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FIRE PROTECTION RESEARCH PROGRAM FOR THE U. S. NUCLEAR REGULATORY COMMISSION
1975-1981

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ABSTRACT

Since early 1975, Sandia National Laboratories has been conducting fire protection research for the U. S. Nuclear Regulatory Commission. Testing has been done on grouped electrical cable fires including electrical initiation, fire propagation, the effects of fire retardant coatings and barriers, suppression, and characterization of the damageability of electrical cables. In addition, several studies of a more generic nature such as fire detection, ventilation, and fire-hazards analysis methodologies were performed.

This report condenses all of the test results, reports, papers, and research findings of the past seven years. Research conducted by contractors to Sandia National Laboratories is also summarized.

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ACKNOWLEDGEMENT

The assistance of Leo J. Klamerus in gathering together the many reports and papers which form the basis of this study is greatly appreciated.

EXECUTIVE SUMMARY

Objectives

Sandia National Laboratories has been conducting a fire protection program for the U.S. Nuclear Regulatory Commission since early 1975. The program was in fact underway before the fire at the Browns Ferry nuclear power plant which occurred on March 22, 1975.[1] Since then the program has grown to cover many areas of fire protection. This report summarizes the major activities of this program from 1975 to 1981.

The objectives of the Fire Protection Research Program at Sandia National Laboratories are to:

1. Provide data either to confirm the suitability of current design standards and regulatory guides for fire protection and control in light water reactor power plants, or to indicate areas where they should be updated.
2. Obtain data to facilitate either modification or generation of standards and guides (changes are to be made where appropriate to decrease the vulnerability of the plant to fire, provide for better control of fires, mitigate the effects of fires on plant safety systems, and remove unnecessary design restrictions).
3. Obtain fire effects data and assess improved equipment, design concepts, and fire prevention methods that can be used to reduce the vulnerability to fire.
4. Conduct special tests to assess the adequacy of specific designs.

Areas of Research

When the project was conceived in July 1974, the only task was to provide the experimental and analytical information to evaluate the adequacy of cable tray spacing designated in Regulatory Guide 1.75, Section 5.14, which covers separation of protective systems in areas of the plant where power cables are included and the only source of fuel is that provided by the cable materials.[2] All evaluations were to involve the testing of equipment and configurations representative of those in new nuclear power plant designs.

Since then, research at Sandia National Laboratories and its contractors has expanded to cover the following areas of fire protection research:

Testing

1. Cable tray separation for both electrically initiated fires and exposure fires.

2. Effectiveness of fire-retardant coatings and fire shields.

3. Contribution of reradiation from walls and ceilings to fire intensity (corner effects tests).

4. Small-scale and large-scale testing of the effects of furnace pressure on cable penetration seal performance.

5. Halon 1301 suppression effectiveness.

6. Water sprinkler (NFPA 13)[3] and directed water spray nozzle effectiveness (NFPA 15).[4]

7. Full-scale replication of several cable trains and the fire protection system for an area in the Browns Ferry Reactor Building.

8. Full-scale testing of the damageability of electrical cables to radiant heat.

Analysis

1. Characterization of cable tray fires.

2. Examination of compartment ventilation in nuclear power plants.

3. Investigation of the adequacy of fire detection as well as the requirements for detector siting in the context of nuclear power plant safety.

4. Assessment of the adequacy of current standards which govern the design and testing of fire barriers.

5. Examination of the adequacy of existing fire-hazards analysis methodologies.

With the exceptions of the penetration seal tests and the Browns Ferry Replication test, most of the testing was performed at Sandia National Laboratories' Fire Test Facility. Figures 1 and 2 show the test facility after modification in 1979.

Major Findings

As a result of the test program conducted at Sandia National Laboratories and its contractors, a number of important findings have emerged which have a direct impact on the suitability of design standards and which provide important information on fire prevention methods. In particular, the following general statements summarize the important conclusions drawn from this research.

1. With regard to cable tray separation, Regulatory Guide 1.75 was found inadequate for exposure fires.

2. All fire retardant coatings offer a measure of additional protection, but there is a wide range in their relative effectiveness.

3. All fire shields tested inhibited fire propagation from tray to tray.

4. In the corner effects test, an inverse relationship was found between fire intensity and wall/ceiling distance; beyond a diagonal distance (from tray edge to corner) of 6 ft (1.8 m) there was little effect.

5. Halon 1301 suppresses deep-seated cable fires if the soak time and concentration are sufficient.

6. Area water sprinklers (meeting NFPA 13-1980) are effective in suppressing cable tray fires in the vertical configuration as well as the horizontal configuration (up to three levels of trays tested).

7. Directed water spray nozzles (meeting NFPA 15-1980) are very effective in suppressing cable tray fires.

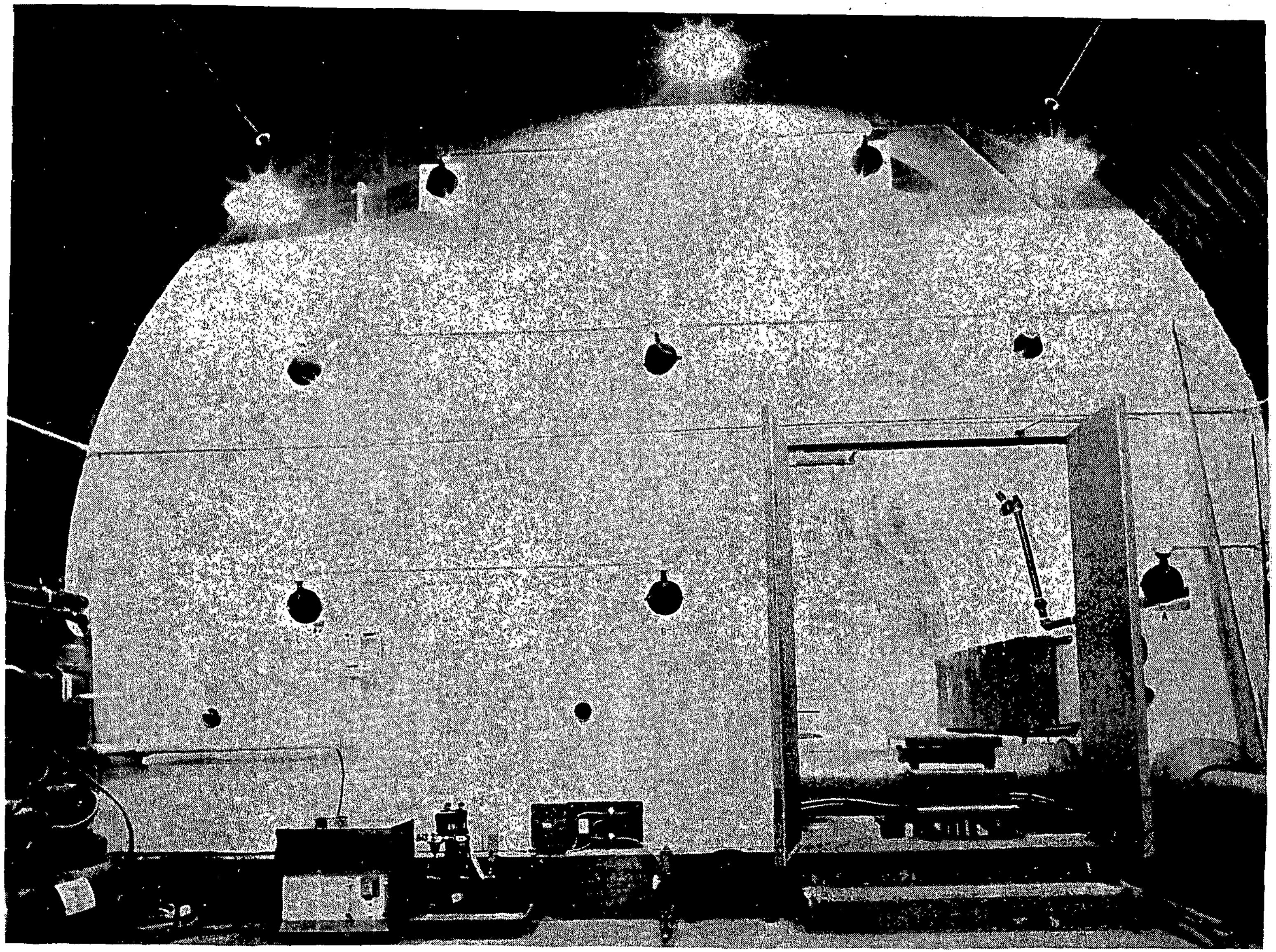

Figure 1

Outside View of Fire Test Facility

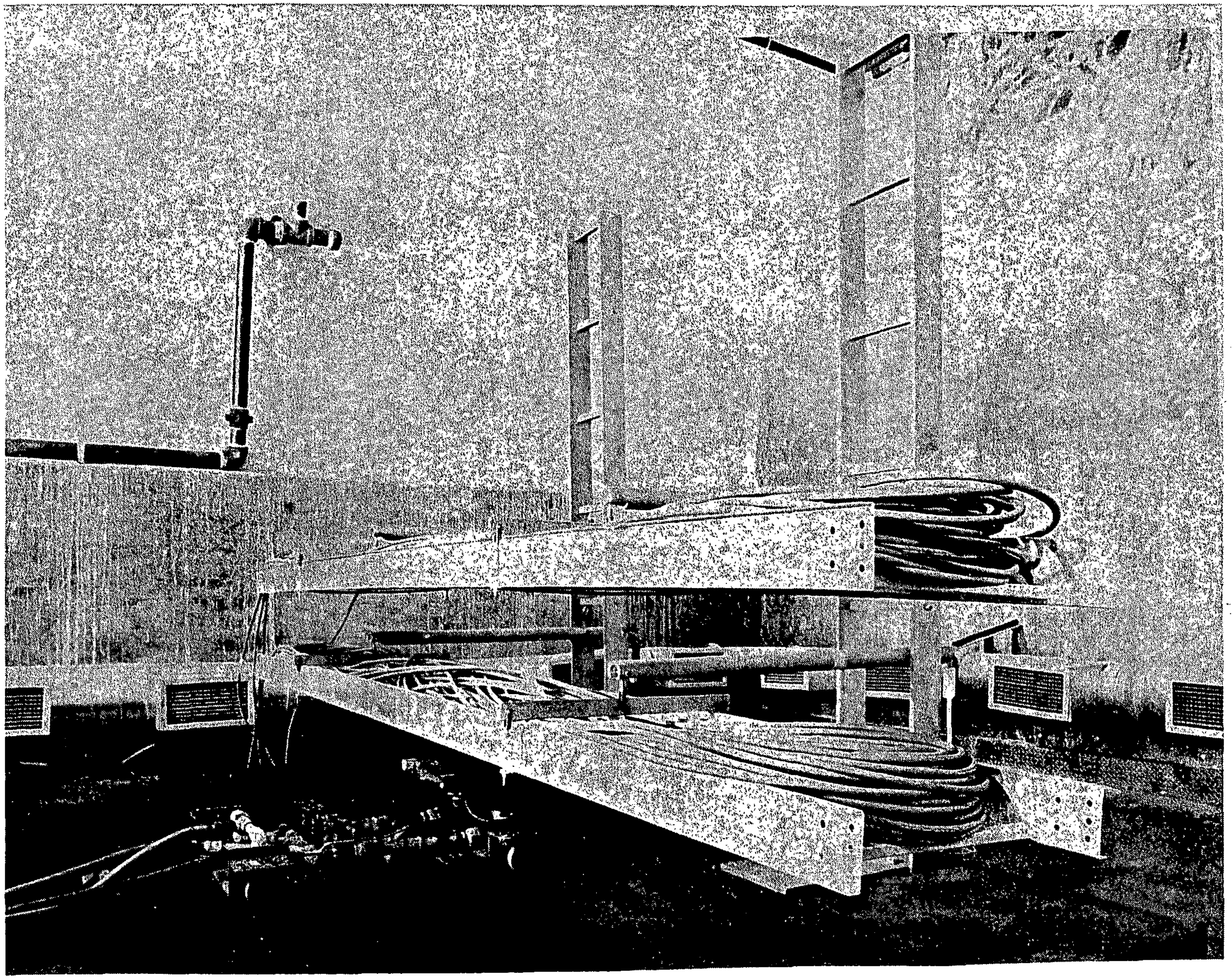

Figure 2

Inside View of Fire Test Facility

8. Positive furnace pressure and excess pyrolyzates are important parameters in cable penetration seal tests.

9. Large-scale tests performed on the damageability of electrical cables to radiant heat generally verified the results of small-scale tests performed at Factory Mutual Research Corporation.

10. Despite the fact that the Browns Ferry Replication test was conducted under stringent conditions, i.e., without any automatic or manual fire suppression efforts attempted, functional capability was not lost and the test verified the survivability of one redundant safety train.

In addition to the above findings which resulted from the test program conducted by Sandia National Laboratories, a number of conclusions have been drawn from studies of generic issues such as fire detection and ventilation.

1. Current standards and regulatory guidelines inadequately define criteria for design of ventilation systems and their operation under fire emergencies.

2. Current design and regulatory guidelines alone are insufficient to ensure satisfactory fire detection system performance; the use of in-place testing of detectors under conditions expected to occur normally in areas being protected is recommended.

3. Because the standard fire (ASTM E-119)[5] cannot be considered as representative of compartment fires, the fact that a given barrier has received a standard rating does not mean that it will last for the rated duration in every fire situation or that a comparative quality rating is achieved.

4. No one fire-hazards analysis method can satisfactorily circumvent the subjective nature of current fire hazards analysis practice.

Interaction With Fire Research Community

Ever since the Fire Protection Research Program was first conceived in 1974 and effectively underway in early 1975, Sandia National Laboratories has been interacting actively with the rest of the fire research community in order to stay abreast of important issues. Figure 3 illustrates the affiliations of Sandia's contractors and consultants. Professor R. Brady Williamson of the University of California at Berkeley has been involved with large-scale testing of cable penetrations. The small-scale penetration seal tests, Browns Ferry Replication Test, and other cable tray fire tests have been performed at Underwriters Laboratories under the direction of L. J. Przybyla and W. J. Christian. Professional Loss Control Incorporated has on several occasions served as consultants on various aspects of testing and analysis. John Boccio at Brookhaven National Laboratory has been instrumental in the work performed on early detection of cable tray fires.

In addition, the Fire Protection Research Program at Sandia National Laboratories has been presented at workshops and conferences held by the American Nuclear Society, the Society of Fire Protection Engineers, the Institute of Electrical and Electronics Engineers, the National Academy of Sciences and the Electric Power Research Institute (see listing of Conference Reports). Moreover, interactions have taken place with other institutions doing research in fire safety such as the National Bureau of Standards Center for Fire Research, the Applied Physics Laboratory of John Hopkins University, Lawrence Livermore National Laboratory, Southwest Research Institute, Factory Mutual Research Corporation, Naval Sea Systems Command, and the Naval Research Laboratory.

Internationally, research information on cable tray fires has been exchanged with Professor K. Yahagi of Waseda University of Japan as well as with representatives of Toshiba Corporation, Hitachi Corporation, the Fujikura Cable Works Ltd., and the National Testing Institute of Sweden.

On September 7, 1978 the Nuclear Regulatory Commission Fire Protection Review Group Meeting[6] was held in Albuquerque, New Mexico and was attended by 170 representatives of electrical cable manufacturers, architect/engineering companies, electric utilities, consulting companies, vendors of fire protection equipment, national laboratories, and government. Sandia National Laboratories' Fire Protection Research Program was presented along with parallel efforts being conducted by other consultants to the Nuclear Regulatory Commission.

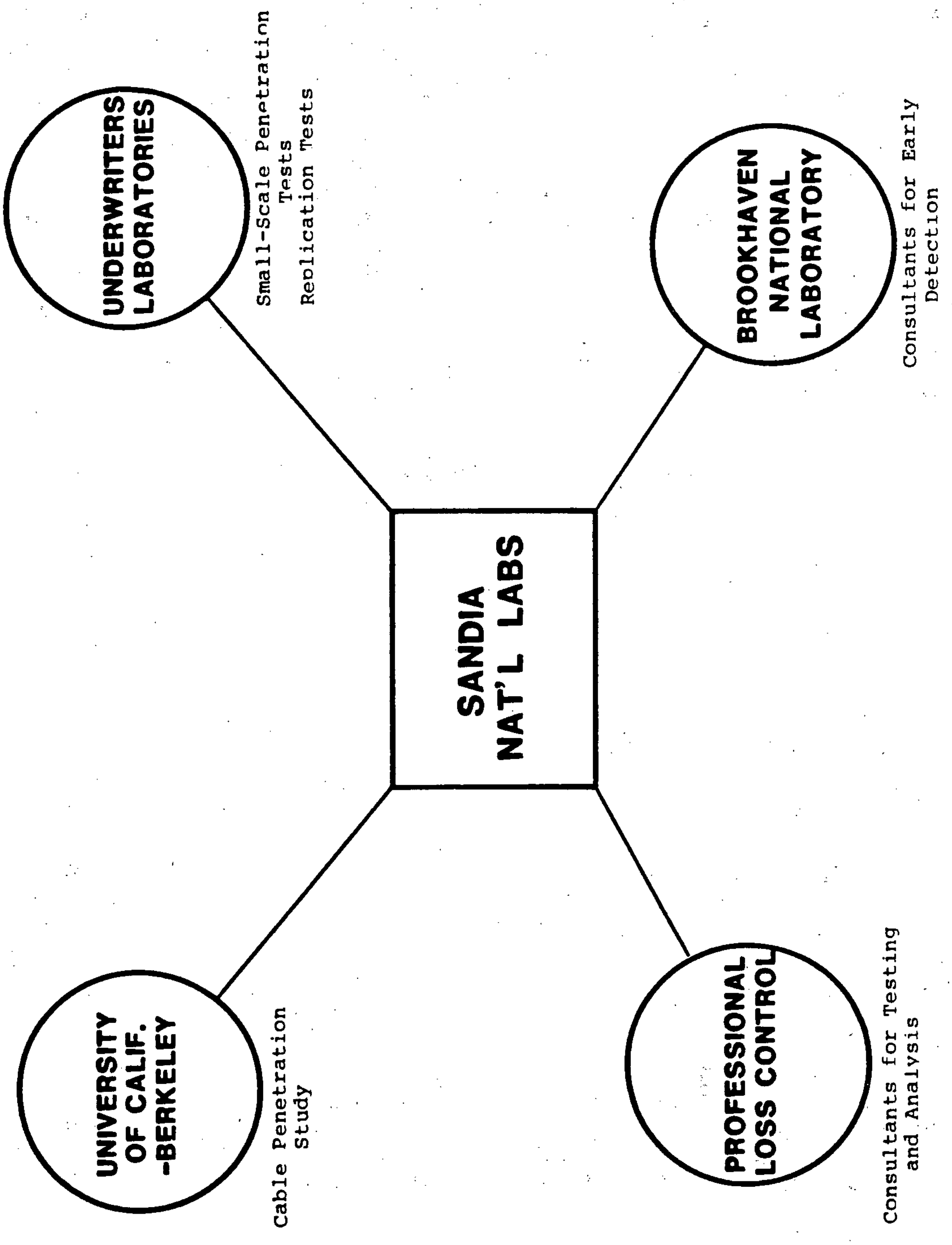

Figure 3

Affiliations of Fire Protection Research Consultants

I. Introduction

Sandia National Laboratories has been conducting fire protection research for the U. S. Nuclear Regulatory Commission since early 1975. The program on cable tray fires was actually underway before the March 22, 1975 Browns Ferry nuclear power plant fire.[7] Since then, a great deal of research has been done on grouped electrical cable fires including electrical initiation, fire propagation, the effects of fire retardant coatings and barriers, suppression, and characterization of the damageability of electrical cables. In addition, several studies of a more generic nature such as fire detection, ventilation and fire-hazards analysis methodologies were performed.

It is the purpose of this report to condense under one cover all of the test results and research findings of the past seven years. Altogether, some 30 reports and 75 tests are summarized. Only an introduction to the particular test series and major test results are given in this report. The reader should refer to the appropriate citations in order to obtain more information on the background of the test, test procedures, and detailed test results. The reference list is exhaustive and, in one report or another, includes all of the major test results through late 1981. No reference is cited for the water suppression tests (both NFPA 13 and NFPA 15) which as of this writing are not complete, although some general statements about the tests conducted to date are given. A selected list of papers on the fire protection research program given at various conferences and workshops is also provided for additional reference. In general, the outline of this report follows in chronological order the testing program conducted at Sandia National Laboratories and its contractors. The analytical studies are grouped separately.

II. Testing Program

II.1 Industry Survey

Early on in the program it was decided that a survey of industry should be made to determine current design practices concerning cable tray spacing and cable types. The cooperation by members of the nuclear power industry was outstanding. Personal visits and correspondence elicited responses from 13 architect-engineering firms, 13 utility companies, and 13 cable manufacturers. Three nuclear power plants were visited, although design practices of existing nuclear power plants were not evaluated. Information obtained during this survey has proven valuable in determining cable and cable tray configurations, cable loading, and types of cable assignments in cable trays. The survey also solicited information about previous incidents and experiences, including the cable tray fire at San Onofre 1 in 1968 and the subsequent investigation to determine the cause.[8]

Since initiating a fire in power cable electrically may be difficult, it was decided early in the project to conduct the test with 12 AWG, the smallest power cable normally used in nuclear power plants, to minimize the amperage demands in the test setup. A preliminary heat transfer analysis was also performed at that time. Only a rough analysis was considered necessary to determine the approximate current required to raise the cable insulation to a combustion temperature and to determine if the conductor temperature is at its melting point (1083°C) when the outside of the cable insulation is at its combustion temperature. The analysis showed that currents in the range of 100 to 120 amps would raise the cable insulation to its combustion temperature. This agreed with subsequent testing.

With the results of the survey and the preliminary analysis as guidelines, a test facility was designed and constructed to perform full-scale testing of electrically initiated fires. Although it was originally intended to test all known types of cable currently specified and accepted, the large number of cable types, coupled with budget limitations, precluded such broad testing. Screening indicated that tests of two cable types most likely to propagate a fire would comprise a conservative approach.

The relative ranking of cable types was based on three different evaluations and were chosen to complement, not duplicate, other evaluations. The evaluations used were: a small-scale electrically initiated cable insulation fire test, Underwriters Laboratories (UL) FR-1 flame test,[9] and a pyrolyzer and thermal chromatograph test (measure of insulation outgassing as a function of temperature).

Although the small-scale electrically initiated cable insulation fire test and the UL FR-1 test indicated that none of the cables under evaluation would be capable of propagating a fire (in support of IEEE-383 qualification),[10] two cable types were designated for use in the full-scale tests by a relative figure of merit. Work performed in Europe in 1975 on radiation and fire resistance of insulating materials was brought to Sandia's attention and is in good agreement with its ratings.[11] These designated cable types were (1) a three-conductor No. 12 AWG, 30 mil (0.76 mm) cross-linked polyethylene (PE), silicon glass tape, 65 mil (1.65 mm) cross-linked PE jacket, 600 V, and (2) a single-conductor No. 12 AWG, 30 mil (0.76 mm) crosslinked PE, no jacket, 600 V. These were used on all subsequent electrically initiated and exposure fire tests whenever IEEE-383 qualified cable was to be used.

II.2 Cable Tray Separation Tests

II.2.1 Electrically Initiated Fire Tests

Three phases of full-scale electrically initiated fire tests in horizontal cable trays were performed. Altogether, nine full-scale tests were run. The first phase was intended to evaluate the adequacy of cable tray spacing as designated in Regulatory Guide 1.75, Section 5.14. Vertical separation of independent safety divisions is designated as 5 ft (1.52 m) and the horizontal separation as 3 ft (0.91 m). The second phase was concerned with varying the separation distance between cable trays. Phase three required a stacking of 14 cable trays as one division with cable trays representing the second division separated by distances as specified in Regulatory Guide 1.75. The vertical and horizontal separations in the first division were 10.5 and 8 in. (0.27 m and 0.20 m), respectively, while the separation between divisions was again 5 and 3 ft. All testing involved equipment and cables representative of those in new nuclear power plant designs.

The first phase involved two tests using single conductor no. 12 AWG cross-linked PE insulation in 24-ft (7.3-m)-long, open ladder type aluminum trays. Five cable trays represented the two safety divisions. Current was increased in the ignition tray until a short circuit was observed and flaming started (about 95 to 99 amps). In these tests, all circuits other than the ignition tray circuits remained functional and the fire did not propagate from the ignition tray.

