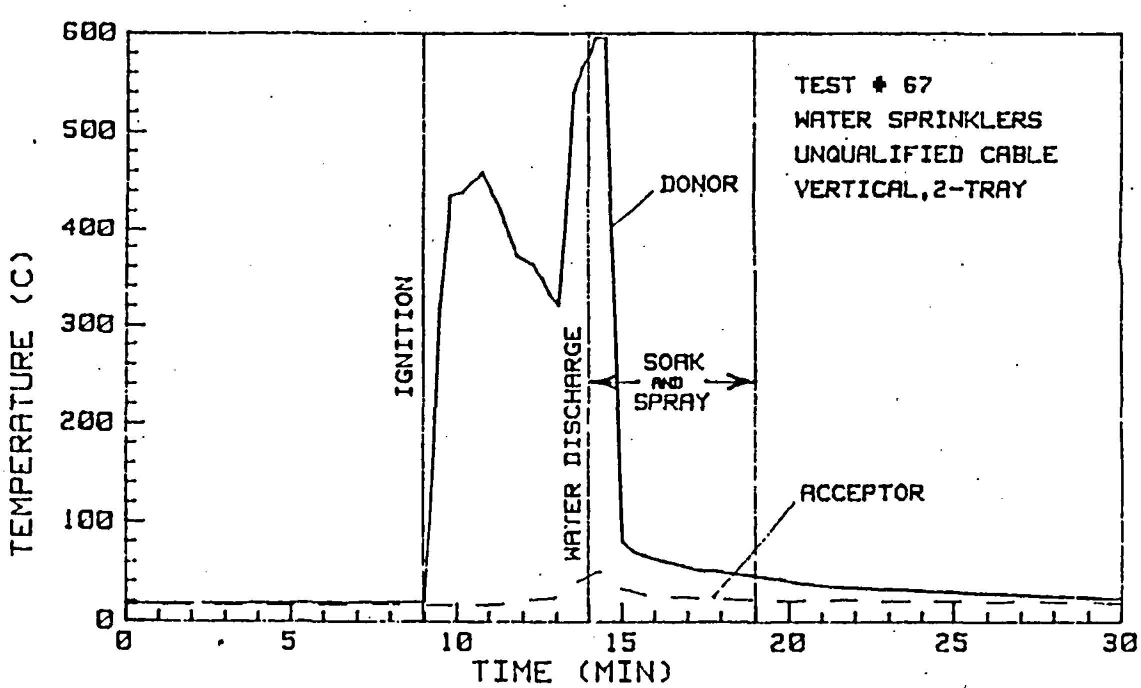

Figure 12. Cable Surface Temperature, Center of Donor and Acceptor Trays, Test 67

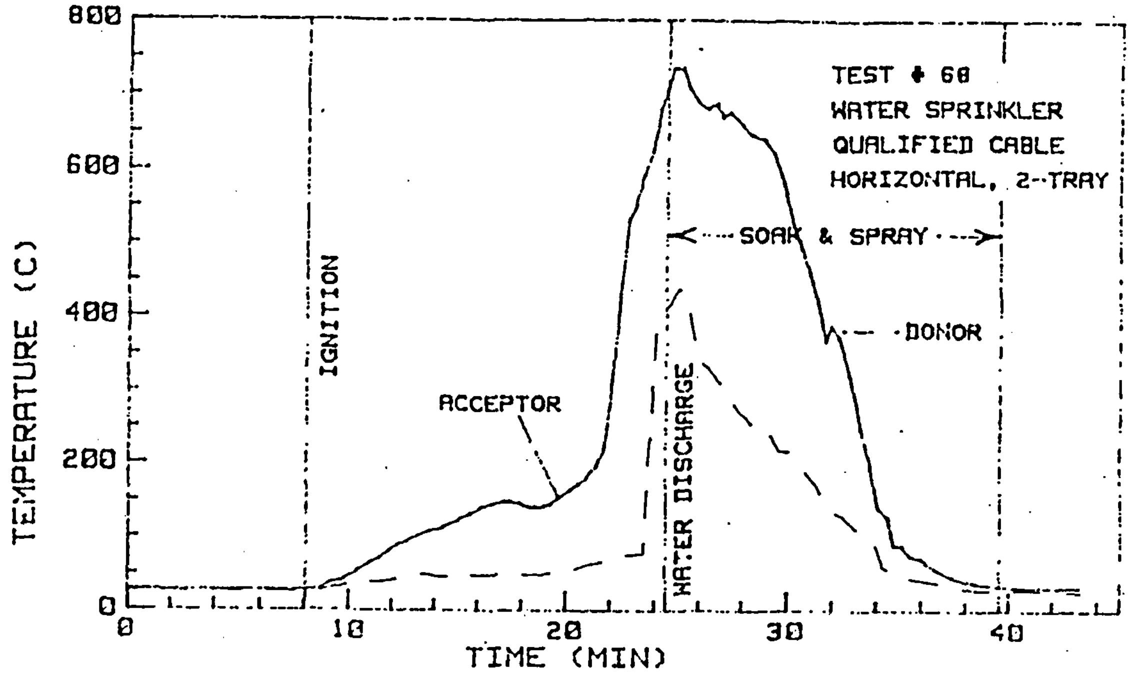

Figure 13. Cable Surface Temperatures, Center of Donor and Acceptor Tray, Test 68

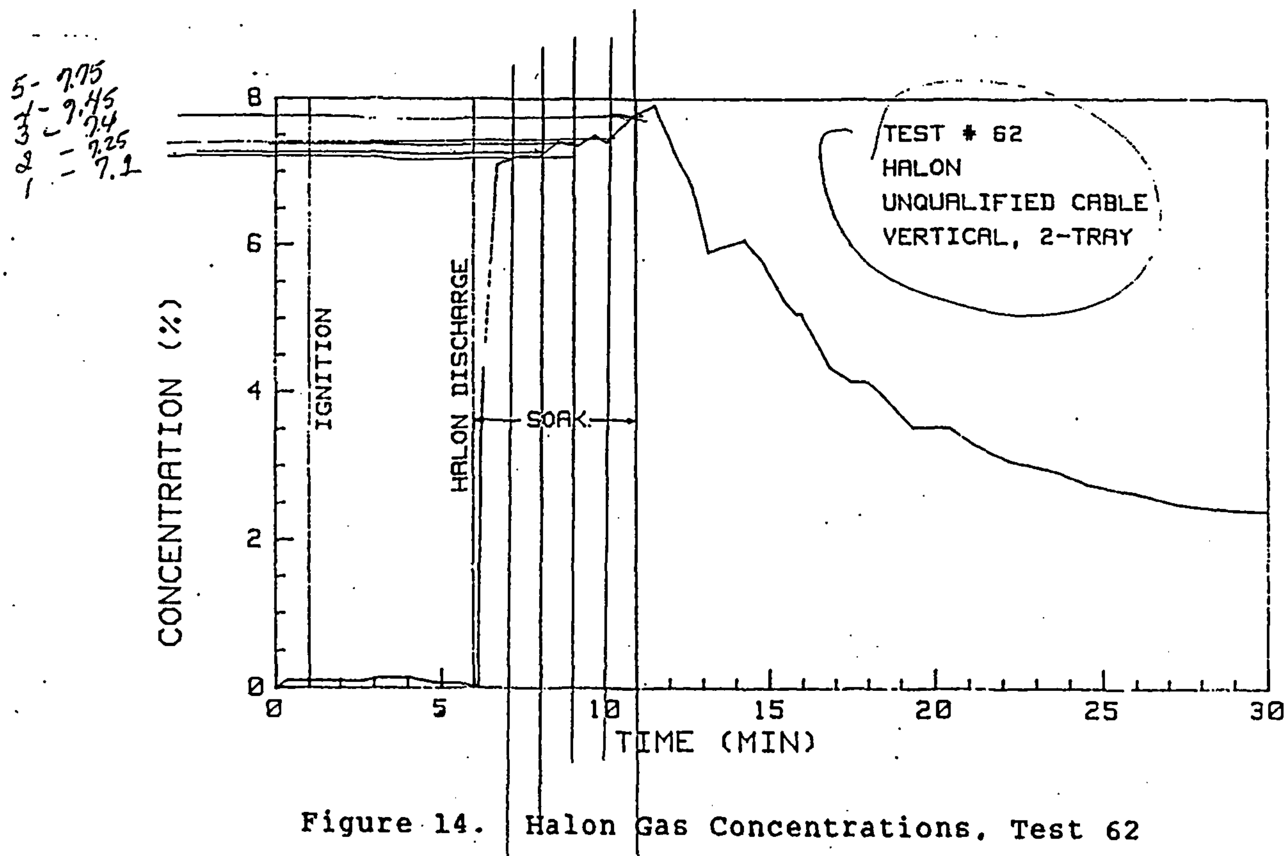

Figure 14. Halon Gas Concentrations, Test 62

however, the gas analyzer port used was at a level of 1.5 m (~5 ft) above the floor where the heavier-than-air Halon 1301 gas tends to settle. Therefore, the overall volumetric room concentration was probably slightly lower. The Halon gas concentrations measured were typically 6 to 9 percent.

For Halon 1301, and fires in the horizontal cable configuration, a soak time of 10 minutes was required for qualified cable (Test 57) and 16 minutes for unqualified cable (Test 61). The soak time for unqualified cable was probably less because the cable does not produce the deep-seated, smoldering fires like the unqualified cable, but no further testing was performed. Exposure fires in vertically oriented trays required soak times of 0 minutes and 5 minutes, for qualified and unqualified cable, respectively. The 0-minute soak time shows that the enclosure was not "closed up" and that fires of this size in a vertical cable tray are easily extinguished with Halon even without a soak time. Unqualified cable may not have required the 5-minute soak time, but no further testing was performed.

Table 6 shows the minimum soak times required to effectively suppress and prevent reignition of the test exposure fires with Halon 1301. Enclosure cooling rates were not high; however, enclosure temperatures never got very high. The Halon was effective in cooling the fire just by extinguishing the flames. The average enclosure temperature cooling rate was negligible.

Table 6

Minimum Soak Times Required Using Halon 1301 Suppression (6 Percent Concentration) for Exposure Fires

Tray Configuration	Cable Type: IEEE-383 Qualified	Cable Type: Unqualified
Horizontal	10 minutes	16 minutes
Vertical	0 minutes	5 minutes

The effectiveness of overhead water sprinklers will be discussed in the following paragraphs. Overhead water sprinklers designed to meet NFPA-13 standards were effective in dousing the exposure fires. In most water sprinkler tests,

except Tests 65 and 66, the soak time was used along with the sprinkler spray duration and is the same length as the sprinkler spray duration. In none of these tests did the fire reignite after suppression, although there was occasionally smoking in the tray.

The soak time (and sprinkler spray durations) for water sprinklers were approximately the same as for the Halon 1301; in the horizontal configuration, 5 minutes and 16 minutes for qualified and unqualified cable, respectively. In the vertical configuration, a spray duration of 4 minutes with no soak time was sufficient to suppress the exposure fires in qualified cable and a soak time and sprinkler spray duration of 5 minutes was necessary for unqualified cable. Again, as with Halon 1301, in the horizontal configuration, less than 16 minutes of spray duration and soak time is probably sufficient but was not tested. As with the Halon suppression system, the vertical tray configuration appears to be easier to suppress with sprinklers; this is probably due to the direct impingement of water on all the cable trays in the vertical configuration.

The suppression soak and/or spray times for water sprinklers on exposure fires are shown in Table 7. It should be noted as discussed in Section 3.1 that except where noted the soak time and spray duration are the same. The soak times for water sprinklers may have been shorter in all cases, but the soak times were based on the results from the Halon tests and no further tests were performed. Based on the results of Test 66 for sprinkler systems, it appears that the spray duration may be more important than the soak time. The water sprinklers were effective in cooling both the enclosure and the cables, with an average cooling rate of 12°C/minute for the enclosure.

Table 7

Soak Time Required Using Water Sprinklers for Suppression of Exposure Fires

Tray Configuration	Cable Type: IEEE-383 Qualified	Cable Type: Unqualified
Horizontal	5 minutes	16 minutes
Vertical	0-minute soak 4-minute spray	5 minutes

3.3 Halon 1301 Suppression of Fully Developed Cable Fires

In addition to the two-tray exposure fire suppression tests discussed earlier, four (4) additional tests were conducted with Halon 1301 to evaluate its capability to suppress fully developed, five-tray cable fires; these tests are shown in Table 8. Both cable types and configurations were tested. For all tests in this series, the 6 percent volumetric room concentration for Halon 1301 specified in NFPA-12A was satisfied. No other concentration levels were tested. In this Section only the Halon 1301 suppression tests on fully developed cable tray fires are discussed.

6% is not "specified" in NFPA 12A

Due to the similarity of the data only three tests will be used to show the effectiveness of the Halon system: two horizontal tray tests, Test 86 (unqualified cable) and Test 87 (qualified cable), and one vertical test, Test 92 (unqualified cable). Only these tests will be discussed in the following paragraphs.

3.3.1 Environment Temperature Response

The enclosure air temperatures for the three tests are shown in Figures 15 (Test 86), 16 (Test 87), and 17 (Test 92). Cable fires in the five-tray configuration, both horizontal and vertical, produce much higher enclosure temperatures and a more dramatic decrease in room temperature when Halon was discharged as compared to the exposure fire tests. Enclosure temperatures for horizontal unqualified cable, Test 86, Figure 15, show a very rapid temperature rise to 342°C with a drop 5 minutes after suppression from 342°C to 75°C, a cool down rate of 67°C/minute. This test experienced a cool down rate during the 10-minute soak time of ~30°C/minute. The unqualified cable in Test 87, Figure 16, resulted in an enclosure temperature profile much like Test 86, except the temperatures were not as high and the Halon decreased the temperature from 300°C to 170°C in the first 5 minutes (a cool down rate of 26°C/minute) and only to 120°C by the end of the soak time (a cool down rate 12°C/minute).

In general, enclosure air temperatures in the vertical tray configurations when compared to the horizontal tray configuration were higher for unqualified cable and lower for qualified cables. This is due to the rapid burning of unqualified vertical cabling described earlier (Section 2.5).

Figure 17, the enclosure temperature for vertical unqualified cable Test 92, shows a rapid temperature rise to 481°C with a drop before suppression to 360°C; 5 minutes after the Halon discharge the temperature dropped another 155°C, a cool down rate of 31°C/minute. By the end of the soak time the enclosure temperature was 120°C, a cool down rate during the

Table 8

Halon 1301 Fire Suppression Tests, NFPA-12A

Test Number	Number of Trays	Orientation of Trays	Type of Cable	Duration[a] of Initiation Fire Exposure	Soak[b] Time (min)	Test Outcome
86	5	H	U	1 5-min burn	10	No reignition, two trays smoking
87	5	H	Q	1 17-min burn	15	No reignition, trays smoking
90	5	V	Q	1 20-min burn	15	No reignition, trays smoking
92	5	V	U	1 5-min burn	10	No reignition, trays smoking

Legend:
- H - Horizontal cable trays
- V - Vertical cable trays
- Q - Qualified IEEE-383 cable
- U - Unqualified cable

[a]Length of time that propane burners were on.

[b]Length of time that the ventilation system was turned off and the stack cover closed. Zero soak time = continuous ventilation with stack cover open during suppression dump.

