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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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Sandia National Laboratories

Prepared for
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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 (18.3×12.2×6.1-m or 60×40×20-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.

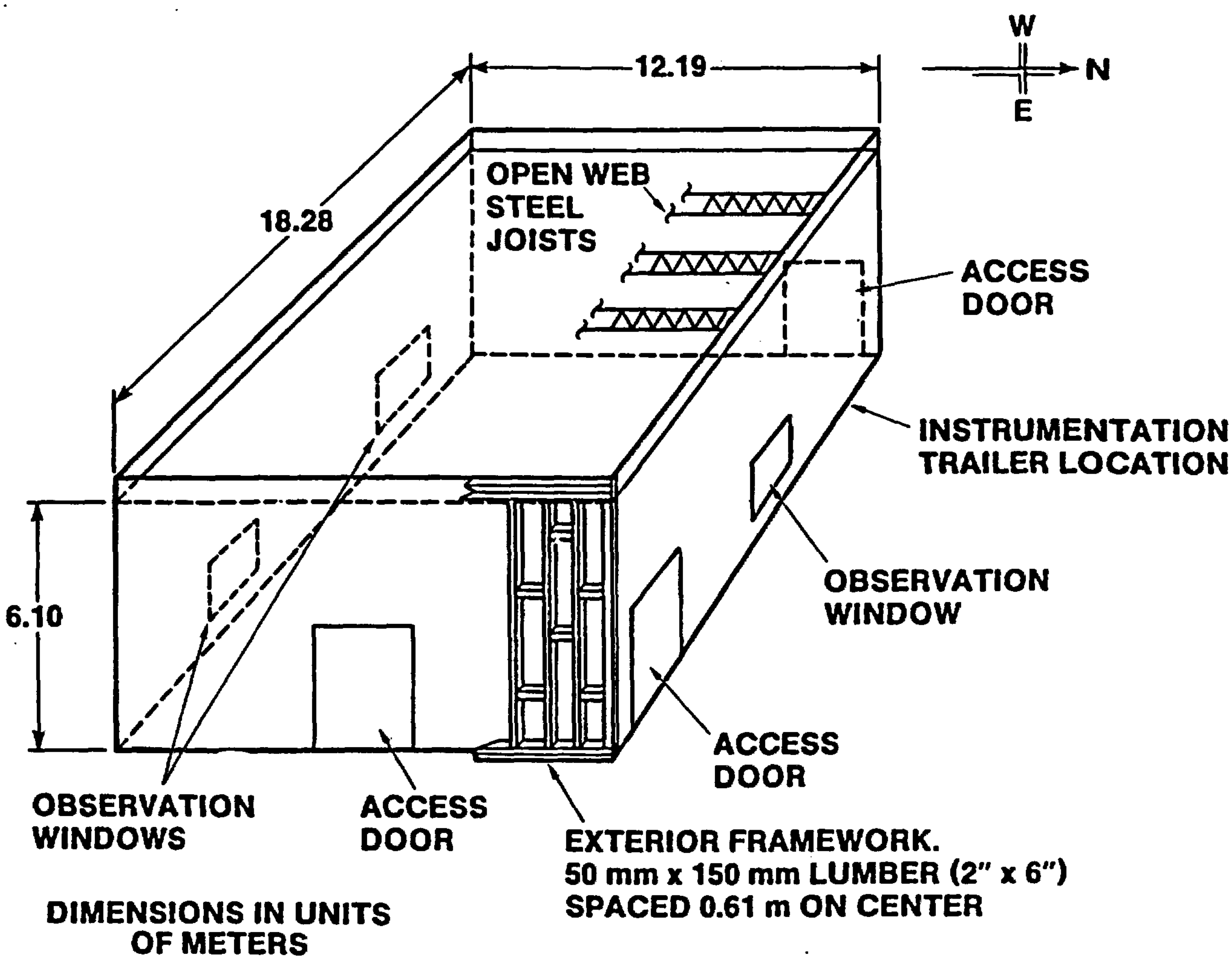
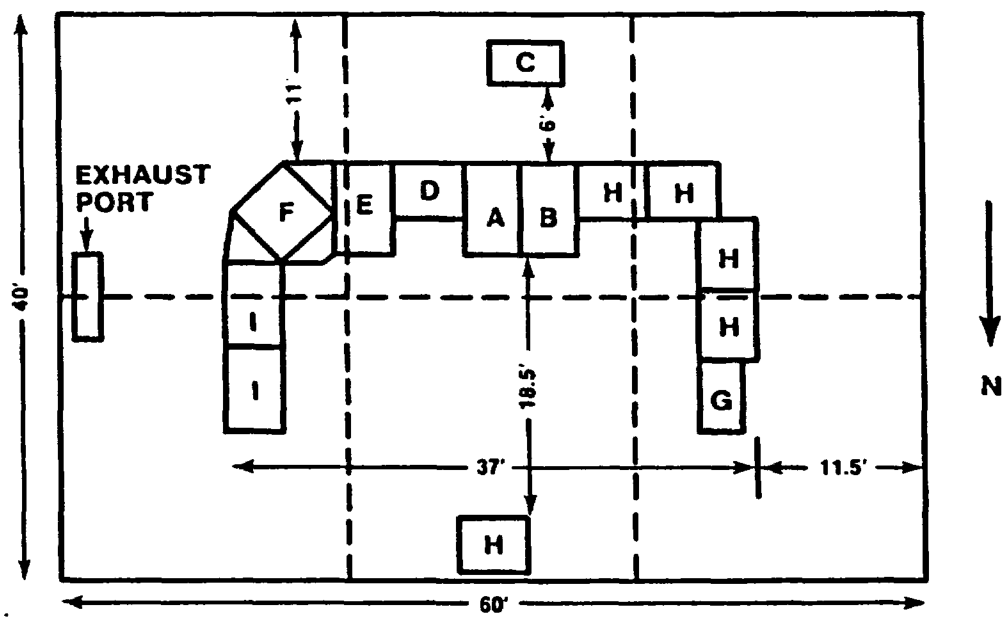