There were four tests run in the second phase, all using three conductor No. 12 AWG cross-linked PE insulation. The first three of these tests involved 24 foot (7.3 m) long, open ladder aluminum trays whereas the fourth test used 12-ft (3.7-m) long, galvanized steel trays. Moreover, the fourth test used a figure 8 pattern (see Figure 4) for the placement of the cables to allow maximum passage of air, and spacing was reduced to 10.5 in. (0.27 m) vertically and 8 in. (0.20 m) horizontally between safety divisions. In these tests, short circuits and fires occurred between 112 and 174 amps in the ignition tray. However, all the circuits in the other trays remained functional and fire did not propagate.

The third phase involved three tests, each consisting of two vertical stacks (total of 14 trays) for one safety division, and three trays for the second division. The spacing conformed to Regulatory Guide 1.75. A mixture of one-conductor and three-conductor No. 12 AWG cross-linked PE cables was used. Short circuits and fires occurred between 94 and 105 amps. Once again, electrical damage was confined to the ignition tray and the fire did not propagate. Figure 5 illustrates the test configuration for the phase three tests as well as the July 6, 1977 exposure test described below.

In all nine tests, all circuits other than the ignition tray circuits remained functional. This was determined by operation of these circuits for some period of time after the test. In addition, samples of the cable insulation at the bottom of the tray over the fire zone were measured for any mechanical change. They showed less than 10 percent increase in elongation due to the fire. Quite often this small increase is attributed to a small change in cross-linking due to heat. Results of these electrically initiated fire tests were reported in seven "quick look" reports to the NRC[12-18] and two summary reports.[19-20]

Major Findings

As a result of this testing program it was determined that Regulatory Guide 1.75 was adequate for electrically initiated fires in horizontal tray configurations using IEEE-383 qualified cables.

II.2.2 Exposure Fire Test

A full-scale fire exposure test was performed at Sandia National Laboratories on July 6, 1977.[21-22] The test was conducted with a single safety division being represented by 14 filled cable trays. Again the 14 trays were spaced 10.5 in. (26.7 cm) vertically and 8 in. (20 cm) horizontally. Three additional filled trays representing the second or redundant safety division were placed vertically

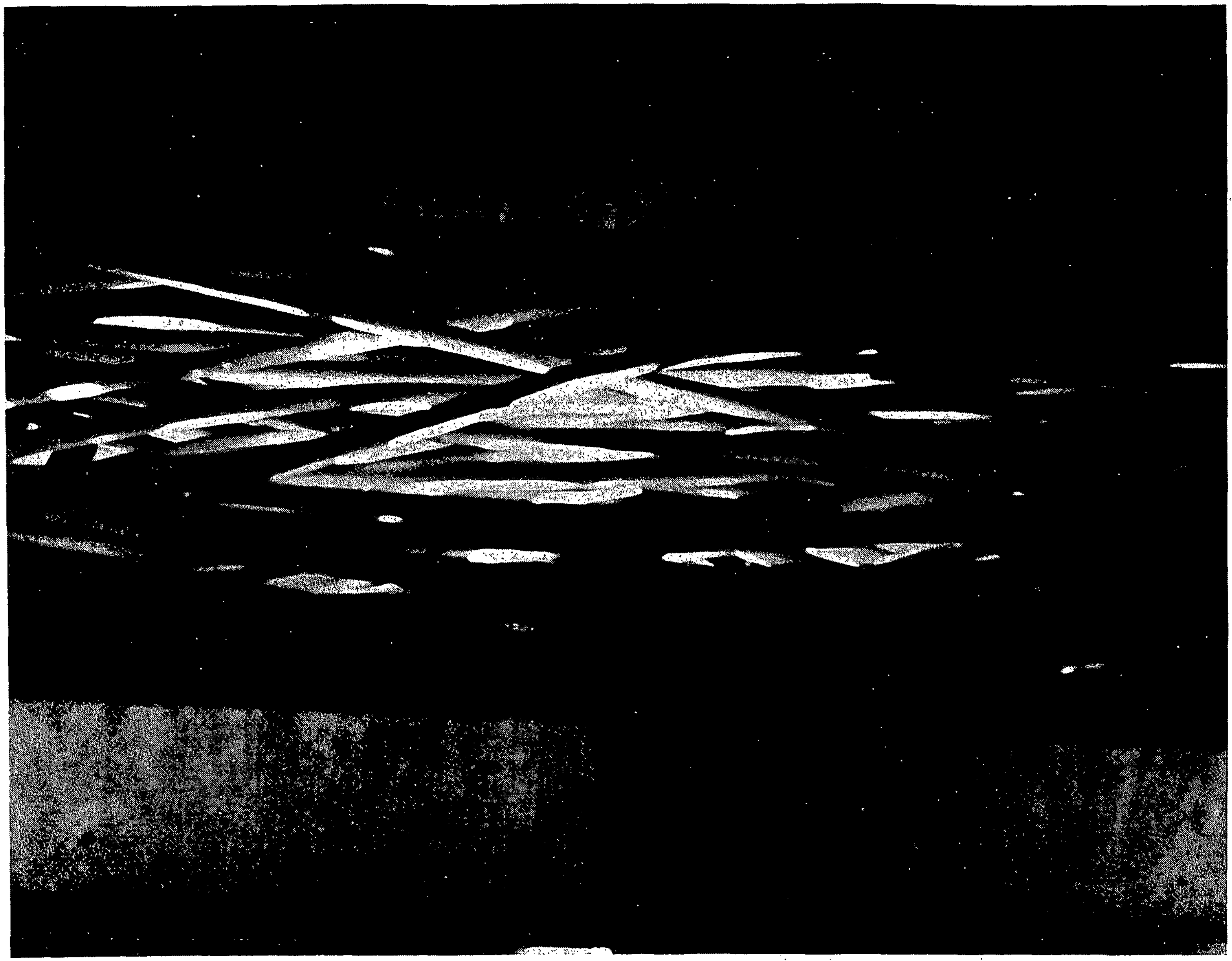

Figure 4

Random Placement of Cables in Tray

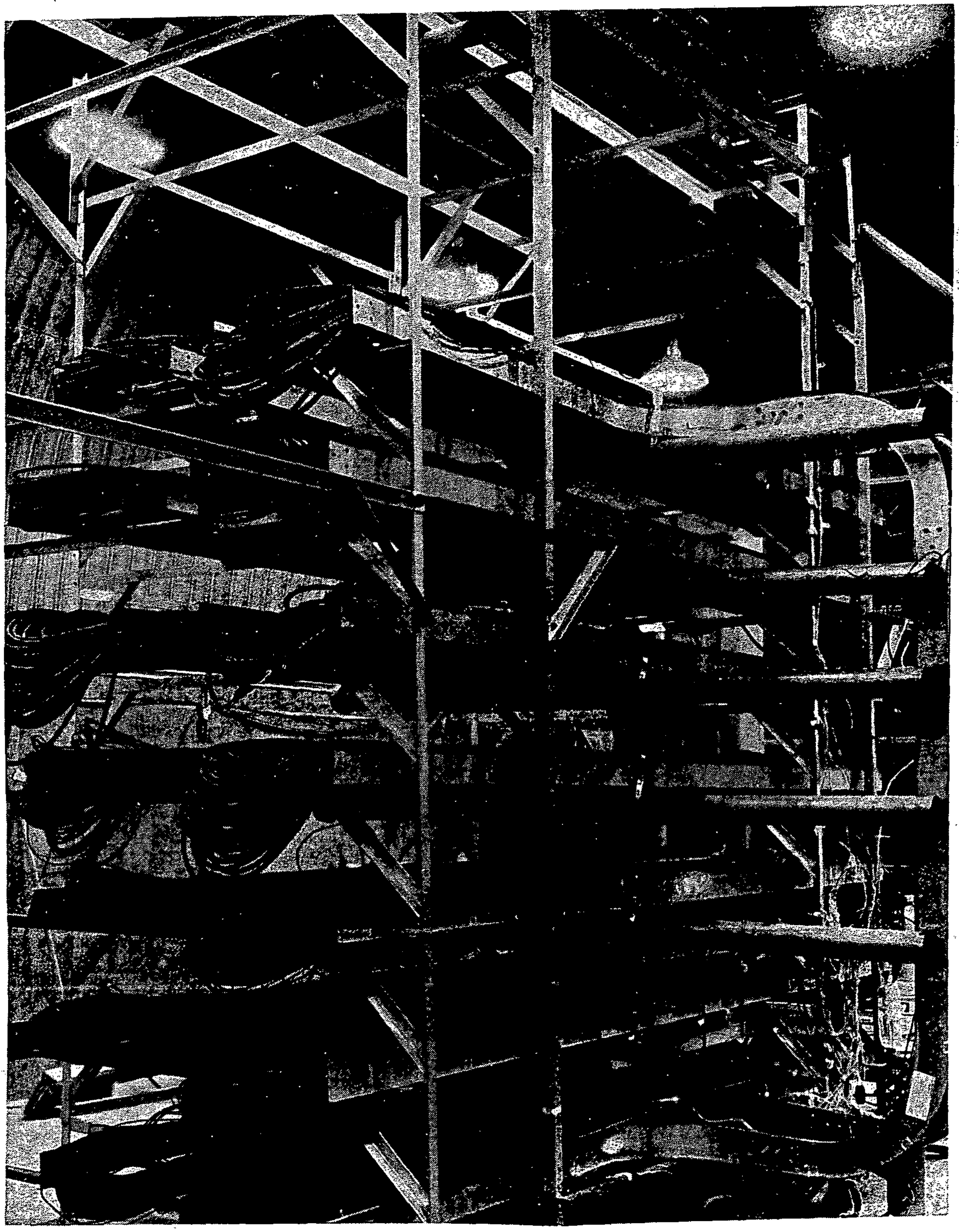

Figure 5

Seventeen Tray Arrangement

and horizontally adjacent to the top of that 7 x 2 matrix of trays, as shown in Figure 5. The separation distances between redundant divisions were those minimum distances allowed by Regulatory Guide 1.75. Flame retardant cables (IEEE-383 qualified) were used.

A 5-minute exposure to standardized (IEEE-383 ribbon type) propane burners produced a fully developed fire within a single cable tray. Optimized parameters for this type of fire were obtained in a series of 12 single-tray tests performed earlier. A barrier was placed over the donor tray until after the propane burners were turned off and was then removed to allow the single-tray fire, with only the cable as fuel, to act as a propagation source. The fire not only propagated through the closely stacked trays of one division but also ignited the cables in the redundant safety division. The after effects of the test are shown in Figure 6. This illustration is a bit deceiving in that the cable tray supports were made of aluminum rather than steel, and hence were more susceptible to structural damage resulting from high temperatures. The important point to make is that the fire propagated from the ignition tray up through the first safety division and to the second safety division.

Comparison of data from this test with the previous electrically initiated fire tests shows that size (area of fire) and time (length of time flames reached a given area in upper trays) were the principal parameters which allowed propagation of this fire. The typical electrically initiated fire had an axisymmetric luminous zone about 6 in. (15.2 cm) in diameter while the luminous zone in the exposure fire test was approximately 2 ft (61 cm) long and 1.5 ft (45.7 cm) wide. This increase in characteristic dimensions increased the emissivity and view factor which in turn increased the radiation heat transfer to the higher trays. The longest period of time an electrically initiated fire remained on the thermocouple or calorimeter area was 240 seconds while this same area was in the flames for 400 seconds in this exposure fire test.

Comparison of thermocouple records for previous tests and the test described here shows a 1400° F (760° C) temperature above the cables at 3/8 in. (0.95 cm) in the electrically initiated fires and at 2.5 in. (6.35 cm) in this fire. A temperature of 1000° F (583° C) was seen at 3 in. (7.62 cm) above the cables in the electrical fires but 8 in. (20.32 cm) above the cables in this fire. These temperatures suggest that the fire resulting from the exposure fire was slightly more severe, but this could have been merely because of a larger fire zone which caused the thermocouples to read closer to true local gas temperature.

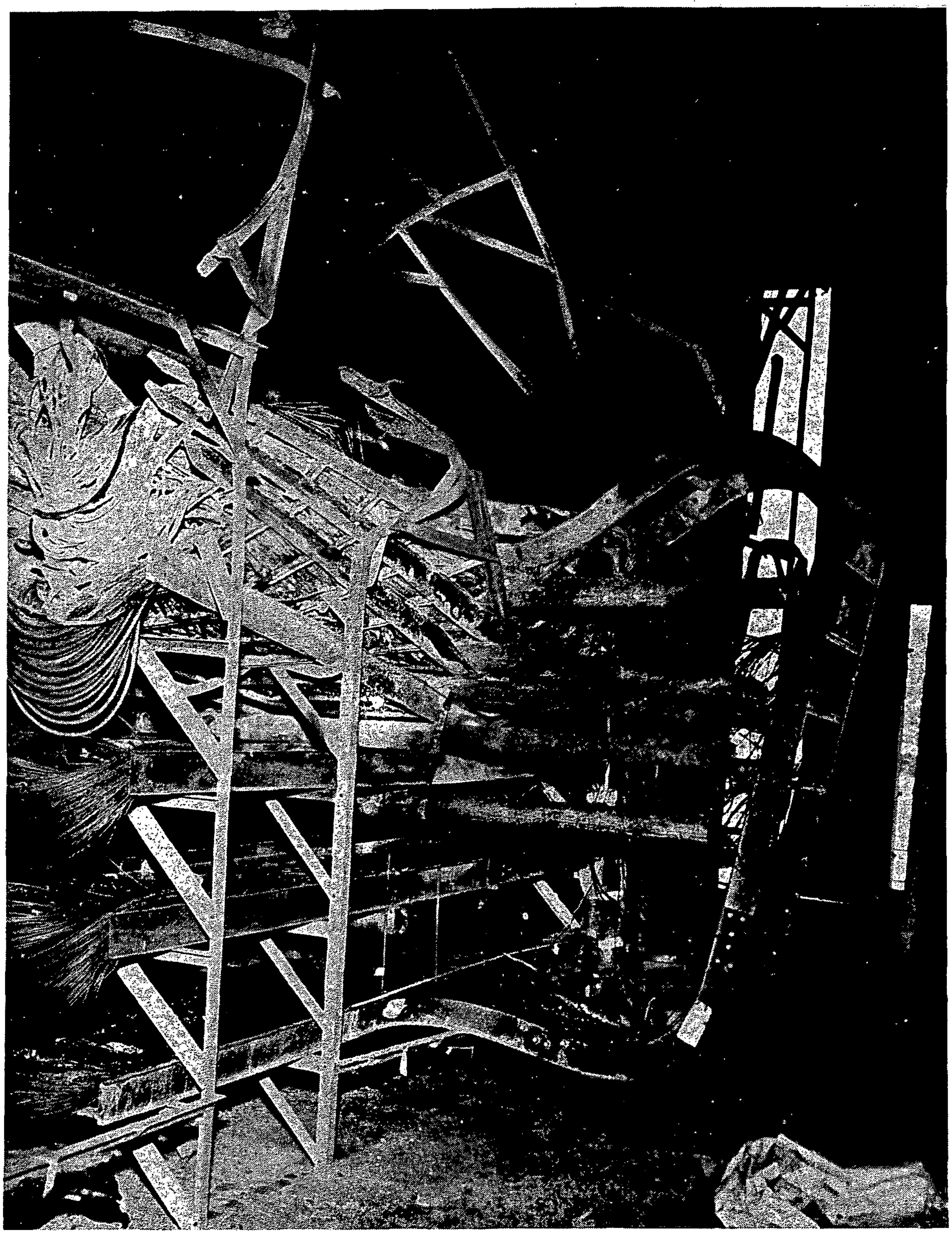

Figure 6

Post-Test Results of July 6, 1977 Test

Heat flux was comparable in both types of tests, varying within 20 percent at corresponding heights on all tests. This fact, plus the lack of large changes in other measurable characteristics, might suggest that the electrically initiated fires were marginally below the capability of propagation across the minimum (10.5 in. or 27.7 cm) vertical distance between trays used to represent one of the redundant divisions. By the same token, this exposure fire test was marginally above ignition as seen from the fact that the donor fire tray stopped flaming within one minute after the tray vertically above this one ignited.

Schedule 40, 3-in. (76.2 mm) pipe was used as conduit containing additional cable and was included in this test. Continuity and insulation resistance measurements of the cables in the conduit were taken before and after the test. Although continuity measurements were normal, insulation resistance showed short circuits to the conduit on all conduits above the third tray. The insulation appeared to have turned to ash without flaming, leaving the conductors touching each other and the pipe.

Major Findings

The results of this test show that fire propagation with flame retardant (IEEE-383 qualified) cable in an open-space horizontal configuration between redundant safety divisions, separated by the minimum distances specified by Regulatory Guide 1.75, is possible if a fully developed cable fire is assumed.

II.3 Fire Retardant Coatings and Fire Shield Tests

The test of July 6, 1977, showed that additional measures were required to protect essential safety systems against the effects of fire and confirmed the Nuclear Regulatory Commission's position in requiring that protection. Two of these additional measures are fire retardant coatings applied on the cable trays and fire shields between cable trays. Small-scale and full-scale testing was performed on the fire retardant coatings. Full-scale testing of the coatings consisted of both propane and diesel-fueled exposure fires. Propane-fueled exposure fires were used to test the ability of various fire shields to prevent fire propagation between horizontal cable trays. These tests are reported in Reference 23 to 25. A summary of the coatings tests conducted is given in Table I.

Table I

Test Matrix of Coatings Tests

Coating	Single Tray Tests			Two Tray Tests		Small Scale Test		Diesel-Fuel Fire
	383 Qualified Cable		Non-383			383 Qualified Cable		Non-383
	Single Conductor	Three Conductor	Three Conductor	383 Qualified Cable	Non-383	Single Conductor	Three Conductor	Two Tray
None	X	X	X	X	X	X	X	
A	X	X		X	X	X	X	X
B	X	X		X	X			X
C	X	X		X	X	X	X	X
D	X	X		X		X	X	
E	X	X		X	X	X	X	X
F						X	X	
G	X	X		X	X	X	X	X

II.3.1 Small-Scale Testing of Coatings

For small-scale testing, coatings were applied to both types of electrical cable used in the electrically initiated and exposure fire tests at Sandia. The cables were cut into 6-in. (15.2-cm) pieces and placed in wood forms lined with plastic, a 6 x 6-in. sample size. The coatings were then troweled to the manufacturer's specified wet thickness and allowed to cure at least 30 days. Each sample was mounted in the holding fixture fronted by 1-in. (2.54-cm) wire mesh and backed by one layer of aluminum foil and cement board.

The Ohio State University release rate apparatus tested two types of cables and six types of fire-retardant coatings to varying levels of radiant heat flux to determine the ignition time and smoke and heat release rates. The apparatus used a flow system in which a known, constant flow rate of air enters an environment chamber. Rate of heat release is monitored by changes in temperature of air leaving the chamber and rate of smoke release by optical density of gas leaving the chamber. The sample is put into the environmental chamber and a small pilot flame is placed to impinge on the center of the lower edge of the vertical sample. A radiant panel provides exposure in terms of heat flux to the sample. The test conditions provide air flow of 84 ft^3/min (0.04 m^3/s) with tests at room temperature and at radiant heat flux levels of 1, 2, 3 and 4 W/cm^2. Table II summarizes the important measurements at a radiant heat flux level of 4.0 W/cm.^{2}

II.3.2 Single-Tray Full Scale Tests

For the full-scale tests performed at Sandia National Laboratories, coatings were applied to the same cables previously described. The cables were loaded into galvanized steel, open-ladder trays 18 in. (45.7 cm) wide and 12 ft (3.7 m) long. Although the trays were filled to approximately the tops of the 4-in. side-rails of the cable trays, the loading technique allowed maximum air passage through the cables. The loading pattern is a figure 8 in the tray, with the crossing point advancing progressively up and down the tray. For the three-conductor cables this resulted in a 25 percent fill by cross-sectional area and for the single-conductor, a 15 percent fill (90 three-conductor cables per tray and 450 single-conductor cables per tray). Non-IEEE-383 qualified cable was loaded into additional cable trays to be included in the testing. This cable was three conductor, 20/10 Poly PVC polyethylene insulation, 45 mil (1.14 mm) PVC jacket. The number of cables per tray and percent filled by cross section were the same as the qualified three-conductor cables previously described.

Table II

Results of Small-Scale Coatings Tests at 4 W/cm^2

Coating	Time to Ignition Minutes	Time to Maximum Heat Release Minutes	Cumulative Heat Release at 10 Minutes MJ/m^2	Cumulative Heat Release at 15 Minutes MJ/m^2
A	8	16	14.6	39.1
C	8	17	28.6	43.7
D	14	28	4.1	8.1
E	24	34	16.2	22.5
F	5	12	23.5	60.4
G	12.5	22	21.5	37.5
No Coating 383 Cable	0.8	6	45.7	78.0

Coatings were sprayed onto the loaded cable trays by their respective manufacturers. The nominal wet thickness applied to the tops and bottoms of the loaded cable trays was the same as that used in the small-scale tests and was applied according to the manufacturer's specifications. The test described here was designed to reproduce the ignition tray conditions of the full-scale stacked-tray test of July 6, 1977.[22] An important difference of course, is that only the ignition tray itself was used in this first phase of the fire-retardant coatings tests. The test procedure and setup were essentially identical to the July fire test. An insulated barrier was placed 9.5 in. (24.1 cm) over the ignition tray. The twin burner assembly was so placed beneath the tray that rungs of the cable tray were not directly over either burner. The distance between the top of each burner and the bottom of the cable was 4.75 in. (12.1 cm). Cable thermocouples were in place before spraying of coatings began.

Propane and air were turned on for 5-minute periods for each burn cycle. Previous tests had shown 5-minute periods as optimum for creating the largest donor fire in a cable tray loaded with IEEE-383 qualified cable, provided an open or random cable fill pattern was maintained. If a fully developed cable tray fire was not achieved after applying this ignition source for 5 minutes, additional 5-minute ignition cycles (up to a total of six) were repeated after 5-minute delays. Fifteen tests were conducted as indicated in Table I. Table III summarizes the test results.

II.3.3 Two-Tray Full Scale-Tests

A series of two-tray tests was conducted to test for fire propagation between trays. In these tests, the physical arrangement of the lowest two trays in the July 6, 1977 fire test was used. The trays were placed horizontally, with one tray 10.5 in. (26.7 cm) above the other. When IEEE-383 qualified cable was used, the bottom tray was loaded with three-conductor and the top with single-conductor cable. An insulated barrier was placed 9.5 in. (24.1 cm) over each tray. The barrier over the bottom tray was movable and could be swiftly removed from between the cable trays when a fire developed in the bottom tray. As in the single-tray tests, thermocouples and calorimeters were placed in each tray.

The same 5-minute burn cycles used in the single-tray tests were repeated in these two-tray tests up to a maximum of six ignition cycles. Electrical resistance and current measurements of the cable were made as in the single-tray tests. Not including the diesel-fueled fire tests and the barrier tests, a total of thirteen two-tray tests were conducted. The results in terms of the relative rankings of

Table III

Results of Full-Scale Single-Tray Coatings Tests

Test Number	Coating	Maximum Cable Temperature (°F)	Maximum Calorimeter Temperature (°F)	Maximum Barrier Temperature (°F)	Time to Electrical Short (min)†	Time to 900°F in Cables (min)†	Time to Ignition (min)†	Length of Burn (min)	Length Affected Area (in.)
1*	A	1280	525	Not Taken	26	16	10	15	30
2*	C	1600	1380	1500	15	12	5	40	43
3*	B	840	1150	1450	60	60	15	7	40
4	A	1340	740	950	60	5	10	6	35
5	B	1250	480	440	60	5	20	7	43
6	C	1240	1525	1580	24	22	10	15	58
7*	D	200	290	380	60	60	60	0	0
8	D	300	350	420	60	60	60	0	0
9	No Coating 383	1600	1490	1550	9	5	5	13	27
10	No Coating 383	1580	1400	1480	5	6	5	10	34
11	E	187	550	750	60	60	60	0	0
12*	E	230	280	325	60	60	60	0	0
13*	No Coating Pre 383	1510	1600	1515	6	1	5	36	70
26	G	1330	900	600	40	30	60	0	30
27*	G	525	460	600	60	60	30	4	30

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*Three-conductor cable

†A value of 60 minutes (length of the test) indicates no short circuit or ignition occurred.

the coatings were generally in good agreement with the single-tray tests. References 25 and 26 give detailed results. Figures 7 and 8 show the cable trays coated with Coating C before and after Test 33 (nonqualified PE/PVC three-conductor cable in a ladder configuration).