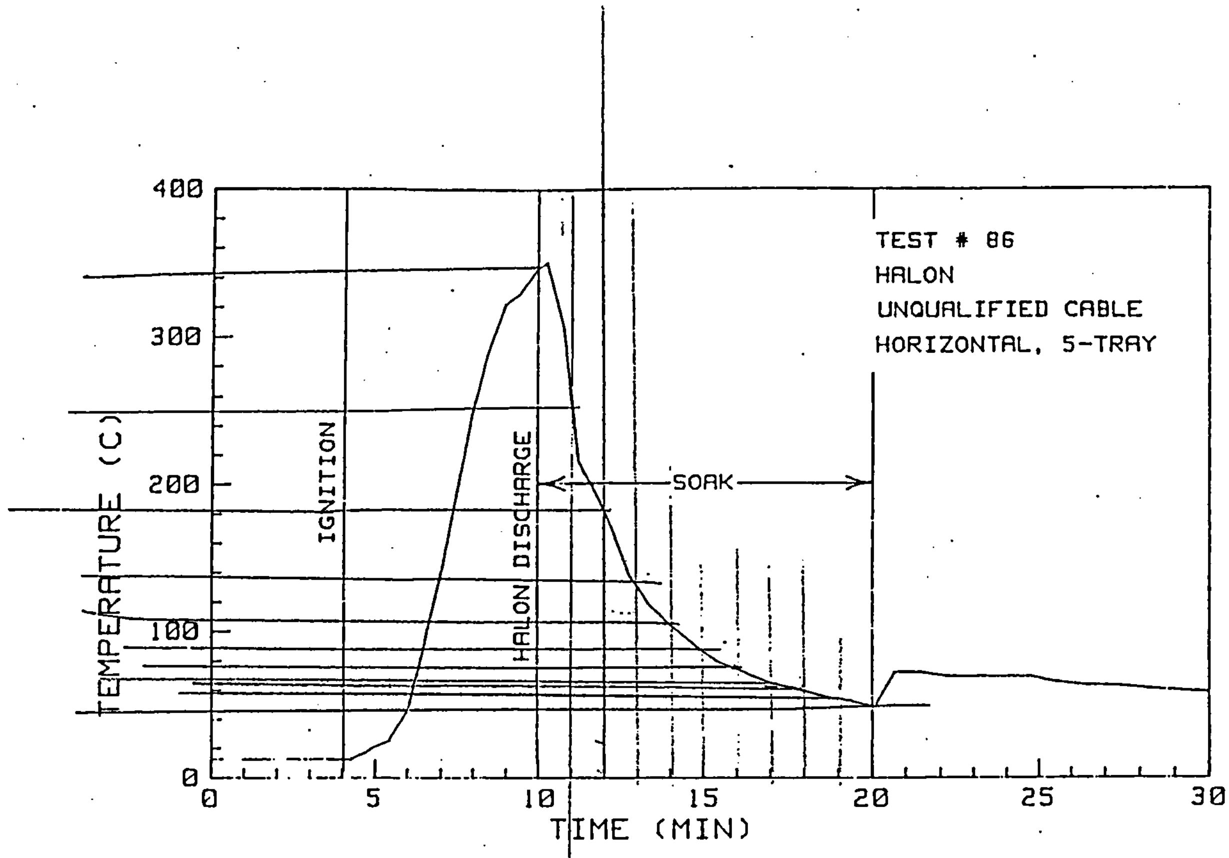

Figure 15. Enclosure Temperature, Test 86

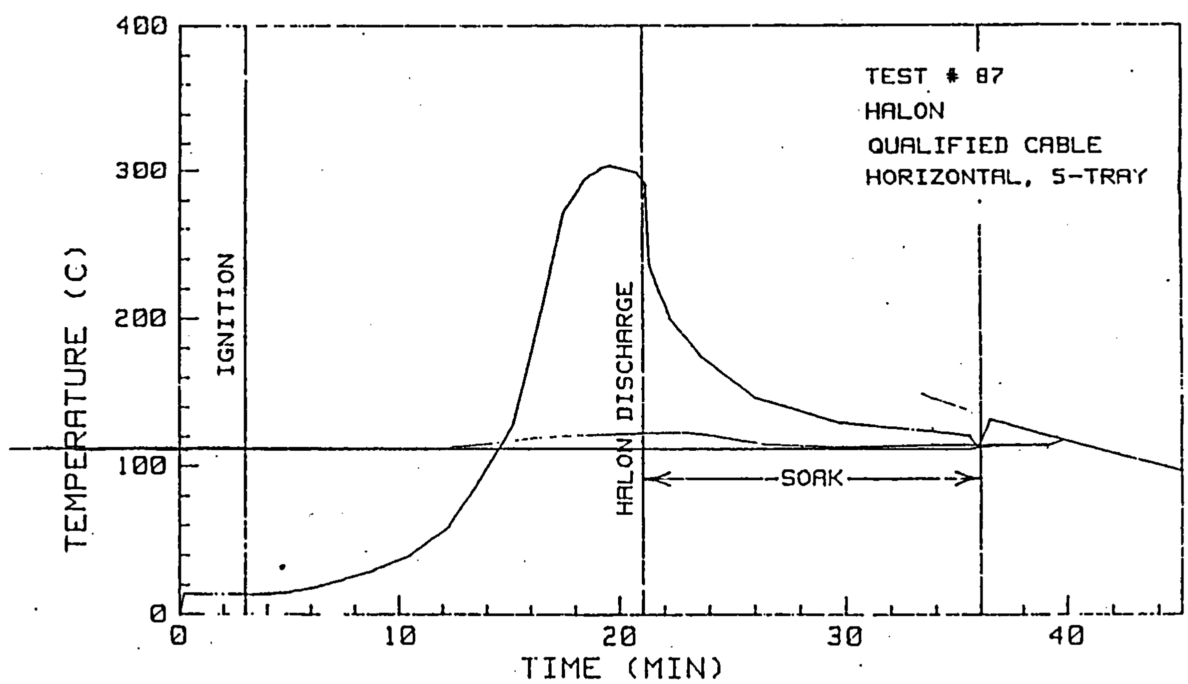

Figure 16. Enclosure Temperature, Test 87

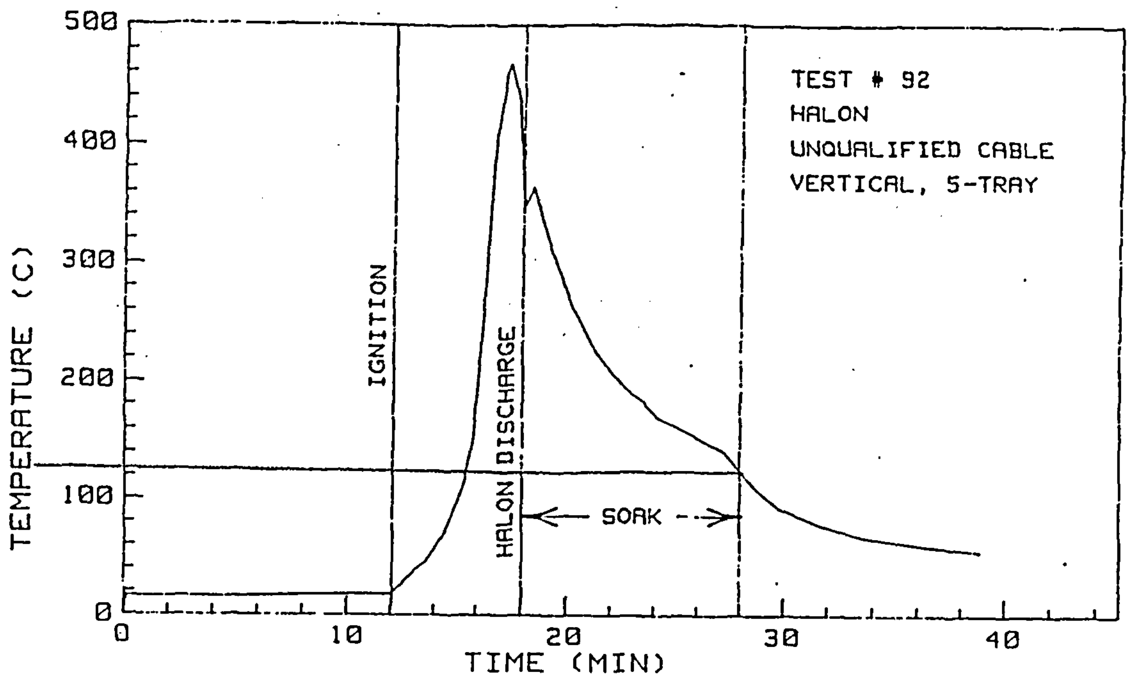

Figure 17. Enclosure Temperature, Test 92

soak time of 24°C/minute. The vertical qualified cable tests were not significantly different except they require additional time to ignite.

In all cases, as can be seen in Figures 15, 16, and 17, the enclosure temperature rose slightly as the hot air was pushed out of the stack at the conclusion of the soak time. The average enclosure cooling rate for both types of cable and both orientations was ~20°C/minute with a range of 30 to 12°C/minute, which is substantially higher than that experienced in the exposure fire suppression tests previously discussed, primarily because the room temperatures were higher.

3.3.2 Cable Temperature Response

The five-tray fully developed fires resulted in a much more deep-seated fire (a fire that is in the conductor insulation of the cable, not just burning the jacket), particularly in the qualified cable, and thus were more difficult to suppress.

Figure 18 shows the temperature responses of cable surfaces and interiors in trays 3 and 5 to the Halon suppression in Test 86 (unqualified cable, horizontal). The temperature data showed a delay in tray 3 before the Halon began to cool the cable surfaces; the temperature then dropped ~150°C.

The Halon gas impinged on tray 5, almost immediately reducing the cable surface temperatures from 492°C to 344°C within 2 minutes (74°C/minute) after the Halon discharge. Subsurface cable temperatures in tray 3 lag the surface temperatures slightly. However, after suppression, the interior cable temperature continued to climb until it peaked at 680°C, 3 minutes after suppression. Then the temperatures began to drop, indicating the fire in the cable had been extinguished. Tray 5 cable subsurface temperatures decreased slightly, then began to climb again until after the soak time had ended, to 679°C. The increase in temperature of the cable may have been a result of a localized hot spot; however, there was smoking observed in the trays, although no flames were visible.

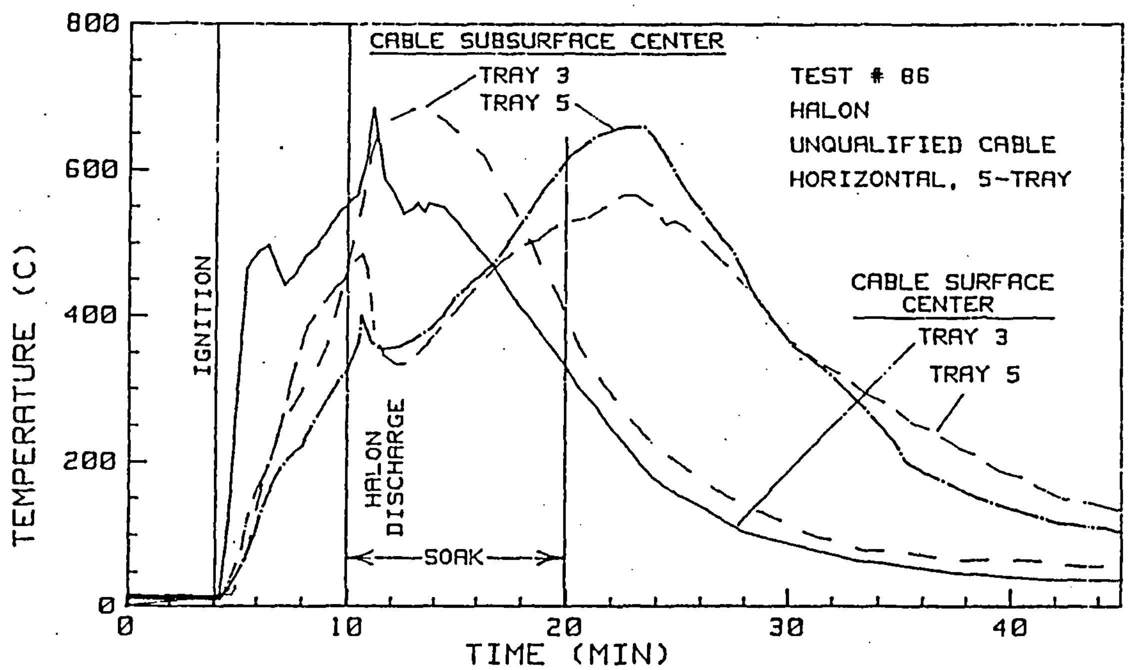

Figure 18. Cable Surface and Subsurface Temperatures, Center of Trays 3 and 5, Test 86

Cable surface and subsurface temperatures for Test 87, a horizontal qualified-cable 15-minute soak, are shown in Figure 19. The temperature profiles for trays 3 and 5 look much the same as in Test 86 (Figure 18), except the temperatures are higher, indicating the qualified cable burned hotter. Also there was not as noticeable a decrease in temperature in the trays when the Halon was discharged. The cables in tray 5 were probably still burning after the Halon discharge as indicated by the continued climb in the cable surface temperature (Figure 19). Obviously, the Halon discharge does not have as significant an effect on the hotter burning qualified cable, because the cable temperatures did not decrease as quickly as they did in Test 86 with unqualified cable. One minute after ventilation was restarted, all

the cable temperatures began to drop rapidly, signaling the end of combustion probably because there was no fuel left to burn.

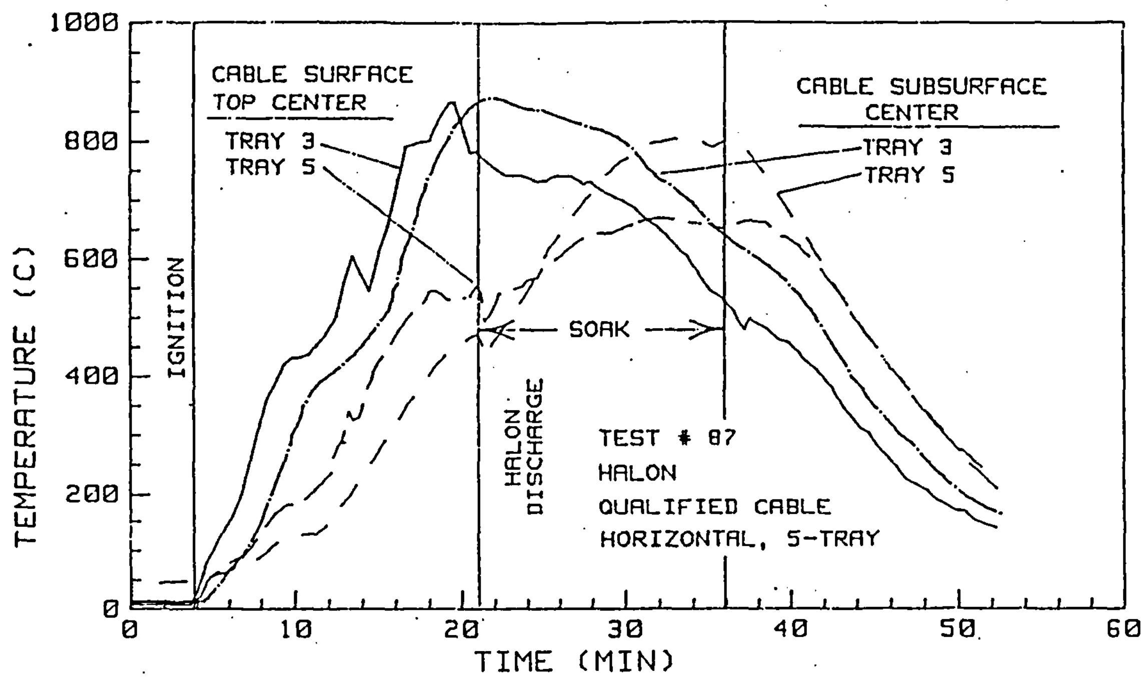

Figure 19. Cable Surface and Subsurface Temperatures, Top and Center of Trays 3 and 5, Test 87

As shown in Figure 20, Test 92, vertical unqualified cable with a 10-minute soak, the cable temperatures, both surface and subsurface, decrease rapidly after the Halon discharge. Only temperatures from cables in tray 3 are shown because tray 5 never ignited in any vertical test, and the surface temperature of the cable in tray 5 only rose 30 to 40°C. The test results demonstrate that unqualified cable in a vertical configuration is the easiest configuration to suppress. Although the results show equal soak times required for the vertical and horizontal configurations.

3.3.3 Suppression Effectiveness and Summary of Results

As with the two-tray exposure fires, the results show that the larger five-tray, fully developed cable fires can also be extinguished with Halon 1301 (6 percent concentration), provided there is a sufficiently long soak time. As discussed previously in Section 3.2.3, the measured Halon gas concentrations were in the range of 7 to 9 percent at the 1.5-m level in the room, with an average room concentration of approximately 6 percent. The soak times required for

suppression of the fully developed fires were longer than those of the exposure fires discussed earlier. In most cases, the qualified cable continued to smolder but did not reignite, demonstrating that Halon is capable of dousing the flame of qualified cable fires but not preventing smoldering combustion which might lead to reignition of the cables or further damage.

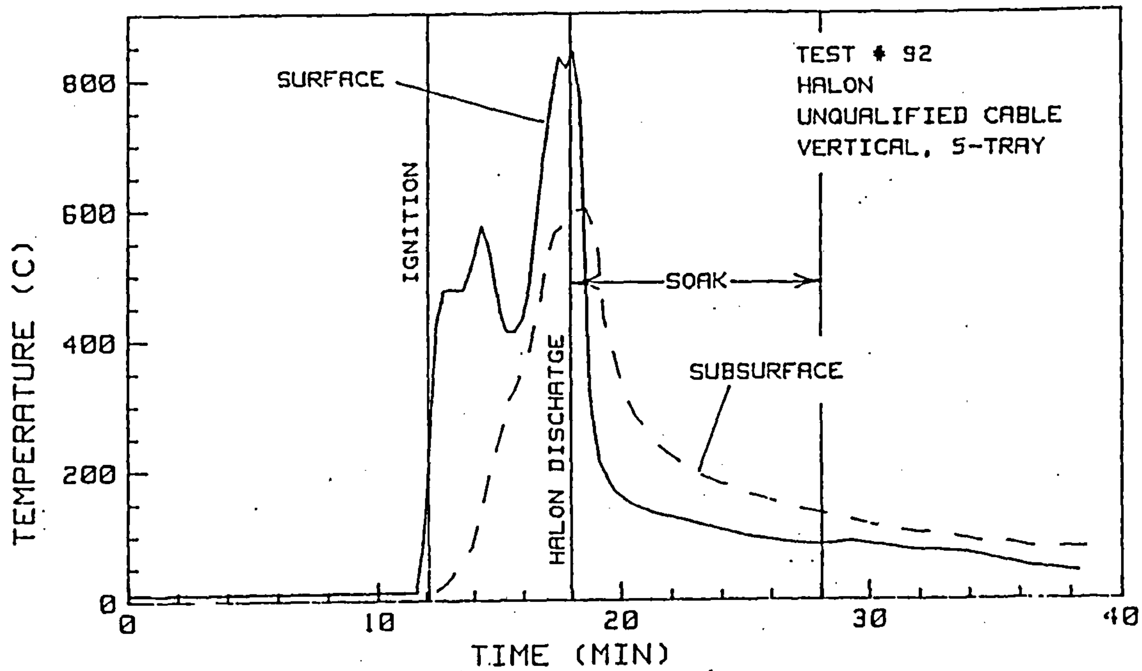

Figure 20. Cable Surface and Subsurface Temperatures, Tray 5, Test 92

Halon 1301 effectively cools the enclosure below cable ignition temperatures (450°C for unqualified cable)[9] or cable damage temperatures (180°C for unqualified cable)[9] but not below normal operating temperatures. The average room cooling rate was 20°C/minute. The Halon 1301 is not effective in cooling smoldering cables although in these tests it did prevent reignition. Halon 1301 can be easily maintained at the specified 6 percent concentration for the required soak times, provided the enclosure is adequately sealed. The minimum soak times required using the Halon 1301 suppression system for fully developed cable tray fires are shown in Table 9. It is obvious from the table that the soak time is not configuration dependent, yet it is cable-type dependent. However, these apparent similarities and differences may not be statistically correct due to the small number of tests conducted.

