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An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Cabinets: Part 1: Cabinet Effects Tests

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AN EXPERIMENTAL INVESTIGATION OF INTERNALLY IGNITED FIRES IN NUCLEAR POWER PLANT CONTROL CABINETS: PART 1: CABINET EFFECTS TESTS

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ABSTRACT

A series of full-scale cabinet fire tests was conducted by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission. The cabinet fire tests were prompted by the potential threat to the safety of a nuclear power plant by a cabinet fire in either the control room or in a switchgear type room. The purpose of these cabinet fire tests was to characterize the development and effects of internally ignited cabinet fires as a function of several parameters believed to most influence the burning process. A primary goal of this test program was to test representative and credible configurations and materials. This series of 22 cabinet fire tests demonstrated that fires in either benchboard or vertical cabinets with either IEEE-383 qualified cable or unqualified cable can be ignited and propagate. However, fires with IEEE-383 qualified cable do not propagate as rapidly nor to the extent that unqualified cable does. Furthermore, the results showed that the thermal environment in the test enclosure and adjacent cabinets is not severe enough to result in autoignition of other combustibles; although in some of the larger fires melting of plastic materials may occur. Smoke accumulation in the room appeared to be the most significant problem, as smoke obscured the view in the enclosure within minutes after ignition. Essentially, a cabinet fire can propagate within a single cabinet; however, for the conditions tested it does not appear that the fire poses a threat outside the burning cabinet except the resulting smoke.

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ACKNOWLEDGMENTS

The efforts of many people who contributed to the completion of this project are gratefully acknowledged. In particular, the excellent work performed by D. Mike Ramirez in p~eparing for and assisting in conducting the tests. Also, for performing the posttest clean up, it was a dirty job but someone had to do it. I would also like to thank all the members of Division 6447 for their technical input and assistance on the test program.

EXECUTIVE SUMMARY

A series of full-scale fire tests has been conducted as part of the Fire Protection Research Program being performed for the U.S. Nuclear Regulatory Commission (NRC) by Sandia National Laboratories (SNL). This series of fire tests has been conducted to investigate the effects of internally ignited cabinet fires on cabinets and rooms.

The cabinet fire investigation was prompted by the potential threat to the safety of a nuclear power plant by a cabinet fire in either the control room or in a switchgear-type room. The items of concern centered around: (1) the potential for a cabinet fire to ignite, (2) the rate of development of a fire in a cabinet, (3) the resulting room environment produced by the fire, and (4) the potential for the fire to spread to other cabinets and damage equipment and components throughout the room.

The cabinet fire tests were performed in two phases. The tests reported here, from the first phase of testing, focus on the development of the fire in the cabinet and the resulting environment in adjacent cabinets and the test enclosure. In essence they are "Cabinet Effect Tests." Subsequent testing, the second phase, was intended to provide confirmation of the first phase tests and investigate the effects of cabinet fires on a large control room size enclosure and arrangement. These second phase tests (Room Effects Tests) have been completed and will be reported on at a later date.

The purpose of the cabinet fire test program was to characterize the development and effects of an internally ignited fire in a cabinet as a function of several parameters believed to most influence the burning process. This was done by testing representative cabinets, configurations, ignition sources, and in situ fuel configurations. The environments inside and in the vicinity of the cabinets directly involved in the fire, and of the other cabinets, components, and combustibles located in the test enclosure were measured. A primary goal of this test program was to test representative and credible configurations and materials. The specific objectives of the Cabinet Effects Tests were to:

a. Identify credible ignition sources capable of igniting a cabinet fire;

b. Determine what credible in situ fuel types, amounts, and configurations can result in ignition and propagation of a cabinet fire;

c. Assess the effects of different ignition source fuels and in situ fuels on fire development rate and equipment damage;

d. Establish the effects of different cabinet styles and ventilation methods on fire development;

e. Determine the development rate of the fire (heat release rate);

f. Investigate the environments developing within and around the cabinets; and

g. Monitor the development of the enclosure environment.

Initially, a series of five Screening Tests and eleven Scoping Tests was conducted to evaluate specific concerns about the ignition sources and in situ fuel configurations. These tests were conducted on a smaller scale (e.g., minimal materials and instrumentation) for a quick test turnaround. These tests provided valuable results and input for use in the subsequent full-scale tests.

The six full-scale tests, called the Preliminary Cabinet Fire Tests, were conducted to investigate how an internally ignited cabinet fire will develop and its effect on adjacent cabinets and the enclosure. Four of these six tests were conducted in vertical nuclear power plant cabinets, two with unqualified cable, one with IEEE-383 qualified cable, and one with a heptane pool. The remaining two tests were conducted in benchboard style cabinets, one each with unqualified and IEEE-383 qualified cable. The effects of the following variables on fire development were investigated (a) different ignition sources, one each transient and electrical, (b) cabinet styles, (c) cabinet ventilation, and (d) in situ fuel types, amounts, and configurations.

The results of the 22 Cabinet Effects Tests are not generally applicable because the results are so configuration and test specific. However, the following conclusions can be made:

1. Cabinet fires can be ignited and propagate in either unqualified or qualified cable with either of the two ignition sources tested (transient and electrical). However, the qualified cable is much more difficult to ignite and propagate.

2. It is possible to have a rapidly developing cabinet fire with either type of cable as the in situ fuel and in either style, vertical or benchboard, of cabinet. Although, fires with qualified cable tended to be less intense than those involving unqualified cable.

3. Ignition, development rate, and spread of a cabinet fire are dependent on "critical" (i.e., just the right combination of variables) ignition sources, in situ fuel type, geometries, and amounts, and on cabinet style and ventilation. These "critical" values are interdependent on many variables and therefore no "critical" values can be identified based on these tests. However, it was found that with unqualified cable, the range of values causing ignition and fire spread was much wider than with qualified cable.

4. For the enclosure conditions tested (i.e., enclosure size and ventilation rates), the thermal environment in the enclosure produced by the fires was not severe enough to cause autoignition of materials, but the thermal environment may be severe enough to cause equipment damage. Furthermore, it appears from these tests that a fire will not spread from the burning cabinet to adjacent cabinets. However, under different conditions (e.g., single wall, larger fires) a cabinet fire could cause autoignition in an adjacent cabinet and continue to propagate. A double wall barrier between cabinets appears to play a crucial role in preventing cabinet-to-cabinet fire spread during the larger cabinet fires.

5. For the enclosure conditions tested, dense smoke accumulation in the room became a problem within minutes after ignition, for all fuel types and cabinet configurations.

Essentially, the conclusion of the cabinet fire tests is that a cabinet fire can propagate within a single cabinet; however, for the conditions tested, it does not appear that the fire poses a threat outside the burning cabinet, except for the resulting smoke. Although this test effort involved realistic ranges of parameters, it must be recognized that other cabinet and fuel configurations may result in somewhat different findings. In addition, because of the influence of operation response and overall safety system performance, conclusions regarding cabinet fires causing difficulty in the ability of the plant to shut down cannot be made solely from the fire test data presented in this report.

EXECUTIVE SUMMARY

Based on the findings of the Cabinet Fire Test Program it is recommended that the effectiveness of the following should be investigated:

1. Detection systems in cabinets;

2. Automatic gaseous suppression systems both inside and outside cabinets;

3. Manual suppression of cabinet fires;

4. Smoke control and purge systems;

5. Potential for fire spread in nondivided cabinets; and

6. Independence of remote shutdown capability.

1. INTRODUCTION

1.1 Background

A series of full-scale cabinet fire tests was performed as part of the Fire Protection Research Program. This program is being conducted for the U.S. Nuclear Regulatory Commission (NRC) by Sandia National Laboratories (SNL). The Cabinet Fire Test Program was prompted by the potential threat to the safety of a nuclear power plant by a cabinet fire in either a control room or a switchgear-type room. Although there have been no fires in control room cabinets of operating nuclear power plants, there have been fires in cabinets in other parts of plants that have resulted in significant damage due to heat, smoke, and corrosion.[1] Furthermore, based on probabilistic risk analysis, a fire in a nuclear power plant represents one of the greatest threats to the safety of a plant. Based on plant operating experience, a typical nuclear power plant can expect to have three to four major fires during its lifetime.[1] In addition, a recent study [2] has shown that not all remote shutdown areas are truly independent of the control room and that short circuits and other electrical problems could potentially propagate from the control room to the remote shutdown area.

Due to the potential level of risk, the NRC staff had a number of concerns about cabinet fires. These concerns centered around (a) the ability of a cabinet fire to ignite and spread, (b) the rate of development of the fire in a cabinet, (c) the resulting room environments produced by the fire, and (d) the potential for the fire to spread to other cabinets and damage equipment and components throughout the room. In the tests described in this report, concerns (a), (b), and (d) are investigated. Additionally, concern (c) was monitored, but due to the relatively small enclosure size used in these tests, the results were validated by control room testing performed as the second phase of this test series (Part 2 of this report).

1.2 Program Objectives

To address the concerns described above the cabinet fire test program was initiated. The overall program objective was to characterize the fire room development in electrical cabinets and investigate the resulting room environment as a function of several parameters that most influence the burning process.[3] The cabinet fire tests were performed in two parts: Part 1, the tests discussed in this report, are called the Cabinet Effects Tests. These are all the cabinet fire tests that were conducted at SNL and are reported here. The second part of the testing was called the Room Effects Tests and will be described in a subsequent report.

The purpose of the Cabinet Effects Tests (Part 1 tests) was to evaluate the potential for an internally ignited cabinet fire to occur and to investigate the development of the fire in the cabinet and the resulting environment in adjacent cabinets. This was done "...by measuring, for representative cabinets, configurations, ignition sources and in situ fuel configurations, the environments inside and in the vicinity of the cabinet directly involved in the fire and of other cabinets, components, and combustibles located in the test enclosure."[3] The Room Effects Tests (Part 2) were performed to provide confirmation of the Part 1 tests and to investigate the effects of cabinet fires on a control room size room and arrangement.

Specifically, the objectives of the Cabinet Effects Tests (the tests described in this report) were to:

a. Identify credible ignition sources capable of igniting a cabinet fire;

b. Determine what credible in situ fuel types, amounts, and configurations can result in ignition and propagation of a cabinet fire;

c. Assess the effects of different ignition source fuels and in situ fuels on fire development rate and equipment damage;

d. Establish the effects of different cabinet styles and ventilation methods on fire development;

e. Determine the development rate of the fire (heat release rate);

f. Investigate the environments developing within and around the cabinets; and

g. Monitor the development of the enclosure environment (secondary purpose).

A major goal of these tests was to make them as representative and credible as possible, yet not plant specific, so that the results of the tests would be as realistic as possible.

1.3 Previous Studies

Previous studies, both system studies and testing, have shown that cabinet fires in nuclear power plants can be a potential threat to the safety and shutdown capabilities of a plant.[4-7]

The first cabinet testing was performed as a result of NRC concern about the proximity of redundant safety systems in adjacent control cabinets at Enrico Fermi Nuclear Power plant, Unit 2. As a result, two tests and some supporting analysis were performed in an attempt to resolve those concerns. The first test [4] was a pool fire test with a simulated cabinet panel with which the utility hoped to determine the conditions of safe shutdown components, which were internal to the control panel, following a flammable liquid exposure fire. The components survived the test; yet the use of a simulated panel was questioned because the utility could not evaluate the effects that the cabinet ventilation might have on enhancing damage or cooling the components. In an attempt to resolve concerns raised in the first test about the cabinet internal temperature being high and the plume directly impinging on the cabinet, Fermi conducted an oven test and a plume analysis [5] was performed. Detroit Edison Co. concluded that the tests were bounding and that components in a cabinet could survive an external pool fire. However, these fires did not address the possibility of ignition of the in situ cabinet fuels or the effects of a fire on adjacent cabinets or the room. Haddam Neck nuclear power plant performed an analysis similar to Ferris as part of their evaluation of cabinet fires.[6]

Two cabinet fire tests [7] were performed for SNL by Lawrence Berkeley Laboratory to assess the susceptibility of electrical cabinets to fire damage. The test cabinet used was not typical of nuclear power plant control cabinets (too small and too light); however, it had two doors, one with ventilation grills at the top and bottom. Both tests were performed with an external solid fuel as the ignition source which consisted of trash-type materials. The first test was intended to characterize the ignition source and its effects on the test enclosure. In the second test, the cabinet contained an in situ fuel load (cables) in addition to the external ignition source. The intent of this test was to evaluate the effects of the burning ignition source on the in situ fuel.

These tests demonstrated that a large, 14.13 kg (31.1 lb), external (to the cabinet) transient fire source could result in high temperatures and possible ignition in both the cabinet and the room. However, it must be emphasized that the conditions (i.e., cabinets, fuel loading, and test enclosure) were not typical of those found in a nuclear power plant.

As part of the background investigation into the cabinet fire testing program, SNL initiated a study performed by Ebasco Services, Inc. to evaluate the current industry standards and design practices related to cabinet and component setup and to conduct a detailed analysis on the potential effects of a cabinet fire on plant safety. Part of this

study was to analyze four plants to determine the present practices, with a very detailed analysis being conducted on two of the plants. Some results of this study, based on the two plants analyzed in detail, were:

1. "The probability of occurrence of a fire that does extensive damage to a control panel is exceedingly low due to the absence of ignition sources and the ease of detecting and suppressing fires--but a fire cannot be ruled out.

2. A failure mode analysis of critical components when subjected to fire environments showed that faults can propagate, which means the remote shutdown area must be isolated."

In order to evaluate the effects of a cabinet fire on the components and their ability to function, Ebasco recommended tests that investigate the following: (a) how long must the control panel fire progress until panel component damage occurs, (b) how long must a control panel fire progress until the control room must be evacuated, and (c) what is the relative likelihood and extent of the specific modes of panel component damage?

The tests and system studies to date have only shown that cabinet fires can be a significant threat and that the fires can result in component damage that could propagate shorts and faults. However, no full-scale, realistic cabinet fire testing had been conducted to investigate fire development rates or room effects of cabinet fires.

1.4 Program Approach

In order to make the tests as realistic and credible as possible, a large amount of background research was conducted.[2,8] Figure 1, the flow diagram, shows how and what background information was used in selecting the ignition sources, cabinets, and in situ fuels. A detailed description of how these materials were selected is described in the test plan.[3]

There are a large number of variables that could be investigated which could affect the cabinet burning characteristics. These variables fall into the following broad categories: (a) cabinet details, (b) fuel materials, and (c) external variables. The cabinet details are anything specific to the cabinet (e.g., size, style, etc.). Fuel material variables include both the ignition source and in situ fuel materials, while external variables encompass all other variables affecting the cabinet fire (e.g., enclosure size and ventilation, other cabinets, etc.). Due to the large number of

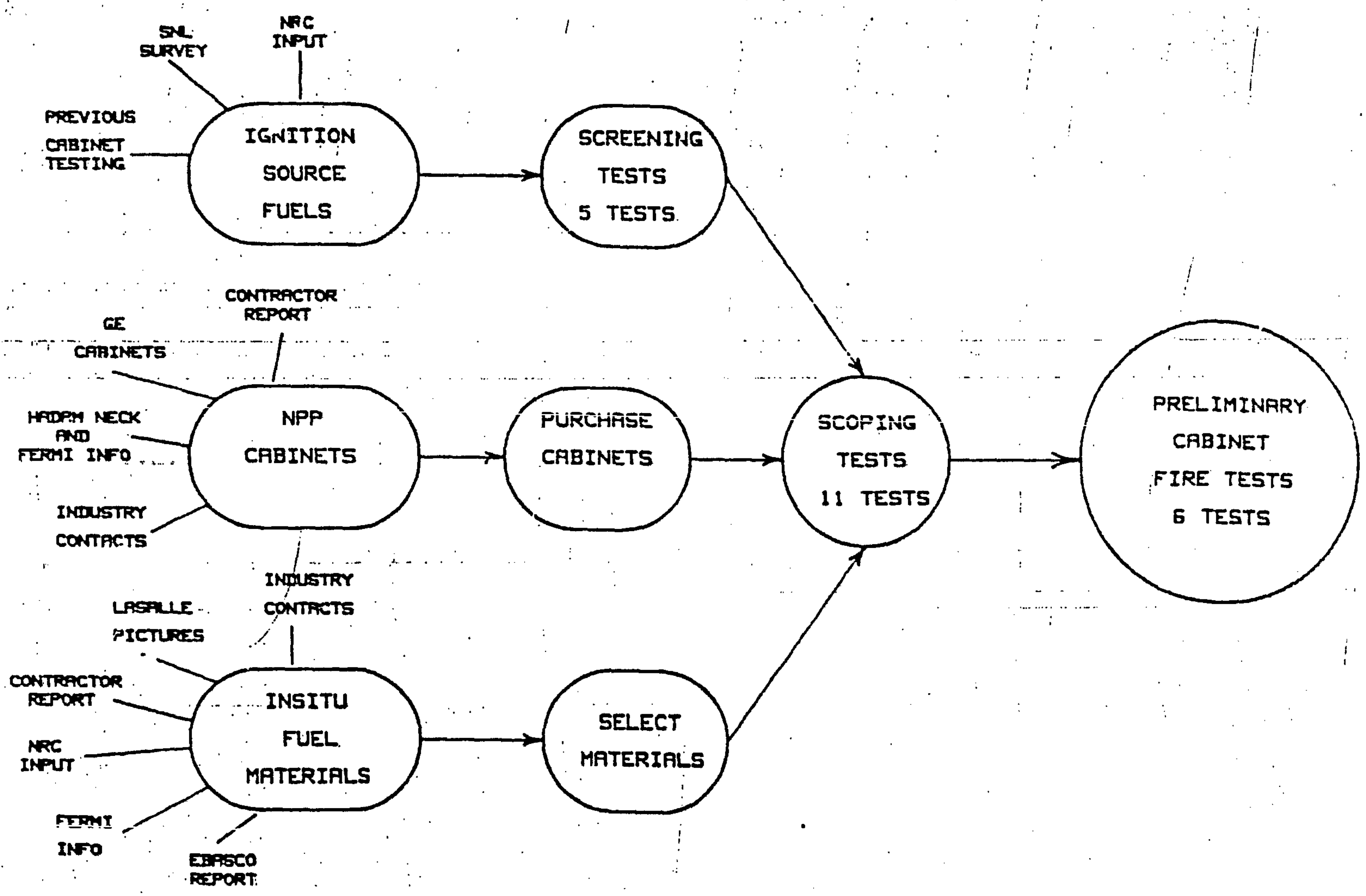


Figure 1. Flow Diagram for the Cabinet Fire Test Program

variables, only a few selected variables that were felt would have the most pronounced effect on the burning process were investigated. The flow diagram, Figure 1, shows the three categories of variables that were investigated and the tests that were performed to determine the effects of changing the test variables. The flow diagram shows how the selected test materials were investigated in the Screening and Scoping Tests to enable us to reduce the number of realistic and credible full-scale Preliminary Cabinet Tests. The results of the Screening and Scoping Tests will be discussed in Sections 2.3 and 2.4, while the Preliminary Cabinet Tests will be discussed in Section 3.0.

2. METHODS AND MATERIALS

2.1 Test Facility and Instrumentation

The Sandia Fire Test Facility is located at Sandia National Laboratories in Albuquerque, NM. The facility is housed within a 15.2 x 7.32 x 5.49 m (50 x 24 x 18 ft) quonset building. In one end of the building is the test enclosure, while the other end comprises the instrumentation and storage room as shown in Figure 2. The test enclosure (also called the burn room) has a floor area of 55.7 m^2 (600 ft^2) with a maximum ceiling height of 5.48 m (18 ft). The test enclosure, constructed of concrete and plastered metal lathe, has a volume of 272 m^3 (9624 ft^3). Ventilation to the enclosure is provided by a variable ventilation system, capable of supplying 113 m^3/min (4,000 cfm). Typically, during a cabinet fire test, the ventilation system was run at 70.8 m^3/min (2500 cfm). As shown in Figure 2, the ventilation system has six exit ports along each wall with the enclosure exhaust vent located in the top center of the room where the air and combustion products are exhausted out a 0.46 m (1.5 ft) circular exhaust duct. Six observation ports were located in the test enclosure to provide lighting to the room and allow video recording of the tests. Access to the room is provided by a 1.83 x 2.44 m (6 x 8 ft) door that is sealed prior to testing. The test facility is described in more detail in Appendix A.

Instrumentation for the tests varied for the Screening and Scoping Tests; however, approximately 100 channels of data were recorded in all the Preliminary Cabinet Tests. A wide variety of instrumentation was required for measuring temperatures, heat fluxes, pressure, mass losses, smoke densities, gas concentrations, and heat release rates. The instrumentation was monitored by an HP3497A data acquisition unit capable of logging up to 100 channels of data and controlled by an HP216 computer system. Data was typically recorded at 20-second intervals.

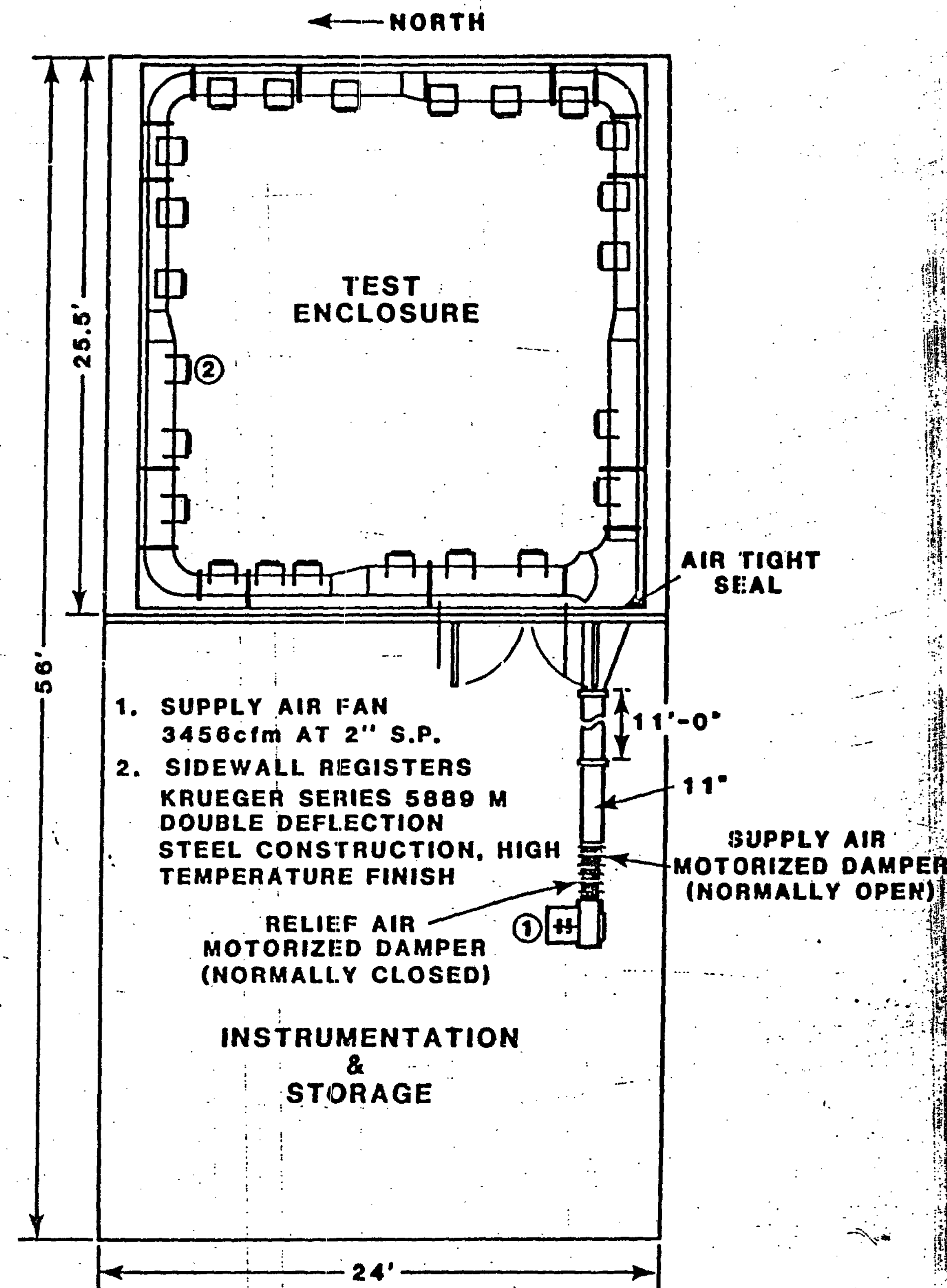


Figure 2. Floor Plan of the Sandia Fire Test Facility

One of the most important measurements required was the heat release rate (HRR) measurement. This was measured using oxygen consumption calorimetry,[9] in which the oxygen concentration, temperature, and velocity of the effluents were recorded in the exhaust duct. A more detailed description of the instrumentation is provided in Appendix A.

2.2 Selection of Test Materials and Equipment

In this section the materials and equipment that were used in the Cabinet Effects Tests will be described.

The ignition source fuels used in the tests were one transient and one electrical ignition source. The transient ignition source was made up of a 9.463 ℓ (2.5 gal) polyethylene bucket, with an opened 0.455 kg (16 oz) box of kimwipes, and 0.946 ℓ (1 quart) of acetone placed in the bucket. One half of the acetone was poured into the bottom of the bucket, the bottle and remainder of the acetone were placed in the bucket, and the cap was left off the plastic bottle to simulate the bottle spilling. Also, 15 kimwipes were balled up and put in the bottom of the bucket. This ignition source, shown in Figure 3, was ignited by an electrically ignited gas pilot lighting one of the kimwipes hanging out of the bucket. The electrical initiation arrangement, used only in the unqualified cable fires, consisted of a terminal strip and 25 pieces of stripped (unjacketed) cables shown in Figure 4. This arrangement was ignited by providing ~165 watts of power to the terminal strip resulting in an overheating at the connection and culminating in a fire. These ignition sources will be described in more detail in Section 2.3.

One of the key objectives of this test program was to test representative-type electrical cabinets. In order to achieve this objective, many sources were drawn upon, as discussed in Section 1.4 (i.e., GE, CE, Westinghouse, Ebasco, NRC input, utilities, and SNL survey), to obtain the most comprehensive and accurate information possible. In general, there are three styles of electrical cabinets found in nuclear power plants: benchboards, verticals, and consoles. Benchboard-style cabinets are found primarily in the control room. These cabinets contain systems important to the control of the plant and systems critical to safe shutdown; hence, the safety of these cabinets is paramount. Vertical cabinets are found throughout the plant as termination cabinets, relay or logic circuit cabinets, switchgear cabinets, etc. The vertical cabinets also contain systems important to plant control and safety; thus, their safety is also critical. The console cabinets, found mostly in the control room, generally contain computer processing and operating equipment, which is not as vital to plant safety. Consequently, because of their importance, only the benchboard and vertical cabinets

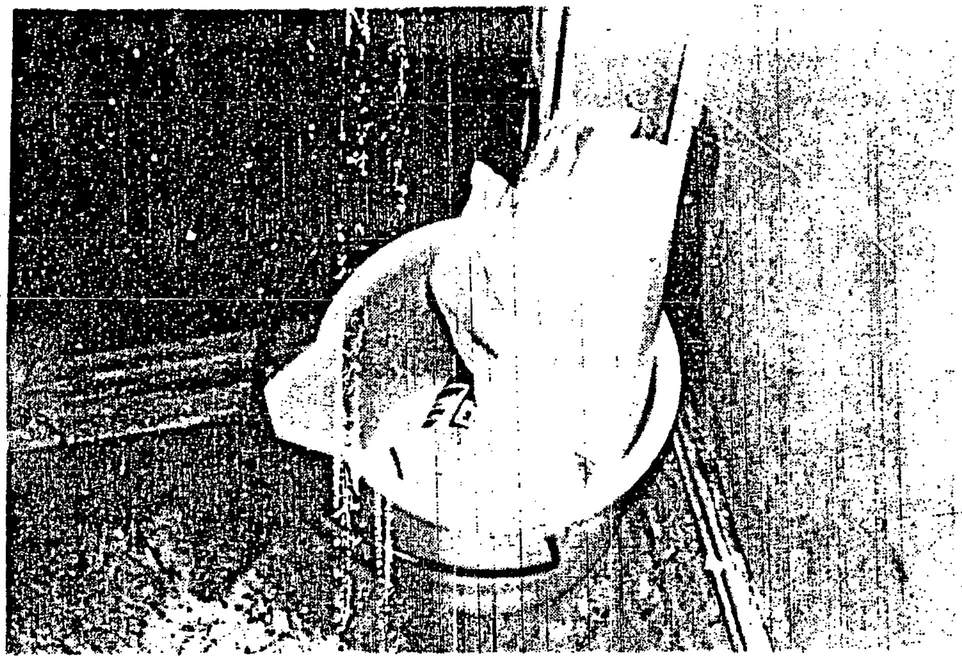


Figure 3. Photograph of the Transient Ignition Source Fuel Packet

Figure 4. Arrangement for the Electrical Ignition Source Apparatus

were used in the Cabinet Effects Tests. A list of the cabinets that were used in these tests is given in Table 1 along with the cabinet parameters. All the vertical cabinets were surplus cabinets obtained from a nuclear power plant vendor, while the benchboard cabinets were constructed specifically for this test program to specifications typically used for nuclear power plant cabinets. Figures 5a, b, and c are schematics of some of the vertical and benchboard cabinets tested.

The in situ fuels are the primary source of fuel in the cabinets. The amounts, types, and configurations of the in situ fuels are primarily dependent on the control system in the cabinet and style of cabinets involved. Therefore, specifying a single in situ fuel type, arrangement, or amount was not possible. Based on the background studies and surveys, it became obvious that most of the cabinet fuels were made up of plastics (e.g., cable insulation, components, wire ways, wire ties, etc.). Therefore, it was considered reasonable to represent all the fuels in the cabinets with cables, which are the largest source of in situ fuels in cabinets. Furthermore, cables simplified the test setup and cables are better characterized as to their burning characteristics than most other materials. Most plants (approximately 80 percent based on an informal survey) use IEEE-383 qualified cable; however, some of the plants (approximately 20 percent) still use unqualified cable in their control cabinets. Because both types of cable are still found in plants, both types of cable were used in the testing.

The IEEE-383 qualified cable, to be called qualified cable in the text and designated as "Q" cable in the plots and tables, was a three-conductor, No. 12 AWG, with 0.76-mm (30-mil) cross-linked polyethylene (XPE) insulation, silicon glass tape, and a 1.65-mm (65-mil) cross-linked polyethylene (XPE) jacket, rated at 600 V. This qualified cable was used in all the Scoping Tests and one of the Preliminary Cabinet Tests. A different qualified cable was used in one of the Preliminary Cabinet Tests because the supply of the XPE/XPE qualified cable was exhausted. The "new " qualified cable was a three-conductor, No. 12 AWG, with a 1.65 mm (65 mil) Hypalon jacket (Hyp) and a 0.89 mm (35 mil) cross-linked polyethylene (XPE) insulation, rated at 600 V. This "new" qualified cable was only used in Preliminary Cabinet Test #6.

The unqualified cable, designated as "UQ" cable in the plots and tables, was a three-conductor, No. 12 AWG, with 20/10 polyethylene/polyvinylchloride (PE/PVC) insulation, and a 45-mil (1.14-mm) polyvinylchloride (PVC) jacket.

The cable amounts and configurations will be discussed in more detail in Section 3 because they varied from test to test in the Cabinet Effects Tests. However, it should be

Table 1

List of Cabinet Parameters

Type of Cabinet	Size (m) [ft] L W H	Doors #	Doors (m) [ft] Size	Ventilation Grills #	Ventilation Grills (m) [ft] Size	Comments
1 - Vertical	.914 x .762 x 2.29 [3 x 2.5 x 7.5]	1	.61 x 2.1 [2 x 7]	0	Open	No Door
1 - Vertical	1.22 x .914 x 2.29 [4 x 3 x 7.5]	2	.61 x 2.1 [2 x 7]	4	.369 x .344 [1.21 x 1.13]	Ventilation Grills on Doors - 2 ea. Top and Bottom
1 - Vertical	1.52 x .914 x 2.29 [5 x 3 x 7.5]	2	.61 x 2.1 [2 x 7]	4	.369 x .344 [1.21 x 1.13]	
2 - Vertical	1.52 x .914 x 2.29 [5 x 3 x 7.5]	2	.61 x 2.1 [2 x 7]	4	.369 x .344 [1.21 x 1.13]	Partial Partition between L.H. and R.H. Sides of Cabinet
4 - Benchboard [1.0 x 1.83]	1.22 x 1.83 x 2.44 [4 x 6 x 8] Blocked	1	914 x 1.83		.305 x 5.58 [3 x 6]	Back Vent Typically 2
2 - Mitered Benchboard	See Drawing in Figure 5c					

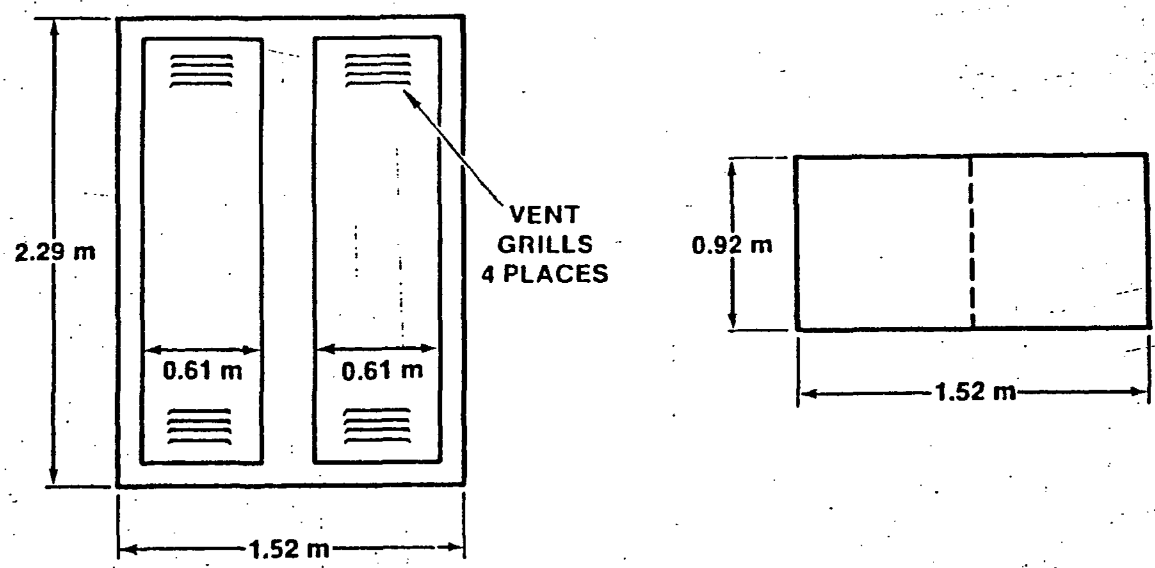


Figure 5a. Schematic of a Vertical Cabinet

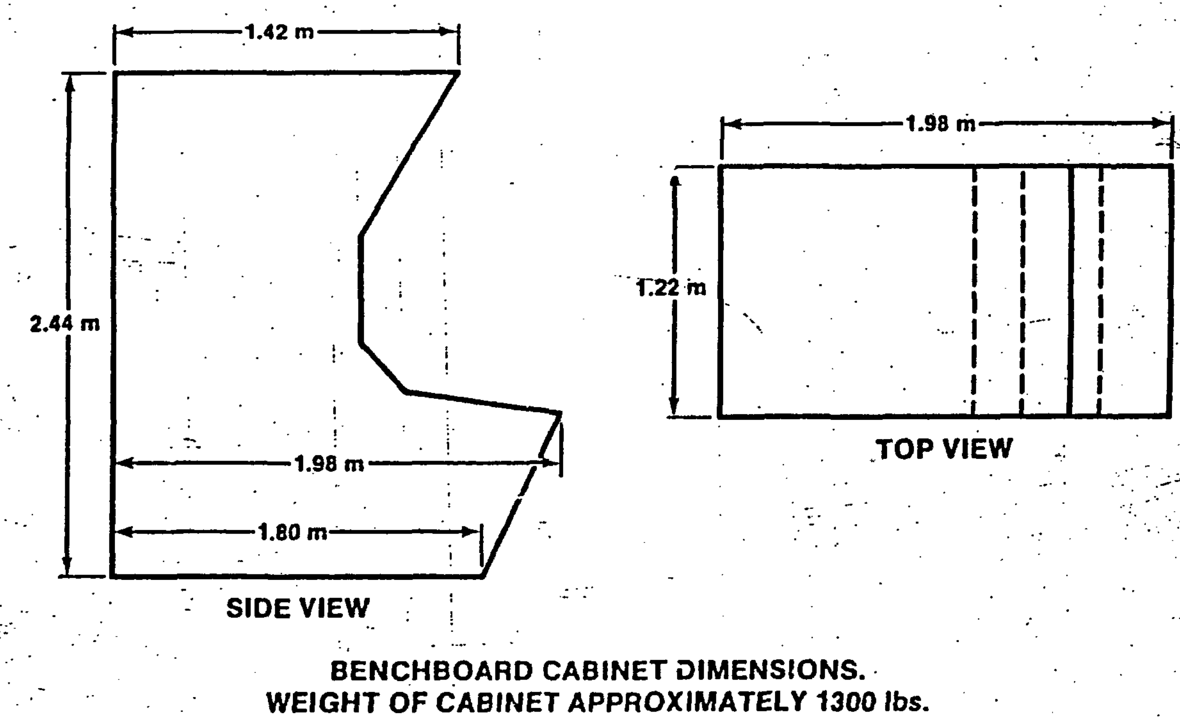
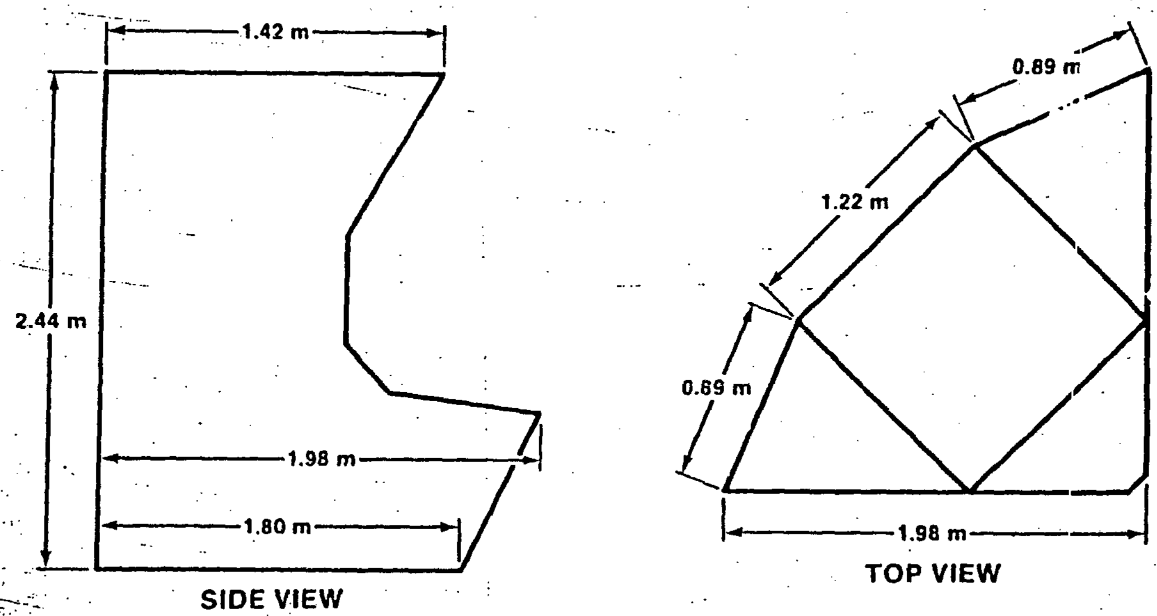


Figure 5b. Schematic of a Benchboard Cabinet



MITERED CORNER CABINET DIMENSIONS.
CABINET WEIGHT APPROXIMATELY 1600 lbs.

Figure 5c. Schematic of a Mitered Benchboard Cabinet

noted that based on the background survey, a maximum fuel loading for control cabinets, based on the cabinet floor areas, is 257,800 kJ/m^2 (22,700 Btu/ ft^2) with a typical fuel loading of 170,340 kJ/m^2 (15,000 Btu/ft^2).[3]

2.3 Ignition Source Fuel Packet Screening Tests

In order to resolve the full range of concerns about cabinet fires, a number of credible ignition sources needed to be considered in initiating the internal cabinet fires. It was not the goal of this study to demonstrate that a "credible ignition" source could actually ignite; rather it was to identify possible ignition sources and evaluate their ability to initiate a fire in cabinet in situ fuels.

As discussed in Section 1.3 and shown in Figure 1, many sources were employed in determining what were credible ignition sources. After the review, and in order to minimize the number of tests, it was concluded that one transient solid fuel ignition source and one electrical ignition source should be employed in the cabinet fire tests. The tests that were conducted to evaluate the ability of the electrical ignition source were performed separately and are discussed in detail in a report by Spletzer.[10]

A total of five (5) Screening Tests were performed with the purpose of evaluating two different transient ignition source fuel packets for their ability to ignite an in situ fuel (cables) in nuclear power plant cabinets. From these tests, a single transient ignition source was to be selected. The criteria used for evaluating the ignition source fuel packets were: (1) peak temperature, (2) sufficient burn duration, and (3) visual observation of flame height. Based on these criteria, the most severe of the fuel packets tested was to be selected for use in the Scoping Tests and later in the Preliminary Cabinet Tests.

The transient ignition source fuel packets (heat values calculated using values available in the literature [11]) chosen for testing were selected as discussed in the test plan [3] and consisted of the following:

1. Empty computer paper box, 0.455 kg (16 oz) box of kimwipes, and 0.946 ℓ (1 qt) of acetone [total heat content approximately 30,800 kJ (29,200 Btus)]

2. 9.46 ℓ (2.5 gallon) polyethylene bucket, 0.455 kg (16 oz) box of kimwipes, and 0.946 ℓ (1 qt) of acetone [total heat content approximately 72,200 kJ (68,500 Btus)]

The Screening Tests were conducted in an actual cabinet and setup so that the kimwipes and acetone were placed in the box or bucket, depending on the fuel packet being tested. All the Screening Tests were initiated by igniting one of the kimwipes with an electrically ignited pilot light. The Screening Test setup and results are described in detail in a separate test report.[12] Based on the test criteria previously discussed, the outcome of these tests was that the fuel packet (previously shown in Figure 3), consisting of the polyethylene bucket, kimwipes, and acetone, was the more severe of the ignition sources tested. It resulted in the largest flames and highest temperatures with an average flame height of 0.91 m (3 ft) and a peak flame temperature of 640°C, 0.46 m (1.5 ft) above the fuel packet. The fuel burned steadily for approximately 35 minutes with a peak heat release rate of 32 kW. In Figure 6 the heat release rate produced by this ignition source is shown. Based on the observation of these tests, it was felt that this transient fuel packet would be capable of igniting the in situ fuels that would be placed in the cabinets.

The electrical ignition apparatus (shown in Figure 4) causes overheating at the point of connection on the terminal strip, with ignition of the single stripped (unjacketed) cables occurring at approximately 165 watts in unqualified cable. This method of electrical ignition provides a relatively credible electrical ignition source for igniting the cabinet fires based on the power required to cause ignition.

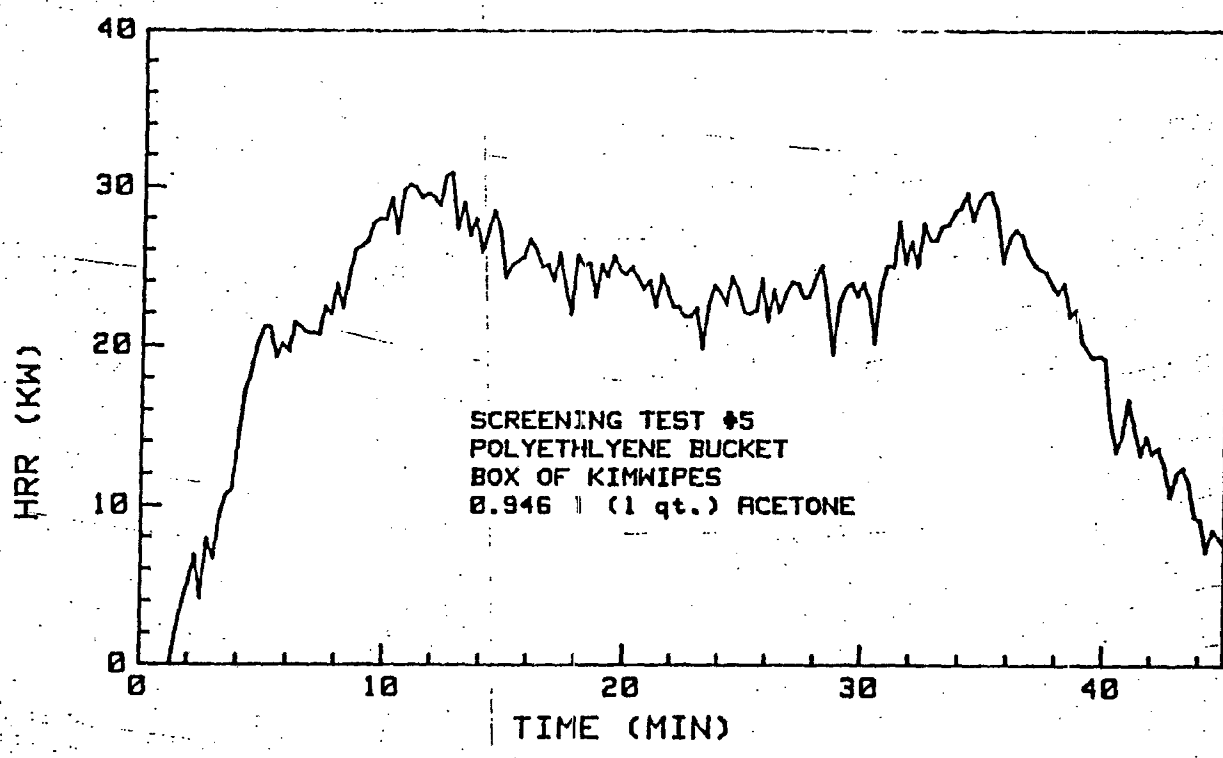


Figure 6. Heat Release Rate for the Transient Ignition Source; Screening Test #5

Through these Screening Tests, we were able to select a transient ignition source and an electrical ignition source. Both appear capable of igniting in situ fuel (cable bundles) in a cabinet. Also, both ignition sources appear to be relatively credible based on their size and the background information gathered (shown in Figure 1).

2.4 Cabinet In Situ Fuel Scoping Tests

A total of 11 Scoping Tests (ST) were performed to evaluate the ability of the selected ignition source fuels to ignite and propagate a fire in a cable bundle and to select credible in situ fuel amounts and configurations (i.e., amounts and configurations that might be found in a nuclear power plant

control cabinet). These tests were conducted on a smaller scale (i.e., minimal instrumentation and equipment) than the planned Preliminary Cabinet Tests for a quicker test turnaround time, reduced test cost, and increased total testing. The criteria for evaluating the Scoping Tests was somewhat arbitrary in that there were no pass/fail requirements and with each test the goals differed somewhat. Typically, the tests were evaluated to determine if the ignition source ignited the in situ fuel and if the fire propagated. Results of the Scoping Tests are discussed in more detail in a separate test report [12] and in Appendix B. No Scoping Tests were conducted with the electrical ignition source.

The parameters of concern for these tests focused on the ignition source and the in situ fuel. The transient ignition source fuel packet discussed in the previous section was used in most of the Scoping Tests. However, a similar fuel packet, but with only 0.473 ℓ (1 pint) of acetone instead of 0.946 ℓ (1 quart), was used in ST #1 and #2 to evaluate if a smaller ignition source was capable of igniting a cabinet fire. In ST #1 through 5 a vertical, single bay cabinet measuring 0.762 x 0.914 x 2.29 m (2.5 x 3 x 7.5 ft) was used while a vertical, single bay, 0.91 x 1.22 x 2.29 m (3 x 4 x 7.5 ft), nuclear power plant cabinet was used in ST #6 through 11. The ignition source and in situ fuel bundle were placed inside the cabinet. The cables used as the in situ fuel source were the qualified cable and unqualified cable described in Section 2.2.

Table 2, a matrix of the eleven cabinet fire Scoping Tests, shows the variables investigated and a brief summary of the results. The eleven tests can be broken down into three categories: (a) Scoping Tests #1 through 5, were performed to investigate the ability of the ignition source to ignite a cable bundle and the effects of location/arrangement of the in situ fuels; (b) Scoping Tests #6 through 9, were cabinet fire propagation tests on qualified cable, and (c) Scoping Tests #10 and #11 investigated the in situ fuel amounts and configurations to be used with unqualified cable. In the following paragraphs, the tests and results will be briefly described.

The Scoping Tests in category (a) used only a single cable bundle in an attempt to evaluate if the transient ignition source could ignite the cable bundle and propagate a fire in it. The setup for these tests is shown in Figure 7. The cabinet had no doors so that the fire could be videotaped and to ensure adequate ventilation for the fire.

As can be seen in Table 2 and in Figure 8, the heat release rate for ST #1 and ST #2 is lower than that produced by only the larger ignition source in the Screening Test (see Figure 6) indicating that little cable insulation was burned.

Table 2

Matrix of Scoping Tests

Test #[a]	Cable Type	Amount of In Situ Fuels[b,c] (KJ)	Cabinet[d] Ventilation Method	Peak HRR (KW)	Intense Burn Duration (min)	Test Result
ST1	Q	117,000	No doors	24	15	Bundle did not burn
ST2	Q	117,000	No doors	27	17	No propagation
ST3	Q	117,000	No doors	77	18	Entire bundle consumed
ST4	Q	117,000	No doors	82	17	Almost entire bundle consumed
ST5	UQ	117,000	No doors	132	17	Entire bundle consumed
ST6	Q	348,500	No doors	82	25	No propagation
ST7	Q	348,500	Doors closed	95	25	No propagation
ST8	Q	582,875	Doors closed	93	30	No propagation
ST9 barriers	Q	234,990	Doors open	74	20	No propagation
ST10	UQ	611,530	Doors closed	280	30	Propagated All burned
ST11	UQ	611,530	Door open	506	20	Propagated All burned

[a] Standard ignition source was 0.946 ℓ Acetone, 9.463 ℓ polyethlyene bucket, and 0.455 kg box of kimwipes--Scoping Tests 1 and 2 differed slightly in that only 1 pint acetone was used.