II.3.4 Diesel-Fueled Exposure Fires

Another series of tests used the two-tray configuration previously described. However, the ignition source was a diesel-fueled fire which burned for about 13 minutes before self-extinguishing. Another important difference is that no barrier was placed between the trays so that both trays might be exposed to the diesel fire. Five tests were conducted altogether. The rankings of the relative performance of the cable coatings was in good agreement with single-tray and two-tray tests. Figure 9 shows the intensity of the fire during Test 47 (Coating C, unqualified cable in an open ladder configuration). Detailed results can be found in References 25 and 26.

II.3.5 Fire Shield (Barrier) Tests

In addition to the fire retardant coatings tests, eight single-tray and five two-tray tests were conducted using various fire barriers or shields such as solid bottom trays, 1-in. solid barriers (ceramic fiber board), and ceramic wool. The test program is summarized in Table IV. Results of the two-tray tests are given in Table V. Note that in all instances fire propagation was prevented. In these tests, no fire-retardant coatings were used. Additional results are provided in Reference 26. Figure 10 illustrates the use of the ceramic fiber board as a fire shield.

Major Findings

These tests indicate that all coatings and barriers offer a measure of additional protection against cable tray fires. No propagation to the second tray was observed in any of the two tray tests where IEEE-383 qualified cable was used. In the three tests where propagation to the second tray was observed, non-qualified cable was used.

There is a wide range in relative effectiveness of the different fire retardant coatings tested here. Table VI summarizes a ranking of coating effectiveness derived from the small-scale and full-scale tests reported here and in Reference 25. These rankings are based on both combustion and propagation properties.

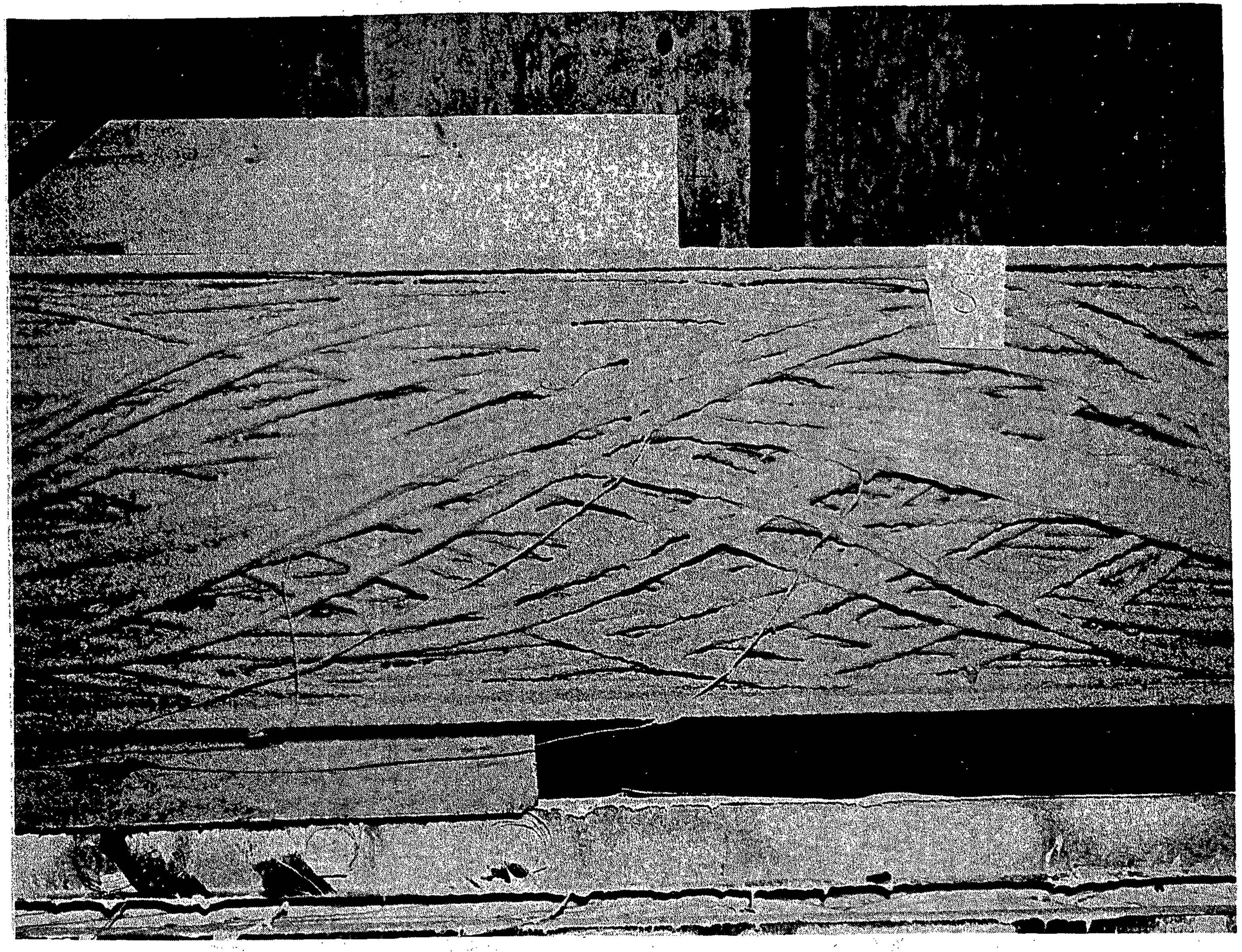

Figure 7

Coating "C" Prior to Test 33

Figure 8

Results of Test 33 Using Coating "C"

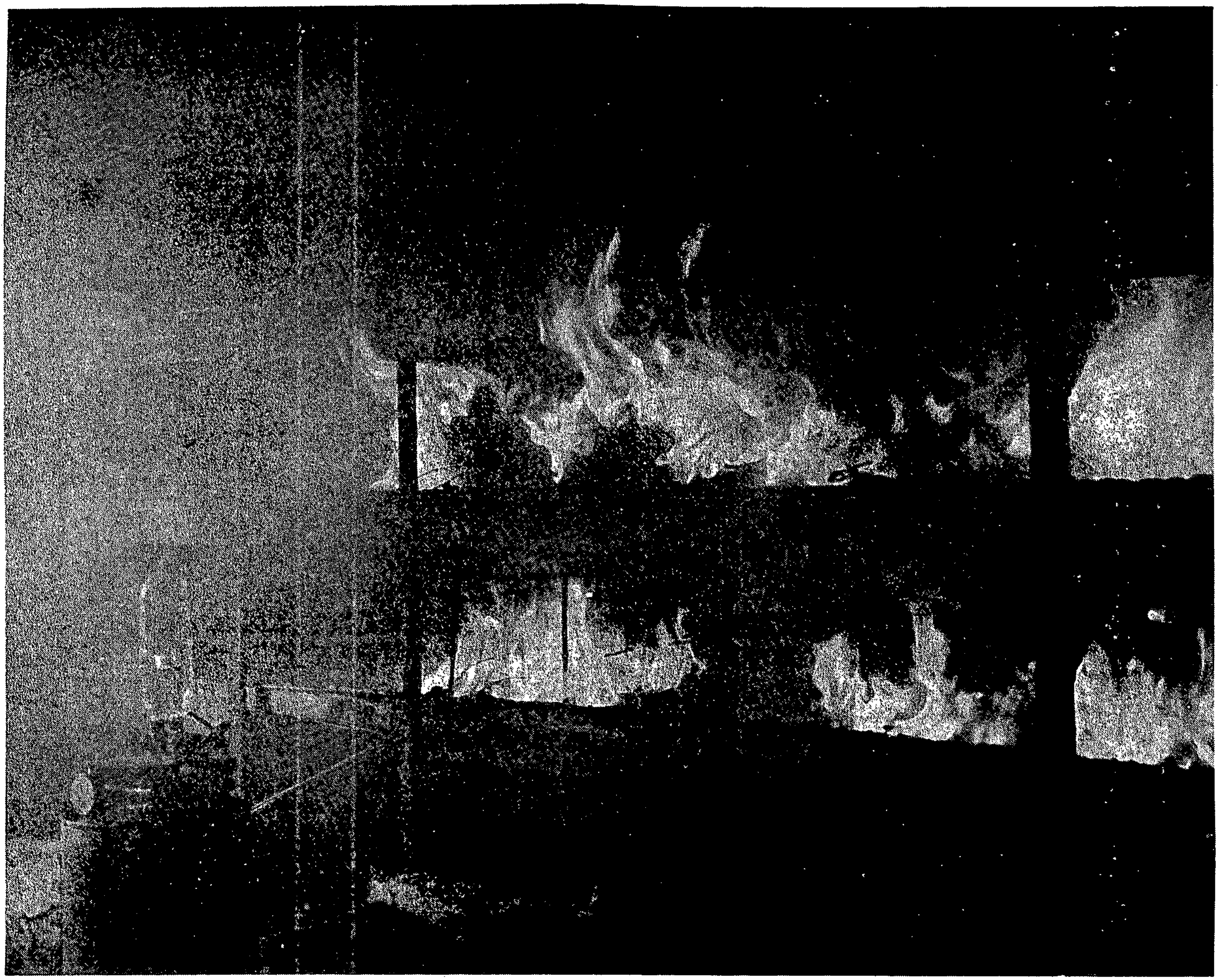

Figure 9

Test 47 Diesel-Fueled Fire

TABLE IV

Test Matrix of Barrier Tests

	Single Tray Tests			Two Tray Tests	
	383 Qualified Cable		Non-383		
Barrier Type	Single Conductor	Three Conductor	Three Conductor	383 Qualified Cable	Non-383
Ceramic wool blanket over ladder tray			X		X
Solid bottom tray no cover	X	X	X		X
Solid cover no vents ladder tray			X		X
Vented cover solid bottom	X	X	X		X
1-in. fire barrier between trays					X

Table V

Results of Full-Scale Two-Tray Fire Shield Tests

Shield and Cable Type	Max Cable Temp (°F)	Max Calorimeter Temp (°F)	Max Barrier Temp (°F)	Time to Electrical Short (min)†	Time to 900° in Cable (min)†	Time to Ignition (min)†	Length of Burn (min)	Length Affected Area (in)	Weight Loss (lbs)	Propagation
Solid Bottom Tray, Non-383 Cable										
Top	91	127	128	60	60	60	0	0	0	No
Bottom	650	480	430	8	60	20	4	43	1.5	
Solid Bottom Tray, Vented Top, Non-383 Cable										
Top	265	170	190	45	60	60	0	0	0	No
Bottom	1300	780	430	5	16	10	55	66	12.5	
1-inch Solid Barrier Between Open Ladder Trays, Non-383 Cable										
Top	265	--	560	14*	60	60	0	0	0	No
Bottom	1350	--	400	2	1	5	42	120	37.5	
Solid Top, Open Ladder Tray, Non-383 Cable										
Top	250	87	94	60	60	60	0	0	0	No
Bottom	1500	305	340	5	4	10	67.5	120	17.75	
Ceramic Wool, Ladder Tray, Non-383 Cable										
Top	100	98	116	60	60	60	0	0	0	No
Bottom	900	330	500	2	13	15	45	108	12.5	

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*Short occurred beyond end of 8-ft barrier as fire progressed beyond that point in bottom tray.

†A value of 60 minutes (length of the test) indicates no short circuit or ignition occurred.

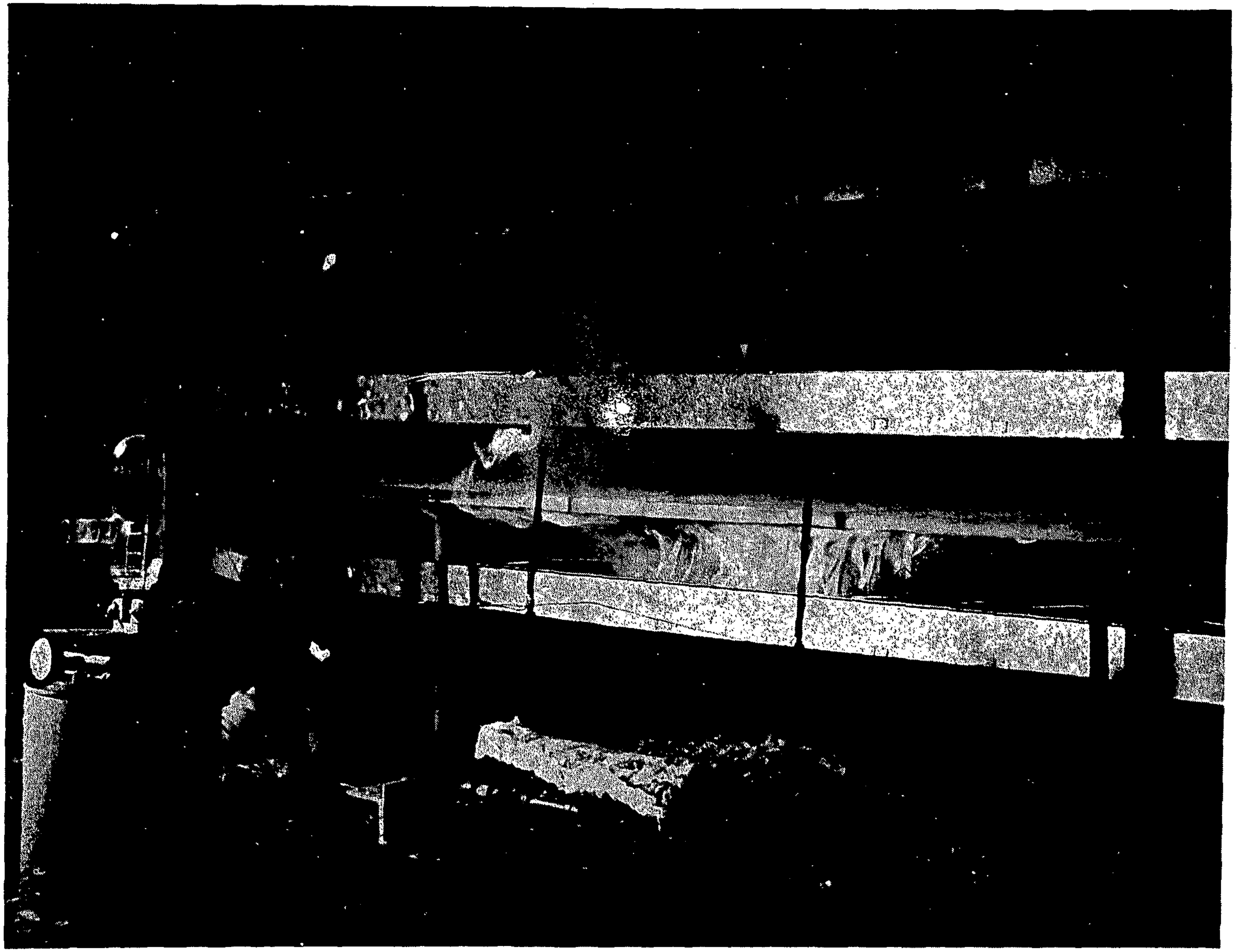


Figure 10

Ceramic Fiber Board Fire Shield

TABLE VI

Fire Retardant Coating Tests
Ranking of Resistance to Combustion (Relative)
(Lowest Numerical Value Provides Most Resistance)

Coating	Small Scale	Single-Tray Tests	Full-Scale Two-Tray Tests Propane Fueled	Full-Scale Two-Tray Tests Diesel Fuel Fire
A	4	5	4	3
B	-	4	3	2
C	5	6	6	5
D	1	1	1	-
E	2	2	2	1
F	6	-	-	-
G	3	3	5	4
Uncoated 383 Cable	7	7	7	-
Uncoated Pre-383 Cable	-	8	8	-

II.4 Corner Effects Testing

Throughout the previous testing, cable tray arrays were arranged to simulate the open plant area with no ceiling or wall in proximity. To get some quantitative measure of the effect of reradiation of heat to the cables, a modest series of full-scale tests was conducted.[27-29] The same cable types, ladder trays, fire facility and fire testing procedures were used in these tests as in the previous tests.

Originally, it was planned to have concrete walls and ceilings provide a corner to simulate the usual conditions found in a nuclear power plant. A review of fire literature and a brief investigation led to the conclusion that a corner made of ceramic fiber boards would be little different from a concrete corner for the duration of the test fire.[30-32] This construction was used for ease of assembly and economy. Six 4 x 8 foot (1.2 x 2.4 m) ceramic fiber boards 1 in. (2.54 cm) thick were arranged as shown in Figure 11 to form a corner above and beside two horizontally oriented cable trays, with the top tray 10.5 in. (26.7 cm) above the other.

The cables were loaded into galvanized steel, open-ladder trays, 18 in. (45.7 cm) wide and 12 ft (3.7 m) long. Although the trays were filled to approximately the tops of the 4-in. side rails of the cable trays, the loading technique allowed maximum air passage through the cables. The cables formed a figure 8 with the crossing point advancing progressively up and down the tray. This resulted in a 25 percent fill by cross-sectional area for three conductor cables (90 cables per tray).

Two types of cable were used in these tests. One type was IEEE-383-qualified three conductor No. 12 AWG, 30 mil (0.76 mm) cross-linked PE, silicon glass tape, 65 mil (1.65 mm) cross-linked PE jacket, 600 V. The other type was non-IEEE-383 qualified cable, three-conductor, 20/10 Poly-PVC, polyethylene insulation, 45 mil (1.14 mm) PVC jacket.

Six tests were run in this series, three each with the IEEE-383 qualified and unqualified cable. The three distances from the ceiling to the top tray were 10.5, 18, and 120 in. (0.27, 0.46, and 3.05 m). The wall distances to the edge of the tray were 5, 10.5, and 60 in. (0.13, 0.27 and 1.52 m).

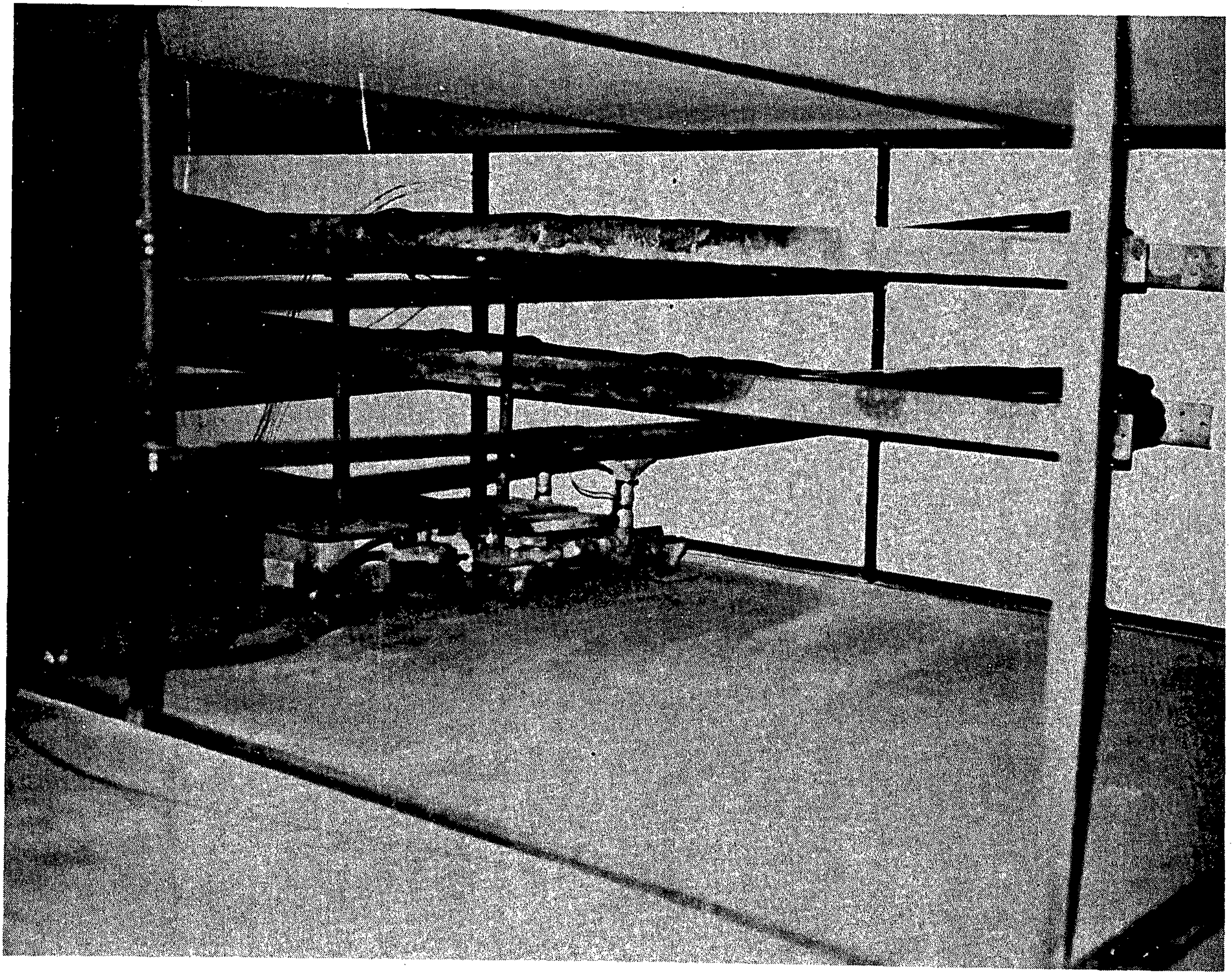


Figure 11

Corner Effects Test Arrangement

Effective measures of the corner effects are weight loss (from cable pyrolization) and maximum heat flux from the cable tray fires. These values are plotted in Figures 12 and 13 for both the IEEE-383 qualified and the unqualified cable. The diagonal distance is measured from the top of the top tray to the corner (intersection of wall and ceiling).

As expected, the effect of reradiation of heat from walls and ceilings varies inversely with distance. Although the relationship between corner proximity and certain fire severity parameters is demonstrated, these functions are derived for two types of cable. It is expected that all cables would demonstrate similar effects but differ in magnitude of fire severity.

The minimum corner distance used in these tests is a reasonable minimum in order to allow access to the trays in a real power plant situation. The proximity of ceiling and wall would probably introduce a secondary effect of oxygen depletion in the limiting case of small distances, but this was not found to be a factor in these tests.

Major Findings

An inverse relationship was found between fire intensity and wall/ceiling distance in these corner effects tests. Beyond a diagonal distance (from tray edge to corner) of 6 ft (1.8 m) there was little effect.

II.5 Fire Suppression Tests

II.5.1 Fire Barrier and Suppression Test (UL)

On September 15, 1978, a full-scale fire test was conducted at Underwriters Laboratories Incorporated to demonstrate the effectiveness of a ceramic fiber blanket and automatic fire suppression system in protecting a vertical cable tray configuration.[33] The spacing of the cable trays was in compliance with separation criteria guidelines at the time. An open pool fire fueled by liquid hydrocarbon was used.