Table 9

Minimum Soak Times Required Using Halon 1301 Suppression Systems at 6 Percent Concentration for Fully Developed Cable Tray Fires

Tray Configuration	Cable Type: IEEE-383 Qualified	Unqualified
Horizontal	15 minutes	10 minutes
Vertical	15 minutes	10 minutes

3.4 Water Sprinkler Tests on Fully Developed Cable Fires

Table 10 lists the 4 tests conducted using the water sprinkler fire suppression system on the five-tray fully developed fires. Both qualified and unqualified cable, and both vertical and horizontal tray orientations were included in the test matrix. For all tests, the delivery rate of the water sprinkler system satisfied the specifications of NFPA-13. In all the water sprinkler suppression tests, the soak time was the same as the sprinkler spray duration. Therefore, as stated previously for consistency "soak time" will be used in the discussion. Tests 80 and 81 will be used in the discussion of the water sprinkler tests, the results of Tests 79 and 82 are very similar, therefore, they will not be used in the discussion of the results.

3.4.1 Environment Temperature Response

The thermal environment in the room was quickly cooled by the sprinkler spray due to water droplets absorbing heat. Test 80 used the vertical, five-tray configuration with unqualified cable. The vertical orientation and the unqualified cable encouraged rapid ignition of the lower trays. Figure 21 is a plot of the enclosure air temperature for this test. The sprinklers cooled the air temperature in the room from 363 to 78°C in 0.75 minutes (380°C/minute) with an enclosure cool down rate of 69°C/minute during the 5-minute soak time.

The rapid drop in temperature was not as dramatic for the five-tray horizontal configuration, Test 81, as shown in Figure 22. The initial temperature drop was very rapid; however, the cooling rate leveled off as the temperature dropped from 350°C to 140°C (~42°C/minute) during the soak

Table 10

Water Sprinkler Fire Suppression Tests, NFPA-13

Test Number	Number of Trays	Orientation of Trays	Type of Cable	Duration[a] of Initiation Fire Exposure	Sprinkler Duration (min)	Soak[b] Time (min)	Test Outcome
79	5	V	Q	1 17-min burn	5	5	No reignition, some smoking
80	5	V	U	1 5-min burn	5	5	No reignition after ventilation
81	5	H	Q	1 16-min burn	5	5	Reignition, small intermittent fire
82	5	H	U	1 7-min burn	5	5	No reignition after ventilation

Legend: H - Horizontal cable trays
V - Vertical cable trays
Q - Qualified IEEE-383 cable
U - Unqualified cable

[a]Length of time that propane burners were on.

[b]Length of time that the ventilation system was turned off and the stack cover closed. Zero soak time = continuous ventilation with stack cover open during suppression dump.

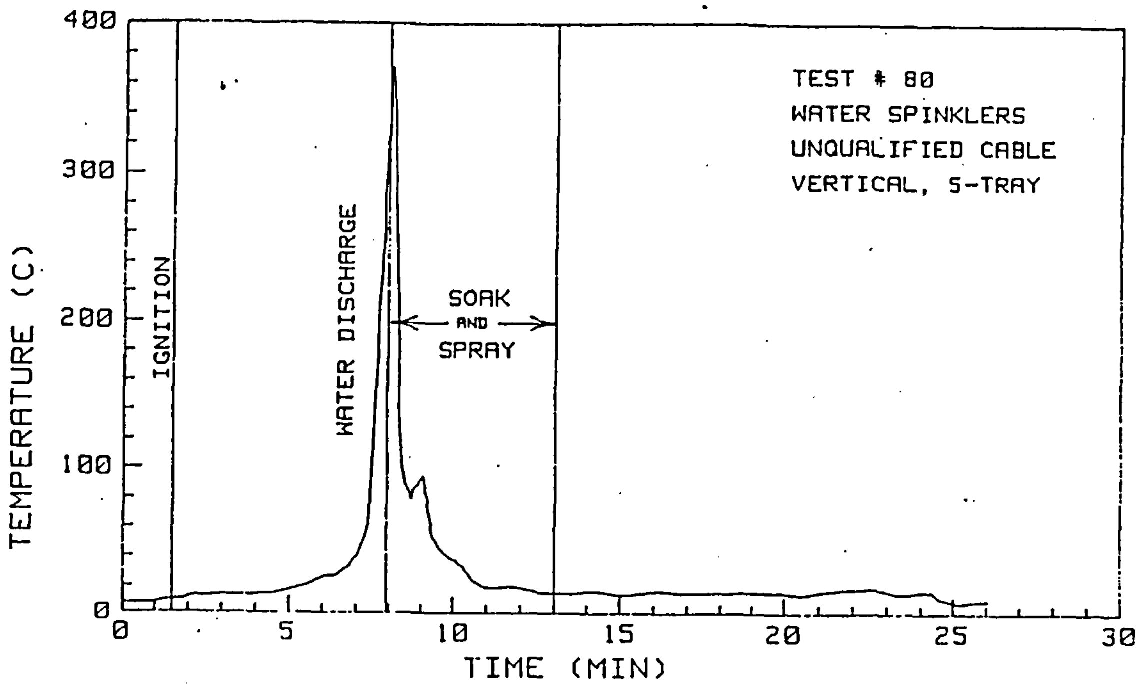

Figure 21. Enclosure Temperature, Test 80

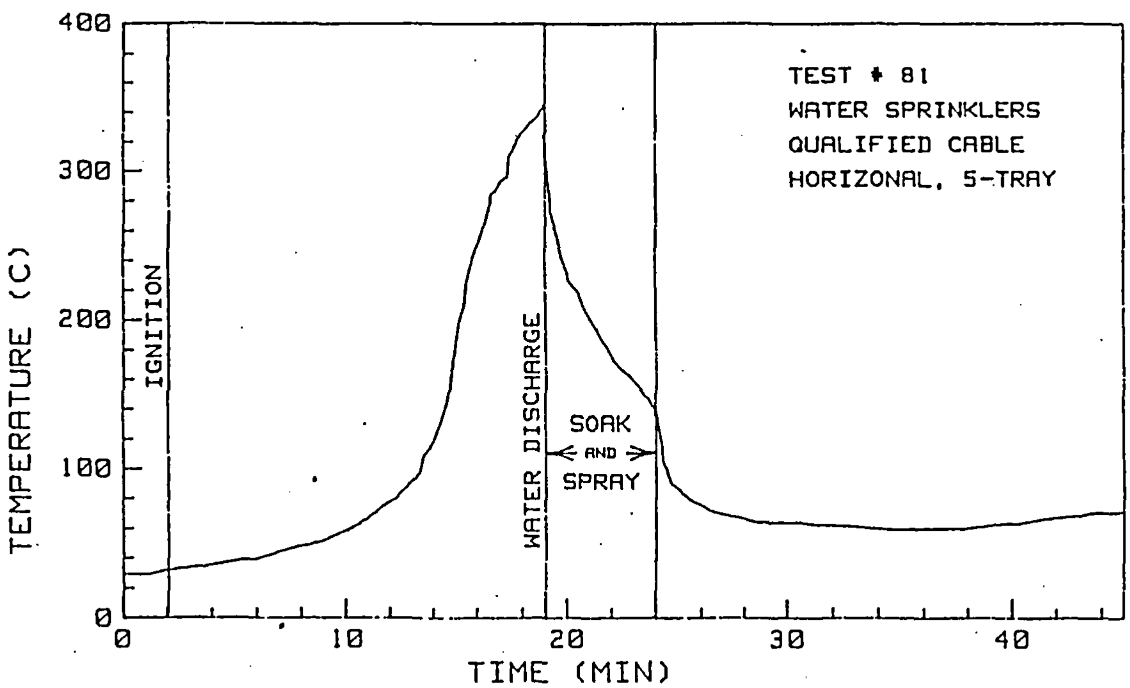

Figure 22. Enclosure Temperature, Test 81

time. Furthermore, after the ventilation was restarted and oxygen was again available, the fire restarted. This indicated that for the horizontal configuration the sprinkler duration should have been longer because the lower trays were shielded from the sprinklers by the upper trays. The fire appeared to restart in trays 3 and 4. An average room-cooling rate of ~50°C/minute was experienced in the successfully suppressed fully developed cable tray suppression tests with a range of 69°C/minute to 40°C/minute.

3.4.2 Cable Temperature Response

The cable temperatures dropped rapidly under the sprinkler suppression system due to the direct impingement of the water on the cables. The cable surface and subsurface temperatures in tray 3 for Test 80 are shown in Figure 23. The surface temperature dropped from 700° to 80°C in 1 minute (620°C/minute) due to the direct impingement of water on the cabling. The subsurface temperature was not as significantly affected. In Test 80, the trays were vertically oriented so that the water reached each tray. In the horizontal configuration, the lower trays were shielded and reignition was possible. This is shown in Figure 24 (Test 81). The subsurface temperature of the cable in tray 4 decreased immediately after the sprinklers were turned on but began climbing again 1/2 minute after the sprinklers were turned off, eventually reaching 900°C. Test 81 is the only water sprinkler test in which reignition occurred. These results indicate that a 5-minute sprinkler suppression spray time is insufficient for the horizontal tray configurations with qualified cable.

3.4.3 Suppression Effectiveness and Summary of Results

Water sprinklers were shown to be effective in suppressing fully developed fires in cable trays in the vertical configuration and somewhat less effective on cable fires in a horizontal configuration. In all tests the flames were initially extinguished with the water; however, in the horizontal cable tray configuration using qualified cable, the water did not penetrate enough of the cable trays to prevent reignition of the cables.

Although soak time is used in the discussion, it appears that water sprinkler effectiveness is dependent on having a long enough sprinkler spray time and on the water having direct access to cables in the tray. The method of packing the cables could have a significant effect on the ability of water to suppress the fires on a horizontal cable tray. It should be noted that the method of cable packing used in these tests allowed the maximum amount of air flow, and hence, water flow through the cables.

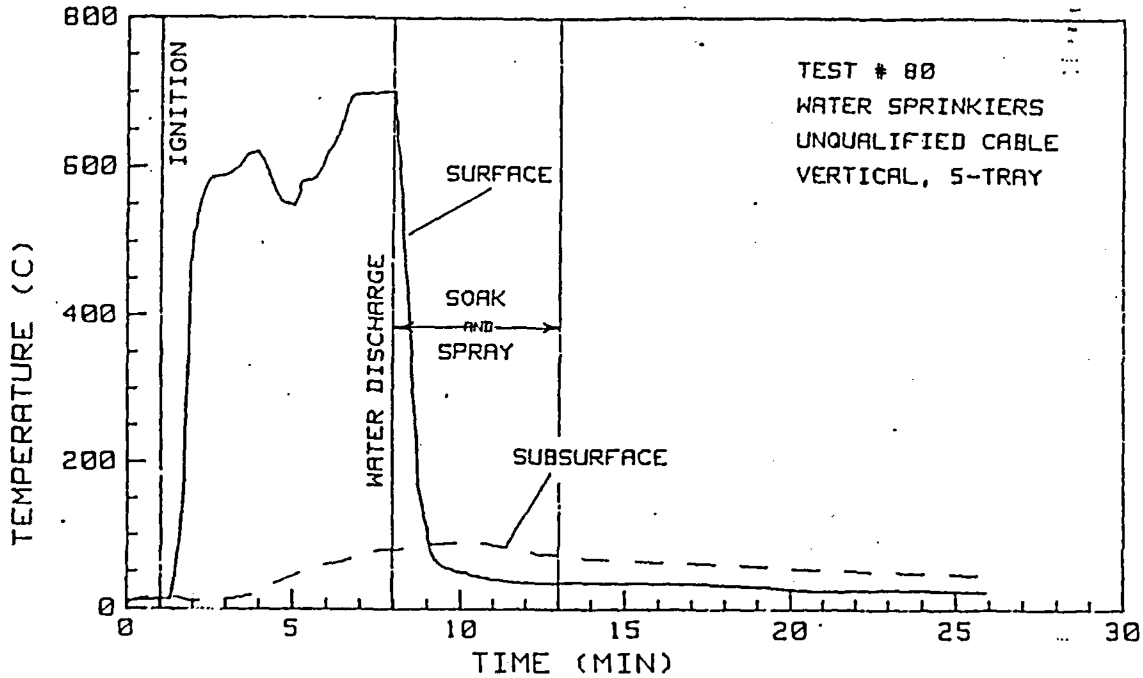

Figure 23. Cable Surface and Subsurface Temperature, Tray 3, Test 80

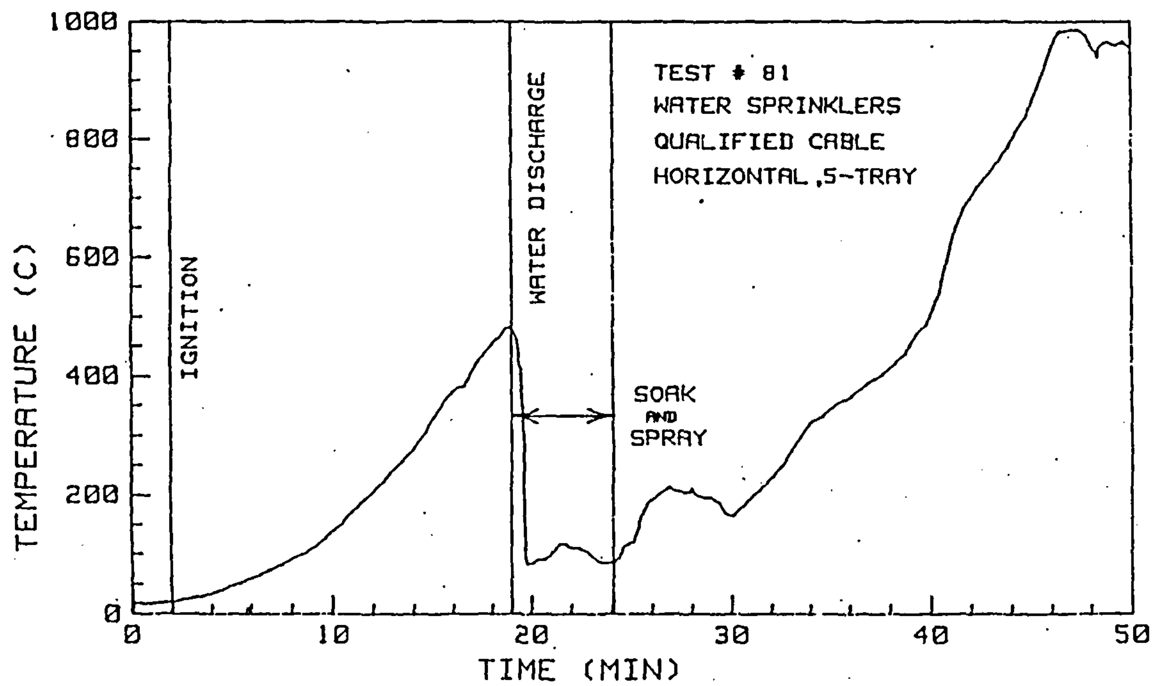

Figure 24. Cable Subsurface Temperature, Center of Tray 4, Test 81

The minimum soak times required using water sprinkler suppression systems for fully developed cable tray fires are given in Table 11. An effective soak time (spray duration) was not found for qualified cable in the horizontal configuration during this test series because no further tests were conducted; however, the soak time is greater than 5 minutes. The vertical configuration was more readily suppressed than the horizontal because of the blockage effects of the upper trays. It appears that the water does not seep through the upper trays because the water evaporates before it reaches lower cable trays.

Table 11

Minimum Soak Times[a] Required Using Water Sprinkler Suppression Systems for Fully Developed Cable Tray Fires

Tray Configuration	Cable Type	
	IEEE-383 Qualified	Unqualified
Horizontal	>5 minutes	5 minutes
Vertical	5 minutes	5 minutes

[a]In the water sprinkler suppression tests the soak times are the same length as the sprinkler spray durations.

Water sprinklers were found to be effective in cooling the enclosure air temperature, typically below 100°C, within 1 to 3 minutes after initiation of the suppression system. Temperature cool down rates of 380°C/minute were measured for the vertical configuration, with the average enclosure cool down rate for water sprinklers being ~50°C/minute. The water was effective in cooling the cable surfaces but was not as effective in cooling subsurface cable temperatures.

In summary, water sprinklers were found effective in cooling the environment, the cable surfaces for cable trays in a vertical configuration, and also for the horizontal configuration if the water has direct access to the tray.

3.5 Directed Water Spray Tests on Fully Developed Cable Fires

Table 12 lists the five tests conducted using the directed water spray suppression system. Only the five-tray configuration was tested with directed water spray. Both

Table 12

Directed Water Spray Fire Suppression Tests, NPFA-15

Test Number	Number of Trays	Orientation of Trays	Type of Cable	Duration[a] of Initiation Fire Exposure	Spray Duration (min)	Soak[b] Time (min)	Test Outcome
72	5	H	Q	1 19.5-min burn	5	5	No reignition after ventilation
73	5	H	Q	1 16.1-min burn	5	0	No reignition
74	5	H	U	1 6-min burn	5	0	No reignition
75	5	V	Q	1 25-min burn	5	0	No reignition, some smoking
77	5	V	U	1 5-min burn	5	5	No reignition after ventilation

Legend: H - Horizontal cable trays
V - Vertical cable trays
Q - Qualified IEEE-383 cable
U - Unqualified cable

[a]Length of time that propane burners were on.

[b]Length of time that the ventilation system was turned off and the stack cover closed. Zero soak time = continuous ventilation with stack cover open during suppression discharge.

horizontal and vertical configurations and qualified and unqualified cable were included in the test matrix. As in previous sections, unless the soak time and spray duration are different, only the soak time is used in the discussion.