[b] Excludes ignition source.

[c] Tests #1 though 5 conducted in a 0.762 x 0.414 x 2.28 m cabinet and Tests #6 though 11 performed in 0.91 m x 1.22 m x 2.29 m cabinet.

[d] In tests with closed doors, ventilation is provided through ventilation grills.

Figure 7. Test Setup for Scoping—Test #4

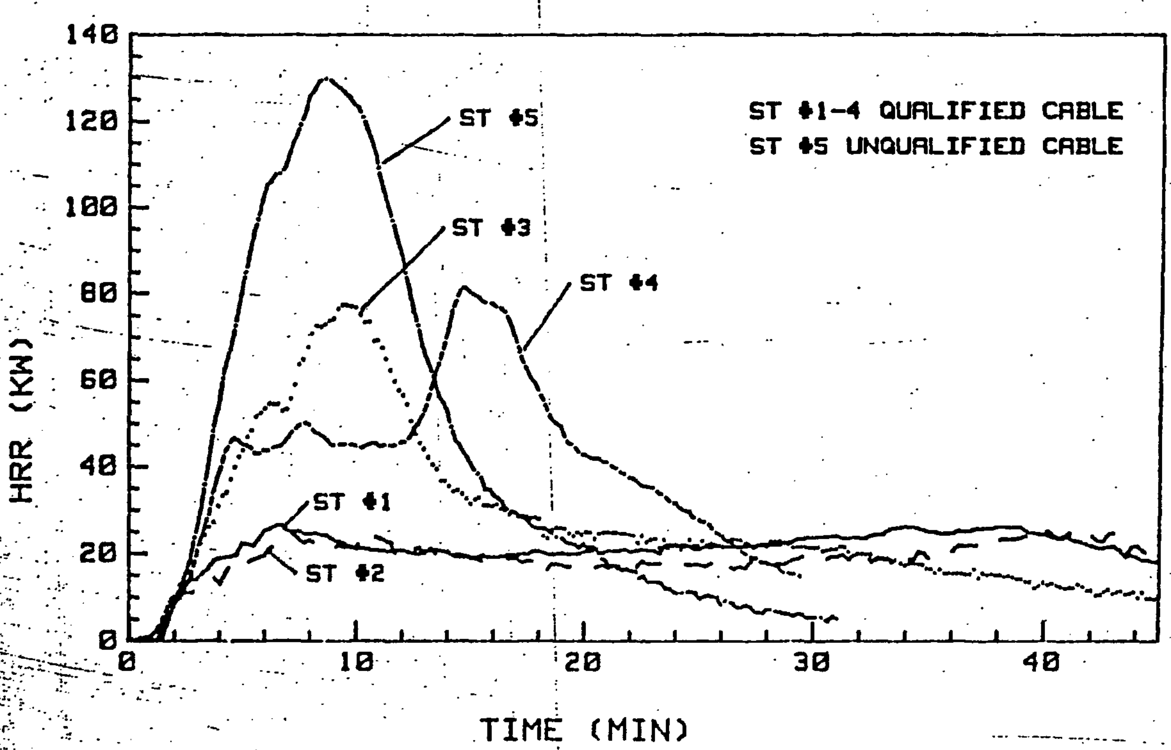


Figure 8. Heat Release Rate Plots for Scoping Tests #1 through 5

In ST #1, the cable bundle was in a configuration which did not allow the ignition source fire to impinge on the cable bundle and in ST #2 the ignition source simply was not adequate to ignite and propagate a fire in a vertical bundle of qualified cable. Consequently, for the remaining tests the originally selected ignition source, with 0.946 ℓ (1 qt) of acetone, was used. In ST #3, the cable bundle was loosened up to allow additional air flow, and flames, through the cables. In this test, the cable bundle ignited and the fire propagated up the bundle. Scoping Test #4 was similar but with an even looser cable bundle arrangement (Figure 7). The cable bundle ignited and burned quickly in ST #4 as shown by the HRR, Figure 8. Unqualified cable was used in ST #5 and was easily ignited by the transient ignition source and burned completely with a peak HRR of 132 kW.

Once it was established that the ignition source could ignite qualified cable (from ST #3 and #4), tests were needed to evaluate if a fire in qualified cable would propagate throughout a cabinet. Scoping Tests #6 through 9 used only qualified cable with different in situ fuel loading amounts and configurations to investigate if the fire would propagate from one side of the cabinet to the other. Different cabinet ventilation methods, and even barriers were used; however, in none of the tests with qualified cable did the fire propagate from the ignition corner bundle to the opposite side of the cabinet. The cable arrangement used in ST #8 is shown in Figure 9. Note the significantly higher fuel loading than that used in ST #4 (shown in Figure 7). The outcome of ST #6 through 9 is shown in Table 2 and Figure 10 is a plot of the HRR from these tests. The resultant HRR for all these tests is similar to that from ST #4 where only the corner cable bundle was burned, indicating that little more than the corner bundle actually burned. This was confirmed by the visual inspection of the cables after the test. Based on these tests, it appears that a fire in the tested qualified cable will not spread in a vertical cabinet with the given ignition source.

The last Scoping Tests, #10 and #11, were conducted to investigate in situ fuel loading amounts and geometries for unqualified cable and to determine if a fire in unqualified cable would spread throughout a cabinet. The tests used similar fuel loading amounts and configurations but with different cabinet ventilation methods. These tests demonstrated that for the configurations tested, a fire can propagate throughout a cabinet. Furthermore, it was noted that although the cabinet temperatures were higher due to trapped heat with closed cabinet doors (ST #10, ventilation grills on doors) the HRR was lower, as shown in Figure 11. This result is most likely because the fire was not getting sufficient oxygen due to the limited ventilation and therefore

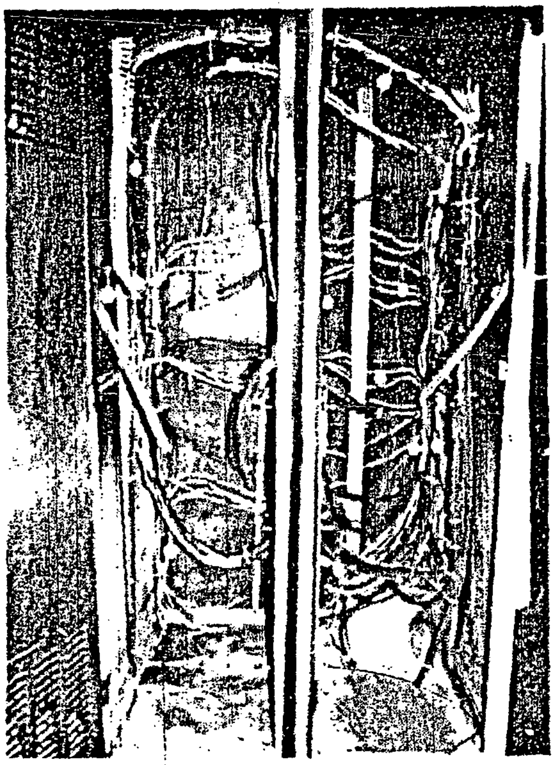


Figure 9. Test Setup for Scoping Test #8

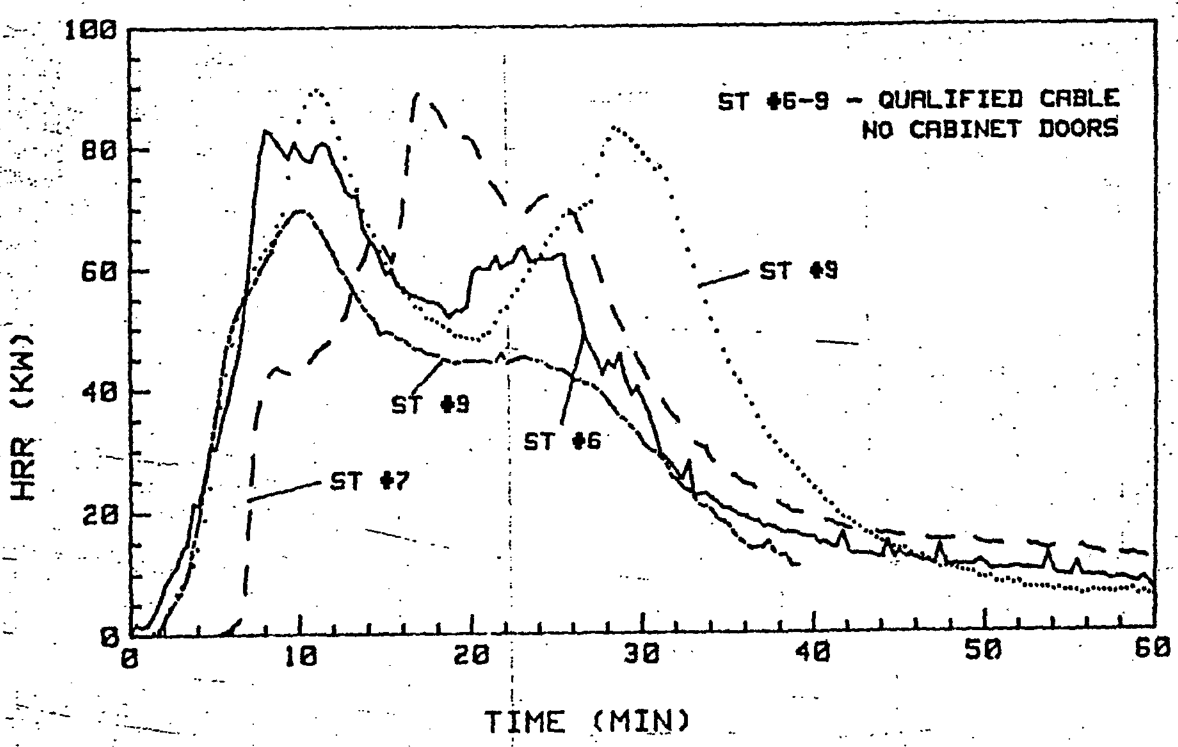


Figure 10. Heat Release Rate Plots for Scoping Tests #6 through 9

the fire did not grow as large as it could have otherwise. The enclosure air temperature in ST #11 (in the upper part of the test enclosure, ~3.35 m up) was the highest of any of the Scoping Tests with a peak temperature of 136°C at 18 minutes after ignition. In both of these tests, the smoke obscured the view within the room in approximately eight minutes.

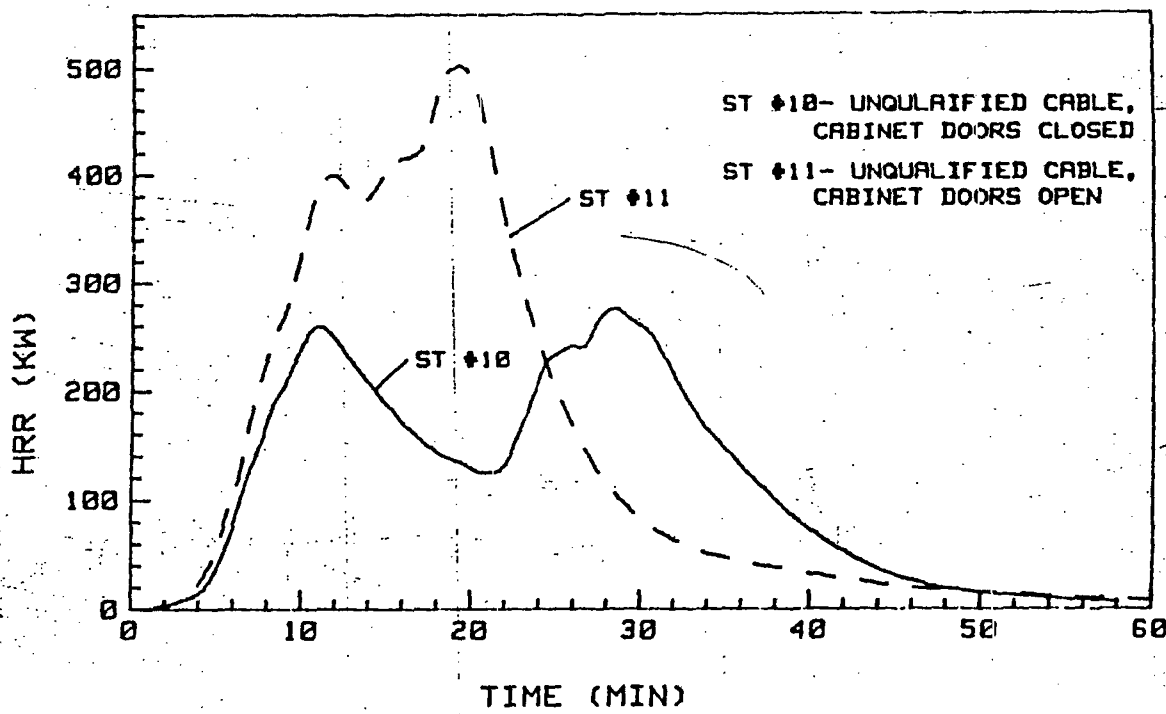


Figure 11. Heat Release Rate Plots for Scoping Tests #10 and 11

A number of conclusions can be made as a result of the Scoping Tests that give insight into cabinet fire development and input into the Preliminary Cabinet Tests. The conclusions are as follows:

a. There is a "critical" amount of "ignition source fuel" that is necessary to ignite a cable bundle, particularly qualified cable.

b. Qualified cable fires (with the selected cable and ignition source) in vertical cabinets do not spread throughout the cabinet.

c. Unqualified cable in vertical cabinets will easily ignite (with the selected ignition source) and propagate a fire in a single cabinet.

d. Burning rate (as measured by the HRR) is affected by the ventilation method (i.e., closed or open cabinet door) in tests using unqualified cable. Closed cabinet doors appear to result in higher cabinet temperature but also cause oxygen deprivation that appears to limit the burning rate.

e. Smoke obscuration in the test enclosure occurs within eight minutes in unqualified cable cabinet fires in the configurations tested.

f. The thermal environment in the enclosure does not become severe enough to cause melting of components or result in flashover.

Furthermore, an important observation made during the tests was that when comparing the test cabinets loaded with in situ fuel (loadings are based on survey information) to pictures of actual nuclear power plant cabinets, the fuel load appears to be small. As a result of the Scoping Tests, it appears that cabinet fires with qualified cable do not propagate significantly. However, cabinet fires with unqualified cable may be a real threat to the safety of a nuclear power plant, from the standpoint of fire spread, and control room habitability, given the "critical" conditions and configurations.

3. INVESTIGATION OF FULL-SCALE INTERNALLY IGNITED CABINET FIRES--PRELIMINARY CABINET TESTS

3.1 Purpose

This series of testing, designated the Preliminary Cabinet Fire Tests, was conducted to investigate the potential for full-scale cabinet fires to ignite and propagate. These tests differed from the earlier Screening and Scoping Tests in that (a) larger in situ fuel loads were tested, (b) more cabinet styles were tested, and (c) more adjacent cabinet and room effects were investigated. However, the primary purpose of these tests was to investigate cabinet effects as described in Section 1.2. As previously stated, only internally ignited cabinet fires were investigated because they were deemed to be more of a threat to a cabinet than external fires. These tests were performed with materials and setup such that they were as representative of nuclear power plant conditions as possible.

3.2 Methodology

The materials used in the testing were described in Section 2.2. In this section the cabinet arrangements and cabinet fuel loading will be discussed.

The arrangement of the vertical cabinets inside the test enclosure is shown in Figure 12. Cabinet A is the cabinet in which the fire was ignited, and cabinets B and C were placed on either side of cabinet A so that the effects of the fire on adjacent cabinets could be monitored. The front of cabinet D was approximately 3.66 m (12 ft) from the front of cabinet A, and was placed there so that the effects of the fire on a "remote" cabinet could be monitored.

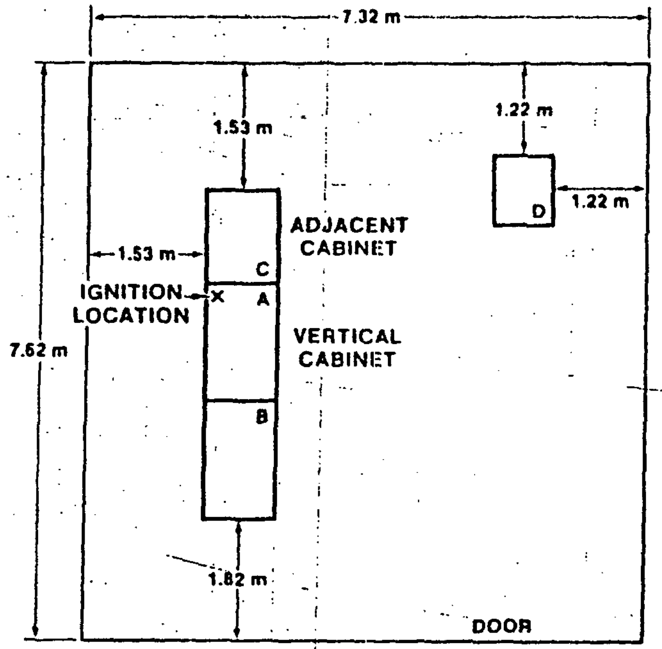


Figure 12. General Arrangement Drawing for Cabinet Fire Tests With Vertical Cabinets

The cabinet arrangement for tests with the benchboard-style cabinets is shown in Figure 13. In these tests there were only three cabinets, due to their size. However, on the side of cabinet A where there was no adjacent cabinet, a barrier was set up next to the cabinet to simulate an adjacent cabinet. This was done so the configuration was similar to the previous Preliminary Cabinet Tests and so the fire would not burn differently due to heat losses through the single wall.

In situ fuel loading arrangements and amounts varied from test to test; however, "standard cable bundles" were used in all the tests to make up the larger cable bundles and cable

arrangements. There were two "standard cable bundles"; #1 consisted of 12 single conductors, with the insulation, stripped out of the cable jacket, each piece 2.13 m (7 ft) long; #2 consisted of three jacketed 2.13-m (7-ft) pieces of 3-conductor cable tied together. In Table 3, the standard cable bundles with their fuel loading are given for both qualified and unqualified cable. The stripped-out single conductors were used because in many cases in nuclear power plant cabinets, the jackets of cables are stripped off as they enter the cabinet leaving only the insulator on the conductor. Larger bundles of cable were made up of these "standard bundles" which allowed for easier setup and better control of the cable configuration. Total fuel loadings in the cabinets are described in the test description sections. In addition to the cables, plastic wire ways that are also found in cabinets were used in the tests to hold cables. These wire ways are made of a polyvinyl chloride (PVC) and are "self-extinguishing." They are an open box type structure with a cover that snaps in place to contain the wires. These were described in detail in the test plan.[3] The fuel loads for the wire ways are also shown in Table 3.

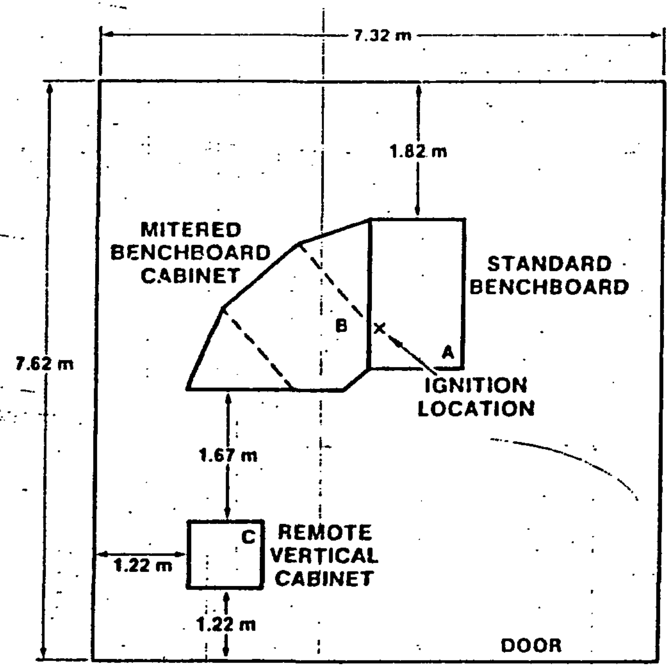


Figure 13. General Arrangement Drawing for Cabinet Fire Test With Benchboard Cabinets

Table 3

Standard Cable Bundle Descriptions and Loadings

STANDARD CABLE DESCRIPTIONS		
FUEL LOAD PER BUNDLE (KJ) [BTU]	#1 12 Conductors (stripped out of jackets) and tied	#2 Three 3 Conductor Cables tied together - 7' length
QUALIFIED CABLE (KJ) [BTU]	8820 [8360]	23,625 [22,393]
UNQUALIFIED CABLE (KJ) [BTU]	7938 [7524]	19,183 [18,183]
"NEW" AND QUALIFIED CABLE (KJ) [BTU]	9515 [9018]	23,980 [22,728]
"NEW" AND UNQUALIFIED CABLE (KJ) [BTU]	9790 [9279]	23,747 [22,507]

NOTES:

1. A plastic wire way and cover were also used in the tests, fuel loading for 1.82 m (6 ft) piece of wire way and cover; 33,760 kJ (32,000 Btu).
2. Heat values for calculating fuel loadings were based on total heat of combustion values from a report by Tewarson.[13]

3.3 Discussion of Tests and Results

A total of six Preliminary Cabinet Tests were conducted to evaluate the ignition and development of full-scale internally ignited cabinet fires. A test matrix of the variables investigated in this test series is shown in Table 4. The tests are described in detail in the following sections.

3.3.1 Tests in Vertical Cabinets

A total of four (4) Preliminary Cabinet Tests (PCTs) were conducted in vertical cabinets with differing types and amounts of in situ fuel. The test parameters are shown in Table 4. A summary of the results from these tests are shown in Table 5. Two types of cabinet ventilation, open cabinet doors and closed doors with ventilation grills on the doors, were investigated with vertical cabinets, both in tests with unqualified cable. Two of these cabinet fire tests in vertical cabinets used unqualified cable, one used qualified cable, and one used a pan of heptane as the fuel source in the cabinet. These tests will be discussed in the following section.

PCT #1 was conducted with unqualified cable as the fuel, had closed cabinet doors, and was ignited with the standard transient ignition source discussed in Section 2.2. A complete description of the test variables and a timeline describing the highlights of the test are provided in Figure 14. The fuel loading, shown in Figure 15a, was higher (in total) than had been used in any of the previously conducted Scoping Tests due to the larger floor area of the cabinet, although the loading per square meter of cabinet floor area was the same. The cabinet was set up so that the cabinet doors were closed as shown in Figure 15; however, the doors had top and bottom ventilation grills to provide ventilation (this test was similar to ST #10). In addition, eight meters and eight switches were placed in adjacent cabinets and around the enclosure to investigate how the fire affected components.[15]

A pictorial sequence of PCT #1 is shown in Figure 15. Since the cabinet doors were closed, no pictures of the burning cables could be taken. Figure 15b was taken at 11.66 minutes after ignition and shows the smoke level beginning to obscure the cabinets. The smoke took longer to obscure the cabinets in PCT #1 than it did in ST #10. A possible explanation for this is that PCT #1 did not burn as fast as ST #10 (to be discussed). Plots of four temperatures that are indicative of the thermal development in the burning cabinet, the adjacent cabinets, and in the enclosure are provided in Figure 16. Thermocouple (TC) 37 is a measure of the air temperature in the center of cabinet A, and shows a peak of 305°C at 20 minutes then quickly drops off. Thermocouples 82 and

Table 4

Matrix of Preliminary Cabinet Tests

TEST #	IGNITION FUEL	CABINET TYPE	CABINET VENTILATION	IN SITU FUEL TYPE	IN SITU FUEL AMOUNT (KJ) [BTU]
PCT 1	Transient	Vertical	Vent Grills on Doors	UQ	7.283×10^5 [6.90×10^5]
PCT 2	Transient	Vertical	Doors Open	UQ	1.051×10^6 [1×10^6]
PCT 3	Transient	Vertical	Doors Open	Q	1.055×10^6 [1×10^6]
PCT 4	Heptane	Vertical	Doors Open	Heptane	56.78 ℓ (.929 m^2 pan) [15 gal (10 ft^2 pan)]
PCT 5	Electrical	Benchboard	Door Open Front Grill	UQ	1.519×10^6 [1.44×10^6]
PCT 6	Transient	Benchboard	Door Open Front Grill	Q	1.551×10^6 [1.47×10^6]

Table 5

Summary of Results From Vertical Cabinet Tests

TEST #	IN SITU FUEL TYPE	PEAK HRR (kW)	PEAK TEMPERATURES (°C) ROOM	ADJACENT CABINET	BURN DURATION (MIN)	OBSERVATIONS
PCT 1	UQ	185	60	52	40	Propagation, obscuration at 11 minutes
PCT 2	UQ	995	160	82	15	Propagation, obscuration at 6 minutes
PCT 3	Q	56	50	60	25	No propagation, obscuration at 10 minutes
PCT 4A	Heptane	750	--	115	25	
PCT 4C	Heptane	1900	340	275	25	

TEST #: PCT #1

CABINET TYPE AND SIZE: VERTICAL CABINET, 0.91 x 1.53 x 2.29 m (3 x 5 x 7.5 ft)

CABINET VENTILATION METHOD: DOORS CLOSED, DOORS WITH VENTILATION GRILLS, 2 TOP AND 2 BOTTOM

CABLE TYPE: UNQUALIFIED CABLE (PE/PVC)

IN SITU FUEL LOADING: 7.84×10^5 kJ (7.43×10^5 Btu)
562,712 kJ/m^2 (49,550 Btu/ft^2)

IGNITION SOURCE: PLASTIC BUCKET, BOX KIMWIPES, 0.946 ℓ ACETONE
72,220 kJ (68,450 Btu)

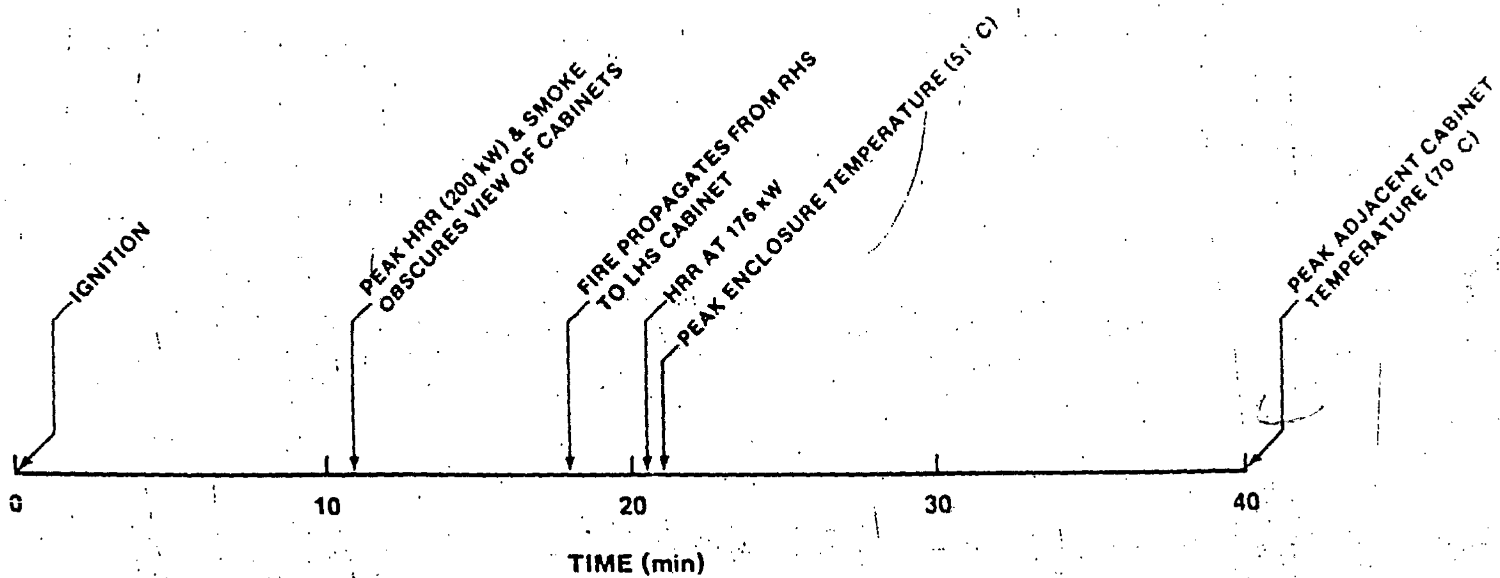


Figure 14. Description and Timeline of PCT #1

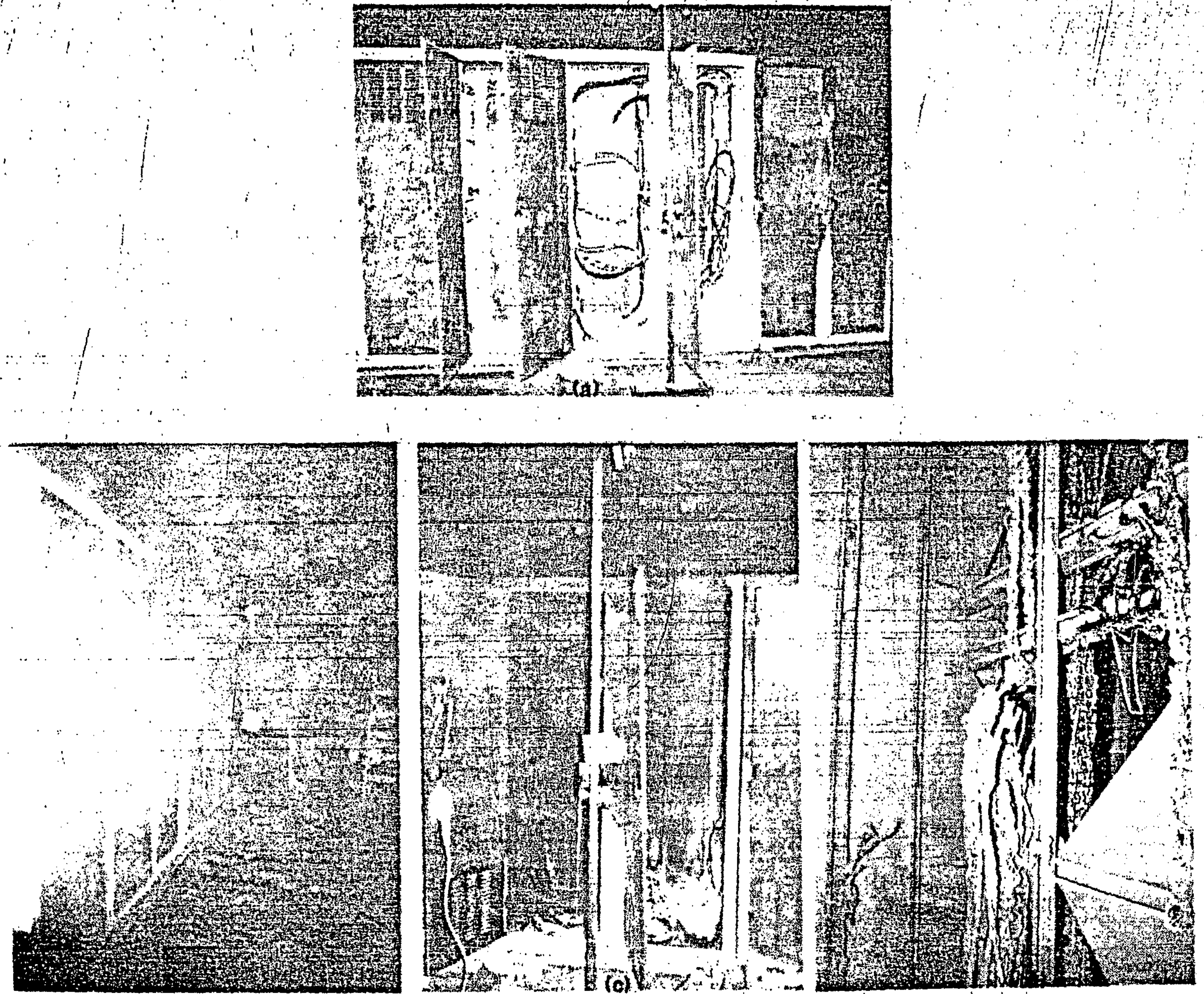


Figure 15. Photographic Sequence of PCT #1

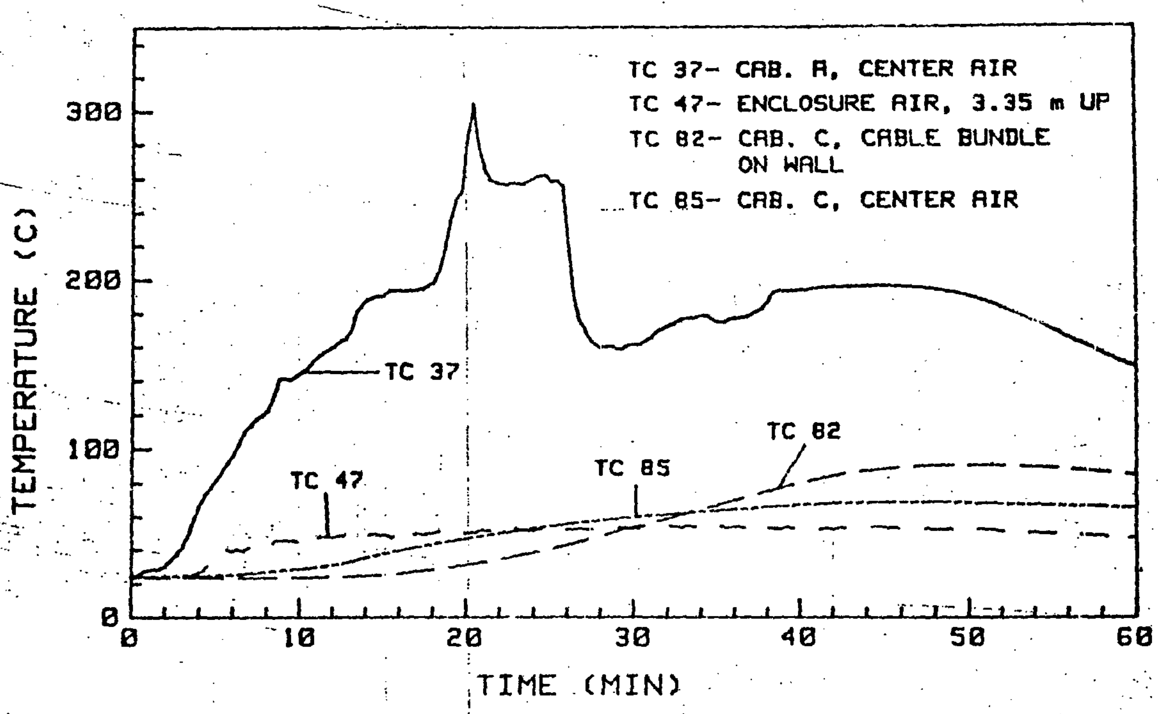


Figure 16. Temperature Measurements in PCT #1

85 are located in an adjacent cabinet, cabinet C (see Figure 12). TC 82 is in a cable bundle on the wall adjacent to cabinet A, and TC 85 is the center air temperature. Both of these temperature measurements are less than 90°C and peak long after the peak temperature occurs in cabinet A due to the thermal lag caused by the cabinet walls. Enclosure temperature, as measured by TC 47 (3.35 m [11 ft] up in the center of the test enclosure), does not show a significant rise and is steady throughout most of the test. The heat release rate (HRR) rises very quickly up to 180 kW as shown in Figure 17. After the HRR peaked, at approximately 11 minutes, it drops off slightly and rises again indicating additional combustion. The fire then slowly burns down. Based on the temperature measurements in cabinet A, TC 37, the results of ST #10, and the HRR, it appears that oxygen deprivation was beginning to occur in the cabinet due to the limited ventilation provided by the ventilation grills and closed doors resulting in the steady burn rate of 150 to 160 kW. However, because there was no oxygen probe in the cabinet, this cannot be confirmed. Based on the total heat released, also shown in Figure 17, it appears that ~47 percent of the total potential heat content of the fuel load was released. The fire growth rate during the first 11 minutes of the test was ~20 kW/min or 0.33 kW/sec and was steady as shown by the curve of the total heat released. A posttest

inspection of the cabinet in situ fuel revealed that all the cables on the right-hand side of the cabinet were combusted, as shown in Figure 15. However, the cables on the left-hand side of the cabinet were only partially combusted. The total weight loss was 18.63 kg (41 lbs) (this includes the ignition source fuels), which is 73.5 percent of the available fuel. The maximum weight loss rate during the test was ~0.91 kg/min (2 lbs/min). The total heat released does not appear to be consistent with the total mass lost. An explanation for this inconsistency is that the heat-of-combustion value used to calculate the fuel loading was the total heat of combustion [13] and typically a cable fire burns at about 50 percent efficiency.

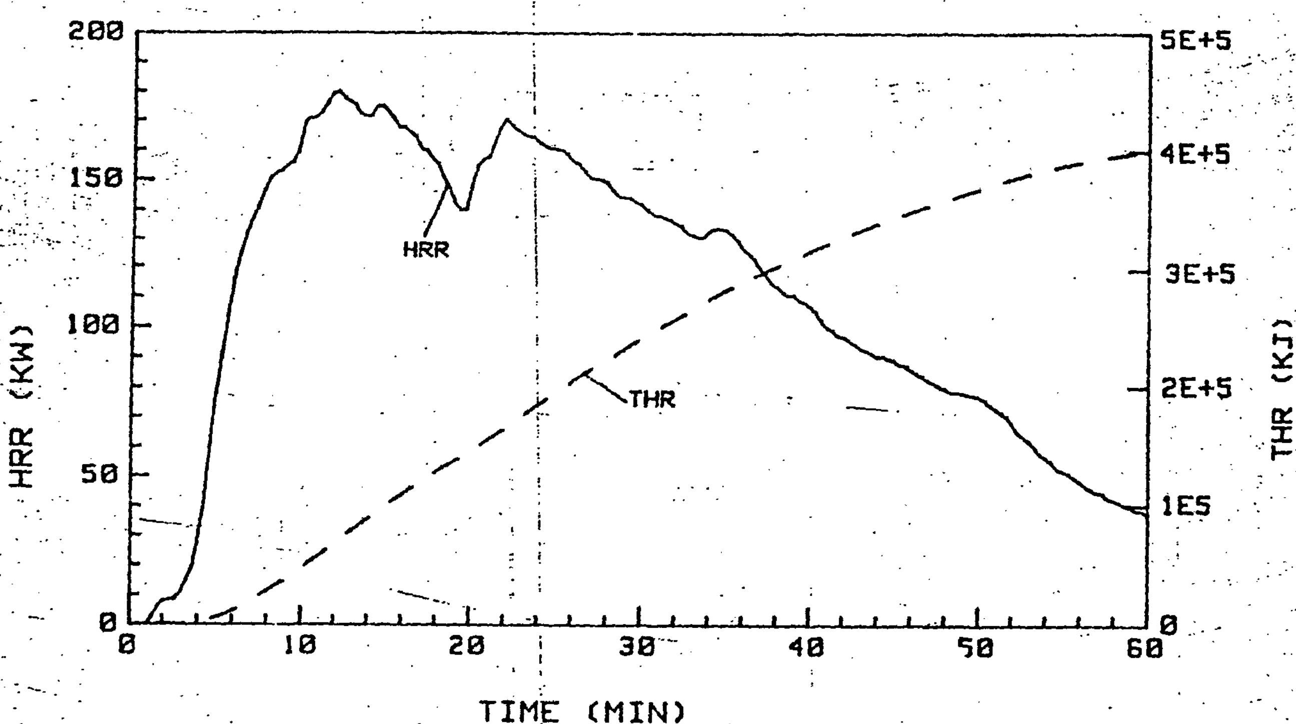


Figure 17. Heat Release Rate and Total Heat Released From PCT #1

PCT #1 showed that a cabinet fire with unqualified cable as the in situ fuel can propagate in a vertical cabinet with closed doors and ventilation grills; yet, there is the potential for oxygen deprivation occurring in the cabinet due to the limits on ventilation. None of the seven meters or switches experienced short-term damage (except those in the burning cabinet), and the results of the inspection of these components is discussed in Jacobus' report.[15] Furthermore, although the thermal environment in the enclosure and adjacent cabinets was not severe enough to result in autoignition of the cables or components, the environment in the enclosure was severe from a habitability standpoint, due to the smoke which obscured vision within 11 minutes after ignition.

As a result of discussion with NRC, the fuel loading amount in the cabinet was changed in PCT #2 as shown in Table 4. This test was conducted with unqualified cable, and open doors provided cabinet ventilation, and the standard transient ignition source was employed in igniting the cabinet fire. Open cabinet doors are a legitimate configuration because in many real applications the cabinets contain no doors at all. In Figure 18, a complete description of the test variables and a timeline showing the highlights of the test are provided. The larger fuel load used in this test, 1.05×10^6 kJ (1.0×10^6 Btu), shown in Figure 19a, was used because the fuel loading in PCT #1 still appeared to be too small based on pictures of real cabinets from operating plants. Eight switches and meters were also included in this test to investigate the effects of the fire on them. In addition, cable bundles were placed in the adjacent and remote cabinets.

The fire in this test developed very quickly as is shown in Figures 18 and 19. In fact, by nine minutes after ignition, as shown in Figure 19b, the entire right-hand side of the cabinet was burning. It is obvious from the plots of the cabinet temperatures, Figure 20, that the fire developed quicker and was much more severe than PCT #1. The thermocouple placement was different in this test (PCT #2) as compared to PCT #1; therefore, the thermocouple numbers are not the same. Thermocouple 24 shows the air temperature in the center of cabinet A, with temperatures rising very rapidly in 10 minutes to flame temperature (950°C). However, TC 83, the center air temperature in cabinet C, only reached 82°C which does not appear severe enough to result in melting the cables or components in the adjacent cabinets. The temperature measurement in the cable bundle in the adjacent cabinet was lost; although, TC 22 gives an indication of the inside adjacent cabinet wall temperature (inside cabinet C). The wall temperature begins to climb very rapidly at 8 minutes to a peak of 280°C, which is hot enough to melt many plastic materials, yet, not high enough to result in autoignition of cables [16] or other components. The thermal environment in the enclosure, as measured by TC 47, was much higher than in PCT #1, and reached a peak of 182°C at 12 minutes after ignition. The enclosure temperature stayed above 150°C for ~7 minutes.

The HRR plot shown in Figure 21, provides a good indication of how quickly the fire developed in PCT #2. Within 7 minutes the HRR rose from 100 kW to almost 1000 kW, a rate growth of 128 kW/minute or 2.13 kW/sec, which is substantially higher than that experienced in PCT #1. In looking again at Figure 20, the peak temperature in the cabinet A occurs almost simultaneously with the peak HRR, and the peak enclosure temperature lags a couple minutes behind the peak

TEST #: PCT #2

CABINET TYPE AND SIZE: VERTICAL, 0.91 x 1.51 x 2.29 m (3 x 5 x 7.5 ft)

CABINET VENTILATION METHOD: DOORS OPEN, TWO OPENINGS, DOORS 0.61 x 2.13 m (2 x 7 ft)

CABLE TYPE: UNQUALIFIED CABLE (PE/PVC)

IN SITU FUEL LOADING: 1.054 x 10^6 kJ (9.99 x 10^5 Btu)
70,260 kJ/ft^2 (66,600 Btu/ft^2)

IGNITION SOURCE: PLASTIC BUCKET, BOX KIMWIPES, 0.946 ℓ ACETONE
72,220 kJ (68,450 Btu)

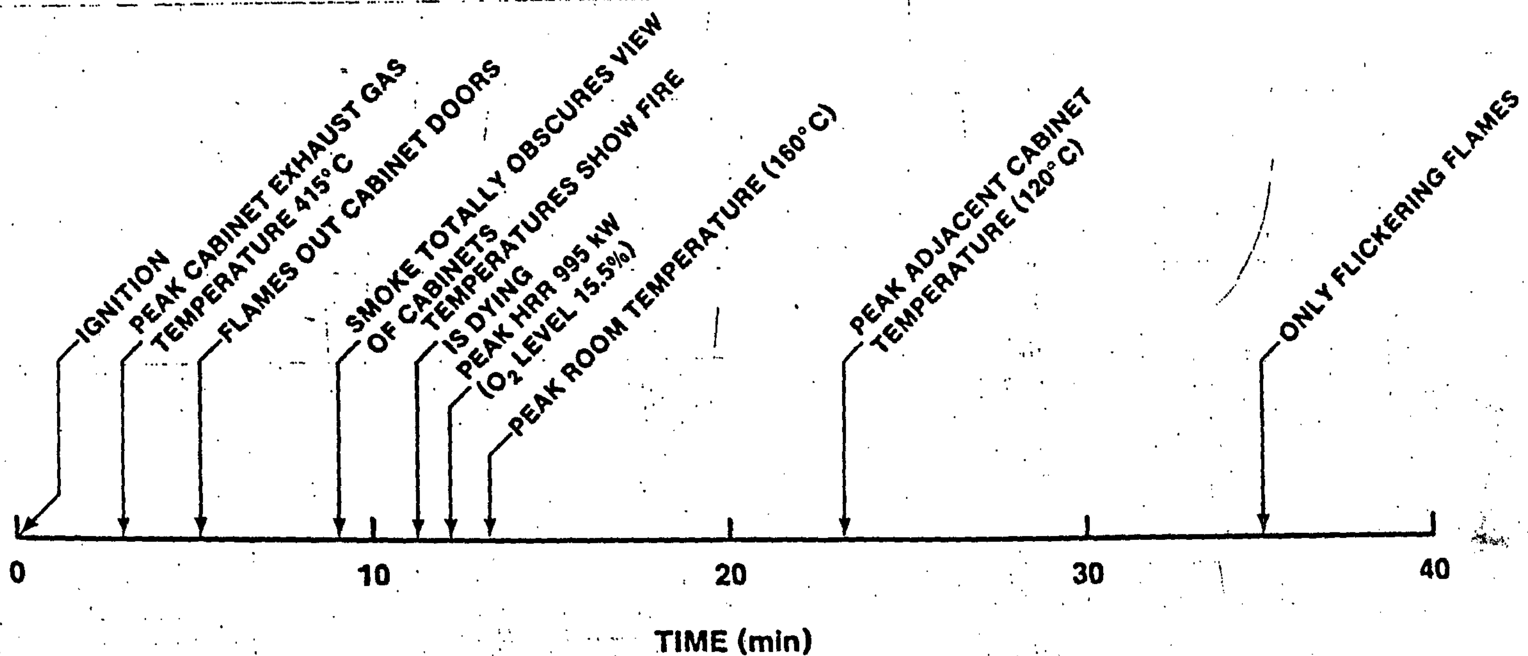
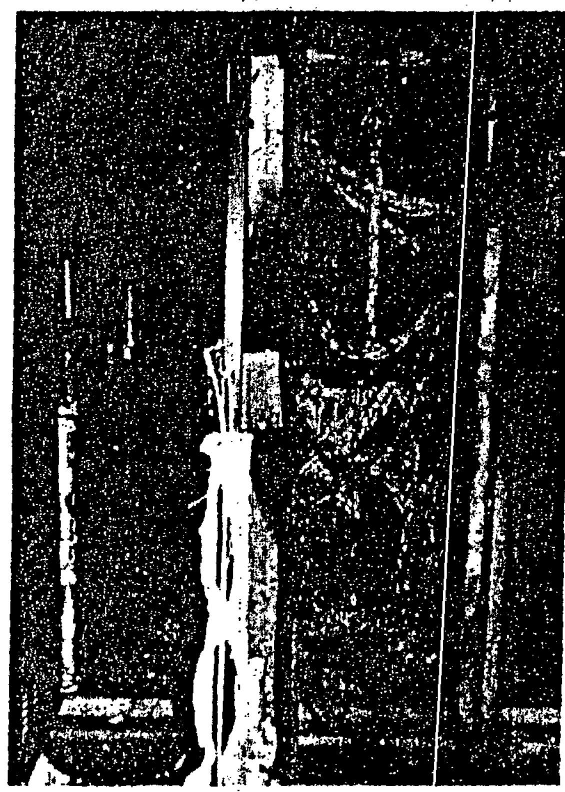


Figure 18. Description and Timeline for PCT #2

(a)

(b)

(c)



(d)

Figure 19. Photographic Sequence of PCT #2

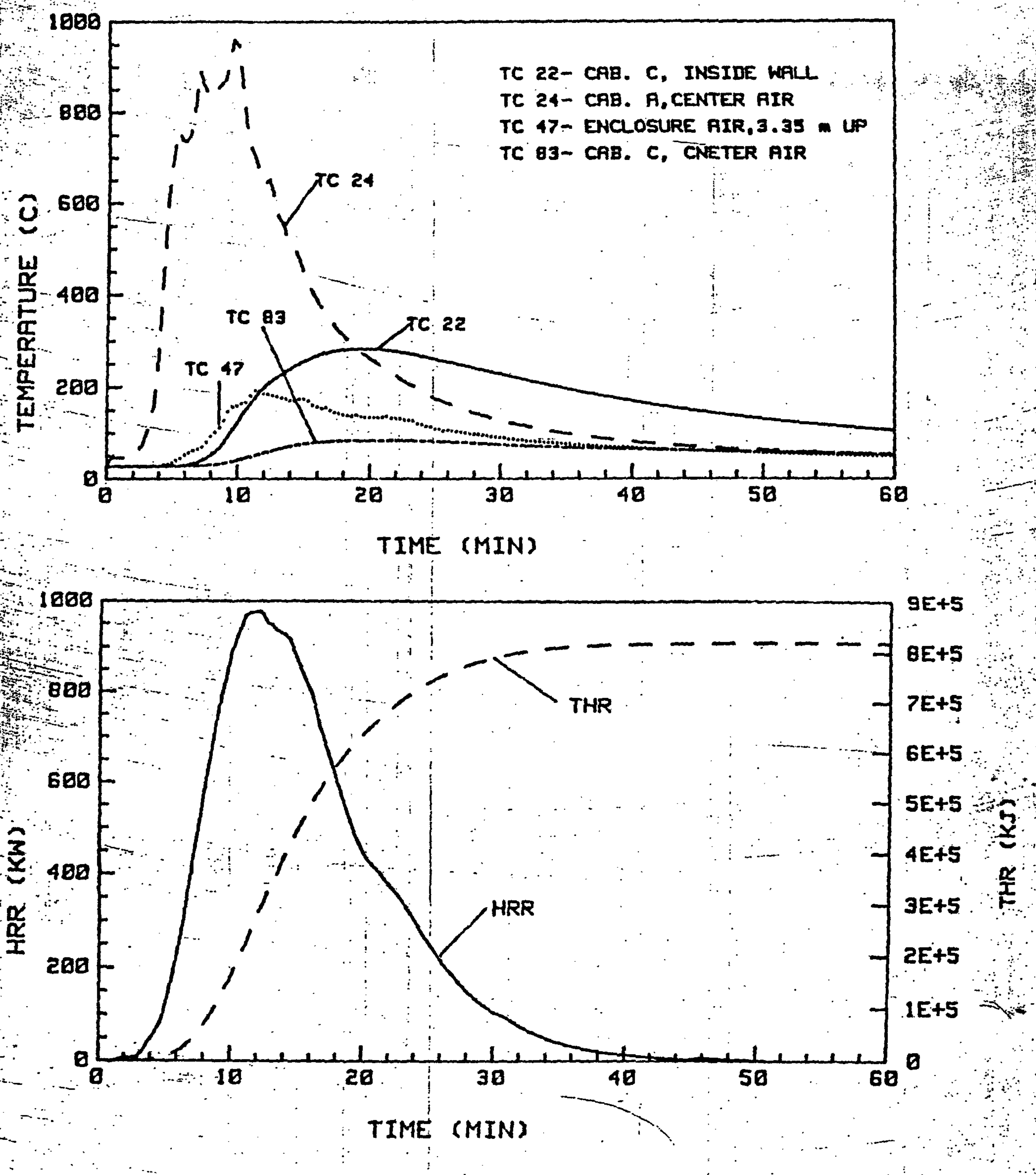


Figure 21. Heat Release Rate and Total Heat Released for PCT #2

HRR. A total of 8.39 x 10^5 kJ of heat was released as shown in Figure 21, and all the cables in cabinet A appeared to have burned. Based on the total heat release plot, approximately 79.6 percent of the potential heat available in the fuel load actually combusted. A total of 25.5 kg (56 lbs) of cable insulation (including the ignition source) was burned, representing ~73.5 percent of the cable insulation weight. The maximum burn rate was 0.805 kg/min (1.77 lb/min) which is lower than that experienced in PCT #1. These numbers are inconsistent because PCT #2 had a higher peak HRR and a lower mass loss rate. One possible explanation is that the burning cabinet tilted against one of the adjacent cabinets during the fire, thus offsetting the load-cell reading and resulting in bad mass loss data. In any case, the maximum weight loss calculated using the HRR and total heat of combustion value is 1.93 kg/min (4.24 lb/min). Since the mass loss data appears inaccurate for this test, it is not possible to compare the fuel burned from the standpoint of total heat released and total mass lost. However, it does appear that PCT #2 had a higher efficiency of burning than PCT #1 since a greater percentage of the potential heat of combustion was apparently released. Monitoring of the combustion gases showed peak readings for CO_2, CO, and hydrocarbons of 2.28 percent, 10,689 ppm, and 10,400 ppm respectively. All these combustion gases peaked at approximately the same time, ~11 minutes after ignition.