A corner-ceiling assembly approximately 20 x 20 x 15 ft high (6.1 x 6.1 x 4.6 m) was used to simulate a corner-room situation. The walls and ceiling consisted of steel framing and 1/2 in. (1.3 cm) thick marinite boards. The five cable trays used in the tests were open ladder type and made from

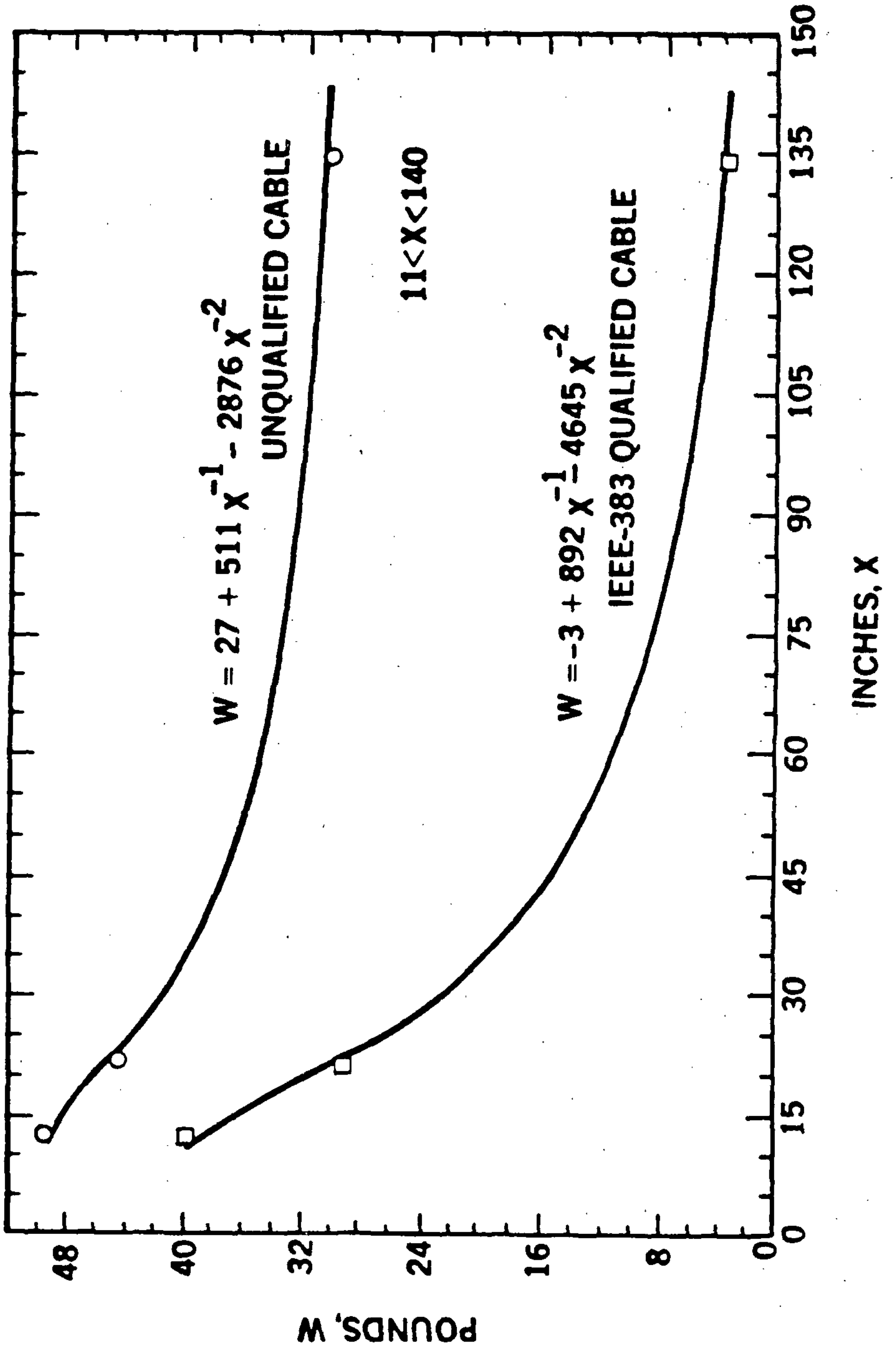


Figure 12

Cable Weight Loss as Function of Corner Distance

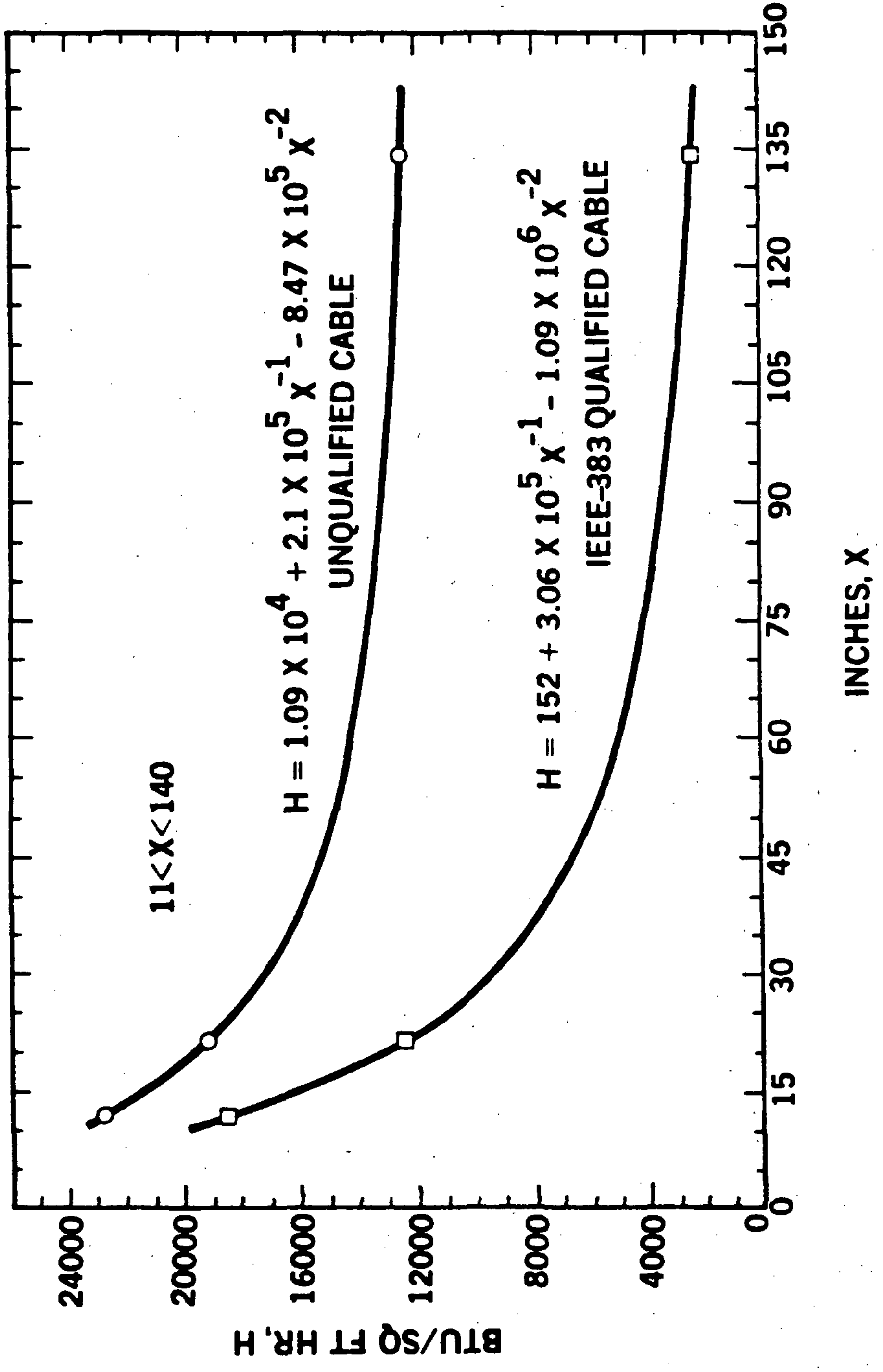


Figure 13

Maximum Heat Flux From Cable Tray Fire as Function of Corner Distance galvanized steel. Three-conductor, No. 12 AWG PE/PVC electrical cables were used (not qualified to IEEE-383). A steel pan about 25 ft^2 in area (2.3 m^2) was used to contain the 2 gal (7.6 P) of heptane fuel. The barrier installed about each cable tray consisted of an assembly of 1-in. (2.54-cm)-thick ceramic wool blanket pieces. Three upright automatic sprinklers rated at 165°F (74°C) and 35 psig (2.4×10^5 Pa) were installed 12 in. below the ceiling. One ionization chamber type and one photoelectric type smoke detectors were also installed at the ceiling.

All cables were energized at low voltage during the test, and each circuit carried low current and was monitored continuously for shorts between conductors or between conductor and tray. In addition to the three open-head sprinklers, three dummy sprinkler heads without connection to the water supply were suspended near each open head. The dummy heads were monitored electrically, and only after activation of all three dummy heads at one location would the water system be manually operated. Temperatures at various locations within the cable trays were recorded.

Figure 14 shows the heptane fire about 1 minute into the test. Maximum flame height during the test was about 3 ft (0.9 m), and flaming continued at various levels of intensity for up to 40 minutes. The two smoke detectors were activated in less than 15 seconds. Only two of the nine dummy heads were activated at all, and these occurred about 53 seconds into the test. Hence, the sprinkler system was never activated manually. Recordings indicated that short circuits first occurred at 3 minutes and 13 seconds. Posttest inspection of the cables indicated thermal damage near the base of four of the five cable trays.

Major Findings

Analysis of the cable temperatures during the test indicates that had the ceramic fiber blanket been adequately sealed at the base, physical and electrical damage to the cables in this test probably would not have occurred. Moreover, if a 2-out-of-3 logic had been used for activation of the water suppression system by the dummy heads, the suppression system would probably have extinguished the fire before short circuits were observed.

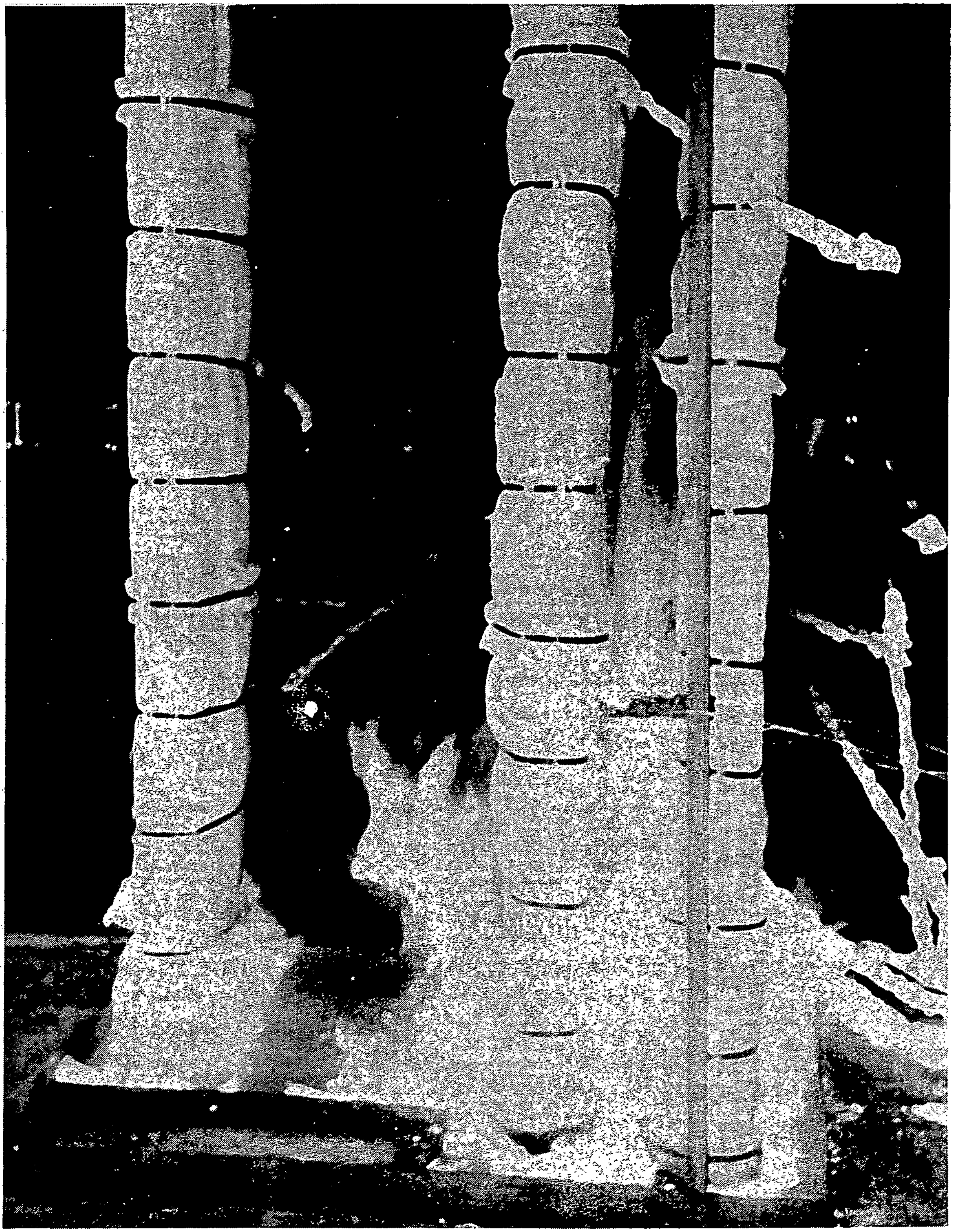


Figure 14

UL Fire Barrier and Suppression Test

II.5.2 Halon Suppression Tests

A series of nine tests were conducted at Sandia National Laboratories to determine the effectiveness of Halon 1301 in suppressing flaming and deep-seated cable tray fires.[34] This halogen compound is produced by E.I. DuPont de Nemours and Company, Incorporated and has the chemical formula $CBrF_3$. Halon 1301 has been extensively tested as a fire suppressant.[35] In addition to the retardant action on fires, it is believed that Halon 1301 presents less of a personnel hazard than carbon dioxide or nitrogen inerting systems. According to human effects experiments conducted by Haskell Laboratories[36] the health hazard threshold for Halon 1301 is 7 percent by volume. The room volumetric concentration of Halon did not exceed 6 percent for this series of cable fire suppression tests.

The experimental facility used in all earlier tests had to be modified in order to install the various suppression systems to be tested. One new feature of the facility was a ventilation system, installed to allow simulation of normal air ventilation and circulation in a room of a nuclear power plant. The flow rate of the ventilation system, when used, was set to approximately 2100 ft^3 per minute which provided an air turnover rate in the room of about once every 4.6 minutes.

Tests were conducted in both the horizontal and vertical configuration of cable trays, and both IEEE-383 qualified (cross-linked polyethylene, 3 conductor) and unqualified (PE/PVC, 3 conductor) cables were used as in previous tests. Trays were separated by 10.5 in. (27.6 cm). "Dummy" trays consisting of an insulating barrier were placed adjacent to the two trays (vertical tests) or above the top tray (horizontal tests) to provide reradiation of heat. In these tests, the ignition tray was designated the donor tray, while the second tray was designated the acceptor tray. Five-minute on-and-off burn cycles using a total of 140,000 BTU/HR (41-kW) propane burners were used until a "well-developed" fire was started. At this point, an insulating barrier separating the two cable trays was removed and 1 minute later the Halon discharged. The discharge rates complied with NFPA 12A-1980.[37] The room was also sealed at the time of discharge as required.

Table VII summarizes the tests conducted as well as the results. Tests 58 and 59 used no Halon but instead allowed the fire to proceed until the ventilation system was

TABLE VII

Halon Suppression Tests Summary

Test Number	Configuration	Cable Type	Suppression Method	Results
56	Horizontal	IEEE-383 Qualified	45-minute soak using Halon	No reignition after admission of fresh air
57	Horizontal	Qualified	10-minute Halon soak	No reignition
58	Horizontal	Qualified	No Halon; 45 minutes without ventilation	Self-quenched after 30 minutes
59	Horizontal	Qualified	No Halon; 10 minutes without ventilation	Burning after 10 minutes
60	Horizontal	Qualified	4-minute Halon soak	Reignited when ventilated
61	Horizontal	Unqualified	16-minute Halon soak	No reignition
62	Vertical	Unqualified	5-minute Halon	No reignition
63	Vertical	Qualified	4-minute Halon soak	No reignition
64	Vertical	Qualified	Halon discharged but room continuously vented	No reignition

turned on later. In only one instance using Halon, Test 60, did the cable insulation reignite after readmission of fresh air. The soak time represents the amount of time the room was sealed, i.e., time between discharge of Halon and readmission of fresh air using the ventilation system.

Halon 1301 was very effective in suppressing flames. Figure 15 shows that 5 seconds after discharge the flames have been extinguished and all that remains is smoke and condensed water vapor. Figure 16 taken from Test 61 shows the dramatic temperature drop in the flaming region as Halon is discharged.

Halon 1301 was not as rapid in suppressing deep-seated cable tray fires. Figure 17 indicates that even after the Halon has been discharged the interior cable bundle temperature continues to rise, probably resulting from continued combustion of cable insulation. The second increase in temperature occurs after the readmission of air and reignition of the cable insulation.

Finally, Figures 18 and 19 show the dynamic mass loss of cable insulation in the donor trays for Tests 57 and 59. These two tests were identical in every respect except that in Test 57 a 10-minute Halon soak was provided whereas no Halon was used in Test 59. However, only 3.7 kg of insulation was lost when Halon was used (most of it before Halon discharge) compared to a loss of 6 kg when the fire was allowed to self-extinguish. Clearly, Halon is an effective fire suppressant agent even for deep-seated cable fires.

Major Findings

Six very obvious but important items stand out among all conceivable findings from the Halon suppression systems tests. They number as follows:

1. No damage to, or reduction in, the acceptor tray cables' current-carrying capacity as a result of Halon was observed in any of the tests.
2. In all of the tests in which it was used, the Halon effectively extinguished fires in both the acceptor and donor trays. In only one test (60) was a flame rekindled in either tray after the room was ventilated.