Only Tests 72 and 75 will be used in the discussion of the directed water spray tests because the results from Tests 73, 74, and 77 are very similar.

3.5.1 Environment Temperature Response

In Test 72, a slow but steady decrease in room temperature occurred after initiation of the directed water spray suppression (Figure 25). The enclosure temperature decreased from 220° to 95°C during the 5-minute soak time resulting in a cool down rate of 25°C/minute. The ventilation system was turned on after the soak time, at 38 minutes into the test as shown in Figure 25. At that time a small but sharp temperature reduction occurred due to the hot gases in the enclosure being exhausted. In Test 75, with vertical orientation and continuous ventilation (no soak time) and a spray duration of 5 minutes, the enclosure temperature as shown in Figure 26, decreased at a rate of ~30°C/minute, from 302°C to 155°C, during the spray time of 5 minutes.

Unlike the other suppression systems tested, the directed water spray system did not have a direct effect on the enclosure because the water was only being sprayed onto the cables. However, because of the instantaneous extinguishment of the flames, the system was able to cool the enclosure at an average rate of ~37°C/minute with a range of 66°C/minute to 25°C/minute. The enclosure cooling may also be a result of maintaining the ventilation in the room during most of these tests.

3.5.2 Cable Temperature Response

Measurements of the cable temperatures clearly demonstrate the cooling effectiveness of the directed water spray system. Figure 27 shows cable surface and subsurface temperatures for tray 3 in Test 72. The surface temperature dropped from 900°C to 80°C in 0.75 minutes (more than 1000°C/minute) due to the direct and unimpeded water spray on the cables. The subsurface temperature in tray 3 dropped dramatically also, although it lagged behind the surface temperature. A similar pair of curves is shown in Figure 28 for tray 5 in the same test. The same sharp drop in temperature (from 430°C to 55°C in 0.75 minutes) occurred in tray 5, illustrating that this effect occurs in all of the trays in the horizontal configuration. This is a marked difference from the effects observed in the water sprinkler and Halon 1301 tests discussed in Sections 3.3 and 3.4.

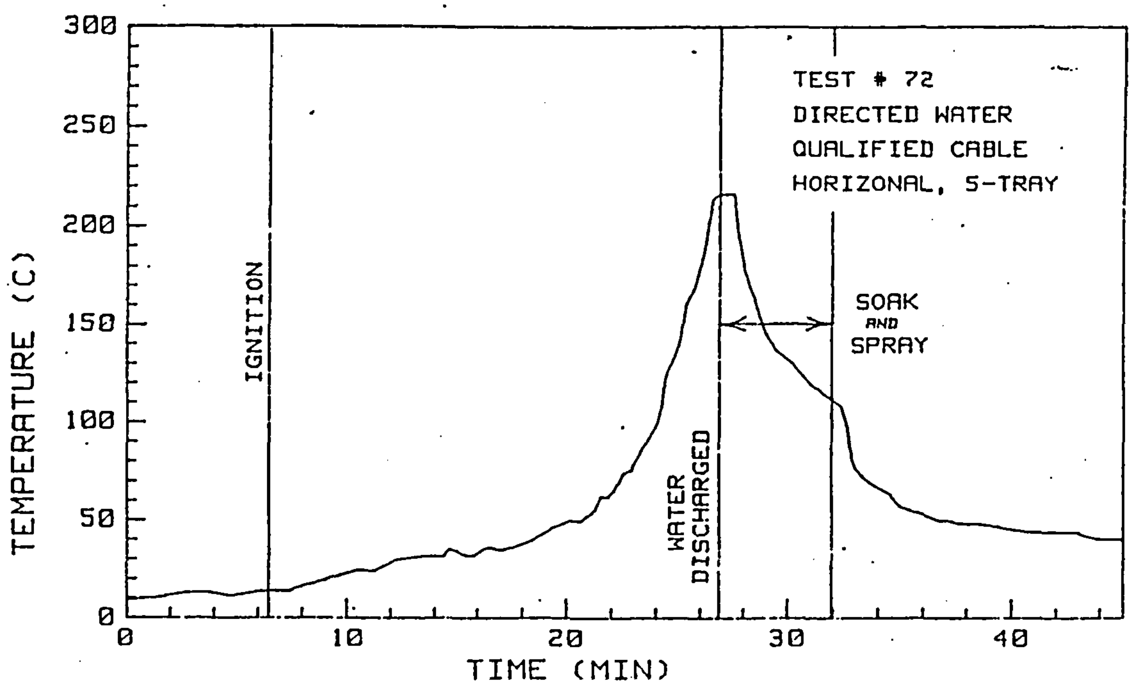

Figure 25. Enclosure Temperature, Test 72

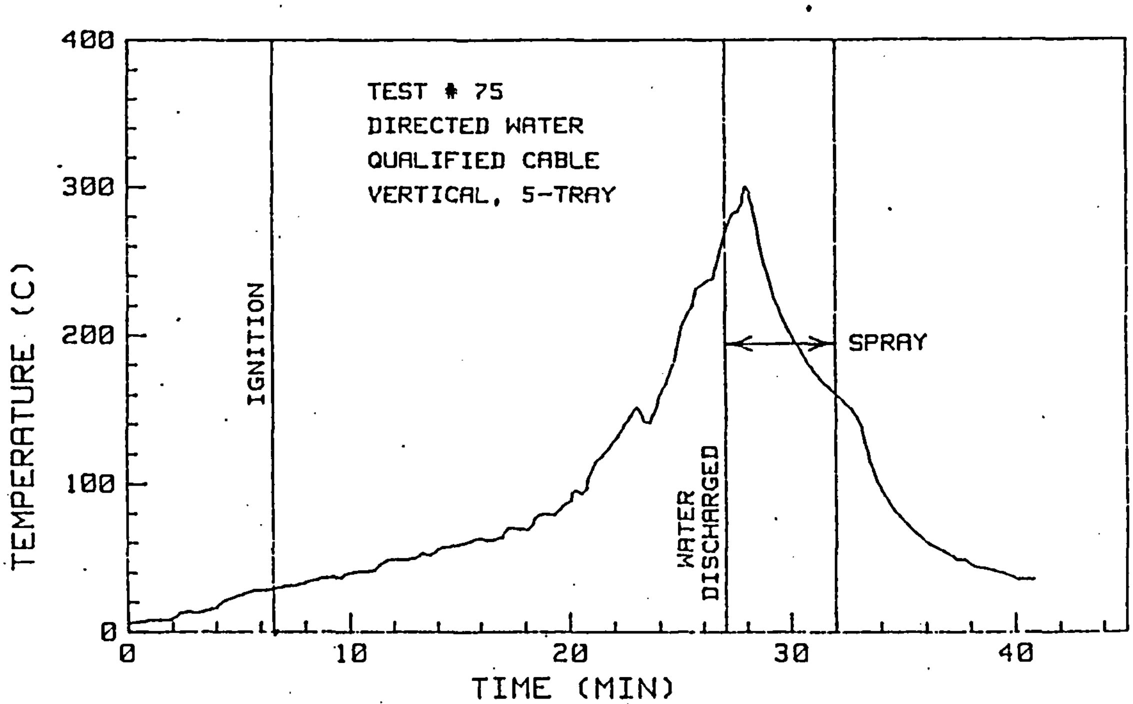

Figure 26. Enclosure Temperature, Test 75

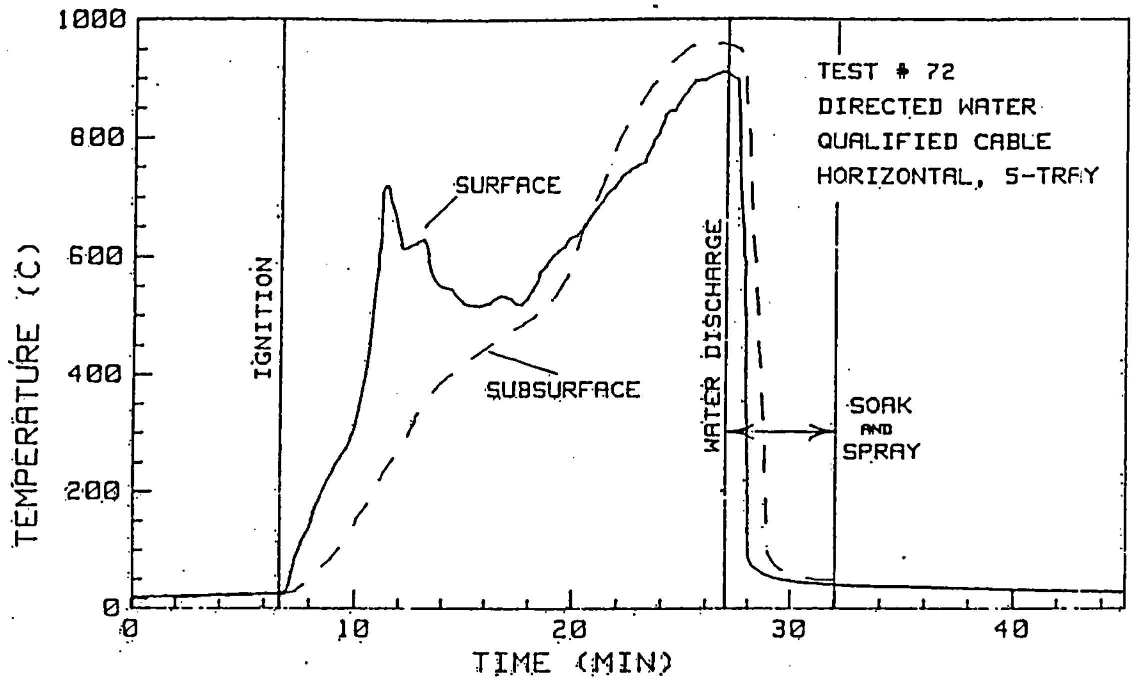

Figure 27. Cable Surface and Subsurface Temperatures, Center of Tray 3, Test 72

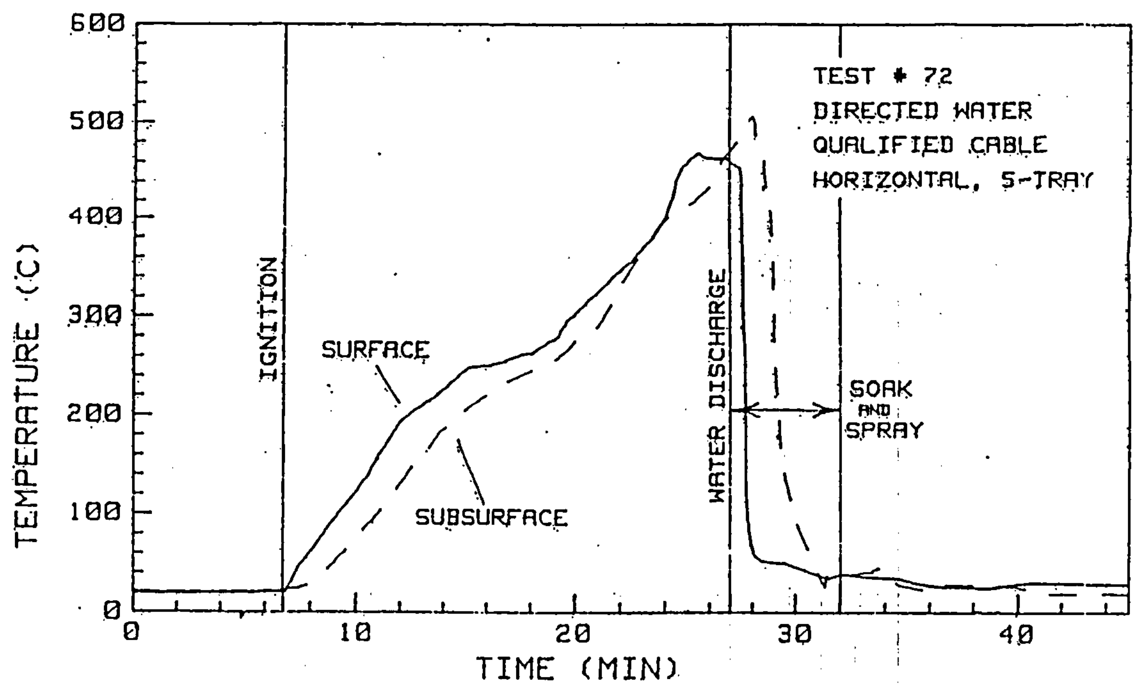

Figure 28. Cable Surface and Subsurface Temperatures, Center of Tray 5, Test 72

A third pair of curves similar to those in previous figures are shown in Figure 29 for tray 3 in Test 75 (vertical, 5-minute spray), which used the vertical tray orientation and continuous ventilation. This figure illustrates that the directed water spray system was equally effective for both horizontal and vertical tray orientations. Although the cooling rate was somewhat slower (~230°C/minute) in the vertical configuration, this was most likely due to the fact that the water did not penetrate the cables the way it did in the horizontal configuration. In addition, direct water spray was as effective in cooling the qualified cable fires, which have deep-seated fires, as it was in suppressing unqualified cable fires.

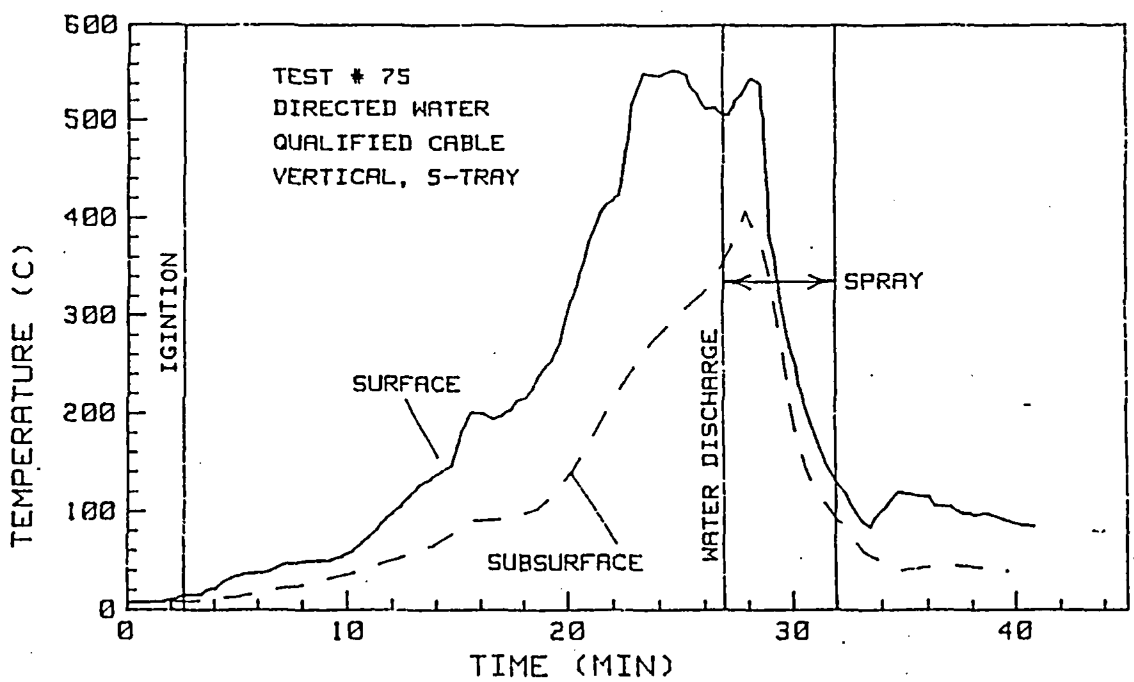

Figure 29. Cable Surface and Subsurface Temperatures, Tray 3, Test 75

3.5.3 Suppression Effectiveness and Summary of Results

As expected, the directed water spray suppression system was effective in suppressing all fully developed cable tray fires. The first test with directed water spray, Test 72, demonstrated such a dramatic effect in suppressing the fire and cooling the cables that the three succeeding tests were

performed with continuous ventilation. In none of the subsequent tests did fires reignite.

The spray nozzles were pointed directly into the trays, in both tray orientations, and knocked down the flames with both pressure and direct water impingement. The directed water suppression system proved to be very effective in suppressing fires for the spray durations tested. However, due to the pressure of the spray, the water also knocked away burned insulation, revealing bare conductors. This did not occur with the other suppression systems. Minimum soak times required using directed water spray suppression systems for fully developed cable tray fires are given in Table 13. This method provides very rapid cable cooling because of the direct and unimpeded application of water on the cables. The average enclosure cooling rate was ~37°C/minute. Vertical cable configuration cooled at a slower rate. The fact that no 'soak time" is required for most cable types and tray orientations indicates that the critical parameter in directed water spray suppression is the spray duration. The 5-minute soak time used with the 5-minute spray duration for unqualified cable in a vertical configuration may not be required; however, no further tests were performed.

Table 13

Minimum Soak Times[a] Required Using Directed Water Spray Suppression Systems for Fully Developed Cable Tray Fires

Tray Configuration	Cable Type: IEEE-383 Qualified	Cable Type: Unqualified
Horizontal	0-minute soak 5-minute spray	0-minute soak 5-minute spray
Vertical	0-minute soak 5-minute spray	5 minutes

[a]In these tests it appears that spray duration is more critical than soak time.

3.6 Carbon Dioxide Tests on Fully Developed Cable Fires

Table 14 lists the five tests conducted using the carbon dioxide fire suppression system. Only the five-tray configuration was tested. Both horizontal and vertical orientations and both qualified and unqualified cable were included in the test matrix.

Table 14

Carbon Dioxide Fire Suppression Tests, NFPA-12

Test Number	Number of Trays	Orientation of Trays	Type of Cable	Duration[a] of Initiation Fire Exposure	Soak[b] Time (min)	Test Outcome
83	5	H	Q	1 18-min burn	10	Reignited when ventilated
84	5	H	Q	1 16-min burn	15	No reignition, trays smoking
85	5	H	U	1 5.5-min burn	10	No reignition after ventilation
88	5	V	Q	1 17-min burn	15	No reignition, trays smoking
91	5	V	U	1 5-min burn	10	No reignition after ventilation

Legend: H - Horizontal cable trays
V - Vertical cable trays
Q - Qualified IEEE-383 cable
U - Unqualified cable

[a]Length of time that propane burners were on.