The large difference in burning rate between PCT #2 and PCT #1 was a result of both the increase in the fuel loading, ~30 percent, and also because of the increased ventilation in the cabinet allowed by the open cabinet doors. Exactly how much each of those factors contributed to the increase in the burning rate cannot be determined. All the parameters measured (e.g., HRR, temperature, etc.), except for weight loss data, were significantly higher in PCT #2 than in previous tests. In addition, the oxygen level in the room was down to ~15.5 percent in the enclosure near the ceiling. It should be noted that combustion cannot be maintained below 16 percent oxygen; however, near the floor the oxygen level was probably higher because that is where the ventilation inlets are located. The smoke began to obscure the view of the cabinets within nine minutes after ignition of the fire; consequently, nothing could be seen in the enclosure. Based on the temperature readings in the enclosure, it does not appear that there was any burning outside the cabinet or in the "hot layer."

Video recordings and data from the thermocouples located in cabinet A, the burning cabinet, indicate that the fire development progressed as shown in Figure 22. First, the right-hand side of the cabinet, where the ignition source was started, burned. Next, the fire burned across the

right-hand side and ignited cables on the top part of the left-hand side of the cabinet. The fire then spread across from the right-hand side and progressed down the left-hand side. The reason the left-hand side started burning from the top down was because hot combustion gases from the right-hand side were forced over to the top of the left-hand side by the door soffit. There was no burning or damage to the cable bundles located in adjacent cabinets B and C. Three components, located in the enclosure and adjacent cabinets, were powered and monitored throughout the test. All components performed as designed (the component highest up was 1.83 m [6 ft] up and 3.05 m [10 ft] away from the burning cabinet and saw a peak temperature of 90°C). The results of the component evaluation are described by Jacobus.[15]

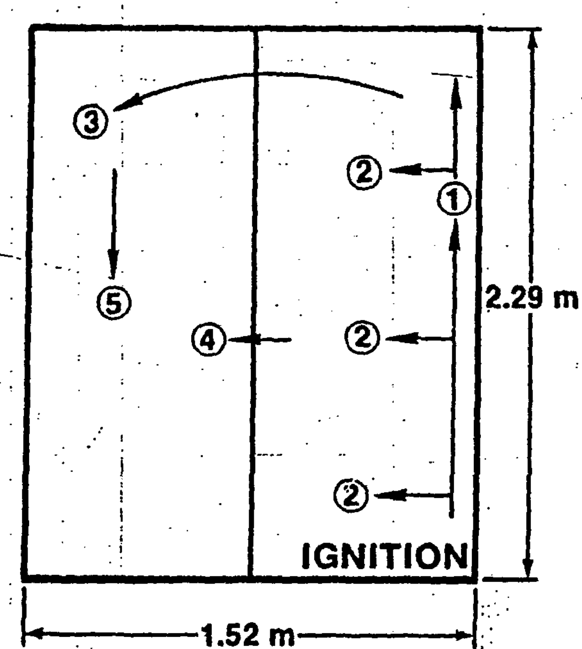


Figure 22. Burn Pattern for PCT #2

PCT #2 demonstrated that for a vertical cabinet with open doors and with an in situ fuel loading of unqualified cable that appears similar to real fuel loadings in nuclear power plants, the fire will develop and spread rapidly throughout the burning cabinet.

However, even a fire as large as this did not have a significant thermal effect (i.e. temperature rise that could result in melting of cables or components) on the adjacent cabinets in the configuration tested. It should be noted that in this test each cabinet had a side wall which means there was a double wall between cabinet interiors. In some plant applications there is only a single wall and in some cases there is no wall or barrier between cabinets which could result in a more severe thermal environment in the cabinet. The thermal environment in the enclosure near the ceiling was severe enough to have caused melting of some plastics and the smoke concentration in the enclosure was very dense throughout the test.

Although previous Scoping Tests (i.e., ST #6 through 9) had already shown that a fire in qualified cable in a vertical cabinet would not spread, PCT #3 was conducted to determine what effect a larger fuel loading of qualified cable in a vertical cabinet would have on ignition and propagation of a fire. This test was conducted with open cabinet doors and with an in situ fuel loading of ~1.051 x 10^6 kJ (1.0 x 10^6 Btu) as shown in Table 4. In Figure 23, a complete description of the variables used in PCT #3 as well as a timeline providing the highlights that occurred during the test is provided. The cabinet and cable setup used in this test was similar to that used in PCT #2. The fuel loading shown in Figure 24a varied somewhat from PCT #2 in that fewer standard cable bundles were needed to make up the fuel loading because the qualified cable bundles were heavier. Also, many of the cable bundles that were run from the right-hand side of the cabinet to the left-hand side were run diagonally upward to enhance the likelihood of the fire to propagate up the cables and spread the fire to the left-hand side of the cabinet. This method of loading the cables almost succeeded in propagating the fire as shown in Figure 24b; the diagonal cables almost burned over to the left-hand side of the cabinet.

The resulting temperatures produced by the fire in the burning cabinet, the enclosure, and in adjacent cabinets are shown in Figure 25. These thermocouple locations are the same as those used in PCT #2. In comparing these thermocouple readings to PCT #2 they are substantially lower. Even the burning cabinet air temperature, TC #27, only had a maximum temperature of 217°C. The other temperatures monitored by TCs 82, 85, and 47, indicate that there was not a threat of autoignition or damage to cables or components in adjacent cabinets or in the enclosure. The HRR, Figure 26, for PCT #3 shows that the fire only produced a peak heat release rate of 56 kW, which is lower than was experienced in any of the previous Scoping Tests with qualified cable. The total heat released was only 0.65 x 10^5 kJ (0.61 x 10^5 Btu) which is slightly less than that released by the ignition source in

TEST #: PCT #3

CABINET TYPE AND SIZE: VERTICAL CABINET, 0.91 x 1.53 x 2.29 m (3 x 5 x 7.5 ft)

CABINET VENTILATION METHOD: DOORS OPEN, TWO OPENINGS 0.61 x 2.133 m (2 x 7 ft)

CABLE TYPE: IEEE-383 QUALIFIED CABLE (XPE/XPE)

IN SITU FUEL LOADING: 1.056×10^6 kJ (1.001×10^6 Btu)
757,779 kJ/m^2 (70,420 Btu/ft^2)

IGNITION SOURCE: PLASTIC BUCKET, BOX KIMWIPES, 0.946 ℓ ACETONE
72,220 kJ (68,450 Btu)

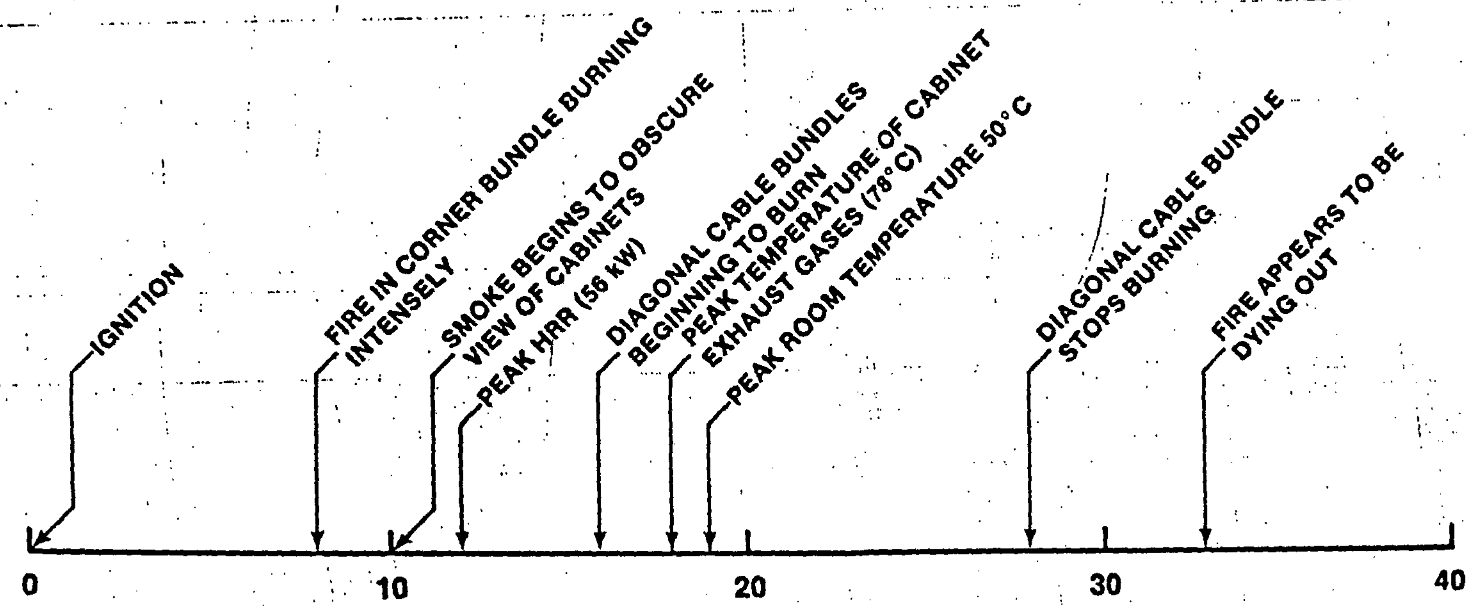


Figure 23. Description and Timeline for PCT #3

Figure 24. Pictorial Sequence of PCT #3

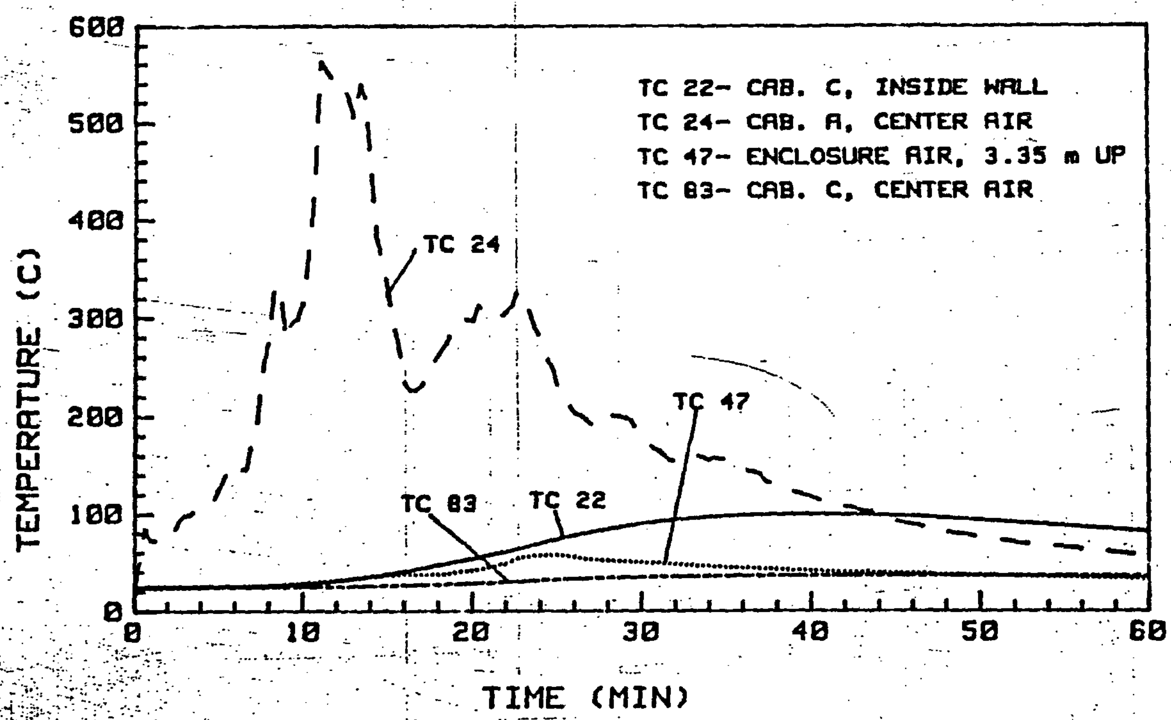


Figure 25. Temperature Measurements in PCT #3

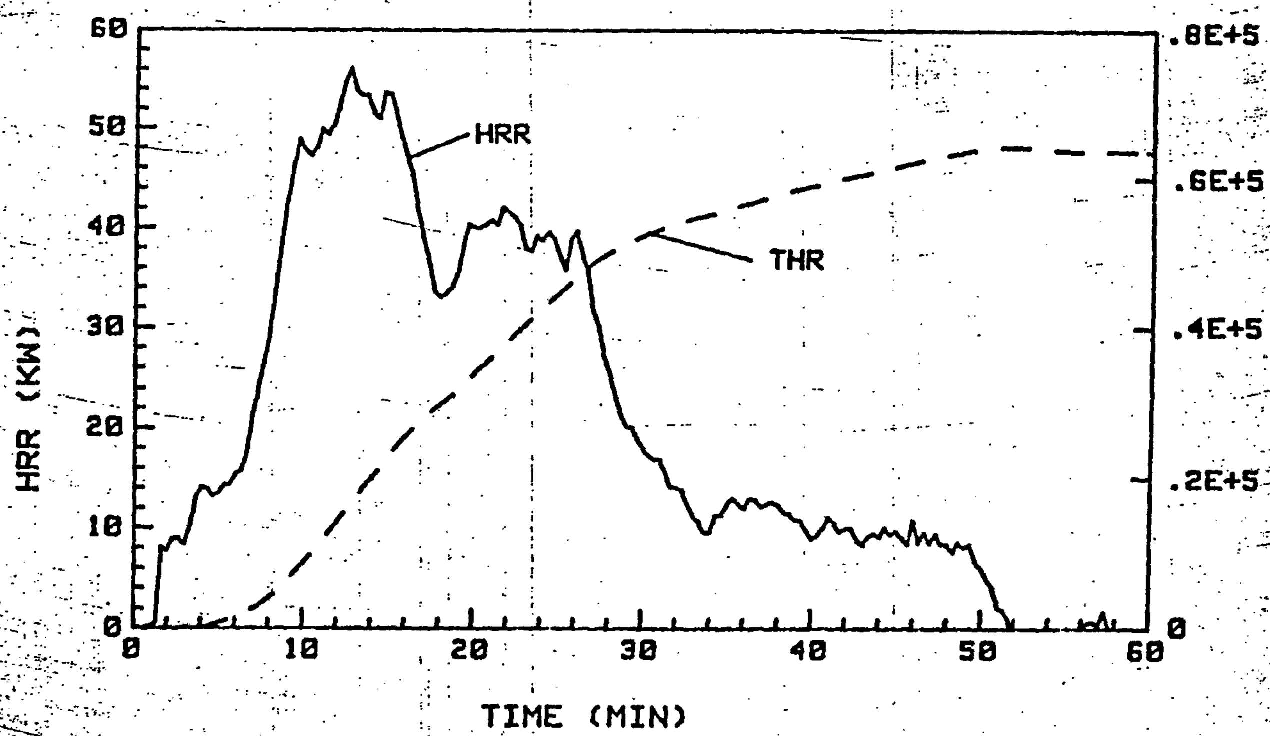


Figure 26. Heat Release Rate and Total Heat Released From PCT #3

Screening Test #5 which was certainly unexpected. One possible explanation for the unreasonably low HRR values is that a valve used in the calibration process for the gas analyzer may have been left partially open allowing ambient air to mix with the stack sample. This would result in higher oxygen and hence lower HRR levels measured than those actually encountered. However, a posttest calibration of the gas analyzer revealed no problems. Aside from the fact that there was a possible malfunction, the fire did not propagate. The weight loss data shows that 10.45 kg (23 lbs.) of cable insulation was burned and a visual inspection after the test showed that most of the cables on the right-hand side of the cabinet were burned. However, none of the cables on the left-hand side were burned, although some of the cables near the top of the cabinet were smoke damaged, as shown in Figure 24d. Based on the weight loss data 14.6 percent of the cable insulation was combusted which should correspond to 3.24×10^5 kJ (3.07×10^5 Btu) of fuel assuming complete combustion.

Preliminary Cabinet Test #3 again showed that a cabinet fire in a vertical cabinet with qualified cable has little potential to propagate and spread throughout a single vertical cabinet. This is not to say that the fire would not spread given a "critical" ignition source and in situ fuel configuration. However, with the in situ fuel and configurations tested, a fire in a vertical cabinet with qualified cable is not likely to propagate or result in damage to cable components or equipment outside the cabinet as a result of the thermal environment. It should be noted, however, as described in the timeline, the smoke became very thick within 10 minutes after ignition of the cables, showing that even if the fire does not become large and propagate, it could result in problems with habitability in the enclosure or equipment smoke damage.

PCT #4 was conducted because of the concern about high temperatures experienced in the enclosure and adjacent cabinet air and walls during the large fire in PCT #2 (1000 kW) and the effect an even larger cabinet fire might have on the thermal environments. Since it was impractical (and unrealistic) to put twice as many cables in a cabinet, Preliminary Cabinet Test #4 was conducted using a heptane pool in a cabinet to achieve a desired HRR. The purpose of PCT #4 was to produce a cabinet fire using a heptane pool in a cabinet that resulted in an ~2000 kW fire, and to investigate the temperature excursions in the enclosure and adjacent cabinets. Three tests were conducted using heptane pool fires in cabinets to investigate the thermal effects of large cabinet fires. These tests were designated PCT #4A, PCT #4B, and PCT #4C. The reason for three tests was because it took three tests to produce the desired HRR. In all the tests with the heptane pools, the same cabinet configuration used in the previous tests (PCT #2 and #3) was used.

PCT #4A, in which 37.85 ℓ (10 gal) of heptane was burned in two pans with a total area of 0.58 m^2 (6.2 ft^2), produced a very intense fire with large flames shooting out the cabinet doors and high temperatures in the enclosure and adjacent cabinets. However, as the HRR shows in Figure 27, a peak HRR of only 750 kW was reached. In PCT #4B 56.78 ℓ (15 gal) of heptane in two pans with a total area of 0.93 m^2 (10 ft^2) was burned. This test did not yield any useful data because the explosion relief doors of the burn enclosure activated due to the large initial pressure spike when the fire was ignited. PCT #4C was the same configuration as PCT #4B but with the relief doors strengthened. The HRR in this test reached ~1900 kW and is shown in Figure 27. This resulted in temperatures in and on the adjacent cabinet that were significantly higher than any tests with cable as the in situ fuel source. Adjacent cabinet temperatures from PCT #4C, Figure 28, show that the peak temperatures of 560°C and 275°C, for the cabinet wall and air respectively. The enclosure had a peak temperature of ~320°C. During all of these tests cabinet A was essentially at flame temperature.

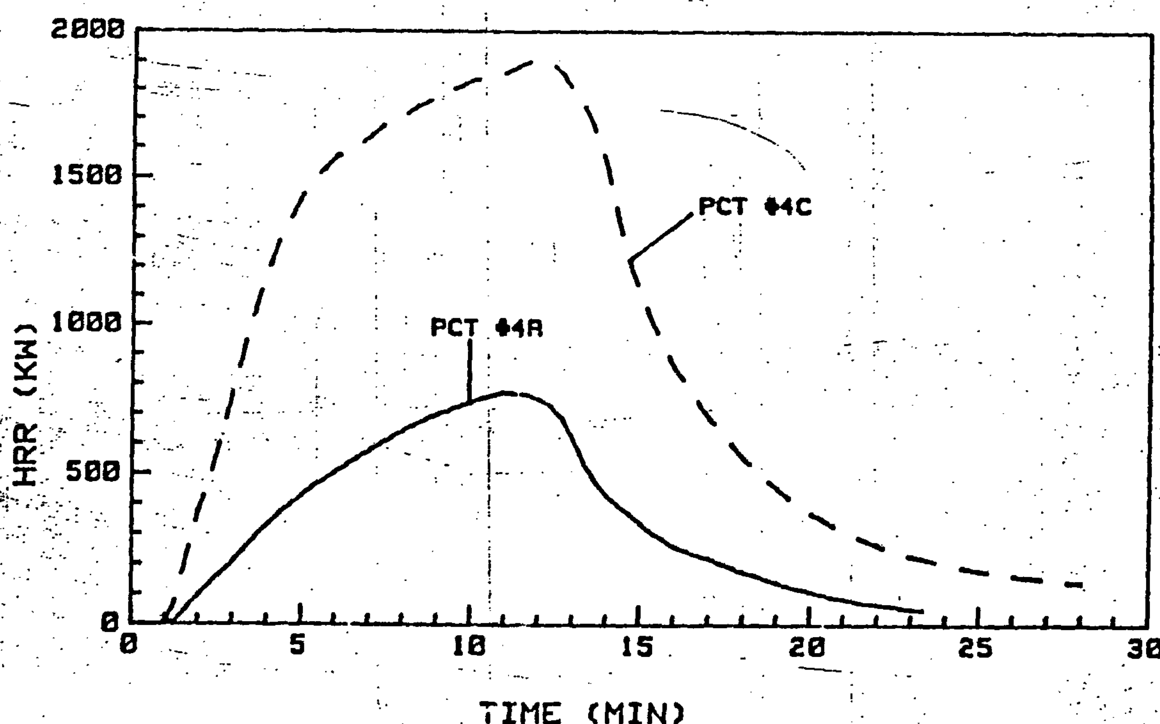


Figure 27. Heat Release Rate for PCT #4A and PCT #4C

Based on a comparison of PCT #4A, PCT #4C, and PCT #2, it appears that the heptane pool fires burn more intensely than cabinet fires with cable, in that even in the smaller (based on HRR) PCT #4A, the temperatures in the adjacent cabinets

and enclosure were significantly higher than in PCT #2. This is shown in Figures 29 and 30, which compare the adjacent cabinet wall and air temperatures for the three tests. Apparently, the larger flames in the pool fire result in the higher adjacent cabinet temperatures because of the radiant heat.

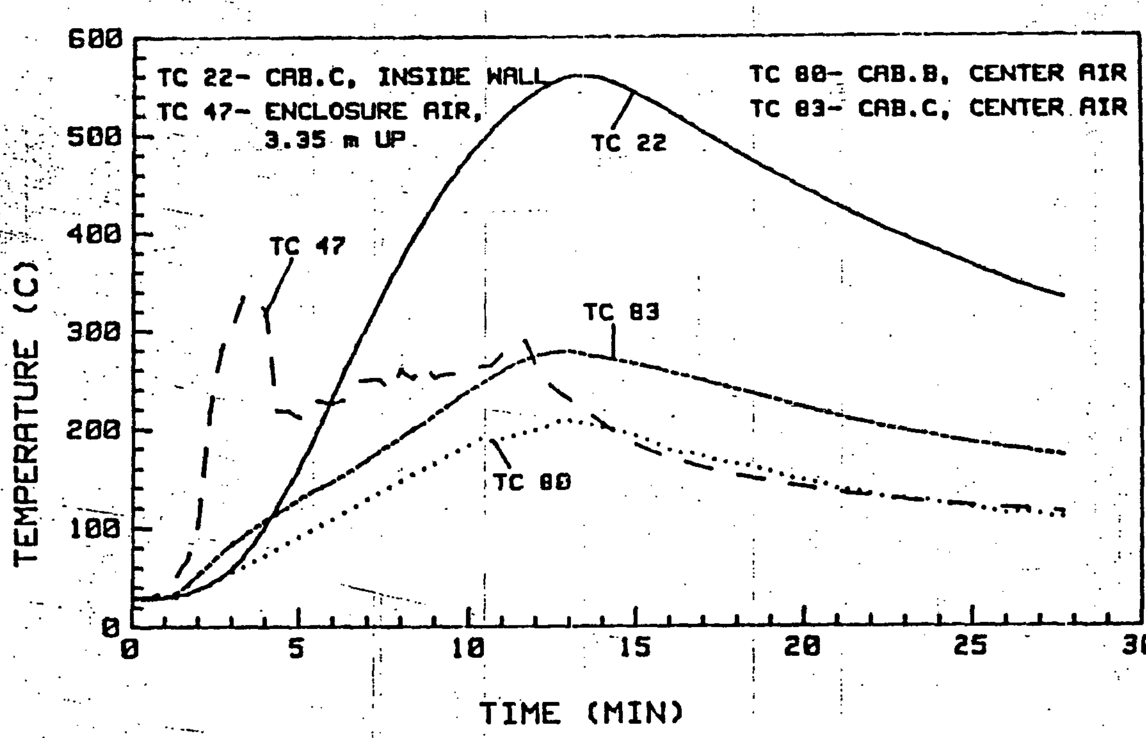


Figure 28. Adjacent Cabinet and Enclosure Temperatures for PCT #4C

The following conclusions are based on the pool fire test results and an analysis of the test results: (a) pool fires in cabinets and cable fires in cabinets burn significantly different, (b) based on the data and heat transfer calculations, it appears that the heat transfer mechanisms to adjacent cabinets are dominated by radiation from the cabinet walls, (c) it appears that a single cabinet alone, will most likely burn differently than a cabinet with adjacent cabinets due to the heat transfer mechanisms, and (d) calculations using the test data showed that cabinets with a single adjacent wall as opposed to a double wall with an air gap can result in temperatures on the adjacent cabinet wall and possibly in the adjacent cabinet air that could lead to melting or autoignition of combustibles. Although the pool and cabinet fires do not develop and burn the same, these tests have shown that single adjacent cabinet walls can result in thermal problems in adjacent cabinets.

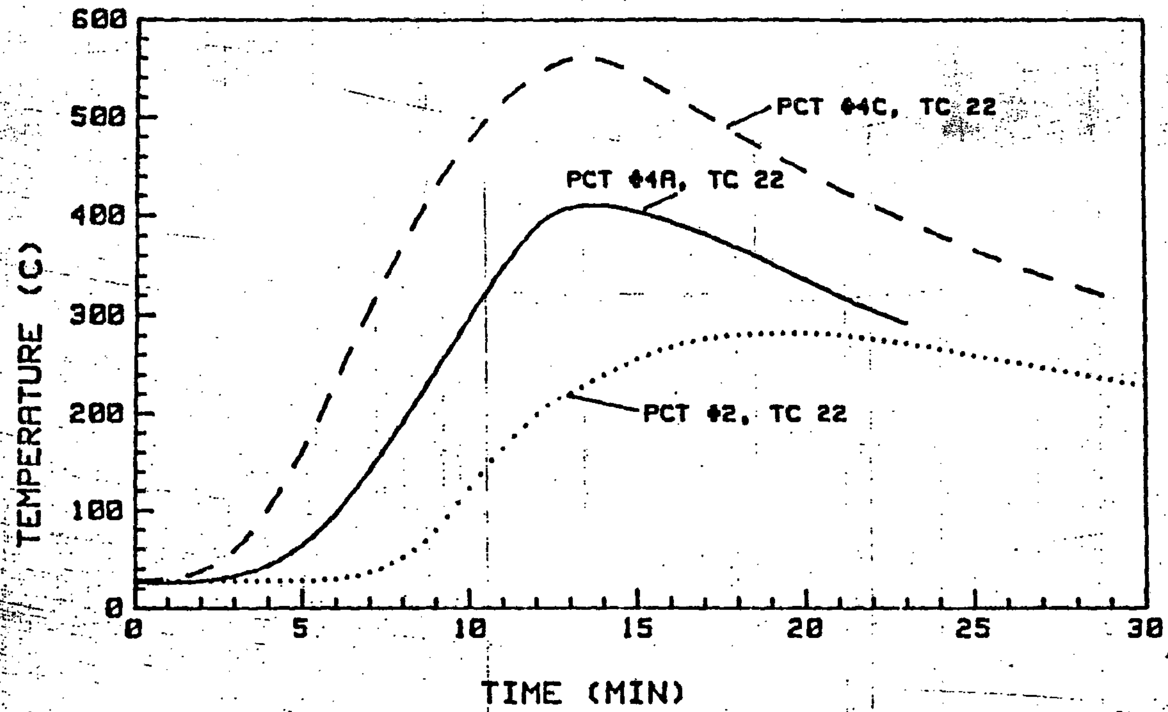


Figure 29. Adjacent Cabinet Wall Temperatures for PCT #2, PCT #4A, and PCT #4C

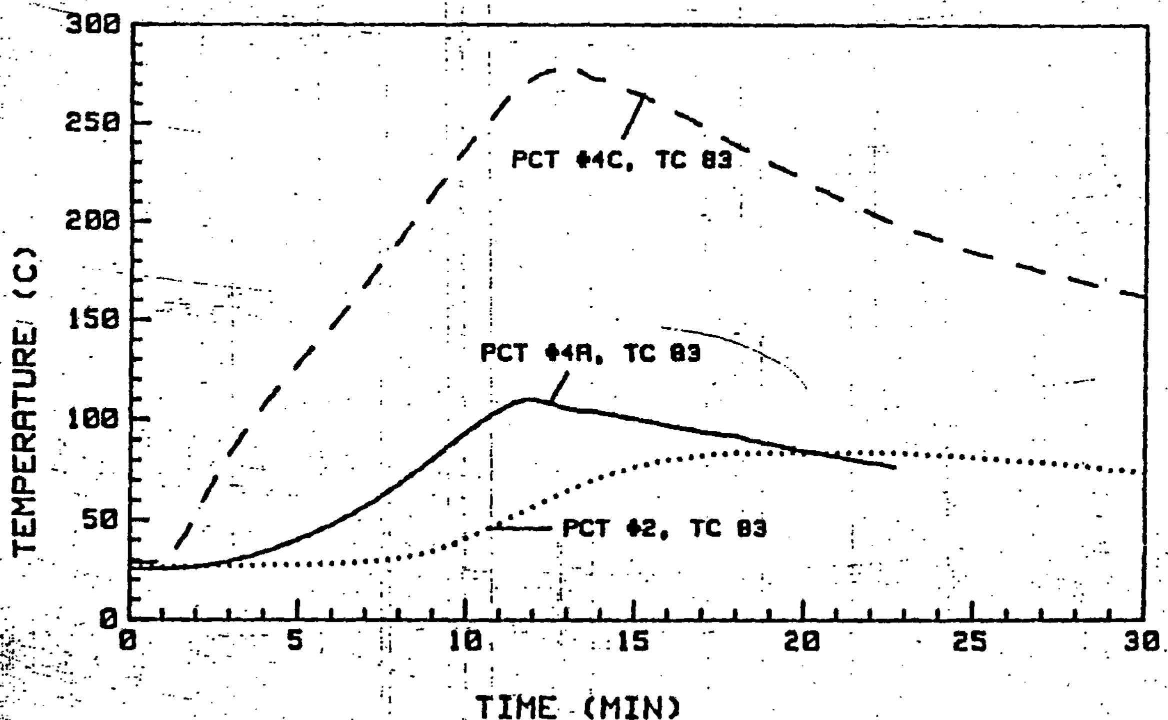


Figure 30. Adjacent Cabinet Air Temperatures for PCT #2, PCT #4A, and PCT #4C

3.3.2 Tests in Benchboard Cabinets

A total of two cabinet fire tests in benchboard cabinets were conducted as shown in Table 4. These two tests, one each with qualified cable and unqualified cable were conducted to investigate the way a fire in a benchboard cabinet would develop. A summary of the results from these tests are shown in Table 6.

Table 6

Summary of Results From the Benchboard Cabinet Tests

Test #		5	6
In Situ Fuel Type		UQ	Q
Peak HRR (kW)		791	215
Peak Temperatures (°C)	Room	210	115
	Adjacent Cabinet	100	35
Burn Duration (min)		20	35
Observations		Propagation of the fire, obscuration at 9 min	Propagation 1.22 m up, obscuration at 11 min

Preliminary Cabinet Test #5 (PCT #5) was conducted with unqualified cable as the fuel with a loading of ~1.5 x 10^6 kJ (1.42 x 10^6 Btu). A complete description of the test variables and a timeline showing the highlights of the tests are provided in Figure 31. A significantly larger fuel load than that used in previous tests was used in PCT #5 because the floor area of the benchboard cabinets was approximately 50 percent higher than that in the vertical cabinets. Consequently, the fuel loading was increased so that the fuel loading per cabinet floor area was the same as that used in PCT #2 and #3. The different cabinet geometry resulted in a higher percentage of cables located near the ignition source, as can be seen in Figure 32a. It should also be noted that, although it cannot be seen in Figure 32a, a large amount of fuel was loaded under the bench. A different manufacturer's

TEST #: PCT #5

CABINET TYPE AND SIZE: BENCHBOARD CABINET, 1.22 x 1.82 x 2.44 m (4 x 6 x 8 ft)

CABINET VENTILATION METHOD: ONE BOTTOM FRONT GRILL, OPEN BACK DOOR

CABLE TYPE: UNQUALIFIED CABLE (PE/PVC)

IN SITU FUEL LOADING: 1.519×10^6 kJ (1.44×10^6 Btu)
7.11×10^6 kJ/m^2 (6.26×10^5 Btu/ft^2)

IGNITION SOURCE: ELECTRICAL IGNITION APPARATUS

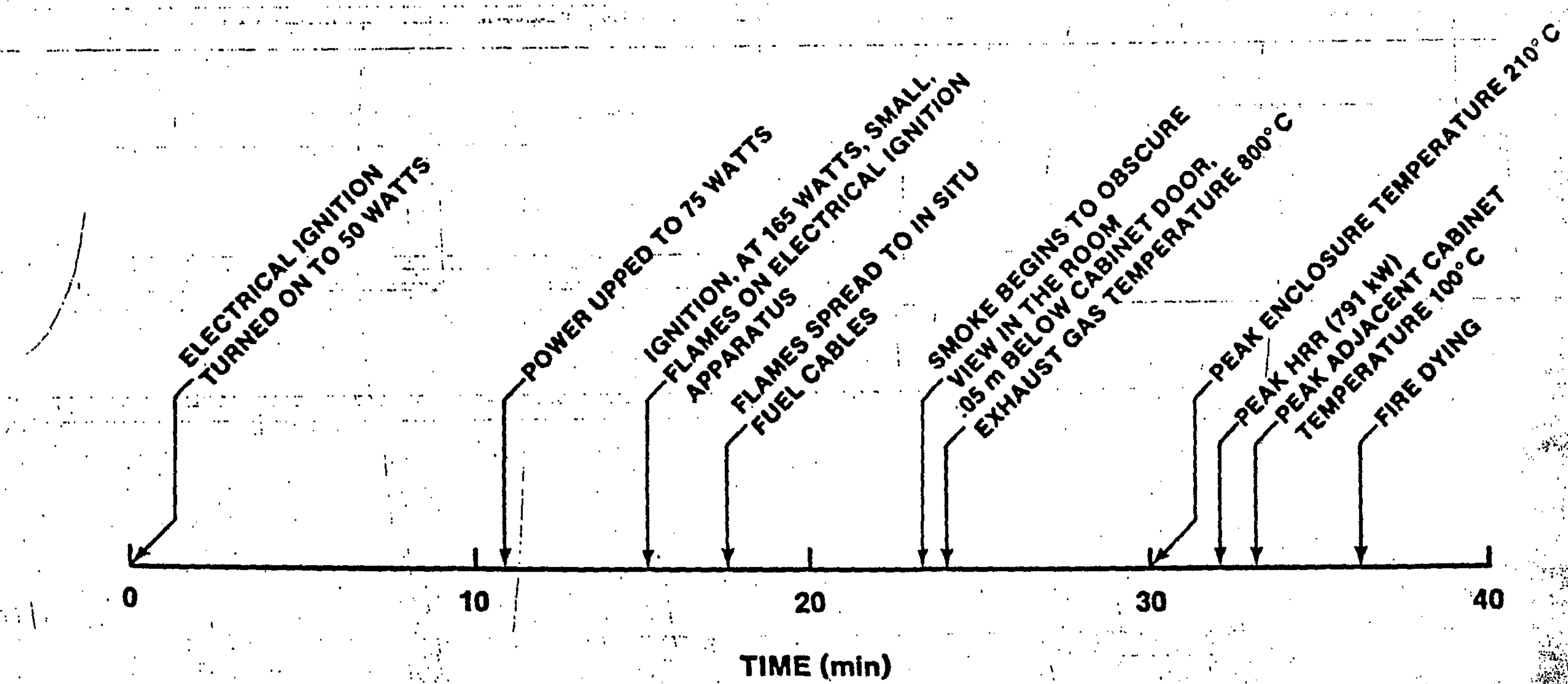


Figure 31. Description and Timeline for PCT #5

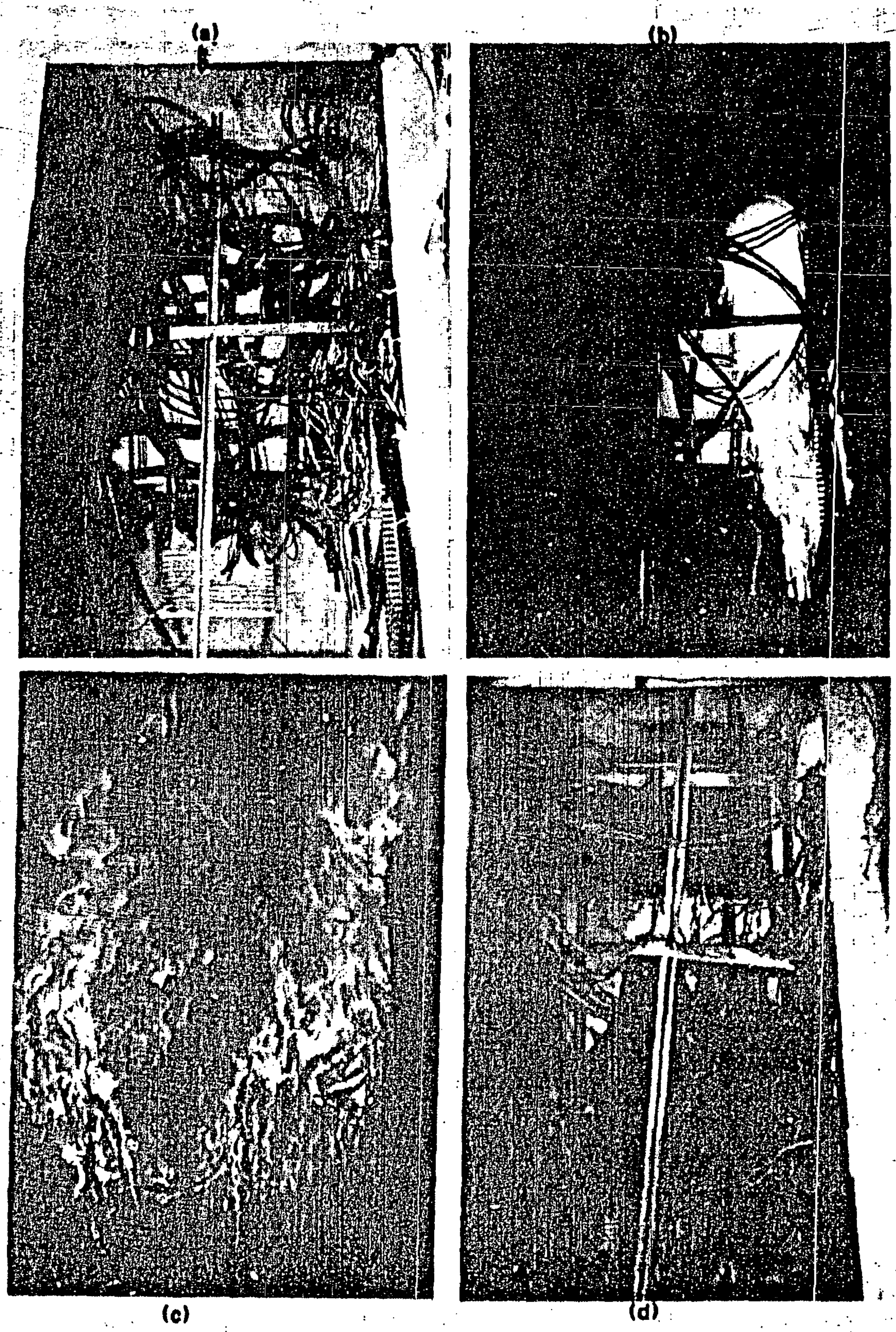


Figure 32. Photographic Sequence of PCT #5

(although the same composition, PE/PVC) cable was used in this test because the supply of the previous unqualified cable was exhausted. As can be seen in the photograph in Figure 32, a front ventilation grill and an open back door provided ventilation to the cabinet. The photographs in Figure 32 were taken through the open back cabinet door. Ignition of the in situ fuel in PCT #5 was provided by the electrical initiation apparatus described in Section 2.2.

Ignition of the fire occurred 15.33 minutes after the electrical initiation apparatus was turned on and occurred at a power of ~165 watts. All the subsequent figures for PCT #5 in which plots of the data are shown include the 15.33 minutes prior to ignition of the cables. Figure 32 shows a photographic sequence of this test. Figure 32b was taken at 4.6 minutes after ignition (19.6 minutes after the electrical initiation device was turned on), and Figure 32c was taken 10.7 minutes after ignition (26.3 minutes after test start). Although the photographs do not show it because of a light shining into the cabinet and the close range at which the pictures were taken, the smoke obscured the view of the cabinets from the front within 9 minutes after the ignition of the fuel.

In order to illustrate the resulting thermal environment that was produced by the the fire, a number of plots of the temperature in the burning cabinet, cabinet A, are shown in Figure 33. These thermocouples, TCs 89, 90, and 91, were located in the center of cabinet A at 0.61, 1.22, and 1.83 m (2, 4, and 6 ft) above the floor, respectively. As expected the temperatures at TC 91 are higher because of the air flow pattern in the cabinet and because the soffit of the cabinet door which results in a "hot layer" in the top of the cabinet, resulting in higher temperatures. This "hot layer" was ~1.22 m (4 ft) deep at the time of maximum HRR. It appears that there was burning in the top part of the cabinet and flames outside the cabinet were visible in some of the video replay; however, this observation is not conclusive because the temperatures of the combustion gases coming out of the cabinet are so high. The temperatures inside and on the walls of cabinet B and the enclosure temperature are shown in Figure 34. The adjacent cabinet wall temperatures (inside) reached almost 300°C while temperatures between the two cabinets were over 400°C. Also the adjacent cabinet center air temperature peaked at 100°C 30 minutes after the start of the test (15 minutes after ignition). The thermal environment in the enclosure as monitored by TC 47 shows peak temperatures of 235°C at 12 minutes after ignition of the fire, which was when the fire was burning most intensely.