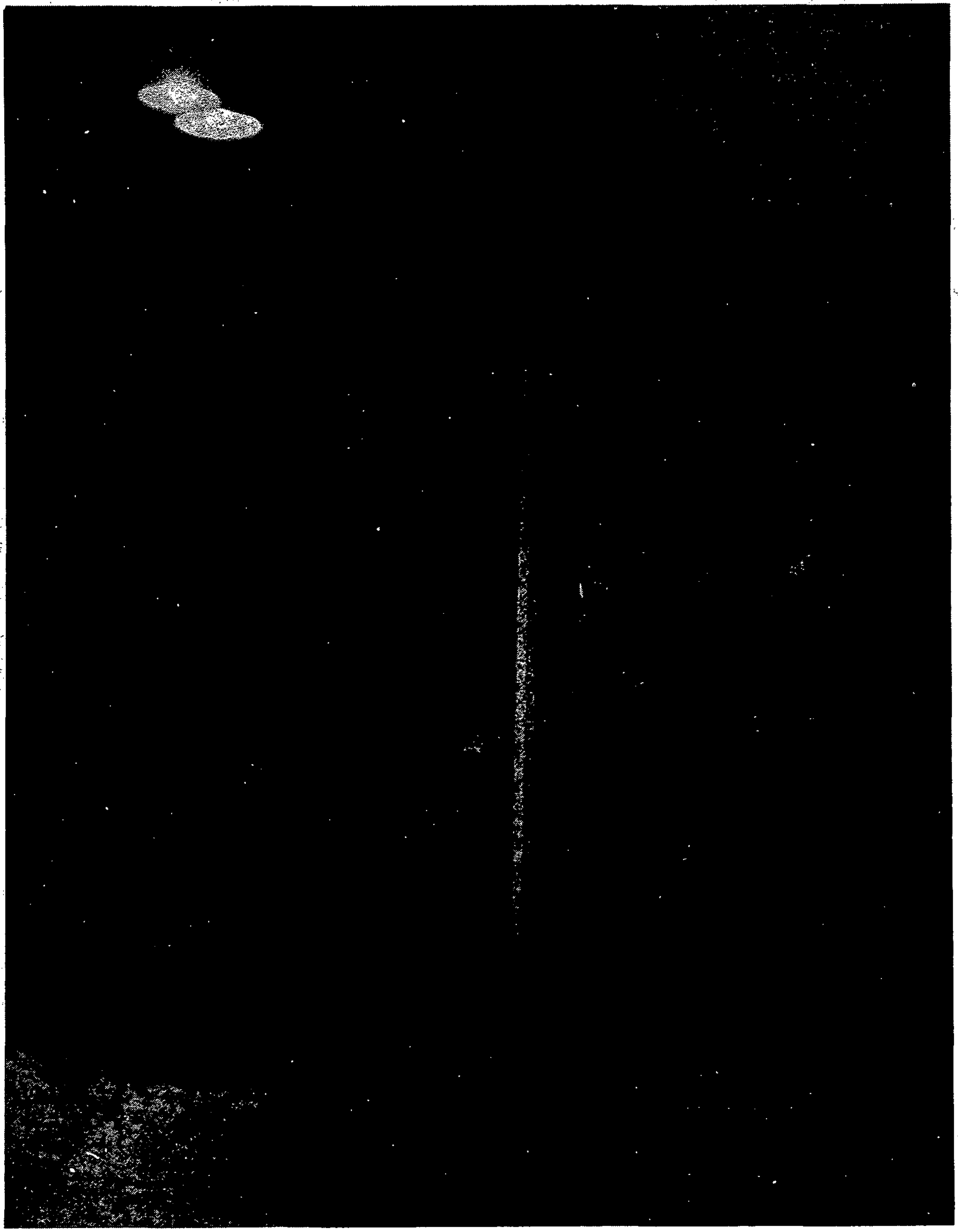


Figure 15

Immediate Suppression of Flames by Halon 1301

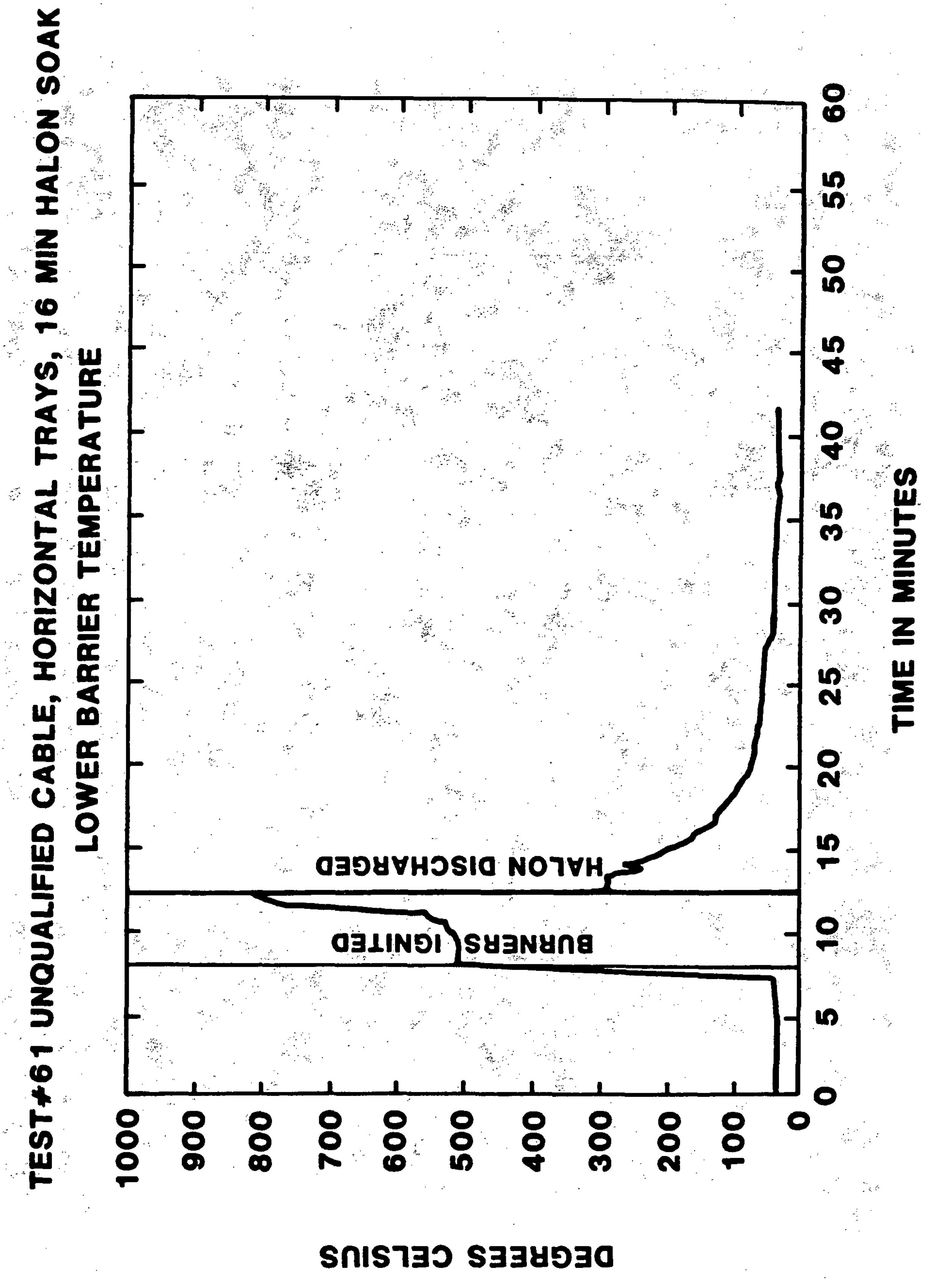


Figure 16

Temperature Drop in Flaming Region

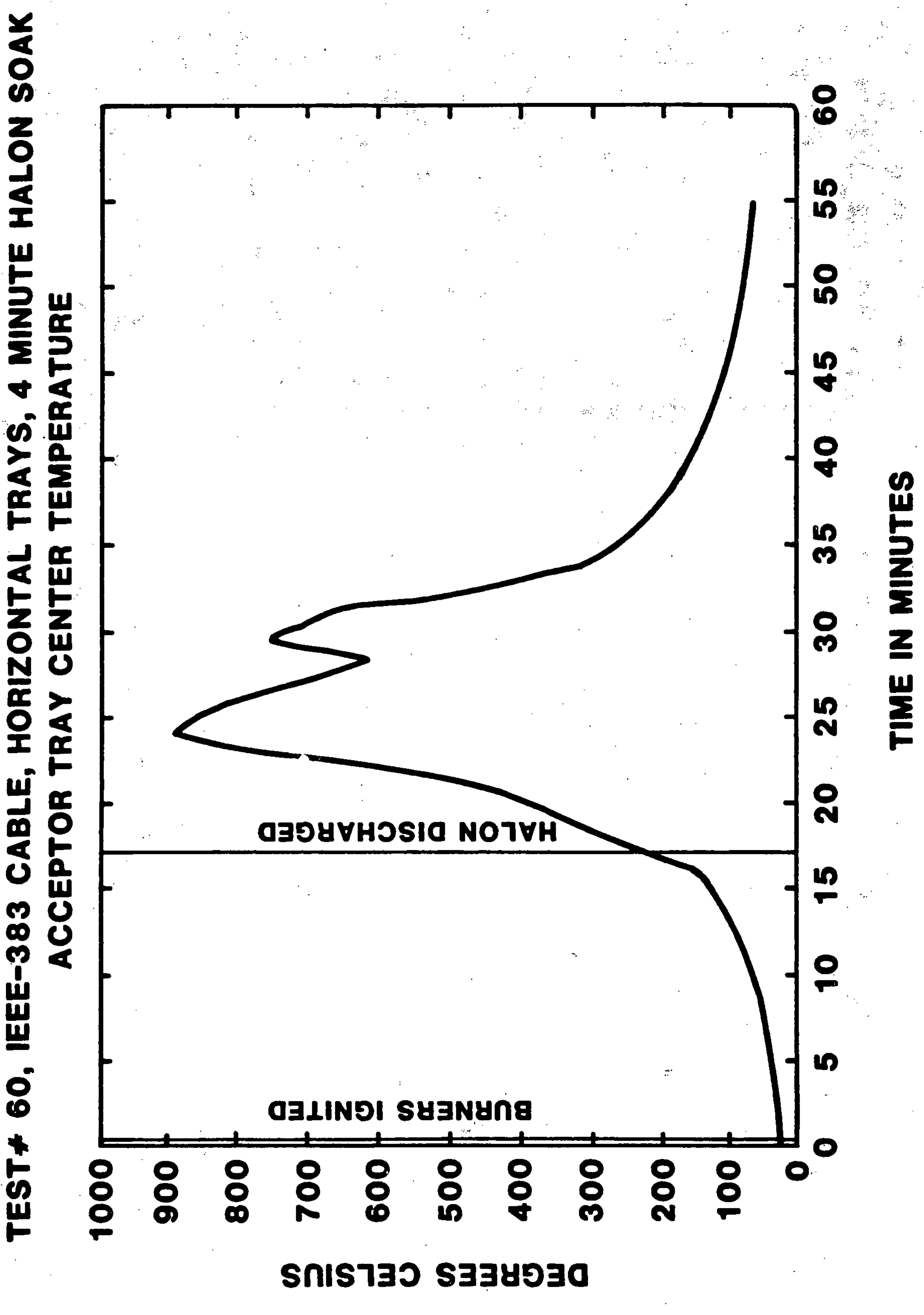


Figure 17

Indication of Deep-Seated Fire and
Reignition of Cables

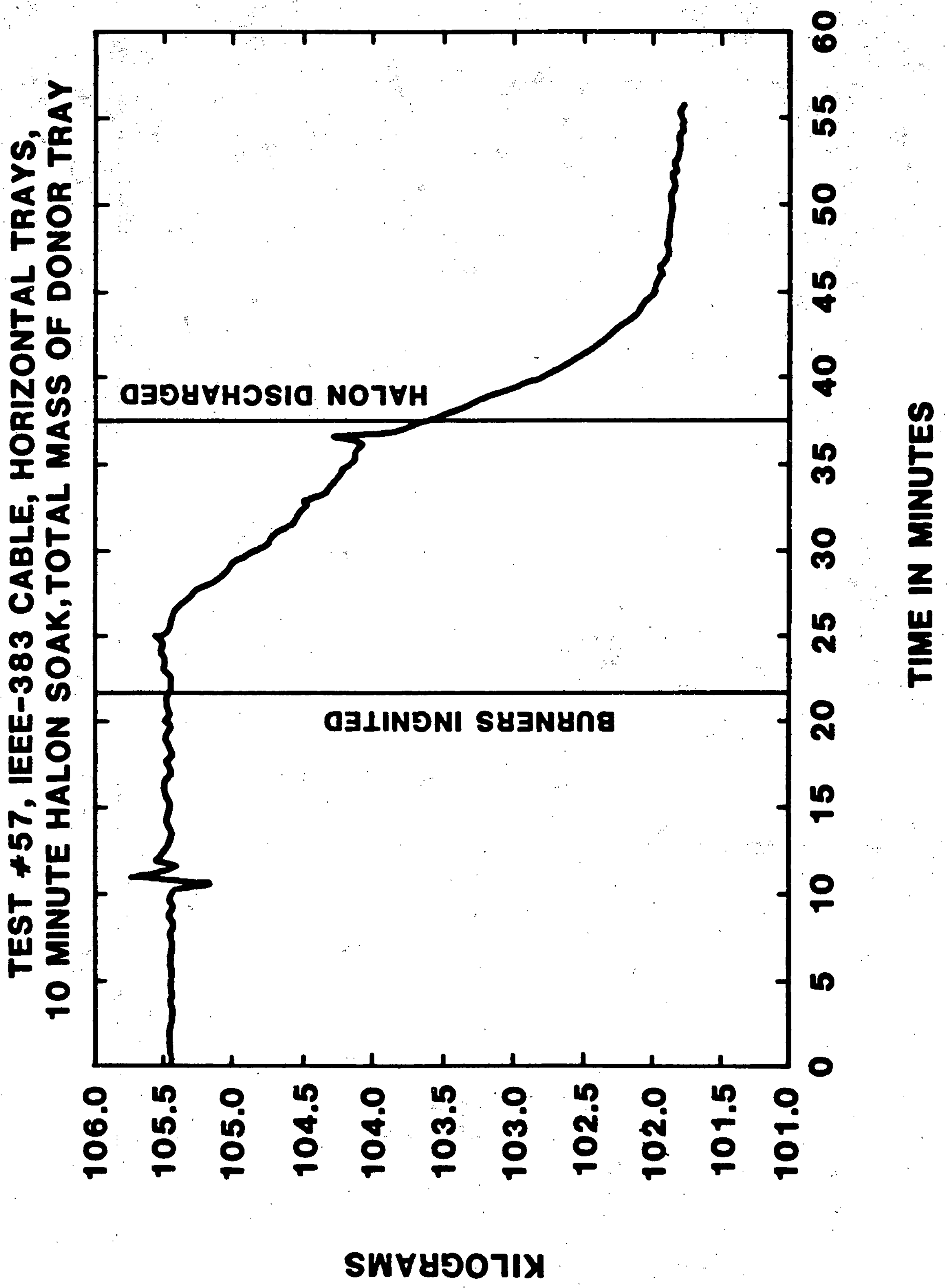


Figure 18

Mass Loss in Presence of Halon

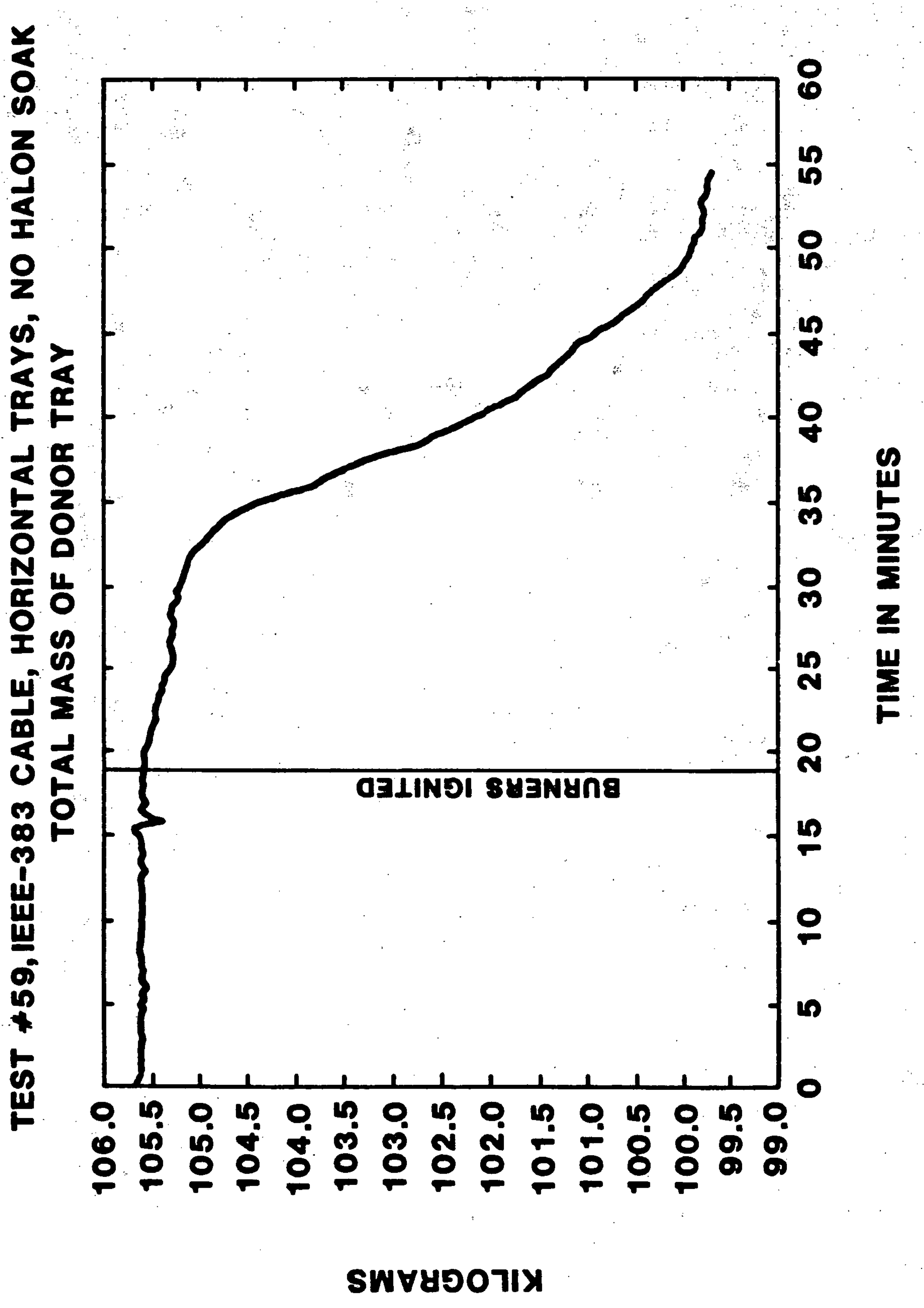


Figure 19

Mass Loss Without Halon Suppression

3. No flammable concentrations of unburned hydrocarbons were pyrolyzed during the Halon soak time in any of the tests.

4. A time limit on the Halon's ability to permanently extinguish a cable tray fire may have emerged. While a 10-minute interval of Halon soak was enough to extinguish a fire in a horizontally oriented tray filled with qualified cable, a 4-minute interval was inadequate for this task.

5. As mentioned above, the Halon permanently extinguished a fire after only a 10-minute soak time, whereas the same time limit on simple oxygen deprivation was insufficient to keep the flame from returning upon ventilation.

6. While a 4-minute soak time was not enough to prevent a rekindling in a horizontally oriented tray filled with qualified cable, it was enough to prevent reignition in a vertically oriented tray filled with the same cable. From this, the conclusion is that Halon more effectively quenches fires in vertically oriented trays than in those horizontally oriented.

II.5.3 Water Sprinkler Tests (NFPA 13)

A series of tests was conducted to determine the effectiveness of overhead sprinklers in suppressing cable tray fires. The original intention was to duplicate the Halon test series in order to get a direct comparison between Halon suppression and water sprinkler suppression. Although no final report on the water tests has been issued as yet, the results are briefly summarized here. Table VIII lists the tests performed and the results.

Two pendent-type, open-head sprinklers with standard orifices of 1/2 in. (1.3 cm) diameter were used. The sprinklers were 12.5 ft high (3.8 m), were offset from the cable trays and were separated by 12 ft (3.7 m). The water system was designed to produce a pressure of 35 psig (2.4×10^5 Pa) at each open head. A total flow rate of 71 gal per minute (4.5 ℓ per second) was obtained. The system was activated manually. The

TABLE VIII

Water Sprinkler Suppression Tests Summary

Test Number	Configuration	Cable Type	Suppression Method	Results
65	Vertical	IEEE-383 Qualified	71 GPM For 4 minutes	Fire extinguished (water caused short in acceptor tray)
66	Vertical	Qualified	71 GPM for 4 minutes with ventilation on	Fire extinguished (water caused short in acceptor tray)
67	Vertical	Unqualified	71 GPM for 5 minutes	Fire extinguished (short in acceptor tray before water)
68	Horizontal	Qualified	71 GPM for 15 minutes	Fire extinguished (water caused short in acceptor tray)
69	Horizontal	Qualified	71 GPM for 10 minutes	Fire extinguished (no short)
70B	Horizontal	Qualified	71 GPM for 5 minutes	Fire extinguished, but continued temperature rise for 5-10 minutes (water caused short in acceptor tray)
71	Horizontal	Unqualified	71 GPM for 16 minutes	Fire extinguished (water caused short in acceptor tray)

spacing and flow densities were in compliance with NFPA 13.[3] Figure 20 shows the water sprinkler setup for the vertical configuration. The test procedure was very similar to that used in the Halon tests.

The water sprinklers were successful in extinguishing all cable trays fires in the configurations tested. Suppression was more effective in the vertical configuration, with 4 to 5 minutes of suppression an adequate amount of time for vertical trays but marginally adequate for horizontal tray fires. Short circuits occurred quite readily in the acceptor tray when the water was discharged, but the cause of the shorts is uncertain.

Major Findings

Area water sprinklers are effective in suppressing cable tray fires in the vertical configuration; they are somewhat less effective for trays in the horizontal configuration. No general statements can be made concerning their effectiveness for horizontal tray fires of more than the three levels of trays tested.

II.5.4 Directed Water Spray Tests (NFPA 15)

Another series of water tests was conducted to determine the effectiveness of directed water sprays in suppressing cable tray fires. Tests were conducted in both the vertical and horizontal configurations, and with both IEEE-383 qualified and unqualified cables. A total of five, 12-ft (3.7-m)-long cable trays filled to 25 percent were used in each test. Unlike the Halon and water sprinkler suppression tests, the intention in these tests was to obtain fully developed fires in four of the five cable trays before manually activating the water suppression system. Although no final report on these tests has been issued as yet, the results are briefly summarized here. Table IX lists the tests performed to date and the results.

Flat, fan-type spray nozzles were used. A uniform distribution of spray was provided over an angle of 100°. The orifice size was 7/64 in. (2.8 mm) and each of the ten nozzles used in all the tests provided 2.7 GPM (0.17 ℓ/s) at a static pressure of 81 psig (5.6×10^5 Pa), or a flow density of 0.3 GPM per ft^2 (12.2 ℓ/min-m^2) of cable tray surface area. These values are in compliance with NFPA 15 standards for identified fire hazards.[4]

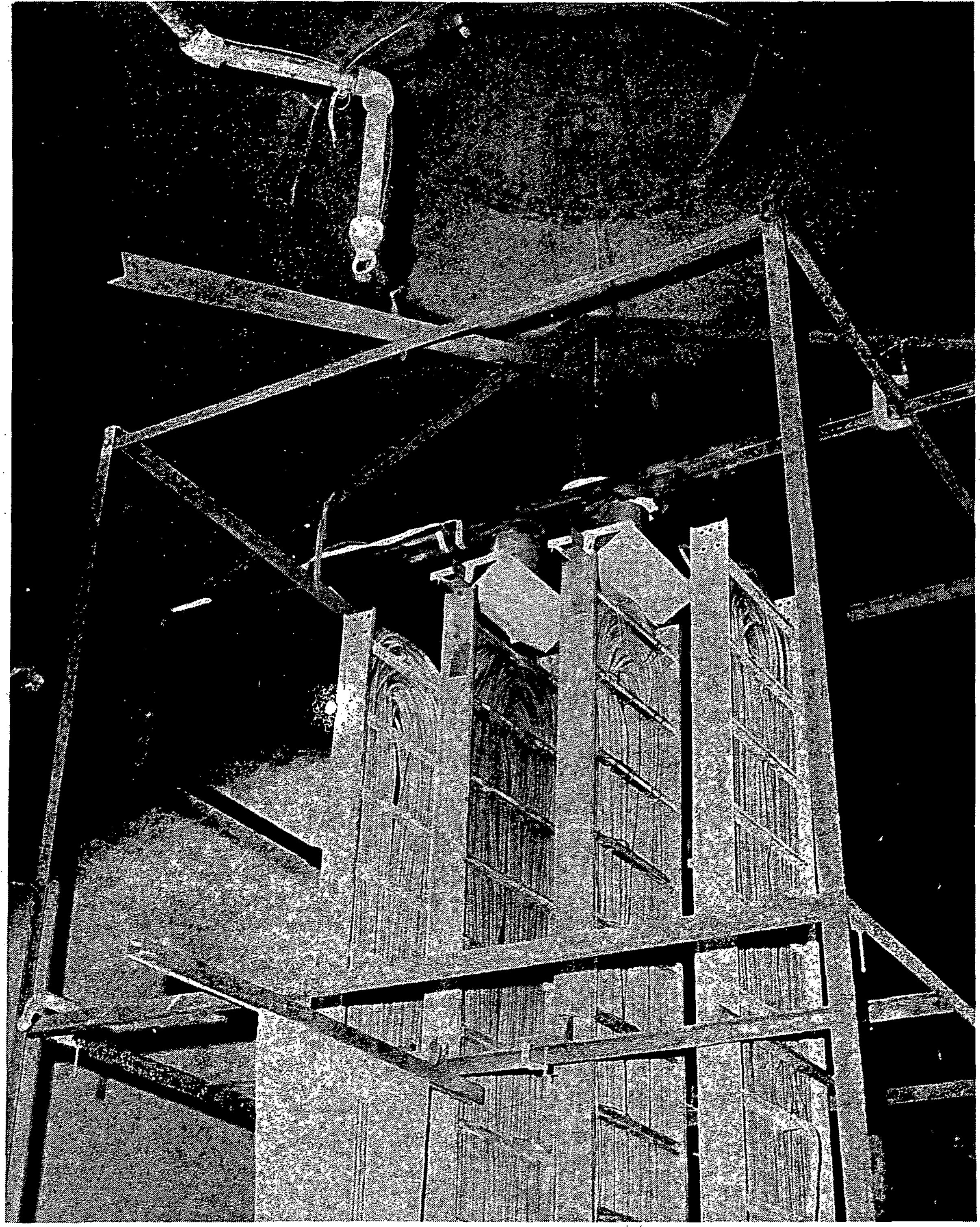


Figure 20

Water Sprinkler Test Arrangement
(Vertical Configuration)

TABLE IX

Directed Water Spray Suppression Tests Summary

Test Number	Configuration	Cable Type	Suppression Method	Results
72	Horizontal	IEEE-383 Qualified	0.3 GPM/ft^2, 5 min, no ventilation	Fire extinguished easily
73	Horizontal	Qualified	0.3 GPM/ft^2, 5 min, forced ventilation	More severe fire than 72 but easily extinguished
74	Horizontal	Unqualified	0.3 GPM/ft^2, 5 min, forced ventilation	Fire extinguished easily
75	Vertical	Qualified	0.3 GPM/ft^2, 5 min, forced ventilation	Fire extinguished easily
77	Vertical	Unqualified	0.3 GPM/ft^2, 5 min, forced ventilation	Fire extinguished easily

Figure 21 shows the setup for the horizontal configuration in Test 73. In general, the directed spray was a very effective means of suppressing cable tray fires. Most flaming was suppressed in a matter of 15 seconds or less, and near-ambient temperatures were obtained within the cable trays in a matter of minutes. Hence, there was no chance of reignition after 5 minutes of water spray. Figure 22 illustrates this dramatic temperature drop during Test 75.

Major Findings

Directed water sprays are a very effective means of suppressing cable tray fires, including deep-seated fires, and means of preventing reignition. Five minutes of water spray at a flow density of 0.3 GPM/ft^2 (12.2 ℓ/min-m^2) was adequate for suppressing large cable tray fires.

II.6 Penetration Seal Tests

II.6.1 Small-Scale Tests (UL)

An experimental investigation was performed at Underwriters Laboratories to determine the effects of pressure differential, fire exposure conditions and sample construction on the performance of fire stops used to seal electric cable and conduit penetrations through concrete fire barriers.[38] Experiments were conducted using a differential pressure of -12 to +125 Pa, various sample constructions and two fire exposure conditions.

This investigation consisted of conducting 50 small-scale fire experiments using several types of fire stop samples. A summary of the experiments conducted is shown in Table X. These experiments were organized into 21 groups to facilitate comparison of results. Within each group, the parameter under consideration was varied with the sample and test procedure held constant.

Each sample was subjected to the prescribed fire exposure until either flaming occurred on the unexposed side or until the appropriate information was obtained. During each experiment, temperatures of the unexposed surface and visual observations of physical performance were recorded. For some experiments, temperatures within the fire stop material were recorded for supplemental information.