[b]Length of time that the ventilation system was turned off and the stack cover closed.

Prior to conducting these tests, there was speculation that the rapid cooling caused by the expanding carbon dioxide might cause thermal shock effects in the metal cable trays. To investigate this concern, a thermocouple was placed in a piece of mild steel and positioned near the cable trays. Figure 30 is a plot of the temperature response of the thermal shock sample during the test. The rate of change of the temperature is approximately 8°C/minute over the 10-minute soak time, which appears to be too low to cause thermal shock in metal cable trays.

The following discussion of the carbon dioxide cable tray fire suppression tests will employ the results of Tests 83, 85, and 91. The results from Tests 84 and 88 are very similar.

3.6.1 Environment Temperature Response

The cooling effect of the carbon dioxide suppression system on the air in the test enclosure for Test 83, using qualified cable and the horizontal orientation, is shown in Figure 31. The enclosure temperature initially dropped ~185°C in 1.5 minutes (~120°C/minute) from 295°C to 110°C. In this test, the cables reignited when the ventilation was restarted. Figure 32 shows a similar trace for Test 85, which used unqualified cable. In the first few minutes, the same cooling rate occurred in unqualified cable as for qualified cable; however, the unqualified cable in Test 85 did not reignite after the soak time and experienced a cool down rate of 29°C/minute during the soak time. This again shows that the deep-seated fires in qualified cable can cause reignition. A similar plot is shown in Figure 33, showing the room temperature in Test 91, in which unqualified cable in the vertical orientation was used. The peak temperature was much higher, 520°C, because of the rapid burning in the vertical configuration; however, the room had already begun to cool down before the suppression discharge, probably because one of the vertical cable trays had self extinguished. In any case, the carbon dioxide caused rapid cooling from 325°C to 110°C within 1.5 minutes (~140°C/minute) with a cool down rate of 38°C/minute during the soak time. The average room cooling rate during the soak time for carbon dioxide suppression systems was ~24°C/ minute, with a range of 38°C/minute to 12°C/minute.

3.6.2 Cable Temperature Response

The cooling effect of carbon dioxide on the cables is shown in Figure 34, which shows cable surface and subsurface temperatures in trays 3 and 5 for Test 83. The suppression system caused an initial rapid cooling of the cable surface in both trays. However, after ventilation was restarted

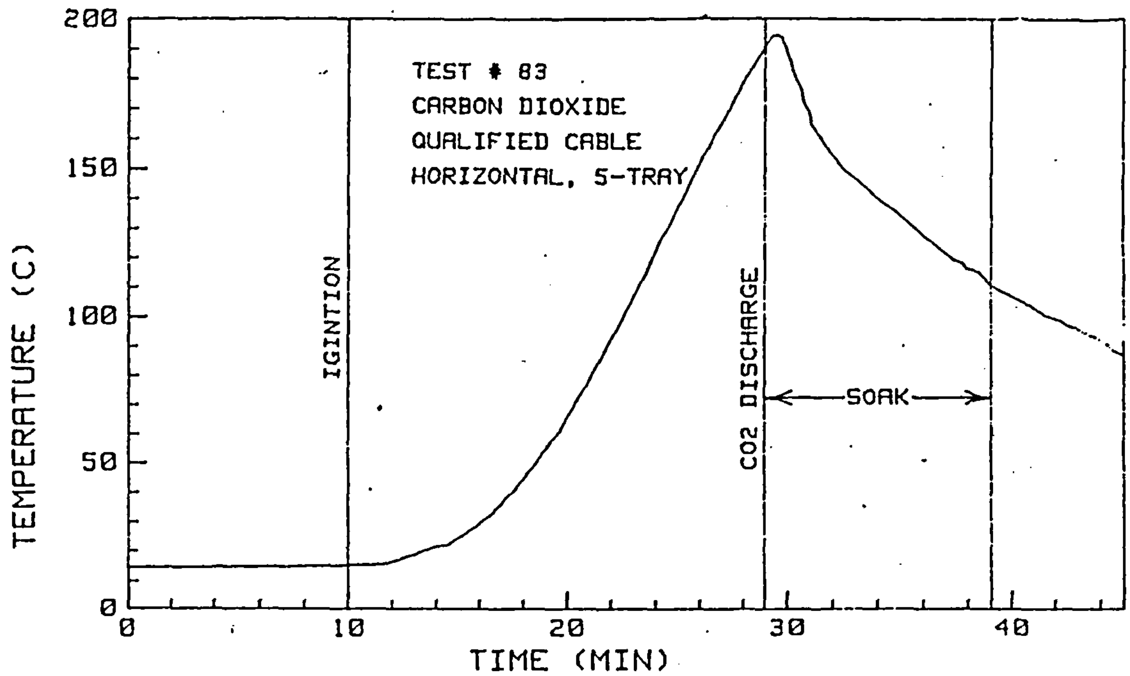

Figure 30. Temperature of Thermal Shock Test Sample, Test 83

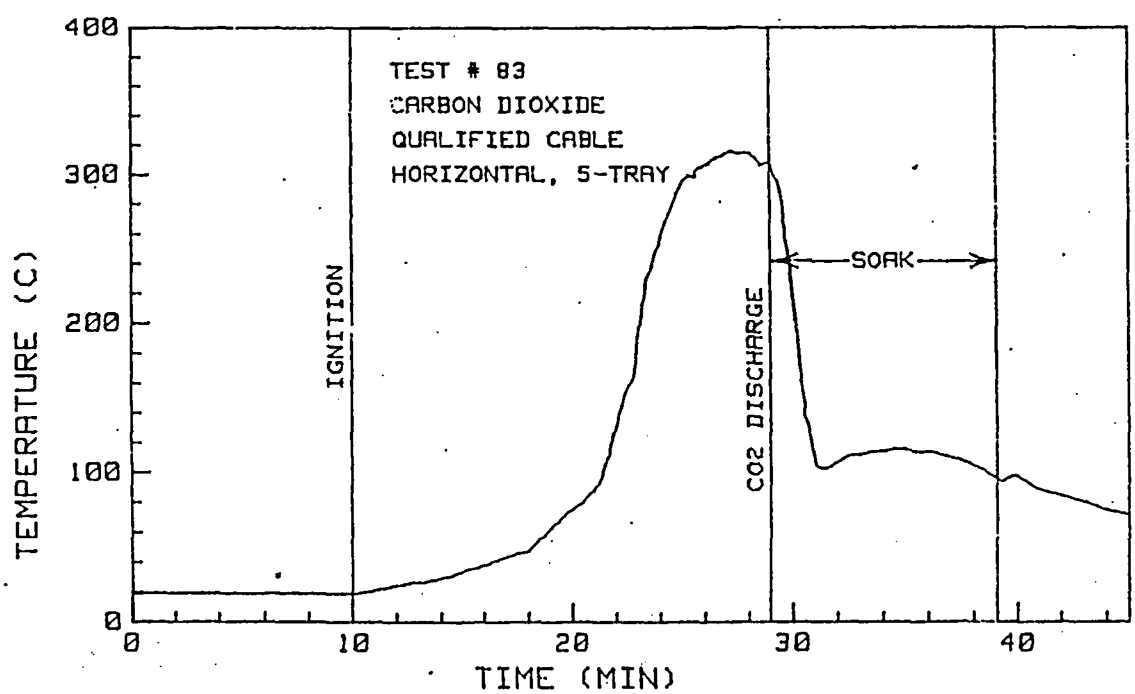

Figure 31. Enclosure Temperature, Test 83

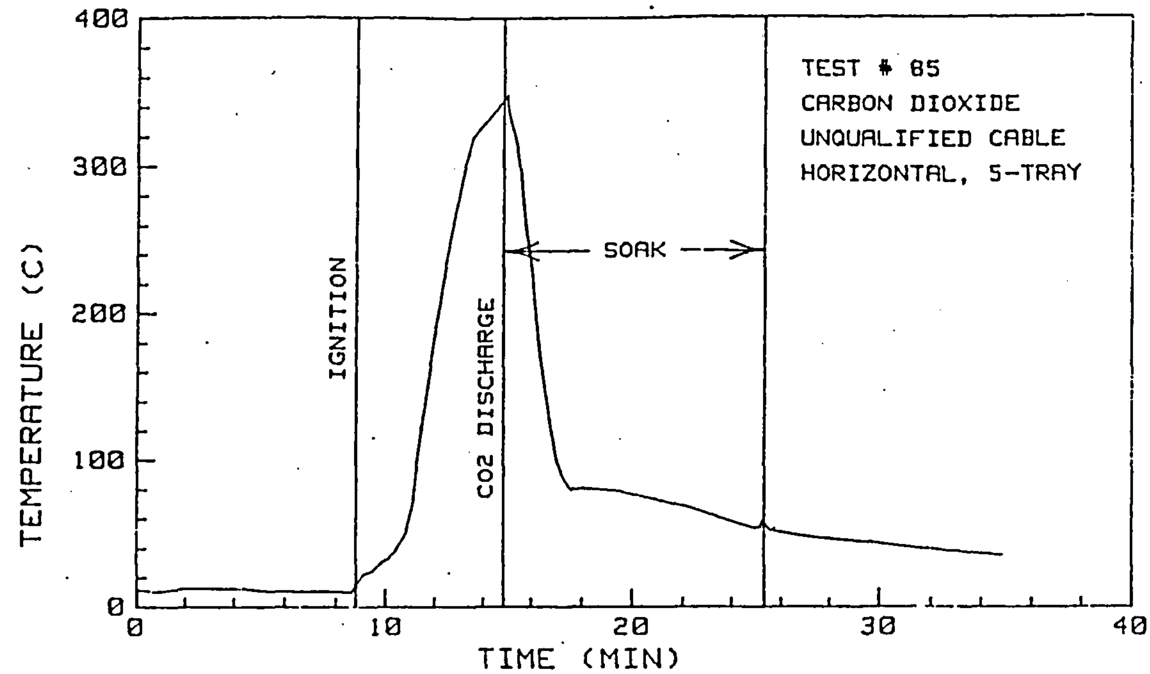

Figure 32. Enclosure Temperature, Test 85

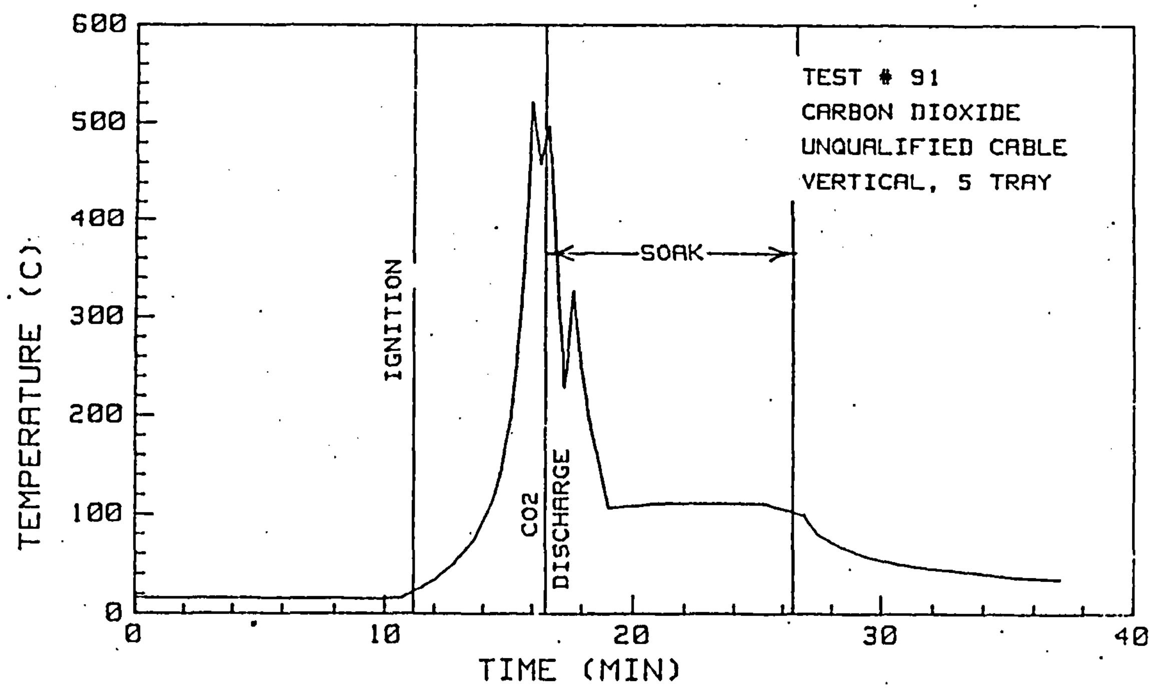

Figure 33. Enclosure Temperature, Test 91

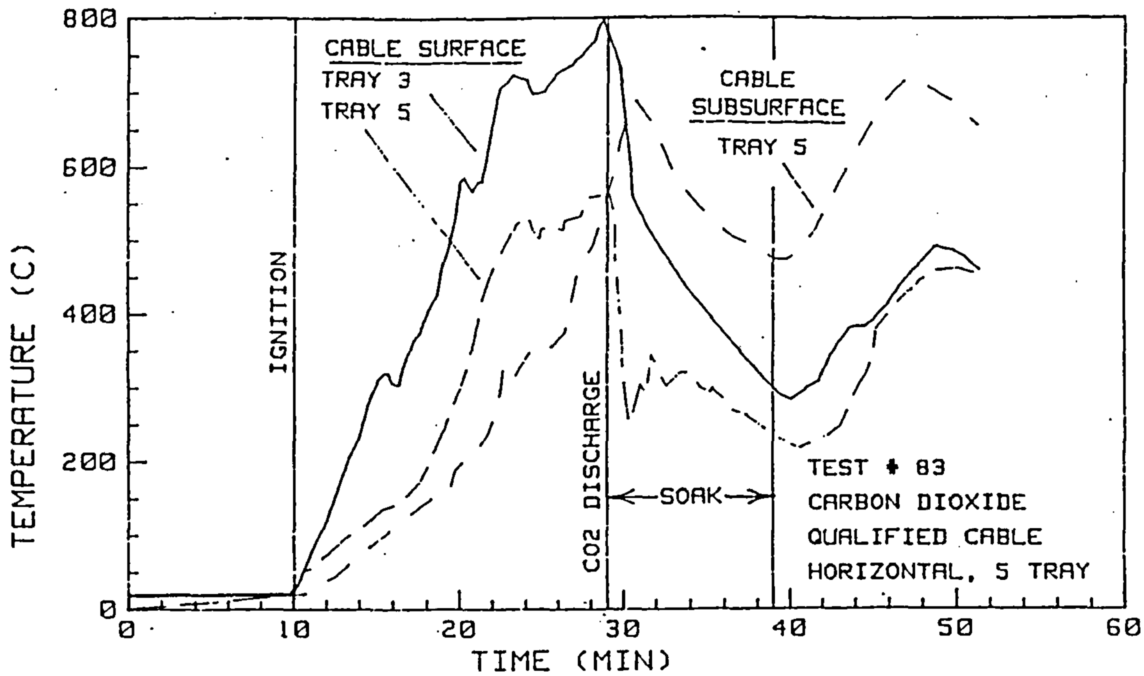

Figure 34. Cable Surface Temperatures, Centered in Trays 3 and 5, Test 83

(approximately the 39-minute mark), the temperatures climbed again. This indicated continuing smoldering combustion or flames. The cable surface temperature in tray 5 cooled from 560° to 270°C within 1 minute (~290°C/minute). After ventilation was restarted the cable temperature rose to above 700°C, showing reignition of the cables.

For unqualified cable in the horizontal orientation (Test 85), the cable surface temperatures (Figure 35) show a continuous decrease after the carbon dioxide discharge. Note that the cable surface temperature at the top of the tray initially dropped very steeply from 440°C to 230°C within 1.5 minutes (140°C/minute). The temperature at the center of the tray did not experience this steep initial drop because the overlying cables provide shielding from the cooling effect of the carbon dioxide.

3.6.3 Suppression Effectiveness and Summary of Results

The carbon dioxide suppression system (50 percent concentration) was effective in extinguishing fully developed cable tray fires, provided there was a sufficient soak time and the room was adequately sealed. The carbon dioxide suppression system effectively starves the fire. In all cases where qualified cables were tested, there was continued

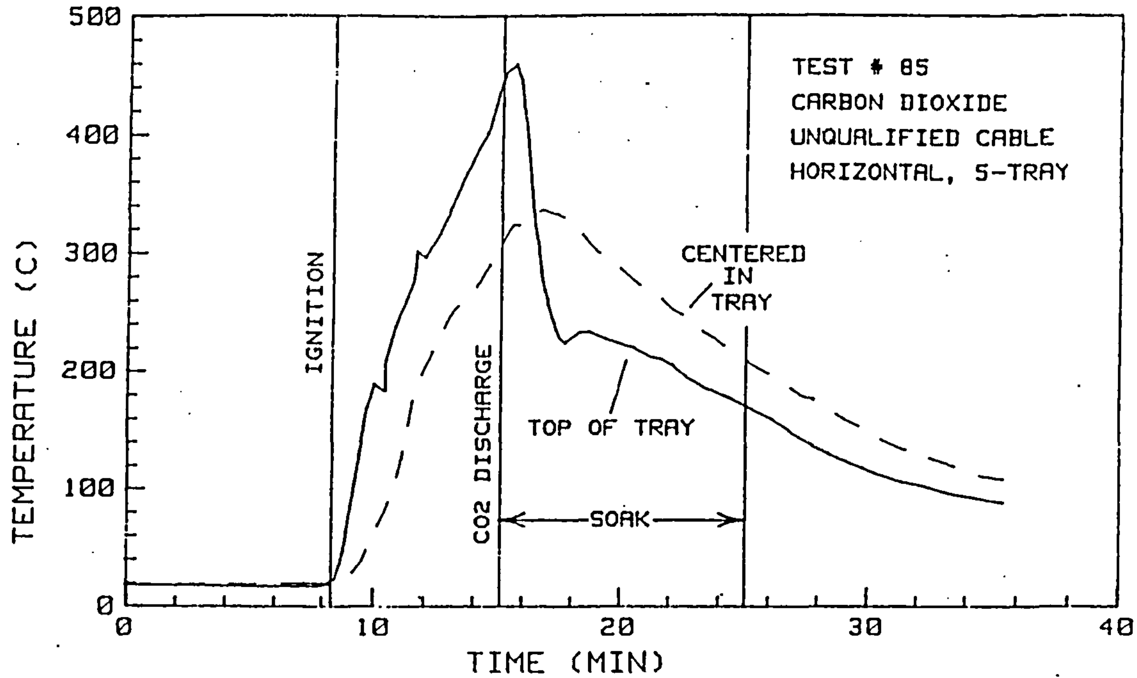

Figure 35. Cable Surface Temperatures, at Top of and Centered in Tray 5, Test 85

smoldering in the cable tray after the soak time. In one case this led to reignition of the fire after oxygen was reintroduced into the test enclosure. Carbon dioxide suppression effectiveness appears to be cable type dependent but not cable tray orientation dependent.