The HRR for PCT #5 is shown in Figure 35 along with a plot of the total heat released. This figure shows a peak HRR of 784 kWs. The HRR climbed very quickly up to the peak and

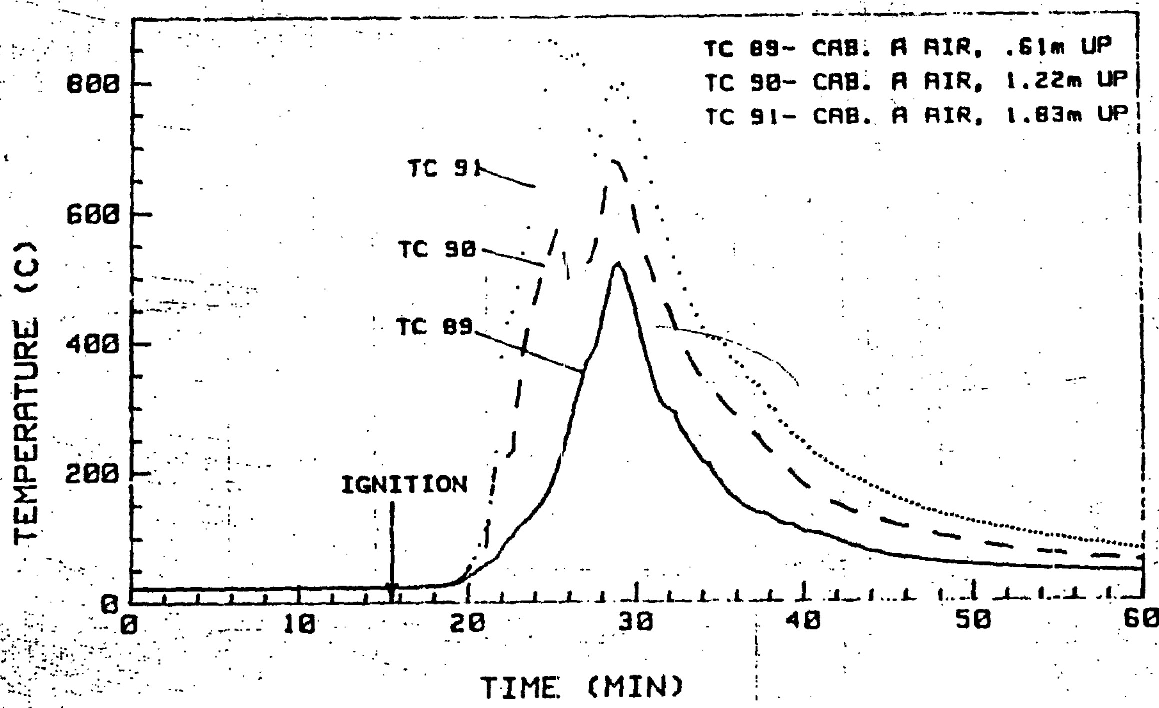


Figure 33. Temperatures in Cabinet A, the Burning Cabinet, PCT #5

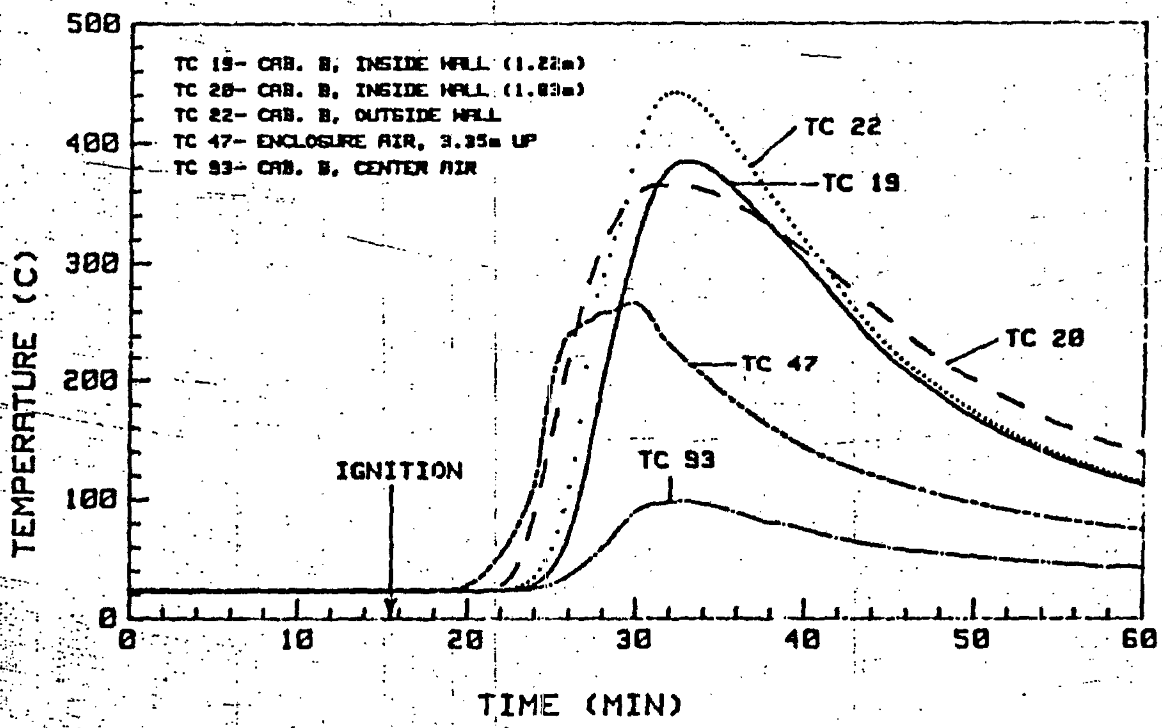


Figure 34. Adjacent Cabinet and Enclosure Temperatures, PCT #5

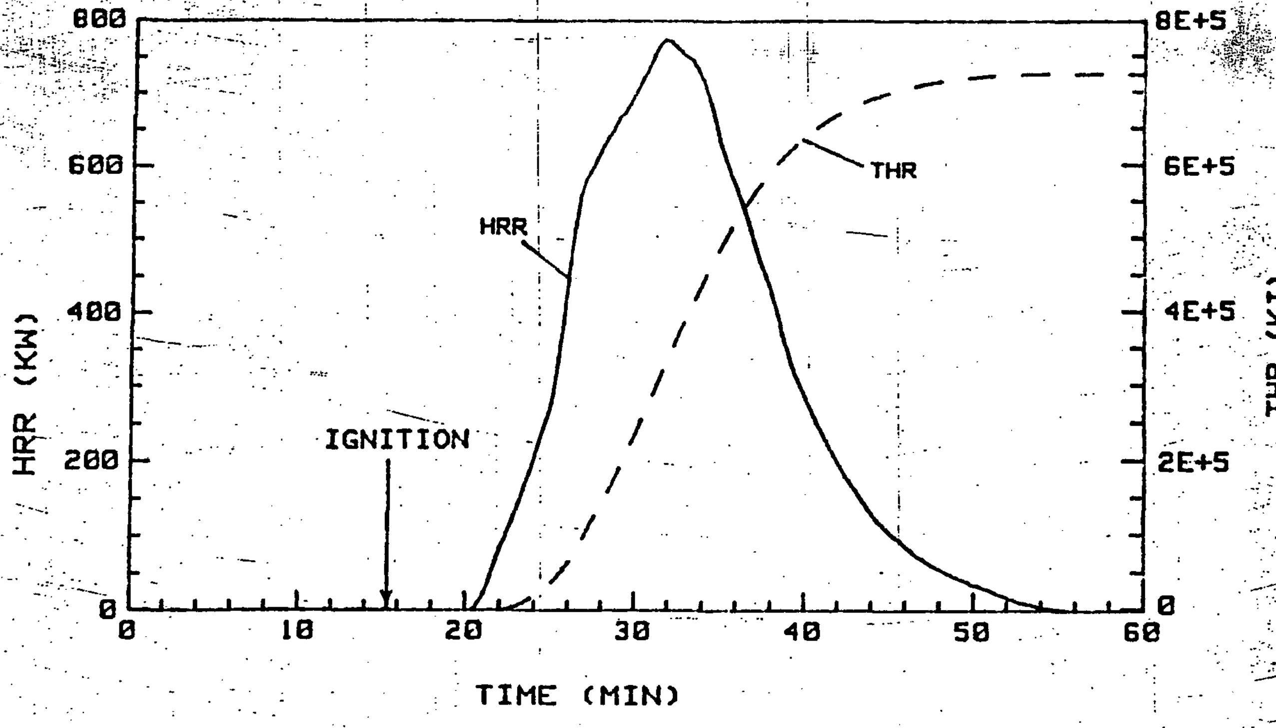


Figure 35. Heat Release Rate and Total Heat Released From PCT #5

then dropped off quickly, indicating that the fire burned very intensely for a short duration. Unfortunately, the mass data was lost during this test due to overheating of the load cells. Consequently, the mass loss rate and total mass lost are not known. However, using the HRR to calculate the peak mass loss rate, a peak mass loss rate of approximately 1.52 kg/min (0.6891 lb/min) occurred. The fire growth rate during the first 10 minutes after ignition was 71.9 kW/min, which is lower than that observed in PCT #2. The total heat released during this test based on HRR is 7.4×10^5 kJ (6.066×10^5 Btu) which is less than 50 percent of the fuel's potential heat of combustion. This percentage of combustion is less than was experienced for all the other tests with unqualified cable which appears odd because of the intense burning and because a posttest inspection, as shown in Figure 33d, revealed that all the cable insulation appeared to have burned. At approximately the same time as the HRR and temperatures peaked out in the test, 30 minutes after the start, the combustion gases also reached a maximum, with values for hydrocarbons, CO, and CO_2 of 6000 ppm, 6000 ppm and 0.7 percent by volume, respectively.

It is difficult to determine what effects each of the changes in the setup (e.g., cabinet style, ignition source, fuel

amount, and configuration) had in causing the different HRR (as compared to PCT #2), the lower than usual percentage of fuel combusted, and the short burn duration. However, the cabinet style had a significant effect because of the ventilation flow path (ventilation from both the front and back) the larger total amount of fuel in the cabinet and near the ignition source, and the soffit over the back door, which kept the hot combustion gases in the cabinet. Rather than the "hot layer" in the cabinet enhancing combustion in the cabinet, because of higher temperatures, it appears that it limited combustion due to a lack of oxygen, resulting in a lower amount of total heat released. The ignition source seemed to have little effect in changing the way the fire developed; it still ignited and propagated quickly as it would have with the transient ignition source. However, with the electrical ignition source there was a lengthy heat up period, and smoke was visible for approximately four minutes before ignition.

The manner in which the fire in PCT #5 burned is shown in Figure 36. The fire spread from the ignition source (just behind the bench) upward into the cables in the top part of the cabinet first, probably because of the hot combustion gases. Temperature measurements show that the top four feet of the cabinet were above autoignition temperature for unqualified cable [16] and some of the cables in the upper parts of the cabinet probably did autoignite.

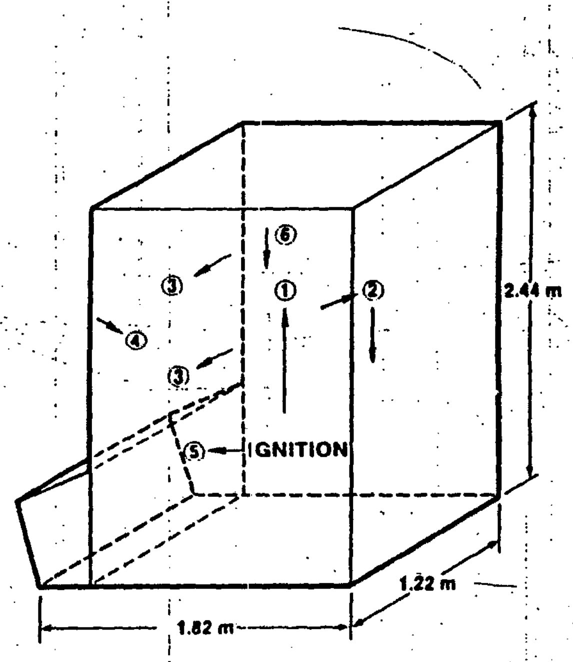


Figure 36. Burn Pattern for PCT #5

The thermal environment in the top of the enclosure and in the adjacent cabinets was severe enough to cause melting in some plastics. However, the one component that did fail in this test failed as a result of a large deposit of soot, not melting.[15] In addition, cable bundles located in the adjacent cabinet and the outside of the barriers (which experienced temperatures of >300°C) did show signs of melting, although there were no signs of possible autoignition in the cables. The cables were checked after the test, and although the insulators had melted together, there was no shorting of the conductors. This test demonstrated that a fire with unqualified cable in the configuration tested in a benchboard-style cabinet could be ignited with an electrical ignition source and propagate quickly throughout a cabinet. Furthermore, the fire can result in a severe (e.g., thermal and smoky) environment in the enclosure and adjacent cabinets that could cause additional problems.

Even though previous tests (ST #6 through 9 and PCT #3) had demonstrated that qualified cable (XPE/XPE) in a vertical cabinet would not propagate a fire, PCT #6 was conducted to investigate if a different type of qualified cable (HYP/XPE) would propagate a fire in a benchboard cabinet. The standard transient ignition source described in Section 2.2 was used along with 1.57×10^6 kJ (1.49×10^6 Btu) of in situ fuel. The test setup was very similar to PCT #5, although a different number of cable bundles were used because of the different cable weights. A complete description of PCT #6 and a timeline describing the highlights of the test are given in Figure 37. A picture of the fuel loading is shown in Figure 38a; as with PTC #5, the pictures were taken from the back of the cabinet.

The photographic sequence of the test is also shown in Figure 38b and c, taken at 12 and 51 minutes, respectively. Smoke began to obscure the view of the cabinets from the front of the enclosure within 30 minutes after ignition. In Figure 39, plots of air temperature measurements taken in cabinet A, the burning cabinet, are provided for TCs 17, 89, 90, and 91, which were located on the inside ceiling, and at 0.61, 1.22, and 1.83 m (2, 4, and 6 ft) from the floor, respectively. It is obvious from the plots that the upper part of the cabinet is hotter, due to the rising hot combustion gases that are kept in by the door soffit. However, the temperatures were not as high as those experienced in PCT #5 (see Figure 33), although the temperatures, in PCT #6, at the ceiling (this was not shown in Figure 33) and 1.83 m (6 ft) up were almost as high (TC 91, 700°C). It was not obvious from the video if there was burning in the top part of the cabinet; it appears that the temperatures were high enough to aid the fire in spreading by heating the cables in the top part of the cabinet and possibly causing autoignition. Figure 38d shows the cabinet after the fire.

TEST #: PCT #6

CABINET TYPE AND SIZE: BENCHBOARD CABINET, 1.22 x 1.82 x 2.44 m (4 x 6 x 8 ft)

CABINET VENTILATION METHOD: ONE BOTTOM FRONT GRILL, OPEN BACK DOOR

CABLE TYPE: IEEE-383 QUALIFIED CABLE (HYP/XPE)

IN SITU FUEL LOADING: 1.551×10^6 kJ (1.470×10^6 Btu)
7.26×10^6 kJ/m^2 (6.390×10^5 Btu/ft^2)

IGNITION SOURCE: PLASTIC BUCKET, BOX KIMWIPES, 0.946 ℓ ACETONE, 72,220 kJ (68,450 Btu)

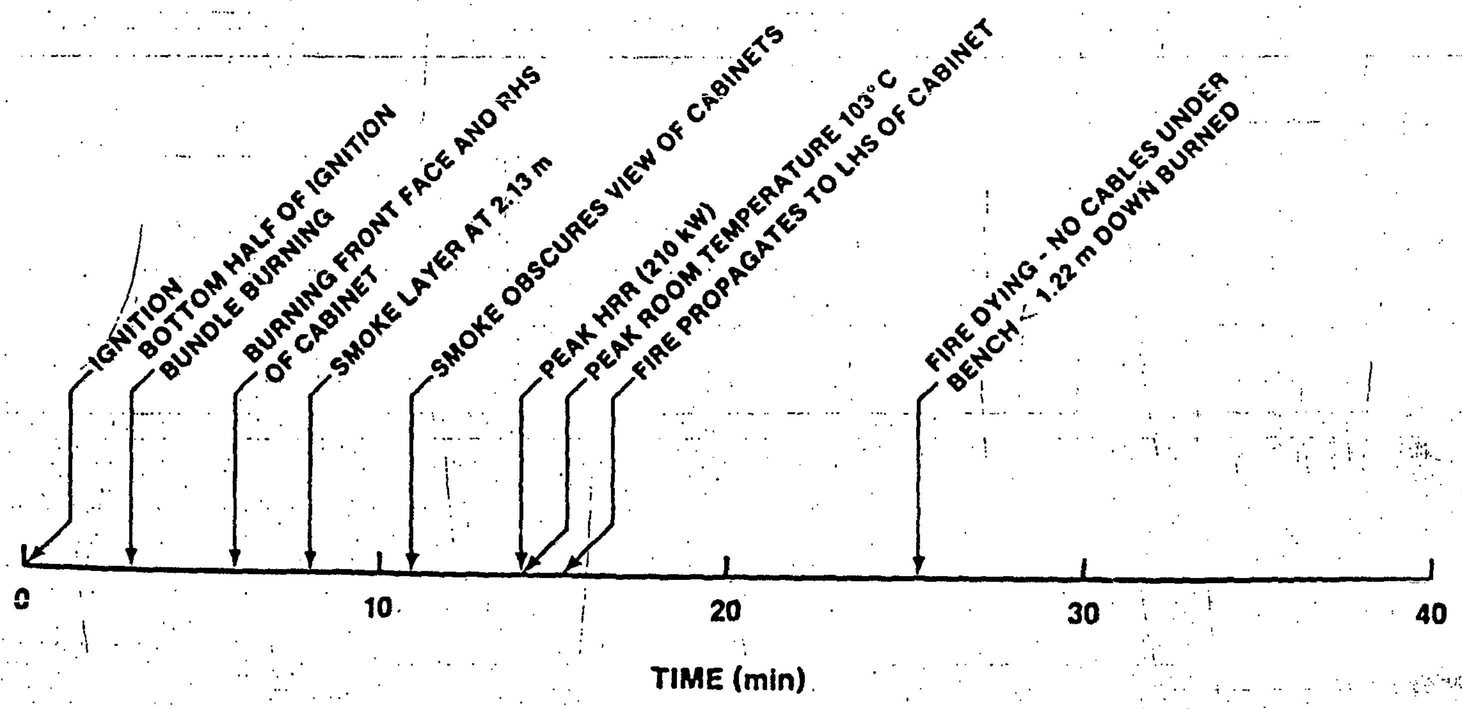


Figure 37. Description and Timeline for PCT #6

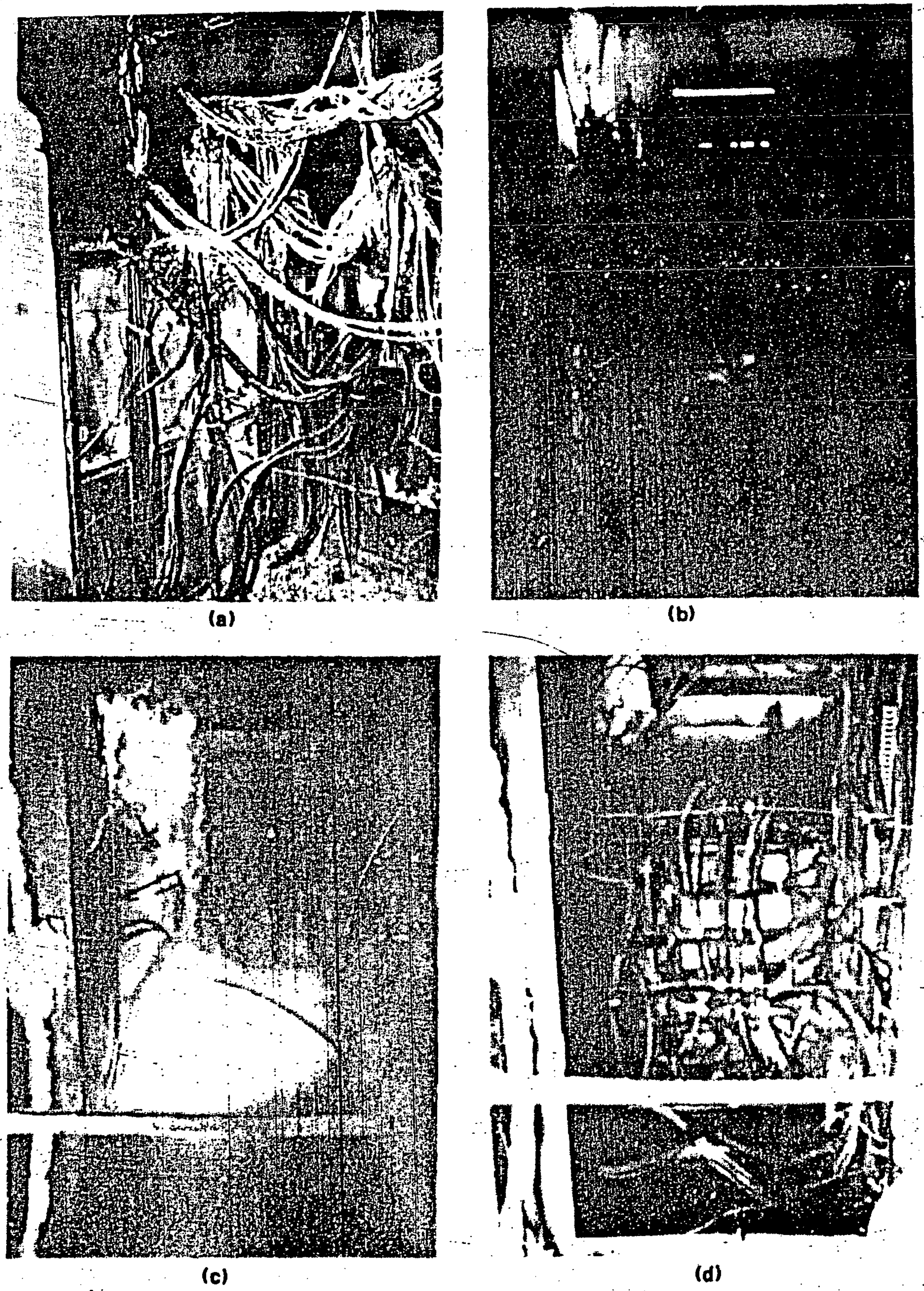


Figure 38. Photographic Sequence of PCT #6

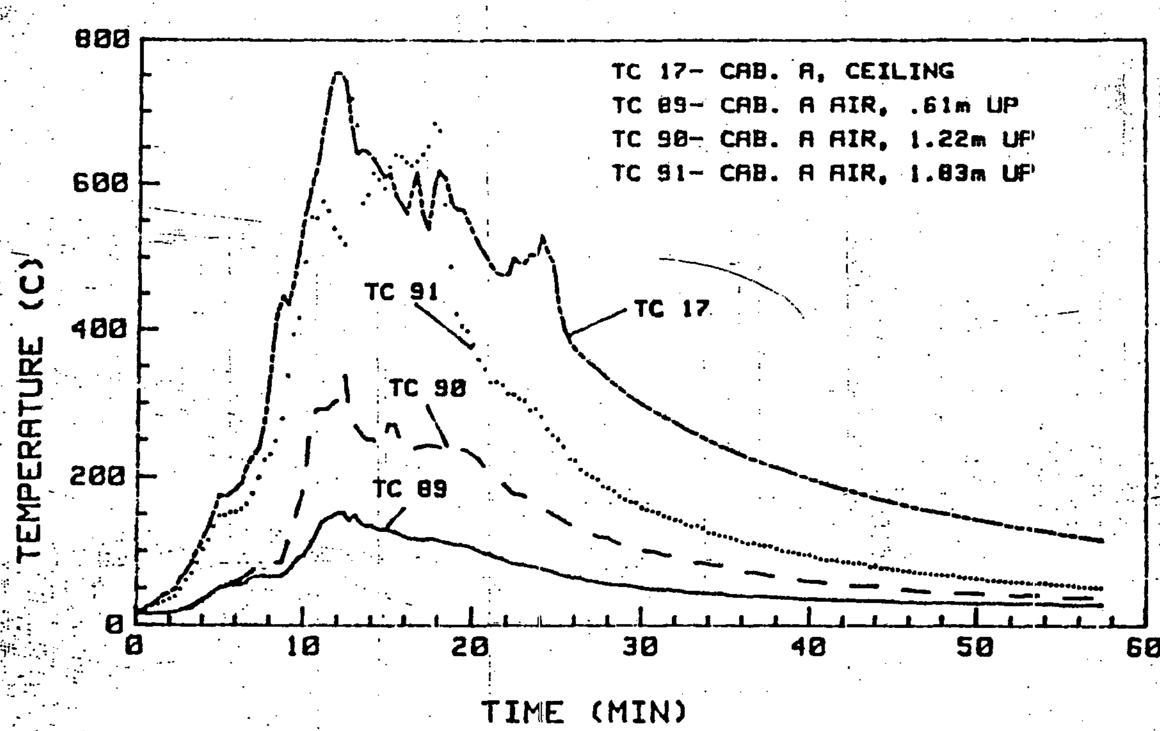


Figure 39. Temperatures in Cabinet A, the Burning Cabinet

Note that the fire only burned the cables 1.22 m (4 ft) and up, and the two bundles closest to the door were not burned.

Plots of the temperatures inside the adjacent cabinet and enclosure are shown in Figure 40. It is interesting to note that TCs 19 and 20, 1.22 m (4 ft) and 1.83 m (6 ft), respectively, on the inside of the adjacent cabinet wall have the same pattern as the air temperatures in cabinet A, indicating there was little burning in the lower part of cabinet A. The air temperature inside cabinet B as measured by TC #93 shows a peak temperature of 30°C (the ambient temperature at the start of this test was 15°C), while the peak enclosure air temperature was 35°C.

The HRR as calculated using oxygen consumption calorimetry, shown in Figure 41, reached a peak of 215 kW at 15 minutes after ignition. This HRR is significantly higher than that in any other qualified cable cabinet fire because the fire spread throughout the top part of the cabinet. The total heat released is also shown in Figure 41, with a total of 2.38×10^5 kJ (2.25×10^5 Btu) of heat released. This is only 15 percent of the calculated total fuel potential heat of combustion, while the mass loss data showed that 28.94 kg (63.67 lbs) of the total of 53.28 kg (117.22 lbs) of fuel were combusted, which is 54.3 percent of the fuel. The reason for the discrepancy could be that the heat of

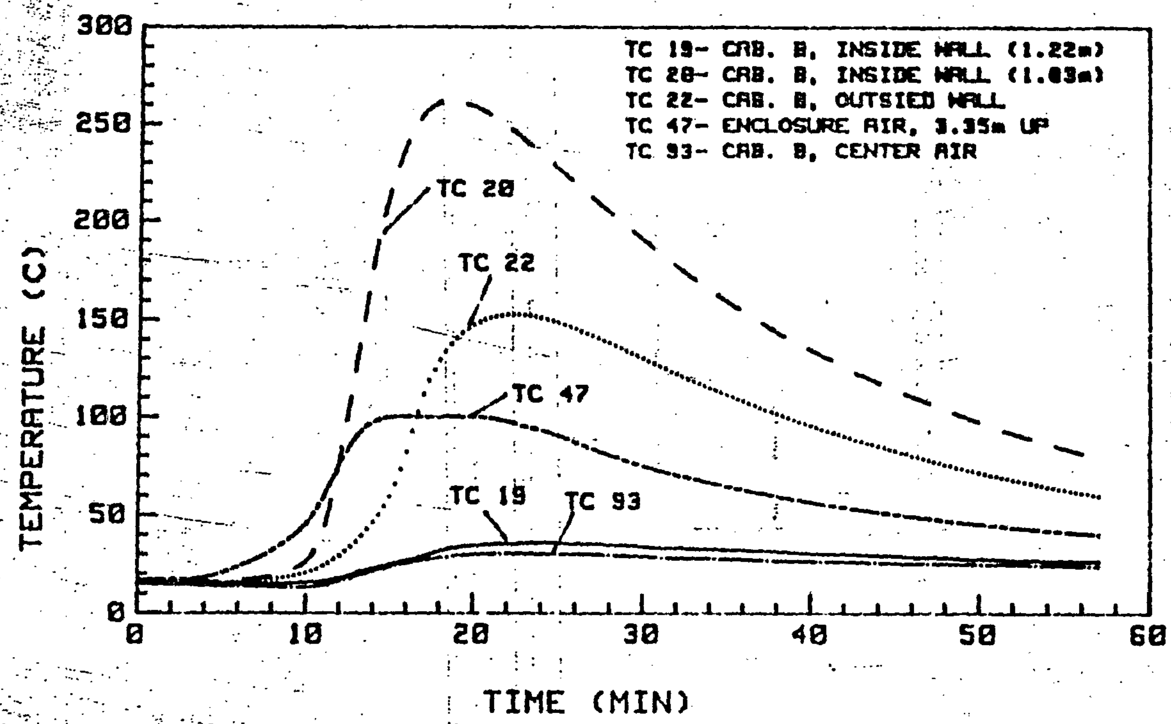


Figure 40. Adjacent Cabinet and Enclosure Temperatures, PCT #6

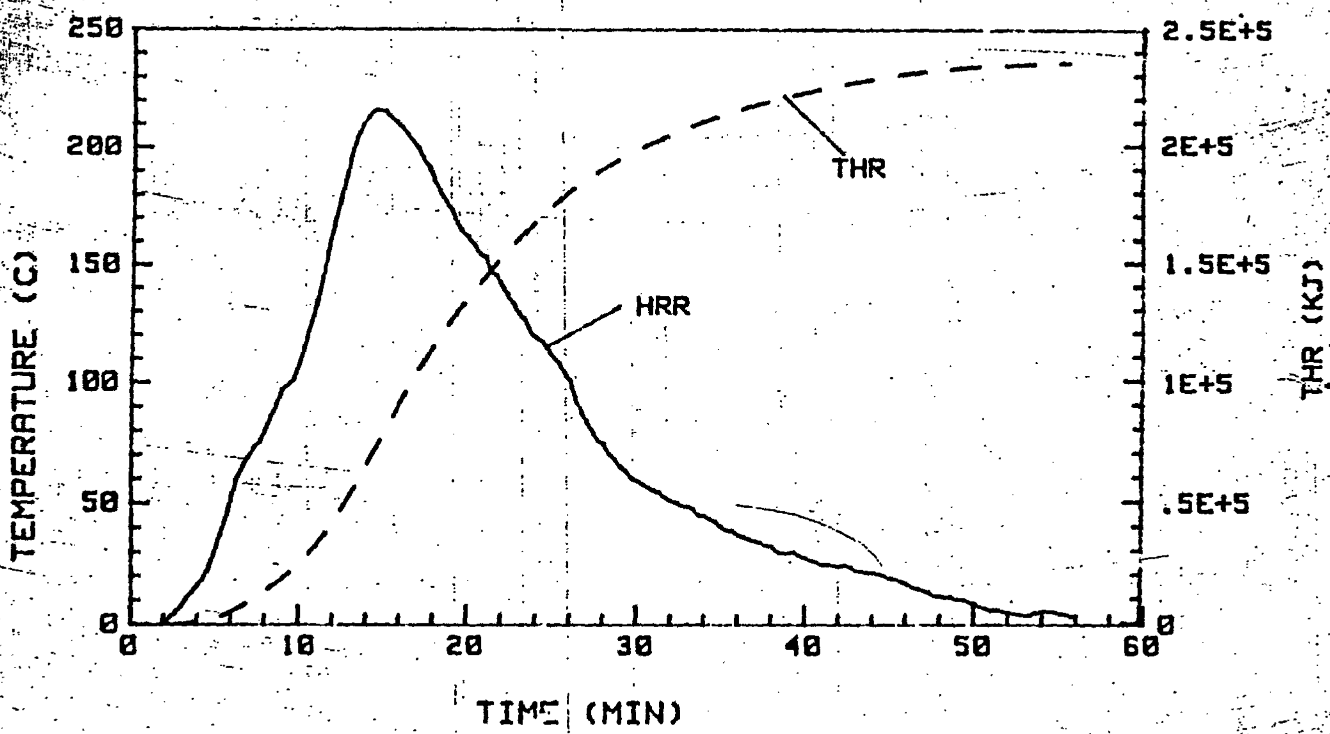


Figure 41. Heat Release Rate and Total Heat Released from PCT #6

combustion values selected to calculate the in situ fuel loading were too high, in which case the fuel loading in the cabinet was not as high as originally thought. The measurement of the combustion gases was not completed due to problems with the gas analyzer.

This test demonstrated that for this type of qualified cable in the test configuration, a fire can spread throughout a single benchboard cabinet, although the adjacent cabinets and the enclosure were not threatened by the fire, except for the smoke.

3.3.3 Summary of Results

A total of six Preliminary Cabinet Fire Tests were conducted as part of this test program to investigate the way an internally ignited cabinet fire will ignite and develop and its effect on adjacent cabinets and the enclosure. A summary of the results from these six tests is provided in Table 7. In all the tests with unqualified cable, the fire was easily ignited and propagated. However, with the qualified cable the fires were difficult to ignite and, except for the fire in the benchboard cabinet (PCT #6), the fires did not propagate. The one fire using the electrical initiation apparatus showed that a cabinet containing unqualified cable could be ignited by electrical overheating of a cable. In PCT #2 and #5 the enclosure temperatures were high enough to cause damage to cables or components located near the ceiling, while it appears temperatures in the adjacent cabinets were never high enough to cause problems. In all the tests, smoke buildup in the enclosure was an obvious problem. A discussion and interpretation of the cabinet fire test results is provided in the following section.

4. INTERPRETATION OF TEST RESULTS

4.1 Ignition of a Cabinet Fire

As stated at the beginning of this report, it was not the goal of the test program to evaluate if the ignition sources chosen to be used in the test program were credible, although through surveys and background studies, they are as credible as possible. Rather, it was to investigate if the selected ignition sources were capable of igniting a cabinet fire. In this test program only one transient and one electrical ignition source were tested. The three series of tests, Screening, Scoping, and Preliminary Cabinet Tests, demonstrated that ignition of the cabinet fire is dependent on three variables: (1) ignition fuel type, intensity and location, (2) in situ fuel type, and (3) in situ fuel geometry. Other test variables do not appear to play a significant part.

Table 7

Results of Preliminary Cabinet Tests at SNL

TEST #	CABLE TYPE	CABINET STYLE VENTILATION	IN SITU FUEL LOADING (KJ) [BTU]	PEAK HRR (KW)	BURN DURATION (MIN)	PEAK ROOM TEMP (°C)	TEST RESULT
PCT 1	UQ	Vertical Doors Closed	7.65×10^5 [7.24×10^5]	185	40	60	Propagation
PCT 2	UQ	Vertical Doors Open	1.05×10^6 [1.0×10^6]	995	15	160	Propagation
PCT 3	Q	Vertical Doors Open	1.05×10^6 [1.0×10^6]	56	25	50	No Propagation
PCT 4	N/A (Heptane)	Vertical Doors Open	56.78 ℓ, .929 m^2 pan [15 gal., pan 10 ft^2]	1900	20	300	N/A
PCT 5	UQ	Benchboard Doors Open	1.5×10^6 [1.44×10^6]	791	20	210	Propagation
PCT 6	Q	Benchboard Doors Open	1.53×10^6 [1.47×10^6]	215	35	115	Propagation 1.22m Up

The transient ignition source fuel tested was capable of igniting either type of in situ fuel, qualified or unqualified cable; however, a "critical" (i.e., a combination of parameters that makes up a configuration that will burn) in situ fuel geometry was necessary to ignite and propagate the fire in the cable bundle (ST #4 and 5). Furthermore, it appears that a critical ignition source amount is necessary, especially when igniting qualified cable. A slightly smaller transient ignition source was not sufficient to ignite and propagate a fire in the qualified cable (ST #1, 2, and 3), although it probably would have been sufficient to ignite unqualified cable.

The electrical ignition source employed in these tests was only used to ignite a fire in unqualified cable, PCT #5. It has been tested with qualified cable and appears capable of igniting and propagating a fire in qualified cable.[10] However, the capability of the electrical ignition source to ignite and propagate a cable fire in an actual test has not been demonstrated. The arrangement of the electrical ignition apparatus, as well the geometry of the in situ fuel were found critical to the ability of the electrical ignition source to ignite and propagate a fire.

Needless to say, the location of the ignition source is critical to the ignition of a fire as it must be near the in situ fuel and impinge upon the fuel for long enough to allow the fire to propagate. In these tests the ignition sources were placed in a corner or along a wall, which make the fire more intense (corner effects) than it would if it was in the center of a cabinet.

The second important variable in the ignition of a cabinet fire is the in situ fuel type. In this test program all in situ fuels were represented by cable insulation, primarily because cables make up the bulk of the in situ fuels. Three types of cable were tested, two qualified; an XRE/XPE and an HYP/XPE, and one unqualified PE/PVC. These tests (and other previous tests [17]) have shown that qualified cable is difficult to ignite and keep burning even under the optimal burning conditions. Direct flame impingement for a relatively long duration (ten minutes) is necessary to ignite and propagate a fire in qualified cable, while unqualified cable is relatively easily ignited and will propagate a fire.

In situ fuel geometry is the third variable affecting the ignition of a cabinet fire. This variable is very critical because if the in situ fuel is not in a "critical" geometry, the fuel may burn for a short time, but the fire will not propagate (ST #1 and 2). A cable bundle in a horizontal configuration is much less likely to propagate a fire, even if it ignited, than a vertical cable bundle, particularly with qualified cable. Furthermore, as some of the earlier Scoping Tests showed (ST #3), the cable bundles that were

wrapped very tightly and wire tied every 0.30 m (1 ft) were very difficult to ignite, again particularly with qualified cable, because the flames and air could not get to the inside cables. Therefore, the fire would not propagate. In addition, stripped cables were used in the area near the ignition source, because the smaller single conductors with insulation were easier to ignite and acted much like tinder would be in a wood fire in helping the fire to become larger. Stripped cables, however, are not uncommon in control cabinets.

Consequently, the tests revealed that there were three variables critical to the ignition of a cabinet fire, and that for the particular ignition sources, in situ fuel types and geometries, that cabinet fires can be ignited and propagated. However, no measure can be made or given that will assist in determining if a particular ignition source, in situ fuel, or fuel geometry is susceptible to a cabinet fire. All that can be said is that given the right conditions (i.e., sufficient ignition source, loose cable bundles, etc.), a fire can be ignited in a cabinet. It is the judgment of some people at Sandia, familiar with nuclear power plant cabinet installations, that the "right conditions" for ignition used in this test program do not vary widely from many of those found in actual power plant installations.

4.2 Propagation of a Cabinet Fire

4.2.1 Rate of Development

In evaluating the results of these tests, it appears that all the variables investigated have some effect on the development rate of the cabinet fire, although some variables (e.g., the ignition source) have a much less significant impact on the rate of development. In situ fuel type, amount, and configuration are large factors in the development rate. In addition, cabinet geometry appears to play a significant role in the fire development.

Often more than one variable was changed from test to test thus making it difficult to determine what effect each of the variable changes had on the development rate of the fire. Even though the electrical ignition apparatus was only used in one test, it does not appear that for the ignition sources tested that they have a significant effect on the rate of development (after the fire is ignited).

In situ fuel type obviously has a large effect on the development rate because qualified cable is made to be flame resistant and has passed IEEE-383 qualification tests, while unqualified cable has not passed IEEE-383 qualification tests. A measure of the rate of development is the derivative of the heat release rate. This is essentially the acceleration of the fire, but it is an indication of the growth rate of the fire. The growth rate during the growing

stage of the fire for PCT #2 (vertical cabinet, unqualified cable) and #3 (vertical cabinet, qualified cable) are 128 kW/min and 5.6 kW/min, respectively, while they are 71.9 kW/min and 16.5 kW/min for PCT #5 (benchboard cabinet, unqualified cable) and PCT #6 (benchboard cabinet, qualified cable), respectively. These growth rates show, ignoring other factors, that the fire with unqualified cable develops many times faster than a fire in qualified cable. In situ fuel amount is important to the development rate of the fire simply because with higher loadings, additional fuel is available and, for a given cabinet, fuel loadings are more dense to combust and therefore the fire can grow quicker and larger. The fuel amount was increased in PCT #2 (over that used in PCT #1); however, since the fuel configuration and cabinet ventilation were also changed, it is difficult to determine what part the increased fuel loading had in making the fire in PCT #2 develop so quickly. Fuel configuration is critical to the development rate of the fire, especially with qualified cable, because a fire will propagate up a vertical cable much quicker than a horizontal cable. Therefore, the more cables that are in a vertical or diagonal configuration, the more likelihood that the fire will spread. Furthermore, the way in which the cables are bundled is important to the development rate. The tighter a cable bundle is wrapped, the less air and flames can penetrate and burn the cables, and the slower the fire development rate will be. Also, in these tests, many of the insulators were stripped out of the cable, resulting in "tinder" for the fire to burn. This type of cable configuration is common in actual installations.

Cabinet geometry, more specifically the style of cabinet, had a significant impact on the rate of development of the fire, the potential for the fire to spread and ultimately the size of the fire. There are two differences in the geometries between benchboard and vertical cabinets that affect the fire development. They are the location of the ventilation and the size of the door soffit. On the vertical cabinets, all the ventilation was provided from the front, while with the benchboard cabinets, the ventilation was provided by the back door and by a ventilation grill in the front of the cabinet. Consequently, if a large enough fire developed, the benchboard cabinet could provide more ventilation; but more importantly, the front grill on the benchboard cabinet provides cooling air to the cables under the bench which could prevent burning. Also, cabinets with closed doors and ventilation grills or no ventilation grills can have a fire that will develop quickly up to a point, then the fire will become oxygen controlled and will no longer grow as in PCT #1. The door soffit is important because the temperature in the top part of the cabinet, the hot smoke layer that develops in the cabinet, appears to be dependent on the size of the door soffit. The vertical cabinets had a very small soffit; therefore, only a small smoke layer formed

in the cabinet. In the benchboard cabinet, the soffit was fairly substantial and a deep hot smoke layer formed in the cabinet which provides radiative feedback to the in situ fuel in the cabinet, thereby possibly increasing the rate of development; although the smoke layer also can slow the development rate (PCT #5) by reducing the oxygen content in the upper part of the cabinet. However, the fire growth rates for PCT #2 (vertical cabinet) and PCT #5 (benchboard cabinet) do not bear this out as they are essentially the same. This could be because the vertical cabinet was 25 percent smaller than the benchboard cabinet, thus providing additional radiative feedback and higher temperatures in the vertical cabinet.

The development rate of the fire is dependent on so many of the variables investigated that it is impossible to select one or two factors as critical to the rate of development. The tests have demonstrated, however, that given a sufficient ignition source and a "critical" cable amount and configuration, that a fire can rapidly propagate throughout either a vertical or benchboard style cabinet. Specifically, the tests conducted in this program have shown that a fire ignited with either source, in either style of cabinet, and with unqualified cable, can result in a rapidly developing and large fire. While fires with qualified cable can develop rapidly up to a point (PCT #6), they will not grow as rapidly nor as large as fires with unqualified cable. Another conclusion that can be made about the growth of the fire is that closed cabinet doors can prevent the fire (up to a point) from growing too large. However, this does result in higher temperatures within the closed cabinet which may result in "flashing" should the cabinet doors be opened.

A few of the regulations specified in IEEE-384 can have an effect on minimizing the development rate of the fire (e.g., barriers between cabinets, "canning components," and tying cable bundles at specific intervals), while other regulations specified (e.g., 6-inch air space) do little to impede or slow the development rate of the fire.

4.2.2 Fire Spread (Outside the Burning Cabinet)

The potential for the fire to spread within the burning cabinet is dependent on the growth rate of the fire and the variables discussed in the previous section. However, the potential for the fire to spread outside the burning cabinet is dependent on other variables as well as the fire growth rate and the variables discussed above.

Fire spread to an adjacent cabinet is very dependent on the location of the adjacent cabinet and on the barrier(s) between the cabinets. All the tests in this series were conducted with double walls (a wall for each cabinet) and an

air gap (~2.54 cm [1 inch]) between the cabinets. Actual nuclear power plant applications, where there are no walls (barriers) between cabinets, partial walls, or single walls as well as double walls, could result in very different situations. Also, the location of the adjacent cabinet (e.g, on the side or behind the burning cabinet) could also affect the potential for the adjacent cabinet in situ fuels to be ignited because of its proximity and the way it receives heat.

The tests in this series, with double walls, showed that the air temperature inside the adjacent cabinets, even in the largest fires (PCT #2 and #5), never got high enough to autoignite cables or components, although the adjacent cabinet wall did get hot enough to melt some cables. An analysis of the situation demonstrated that if the cabinets had shared a common wall (in the larger test fires), that the adjacent cabinet wall temperatures could have been high enough (600°C) to cause autoignition of cables on the walls even though the air temperature in the adjacent cabinet would not have been very high. It should be noted that even if the cabinet wall was high enough to result in autoignition, in situ fuel would have to be located on the wall to spread the fire from the burning cabinet to an adjacent cabinet. In addition, tests conducted with partial barriers in the cabinet showed that the barriers do little to prevent the spread of the fire (with unqualified cable).

However, one of the regulations specified in IEEE-384 will aid in preventing the fire from spreading from cabinet to cabinet by autoignition of materials on the cabinet wall. The regulation specifies that terminal blocks and wire ways are to be mounted at 2.54 cm (1 inch) from a barrier.

The likelihood for one of the cabinet fires tested to spread outside the cabinet to somewhere in the upper part of the room (e.g., a cable tray) is small. In none of the cabinet fire tests that were conducted was there any burning outside the cabinet more than half a meter (PCT #5). It should be noted that all the cabinets tested had solid metal tops with no penetrations. Cabinets with open tops or large penetrations could result in propagation above the cabinet, particularly for unqualified cables. Furthermore, the temperatures in the upper part of the enclosure were never higher than 235°C and that was in one of the largest fires (PCT #5). A similar fire in actual power plant rooms containing similar cabinets would probably be even less likely to propagate because of the larger room size. Therefore, in these tests there is no possibility for any materials in the "hot layer" to autoignite. Also, the enclosure in which these tests were conducted is smaller than most nuclear power plant rooms and the temperature in these tests was never even close to flashover temperature (600°C).

Consequently, although there is a potential for one of the larger fires to spread from cabinet to cabinet given a "critical" configuration, for the configuration and conditions tested, it was not a problem. Furthermore, for fires of the size tested, there is little possibility of the fire spreading to the room.

4.3 Development of the Enclosure Environment

The effects of the fire on the enclosure environment that were considered in this test program were the thermal effects and the smoke effects. The thermal environment was monitored, while the smoke environment was only visually observed (an attempt was made to measure smoke density with a smoke turbidimeter, but was unsuccessful because of the large amount of soot). All the variables that have been previously discussed have an effect on how the enclosure environment develops. In addition, the enclosure size, geometry, and ventilation rate are factors in the development of the enclosure environment. However, none of the three factors just mentioned were varied in this series of tests although they were varied in the subsequent test series (Room Effects Tests).[14]

For the variables and configurations that were investigated in this test series, the cabinet fires never resulted in a thermal environment that was a potential hazard for autoignition of materials in the enclosure. In many of the tests, cables and components were located throughout the enclosure.[15] Only in the case where a component was hung in the hot combustion gases above the cabinets or exiting the enclosure did a component become damaged (from melting). Although, as previously mentioned in PCT #5 (unqualified cable), some of the cables outside the burning cabinet did show signs of melting (with no shorting of conductors). Moreover, in the two tests (PCT #2 and #5) that resulted in large fires, the high temperatures only stayed above 200°C for a few minutes. As noted before, the test enclosure was smaller than most rooms of concern in nuclear power plants. Furthermore, the ventilation rate in these tests was approximately 15 room changes per hour (rm ch/hr), which is higher than would be found in most nuclear power plants. It appears that this higher ventilation rate would tend to push the smoke and heat out of the test enclosure.

The smoke environment in the enclosure was only visually monitored in the tests; however, it was obvious, in all the tests with unqualified and qualified cable, that the enclosure became filled with smoke within 8 to 15 minutes after ignition of the cabinet fire. It should also be noted that because of the high ventilation rate in the enclosure, the smoke was pushed out relatively quickly. Yet, the smoke still filled the enclosure. Although there is no quantitative data on the density and development of the smoke layer

(there is in the subsequent test series [14]), it is obvious that smoke can quickly obscure the location of the cabinets and the fire, making any operation very difficult. In addition, in one of the tests, sufficient smoke accumulated in the enclosure to cause one of the components in the enclosure to fail as a result of a large deposition of soot on the component.

Consequently, even in the relatively small test enclosure, the thermal environment in the enclosure from the resulting fires is not a concern and is not a threat to other equipment. It should be noted this statement is only about the fires tested. However, the smoke environment in the enclosure can become very severe within minutes, resulting in problems with fire fighting and with operator response. These tests also demonstrate that even ventilation rates above smoke-purge rate (typically about 10 rmch/hr) were not sufficient to prevent smoke accumulation in the enclosure.

4.4 Equipment Damage

Many components and cables were located in adjacent cabinets and in the enclosure to investigate the potential for damage. The results of the component damage investigation were reported by Jacobus [15] and therefore will not be discussed here. The cables that were placed on top of and inside of adjacent cabinets were inspected after the tests and in only one of the cases was the cable found to be melted (PCT #5). However, the cable jacket was only slightly melted and the the conductors were not shorted together. Therefore, in none of the tests would there have been electrical shorting of a cable outside the burning cabinet.

5. CONCLUSIONS AND RECOMMENDATIONS

As a result of the the three series of tests conducted as part of this test program, a number of conclusions can be made. The conclusions that are presented are related to the areas of concern that were raised at the beginning of the test program. Those concerns were about the development rate of the fire, the development of the room environment, and the potential for the fire to spread outside the burning cabinet.

The conclusions are as follows:

1. Cabinet fires can be ignited and propagate in either unqualified or qualified cable with either of the two ignition sources tested (transient and electrical). However, the qualified cable is much more difficult to ignite and propagate.

2. It is possible to have a rapidly developing cabinet fire with either type of cable as the in situ fuel

and in either style, vertical or benchboard, of cabinet. Although, fires with qualified cable do not become very large.

3. Ignition, development rate, and spread of a cabinet fire are dependent on "critical" (i.e., just the right combination of variables) ignition sources, in situ fuel type, geometries, and amounts, and on cabinet style and ventilation. These "critical" values are interdependent on many variables and therefore no "critical" values can be identified based on these tests. However, it was found that with unqualified cable, the range of values causing ignition and fire spread was much wider than with qualified cable.

4. For the enclosure conditions tested (i.e., enclosure size and ventilation rates), the thermal environment in the enclosure produced by the fires was not severe enough to cause autoignition of materials, but the thermal environment may be severe enough to cause equipment damage. Furthermore, it appears from these tests that a fire will not spread from the burning cabinet to adjacent cabinets. However, under different conditions (e.g., single wall, larger fires) a cabinet fire could cause autoignition in an adjacent cabinet and continue to propagate. A double wall barrier between cabinets appears to play a crucial role in preventing cabinet-to-cabinet fire spread during the larger cabinet fires.

5. For the enclosure conditions tested, dense smoke accumulation in the room became a problem within minutes after ignition, for all fuel types and cabinet configurations.

Essentially, the conclusion of the cabinet fire tests is that a cabinet fire can propagate within a single cabinet; however, for the conditions tested, it does not appear that the fire poses a threat outside the burning cabinet, except for the resulting smoke. Although this test effort involved realistic ranges of parameters, it must be recognized that other cabinet and fuel configurations may result in somewhat different findings. In addition, because of the influence of operation response and overall safety system performance, conclusions regarding cabinet fires causing difficulty in the ability of the plant to shut down cannot be made solely from the fire test data presented in this report.

It should be noted that in many of the Scoping Tests and all of the Preliminary Cabinet Tests the in situ fuel loadings (based on loading per square meter of cabinet floor area) were higher than that obtained in the background study. This was because fuel leadings in cabinets based on the background

study, when loaded in the cabinet appeared light (e.g., not a lot of cables in the cabinet).

Based on the findings of the Cabinet Fire Test Program it is recommended that the effectiveness of the following should be investigated:

1. Detection systems in cabinets;
2. Automatic gaseous suppression systems both inside and outside cabinets;
3. Manual suppression of cabinet fires;
4. Smoke control and purge systems;
5. Potential for fire spread in nondivided cabinets; and
6. Independence of remote shutdown capability.

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APPENDIX A

TEST FACILITY AND INSTRUMENTATION

A.1 Facility

The Sandia Burn Facility, located at Sandia National Laboratories, Albuquerque, NM has been used for a number of test programs associated with the Fire Protection Research Program. This was the facility to be used for the Preliminary Cabinet Tests. In Figures A-1 and A-2 schematic views and pictures of the test enclosure are presented. The Facility itself is an earth-covered bunker 15.24 m (50 ft) long, 7.32 m (24 ft) wide, and 5.49 m (18 ft) high in the center. This bunker has been partitioned into two enclosures, each 7.62 m (25 ft) long. The outer enclosure is used to house various instrumentation and data conditioning equipment.

The burn enclosure has a floor area of 55.74 m^2 (600 ft^2) and volume of 272 m^3 (9,624 ft^3). The burn enclosure has a system of ducts which provide inlet ventilation air through several vents located around the perimeter of the chamber. The ventilation air is forced from the outer chamber (which is vented to the external environment) and into the burn chamber. The inlet ventilation rate for these tests was approximately 70.79 m^3/min (2,500 ft^3/min) or the equivalent of 15 room air changes per hour. The burn chamber operates under a slight positive pressure during tests. Combustion products and through-flow air are vented out from the burn chamber through an opening in the top center of the burn chamber. This opening is connected to a 0.46-m (18-inch) diameter horizontal stack which houses instrumentation for analysis of the exhaust gases. Six windows with lights provide lighting and there is a port for a video recorder.

A.2 Instrumentation

A wide variety of instrumentation was used for measuring temperatures, heat fluxes, pressure losses, gas analysis, and heat release rates. The instrumentation is monitored by an HP3497A data acquisition unit and an HP216 computer system capable of handling up to 100 channels. Typically during these tests data was taken at 20 second intervals. The following instrumentation was employed in the testing.