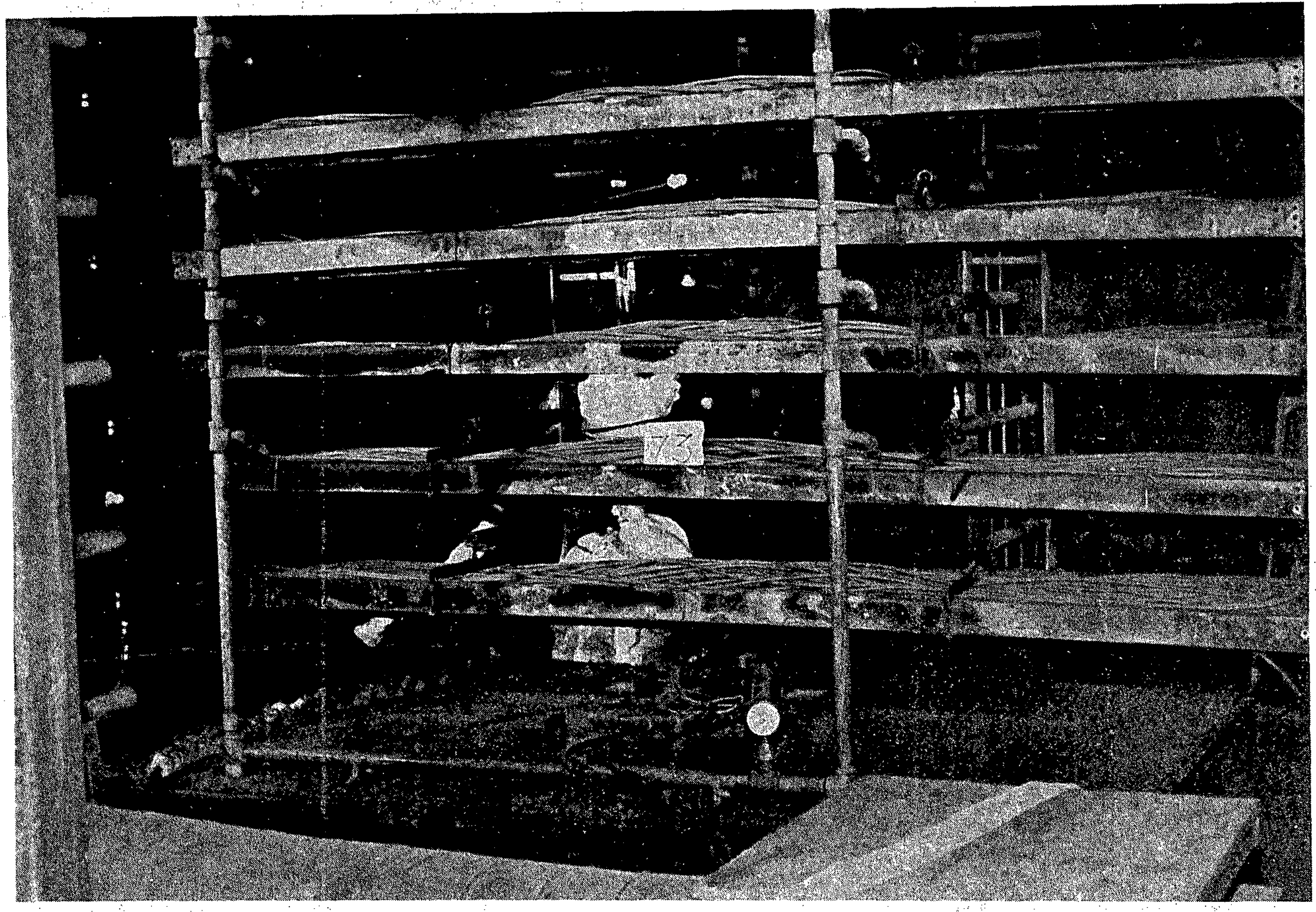


Figure 21

Directed Water Spray Test Arrangement
(Horizontal Configuration)

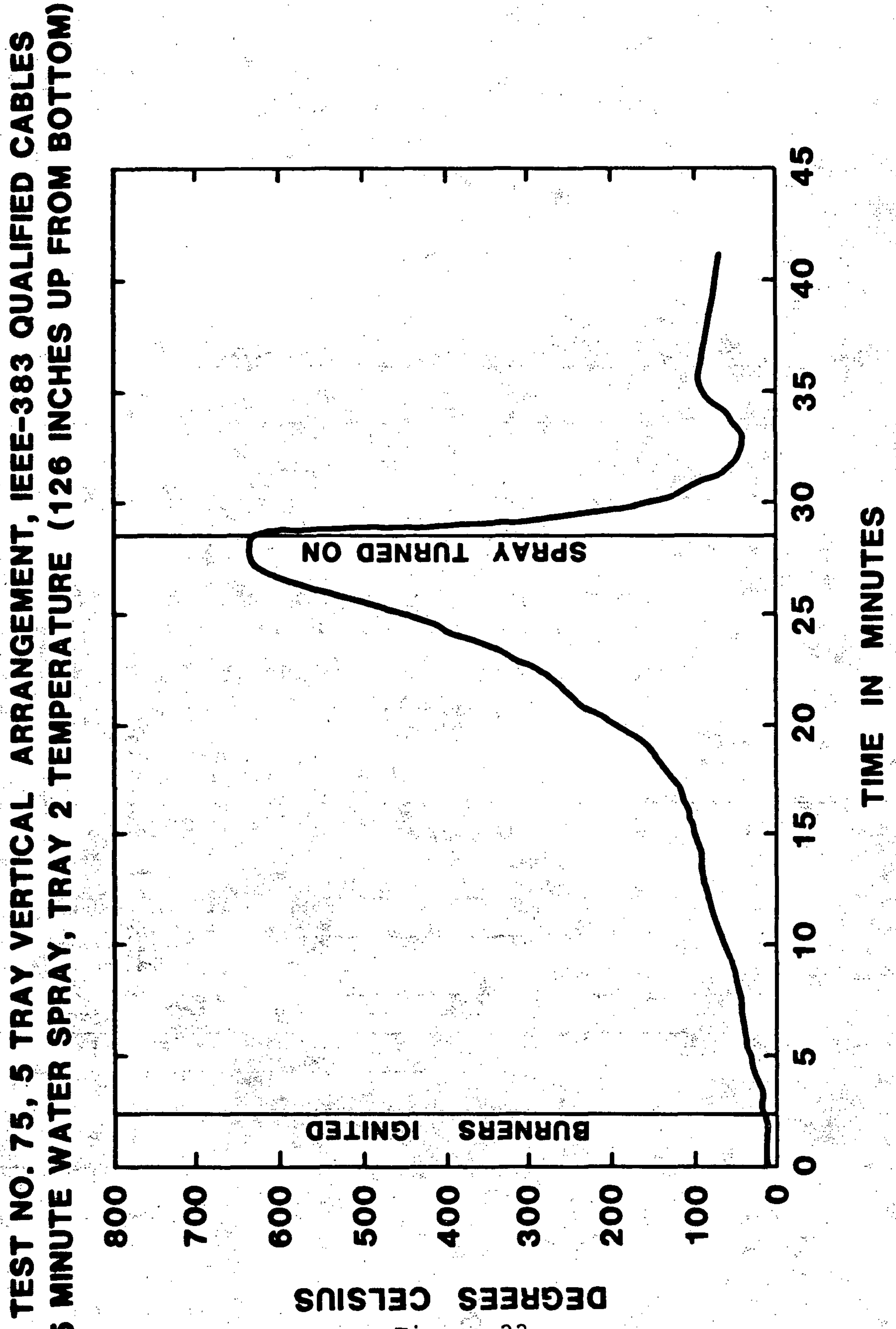


Figure 22

Indication of Effectiveness of Directed Water Spray

TABLE X

Summary of Small-Scale Penetration Seal Tests

Parameter	Group	Experiments	Description
Pressure Differential	1	P22, P19, P1, P3, P5	Pressure +2 to +125 Pa; silicone foam; cables
	2	P23, P20, P2, P4, P6	Pressure +2 to +125 Pa; silicone foam; no cables
	3	P9, P11	Pressure +2 and +125 Pa; silicone elastomer; cables
	4	P10, P12	Pressure +2 and +125 Pa; silicone elastomer; no cables
	5	P13, P15	Pressure +2 and +125 Pa; device; cables
	6	P14, P16	Pressure +2 and +125 Pa; device; no cables
	7	P7, P8	Pressure +2 and -12 Pa; silicone foam; cables
	8	P21	Pressure +125 Pa; silicone foam with formed crack
	9	P17, P18	Pressure +3 and -12 Pa; silicone elastometer with two holes created by cable pull
Fire Exposure	10	FC1, FC2	Silicone Foam--less severe temperature curve
		P7*	Silicone Foam--ASTM E119 temperature curve
	11	FC3	Silicone Elastomer--less severe temperature curve
		CL1*	Silicone Elastomer--ASTM E119 temperature curve
Sample (Conductor size & Type)	12	CT1, CT3	300 MCM CU Cable
		CT2, CT4	300 MCM AL Cable
	13	CS1	3C/12 AWG Cable--Silicone Elastomer
		CS2	7C/12 AWG Cable--Silicone Elastomer
		CT1*	300 MCM Cable--Silicone Elastomer

*Experiment used for comparison with others in group.

Table X (Cont'd)

Parameter	Group	Experiments	Description
	14	CS3	3C/12 AWG Cable--Device
		CS4	7C/12 AWG Cable--Device
		CT4*	300 MCM Cable--Device
Sample (Cable Type)	15	T1	Cable Type A--Silicone Elastomer
		T2	Cable Type G--Silicone Elastomer
		T3	Cable Type H--Silicone Elastomer
		CS2*	Cable Type F--Silicone Elastomer
	16	T4	Cable Type A--Device
		CS4*	Cable Type F--Device
Sample (Pipe)	17	PS1	1 in. Steel Pipe
		PS2	3 in. Steel Pipe
Sample (Conduit)	18	CD1	1 in. Steel Conduit
		CD2	1 in. AL Conduit
	19	CD3	3 in. Steel Conduit
		CD4	3 in. AL Conduit
Sample (Cable Loading)	20	CL1	One Layer of Cables
		CL2	Three Layers of Cables
Sample (Opening)	21	S1	2-in. (51-mm) Opening
		S2	6-in. (152-mm) Opening
		S3	9-in. (230-mm) Opening
		S4	13-in. (330-mm) Opening

*Experiment used for comparison with others in group

All fire stops were installed in 6-in. (150-mm) thick concrete floor slabs. Openings in all but three slabs were either circular 6 in. (150 mm) in diameter or 12 in. (310 mm) square. The remaining slabs had circular openings of 2 in. (51 mm), 9 in. (230 mm) and 13 in. (330 mm) in diameter.

The fire stop materials used were silicone foam, silicone elastomer, and a fire stop device. These are representative of materials currently used in nuclear power plants. The silicone foam and silicone elastomer were two-component materials which vulcanized at room temperature (RTV). These materials were mixed, poured into the openings, and cured in accordance with the manufacturer's installation instructions. Testing was in accordance with IEEE 634-1978.[39] Figure 23 shows the small-scale floor furnace setup used in these tests.

Results indicated that for those materials which remained integral during the test and did not allow a path for gas flow, the effect of changes in pressure differential was not significant.

In tests with a positive pressure differential between 0.01 and 0.50 in H_2O (2 and 125 Pa), no significant change was observed in the transmission of heat through the material, in the time at which flaming occurred, or in the formation of cracks in the decomposing material. (The rate of heat transmission through the silicone foam and silicone elastomer materials can be seen by the rate at which a specific temperature propagates through the material. The propagation rate of the 725°F (285°C) temperature was selected for comparison since it also represents the approximate front of the char layer.)

The time at which flaming occurred on the unexposed side was not affected by changes in positive pressure differential, nor were the formations of cracks in the decomposing material affected by these pressure changes.

Testing with a negative pressure differential did not significantly affect the performance of the silicone foam material installed <u>without through openings</u>. However, testing with a positive pressure differential affected the performance of the silicone elastomer material installed <u>with through openings</u> of 0.50-in. (12-mm)-diameter holes.

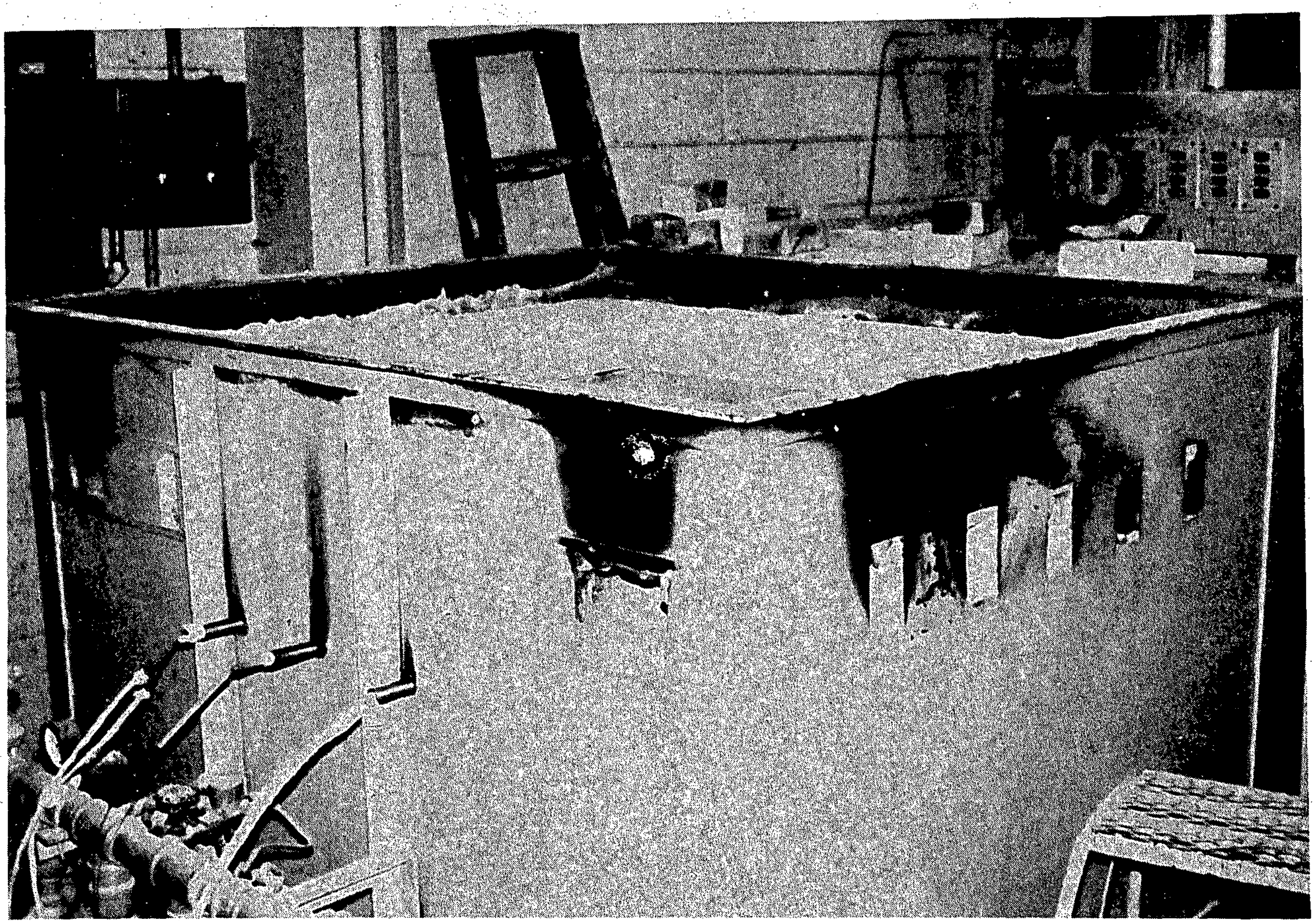


Figure 23

Small-Scale Penetration Seal Tests at UL

Three experiments were conducted with a fire less severe in temperature than the standard temperature-time curve specified in ASTM E119.[5] As expected, temperatures on the unexposed side of the samples for these experiments were lower than for comparable samples subjected to a ASTM E119 fire exposure. Consequentially, the time to failure increased for the samples exposed to the less severe fire.

Changes in sample construction investigated were conductor type and size, cable type, conduit or pipe type and size, cable loading, and opening size. Results indicate that changes in fire stop construction can affect the performance.

Changes in conductor type (copper vs. aluminum) affected unexposed surface temperatures of the fire stop material near the conductor. The temperature rise near the copper 300 MCM cable was greater than at the aluminum 300 MCM cable. Increasing the conductor size also resulted in increased temperature on the unexposed surface of the fire stop material near the conductor.

The size of pipe or conduit affected the temperature of the surrounding fire stop material. Based upon the temperature at the material-pipe interface, the temperature tended to be greater near the 3-in. pipe than at the smaller 1-in. pipe. The type of conduit, either steel or aluminum, also had an effect on the surrounding fire stop material temperature. The temperature at the material-pipe interface tended to be generally greater near the aluminum conduit than near the steel conduit.

It was also observed that increasing the number of cables penetrating the fire stop increased the temperature of the fire stop material near the cables. The temperature near a three-layer bundle of cable was greater than the temperature near a one-layer bundle of cable.

The size of the opening appeared to affect the structural integrity of the material. It was observed that for the larger openings 6 in. (152 mm), 9 in. (230 mm) and 12 in. (300 mm), the material tended to deflect downward at the center of the opening during fire exposure. The rate of deflection appeared to increase with increasing opening size. This downward deflection tended to affect the performance of the material by causing cracks along the periphery of the opening, which in turn decreased the structural integrity of the material.

Major Findings

Results of these tests indicate that the effect of pressure differential is not significant for those firestop materials which have no cracks or other through openings that allow passage of gases during fire exposure. However, if the material allows passage for gases through cracks or other holes, such as those left open after a cable pull, the pressure differential affects fire stop performance. Effects of the size of the opening, size, location and type of the penetrating items installed through the opening, and severity of fire exposure on the performance of fire stops were demonstrated.

II.6.2 Large-Scale Tests (UC-Berkeley)

Three large-scale tests were conducted at Lawrence Berkeley Laboratory, operated by the University of California, to assess the effects of furnace pressure and excess pyrolyzates on the postflashover fire performance of barrier assemblies that contain cable penetrations.[40]

The large-scale vertical furnace used in these experiments consists of a reinforced concrete frame lined with refractory material. The furnace opening is 3.66 m (12 ft-0 in.) wide and 3.35 m (11 ft-0 in.) high. The furnace is fired by 44 burners using natural gas fuel. The burners can be operated in either a premixed or diffusion mode. During these experiments the burners were operated in a premixed mode. The 44 burners are arranged so that the furnace temperature can be maintained in accordance with the standard temperature-time curve as specified by ASTM Designation E-119.

Each of the three experiments employed identical walls (see Figure 24). The walls consisted of a 76 mm (3 in.)-thick, phenolic impregnated, paper honeycomb core covered on each side with three layers of 13 mm (1/2 in.)-thick gypsum wall board. The finished walls were 0.152 m (6 in.) thick, 2.44 m (8 ft-0 in.) high and 3.66 m (12 ft-0 in.) in length. A total of six penetrations were introduced into each wall. The penetrations measured 0.152 m x 0.152 m (6 in. x 6 in.) and were symmetrically arranged. The conditions present at each of the penetrations during the experiments are summarized in Tables XI to XIII.

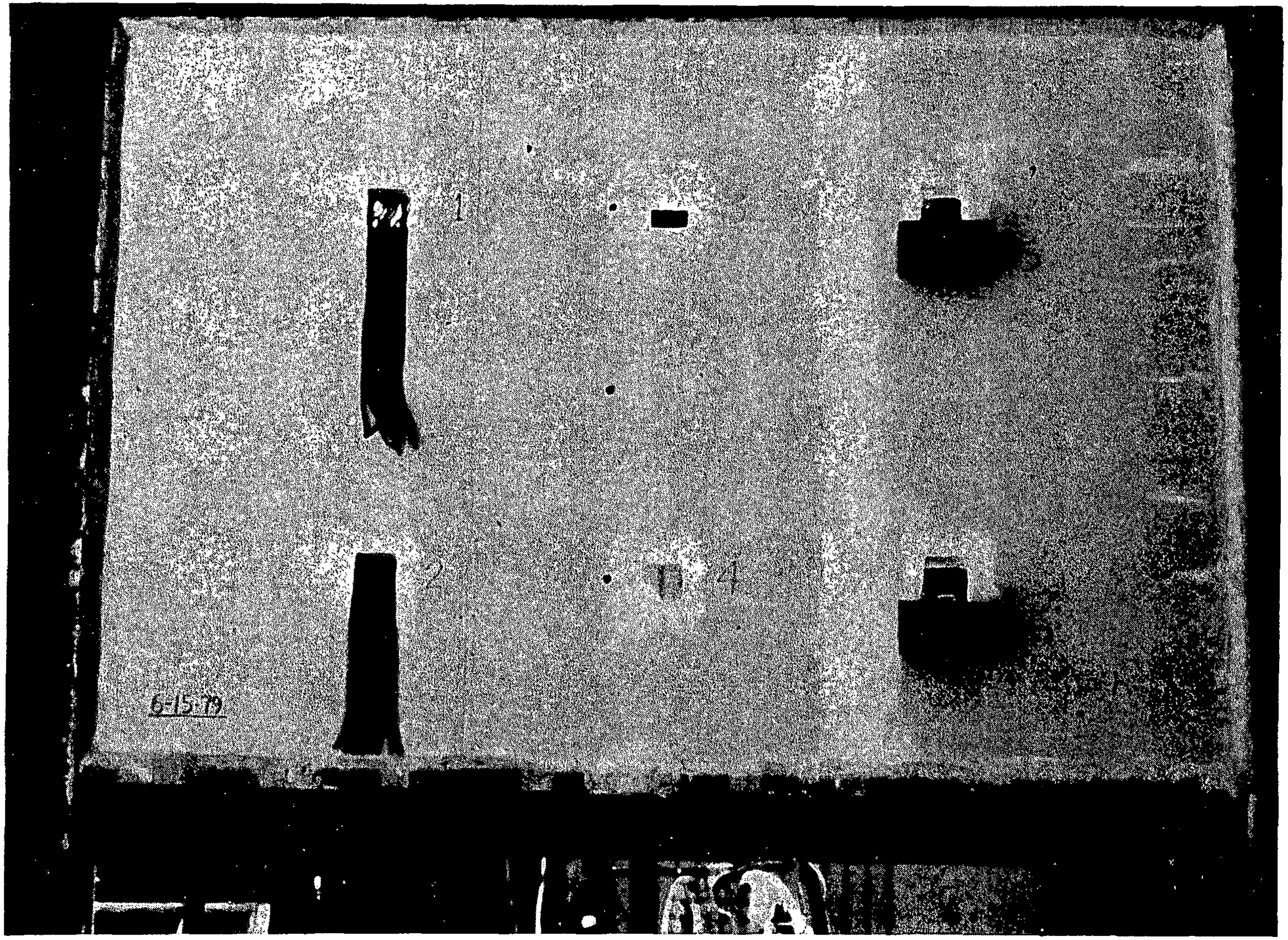


Figure 24

Large-Scale Penetration Seal Tests at U-C Berkeley

TABLE XI

Conditions at Each of the Six Penetrations During Experiment No. 1

Penetration Designation	Pressure Differential	Excess Pyrolyzates	Cable Present	Penetration Seal
1A	Positive	Yes	No	No
1B	Negative	Yes	No	No
2A	Positive	No	No	No
2B	Negative	No	No	No
3A	Positive	No	Yes	No
3B	Negative	No	Yes	No

TABLE XII

Conditions at Each of the Six Penetrations During Experiment No. 2

Penetration Designation	Pressure Differential	Excess Pyrolyzates	Cable Present	Penetration Seal
1A	Positive	Yes	Yes	No
1B	Negative	Yes	Yes	No
2A	Positive	Yes	Yes	No
2B	Negative	Yes	Yes	No
3A	Positive	Yes	Yes	Yes
3B	Negative	Yes	Yes	Yes

TABLE XIII

Conditions at Each of the Six Penetrations During Experiment No. 3

Penetration Designation	Pressure Differential	Excess Pyrolyzates	Cable Present	Penetration Seal
1A	Negative	Heating Oil	No	No
1B	Negative	Paraffin	Yes	Silicon Foam
2A	Negative	Paraffin	Yes	Ceramic Fiber
2B	Negative	Paraffin	Yes	Ceramic Fiber
3A	Negative	Paraffin	Yes	Silicon Foam
3B	Negative	Paraffin	Yes	Urethane Foam

Excess pyrolyzates were introduced locally to selected penetrations by the installation of a fuel pan beneath the penetration. The fuel pans consisted of steel containers measuring 0.152 m x 0.152 m x 0.30 m (6 in. x 6 in. x 12 in.) in Experiment No. 1, and 0.152 m x 0.30 m x 0.30 m in the other two tests. Each fuel pan contained a total of 1 kg (2.2 lbs) of polyethylene in Experiment No. 1, 6.8 kg (15 lbs) of polyethylene in Experiment No. 2, and 6.8 kg (15 lbs) of paraffin in Experiment No. 3 (in this test one container used No. 2 heating oil).

The experimental assemblies were subjected to the ASTM E-119 temperature-time history for a period of 33 minutes in Experiment No. 1, and one hour in Experiment No. 2. Experiment No. 3 lasted 46 minutes, but difficulty with furnace control due to the large amounts of excess pyrolyzates during this experiment prevented maintaining the ASTM E-119 temperature-time history after the first 18 minutes.

The effects of furnace pressure, without excess pyrolyzates on open penetrations were investigated at penetrations 2A and 2B during the first experiment. During periods of positive pressure, the temperature at the center of penetration 2A closely approximated the furnace temperature. However, when the pressure was reduced to a negative value, at an elapsed time of approximately 14 minutes, the temperature at 2A was reduced by about 450°C to a value of approximately 400°C. Similar behavior was noted at penetration 2B. The effects of excess pyrolyzates at penetrations 1A and 1B during Experiment No. 1 were not pronounced because of the small amounts used.

The effects of excess pyrolyzates were, however, very pronounced during Experiment No. 2. An examination of the temperatures recorded at penetrations 1A and 1B during Experiment No. 2 indicated the effects of excess pyrolyzates in combination with both positive and negative furnace pressures. Peak temperatures of approximately 1000°C were attained for penetration 1A (positive pressure), whereas the temperature at penetration 1B did not exceed 100°C during negative pressure conditions.