The carbon dioxide volumetric room concentration of 50 percent was maintained throughout the majority of the soak time. After the actuation of the carbon dioxide fire suppression system, there was a delay of 2 minutes before the first discharge began. The delay was due to a required built-in personnel warning time to evacuate the premises in the event of a real fire. The first discharge brought the carbon dioxide concentration level rapidly up to the 50 percent level. A second discharge maintained the concentration level. Figure 36 shows the carbon dioxide concentration level attained during Test 83. A similar plot for Test 85 is shown in Figure 37. The initial discharge occurred more quickly and the concentration level was steadier in Test 85 than in Test 83. These plots both show a slight drop below the 50 percent concentration level before the second discharge was activated. This does not appear to affect the outcome of the tests or the effectiveness of the carbon dioxide suppression system.

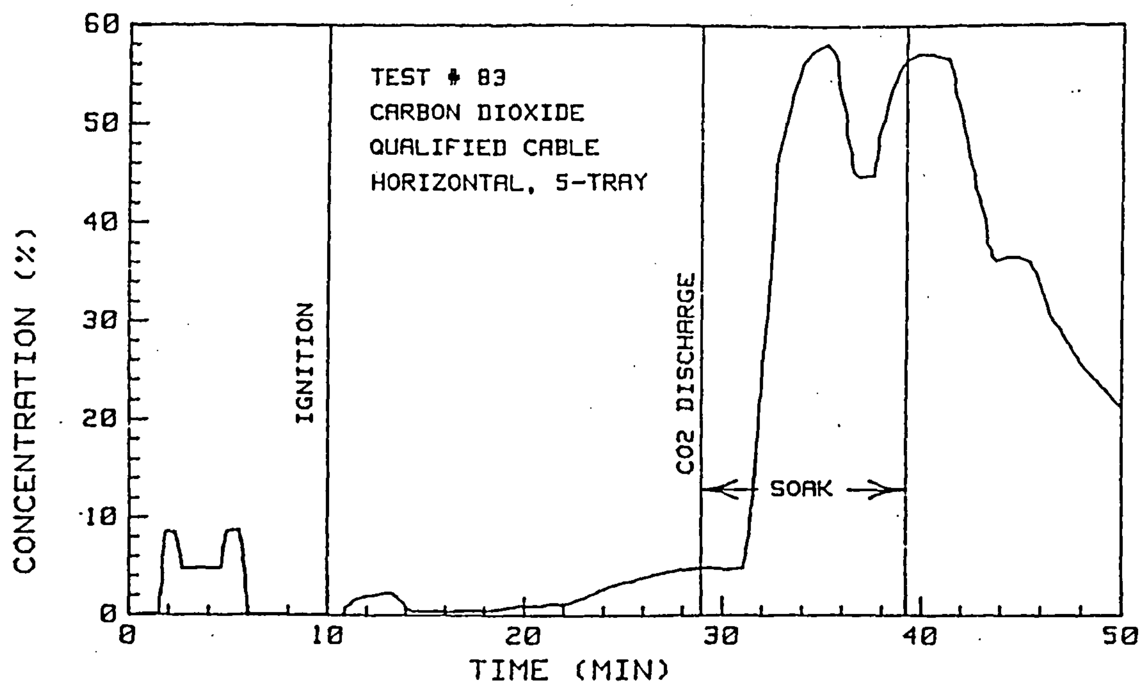

Figure 36. Carbon Dioxide Concentration, Test 83

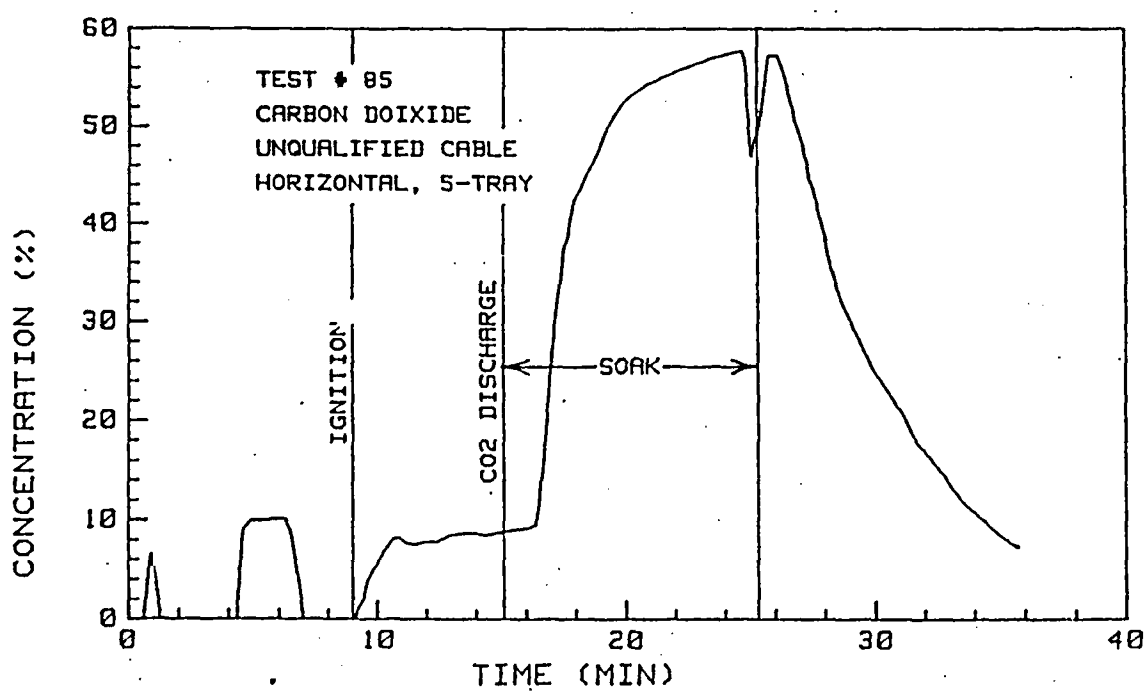

Figure 37. Carbon Dioxide Concentration, Test 85

Minimum soak times for the carbon dioxide suppression system for fully developed cable tray fires are given in Table 15. The carbon dioxide discharge rapidly cooled the air temperature below the cable combustion temperature with an average cooling rate of 24°C/minute. Cable surface and subsurface temperatures were also rapidly cooled.

Table 15

Minimum Soak Times Required Using Carbon Dioxide Suppression Systems for Fully Developed Cable Tray Fires

Tray Configuration	Cable Type	
	IEEE-383 Qualified	Unqualified
Horizontal	15 minutes	10 minutes
Vertical	15 minutes	10 minutes

4. COMPARISON OF SUPPRESSION SYSTEMS

4.1 Suppression Effectiveness

The ability of suppression systems to suppress a fire was judged using the video recordings of the tests and the time vs. temperature plots of the cable tray temperatures.

The two water suppression systems (water sprinkler and directed water spray) were most effective in extinguishing fires. The directed water spray system in particular was very effective, quenching the flames as soon as the spray was activated. The sprinkler system was more effective in the vertical configuration than in the horizontal configuration, where the tray blocked the sprinkler spray.

The Halon 1301 and carbon dioxide systems also quickly quenched fires, yet not with the speed the water system did.

4.2 Environment Temperature Response

Water sprinklers were more effective in cooling the enclosure environment temperature than the other systems; water droplets falling from the ceiling absorbed heat as they dropped (evaporating), cooling the environment.

A rapid drop in room temperatures also occurred with the carbon dioxide system, particularly in the area near the discharge nozzles. However, the enclosure environment temperature usually rose somewhat after the initial discharge before declining after the second discharge. In the Halon 1301 system, the enclosure environment temperature gradually declined, in contrast to the rapid drop observed with the carbon dioxide system.

4.3 Cable Temperatuie Response

Internal cable cooling was most pronounced with the sprinkler and water spray systems. It was difficult to judge the cable cooling effectiveness because, in some cases, the insulator on the cable was burned away, revealing a thermocouple; in other cases, the cable was intact.

The carbon dioxide and Halon 1301 systems also resulted in cooling of the cables, but they did not appear to be as effective in "putting out" smoldering cables as well as the water systems did. This may be due to the fact that in the water environments, the smoldering cables were doused with water, whereas the gaseous systems starve the combustion process.

Surface cooling was greatest in the water systems, although the carbon dioxide system was similar near the tops of the trays.

5. CONCLUSIONS

Conclusions pertaining to the extinguishment capabilities of the tested suppression systems are:

1. All suppression systems were capable of extinguishing cable tray fires. Necessary soak times/spray durations were shown in Table 1.

2. Directed water spray suppression (NFPA-15) was the most effective in extinguishing and preventing reignition of the fires, for all fire sizes, cable types, and tray configurations tested.

3. Water sprinklers (NFPA-13) worked well on the vertical tray configuration, but due to blockage effects by the upper trays in the horizontal configuration, a longer sprinkler duration was necessary to suppress a fire.

4. Both Halon 1301 and carbon dioxide suppression systems worked well in extinguishing all tray configurations and cable types with the specified concentrations; 6 percent for Halon 1301 and 50 percent for carbon dioxide, given an adequate soak time. The soak times were approximately the same length.

5. The water sprinklers and directed water spray systems were most effective in cooling the cable surfaces. Halon 1301 and CO_2 also resulted in steady cable temperature decrease after suppression system actuation, although at a slower rate.

For the gaseous suppression systems, the key in suppressing the fires was maintaining the specified concentration for the required soak times. For the water systems, the sprinkler or spray duration appeared to be more critical than the soak time. The directed water spray system was by far the most effective in suppressing fully developed cable tray fires.

The 37 suppression tests performed at SNLA for evaluating the effectiveness of 4 different suppression systems in suppressing cable tray fires have resulted in the following general conclusion.

> All the suppression methods tested were effective in suppressing fully developed cable tray fires given a sufficient suppressant concentration and an adequate soak time (in the case of the water system, a sufficient sprinkler or spray duration) for the tray configuration and cable types tested.

However, it should be noted that the suppression of a fire (using the required suppressant concentrations and soak times or spray durations) does not assure that additional damage to the burned cables, or to other cables or equipment in the room, will be prevented. The adverse environment produced by the combined fire and suppression activities could affect cables and components and result in immediate damage. Although the occurrence or likelihood of failures was not investigated in this test series it was observed that additional damage to the cables and equipment could result due to the adverse environment (e.g., high temperatures, humidity, corrosiveness) associated with the fire and suppression related activities.

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APPENDIX A

TEST FACILITY AND INSTRUMENTATION

A.1 Fire Test Facility

The SNLA Fire Test Facility is located in a quonset-shaped building at the Sandia National Laboratories in Albuquerque, NM. In one end of the building is the test chamber itself, while the other end comprises the instrumentation and storage room. The floor plan of the facility is shown in Figure A-1. The enclosed volume of the test enclosure is 272 m^3 (9624 ft^3). An adjustable ventilation system with six exit ports along each wall near the floor simulates the normal air ventilation and circulation that would be found in a cable-spreading room in a nuclear power plant. The test enclosure vent is a 1.22-m (48-in) diameter hatch located in the ceiling, which is furnished with a cover that can be remotely operated to open or close the room during a test. Two semicircular metal sheets were placed in the hatch to mix the gases emitted from the test chamber to provide more uniform gas temperature measurements from the exit duct. The west wall of the test enclosure (the wall between the test enclosure and the instrumentation room) is fitted with eight windows to allow for lighting and video monitoring of the fire tests. The access door to the test enclosure is also fire located in this wall. Figure A-2 is a photograph taken from within the instrumentation room showing the windows, with lighting fixtures, and the door into the test enclosure. A movable 2.4 by 3.0-m (8 by 10-ft) platform with a cable tray mounting fixture is shown in the enclosure.

A.2 Instrumentation

Instrumentation for the suppression tests consisted of thermocouples, calorimeters, flow sensors, pressure transducers, and gas analyzers.

Enclosure gas temperatures were measured with shielded quick-response thermocouples located on two vertical ladders at 0.61-m (2-ft) intervals on the north and east sides of the enclosure. These thermocouples were foil type and were mounted inside metal sleeves to isolate the thermocouple from the radiant flux within the room (see Figures A-3 and A-4). Other thermocouples were located in the vent stack. Cable temperatures were measured with sheathed thermocouples 0.05 cm (0.02 in), Type K) placed inside and around the cable jacket. Sheathed thermocouples were also used to measure the flame temperatures of the propane burners as well as between and in the cable trays. Thermocouples located at the Halon 1301 and carbon dioxide (CO_2)