Heat release rates (HRR) were measured indirectly through use of oxygen consumption calorimetry. This system for measuring oxygen, temperature, and velocity of the effluents was incorporated into the exhaust duct of the facility. The concentration of oxygen in the exhaust gas was monitored through a Beckman model 755 paramagnetic gas analyzer. Ventilation flow rates were monitored through the use of pressure probes in both the inlet and outlet flow streams. These pressure readings were converted to velocities through the Bernoulli equation for fluid flow, and in turn to volume flow rates through the cross sectional area. (Traverses of both

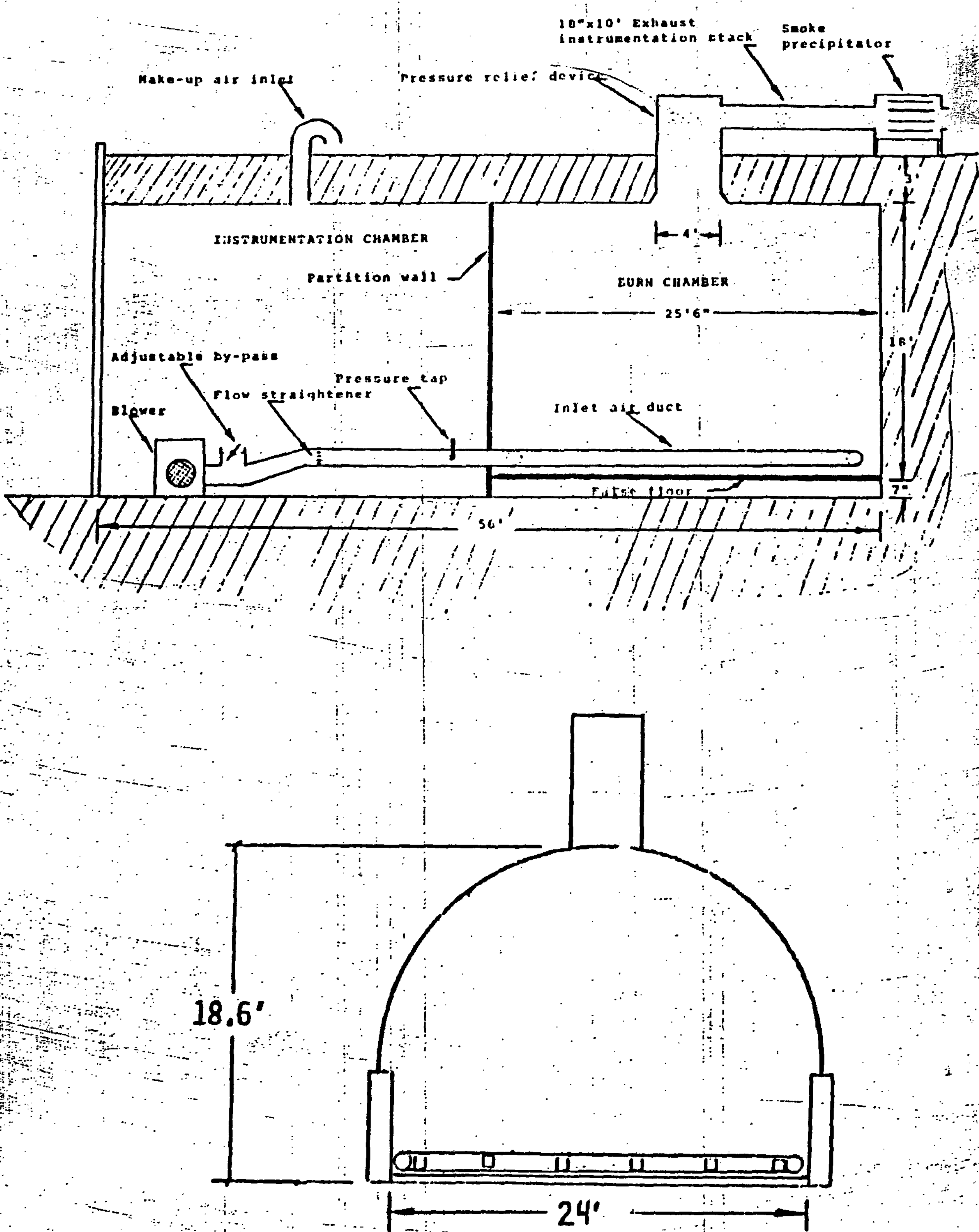


Figure A-1. Schematic of the Fire Test Facility

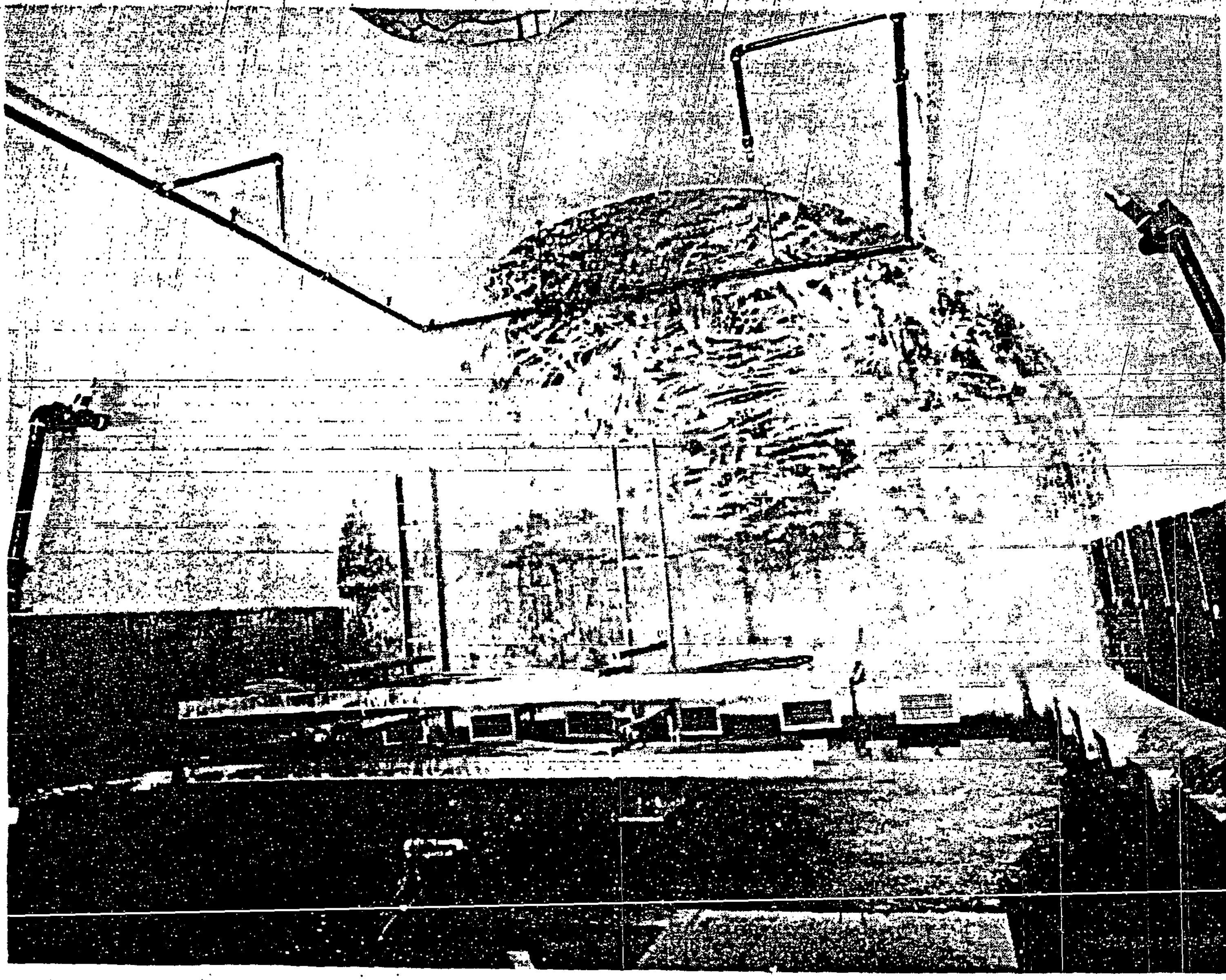


Figure A-2. Photograph of the Entry Into the Test Enclosure

the inlet and exhaust ducts were conducted to ensure that velocity readings were representative of average values.)

Enclosure gas temperature measurements were made with a series of 20 sheathed thermocouples, Type K, 0.05 cm (0.02 in), located in the upper part of the enclosure at 3.35 m (11 ft) and 4.57 m (15 ft) as shown in Figure A-1. These measurements were used to characterize the development of the enclosure environment.

The concentrations of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), and oxygen (O_2), were continuously monitored in the exit duct by gas analyzers. All the analyzers were supplied by Beckman Instrumentation Co. The CO and CO_2 analyzers were nondispersive infrared analyzers, model 865, while the hydrocarbon analyzer was a model 400 flame ionization detector, and the O_2 analyzer was a paramagnetic analyzer.

Surface temperatures were measured with thermocouples placed on the cabinets (faces, sides, backs). In addition, the air temperatures in the burning cabinet and adjacent cabinets were monitored. All thermocouples used for surface and air temperatures were Type K, 0.05 cm (0.02 in) sheathed type. The locations of the 60 thermocouples on and in the cabinets varied depending on the test being performed.

Heat flux measurements, both convective and radiative, were made using Hy-Cal water cooled calorimeters capable of measuring 340.67 $kJ/m^2 \cdot sec$ (30 $Btu/ft^2 \cdot sec$) placed at 0.61 m (2 ft) and 3.05 m (10 ft) from the burning cabinet. In addition, calorimeters were located in the burning cabinet. Fluxes of particular concern are those from the fire to the adjacent and separated cabinets, and the flux from the hot layer to the cabinets.

Small components and other combustible materials (i.e., other cables) were placed at different locations in the test enclosure for qualitative assessment of damageability of those components or sources. These items were also instrumented for surface temperature measurement, and some were powered and monitored for functionality.

Source cabinet mass loss rates were monitored for all cabinets with an in situ fuel loading. Cabinet weights were on the order of 681.82 kg (1500 lbs). Total mass loss of approximately 45.45 kg (100 lbs) was expected. Note that the three cabinets in each test were required to be independent for weighing. Interface and Celesco load cells were used for this purpose and were attached to the bottom of the cabinet.

Static pressure measurements were made in the lower part of the test enclosure. The pressure measurement was located in

a stagnant region of the enclosure. Smoke density measurements were made in the exit duct in some of the cabinet fire tests using a smoke turbidimeter. However, due to the design of the turbidimeter and the path length, no good measurements were acquired.

APPENDIX B

CABINET SCOPING TESTS

B.1 Purpose

The purpose of the Scoping Tests (ST) was to evaluate the ability of the selected ignition source fuels to ignite and propagate a fire in a cable bundle in a cabinet. In addition, these tests were to aid in selecting credible in situ fuel amounts and configurations. Since these are "scoping tests," they were performed with a minimal amount of equipment and instrumentation for quick test turnaround time.

The Scoping Tests were not pass/fail type tests because it was not necessarily a failure or a pass when the ignition source did not ignite the cables. The criteria for evaluating the tests varied from test to test depending on what new requirements were set. Basically, the tests were evaluated to determine if the ignition source fuel ignited the in situ fuel (cable bundle) and if the fire propagated within the cabinet.

All the Scoping Tests were conducted with the transient ignition source fuel packet which was selected in the Screening Tests (described in a separate test report [1]). No Scoping Tests were conducted with the electrical ignition source apparatus as it was unavailable at that time.

This appendix focuses primarily on the results of ST #6 through 11, as the results of ST #1 through 5 were reported on at an earlier date.[1]

B.2 Test Setup

The test arrangement for ST #6 through 11 included the transient ignition source fuel packet, a nuclear power plant cabinet, 0.91 x 1.22 x 2.29 m (3 x 4 x 7 ft), a pilot relighter and a propane pilot light, along with the cabinet in situ fuels (cables).

For ST #8, #10, and #11, the in situ fuel loads and configurations were based on surveys and pictures in an attempt to make them as representative of actual installations as possible. In ST #6, #7, and #9 smaller fuel loads were tested. First, the in situ fuel arrangement was placed in the cabinet in the desired configuration. Next, the cabinet and in situ fuel were instrumented (with thermocouples) and the transient ignition source was placed in the bottom right-hand side of the cabinet. Finally, the test was started when the ignition source fuel was ignited by the pilot relighter and propane pilot light.

The cabinet for these tests was located in the center of the Sandia Fire Test Facility. In addition to the thermocouples located in the cabinet, there were thermocouples in the

enclosure to monitor the enclosure environment. Also, calorimeters and pressure transducers were used to monitor heat fluxes and the pressure in the enclosure. A system of velocity probes, thermocouples, and gas analysis for indirectly measuring the heat release rate (HRR) was also employed.

The cables used as in situ fuel in these tests were an IEEE-383 qualified cable and an unqualified cable. The qualified cable was a 600 V, three-conductor, No. 12 AWG, cross-linked polyethylene (XPE) insulation with a cross-linked polyethylene jacket rated at 600 V. The unqualified cable was a 600 V, three-conductor, No. 12 AWG, polyethylene/polyvinylchloride (PE/PVC) with a polyvinylchloride (PVC) jacket rated at 600 V. The larger cable bundles in the cabinet were made up of smaller "standard cable bundles." The "standard cable bundles" were designated as #1s or #2s; the #1s were made up of 12 single conductors (with insulation) stripped out of the cable jacket, each piece 2.13 m (7 ft) long, while the #2s consisted of 3 cables (the 3-conductor cables) of wire tied together.

B.3 Discussion of Results

Table B-1, a matrix of the eleven Cabinet Scoping Tests, shows the parameters investigated and a brief summary of the results. The eleven tests can be broken down into three categories: (a) Scoping Tests #1 through 5 were performed to investigate the ability of the ignition source to ignite a cable bundle and the effects of location/arrangement of the in situ fuels. (These results are only shown in Table 1 for completeness and will not be discussed here.) (b) Scoping Tests #6 through 9 were cabinet fire propagation tests on qualified cable, and (c) Scoping Tests #10 and #11 investigated the in situ fuel amounts and configurations to be used with unqualified cable.

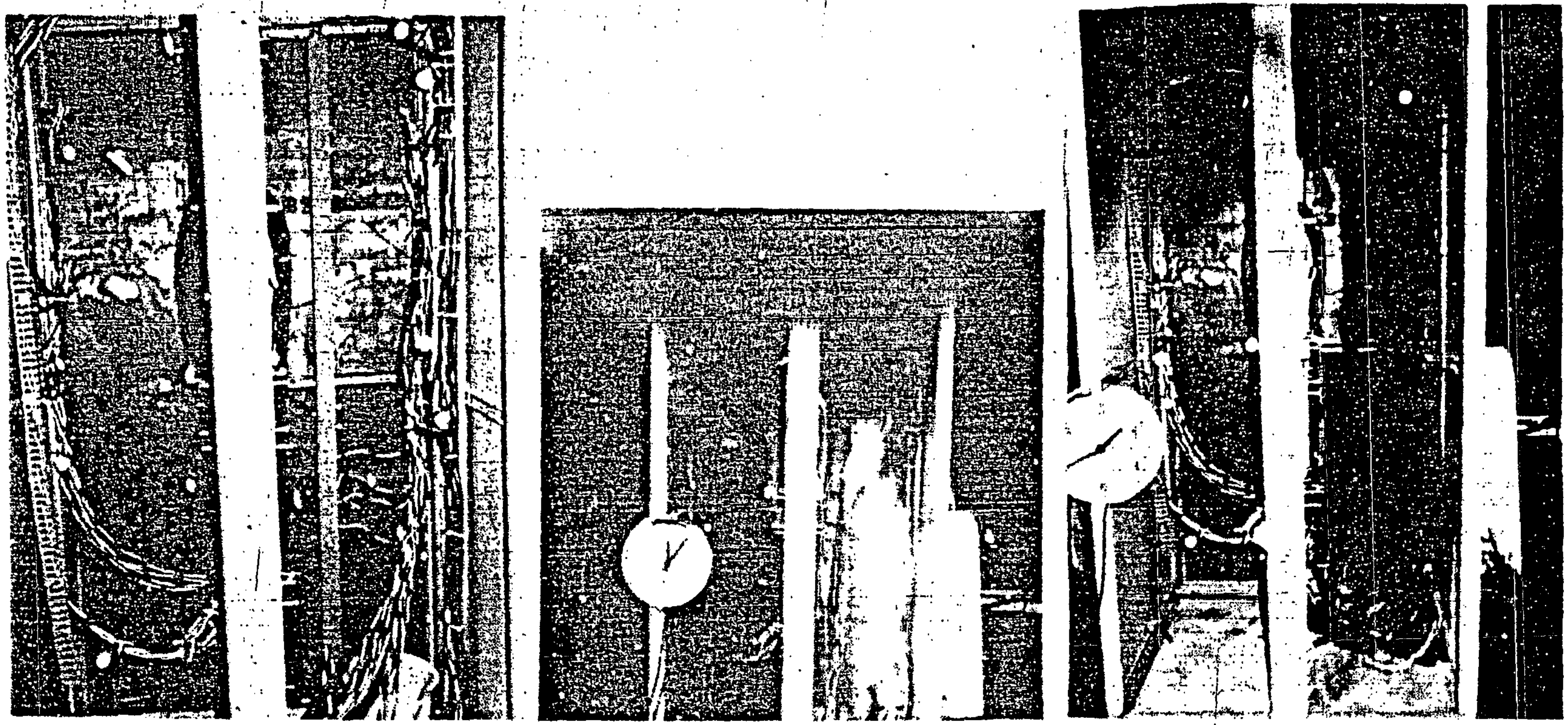
Scoping Test #6 was conducted to determine if a fire ignited in the corner cable bundle would propagate to other cable bundles in the cabinet. Figure B-1 shows "before," "during," and "after" pictures of ST #6. The in situ fuel in the cabinet is the qualified cable, with a total fuel load of 348,520 kJ (330,350 Btus). This is approximately 312,628 kJ/m^2 (27,530 Btu/ft^2). The fuel load in the cabinet is based on a survey of four different sources shown in Figure 1 of this report. The loading in the cabinet appeared to be light (i.e., compared to photographs of actual cabinet fuel loads, this test cabinet does not appear to be heavily loaded). The test was run with no doors on the cabinet in order to ensure adequate ventilation. The fire was ignited using the transient ignition source. Only the cable bundle directly above the ignition source (the main bundle) burned completely. The bundle to the left of

Table B-1

Matrix of Scoping Tests

Test #[a]	Cable Type	Amount of In Situ Fuels[b,c] (KJ)	Cabinet[d] Ventilation Method	Peak HRR (KW)	Intense Burn Duration (min)	Test Result
ST1	Q	117,000	No doors	24	15	Bundle did not burn
ST2	Q	117,000	No doors	27	17	No propagation
ST3	Q	117,000	No doors	77	18	Entire bundle consumed
ST4	Q	117,000	No doors	82	17	Almost entire bundle consumed
ST5	UQ	117,000	No doors	132	17	Entire bundle consumed
ST6	Q	348,500	No doors	82	25	No propagation
ST7	Q	348,500	Doors closed	95	25	No propagation
ST8	Q	582,875	Doors closed	93	30	No propagation
ST9 barriers	Q	234,990	Doors open	74	20	No propagation
ST10	UQ	611,530	Doors closed	280	30	Propagated All burned
ST11	UQ	611,530	Door open	506	20	Propagated All burned

[a] Standard ignition source was 1 qt Acetone, 2.5 gallon polyethlyene bucket, and 16 oz. box of kimwipes - Scoping Tests 1 and 2 differed slightly in that only 1 pint acetone was used.
[b] Excludes ignition source.
[c] All tests performed in 0.91 m x 1.22 m x 2.29 m (3 x 4 x 7.5 ft) cabinet.
[d] In tests with closed doors, ventilation is provided through ventilation grills.



(a) (b) (c)

Figure B-1. Photographic Sequence of ST #6

the main bundles was damaged but not severely burned; however, the cover to the plastic wireway deformed and fell into the fire. There was no horizontal propagation of the fire in any cable bundles. Soot was deposited on the cables in the top left-hand side of the cabinet; yet, they were not damaged. The Heat Release Rate (HRR) produced by this fire is shown in Figure B-2.

In ST #7 the in situ fuel cable, configuration, and fuel load amount were exactly the same as in ST #6. The only difference in this test was that doors were put on the cabinet. The doors each had two ventilation grills, one near the top of the door and the other near the bottom. The reason for putting the doors on and closing them during the test is that it was assumed that the closed doors would produce higher temperatures in the cabinet which might contribute to the propagation of the fire. Again, only the main corner bundle above the ignition source was completely consumed. In Figure B-3, two "before" pictures and one "after" picture of ST #7 are shown. The cover of the plastic wireway to the left of the main bundle fell into the fire. There was, however, a higher level of soot deposition (as compared to ST# 6) on the cabinet walls and cables in the top of the cabinets. Also, the cables in the top of the cabinets showed slight degradation and discoloration; yet, no cables but the main bundle burned. There was no horizontal propagation of the fire. The HRR plot of this test is shown in Figure B-4.

Because the fuel loading appeared light [2] (e.g., not many cables in the cabinet) in the two previous tests, the fuel loading was increased in ST #8. The in situ fuel was qualified cable, with a total fuel load of 582,875 kJ (552,450 Btus). This is approximately 522,827 kJ/m^2 (46,040 Btu/ft^2). The fuel loading and cable configuration in this test were based on pictures of actual NPP control room cabinets. This test was run with the cabinet doors closed as in ST #7. The "during" picture, shown in Figure B-5, shows the highest smoke output rate during the test. The smoke level in the cabinet never descended further than 1.22 m (4 ft) below the cabinet ceiling. The room did not fill with smoke. As in all other tests, the main cable bundle directly above the ignition source burned. In addition, the cable bundle and the plastic wireway to the left of the main bundle burned. However, no other cable in the cabinet burned. There was significant heat and smoke damage to the cables in the top of the cabinet and to those on the left-hand side of the cabinet. It was assumed that the higher fuel loading with the closed cabinet doors might enhance the potential for the fire to propagate; however, this was not observed. The HRR for ST #8 is shown in Figure B-6.

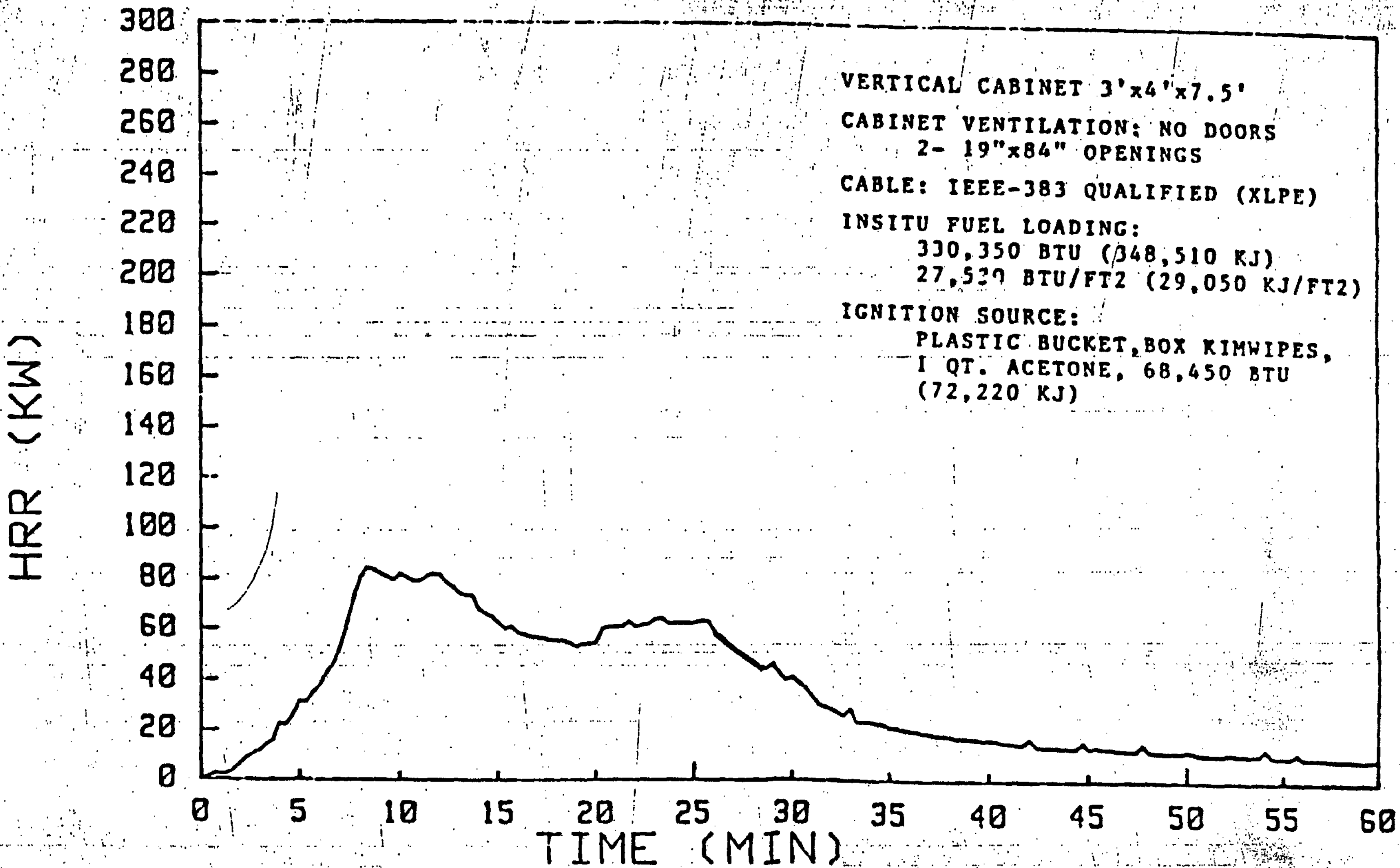


Figure B-2. Heat Release Rate From ST #6

(a) (b) (c)

Figure B-3. Photographic Sequence of ST #7

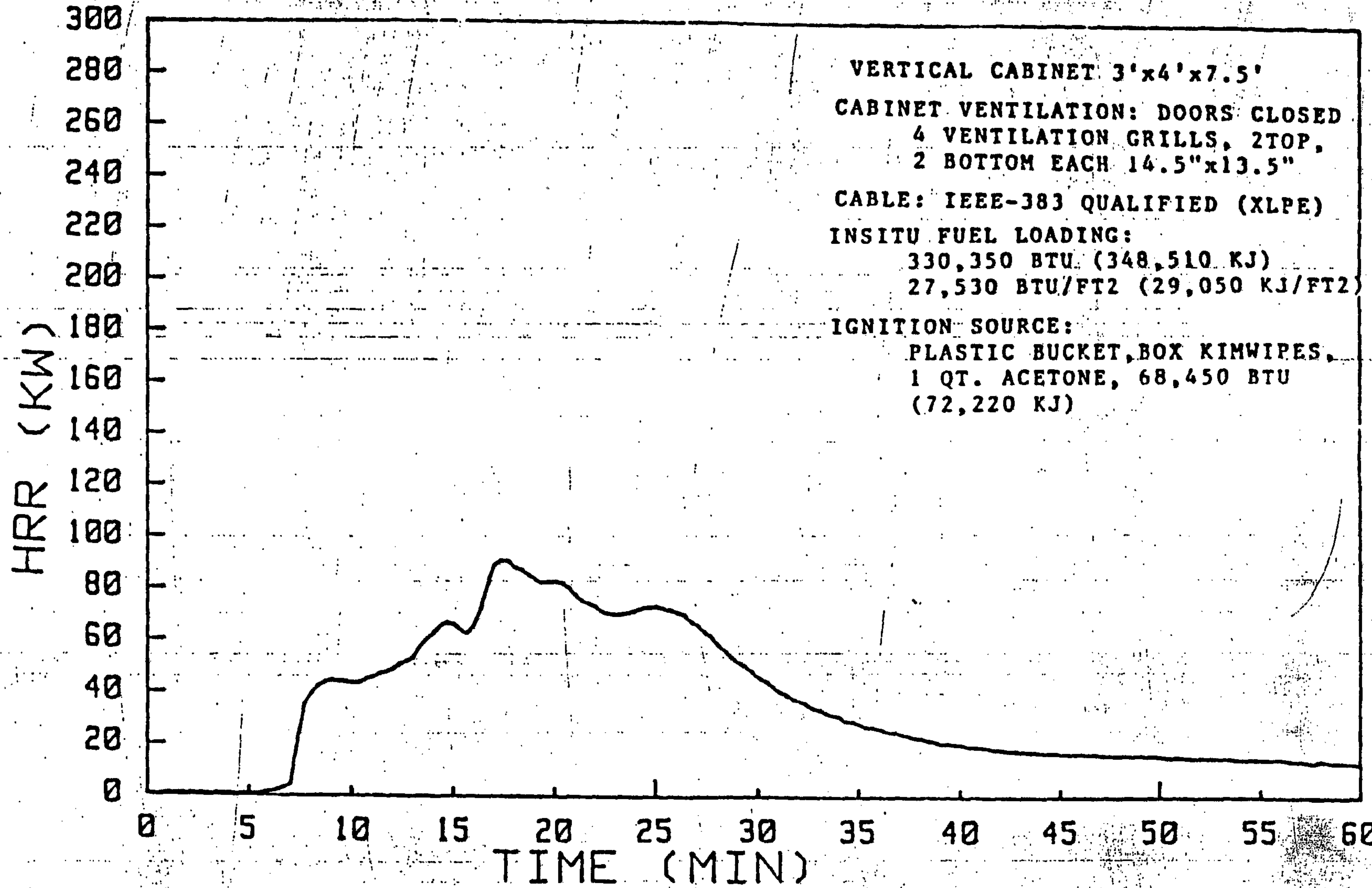
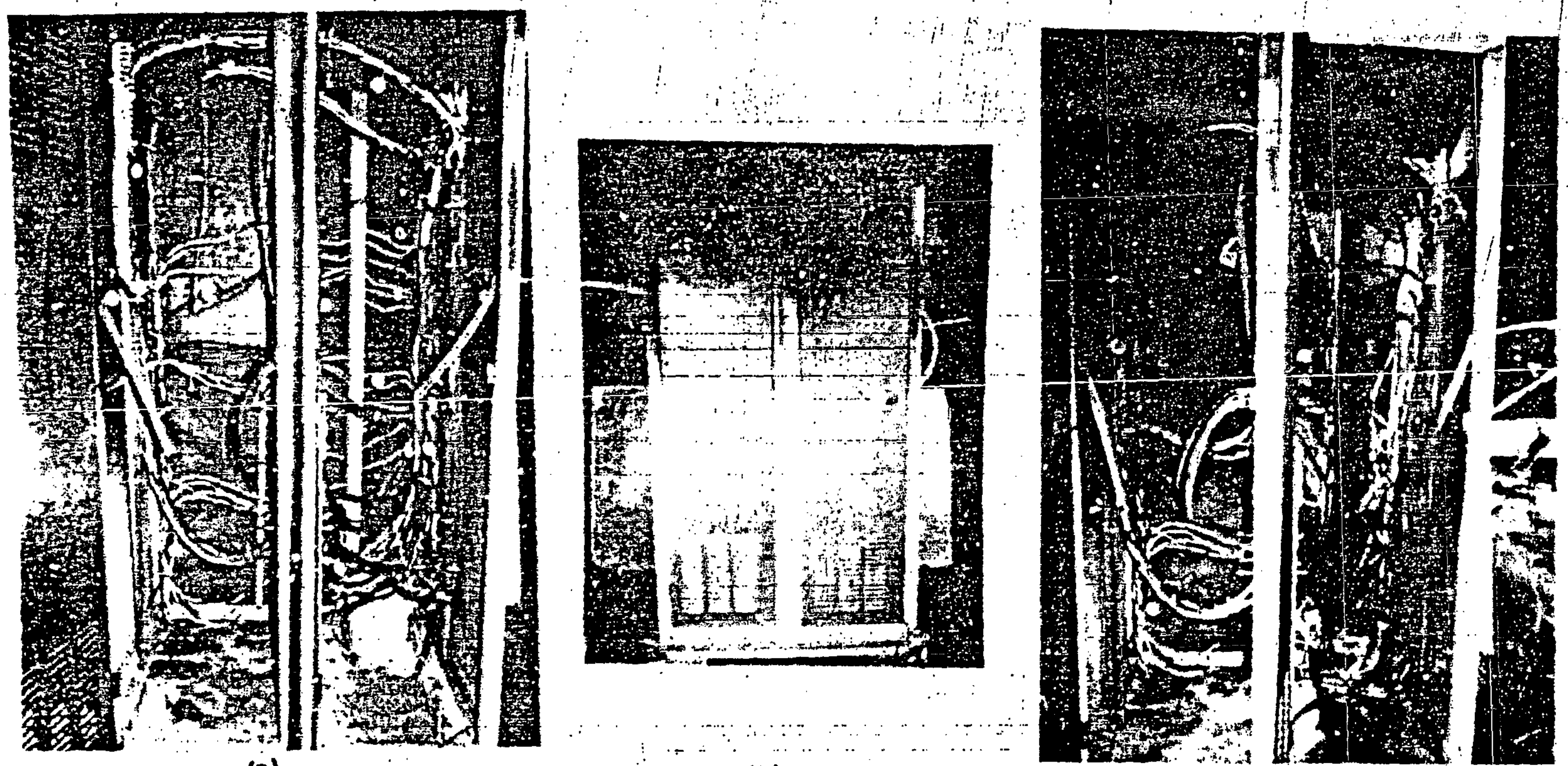


Figure B-4. Heat Release Rate From ST #7



(a) (b) (c)

Figure B-5. Photographic Sequence of ST #8

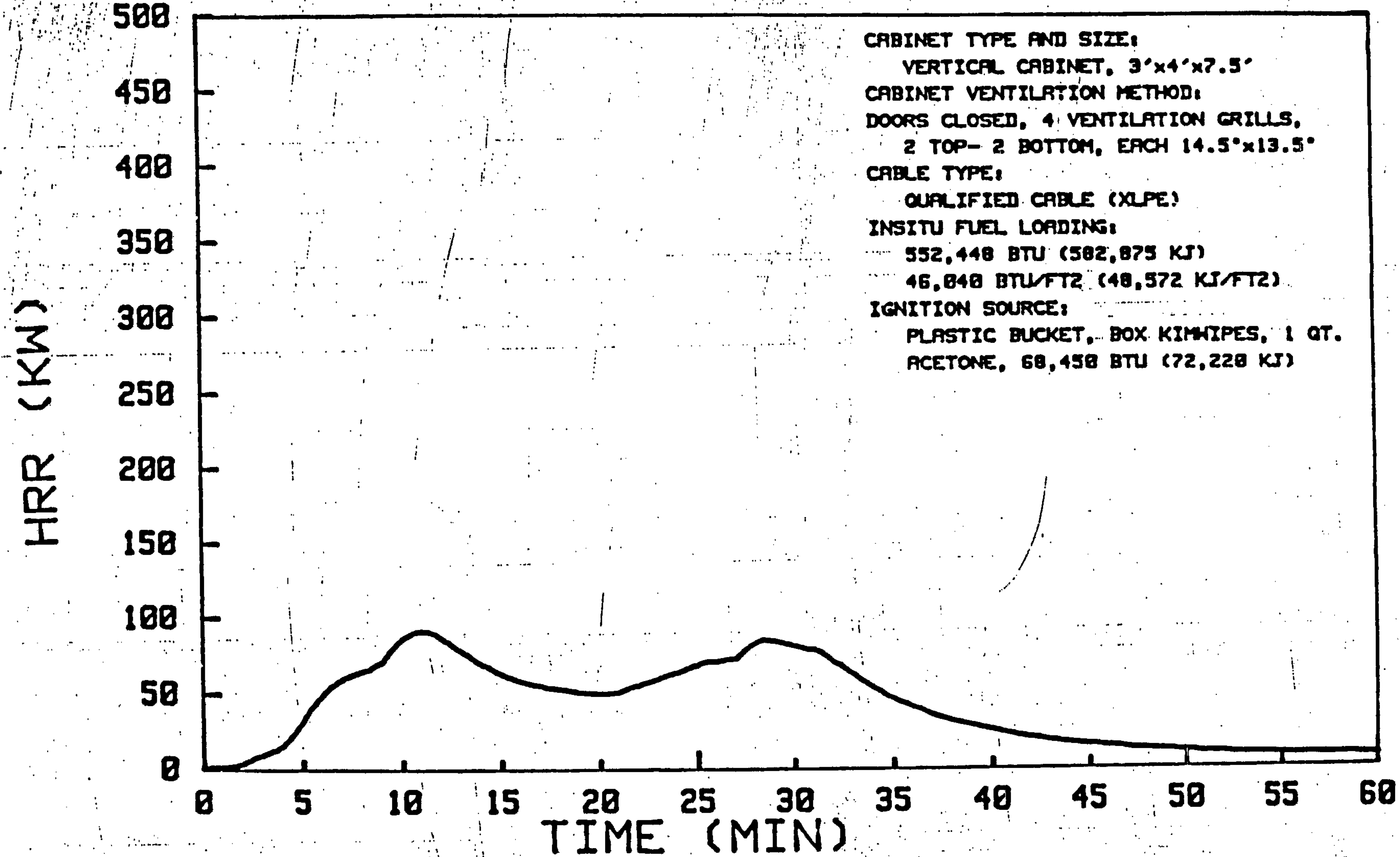
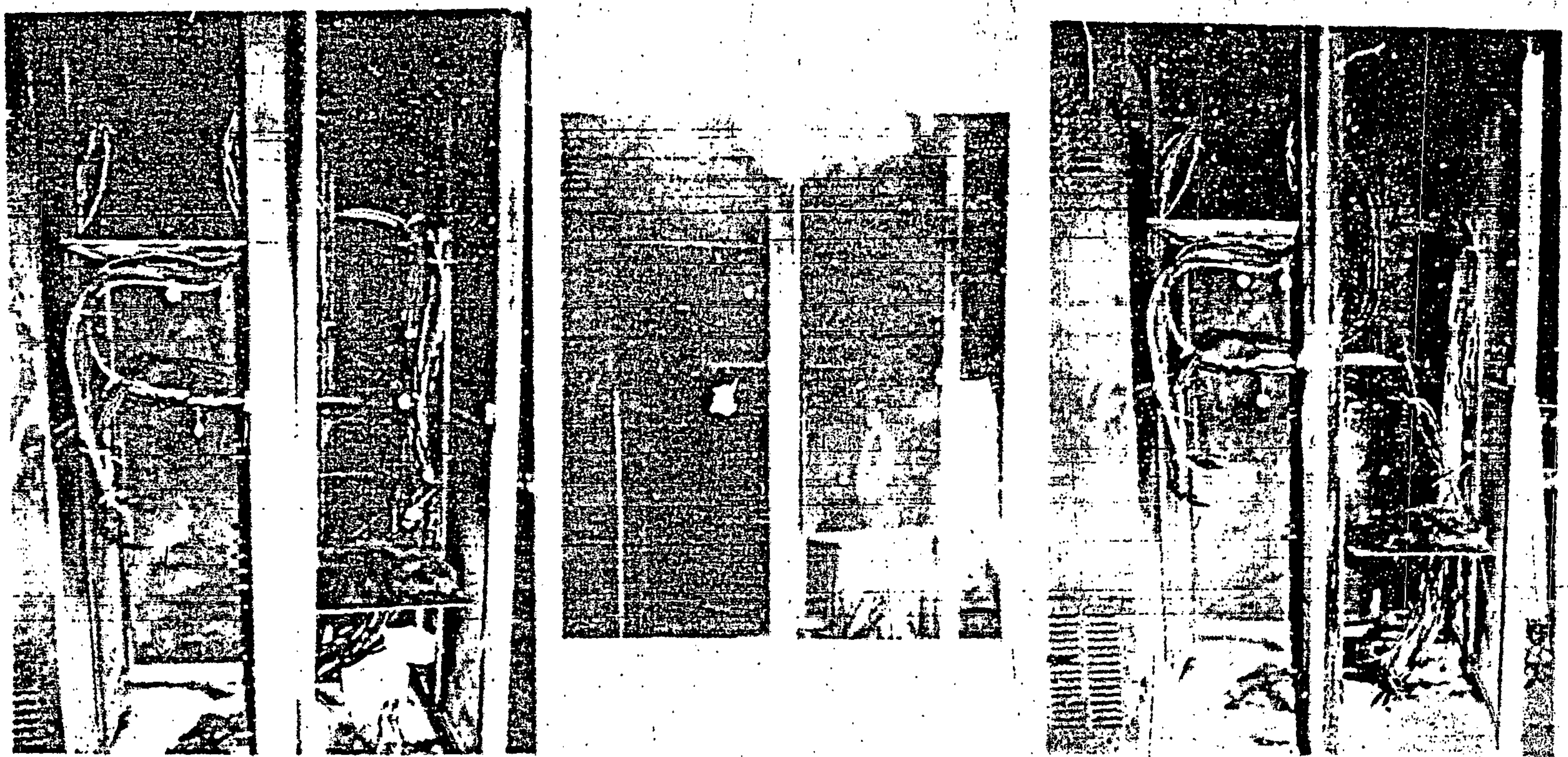


Figure B-6. Heat Release Rate From ST #8

Since it did not appear that the fire would propagate in the configurations tested. Scoping Test #9 was conducted to investigate if internal horizontal barriers (e.g., strip chart recorders, mounting plates, etc.) would enhance the potential for the cabinet fire to propagate. The in situ fuel was the qualified cable with a fuel loading of 234,990 kJ (222,740 Btu), which is approximately 210,766 kJ/m^2 (18,560 Btu/ft^2). The fuel load is higher because the only purpose of this test was to determine if the horizontal barrier would propagate the fire from the right-hand side of the cabinet to the left-hand side. In Figure B-7 a "before," "during," and "after" picture of ST #9 are shown. The main bundle directly above the ignition source was burned; also, the cables below the partition in the right-hand side of the cabinet were burned. However, no other cables in the cabinet were burned. There was thermal damage (i.e, melting) to the cables below the center and left-hand side partitions. Again, the fire did not propagate horizontally even with the partitions. The HRR for this test is shown in Figure B-8.

Figure B-9 shows "before," "during," and "after" pictures of ST #10. The in situ fuel was unqualified cable (PE/PVC) with a total fuel load of 611,530 kJ (579,650 Btus). This is approximately 548,491 (48,300 Btu/ft^2). The fuel loading and cable configuration was as much like that used in ST #8 as possible. The purpose of this test was to investigate the differences in burning between qualified and unqualified cable with all other parameters remaining the same. The test was run with doors on and closed as in ST #8. During the fire, the smoke level in the cabinet appeared to descend to floor level because smoke was exiting the bottom vents of the cabinet. Then the room began to fill with smoke and obscured the view of the cabinet. The fire in the cabinet appeared to die down, then began burning intensely again. During the "second burning," flames were observed shooting from the ventilation grills of the cabinet and between the cabinet doors. All the cables in the cabinet were completely consumed. The residue visible in the cabinet, Figure B-9, is all charred matter. In addition, the cabinet was badly damaged with warped doors and extensive corrosion of the cabinet. The resulting HRR from this fire is shown in Figure B-10.