Figure 1. Three-Dimensional View of Test Enclosure




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.

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

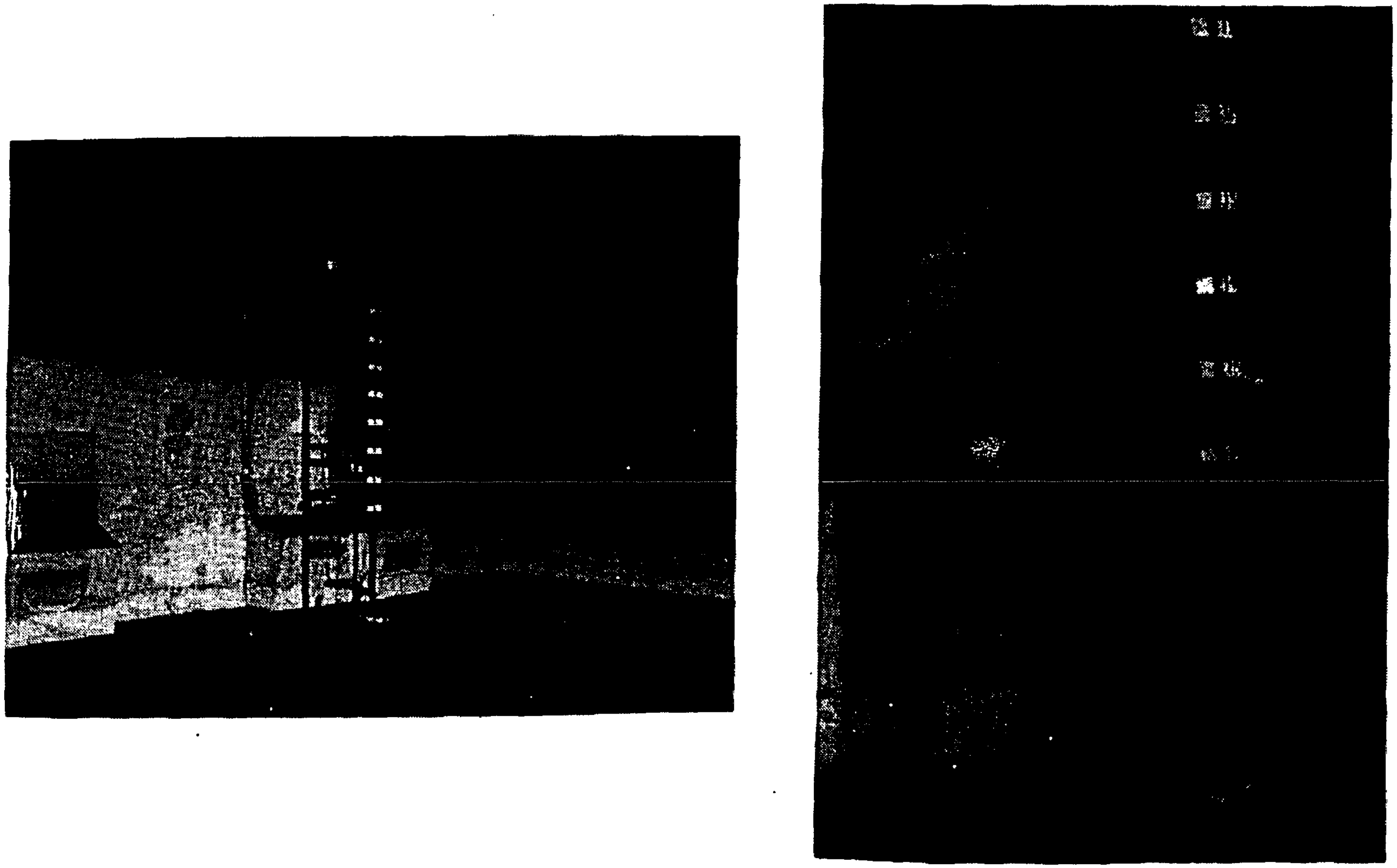

Figure 3. Photographs of Control Room Mockup