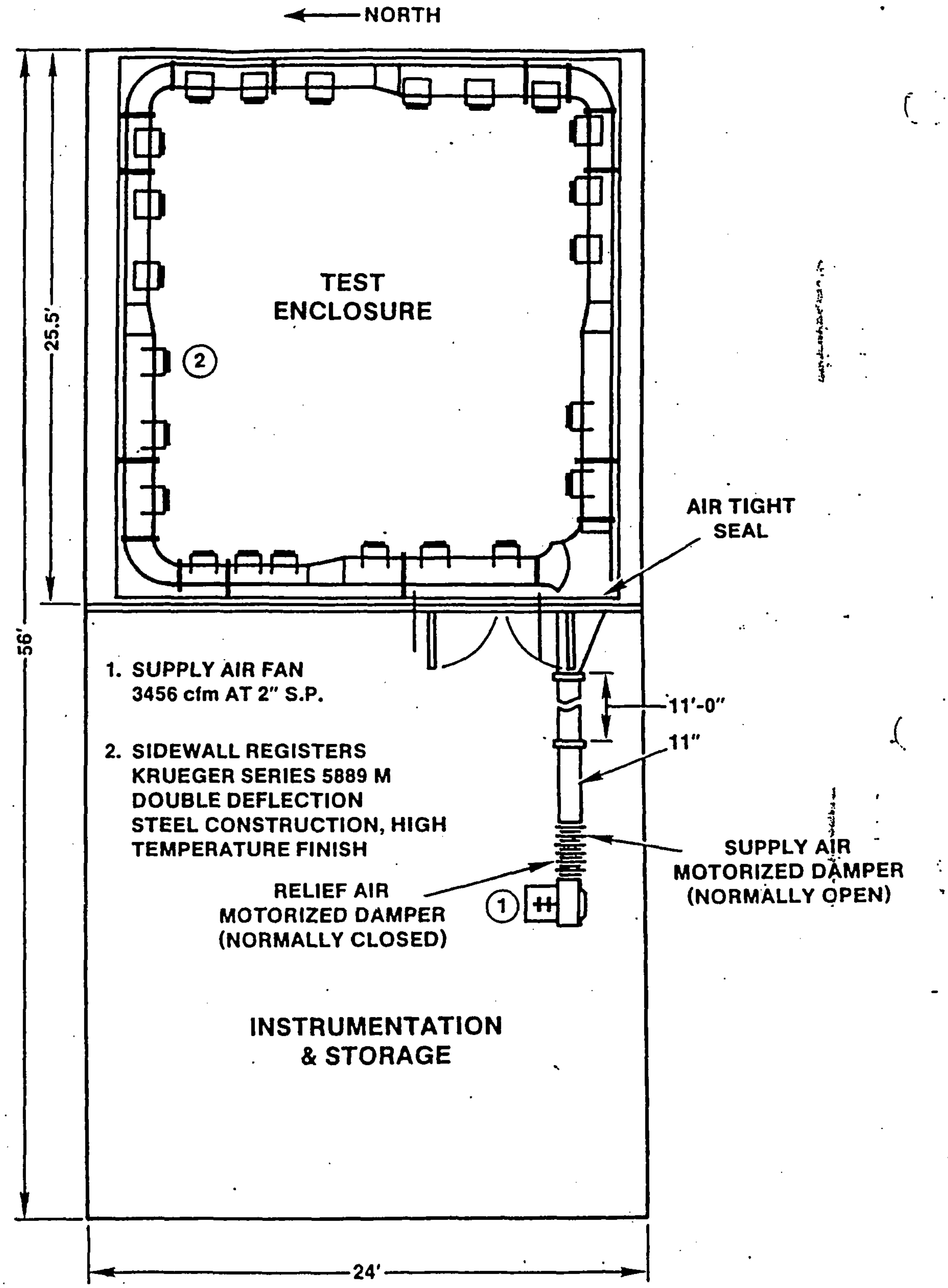

Figure A-1. Floor Plan of the SNLA Fire Test Facility

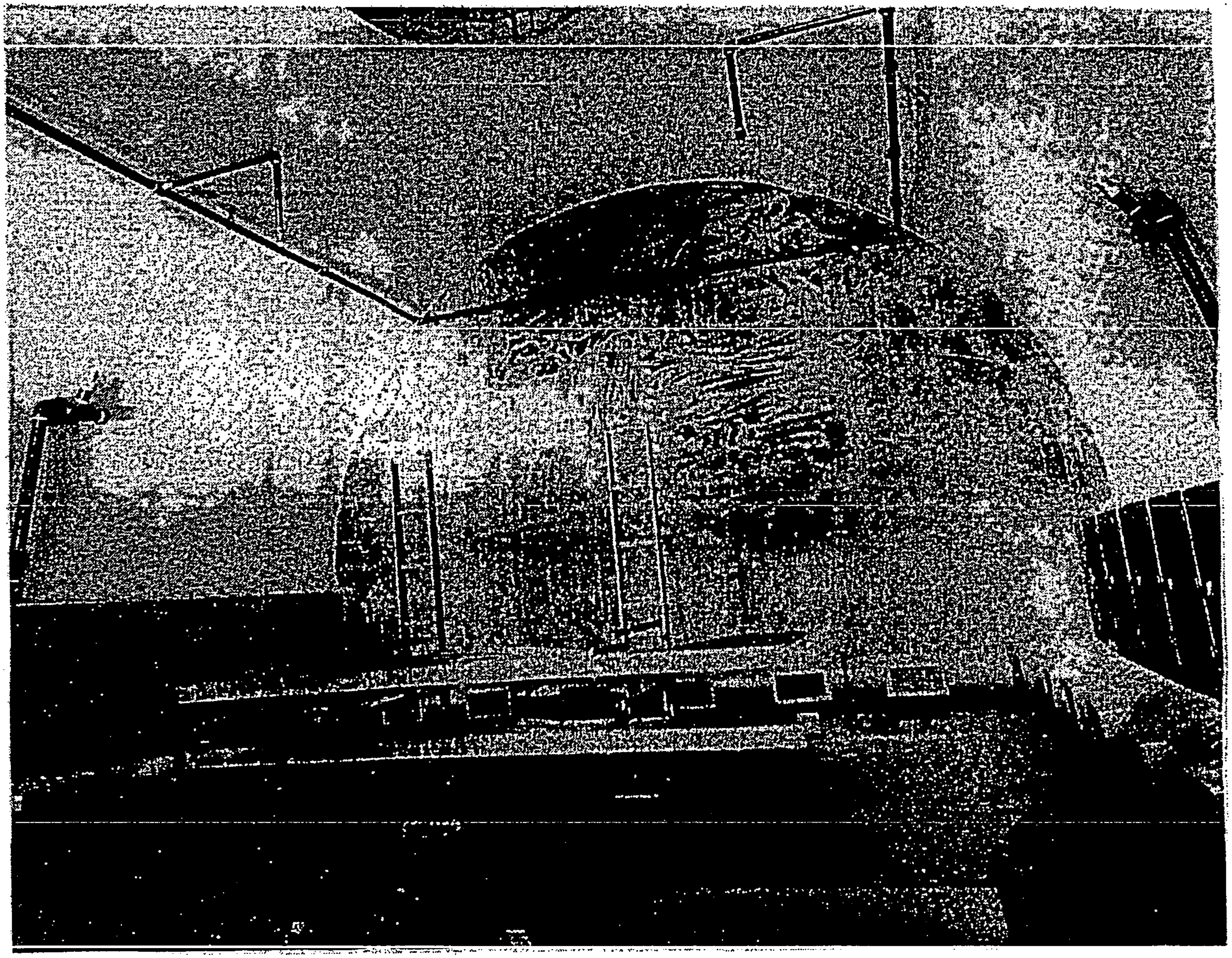

Figure A-2. Photograph of Entry into Test Chamber

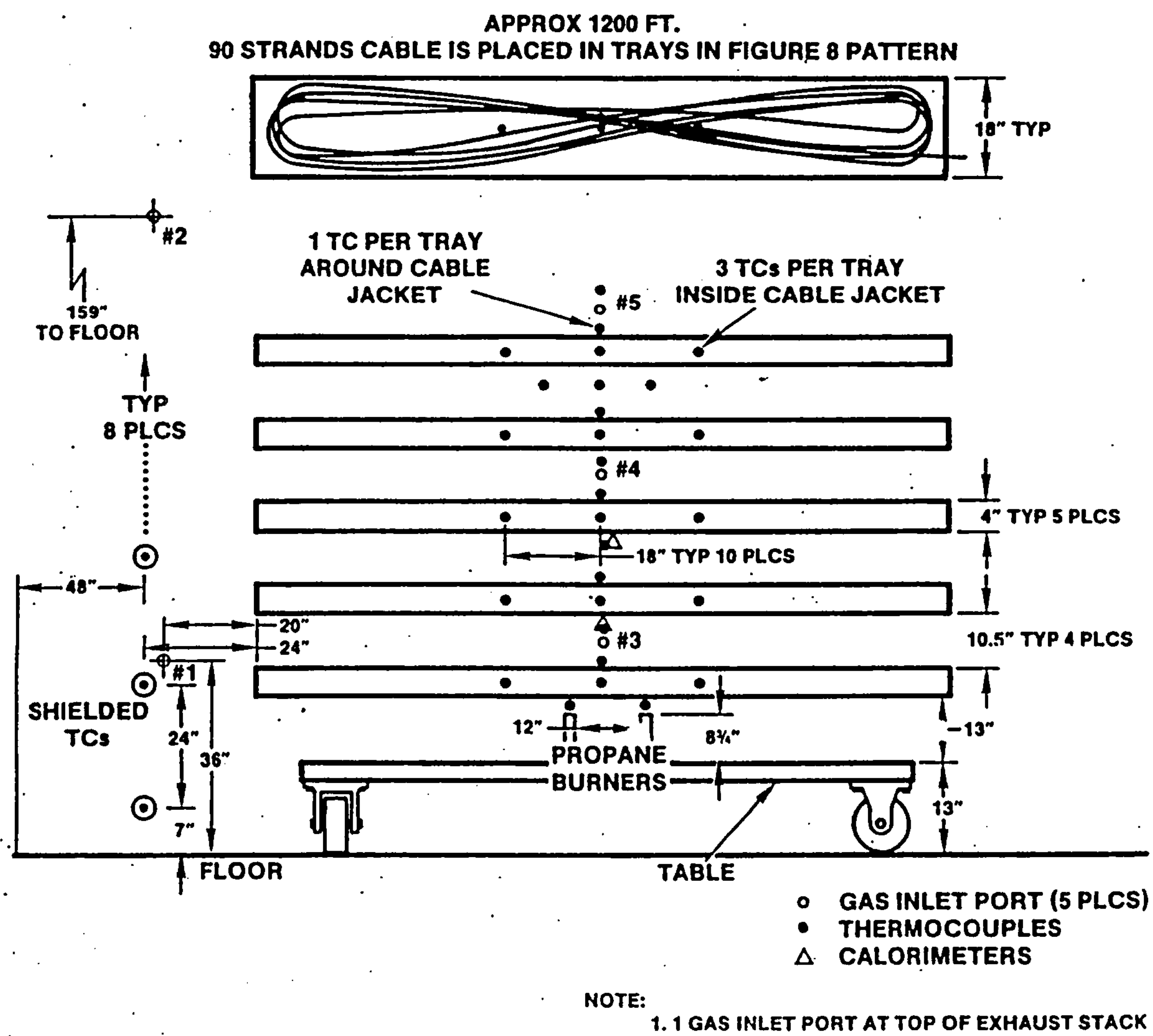

Figure A-3. Five-Tray Horizontal Suppression Tests, East View

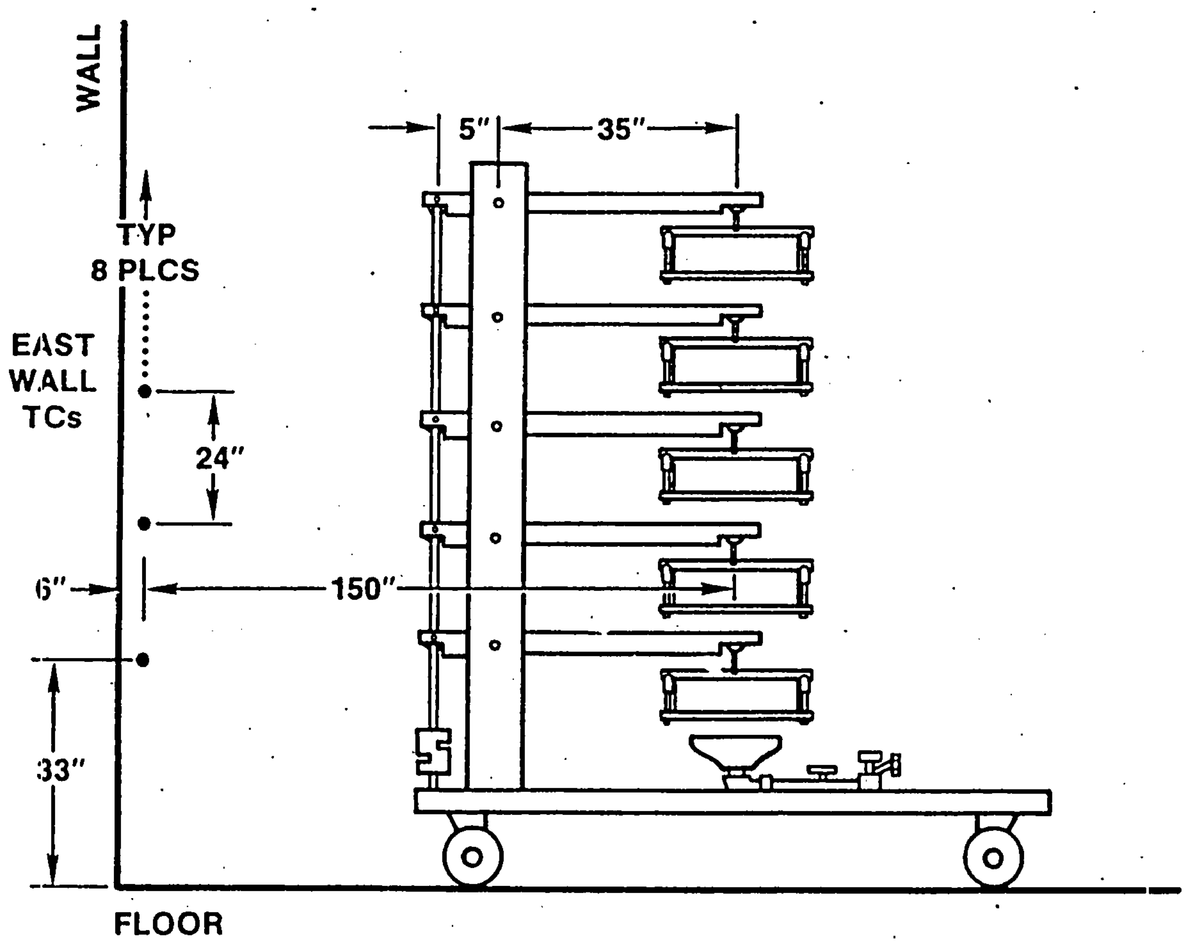

Figure A-4. Five-Tray Horizontal Suppression Tests, North View

discharge nozzles were used to indicate the start of the gas discharge during those tests. Some of the thermocouple locations are shown in Figures A-3 through A-7, which show instrumentation locations for the two-tray setup, both horizontal and vertical orientations, and the five-tray set up, both horizontal and vertical orientations.

Total heat flux from the fire was monitored by placing calorimeters at various locations in the test chamber as shown in Figures A-3 through A-7. The location of the calorimeters was dependant on the test. Both slug type and water-cooled calorimeters were used. The slug-type calorimeter consisted of a 0.635-cm (0.25-inch) copper rod approximately 7.62 cm (3 inch) long with a 0.05-cm (0.020-inch) stainless sheathed thermocouple inserted 1.27 cm (0.5 inch) into one end. These calorimeters were typically suspended between trays in the tests. The water-cooled calorimeters were commercially available units obtained from Hy-Cal Engineering. These calorimeters were typically located in the fire barriers or on the sides of the trays.

Flow sensors, located in the ventilation system inlet duct (measuring inlet duct and stagnation pressures) along with pressure transducers, were used to record the flow rate of air into the enclosure. The differential pressure between the inside and outside of the enclosure were also measured. A water flow meter was used in the water sprinkler/directed water spray tests.

The concentrations of carbon monoxide, carbon dioxide, hydrocarbons, Halon 1301, and oxygen were continuously measured within the test enclosure by a gas analyzer. Gas sample ports were placed at five different locations in the enclosure, and in the vent stack. These sample ports were switch-selectable during a test, and that selection was monitored. All gas analyzer instrumentation is from Beckman Industries.

Instrumentation output was scanned every 20 seconds by an Accurex Auto-Data Nine data logger and recorded on magnetic tape cassette for later data reduction by computer. Video recordings were made of all tests. A typical channel assignment sheet for one of the two tray tests is shown in Figure A-8.

Prior to a test, ambient conditions of temperature, humidity, wind, and barometric pressure were recorded from a weather station at the test site.

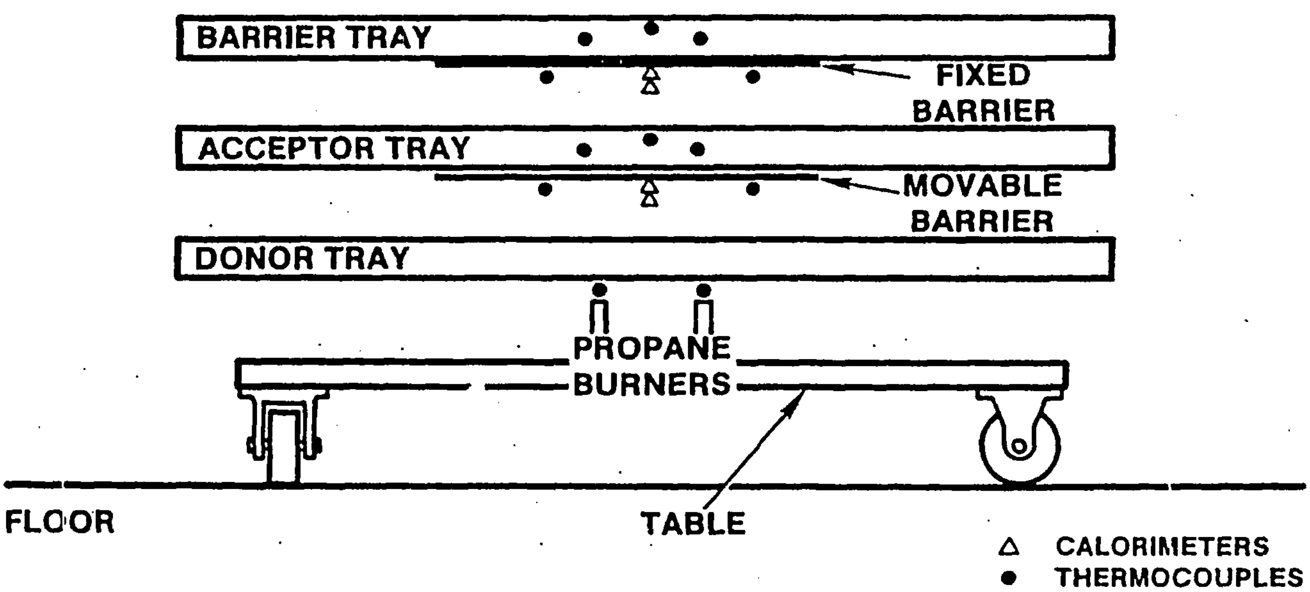

Figure A-5. Calorimeter and Thermocouple Instrumentation for a Horizontal, Two-Tray Exposure Fire Test