The arrangement used in ST #11 is the same as that used in ST #10. The only difference being that the cabinet doors remained open during this test. Before and after pictures of this test are shown in Figure B-11. The purpose of this test was to evaluate what effect the cabinet ventilation had on the fire development. Again, the smoke level quickly descended to the floor obscuring the cabinets in the enclosure. The HRR, shown in Figure B-12, shows that the fire burned much quicker than ST #10, and it appears that in this



(a) (b) (c)

Figure B-7. Photographic Sequence of ST #9

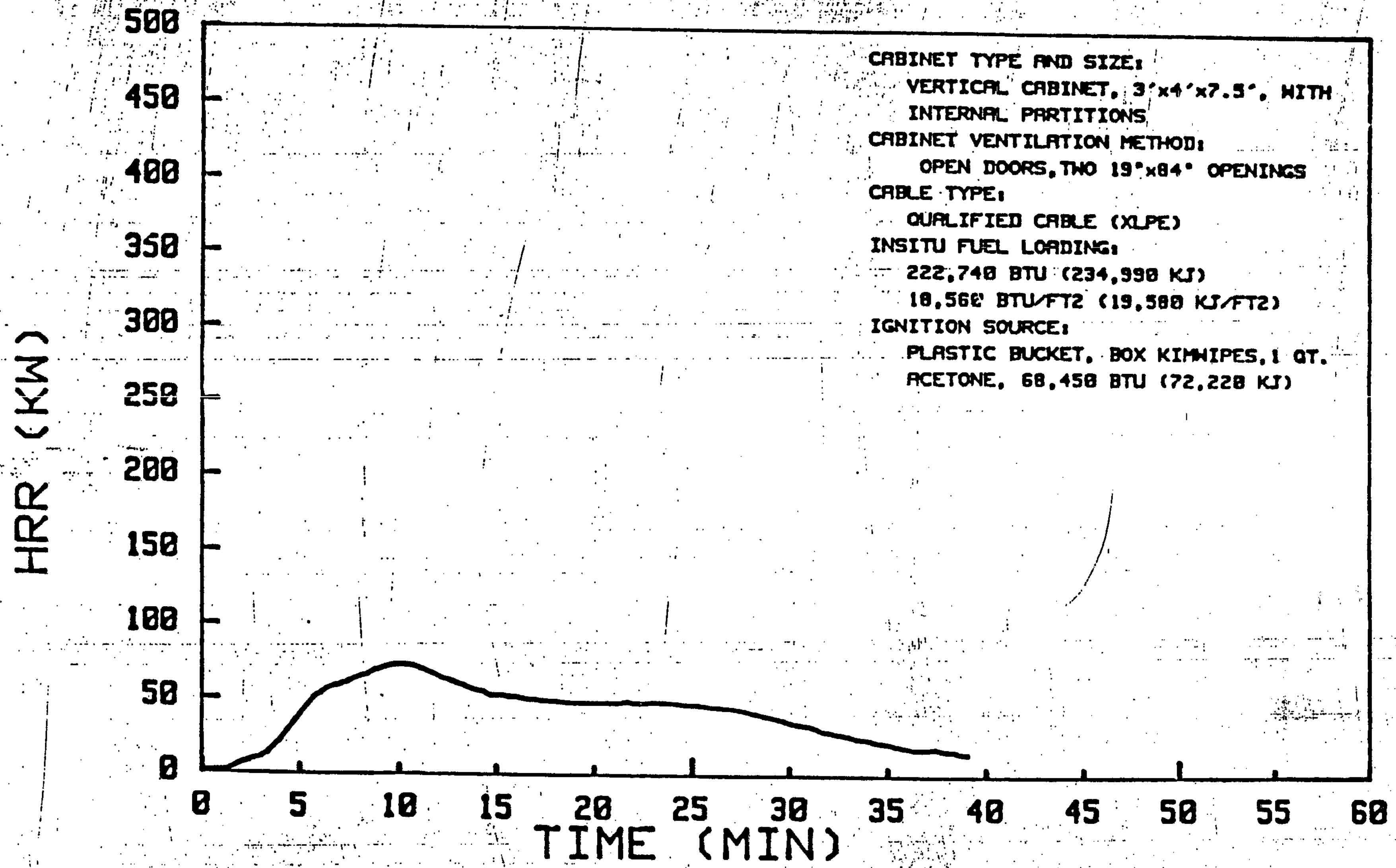


Figure B-8. Heat Release Rate From ST #9

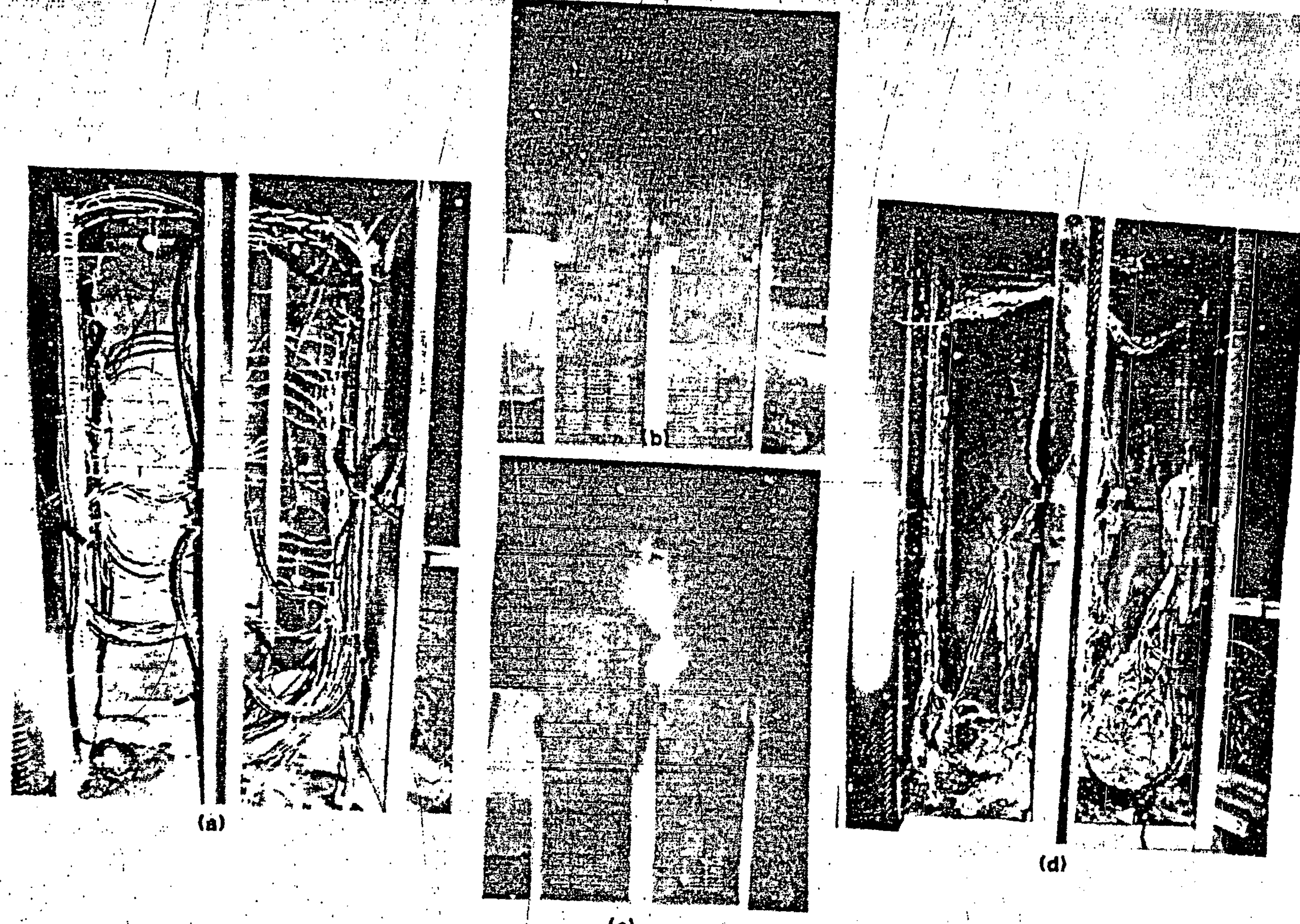


Figure B-9. Photographic Sequence of ST #10

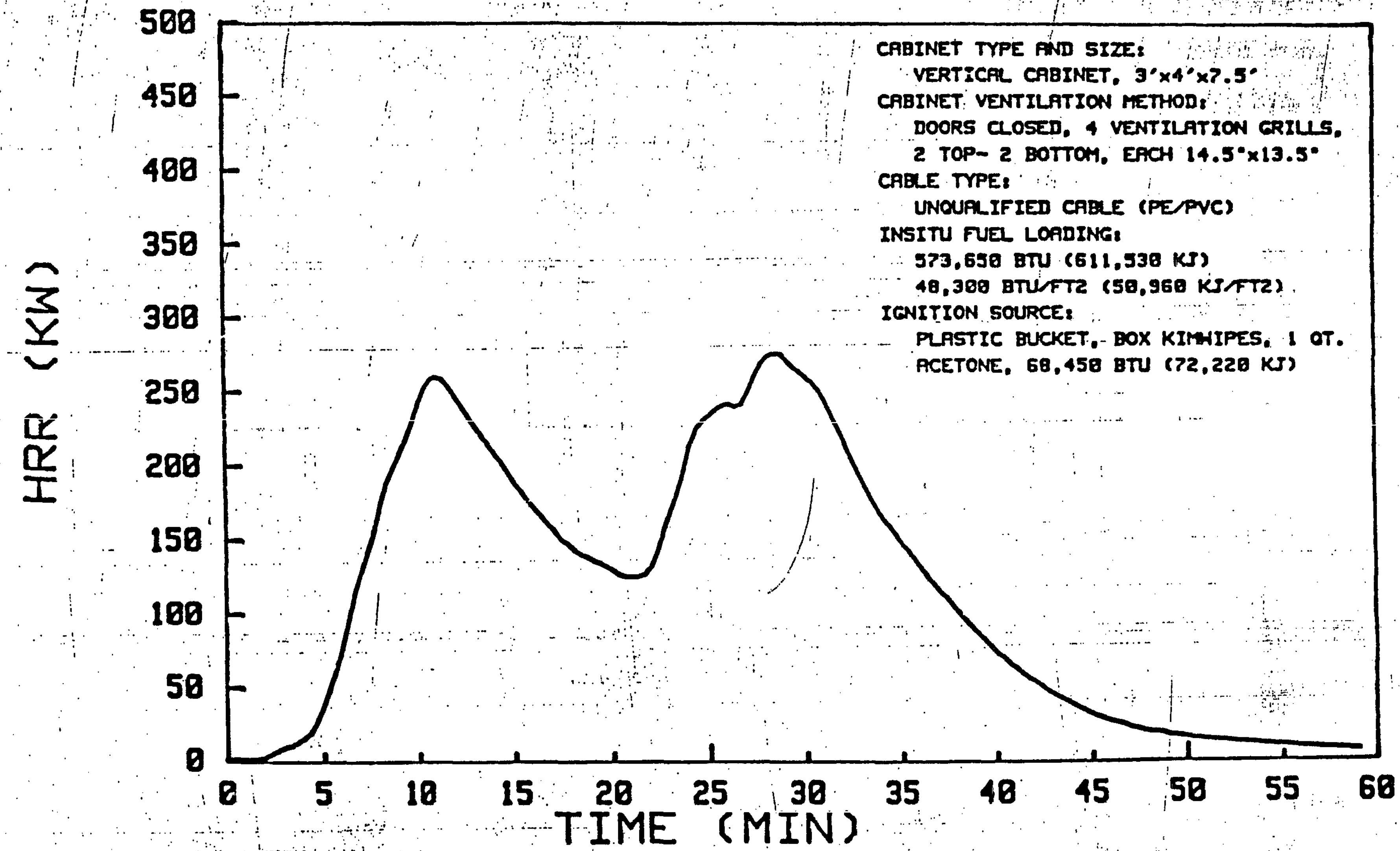
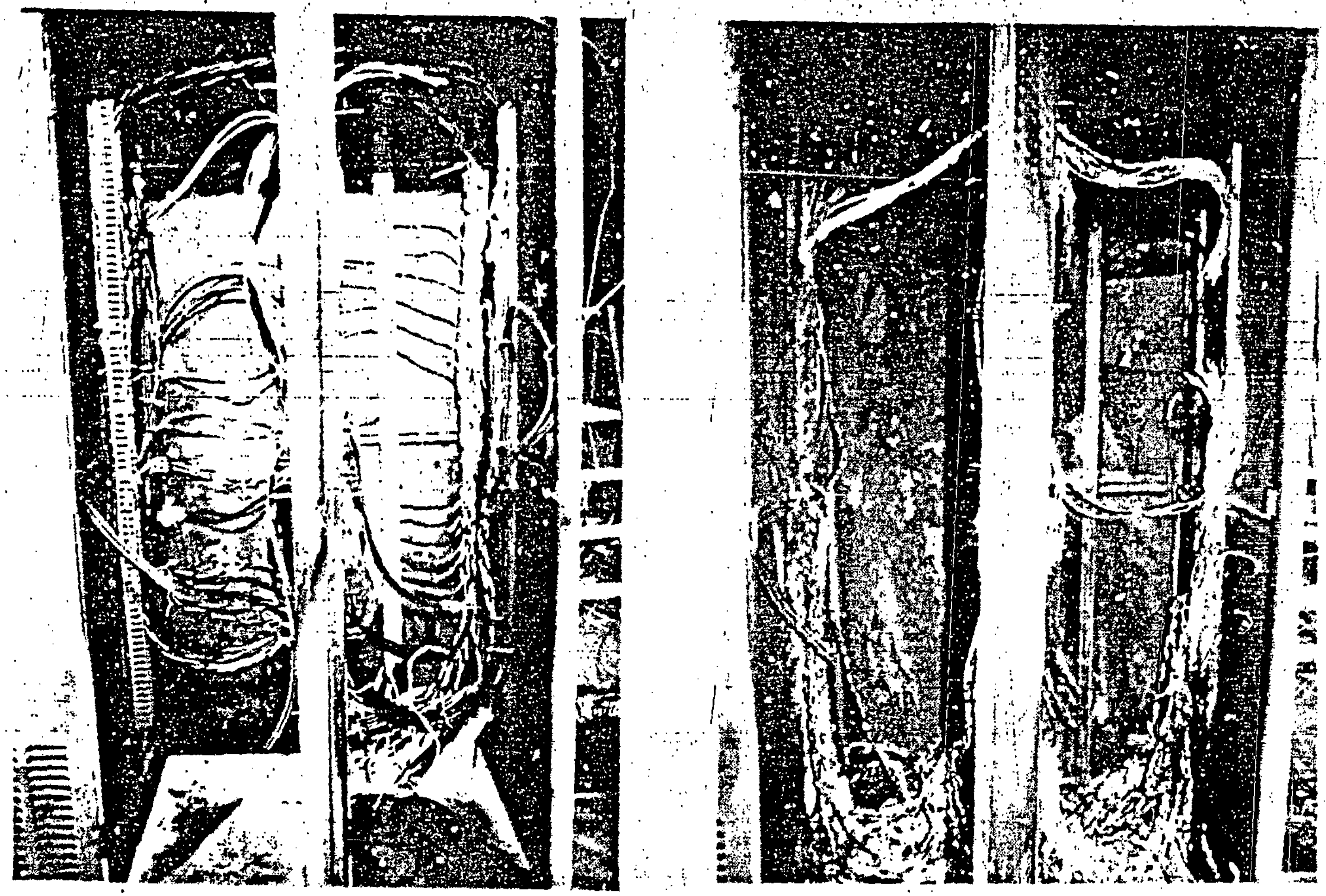


Figure B-10. Heat Release Rate From ST #10



(a) (b)

Figure B-11. Photographic Sequence of ST #11

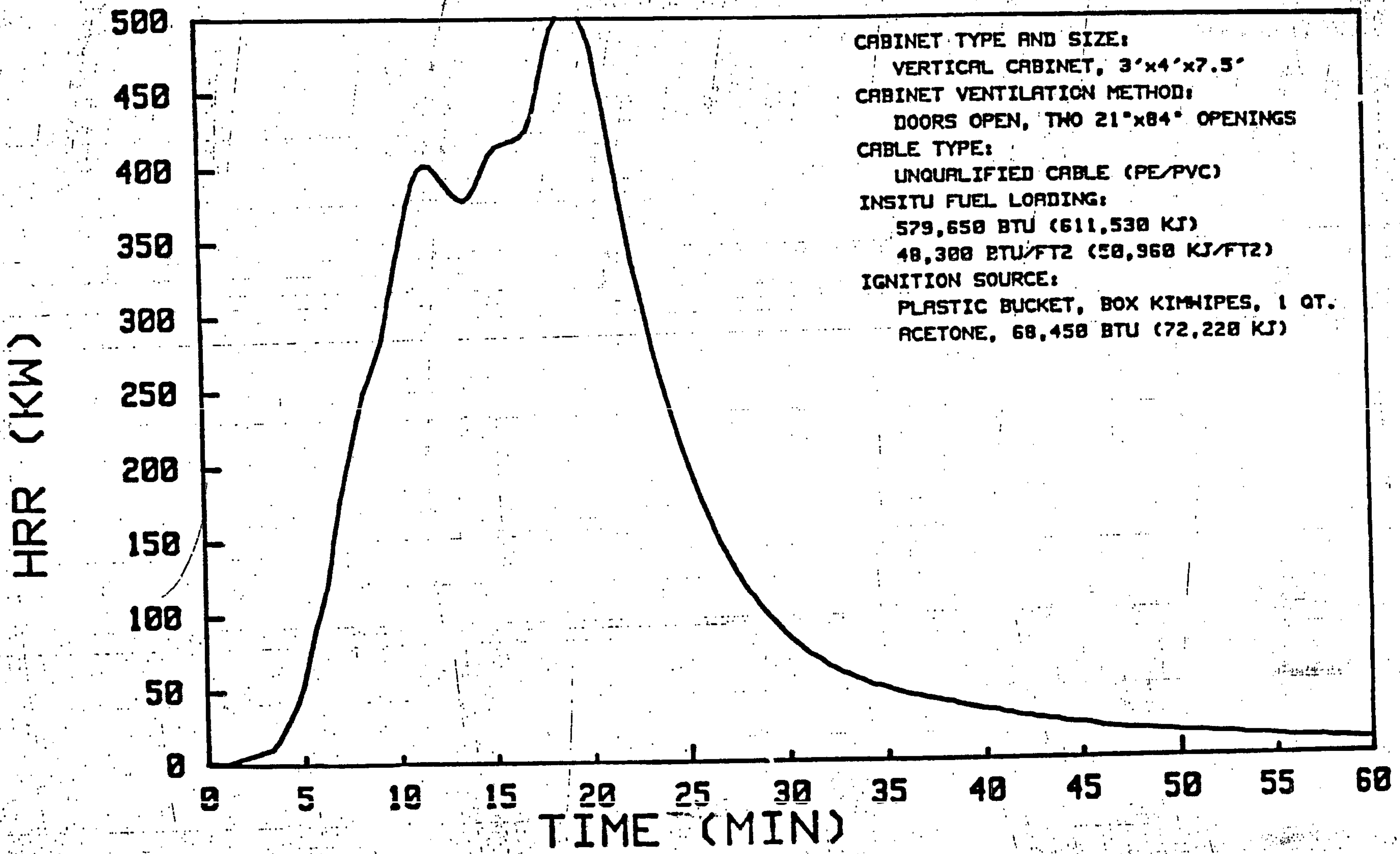


Figure B-12. Heat Release Rate From ST #11

test there was no restriction of oxygen to the fire as occurred in ST #10. All the cables in the cabinet were completely consumed.

As a result of the Scoping Tests, the following conclusions were made:

a. There is a critical amount of "ignition source fuel" that is necessary to ignite a cable bundle, particularly qualified cable.

b. Qualified cable fires in vertical cabinets will not spread.

c. Unqualified cable in vertical cabinets will easily ignite (with the selected ignition source) and propagate a fire.

d. Burning rate (HRR) is affected by the ventilation method (i.e., closed or open cabinet door) in tests using unqualified cable.

e. Smoke obscuration in the test enclosure occurs within five minutes in unqualified cable cabinet fires.

f. In situ fuel amounts when loaded in cabinets, based on survey information, appear light.

g. Oxygen deprivation appears to control burning in fires with closed cabinet doors.

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2. Chavez, J. M. to A. Datta, personal correspondence, June 17, 1986, subject: Fuel Loadings in Cabinets.

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13. ABSTRACT (200 words or less)
A series of full-scale cabinet fire tests was conducted by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission. The cabinet fire tests were prompted by the potential threat to the safety of a nuclear power plant by a cabinet fire in either the control room or in a switchgear type room. The purpose of these cabinet fire tests was to characterize the development and effects of internally ignited cabinet fires as a function of several parameters believed to most influence the burning process. A primary goal of this test program was to test representative and credible configurations and materials. This series of 22 cabinet fire tests demonstrated that fires in either benchboard or vertical cabinets with either IEEE-383 qualified cable or unqualified cable can be ignited and propagate. However, fires with IEEE-383 qualified cable do not propagate as rapidly nor to the extent that unqualified cable does. Furthermore, the results showed that the thermal environment in the test enclosure and adjacent cabinets is not severe enough to result in autoignition of other combustibles; although in some of the larger fires melting of plastic materials may occur. Smoke accumulation in the room appeared to be the most significant problem, as smoke obscured the view in the enclosure within minutes after ignition. Essentially, a cabinet fire can propagate within a single cabinet; however, for the conditions tested it does not appear that the fire poses a threat outside the burning cabinet except the resulting smoke.

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An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Cabinets

Part II: Room Effects Tests

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ABSTRACT

This report presents the findings of the second part of a two-part series of full-scale electrical cabinet fire tests conducted by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission. The first part of this test series investigated the effects of various cabinet parameters on a cabinet fire. The second part of the test series, described here, investigated the effects of such a fire on a large (18.3x12.2x6.1-m or 60x40x20-ft) enclosure.

Five tests involving a fire in a control cabinet were conducted under Part 2 of the test series. These tests investigated the effects of fuel type, cabinet configuration, and enclosure ventilation rate on the development of the enclosure environment. Although fires as large as 1300 kW resulted, enclosure peak temperatures (outside the fire plume itself) were typically less than 150°C, with significant vertical thermal stratification observed. The most significant impact on the test enclosure environment was that dense smoke, in all cases, resulted in total obscuration of the enclosure within 6-15 min of fire ignition. Enclosure ventilation rates as high as 8 room air changes per hour were found to be ineffective in purging the smoke from this large enclosure. Similar obscuration problems had also been observed in the Part 1 tests, which utilized a smaller enclosure with ventilation rates as high as 15 room air changes per hour.

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ACKNOWLEDGMENTS

All those individuals and groups who contributed to the successful completion of this test program are gratefully acknowledged. Jeff Newman and John Hill, both of Factory Mutual Research Corporation (FMRC), were most directly responsible for the conduct of the tests and are singled out for particular praise. The authors are also grateful to Mark Jacobus, of Sandia National Laboratories, Albuquerque (SNLA), for his assistance in the setup of the tests at FMRC. Finally, the work of Barry Spletzer of SNLA and Frank Horine of Ktech, Inc., in designing, testing, and fabricating the electrical initiation apparatus, is acknowledged.

EXECUTIVE SUMMARY

As part of the U.S. NRC-sponsored Fire Protection Research Program, a two-part series of full-scale electrical control cabinet fire tests was conducted by Sandia National Laboratories, Albuquerque. The first part of this test series, referred to as the Cabinet Effects Tests, investigated the effects of various cabinet parameters on fire development. The second part of the test series, the primary subject of this report, is referred to as the Room Effects Tests. These tests investigated the effects of a cabinet fire on a very large (on the order of actual control room size) enclosure.

The cabinet fire testing was prompted by concerns on the part of the NRC staff over the potential effects of a cabinet fire on the ability of a plant to achieve and maintain a safe shutdown state. Electrical control cabinets, particularly control room cabinets, often represent a single-point vulnerability of multiple safety systems or components. Thus compromising a single control cabinet by fire could potentially result in loss and/or spurious operation of multiple safety system components. Historically a number of fires have occurred in electrical cabinets (see Reference 1). While none of these incidents has involved a control room cabinet or resulted in critical degradation of safety features, this historical evidence illustrates the potential for cabinet fires to occur.

In total, the two-part series of cabinet fire tests addressed four aspects of electrical cabinet fires:

- The ability of a cabinet fire to ignite and spread
- The rate of development of a cabinet fire
- The effects of a cabinet fire on the room environment
- The potential for propagating fire and/or fire damage beyond the cabinet of origin

In addressing the final aspect, propagation of fire and fire damage beyond the cabinet of fire origin, only a limited investigation was performed. With respect to propagation of fire, only the potential for spontaneously igniting an adjacent cabinet separated by a solid double-walled barrier was investigated. The potential for spreading fire through a single-wall barrier, or through cables that penetrate the cabinet surfaces, was not investigated. The results with respect to each of these aspects are described below.

As a result of the two-part test series, a number of observations and conclusions were documented. With respect to the initiation and development of a cabinet fire.

- For cables that do not pass the IEEE-383 flame-spread test standard (unqualified cables), cabinet fires are easily ignited and

propagate readily, generally resulting in combustion of all combustible materials within the cabinet. It was also demonstrated that even a low-intensity (170-W) electrically heated fault point could result in full cabinet fire involvement for unqualified cables.

- For cables that pass the IEEE-383 flame-spread testing standard (qualified cables), self-sustaining fires that resulted in full involvement of the cabinet were somewhat more difficult to induce. However, given the proper circumstances, such a fully involved cabinet fire is possible, as demonstrated in Test 23.

- Peak fire intensities observed for both qualified and unqualified cable cabinet fires were approximately 1300 kW (Test 23, qualified cable, 1235 kW peak heat release rate; Test 24, unqualified cable, 1300 kW peak heat release rate). These fires represent very intense fires, which typically grew to peak intensity within 10 min.

- Because of the rate of development and eventual intensity of the observed fires, efforts to suppress these fires with hand-held extinguishers cannot be expected to be very effective beyond approximately 5 min after ignition. This implies that early detection and suppression will be the key to minimizing the effects of a cabinet fire.

With respect to the effects of a cabinet fire on the room environment:

- Peak temperatures at ceiling level (20 ft) directly above the fire source were observed to reach as high as 262°C during a cabinet fire.

- Thermal environments in the test enclosure induced as a result of a fire confined to a single cabinet, were observed to reach no higher than 150°C peak temperatures outside the immediate fire plume. (Many plant situations exist in which groups of cabinets are ventilation-isolated from the general enclosure by solid or vented barriers. In such situations temperatures within these areas can be expected to exceed 150°C. However, this situation was not directly investigated.)

- A significant degree of vertical thermal stratification was observed in all tests conducted in the large (60 × 40 × 20 ft) test enclosure.

- The peak temperatures observed depend strongly on the size of the enclosure and on the ventilation rate provided throughout the course of the fire.

- No attempts were made under this effort to investigate the effects of securing enclosure ventilation such as might be expected as a response to fire under certain fire isolation strategies.

- The build-up of smoke in the enclosure and the deposition of soot particulate were observed to be significant problems in both parts of the test series. Typically, within 6-15 min smoke had totally obscured visibility throughout the test enclosure. In the smaller enclosure used in the Cabinet Effects Tests, ventilation rates of 15 room air changes per hour were typically used. For the large test enclosure used in the Room Effects Tests, ventilation rates as high as 8 room air changes per hour were used. In each case these rates were insufficient to effectively purge smoke from the enclosure. In the case of the Room Effects Tests, times in excess of one hour after completion of a test, at high ventilation rates, were required to purge smoke from the enclosure. It is anticipated that due to this rapid build-up of a thick smoke layer, operator effectiveness would be severely hampered under such conditions.

With respect to the propagation of fire beyond the cabinet of fire origin:

- A solid steel, double-wall barrier was quite effective in reducing adjacent cabinet temperatures, both surface and air, below typical spontaneous ignition temperatures for most materials. Thus the spontaneous cabinet-to-cabinet spread of fire through such barrier configurations is considered unlikely. This conclusion relates only to the actual spread of fire between cabinets. The environments observed indicated that other damaging effects, smoke and high temperatures for example, may threaten electrical equipment in adjacent cabinets, even though flames may not actually propagate. In particular, it is anticipated that integrated circuitry based control components will experience calibration drifts and/or failure at the temperatures observed.

- Many potential fire-spread paths were not investigated. Spread paths associated with cabinet partitioning barriers, which were not investigated, include single-wall barriers and barriers susceptible to warping that might allow flames to pass the barrier. Based on the results of these tests, partial or incomplete barriers and unsealed cable penetrations can be expected to allow further spread of fire, given a fully involved cabinet fire. The vulnerability of cables in raceways above or below a burning cabinet was also not investigated.

With respect to fire-induced damage to remote cables and components:

- No significant damage was observed for cable bundles located in adjacent cabinets (separated by a double-wall barrier) or in other enclosure locations. Both visual and insulation integrity checks were made following relevant tests.

- Heavy soot deposition throughout the enclosure was observed in most tests. In some cases this soot was found to be heavily loaded with chlorides,[7] adding the potential for highly acidic solutions to

form in the presence of moisture (such as that resulting from suppression activities).

- Low-voltage equipment present in these environments was found generally to remain functional (in the absence of moisture).[7] One exception involved a strip chart recorder that jammed due to deposition of soot on mechanical parts. High-voltage equipment was not investigated. Also, the vulnerability of cables in raceways directly above or below a burning cabinet was not investigated.

One additional insight was obtained which was not a part of the original objectives of the program. This involved the effectiveness of smoke detection for this type of fire. During the final cabinet test, two smoke detectors were placed in the enclosure and monitored for actuation. One detector was placed within the source cabinet and one in a remote cabinet. The detector in the source cabinet detected smoke from the electrical ignition apparatus used in this test approximately 1 min after visible smoke first appeared and approximately 5 min prior to open flame ignition. The detector located in a remote cabinet did not activate until 10 min after fire ignition, after the fire intensity had peaked. This experience illustrates the effectiveness of in-cabinet detection systems. Area-type detection systems can be expected to lag in time the response of the in-cabinet detector, though the detector located in the remote cabinet probably would represent the worst possible detector site, given the location of the fire.

1. INTRODUCTION

1.1 Background

A two-part series of full-scale cabinet fire tests was conducted as part of the Fire Protection Research Program. This program is being conducted for the U.S. Nuclear Regulatory Commission (NRC) by Sandia National Laboratories, Albuquerque (SNLA). The Cabinet Fire Test Program was prompted by the potential threat to the safety of a nuclear power plant posed by a cabinet fire in either a control room or a switchgear-type room. Although there have been no fires in control room cabinets of operating nuclear power plants, there have been fires in cabinets in other parts of plants, and these cabinet fires have resulted in significant damage from heat, smoke, and corrosion.[1] Furthermore, based on past probabilistic risk analyses, a fire in a nuclear power plant represents one of the more significant potential threats to the safety of a plant, and, based on plant operating experience, a typical nuclear power plant can expect to have three to four major fires during its lifetime.[1] In addition, a recent study has shown that, given the possibility of multiple spurious equipment operations (such as might be induced by a cabinet fire), remote shutdown may be rendered ineffective.[2]

Because of the perceived level of risk, the NRC staff expressed a number of concerns about cabinet fires. These concerns centered on (a) the ability of a cabinet fire to ignite and spread, (b) the rate of development of the fire in a cabinet, (c) the resulting room environments produced by the fire, and (d) the potential for the fire to spread to other cabinets and to damage equipment and components throughout the room.

The first series of NRC-sponsored tests, called the Cabinet Effects Tests and described in Volume 1 [3], investigated concerns (a), (b), and (d). The second series of tests, described in the present volume and called the Room Effects Tests, validated the results obtained in the first series and investigated concern (c).

This report will describe the general outcome of the Room Effects Tests. Only sufficient data have been processed and evaluated to interpret the results of these tests and to permit comparison with the Cabinet Effects Tests. Further analysis of the data that are not used for this report, such as air velocities or combustion product concentrations, may be accomplished at a later date.

1.2 Previous Studies

Previous system studies and testing have shown that cabinet fires in nuclear power plants represent a potential threat to the safety and shutdown capabilities of a plant. The relevant work performed prior to the Cabinet Fire Test Program is discussed in an earlier report associated with this effort.[3]

Based on the Cabinet Effects Tests, a number of conclusions were reached, as follows.

- Cabinet fires can be ignited and can propagate in either IEEE-383-qualified or -unqualified cable, with either of the ignition sources tested (transient[1] and electrical). However, ignition and propagation are less likely to occur in IEEE-383-qualified cable.

- A cabinet fire, with either IEEE-383-qualified or -unqualified cable as the in situ fuel, in either a vertical or benchboard-style cabinet, can develop rapidly (in minutes). However, in tests with qualified cable, the fires did not become as large as those involving unqualified cables. (This observation has been modified as a result of the room effects tests in that one particular test using qualified cable resulted in a fire as intense as any observed with unqualified cable).

- Ignition, development rate, and spread of a cabinet fire depend on critical combinations of many interdependent variables (ignition source, in situ fuel geometry and amount, cabinet style, ventilation, etc.). Hence, the course of any given cabinet fire is substantially unpredictable unless, as is unlikely, the values of all these variables are known in advance. Even then, it would be difficult to predict the exact course of the fire.

- For the enclosure conditions tested in the Cabinet Effects Test series (enclosure size and ventilation rate), the thermal environment produced by the fires in the enclosure was not severe enough to cause autoignition of remote materials, but the thermal environment may have been severe enough to cause equipment damage. Furthermore, it appears from these tests that a cabinet fire will not spread from the burning cabinet to adjacent cabinets. However, under different conditions (e.g., a single wall, larger fires), a cabinet fire could potentially cause autoignition in adjacent cabinets and continue to propagate. Based on measurements of barrier surface temperatures, the double-wall barrier between cabinets used in these tests appears to have played a crucial role in preventing cabinet-to-cabinet fire spread during the larger cabinet fires. The effects of cable penetrations in the cabinet surface and the potential for spread of fire through such penetrations were not investigated.

- For the enclosure conditions tested, dense smoke accumulation in the room became a problem within minutes after ignition, for all fuel types and cabinet configurations.

Essentially, the general conclusion at the end of the Cabinet Effects Tests (Volume 1) was that a cabinet fire can propagate within a single

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1. consisting of a plastic bucket, paper, and 1 qt of acetone

cabinet; however, for the conditions tested, it does not appear that the fire poses a threat outside the burning cabinet (except for the smoke). Other cabinet and fuel configurations may result in a completely different outcome.

Although these conclusions are significant, the tests on which they are based have not been replicated or validated except as described hereafter in the present volume. The most significant data to be obtained from the Room Effects Tests (Part II as described in this document) are the effects of smoke on the control-room-size enclosure. It is also of interest to note that one particular test in this second series (designated Test 23) resulted in a qualified cable cabinet fire whose intensity exceeded that of any fire experienced during any previous qualified cable cabinet fire test. This particular test provides a graphic demonstration of the inherent variability of fires and the potential pitfalls of over-generalizing the results of a limited series of fire tests.

2. MATERIALS AND METHODS

2.1 Test Facility and Instrumentation

The enclosure used for the tests described here is located at the Factory Mutual Research Center (FMRC) test site in Rhode Island. The entire test enclosure is itself housed within an outer building and thus isolated from the external environment. The enclosure, shown in Figure 1, is 18.3 m long, 12.2 m wide, and 6.1 m high (60 ft × 40 ft × 20 ft). The interior surfaces of the enclosure's ceiling and walls are lined with 2.5-cm-(1-in.-) thick Marinite[2] I panels to simulate the concrete walls encountered in nuclear power plants. The concrete slab that makes up the foundation of the test building served as the floor of the enclosure. A forced-ventilation system with six inlet ports and one outlet port provided ventilation rates of from 1 to 10 room air changes per hour. A detailed description of the test enclosure is provided in Reference 4.

The control room mockup, presented schematically in Figure 2, included six "real" electrical control cabinets (three benchboard style, one mitered-corner benchboard style, and two single-bay vertical style). The remainder of the mockup was constructed of Marinite I panels bolted to metal framing material. The overall height of the mockup was 2.4 m (8 ft). Figure 2 gives the actual dimensions of each section of the control room mockup.

The following instrumentation installed in the test enclosure enabled the monitoring of temperature, heat flux, heat release rate, mass loss, smoke density, gas pressure, gas velocity and gas concentration:

- 31 aspirated thermocouples
- 59 bare-bead thermocouples
- 9 small-sphere calorimeters
- 9 large-sphere calorimeters
- 6 smoke turbidimeters (smoke density meters)
- 9 three-dimensional velocity probes
- 9 gas sampling ports (for oxygen, carbon dioxide, and carbon monoxide)

A more detailed description of the instrumentation and of the measurements taken during the tests is contained in Reference 4.

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2. Marinite I is a registered trademark of the Johns-Manville Corporation.

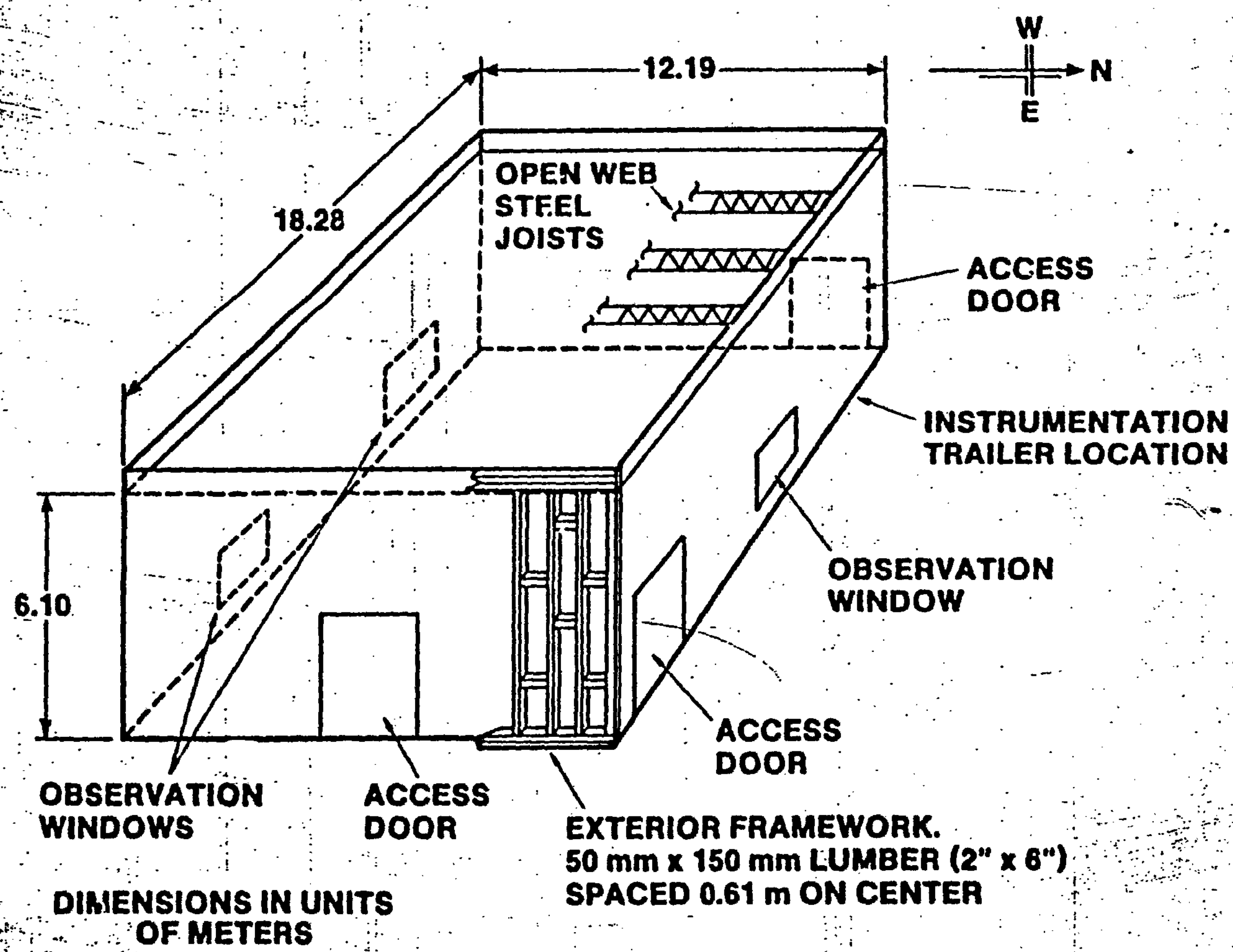
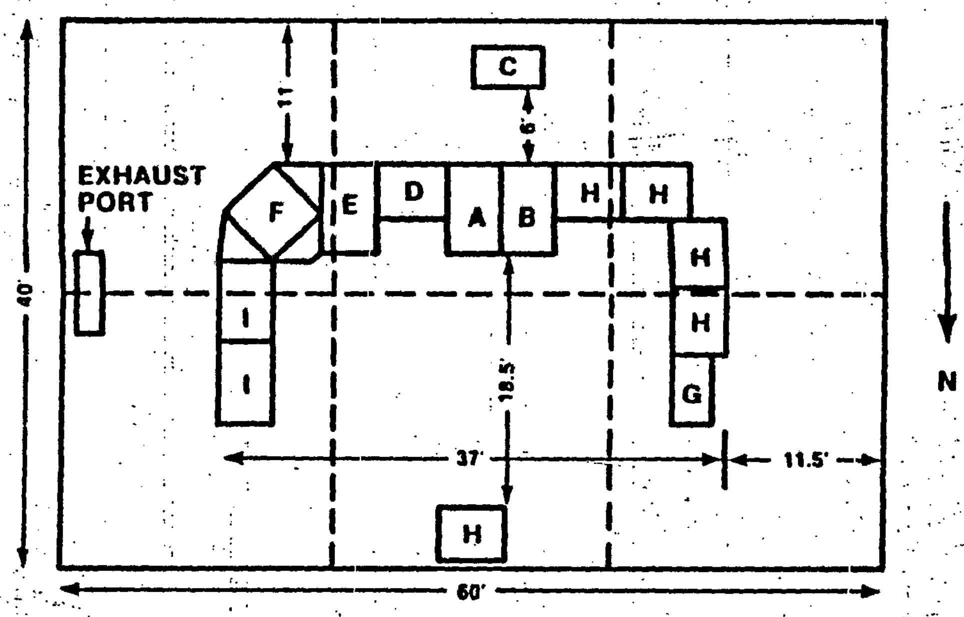


Figure 1. Three-Dimensional View of Test Enclosure



CABINETS A, B, & E - BENCHBOARD CABINETS, 6.5 x 4 x 8 ft
CABINET F - MITERED BENCHBOARD CABINET, 6.5 x 6.5 x 8 ft
CABINETS C & G - VERTICAL CABINETS, 3 x 5 x 7.5 ft
CABINETS D & H - CABINET MOCKUPS, 4 x 5 x 8 ft
CABINETS I - CABINET MOCKUPS, 4 x 6 x 8 ft

Figure 2. Plan View of Test Enclosure Layout

2.2 Test Materials and Arrangements

2.2.1 Control Room Mockup

The control room mockup, photographs of which are shown in Figure 3, was used to simulate the effects of cabinet arrangement on the development of a cabinet fire in the control-room-size test enclosure. The mockup did not represent any particular control room, but its dimensions and arrangement were based on a survey of plant control rooms, and its configuration is generic.[3,5]

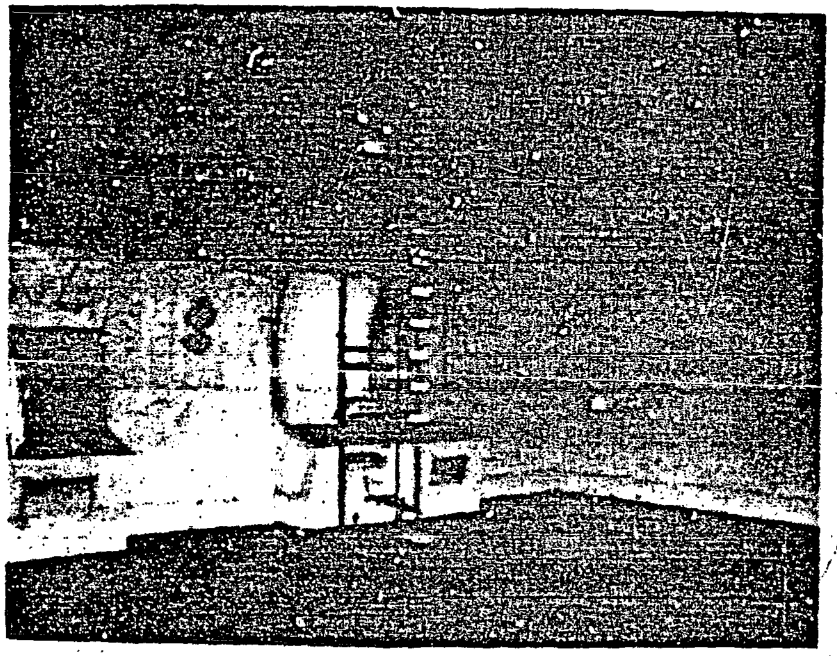
2.2.2 Cabinets

All the vertical cabinets used in the control room mockup were surplus cabinets obtained from a nuclear power plant vendor, while the benchboard cabinets were constructed specifically for this test program to specifications typically used for nuclear power plant cabinets.[3,5] Figures 4 through 6 provide dimensional data on the primary cabinets that were used in the testing.

2.2.3 Ignition Sources

Two ignition sources were used in the tests, one transient and one electrical. The transient ignition source was made up of a 9.5-l (2.5-gal) polyethylene bucket, with an open 0.5-kg (16-oz) box of Kimwipes,[3] and 0.946-l (1 qt) of acetone placed in the bucket. One half of the acetone was poured into the bottom of the bucket, the bottle and remainder of the acetone were placed in the bucket, and the cap was left off the plastic bottle to simulate the bottle spilling. Also, 15 Kimwipes were balled up and put in the bottom of the bucket. This ignition source, shown in Figure 7, was ignited by an electrically ignited gas pilot light setting fire to one of the Kimwipes hanging out of the bucket. This ignition source burns at an intensity of ≈40 kW. (This source can be compared to the peak fire intensities of 1300 kW observed during testing.) A more detailed description of this ignition source is provided in References 3 and 5. The electrical ignition source consisted of a terminal strip and 25 pieces of stripped (unjacketed) cables, shown in Figure 8. This source was ignited by providing ≈165 W of power to the terminal strip, resulting in overheating at the connection and culminating in a fire. The selection and use of these ignition sources are described in more detail in References 3 and 6.

3.Kimwipe is a registered trademark of the Kimberley-Clark Corporation.



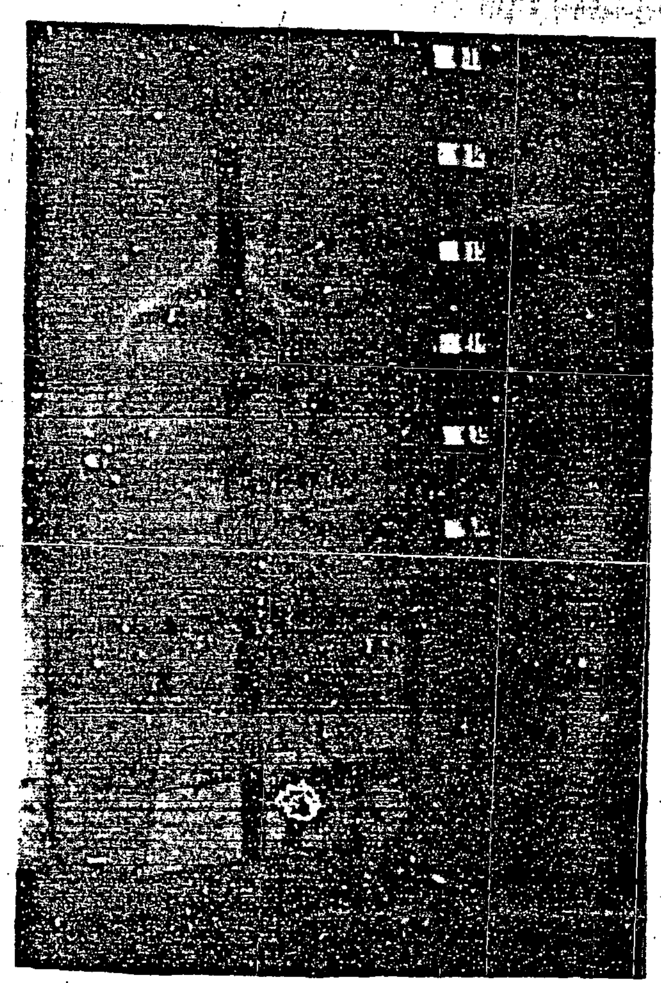


Figure 3. Photographs of Control Room Mockup

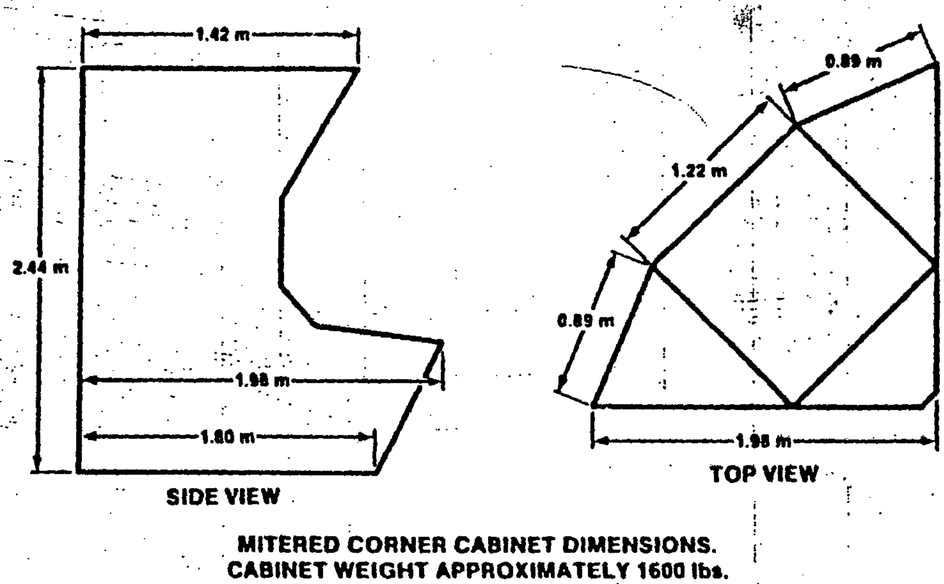


Figure 4. Schematic of Mitered Benchboard Cabinet

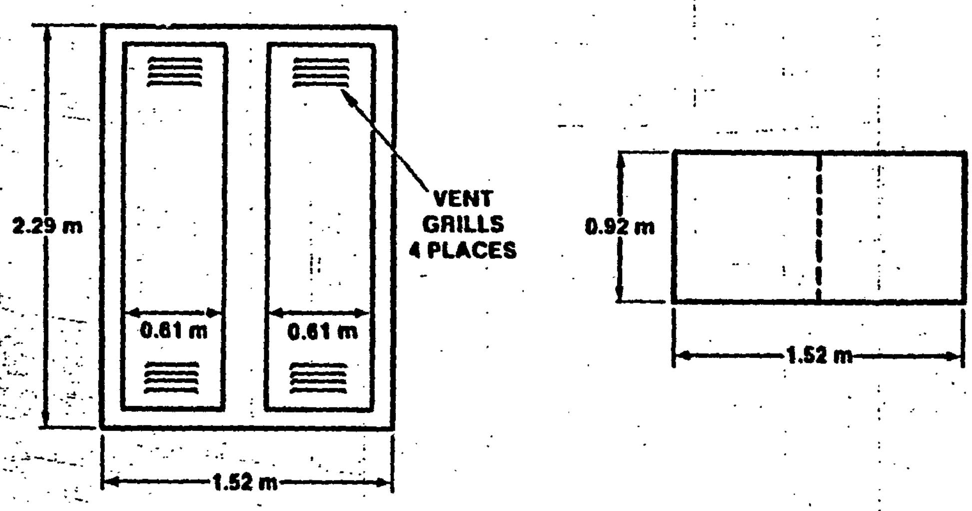


Figure 5. Schematic of Vertical Cabinet

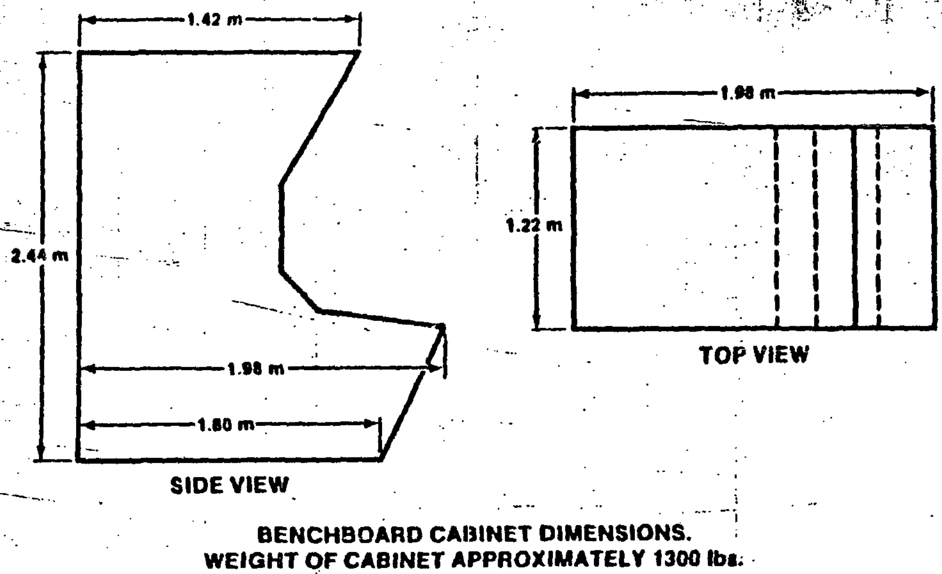


Figure 6. Schematic of Benchboard Cabinet

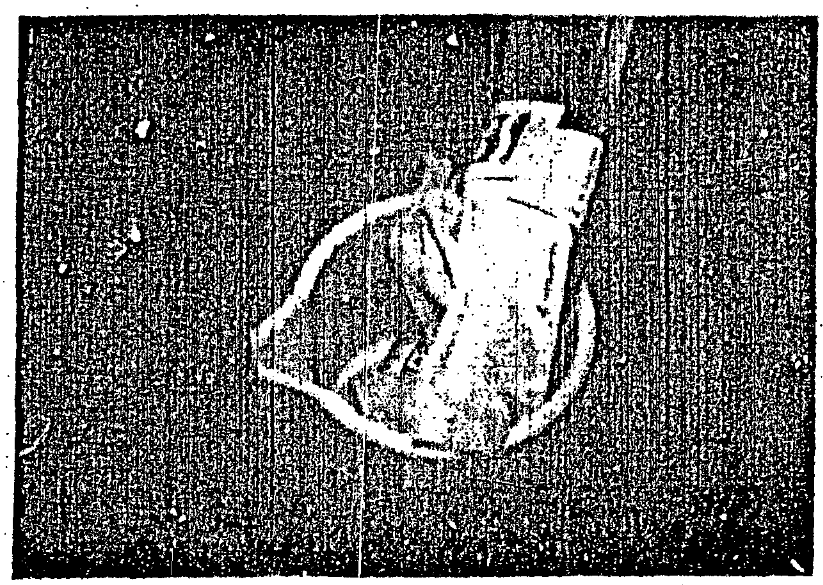


Figure 7. Photograph of Transient Ignition Source

Figure 8. Photograph of Electrical Ignition Source

2.2.4 In Situ Fuels

The in situ fuels were the primary source of fuel in the cabinets.[5] It was considered reasonable to represent all the fuels in the cabinets with cables, which are the largest source of in situ fuels in cabinets. Most plants use IEEE-383-qualified cable; however, some (≈20%)[5] operating plants still use unqualified cable in their control cabinets. Because both types of cable are still found in plants, both types of cable were used in the testing.

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

The fuel loadings and their arrangements in the cabinets were designed to be generic to nuclear power plant (NPP) cabinets (as described in Reference 3), in order to make the applicability of the tests as wide as possible. The fuel configurations used in these tests were as similar as possible to those in the Cabinet Effects Tests.[3]

Cable bundles, similar to those used to make up the in situ fuel load in the burning cabinet, were placed at eight other locations in the enclosure. One bundle was placed on each adjacent wall in the adjacent cabinet, and one bundle on each opposite wall in the adjacent cabinet. The remaining four bundles were placed on top of various cabinets and cabinet mockups around the enclosure. The purpose of placing these cable bundles was to investigate the room environment effects on the cables.

2.3 Cabinet Instrumentation

In addition to the instrumentation installed in the test enclosure, described in Section 2.1 and detailed by Nowlen in Reference 5, the cabinets in the control room mockup were themselves instrumented with free-air or surface-mounted thermocouples, heat flux gages, and bidirectional pressure flow probes. The general arrangement of this instrumentation is shown in Figure 9. A few other cabinets were lightly instrumented with thermocouples; however, only the cabinets shown in Figure 9 were heavily instrumented because they were in the general location of the fires.