The effects of negative furnace pressure and excess pyrolyzates were investigated at penetration 3B during Experiment No. 3, for the case of a highly combustible penetration seal material. During this experiment, penetration 3B was sealed with a highly combustible urethane foam boardstock. The furnace pressure at penetration 3B was maintained at a negative pressure throughout this experiment, thus preventing leakage of combustion gases and excess pyrolyzates through the penetration. The temperatures at penetration 3B showed a steady increase in temperature caused by progressive combustion of the urethane foam seal. The performance of the urethane foam during this experiment served to illustrate the inadvisability of evaluating the fire resistive capabilities of proposed penetration seal designs using a test furnace that is operated at negative internal pressure differentials.

Major Findings

These experiments investigated the effects of two variables, test furnace pressure differential and excess pyrolyzates, on the performance of penetrations into fire resistive wall assemblies. The results indicated that these variables can have a pronounced effect on the measured fire resistance of penetrations.

II.7 Browns Ferry Replication Test

A full-scale replication type experiment was conducted at Underwriters Laboratories to assess the performance provided by a specific fire protection configuration designed in accordance with NRC fire protection guidelines and found acceptable to the staff.[41] The experimental configuration was constructed to replicate several cable trains and the fire protection system for an area in the Browns Ferry Reactor Building (elevation 593 ft, Area p to q and R6 to R7, Unit 1). In this area there are many electrical circuits in cable trays and conduits, water pipes, and other equipment used in operating the plant. Of specific concern is the group of electrical circuits located along the north wall near the centerline for this area. At this location is a group of vertical cable trays and conduits (see Figure 25). One of these cable trays and one conduit contains Division II safety circuits, while another conduit contains Division I safety circuits.

The fire protection for this area consists of detection systems, a suppression system, flame retardant cable coating, and steel cable tray covers. The detection system

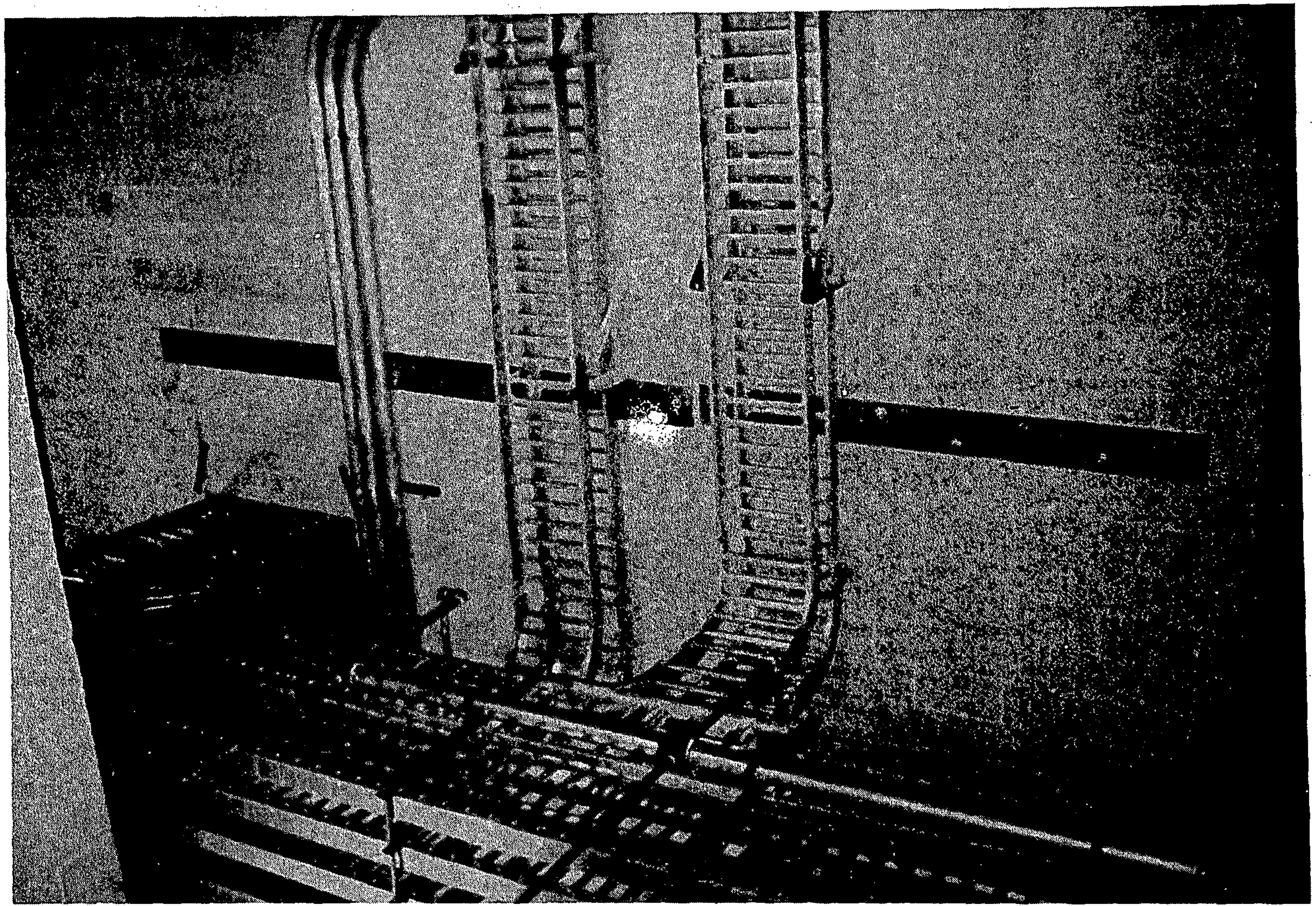


Figure 25

Upper Portion of Browns Ferry Replication Test Setup includes ionization type ceiling mounted smoke detectors and line type cable tray mounted heat detectors. The suppression system is an automatic water spray system which is activated upon signals from both smoke and heat detectors from one fire protection zone within this area. Most cables in trays are protected with a flame retardant coating. TVA specifications allow installation of ten cables or less within a tray without application of the coating. When there are more than ten uncoated cables in a tray, the entire uncoated cable bundle is to be protected with the coating. Although TVA specifications require a minimum 1/8 in. (3.2 mm) dry thickness of coating, cables in this area are protected with an approximate 1/4 in. (6.4 mm) dry thickness of coating.

The ten cables or less which are not required to be coated, are coated with a 1/4 in. dry thickness of material for a minimum of 5 ft (1.52 m) from a wall or floor opening as part of the fire stop design. Tray covers, both front and rear, are installed on vertical trays away from walls for 10 ft (3.05 m) above the floor. Additionally, tray covers are installed on top of trays which are used for low level signal cables. This fire protection configuration was designed in accordance with the NRC fire protection guidelines and found acceptable to the staff.

Originally, the program was to consist of three experiments, but the outcome of this first test (which was the most conservative case) eliminated the need for the last two tests. The fire source in this test was 5 gal (18.9) of heptane which was spilled about a group of vertical trays. The water spray system was purposely made inoperable to simulate a malfunction of the system. The fire was allowed to burn without any suppression for 45 minutes which permitted an assessment of the flame retardant coating. Also, by observing the severity of the fire at several time periods, information was obtained regarding the protection provided by different response times of a plant fire brigade.

The following is a summary of observations made after the experiment. Pull Box 2576 and associated conduits were unchanged with no observable deformation damage. The cover of the box remained securely fastened. The condition of the cables inside of the conduits remained unchanged, ie, no observed physical damage. However, damage to coated cables

TABLE XIV

Operation Times of Detectors

Smoke Detectors

No.	Activation Time(s)
1	12
2	9
3	8
4	9

Heat Detector

Zone	Activation Time(s)
1E	56

Sprinkler Head

No.	Operation Time(s)
1	*
2	45
3	*

*Fusible link had functioned but the time at which it occurred was not obtained due to malfunction of recording equipment.

was found in each of the vertical trays. The damage consisted of consumed insulation material which exposed the copper conductors. The cable insulation and jacket of the ten uncoated cables were consumed to about a height of 19 ft (5.79 m). The trays, coating, and cables of the upper horizontal tray group remained unchanged. Table XIV summarizes the activation times of the smoke and heat detectors and the operation time for the sprinkler head. Table XV shows the times to short circuit in each of the vertical trays.

Major Findings

In this test of a particular configuration of the Browns Ferry Reactor building, a liquid-fuel exposure fire resulted in the disruption of the circuit integrity in all four vertical trays, one of which was a simulated Division II safety circuit. However, the simulated Division I safety circuit inside a conduit located near the tray group remained functional. This test verified the survivability of one redundant safety train during a postulated fire.

II.8 Radiant Heat Tests

A series of tests was performed at the Radiant Heat Facility, Sandia National Laboratories, to determine the damageability of electrical cable insulation to heat.[42] The cables were exposed to thermal radiation at various levels to determine the threshold level of heat flux (kW/m^2) at which significant damage to IEEE-383 qualified and unqualified cables occur. A device was constructed at the Radiant Heat Facility to expose a cable tray, 8 ft (2.44 m) long by 1 ft (0.31 m) wide to thermal radiation at power levels of up to 60 kW/m^2. The cable tray was mounted under a semi-circular cylindrical steel shroud which was heated by three banks of quartz infrared lamps. The ends of the shroud were open to permit ventilation over the top of the cable tray, under the shroud, and to permit observation of the exposed cable during the testing. Figure 26 shows the setup for these tests.

Each cable tray was filled with five bundles, eight loops each, (approximately 800 ft, (244 m) and three 8-ft (2.44-m) lengths of cable for thermocouple placement. Two types of cable were used in these tests. One type was IEEE-383

TABLE XV

Time to Short Circuits

Tray	Time, Min:Sec
Ve	0:50
KS-ESII (Division II)	2:18
KT	14:42
TE	22:40

All shorts were individual conductor to tray (ground) type shorts.

The circuits in all three conduits remained functional during the experiment.

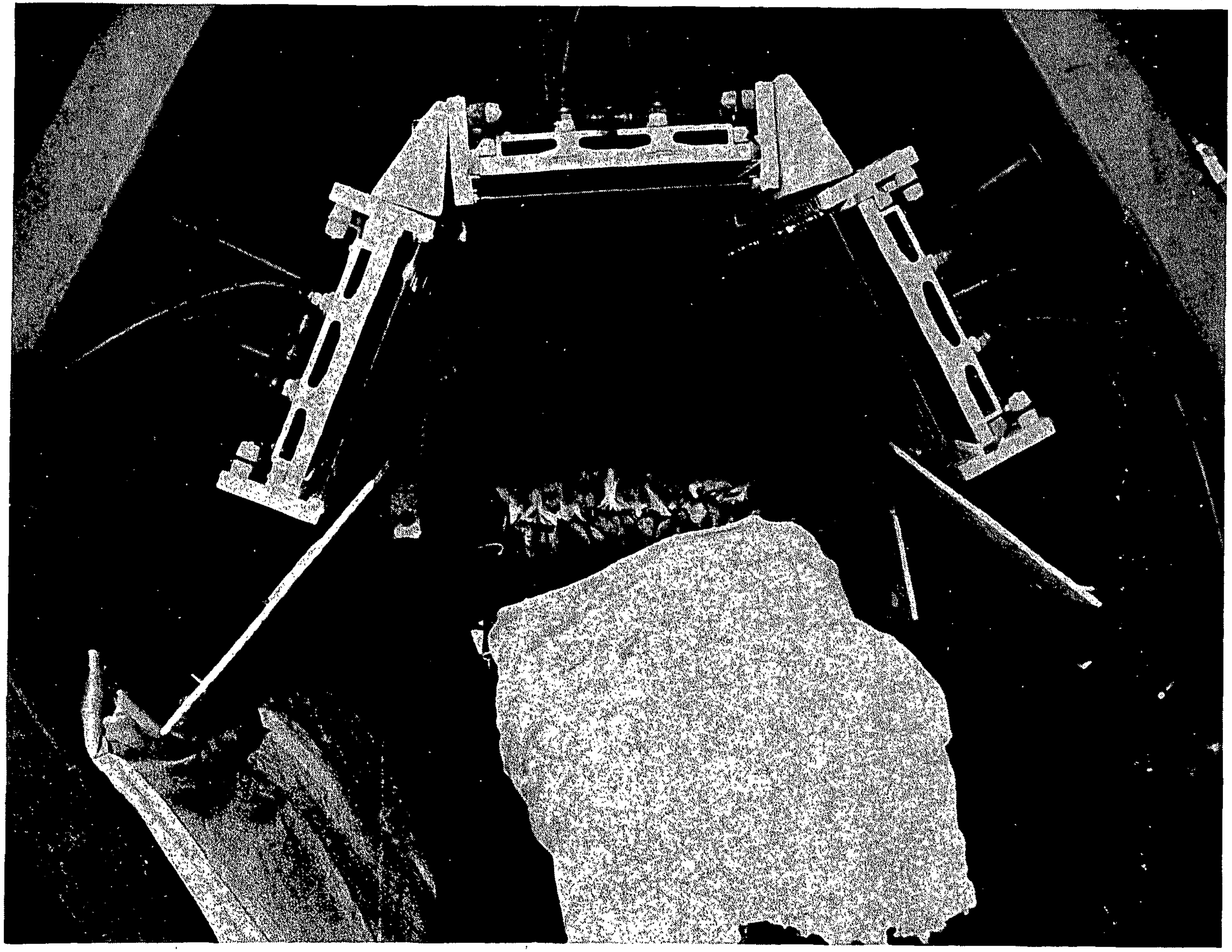


Figure 26

Full-Scale Radiant Heat Test

qualified three conductor No. 12 AWG, 30 mil (0.76 mm) cross-linked PE, silicon glass tape, 65 mil (1.65 mm) cross-linked PE jacket, 600 V. The other type was non-IEEE-383 qualified cable, three conductor No. 12 AWG, 20/10 Poly-PVC, polyethylene insulation, 45 mil (1.14 mm) PVC jacket. The cable was energized during testing with 320 vdc and 5 amps AC. Cable currents, both AC and DC, were recorded during testing and current from cable to cable tray was recorded to detect electrical failure (a short from cable to cable tray). Cable temperatures were also monitored.

A total of ten tests was conducted, five each on IEEE-383 qualified cable and unqualified cable. A brief summary of the results of the tests is given in Table XVI. The damage threshold levels of heat flux were calculated for IEEE-383 qualified cable, and unqualified cable. Electrical failure and nonpiloted ignition were the failure criteria. Figures 27 and 28 show graphically the correlation between external heat flux and time to electrical failure or nonpiloted ignition.

Major Findings

As a result of these tests, the critical heat flux for electrical failure was determined to be about 8 kW/m^2 for non-IEEE-383 qualified cable and 18 kW/m^2 for IEEE-383 qualified cable. The critical heat flux for nonpiloted ignition was likewise determined to be about 22 kW/m^2 for unqualified cable and 28 kW/m^2 for IEEE-383 qualified cable.

TABLE XVI

Summary of Radiant Heat Tests

Test Number	Measured Power Level kW/m^2	Time of Exposure min	Time to Electrical Failure min	Time to Fire min	Weight Loss lbs
1	21	30	t 30*	--	1.0
2	11	40	--	--	0.1
3	41	6.6	6.6	6.5	3.0
4	31	26.5	9.5	26.5	7.4
5	7	30	--	--	0.0
6	11	30	22.5	--	0.2
7	23	30	7.5	t 30¶	5.1
8	6	30	--	--	0.2
9	30	7	4	7	2.3
10	29	6	4	6	1.2

*Partial electrical failure had developed at 30 minutes and it is assumed that total failure would occur if the exposure were continued.

Note that Test No. 2 was run 10 minutes longer than normal.

The first five tests were with IEEE-383 qualified cables, the last five with unqualified.

¶Thermocouple readings indicated that the cables were very close to ignition temperature (600°C) and it is assumed that fire would develop if the exposure were continued.

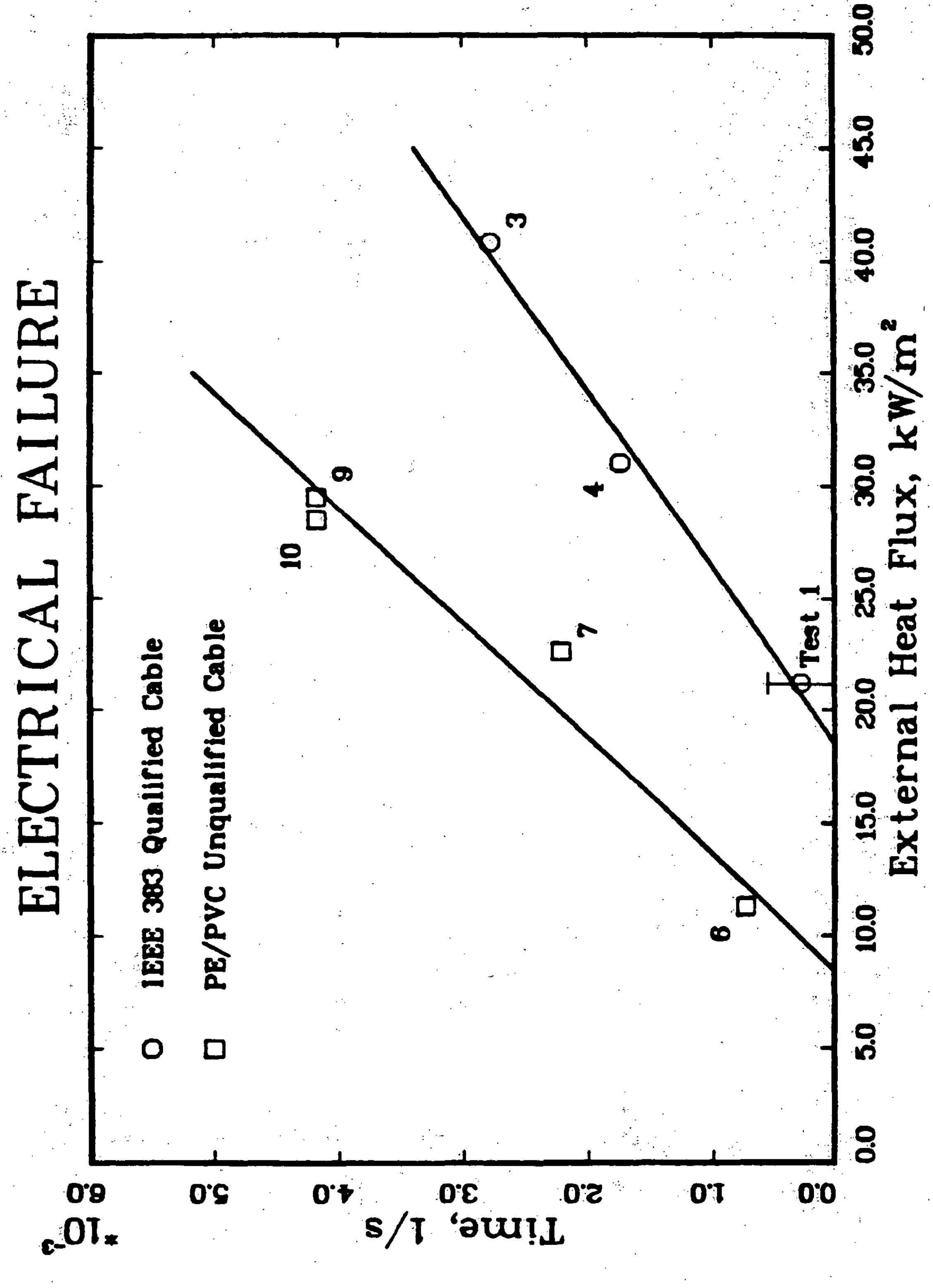


Figure 27

Correlation Between Time to Electrical Failure and External Heat Flux

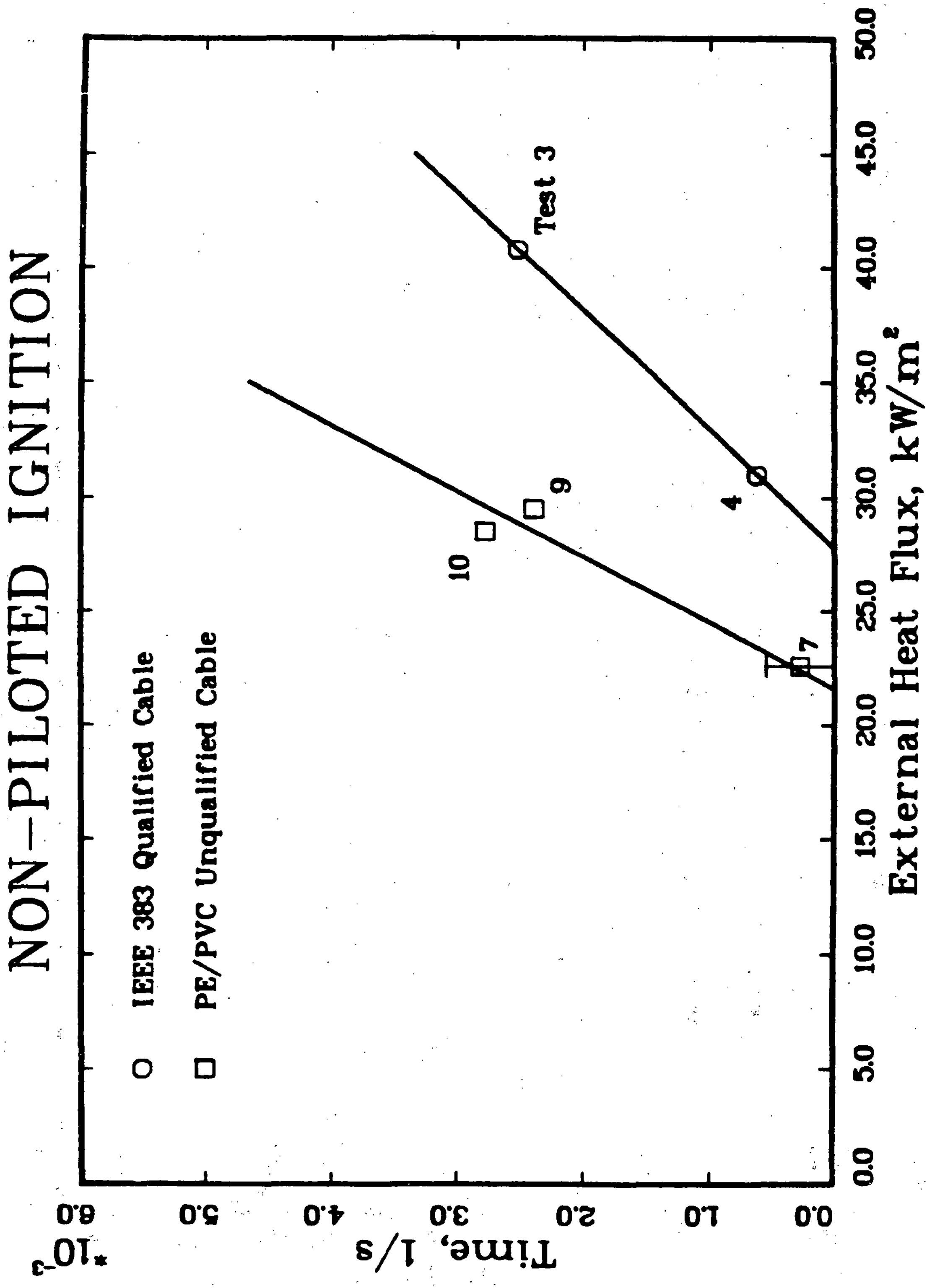


Figure 28.

Correlation Between Time to Non-Piloted Ignition and External Heat Flux

III. Analysis

III.1 Characterization of Cable Tray Fires

Characterization of cable tray fires[20,43-44,52] was based upon a review of the data that was collected in the full-scale testing described earlier in this report. In particular, the cable tray separation tests (Section II.2) and the Halon suppression tests (Section II.5.2) were most useful. With regard to the differences between electrically initiated fires and exposure fires, observation of films taken of the tests revealed the following:

1. In electrically initiated fires the intense period of the fire persisted at a particular location for between 40 and 240 seconds before die-out began to occur. In propane-fueled exposure fires the minimum period found to consistently ignite a tray of IEEE-383 qualified cable was 300 seconds.