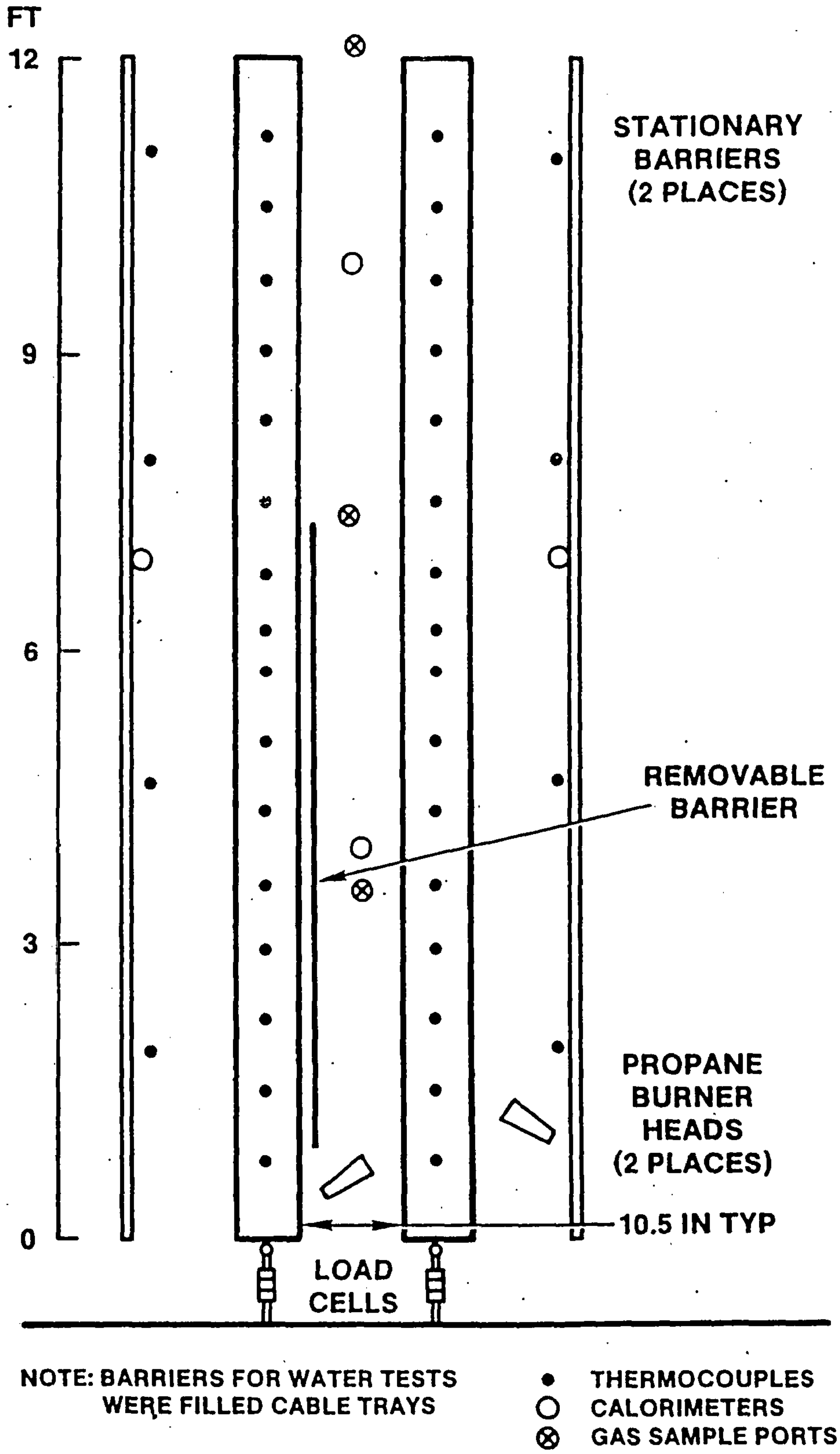

Figure A-6. Suppression Tests, Vertical Orientation, Two Trays

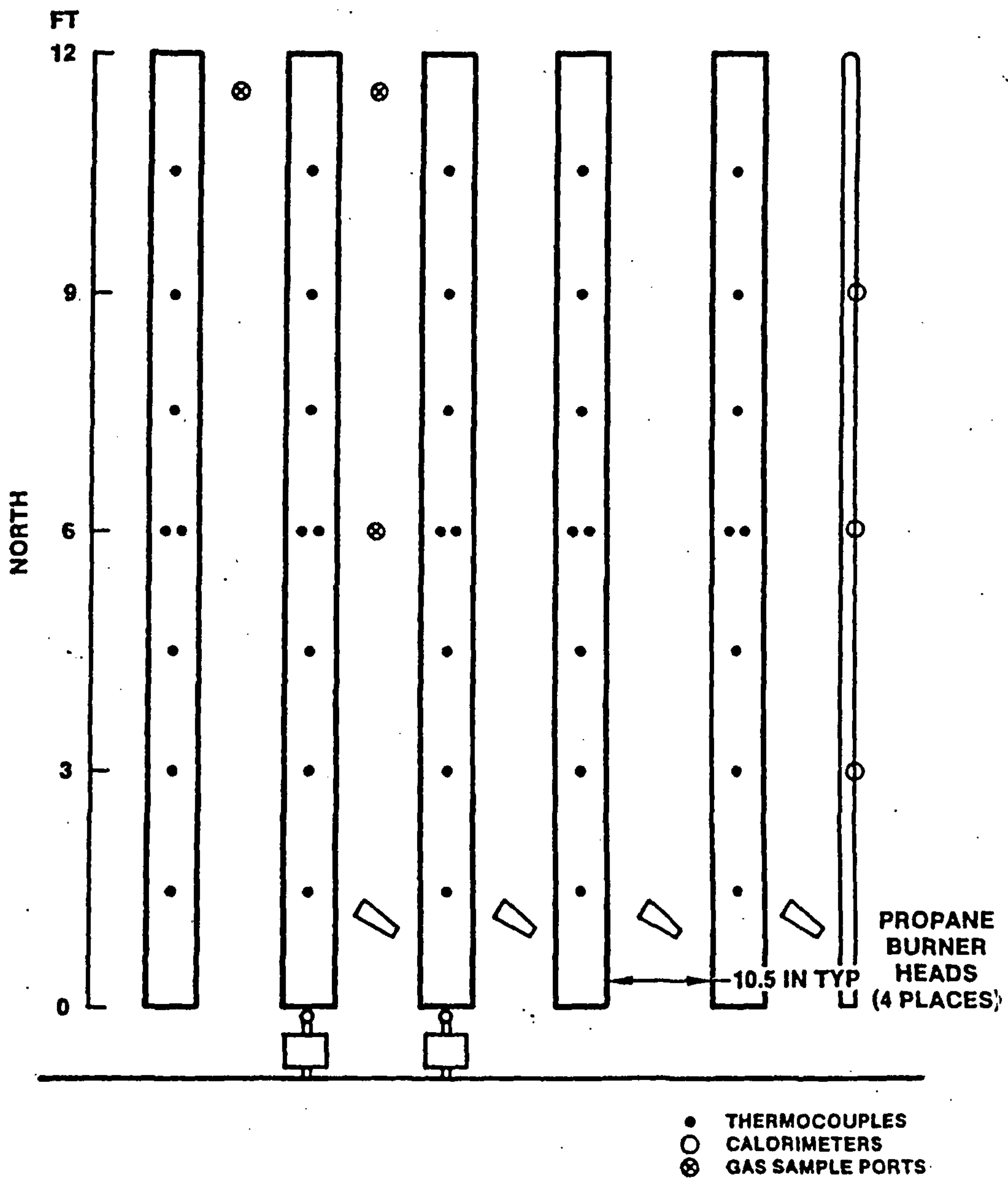

Figure A-7. Suppression Tests, Vertical Orientation, Five Trays

Channel No.	Description
0-7	North gradient thermocouples (TC)
8-15	East wall TC
16-17-18	North, center, south donor tray TC around cable
24-25	35.6 cm (14 inches) north, 20.3 cm (8 inches) south lower barrier TC
27-28-29	West, center, east lower slug calorimeters
30-31-32	West, center, east upper slug calorimeters
33-34	35.6 cm (14 inches) north, 20.3 cm (8 inches) south upper barrier TC
40-41	South, north load cell water bath TC
42-43	West, east sprinkler TC
44-45	Propane burners TC
51-65	Donor tray TC inside cable jacket
66-68	Acceptor tray TC inside cable jacket
70-74	Gas analyzer CO, HC, CO_2, Halon, O_2
80-81	Donor tray load cells south, north
82-83	Acceptor tray load cells south, north
92	Supply air pressure transducer low side
93	Supply air pressure transducer high side
94	Test chamber pressure transducer
95	Water level LVDT
96	Gas sample port indictor
97	Water flow meter
98-99	0-100 MV system check
204-208	Exhaust stack TC
210-212	Supply air inlet TC
222-227	Cable electrical monitors

Figure A-8. Typical Channel Assignment Sheet

APPENDIX B

SUPPRESSION SYSTEM DESIGN

The Halon suppression system consisted of three each 154.5-kg (340-lb) Halon tanks, associated plumbing, and discharge nozzles (Figure B-1). The system was designed to allow volumetric concentrations of up to 25 percent in the test chamber. The six percent concentration level used in the suppression tests was achieved by discharging one tank that had been charged with 92 kg (202 lbs) of Halon. After charging, the tank was pressurized with nitrogen to 1069 kPa (155 psi). The discharge was initiated by a solenoid valve on the tank. This system complied with NFPA-12A and was designed and installed by The Ansul Co., Marinette, Wisconsin.

The carbon dioxide (CO_2) suppression system consisted of 22 each 34-kg (75-lb) carbon dioxide bottles, associated piping, and discharge nozzles (Figure B-1). Because of personnel safety concerns connected with high concentrations of carbon dioxide, the system had safety interlocks on the test chamber doors and a 30-second delay valve in the system.

The electrically triggered explosive valves which initiated the CO_2 discharge were located so as to allow half of the system (11 bottles) to be fired to achieve the desired concentration of CO_2 in the test chamber, thus allowing two tests before system recharge. The CO_2 system was designed and installed by C-O-Two Fire Equipment Company of California to meet requirements of NFPA-12.

The water suppression tests were conducted using a system consisting of a 13,600-ℓ (3000-gallon) storage tank which gravity fed a gasoline engine-driven water pump capable of a delivery rate o˜ 6.34 ℓ/s (100 gpm) at 689.5 kPa (100 psi). The system also included a flow meter, a manually adjustable flow regulator, associated plumbing, and discharge heads. For the water sprinkler tests, per NFPA-13, the discharge occurred via two pendant sprinklers with 1.27-cm (1/2-inch) orifices (Figure B-1). In the directed spray tests, per NFPA-15, the sprinkler heads were replaced by a ladder arrangement of ten spray nozzles (Figure B-2).

Both water suppression systems were designed and installed by SNL to the specifications called out in their respective NFPA standards.

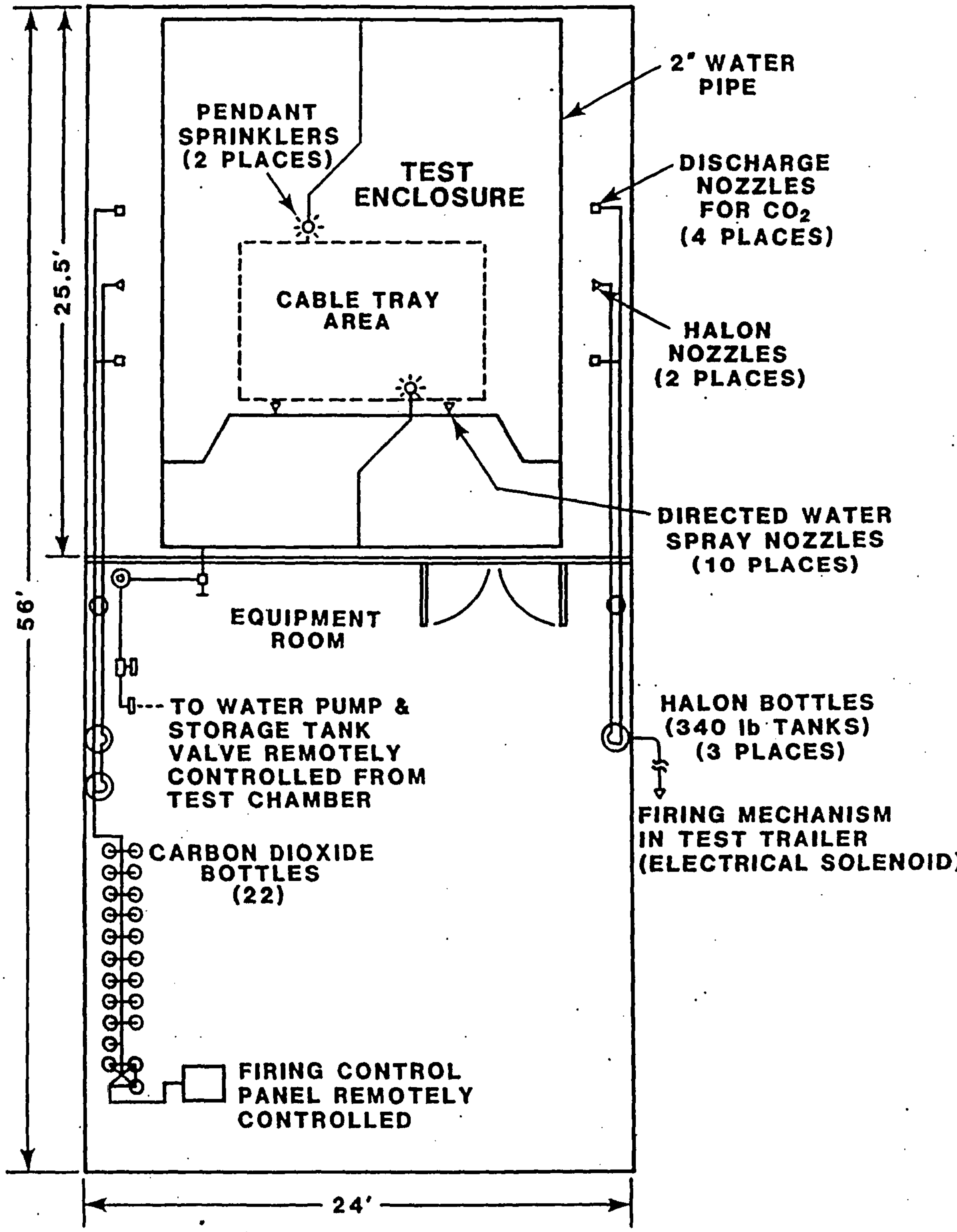

Figure B-1. Fire Suppression System Arrangement

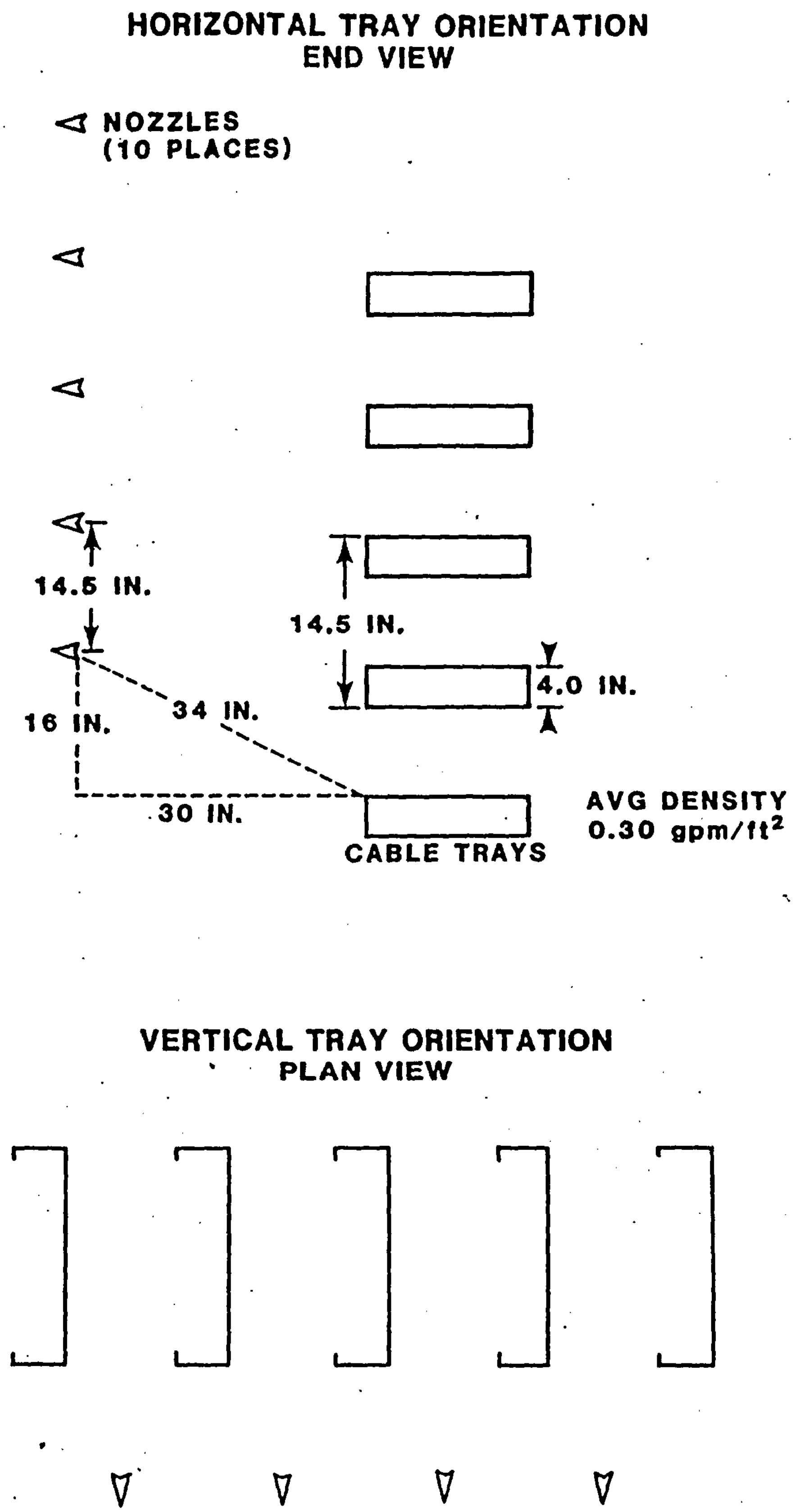

Figure B-2. Arrangement for Directed Water Spray Tests

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13. ABSTRACT (200 words or less)

The electrical cable fire suppression tests conducted at Sandia National Laboratories were performed to provide confirmatory research for the U.S. Nuclear Regulatory Commission (NRC) on suppression systems effectiveness. This report describes full-scale tests on both horizontally and vertically oriented cable trays, filled with either IEEE-383 qualified cables or unqualified cables, to determine the effectiveness of Halon 1301, water sprinklers, directed water spray, and carbon dioxide fire suppression systems. These four methods of fire suppression were evaluated to determine their effectiveness in suppressing both exposure type and fully developed type cable tray fires. The results show that although all methods of suppression were effective, given sufficient suppressant concentrations, spray durations, and soak times, the water suppression methods were the most effective. Despite their effectiveness in suppressing cable fires, it was observed that both gaseous and water suppressants may cause or permit damage to nonburning cables and equipment. The adverse environments associated with the fire and suppression related activities (e.g., high temperatures, humidity, corrosiveness) could damage cables and equipment and result in immediate or latent damage. Occurrence or likelihood of these failures was not investigated in this test series.

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