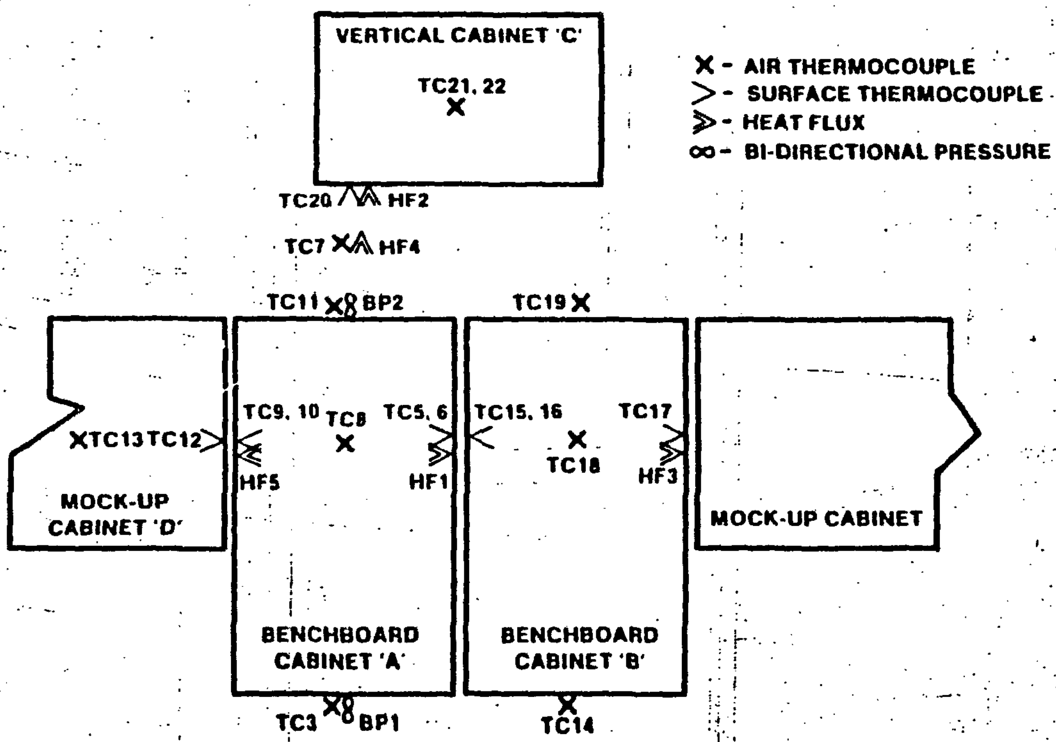


Figure 9. Schematic of Cabinet Instrumentation Layout

3. DISCUSSION OF CABINET AND CONTROL ROOM FIRE TESTS

Five cabinet and control room fire tests, identified hereafter simply as Test 21 through Test 25, were conducted at the FMRC test facility. (Note that Tests 1-20 involved simple fuel sources and are described in Reference 4.) Table 1 summarizes the test setup for Tests 21 through 25.

Table 1

Cabinet and Control Room Tests 21 Through 25
Test Setup Summary

Parameter	Test 21	22	23	24	25
<u>Location of Fire</u>					
Benchboard Cabinet A	X	X	X	X	
Vertical Cabinet C					X
<u>Ignition Source</u>					
Gas Burner	X	X			
Transient Source			X		
Electrical Source				X	X
<u>In Situ Fuel</u>					
Propylene	X	X			
Qualified Cable			X		
Unqualified Cable				X	X
<u>Ventilation Rate</u>					
1 Room Change/hr	X	X	X	X	
8 Room Changes/hr					X

3.1 Gas Burner Tests in Benchboard Cabinets (Tests 21 and 22)

Test 21 used a 0.91-m- (3-ft-) diameter propylene sand burner in the benchboard Cabinet A.[4] This test was also reported on briefly by Nowlen.[4] A description of the test and a timeline of the events that occurred during the test are provided in Figure 10. The purpose of this test was primarily to provide data with a known heat source and rate to use in validating enclosure instrumentation, previous fire tests (Cabinet

4.Note that tests 21-25 followed a series of 20 enclosure fire tests in the large-scale test facility, hence, high test numbers

TEST #: 21 PROPYLENE BURNER IN CABINET "A", GROWING FIRE TO 516 kW IN 240 SECONDS

CABINET STYLE & VENTILATION: BENCHBOARD CABINET, FRONT VENTILATION GRILL AND OPEN BACKDOOR

ROOM VENTILATION RATE: 1 rm ch/hr

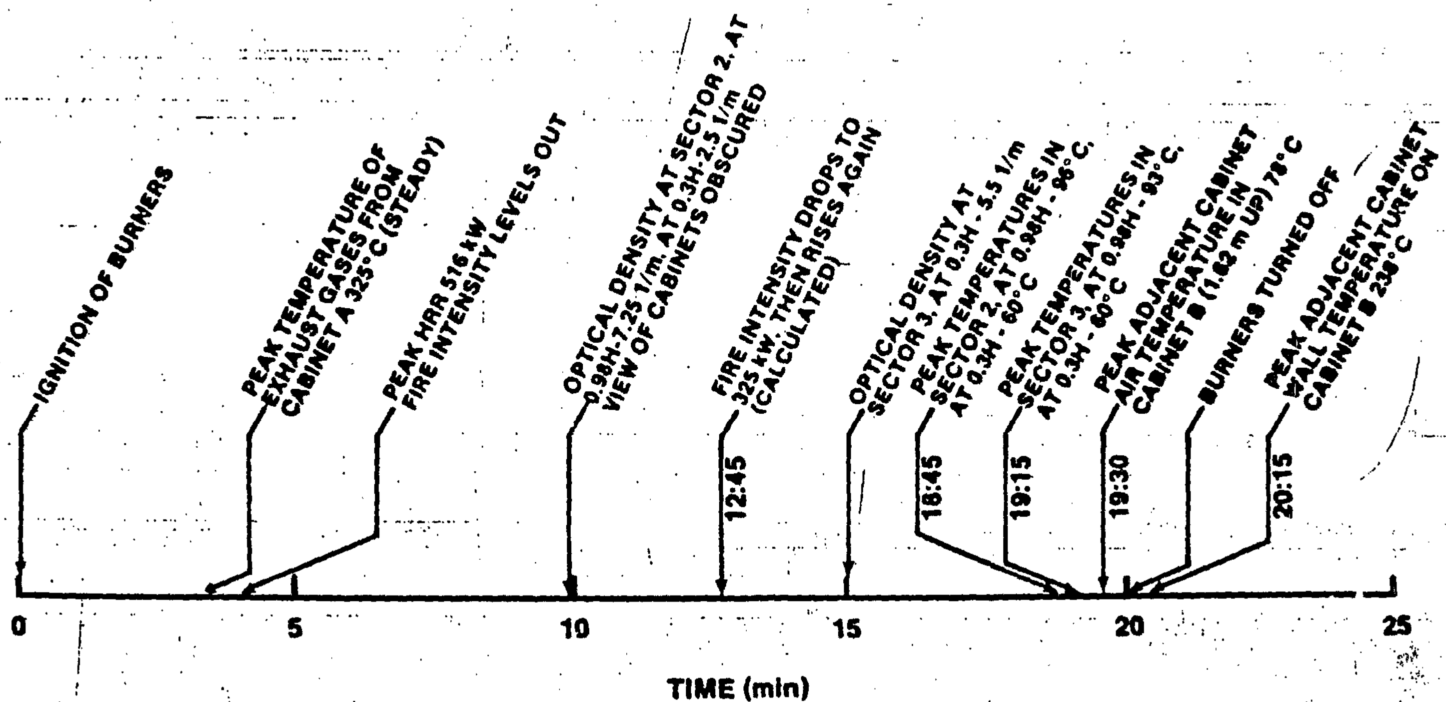


Figure 10. Description and Timeline for Test 21

Effects Tests), and fire models. However, the data are also useful for investigating the effects of a cabinet fire on an enclosure. The room ventilation rate of one room change per hour (rm ch/hr) is typical of many nuclear power plant control rooms. The expected actual heat release rate (HRR) and calculated HRR are shown in Figure 11.

The calculated HRR, evaluated using the method described by Nowlen,[4] is not steady because of variation in the ventilation flow rate and other factors. The calculated values do, however, follow the general behavior and magnitude of the HRR profile, which was based on gas flow rate.

The interior of Cabinet A was essentially at flame temperature because of the large flames produced by the burner. Adjacent cabinet temperatures are shown in Figure 12. Cabinet B, the adjacent benchboard cabinet, had a peak wall temperature at TC #155 of 235°C and was still rising when the burners were shut off. This temperature could potentially damage cables on the wall but would not have ignited them. Air temperatures in Cabinets B, C, and D were all less than 100°C when the burners were shut off.

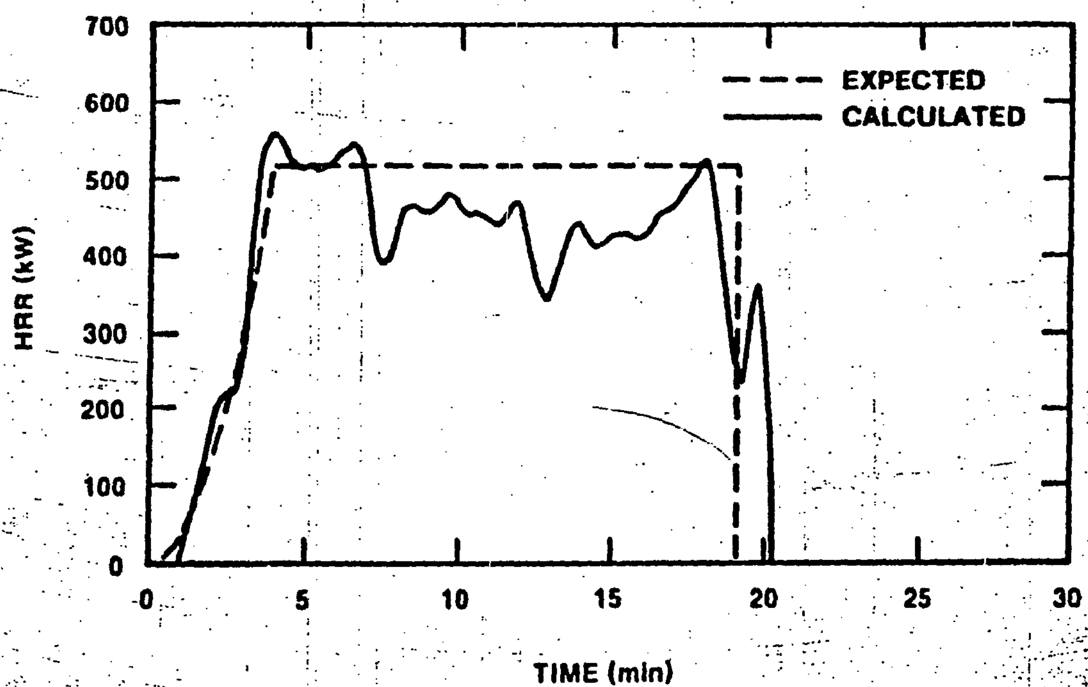


Figure 11. Expected and Calculated Heat-Release Rates During Test 21

The enclosure environment is depicted by Figures 13 and 14, the enclosure temperatures and enclosure optical density. The enclosure temperatures at Sector 2[5] did not rise over 100°C, although they were still rising when the burners were turned off. The vertical temperature stratification in the enclosure was not significant in a 0.305- to 1.82-m (1- to 6-ft) range (but it was significant when the total room height was considered). Also, as shown in Figure 13, there was no obvious hot layer, using the typical definition of a "hot layer" as a sudden, large (>100°C/m) temperature jump. The smoke obscured the view inside the enclosure within 10 min after ignition. The smoke layer could be seen descending from the ceiling during the test, as shown in Figure 14. The smoke was always denser near the upper part of the enclosure. However, even at the 1.82-m (6-ft) elevation, the optical density (Figure 14) was indicative of very poor visibility conditions that developed quite quickly.

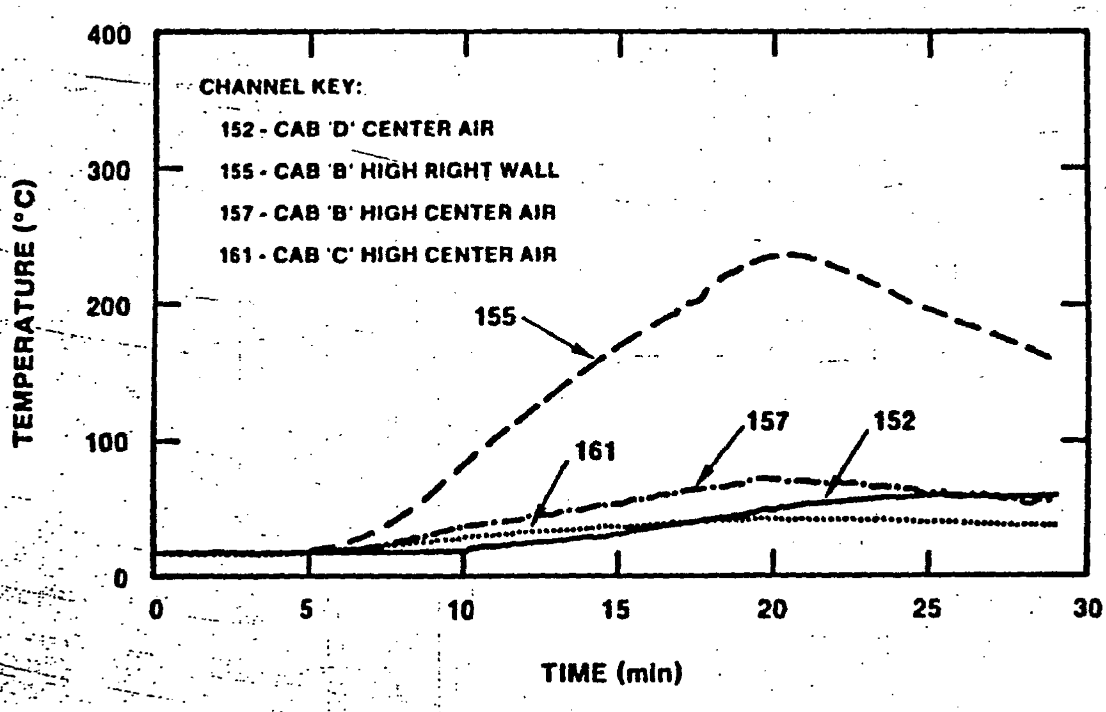


Figure 12. Temperatures in Noninvolved Cabinets During Test 21

5. "Sector 2" is a designation used to identify the instrument tree located at the physical center of the test enclosure (see Reference 4).

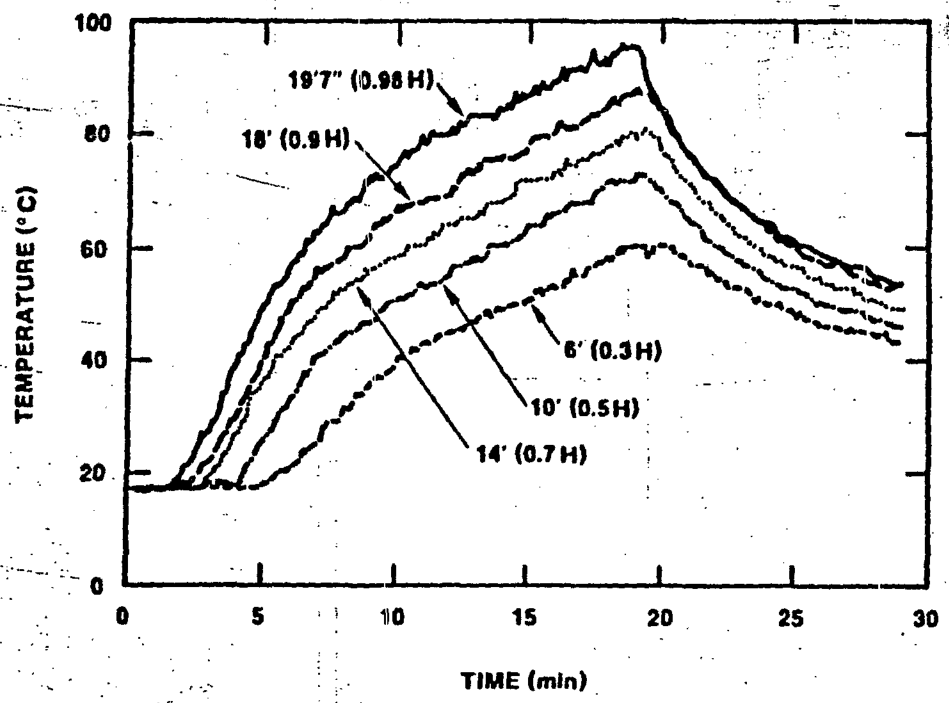


Figure 13. Aspirated Thermocouple Measurements at Sector 2 During Test 21

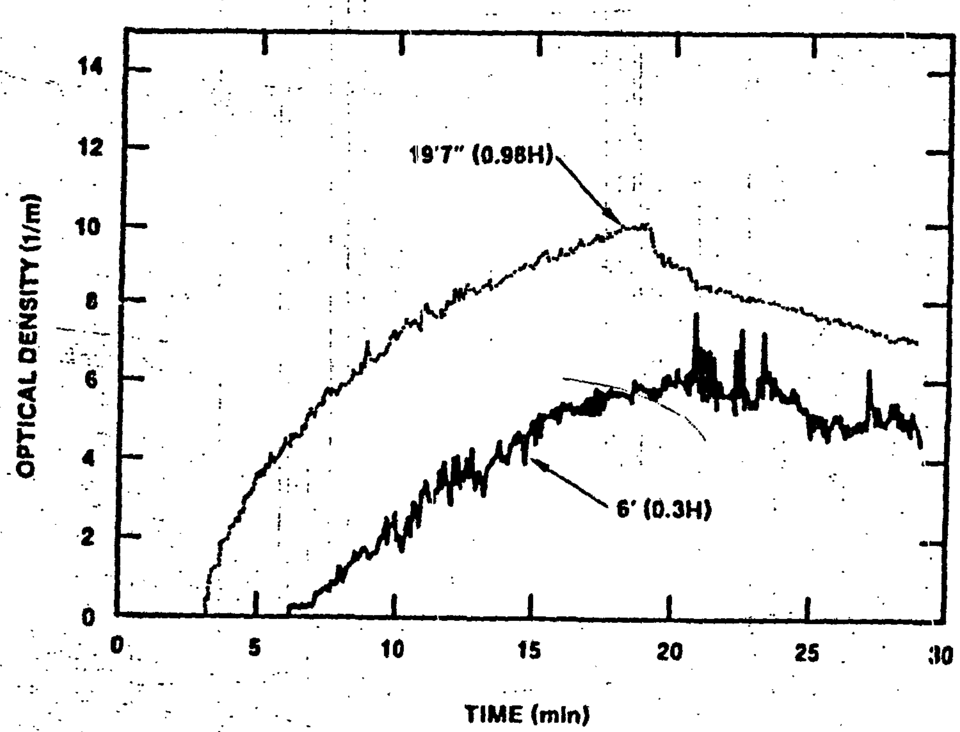


Figure 14. Optical Density at Sector 2 During Test 21

This test demonstrated that with a gaseous fuel (propylene), a fire growing to a peak rate of 516 kW results in only a moderate rise in enclosure temperature. The observed enclosure peak temperature outside the fire plume of less than 100°C would not generally be assumed to result in problems for most equipment, with the possible exception of integrated circuits. The smoke accumulation in the enclosure obscures the view inside the enclosure within 10 min and is potentially a major problem. Previous testing at FMRC has indicated that the smoke-generating properties of propylene are quite similar to those of many types of cable insulation so that similar enclosure effects were expected for the fires of similar magnitude involving cable insulation.

Test 22 employed the same setup as Test 21 except that the burner was programmed to grow to 1000 kW in 8 min. This test was also designed to provide data for computer code, enclosure instrumentation, and previous test (Cabinet Effects Tests) validation. A description of the test and a timeline of the events that occurred in the test are provided in Figure 15. The expected profile and calculated heat-release rates are shown in Figure 16. It should be noted that in this test, the propylene fuel inventory was insufficient to maintain the desired gas flow rate. At approximately 12 min after ignition, test personnel observed that gas pressure had fallen from the initial value of 175 kPa to 133 kPa (25 psig to 19 psig). Further observation of the gas pressure indicated that gas pressure decreased steadily throughout the remainder of the burn. At the time of scheduled burner shutdown, a pressure of approximately 91 kPa (13 psig) was reached. Thus, the calculated HRR shown in Figure 16 accurately reflects the actual fire behavior observed.

Temperatures in the adjacent cabinets are shown in Figure 17. The peak wall temperature in Cabinet B is higher than in Test 21 at 360°C. The temperature appears to have peaked before the burners were turned off. This is most likely a result of the failure to maintain the desired gas flow over the course of the test. Temperatures in this range would not be expected to result in autoignition of either qualified or unqualified cable, although damage to cables or components is likely to occur at these temperatures. Again, as in Test 21, the adjacent cabinet air temperatures were all less than 100°C, with the air in Cabinet B reaching a maximum of 80°C at 14:30 min after ignition.

The peak enclosure temperature in this tests was 107°C near (5.97 m [19 ft 7 in]) the ceiling at Sector 2 (the room center location). As in Test 21, the temperatures were stratified vertically with a peak temperature at the 0.3 × H level, 1.83 m (6 ft), of 62°C. These temperatures are shown in Figure 18 for Sector 2. The smoke layer descended from the ceiling at a steady rate, eventually obscuring the view inside the room within 10 min.

3.2 Benchboard Cabinet Fire Tests (Tests 23 and 24)

Test 23 was the first Room Effects Test in which a "real" fuel was burned. IEEE-383-74 qualified cable (XPE/XPE) was placed inside a benchboard-style

TEST #: 22 PROPYLENE BURNER IN CABINET "A", GROWING FIRE TO 1000 kW IN 480 SECONDS

CABINET STYLE & VENTILATION: BENCHBOARD CABINET, FRONT VENTILATION GRILL AND OPEN BACKDOOR

ROOM VENTILATION RATE: 1 rm ch/hr

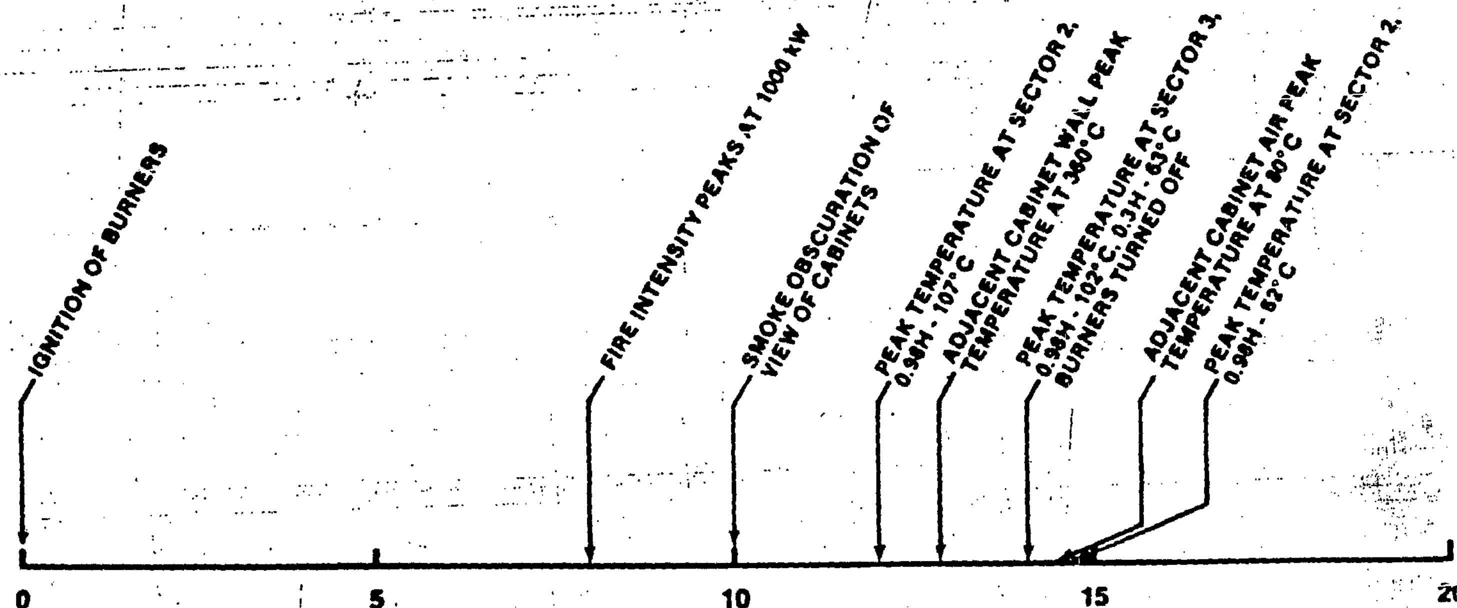


Figure 15. Description and Timeline for Test 22

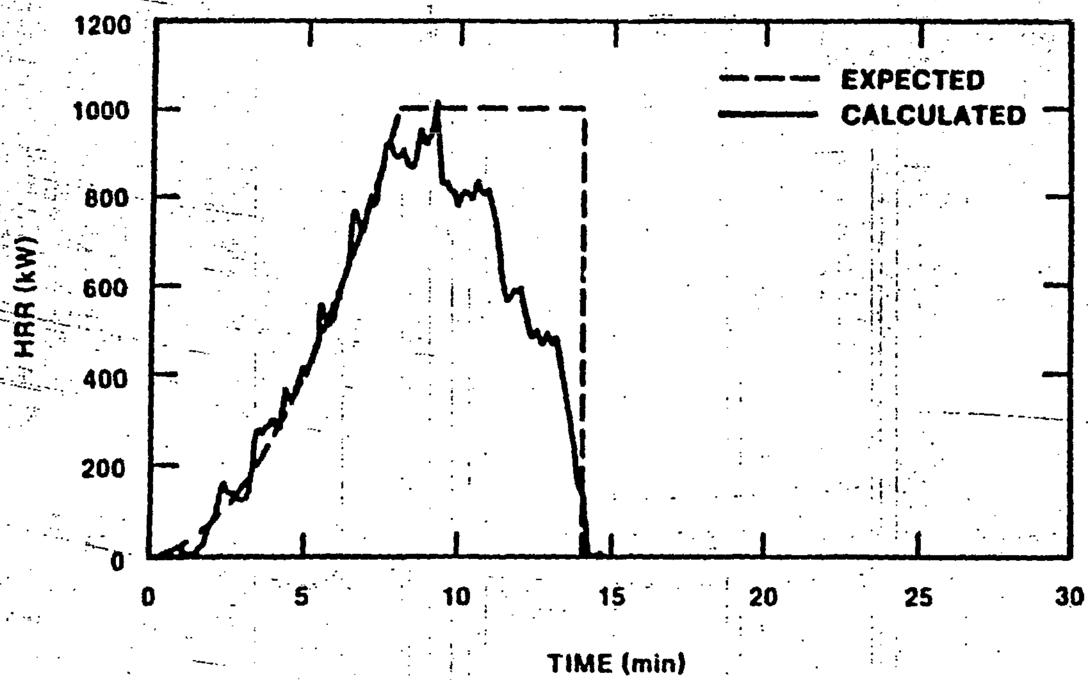


Figure 16. Expected and Calculated Heat-Release Rates During Test 22

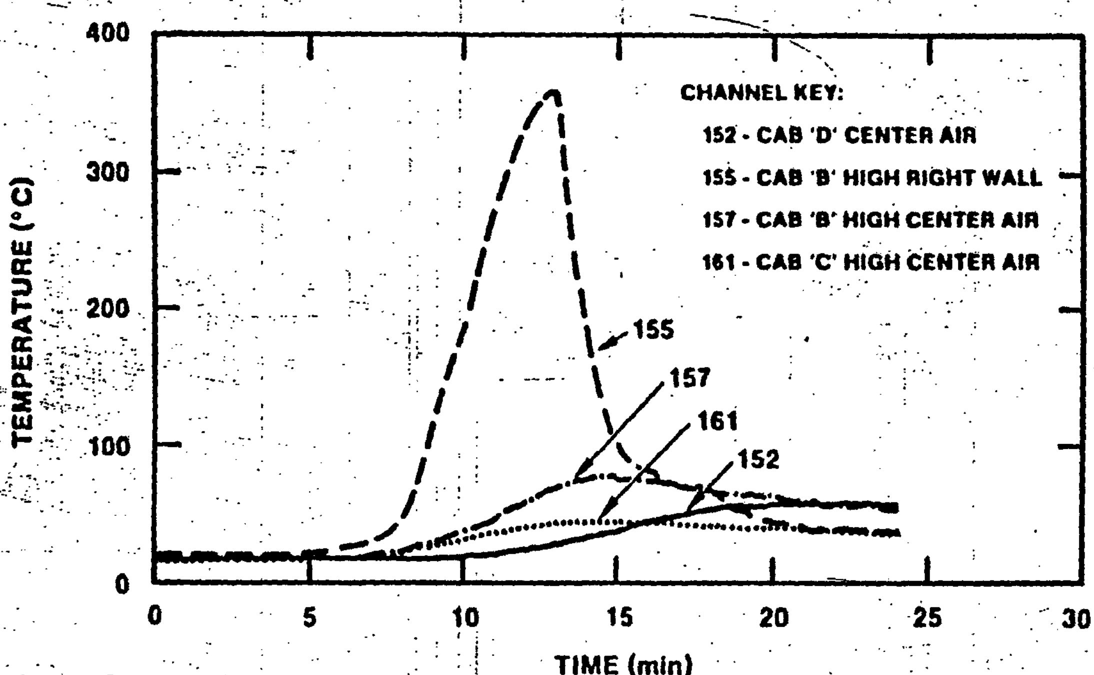


Figure 17. Temperatures in Noninvolved Cabinets During Test 22

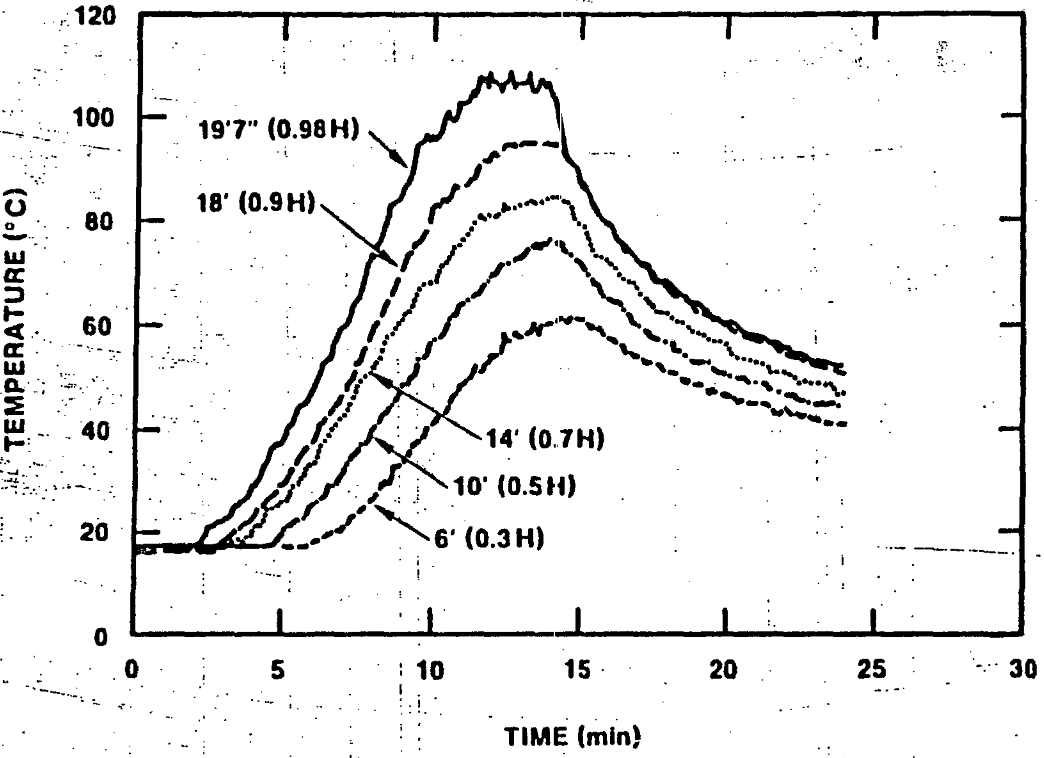


Figure 18. Aspirated Thermocouple Measurements at Sector 2 During Test 22

cabinet and used to make up the in situ fuel configuration. The configuration was arranged as nearly identical as possible to the configuration in Preliminary Cabinet Test 5.[3] The in situ fuel loading for Test 23 was 1.55×10^6 kJ (≈1.47×10^6 Btu). Ignition source for this test was the transient source (i.e., a bucket, a box of Kimwipes, and 0.9 ℓ (1 qt) of acetone). The cabinet was provided with a bottom front ventilation grill, and the door in the rear remained open during the test. Room ventilation was set at 1 rm ch/hr (0.38 m^3/s or 800 ft^3/min).

After ignition, the fire began to propagate rapidly up the ignition bundle and quickly spread throughout the cabinet. Unlike any previous cabinet test performed at SNLA with qualified (XPE/XPE) cable, the fire spread throughout the entire cabinet, consuming all the cable. This is attributed to two potential factors. First, as fires are inherently difficult to reproduce it has been conjectured that the cables were arranged in a "critical" configuration due to seemingly minor differences. It also appears that the soffit above the open cabinet door led to the formation of a "mini" hot layer within the cabinet that enhanced the thermal feedback to the cables, thus accounting for the much higher intensity than that observed with qualified cable in a vertical cabinet with no such doorway soffit. This event illustrates the influence of the so-called critical configuration described in the Cabinet Effects Tests.[3]

A description of Test 23 and a timeline showing the events that occurred during the test are provided in Figure 19. Figure 20 is a sequence of photographs taken during the test. The heat-release rate (HRR) in this test rose rapidly in ≈10 min to a peak of 1235 kW, then dropped off within another 10 min, as shown in Figure 21. This fire was the most intense fire encountered up to this point in the test effort. This fire intensity exceeded that observed in any of the cabinet effects tests, with either qualified or unqualified cables. Only Test 24 of this series, involving unqualified cable in an identical configuration and described below, resulted in a more intense fire.

The air inside the burning cabinet, as shown in Figure 22, was effectively at flame temperature until the fire began to burn down at around 20 minutes. However, the upper left wall temperature (TC 145) stayed at around 700°C until well after observable fire activity ceased. The continuing high temperature was most likely due to a hot spot caused by smoldering cables. Adjacent cabinet air and wall temperatures are shown in Figure 23. The peak adjacent cabinet wall temperature was 272°C at 11:15 min after ignition. As shown in Figure 23 at 11:15 min, the wall temperature dropped sharply to approximately cabinet air temperature (TC 147). The reason for the sharp drop in temperature appears to be because the thermocouple on the wall (TC 155) came loose from its attachment to the wall. The adjacent cabinet wall temperature would have gone higher, but how high is unknown. The peak cabinet air temperature was 114°C in Cabinet B at 16:30 min after ignition. Total cable weight burned during this test was 49.55 kg (109 lb).

The enclosure temperatures for Sector 2 (temperatures at other locations are very similar) are shown in Figure 24. The peak temperature, 132°C, in the enclosure at Sector 2 was at the 5.97-m (19-ft 7-in) level at 13:15 min after ignition. As shown in Figure 24, there is some vertical temperature stratification in the enclosure. The peak temperature at the 1.83-m (6-ft) level was 87°C at 15:30 after ignition. During the test, the smoke began to obscure the view at the 1.83-m level at 9 minutes. The optical densities at Sector 2 for three different levels are shown in Figure 25. The vision distance with a bright light at an optical density of 2 m^{-1} is ≈0.86 m. (Unit of optical density is reciprocal meters, i.e., meters to the -1 power, although conversion to visibility distances is not a linear operation.[4]) An observation made after the test was that there was a thick deposit of soot on the cabinets and floor. Also, it took a long time (1 hr) to purge the smoke from the enclosure after the test. Cable bundles in other cabinets, on top of other cabinets, and in other locations throughout the enclosure did not experience any damage.

In Test 24, unqualified cable (PE/PVC) was placed inside a benchboard cabinet. The in situ fuel configuration for this test was the same as for PCT 5 of the Cabinet Effects Tests. As in PCT 5, the ignition source was electrical, provided by a simulated high-resistance buildup. Again the fuel loading was 1.47×10^6 kJ (≈1.44×10^6 Btu). The room ventilation was maintained at 1 rm ch/hr. Ignition of the cables occurred at a power of

TEST #: 23

CABINET STYLE & VENTILATION: BENCHBOARD CABINET, FRONT VENTILATION GRILL AND OPEN BACKDOOR

IN SITU FUEL TYPE & AMOUNT: QUALIFIED CABLE (XPE/XPE), 1.55 x 10^6 kJ (1.47 x 10^6 Btu)

IGNITION TYPE & AMOUNT: POLYETHYLENE BUCKET, BOX KIMWIPES, 0.946ℓ (1 qt.) ACETONE

ROOM VENTILATION RATE: 1 rm ch/hr

CONDITIONS AT TEST START: TEMPERATURE 13° C, RELATIVE HUMIDITY 43%

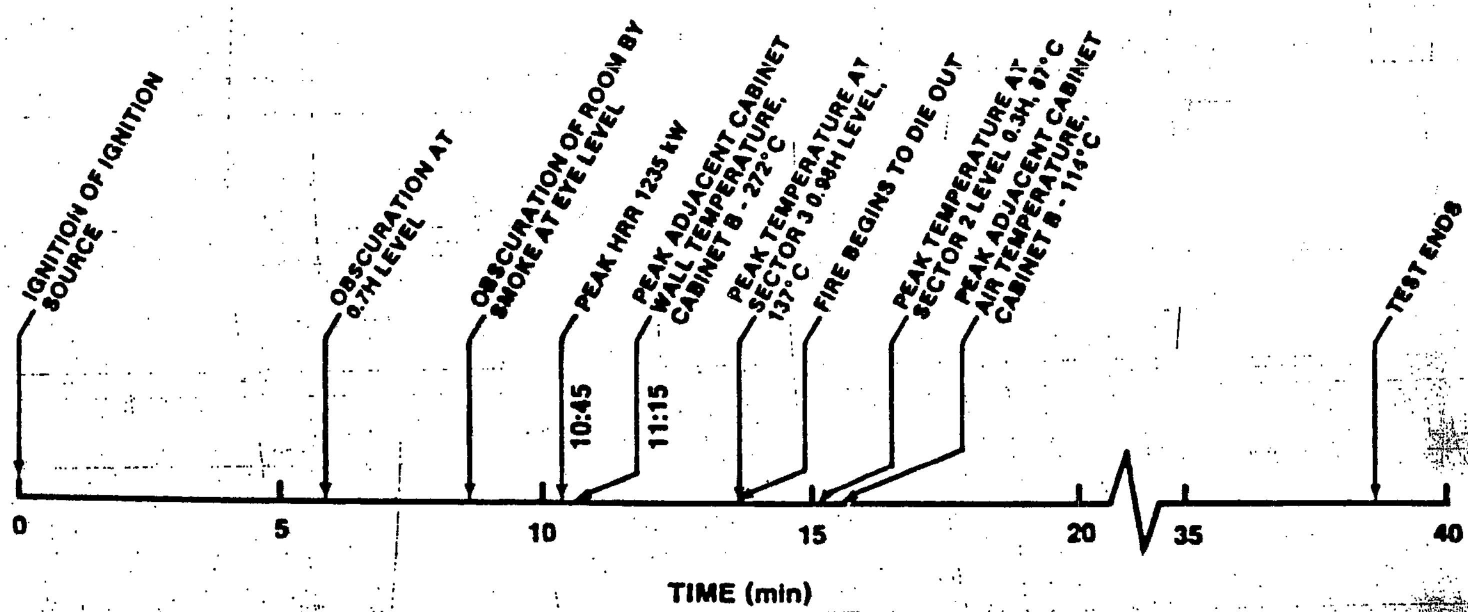
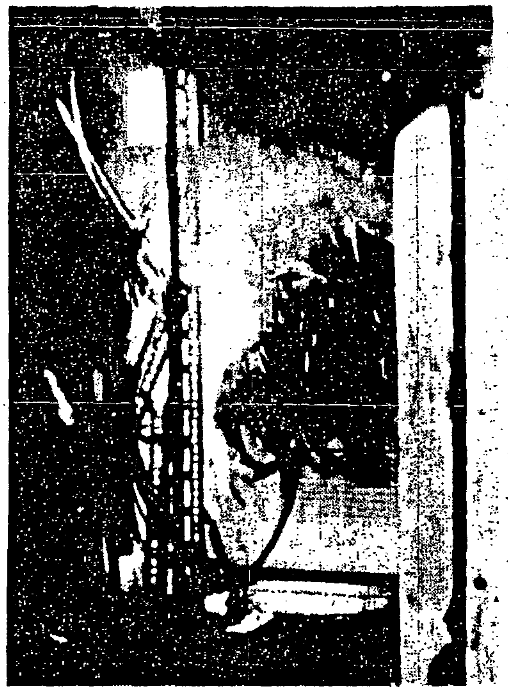


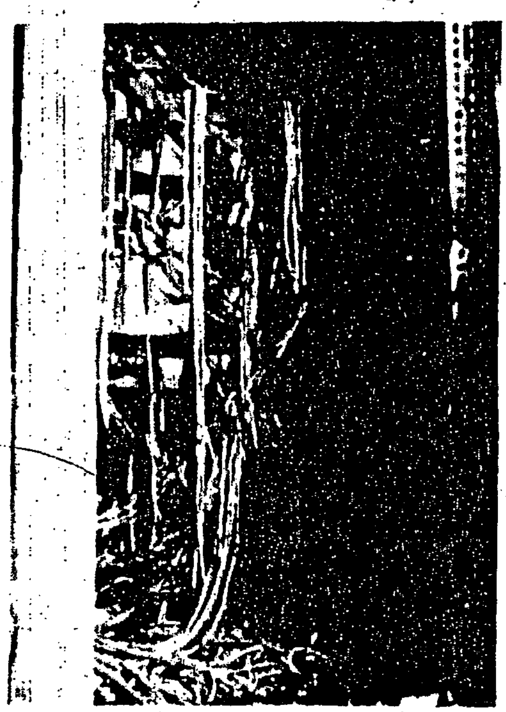
Figure 19. Description and Timeline for Test 23

a. 1:08 minutes



b. 3:40 minutes

c. 7:30 minutes



d. Posttest

Figure 20. Photographs of Test 23

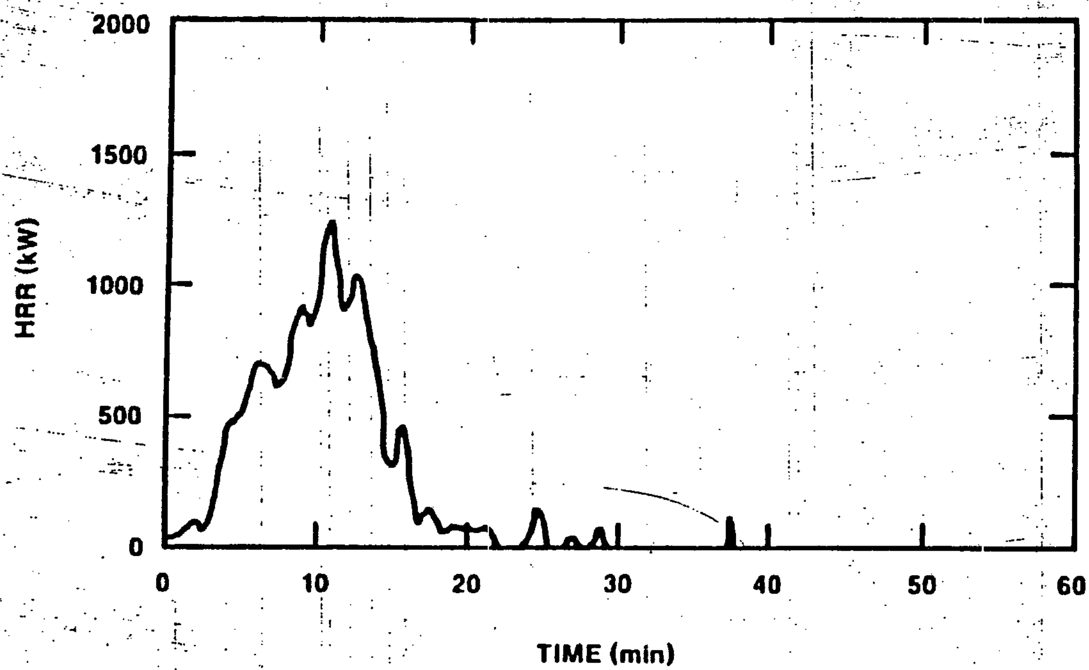


Figure 21. Calculated Heat-Release Rate for Test 23

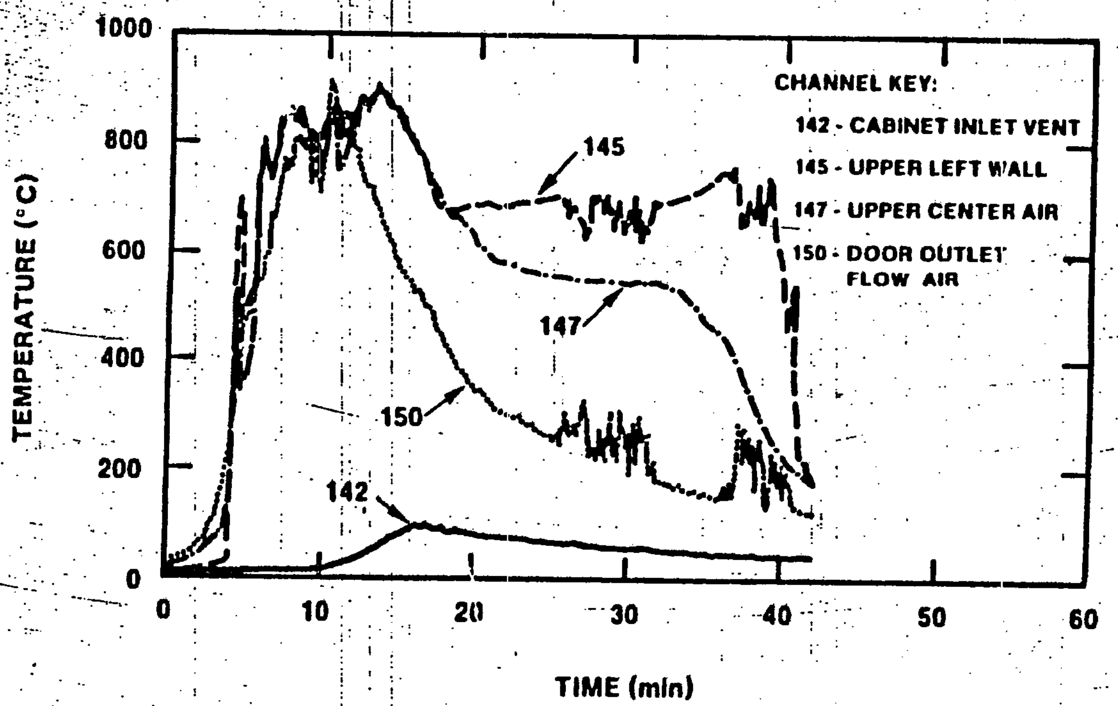


Figure 22. Temperatures in Cabinet A (Subject Cabinet) During Test 23

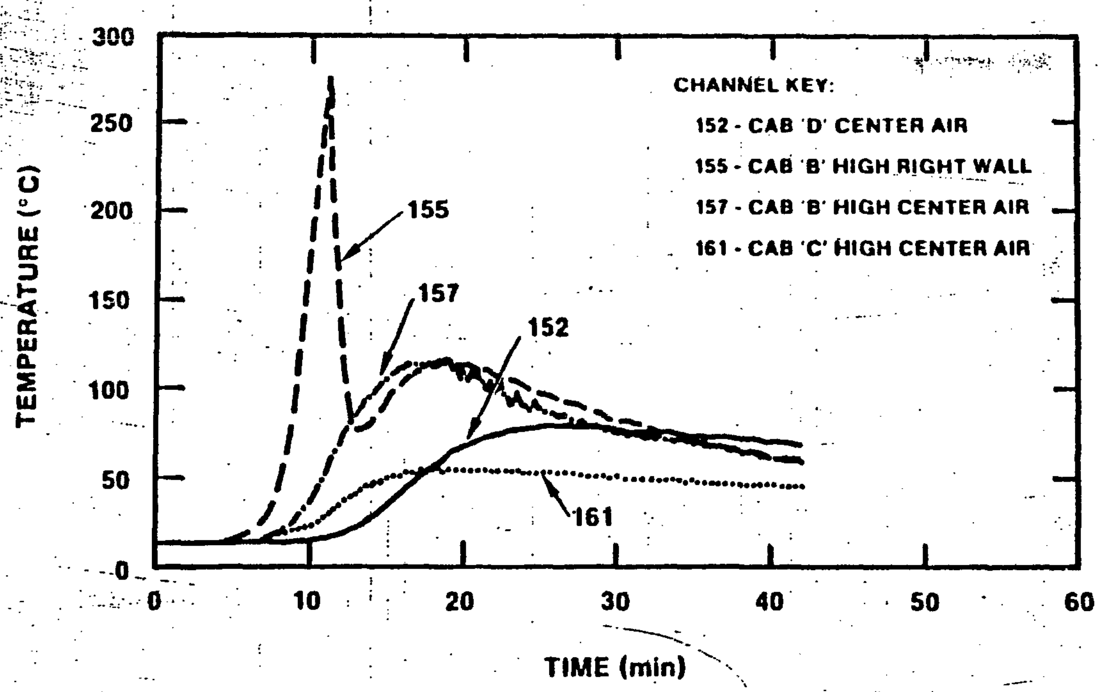


Figure 23. Temperatures in Noninvolved Cabinets During Test 23

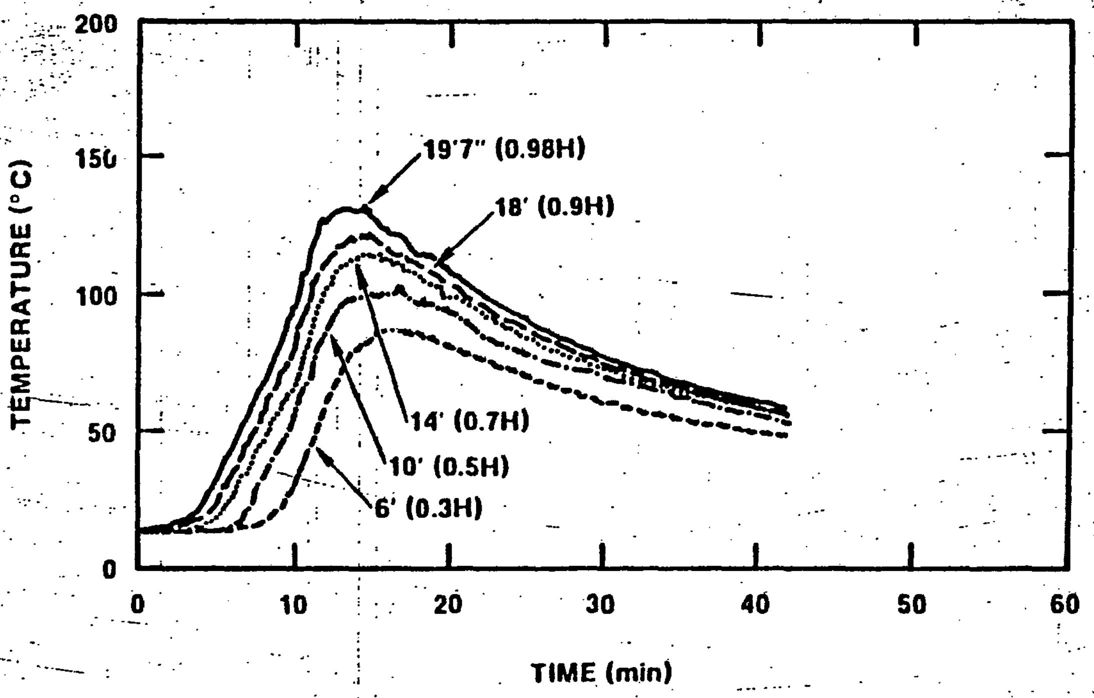


Figure 24. Sector 2 Air Temperatures at Each of Five Elevations During Test 23

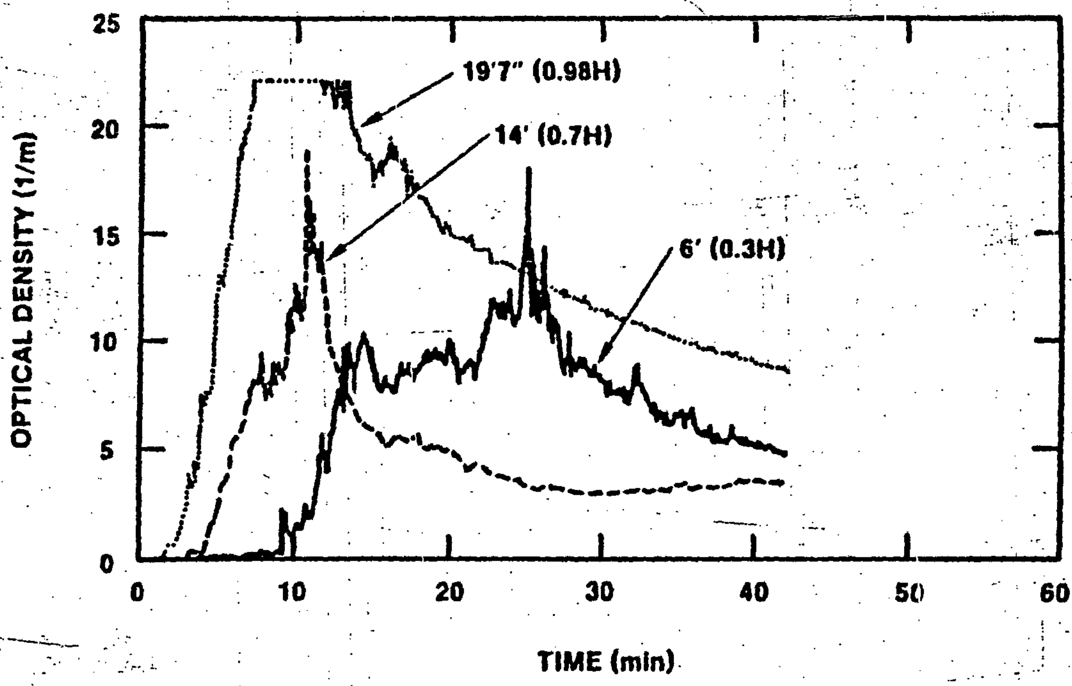


Figure 25. Sector 2 Optical Densities at Each of Three Elevations During Test 23

170 W through the circuit used to provide the high-resistance buildup. The fire burned and propagated in much the same manner as it did in PCT 5. A large quantity of soot was deposited on the cabinet, and on the walls and floor of the facility. Figure 26 provides a description and a timeline giving the highlights of Test 24; Figure 27 is a sequence of photographs illustrating this test. The curve shown in Figure 28 reveals that the heat-release rate peaked at an intensity of 1300 kW 27:30 min into the test, 12:10 min after ignition. It took approximately 6 min for the fire to become large enough to register on the instrumentation, but very shortly thereafter the HRR peaked, indicating an extremely high rate of combustion. The mass-loss instrumentation did not function properly during Test 24, so no data were recorded from which the rate of mass loss could be computed. However, posttest examination showed that the total mass loss was 50 kg (110 lb). Once the combustibles had been exhausted, the fire died out as quickly as it had risen.