2. In electrically initiated fires the luminous flame zone fluctuated rapidly between 4 and 10 in. (0.1-0.25 m) in height. In propane-fueled fires the luminous flame zone fluctuated between 10 and 12 in. (0.25-0.30 m) in height. In the diesel-fueled fire the luminous flame zone fluctuated between 30 and 50 in. (0.76-1.3 m).

3. Gas temperature in the luminous zone was roughly 1900°F (1300 K) in all fires.

4. Velocity of rising gases was about 3 to 4 ft/s (0.91-1.22 m/sec) in all fires.

5. The luminous zone of the electrically initiated fires was optically thin with an apparent emissivity of the order of 0.1 while the exposure fires had an optically thicker and correspondingly higher emissivity.

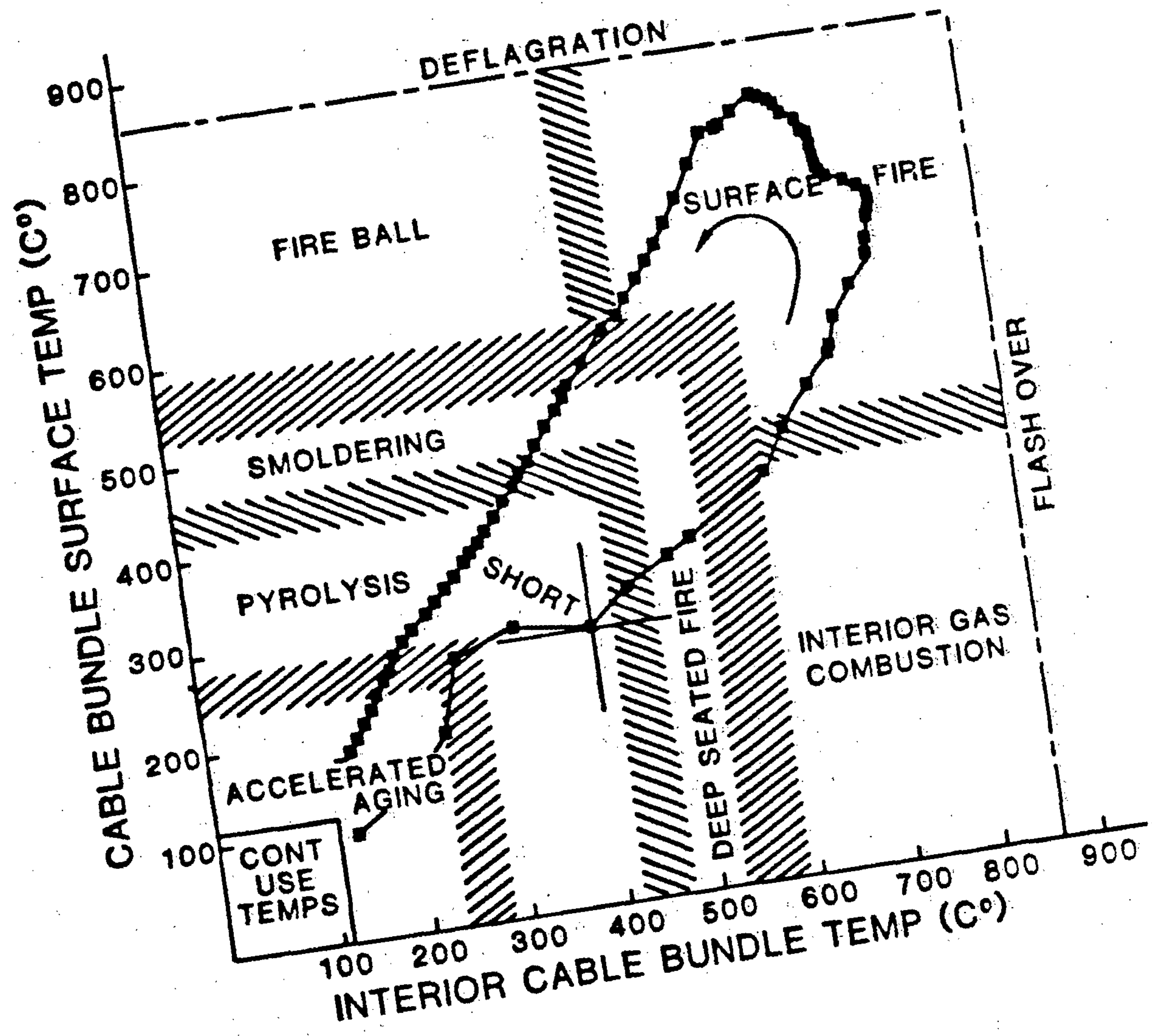
6. Heat transfer to immersed objects is convection dominated in the electrically initiated fires and radiation dominated in the exposure fires.

The mechanism of fire spread, as observed in the July 6, 1977 exposure test,[22] was determined to be a leap frog process. A fire in one tray, say no. 1, induces a fire ball above the next tray, no. 2, against the underside of the third one. The fire ball then grows downward until it contacts tray no. 2, at which time that tray ignites and the fire-ball burns out.

The thermodynamic phenomena observed and measured during cable fire tests have been classified into burn modes. They are, in fact, event modes from the statistical standpoint. Once identified, the burn modes can be used to describe and evaluate electrical cable fires. Consequently, the development of the burn mode concept for cable fires is regarded as an important development in fire physics.

The electrical cable thermodynamic phenomena are temperature dependent, and the burn modes are defined within temperature limits characteristic of each particular type of cable. Except for extreme burn modes at either end of the temperature spectrum, temperature boundaries for the modes are determined by abrupt changes in the rate of rise of cable temperatures in the cable fire tests. The established burn modes are continuous use temperatures, accelerated aging, pyrolysis, smoldering, deep-seated fire, interior gas combustion, fireball, surface fire, flashover, and deflagration. Figure 29 shows a representative cable temperature history plotted on a burn mode matrix. Similar temperature profiles have been developed for the other cable fire tests. The temperature boundaries are shown by dashed lines to indicate one standard deviation ($\pm 1\ \sigma$) in the test data. The direction of the temperature profile curve is indicated, and the data points represent 30-second time intervals. A cross shown on the figure indicates the time at which an electrical short (if any) occurs.

The burn modes for electrical cable fires are by nature divided into oxygen-sufficient and oxygen-starved categories upon the evolution of pyrolytic gases. The temperature limits for the various modes are dependent on the composition of the combustible material used for the insulation in the different types of electrical cables and are determined by abrupt increases in temperature rise rates.



TEMPERATURE PROFILE ON BURN MODE MATRIX FOR PRE-IEEE-383 CABLE TEST

Figure 29

Temperature Profile on Burn Mode Matrix for Pre-IEEE-383 Cable Test

Major Findings

Characterization of fires revealed a margin of safety in the separation criteria of the regulatory guide for electrically initiated fires in IEEE-383 qualified cable. However, exposure fire tests have shown it is possible for a fire to propagate across the vertical separation distance between safety divisions if a fully developed cable fire is the initiating event.

III.2 Studies of Generic Fire Protection Issues

An earlier Sandia National Laboratories fire protection study[45] surveyed the guidelines and standards pertaining to nuclear power plant fire protection and the investigative reports which followed in the aftermath of the Browns Ferry Nuclear Power Plant fire of March 22, 1975. The purpose of that survey was to establish a firm basis for future activities in assessing the adequacy and development of improved design criteria for nuclear power plant fire protection systems. Based on this and several other considerations, the NRC Office of Standards Development funded a new program to carry out a more detailed investigation. In particular, the following tasks were identified for study:

Task 1. Ventilation Systems

Task 2. Fire Detection Systems

Task 3. Fire Barriers

Task 4. Fire-Hazards Analysis

This section briefly summarizes the major conclusions and recommendations drawn from these studies.

III.2.1 Ventilation Systems

It was the objective of this task to examine the role of compartment ventilation as it affects nuclear power plant fire protection safety.[46] To do this, the following general approach was used:

1. Review and compare existing standards for ventilation systems to evaluate the adequacy of the guidance provided.

2. Develop technical bases for ventilation system functions and performance in fire emergencies and identify topics requiring further investigation or testing.

3. Recommend changes or additions to existing guidance to clarify intent and define design criteria.

The existing guidelines and standards, as they apply to the effect of ventilation systems on fire protection in nuclear power plants, were reviewed from the point of view of a design organization attempting to bring a facility into compliance. Specific criteria were listed and examined to determine if they were adequate to evaluate and specify system designs.

Current literature in the fire protection field was surveyed to locate investigative research reports on ventilation related aspects of fire phenomenology. Particular attention was directed to reports dealing with the effects of variable ventilation rates on the growth of compartment fires and burning rates in fully developed compartment fires.

Information gathered from the review of the standards and the literature search was used in formulating and evaluating four candidate technical bases for ventilation system design. The four bases were smoke removal, smoke control, fire control, and temperature control. Each candidate basis was examined to determine whether or not it fully met the intent of the guidelines and standards. The question of feasibility was also addressed in each case, with regard to equipment design, plant layout implications, and the availability of data upon which to base design parameters.

It was concluded that, based on the current state of the art in fire protection technology, the technical design basis for the fire protection design of ventilation systems should be that of heat removal from the involved fire area for the purpose of controlling fire temperatures. The only problem found with this design basis was that of control of radioactive releases from controlled areas of the plant. The normal HVAC system, which is equipped to remove these radioactive substances, is generally incapable of handling the particulate concentrations and temperatures associated with fire-generated effluent. If a system of prefilters were added to the normal filter banks serving the controlled areas, the particulate concentration of contaminated smoke could be reduced to manageable levels. The addition of an upstream water curtain and demister would reduce temperatures and corrosive properties before filtration. But the design or backfitting of such systems would be a formidable task.

Further recommendations include:

1. An evaluation needs to be made of the benefits and detriments of a heat removal fire ventilation system relative to other available fire protection measures (eg, automatic suppression, automatic detection, or separation). This effort should be completed before serious consideration is given to implementing a temperature control ventilation scheme in nuclear power plants.

2. If the use of a heat removal fire ventilation system is evaluated as worthwhile, the technical design basis for the fire venting system should be the required rate of heat removal from involved fire areas.

3. Existing guidelines and standards are generally lacking in sufficient detail to function as criteria for the design of ventilation systems as an integral part of the fire protection system.

4. Current fire protection research activities are directed primarily toward the solution of light fire loadings, which are not typical of all areas of a nuclear power plant setting. Experimental programs should be proposed to provide basic fire performance data on combustibles normally found in critical areas of power plants.

5. In areas of the plant which involve high probability for entrainment of radioactive containments in the smoke and gases and in

backfitting of existing facilities, emphasis should be placed on the design and reliability analysis of fire detection and suppression systems with accompanying deemphasis on venting requirements.

6. To allow sufficient flexibility of operation during fire emergencies to adequately control the spread of smoke and provide makeup air for fire vented compartments, the fans, isolation dampers, and their associated power supply and control cables should be protected from fire damage. Manual remote operation capability should be provided so that regulation and realignment of the systems can be accomplished as the particular fire situation demands.

Major Findings

Current standards and regulatory guidelines inadequately define criteria for design of ventilation systems and their operation under fire emergencies.

III.2.2 Fire Detection Systems

The fire detection subsystem review was undertaken to evaluate the following from the standpoint of overall plant safety:[47-48]

1. The technical bases for detection system design criteria.

2. The adequacy of detailed design guidance currently available.

3. The effectiveness of qualification testing procedures to simulate actual design applications.

For each of these three evaluations categories, numerous recognized fire protection information sources were chosen for review. The assignment of each information source to an appropriate evaluation category was based upon the level of detail and scope of information available in each source.

After establishing evaluation categories and information sources, it was decided to focus on the selection and use of detector sensing units, rather than to investigate either the internal design details of the units or the operation of each ancillary detection system component (ie, transmitters, alarm units, satellite stations, or interconnection wiring). This decision stemmed from a realization that:

1. Existing detection theory lacks the ability to predict detector performance solely from known internal sensing unit design features.

2. Ancillary detection system components primarily function to transmit electrical signals from detector sensing units to various panels and alarm devices, generally through the use of fundamental electrical design techniques which have been accepted and used extensively throughout other nuclear power plant systems.

The following five major types of commercially available detectors were chosen for investigation:

1. Area heat detectors.

2. Continuous line heat detectors.

3. Ionization type products of combustion detectors.

4. Photoelectric smoke detectors.

5. Ultraviolet/infrared flame detectors.

Topics considered in this investigation were (1) establishing area detection requirements, (2) selecting specific detector types, (3) locating and spacing detectors, and (4) performing installation tests and maintenance. The major conclusions drawn from these investigations can be summarized as follows:

1. Establishment of Area Detection Requirements --Current insurance and regulatory agency criteria are inconsistent and often conflict by referring to various plant areas by different names and by requiring different levels of detection coverage for the same plant areas.

2. Selecting Specific Detector Types--Although it is possible to make gross judgments in choosing a particular detector type, such as an area heat detector in preference to a smoke detector, it is difficult to make more subtle selections among similar detector types, such as ionization versus photoelectric detectors. Furthermore, since different detector types are tested under different conditions, it is doubtful whether any predictable correlation of detector performance can be made for candidate detectors. This is because there are conditions under which detectors now are not fully tested.

3. Locating and Spacing Detectors--Locating and spacing cannot be accomplished in an analytical manner based on present testing methods. Instead, engineering judgment and vendor recommendations must bridge the gap between test conditions and installed conditions. Unfortunately, judgment and recommendations can vary widely, depending on the skill of the individual providing the guidance.

4. Performing Installation Tests and Maintenance--There is no uniformly applied set of installation tests and maintenance procedures at this time. Only the recommendations of detector manufacturers are available to a designer. Since detector manufacturers often have diversified interests, only a fraction of which may involve nuclear power plant fire protection, there has been little incentive for a manufacturer to develop installation test and maintenance procedures primarily geared to the nuclear power plant market.

Major Findings

Current design and regulatory guidelines alone are insufficient to ensure satisfactory fire detection system performance; the use of in-place testing of detectors under conditions expected to occur normally in areas being protected is recommended.

III.2.3 Fire Barriers

It was the objective of this study to assess the adequacy of current standards which govern the design and testing of fire barriers.[49] Specific areas of investigation included the severity of test conditions, the ability of test procedures to represent actual fire conditions, the repeatability of test results, the amount of safety margin afforded by current tests, and the sensitivity of barrier performance to specific design details.

To accomplish the study objective, it was necessary to become familiar with the way in which fire barriers are presently tested and, where possible, they mathematically model the response of barriers under test conditions. Where a clear definition of certain test conditions was lacking or, because of physical complications, the conditions could not be accurately modeled, a qualitative assessment of the test requirements was made. The study procedure can be generally described as follows:

1. Study and evaluate the standards currently in force or proposed to determine if the needs of fire safety in nuclear power stations are satisfied by these standards.

2. Evaluate thermal characteristics of typical 3-hour barriers and calculate their thermal response when exposed to the standard ASTM E119 furnace test, using a computerized mathematical model.

3. Determine and recommend necessary follow-up action.

Based on this study, a number of important conclusions and recommendations were made:

1. Capability of Walls--Based on analysis using heat transfer models, it was determined that walls constructed of reinforced concrete, concrete block, and gypsum are adequate fire barriers if exposed to actual fire conditions which do not exceed the temperature and duration limits to which the walls were originally tested.

2. Standard Time-Temperature Curve--Because the standard fire connot be considered as representative of compartment fires, the fact that a given barrier has received a standard rating does not mean that it will last for the rated duration in every fire situation or that a comparative quality rating is achieved. Nevertheless, it is recommended that no change be made to the standard time-temperature exposure because

   a. A large amount of experience has been gained using the standard exposure.

   b. No "standard" exposure can be defined which will eliminate all such objections.

   c. Utilities are expected to assess the types of fires to which a given barrier may be exposed and evaluate the barrier in the light of such knowledge.

3. Hose-Stream Test--Because of an inability to accurately calculate or control the forces applied to a test specimen during the hose-stream test, and improved method should be defined to replace that test. Such a method should be suitable for analysis or direct measurement of the applied forces.

4. Furnace Pressure--To ensure that the test realistically represents compartment fires and the response of doors to these fires, it is recommended that fire exposure tests be performed with a slight positive furnace pressure. The German standard DIN 4102 requires a positive furnace pressure of 10 ± 2 Pa (0.00145 psi or 0.04 in. water).[50] A positive furnace pressure of at least that magnitude should be required for the testing of door assemblies as well as penetration seals.

5. Definition of Test Specimens--The ANSI/IEEE 634 standard on penetration seal testing should

specify that the configuration tested be representative of the assembly as it is installed in the power plant, not only duplicating the penetration seal itself, but also providing the same layout among cable trays with the same suspension and restraints as will be incorporated into the power plant barrier. While it is presumed that the NRC has consistently required that this be done as a condition of licensing, the practice does not appear to be documented as a requirement.

Major Findings

A number of changes should be made to the current methods of testing fire-rated walls, doors, and penetration seals. In particular, the hose-stream test should be improved, the test furnace should be maintained at a positive differential pressure, and commercial penetration seals should be tested in a more realistic fire environment.

III.2.4 Fire-Hazards Analysis

The major objective of this particular study was to assess the adequacy of existing fire-hazards analysis techniques in the context of nuclear power plant safety.[51] It was concluded early in the study that a viable fire-hazards analysis for nuclear power plant application should (1) be derived from, but not necessarily duplicate, available and proven analysis techniques; (2) be defendable in terms of being conservative and technically sound; and (3) be easily used by both designers and regulators. With these criteria established, a large number of analysis methods were reviewed. By limiting this review to only those methods which have received at least some practical scrutiny, the first criteria automatically is satisfied; only the second two criteria remained to be met.

For ease of understanding, it proved convenient to assign each candidate analysis method to one of three categories depending on whether a particular method was based on subjective judgments, deterministic calculations, or probabilistic logic. Since it was found that all of the available analysis methods reviewed proved deficient in meeting at least one of the analysis criteria, it was decided to select and combine from available analyses those attributes most responsive to the needs of nuclear power plant designers and regulators.

The analysis method which resulted from this approach relies initially upon conservative assumptions and deterministic calculations of fuel load and ventilation conditions to bound expected fire severity. If such bounding conditions are found to be acceptable to plant safety, the analysis is terminated. If, however, plant safety cannot be ensured under conditions of a conservative bounding analysis, other supplementary fire protection measures (e.g., detection, manual suppression, and automatic suppression) are evaluated in a probabilistic fashion to assess what level of fire protection can be derived from these measures. If the results of a probabilistic analysis also are found to be unsatisfactory or inconclusive, a subjective analysis is finally performed. Figure 30 places in perspective the model arrived upon which is most suitable for assessing fire severity in nuclear power plants.

Major Findings

On the basis of this study and a review of the fire-hazards analyses performed to date for several nuclear facilities, it is concluded that improvements can be made in most of the analysis techniques presently used. These improvements are important in eliminating the lack of both conservatism and technical merit inherent in many traditional analysis approaches.

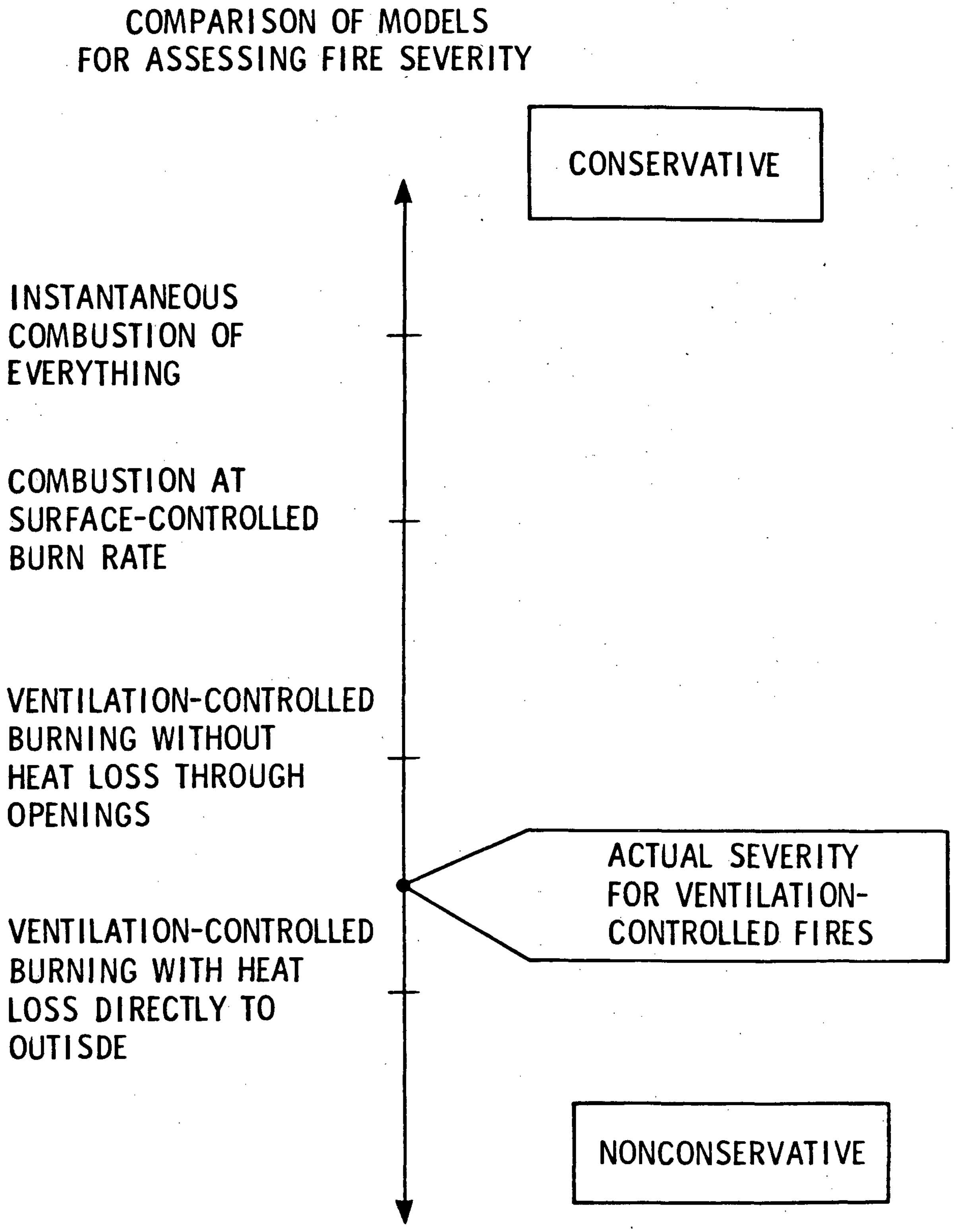


Figure 30

Comparison of Models for Assessing Fire Severity
in Nuclear Power Plants

IV. Summary

This report has summarized all of the test results and research findings of the fire protection research program at Sandia National Laboratories for the past 7 years. Altogether, some 30 reports and 75 tests are described. For each test series conducted, the purpose of the tests and results are described, and the major findings are summarized for easy reference. A comprehensive reference list is provided which includes every major report released through the end of 1981. A list of important papers presented at workshops and conferences is given for additional reference. The executive summary describes the objectives of the research program, the major areas of testing, major findings, and the interaction of researchers at Sandia National Laboratories with the general fire protection community.

It is found that a number of test results have had a measurable impact on fire protection guidelines for nuclear power plants. In particular, the July 6, 1977 full-scale exposure fire test clearly indicated that the cable tray spacing as designated in Regulatory Guide 1.75 was inadequate for exposure fires. The small-and large-scale penetration seal tests also raised the important issue as to whether penetration seals should be tested under furnace conditions of positive differential pressure or not. The Browns Ferry Replication Test confirmed the survivability of one redundant safety train during a postulated fire at one important location in the Unit 1 reactor building. The Halon tests have confirmed that for the configurations tested, Halon 1301 can suppress deep-seated cable tray fires provided that there is adequate Halon concentration and soak time. And finally, fire retardant coatings and fire shields were found to offer a measure of additional protection, although there was a wide range in the performance of the coatings.

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Since early 1975, Sandia National Laboratories has been conducting fire protection research for the U.S. Nuclear Regulatory Commission. Testing has been done on grouped electrical cable fires including electrical initiation, fire propagation, the effects of fire retardant coatings and barriers, suppression, and characterization of the damageability of electrical cables. In addition, several studies of a more generic nature such as fire detection, ventilation, and fire-hazards analysis methodologies were performed.

This report condenses all of the test results, reports, papers and research findings of the past seven years. Research conducted by contractors to Sandia National Laboratories is also summarized.

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