TEST #: 24

CABINET STYLE & VENTILATION: BENCHBOARD CABINET, FRONT VENTILATION GRILL AND OPEN BACKDOOR

IN SITU FUEL TYPE & AMOUNT: UNQUALIFIED CABLE (PE/PVC), 1.47×10^6 kJ (1.44×10^6 Btu)

IGNITION TYPE & AMOUNT: ELECTRICAL, IGNITION SOURCE

ROOM VENTILATION RATE: 1 rm ch/hr

CONDITIONS AT TEST START: TEMPERATURE 20° C, RELATIVE HUMIDITY 71%

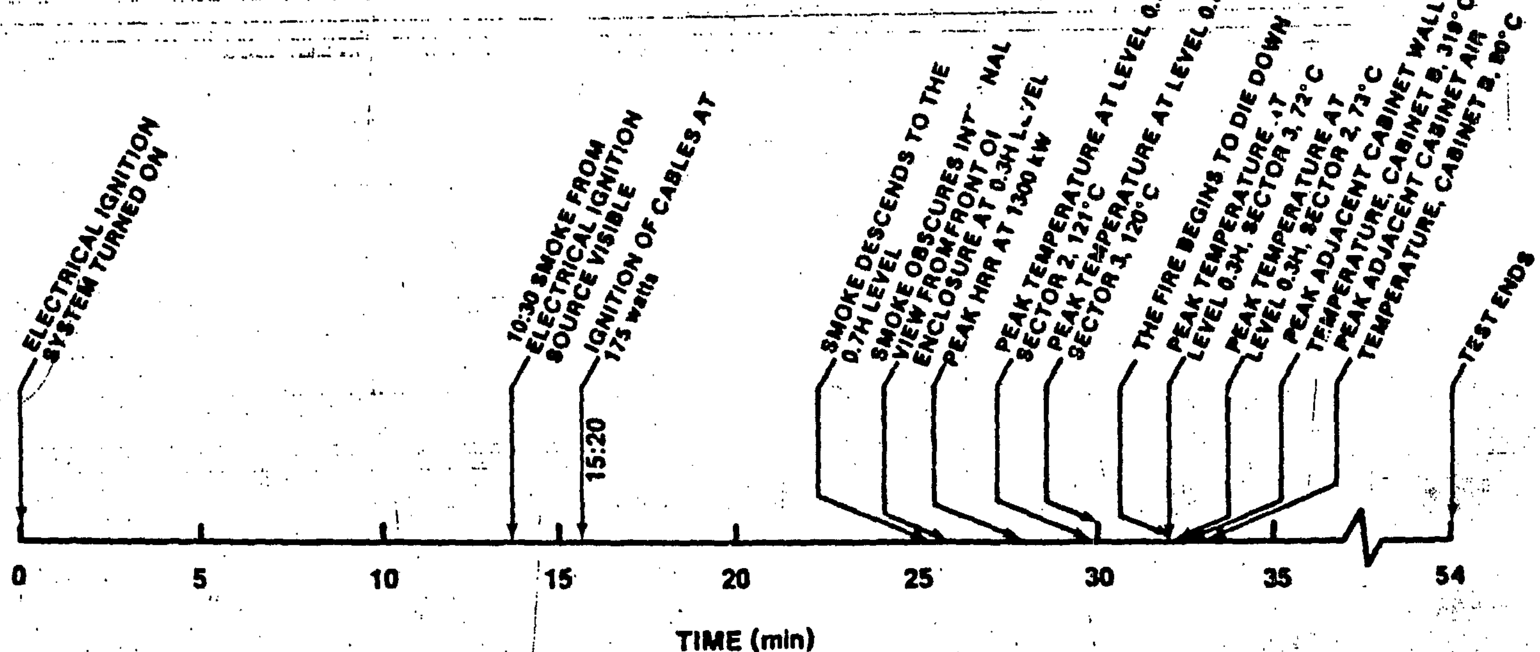


Figure 26. Description and Timeline for Test 24

a. 2:15 minutes

b. 8:00 minutes

c. 9:00 minutes

d. Posttest

Figure 27. Photographs of Test 24.
(All times are after ignition)

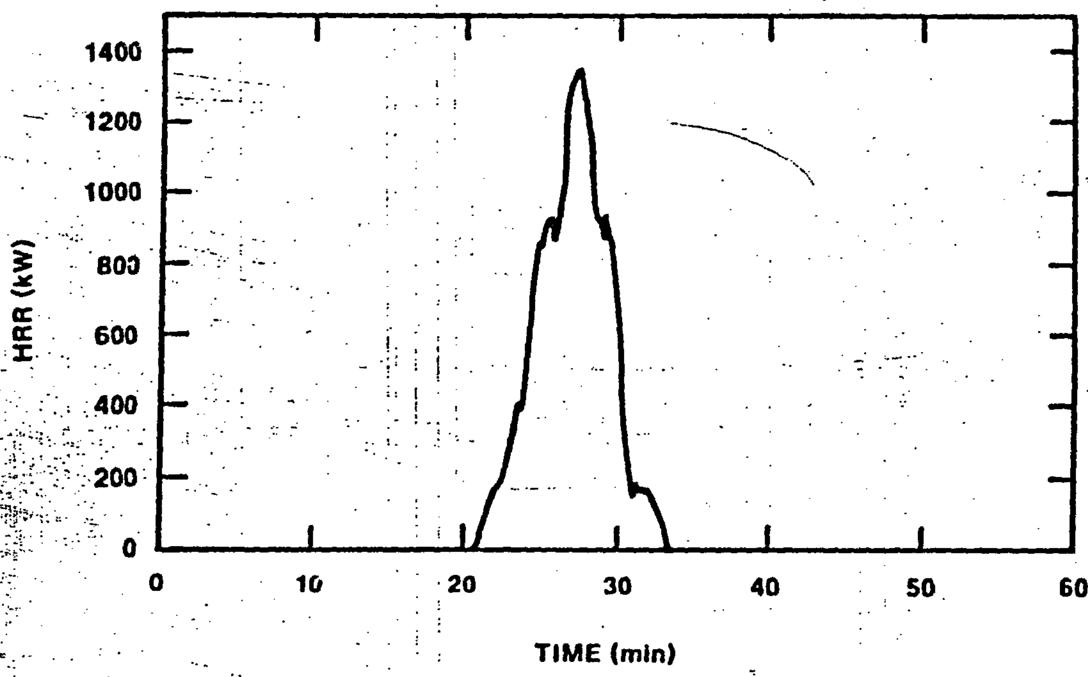


Figure 28. Calculated Heat-Release Rate for Test 24

Figure 29 is a plot of temperatures inside Cabinet A during Test 24. It shows that the cabinet's interior essentially reached the flame temperature once the fire began to spread. Flames were, in fact, observed coming out of the cabinet near the top of the door. There appeared to be combustion of the gases in the top of the cabinet. Figure 30 is a plot of temperatures inside Cabinet B, the adjacent cabinet, during Test 24. The peak temperature in Cabinet B reached only 90°C at 34 min, but the right cabinet wall recorded a temperature of 319°C at 32:30 min (18:40 and 17:10 postignition, respectively).

Figure 31 is a plot of air temperatures at Sector 2 of the test enclosure (temperatures at other locations were similar to those at Sector 2). At the 5.97-m (19-ft 7-in) elevation, the peak of 121°C was reached at 29:45 min; at 1.83 m (6 ft) above the floor, the highest temperature recorded was 75°C at 32:16 min (14:25 and 16:54 postignition, respectively). Some vertical temperature stratification is apparent, but not as much as in Test 23 with qualified cable. The temperatures seen in Test 24 are below damage levels for most equipment and cables, with the possible exception of integrated circuits. Figure 32 indicates the gradual descent of the smoke layer as the test progressed. Smoke completely obscured the view

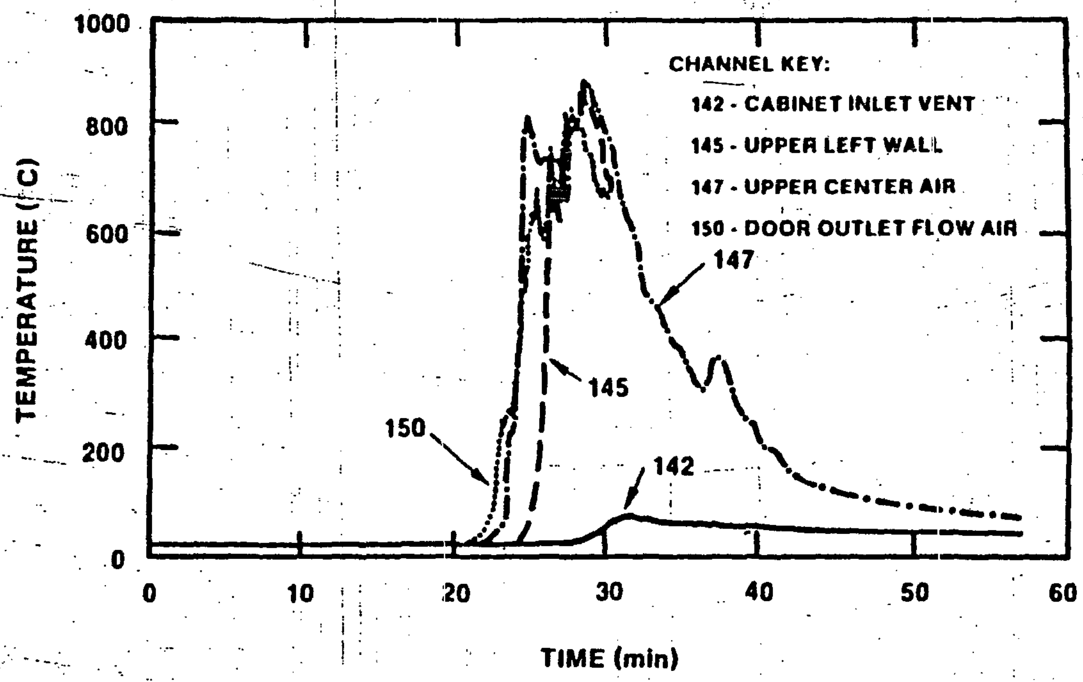


Figure 29. Temperatures in Cabinet A (Subject Cabinet) During Test 24. Note failure of TCs 145 and 150 at 30.5 min

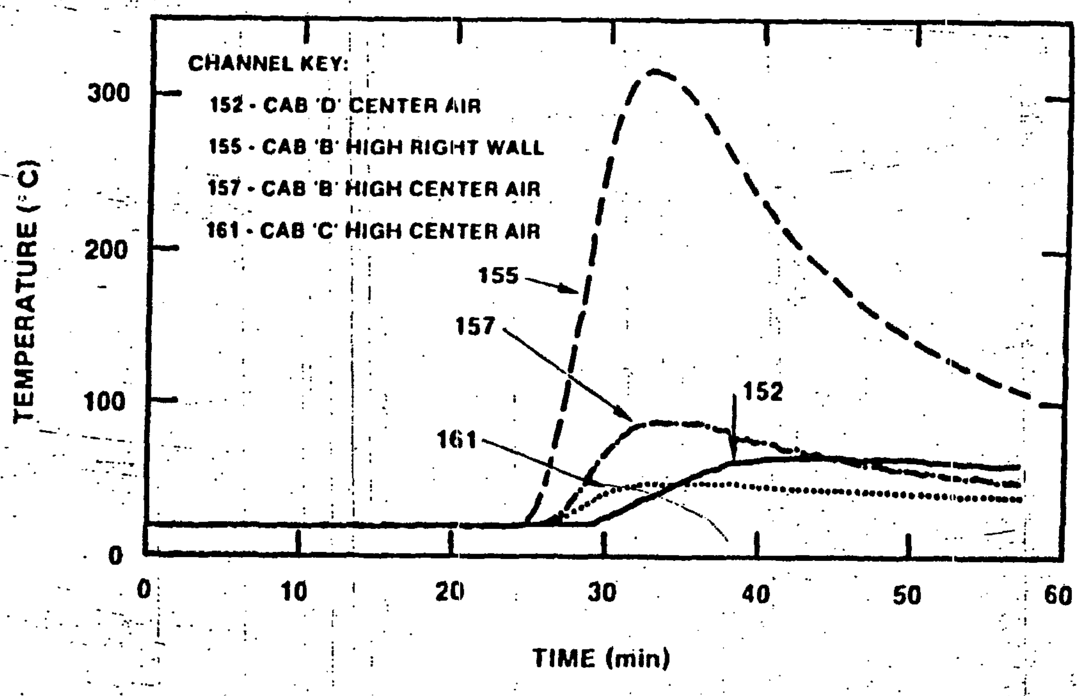


Figure 30. Temperatures in Noninvolved Cabinets During Test 24

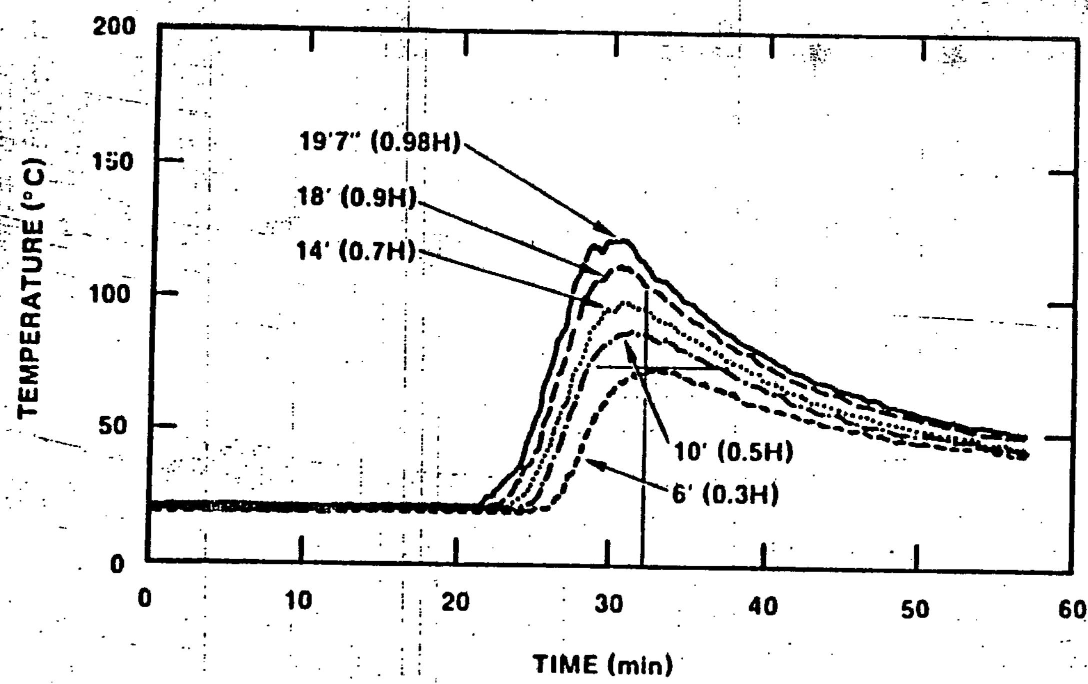


Figure 31. Sector 2 Air Temperatures at Each of Five Elevations During Test 24

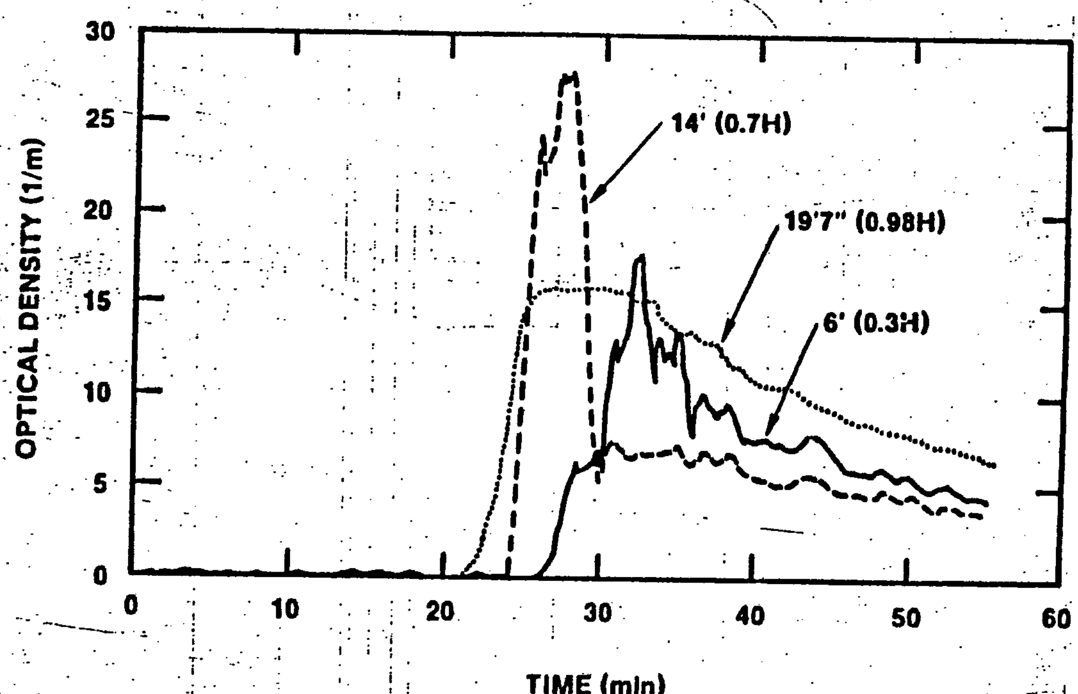


Figure 32. Sector 2 Optical Densities at Each of Three Elevations During Test 24

from the front of the enclosure of the 1.8-m (6-ft) level beginning approximately at 15 min after ignition. This visual observation is somewhat at variance with the plot, which shows an optical density of 1 m^{-1} at 27 min, or 12 min after ignition, shortly prior to the time at which smoke was visually observed to obscure vision.

Significantly more soot was observed to have been deposited on the floor and cabinets than had been seen in Test 23 or in any of the Cabinet Effects Tests. There are three likely causes, which may have operated separately or in combination to produce this result: (1) the recorded relative humidity of 71% (this parameter never reached that value in the Cabinet Effects Tests), (2) the use of unqualified cable as the in situ fuel; or (3) the low ventilation rate (1 rm ch/hr) compared to the Cabinet Effects Tests. This discussion is carried further by Jacobus in Reference 7. As in Test 23, no damage to cables outside the burning cabinet was observed.

3.3 Vertical Cabinet Fire Test (Test 25)

The last test performed was Test 25, in which unqualified cable (PE/PVC) was burned inside a vertical cabinet. The in situ fuel arrangement and amount were approximately the same as in PCT 2.[3] Approximately 1.05×10^6 kJ (1.0×10^6 Btu) of cable insulation was loaded into the vertical cabinet. The doors to the cabinet were left open throughout the test. Ignition was induced by simulated electrical high-resistance heat buildup (in PCT 2, the equivalent test from Part 1 of the test series, a transient ignition source was used). Room ventilation was maintained at an exchange rate of 8 rm ch/hr (6400 ft^3/min) to investigate the effect of high ventilation rates. The fire propagated in much the same way it did in PCT 2, consuming most of the cables except a few near the floor of the cabinet.

Figure 33 is a description and timeline, showing significant events during Test 25. Figure 34 is a sequence of photographs taken during the test (times shown are after ignition). The heat-release-rate curve shown in Figure 35 shows an 840 kW peak at 22 min into the test, 6:20 min after ignition. This is compared to the approximate peak HRR of 995 kW seen at 12 min after ignition in PCT 2. The fire appears to have spread much more quickly in this test than it did in Test 24, when peak HRR was not reached until 12 min after electrical ignition. The fire grew very quickly yet died down slowly, compared with Tests 23 and 24. The most probable causes of this difference in fire behavior were that in Test 25, the fuel was more widely dispersed horizontally, and there were fewer vertical cable runs in the cabinet; thus, it reached a lower peak HRR sooner and burned at a lower rate for a longer period.

In this test, a smoke detector was mounted on the ceiling of the cabinet directly above the electrical ignition source. A second detector was also placed on the ceiling of remote cabinet "F", as shown in Figure 2. The purpose of the smoke detector was to determine when a typical in-cabinet

TEST #: 25

CABINET STYLE & VENTILATION: VERTICAL CABINET, OPEN DOORS

IN SITU FUEL TYPE & AMOUNT: UNQUALIFIED CABLE (PE/PVC) 1.05×10^6 kJ (1×10^6 Btu)

IGNITION TYPE & AMOUNT: ELECTRICAL IGNITION SOURCE

ROOM VENTILATION RATE: 8 rm ch/hr

CONDITIONS AT TEST START: TEMPERATURE 13°C, RELATIVE HUMIDITY 34%

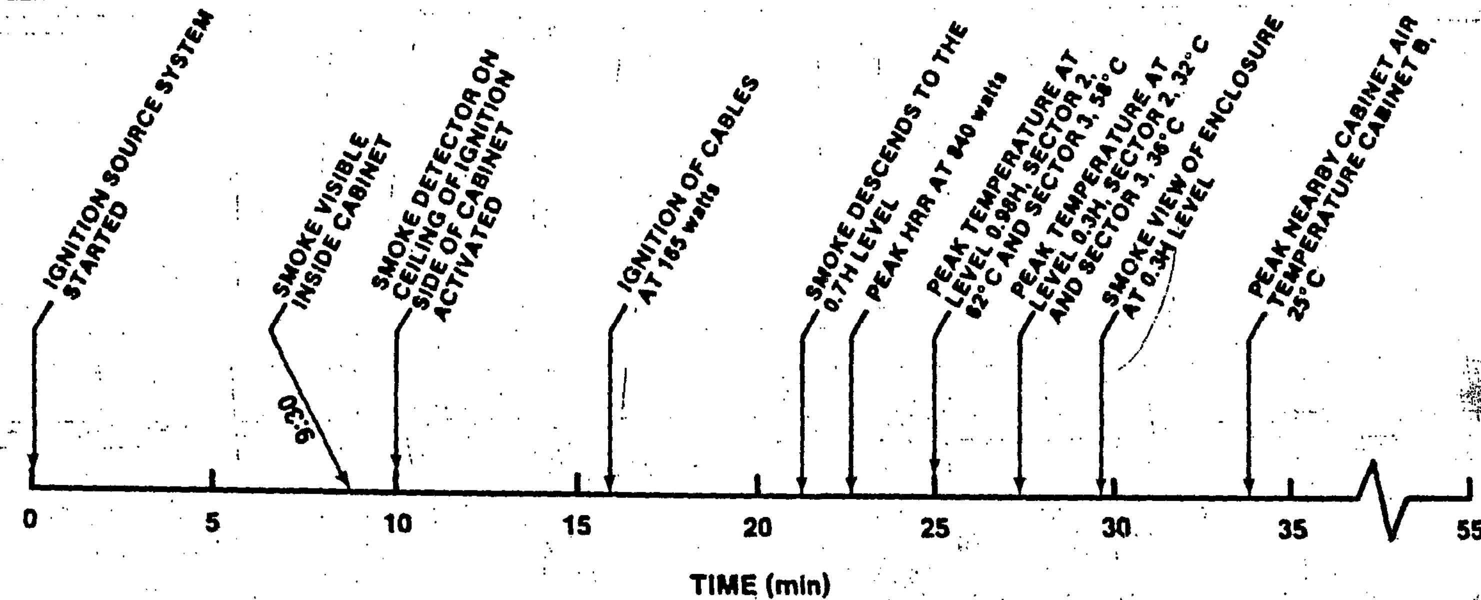
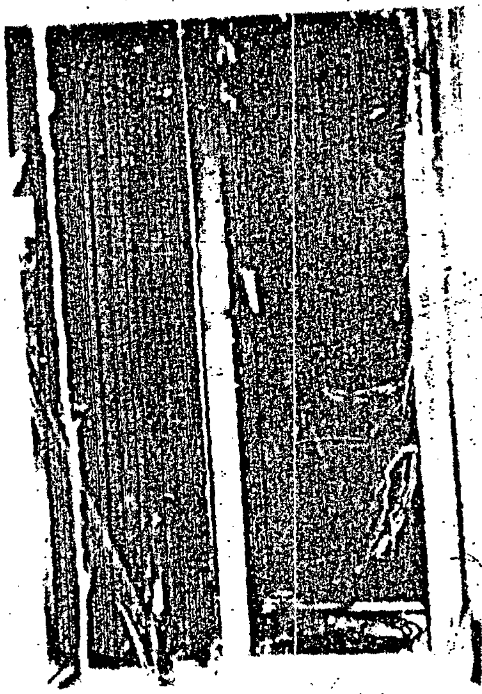


Figure 33. Description and Timeline for Test 25

a. 2:15 minutes

b. 7:10 minutes

c. 10:15 minutes



d. Posttest

Figure 34. Photographs of Test 25

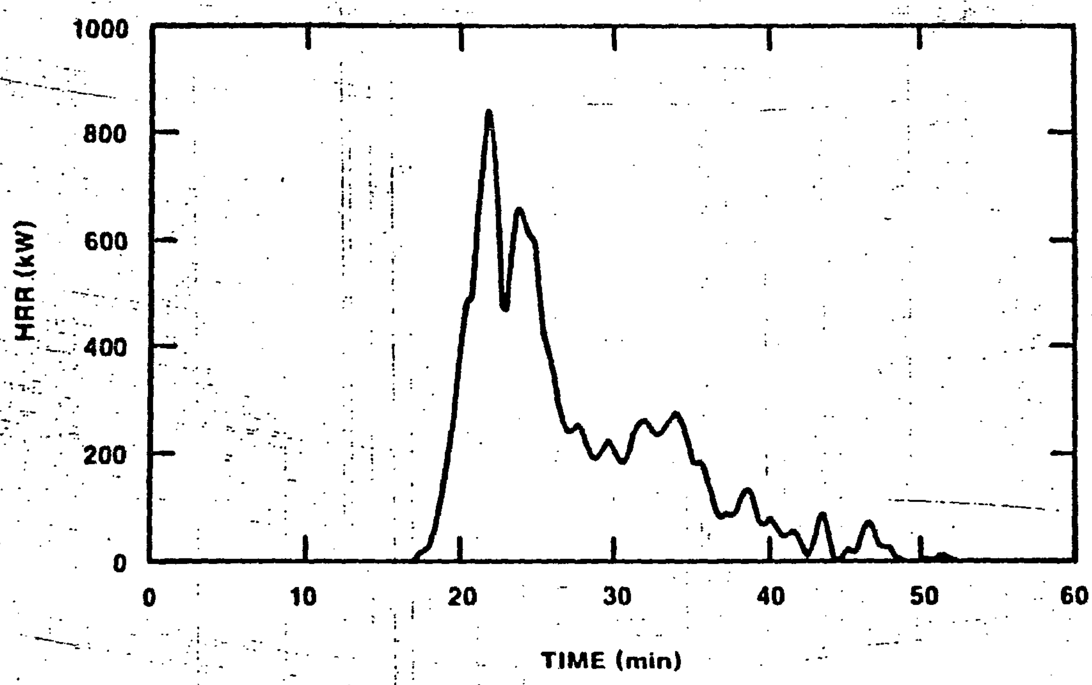


Figure 35. Heat-Release Rate for Test 25. Based on 8 rm ch/hr and then smoothed

detector would detect smoke from an electrical ignition source such as that used here. Smoke was visually observed, in a very small amount, from the electrical ignition source at 9.5 min after the source was turned on or 6 min prior to actual ignition. The detector within the source cabinet signaled smoke detection at approximately 10.5 min after the source was turned on, or approximately 1 min after visual detection of smoke. The second detector in the remote cabinet did not activate until 25.5 min after the source was turned on, 10 min after actual ignition. This experiment showed only that the in-cabinet detector (source cabinet) could detect smoke from the electrical ignition source before a fire actually started. Had the doors on the cabinet been closed, the smoke might have been detected earlier (due to smoke accumulation in the cabinet). Also, this detector had been placed in the optimum location, based on pre-event knowledge of the fire source's location, for detection of the source.

Figure 36 shows temperatures recorded at three different locations within Cabinet C (the subject cabinet) during Test 25. Generally, these temperatures are substantially lower than the corresponding temperatures in the earlier tests (400° versus 800°C). Again, the most probable cause was the great horizontal dispersal of the fuel in the benchboard cabinet. Figure 37 portrays the air temperature at the high center location in Cabinet B (the cabinet nearest the subject cabinet) during Test 25. This parameter never exceeded 25°C, which was reached at 34 min into the test

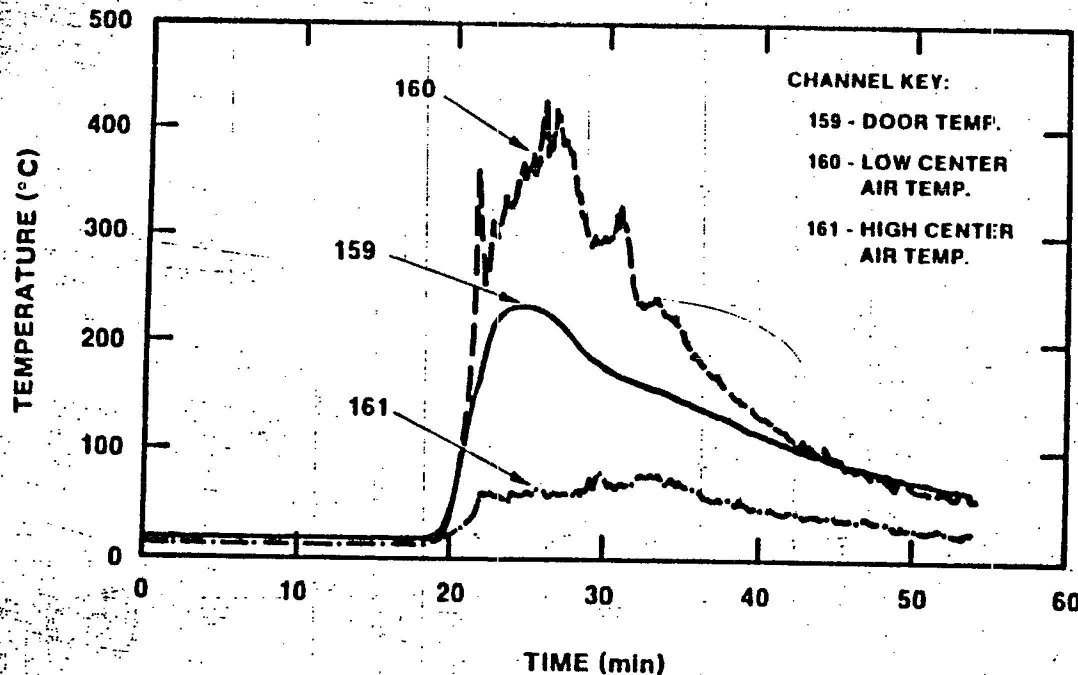


Figure 36. Temperatures in Cabinet C (Subject Cabinet) During Test 25

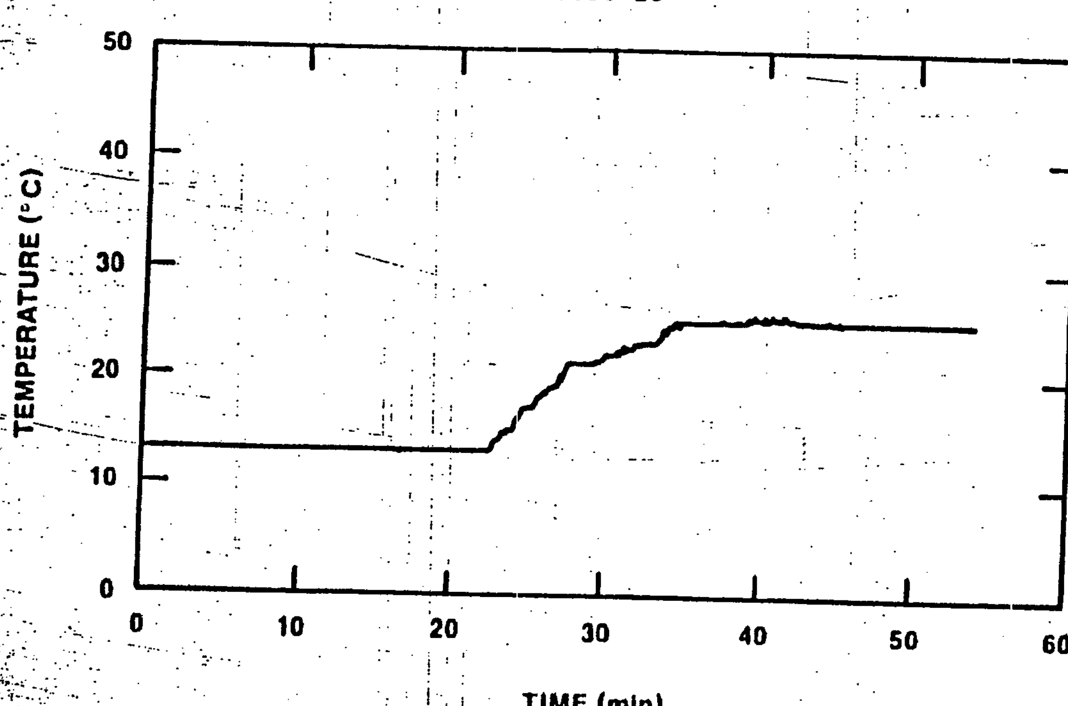


Figure 37. High Center Air Temperature in Cabinet B During Test 25

(18 min after ignition). Note from Figure 2 that there were no cabinets immediately adjacent to Cabinet C, so there are no data available on temperatures in "adjacent" cabinets.

Figure 38 shows temperature profiles at Sector 2 of the test enclosure during Test 25 (similar to the profiles at other locations). Peak temperature at the 5.97-m (19-ft 7-in.) level was 62°C at 25 min (9 min after ignition). At the 1.83-m (6-ft) level, the peak was 32°C at 27 min (11 min after ignition). Overall, the temperatures experienced were relatively low. As usual, there was some vertical temperature stratification in the enclosure. The higher ventilation rate in this test, pumping 6400 ft^3/min of cold air into the enclosure, may have held temperatures down. Figure 39 depicts the recorded optical density data for Test 25. Visual observations were that smoke did not begin to obscure the view at the 1.83 m (6 ft) elevation until 30 min (14 min after ignition); the data indicate obscuration at this level beginning at 23 min (7 min after ignition). This disagreement between optical density instrumentation data and visual observation is more pronounced in this test than in any of the others. This discrepancy may be a result of the partitioning effects of the cabinets. Measurements were made at the room center in front of the cabinets, while observations were made from the backside viewing windows. Optical densities appear to be lower in this test, presumably because of the high ventilation rate.

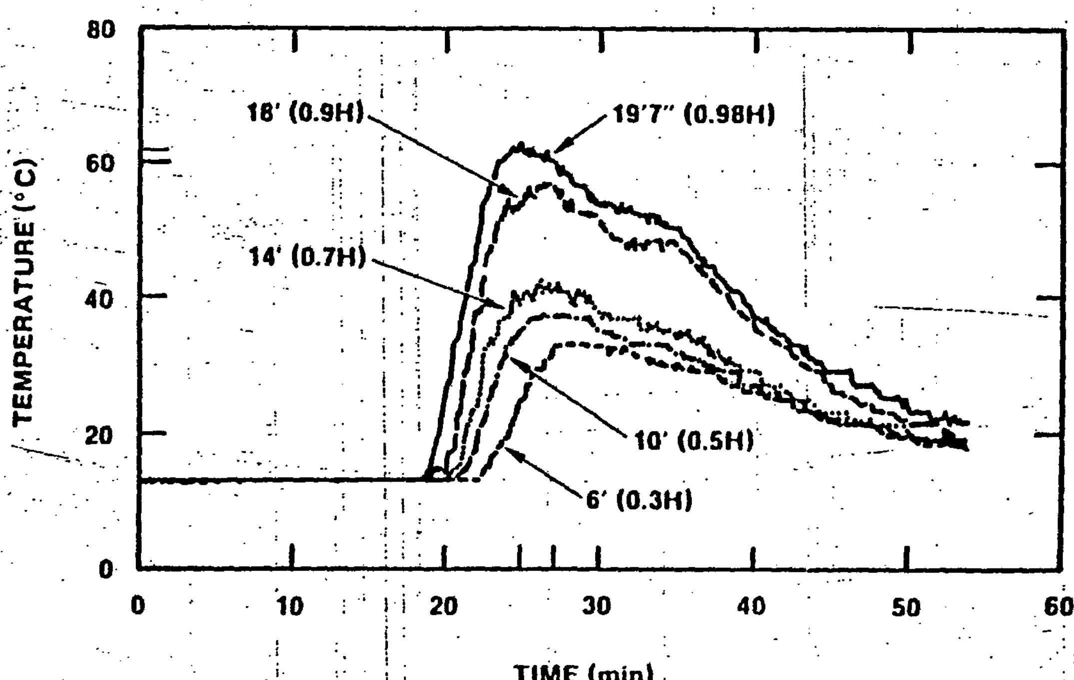


Figure 38. Sector 2 Air Temperatures at Each of Five Elevations During Test 25

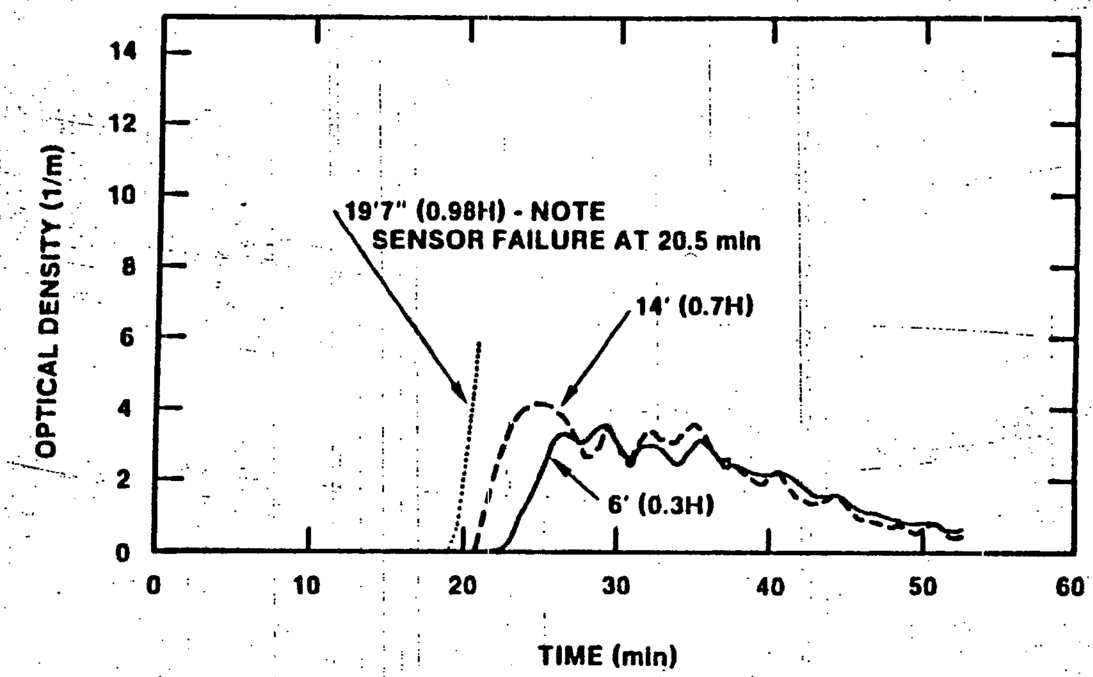


Figure 39. Sector 2 Optical Densities at Each of Three Elevations During Test 25

4. CONCLUSIONS

These "Room Effects Tests" provided validation of the "Cabinet Effects Tests" in showing that, for similar configurations, the fires could be duplicated and burn in much the same way. In addition, with both types of ignition sources, the tests provide confirmation that the threat of spontaneous (non-piloted) ignition to an adjacent cabinet (assuming a double wall between cabinets) from high temperature either on the adjacent cabinet wall or in the adjacent cabinet is small. Typical adjacent cabinet air temperatures during the fire were less than 120°C. For most equipment, with the possible exception of integrated circuits, these temperatures will probably not result in operational failure. Some types of sensitive control circuits could be expected to experience calibration shifts at these temperatures as well. Adjacent cabinet wall temperatures reached as high as 360°C, which may cause failure of cables and of equipment mounted very near this wall. Again, the double-barrier cabinet wall configuration was most likely responsible for moderating wall temperatures. It was also demonstrated during this test phase that given the right configuration of cabinet, ignition source, and in situ fuel, the IEEE-383 qualified cable (XPE/XPE) could result in a quickly propagating intense fire that would burn all the fuel in the cabinet.

Conclusions relating to the effect of a cabinet fire on a control-room-size enclosure are as follows:

- The smoke begins to obscure the view inside the enclosure within 6 to 15 min after ignition, even in the large enclosure. The time to obscuration is slightly longer at the higher ventilation rate, presumably due to enhanced dilution of the smoke. A ventilation rate of 8 rm ch/hr was not high enough to effectively purge the smoke from the enclosure. It appears that significantly higher air exchange rates and a reconfiguration of the system with inlets at floor level will be required to purge the smoke from the enclosure. This aspect was not fully investigated.

- No true uniform "hot layer," as often indicated by a significant temperature discontinuity, developed in the enclosure; rather there is significant vertical temperature stratification. Peak temperatures (near the enclosure ceiling outside the fire plume) are typically less than 150°C even given fires on the order of 1 MW in intensity. This temperature does not pose a threat from autoignition. The enclosure temperatures in these tests were lower than those in the Cabinet Effects Tests because of the larger enclosure volume, even though lower relative ventilation rates were used. These tests did not investigate the isolation of groups of cabinets from the general enclosure, as is often done for ventilation purposes. Such isolation of cabinets could result in significantly higher local temperatures, because one is in effect creating a small room within the larger enclosure.

- The amount of soot deposition from burning cable fires (which could cause shorting in some components in the enclosure) appears to be a function of fire development rate, ventilation rate, and humidity in the enclosure. In all cases fairly heavy soot deposition throughout the enclosure was observed. Further, it was found that in the case of unqualified cables this soot was heavily loaded with chlorides, raising the possibility that if combined with moisture a highly acidic solution could result (see Reference 7).

It should be noted that these tests are very configuration-specific, that is, with different cabinet types and configurations, in situ fuels and loadings, and ignition sources, the fires could have burned quite differently. The data from these tests should be extrapolated with care. Test 23 was particularly significant in this respect. As a result of the Cabinet Effects Tests, it was initially concluded that use of IEEE-383-qualified cable would significantly reduce the potential intensity of a cabinet fire. The intensity of the fire in Test 23, 1235 kW peak release rate, was exceeded in both test series only by Test 24, at 1300 kW. This test clearly demonstrates the inherent variability of fires, and that, given the proper circumstances, a quite severe fire in qualified cables is a realistic possibility.

No effort was made to determine the capability of a nuclear power plant to shut down in the event of a cabinet fire. In addition (although there are data available), no effort was made to evaluate the combustion-product gases and their effects on operators. For the configurations tested, it appears that the most significant problems with respect to the enclosure environment that could arise are those related to obscuration of the view within the enclosure and to the inability to purge the smoke from the enclosure. Due to the rapid build-up of smoke and the resulting degradation of visibility conditions, operator effectiveness in such situations would be severely compromised, probably to the point of essentially no effectiveness.

Cables that were placed in adjacent cabinets and throughout the enclosure showed no sign of significant damage externally or internally (except large deposits of soot). Cables in adjacent Cabinet B experienced some melting of the jacket (of one cable on the right wall), although there was no shorting of the internal conductors and no sign of potential autoignition. While adjacent cabinet temperatures did not pose an autoignition problem, some sensitive items of control equipment, particularly those based on integrated circuits, may experience calibration drifts and/or failures at the observed temperatures. This question was not directly investigated. This series of tests did not address the potential for spread of fire beyond the cabinet of origin through cables penetrating the cabinet surfaces. Given the intensity of the observed fires this potential cannot be discounted.

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UPPLEMENTARY NOTES

ABSTRACT (200 words or less)

This report presents the findings of the second part of a two-part series of full-cale electrical cabinet fire tests conducted by Sandia National Laboratories for the .S. Nuclear Regulatory Commission. The first part of this test series investigated he effects of various cabinet parameters on a cabinet fire. The second part of the est series, described here, investigated the effects of such a fire on a large 18.3x12.2x6.1-m or 60x40x20-ft) enclosure.

Five tests involving a fire in a control cabinet were conducted under Part 2 of he test series. These tests investigated the effects of fuel type, cabinet onfiguration, and enclosure ventilation rate on the development of the enclosure nvironment. Although fires as large as 1300 kW resulted, enclosure peak temperatures outside the fire plume itself) were typically less than 150°C, with significant ertical thermal stratification observed. The most significant impact on the test nclosure environment was that dense smoke, in all cases, resulted in total obscuration f the enclosure within 6-15 min of fire ignition. Enclosure ventilation rates as high s 8 room air changes per hour were found to be ineffective in purging the smoke from his large enclosure. Similar obscuration problems had also been observed in the Part tests, which utilized a smaller enclosure with ventilation rates as high as 15 room ir changes per hour.

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Fire

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