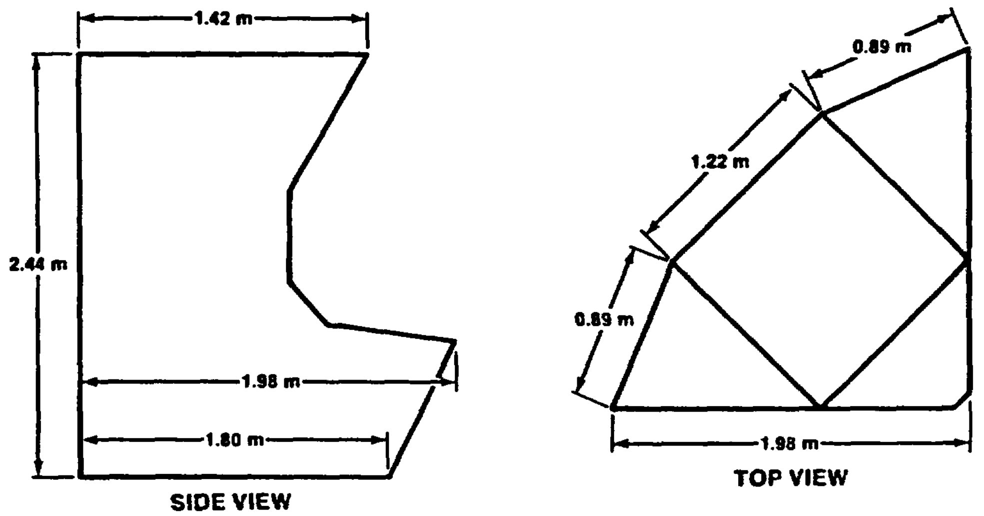


Figure 4. Schematic of Mitered Benchboard Cabinet

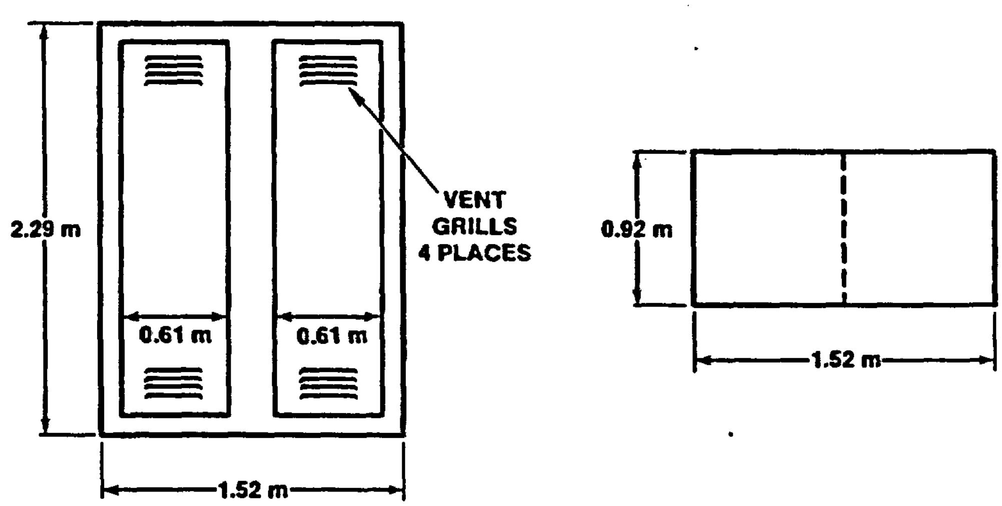


Figure 5. Schematic of Vertical Cabinet

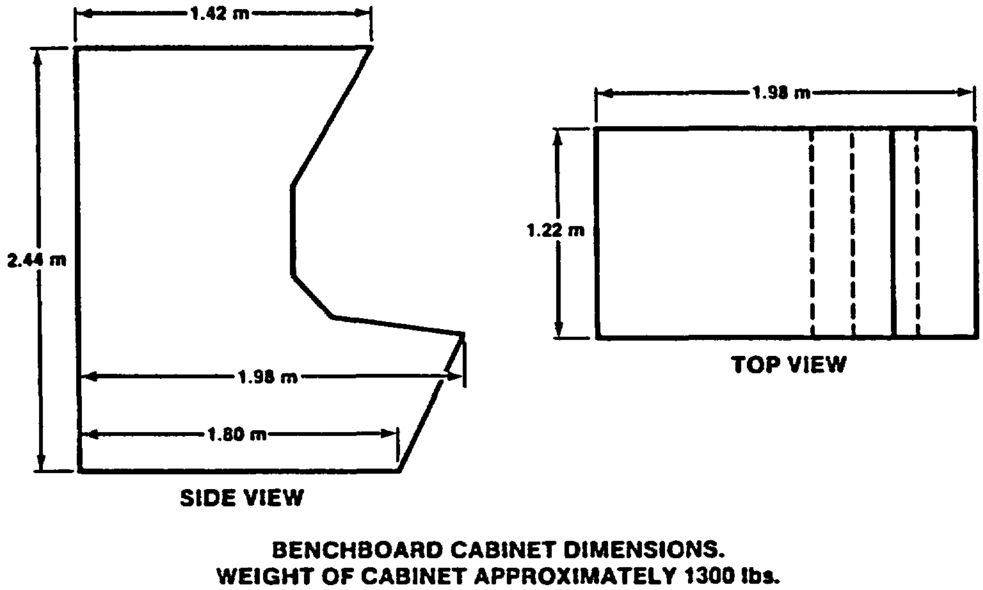


Figure 6. Schematic of Benchboard Cabinet

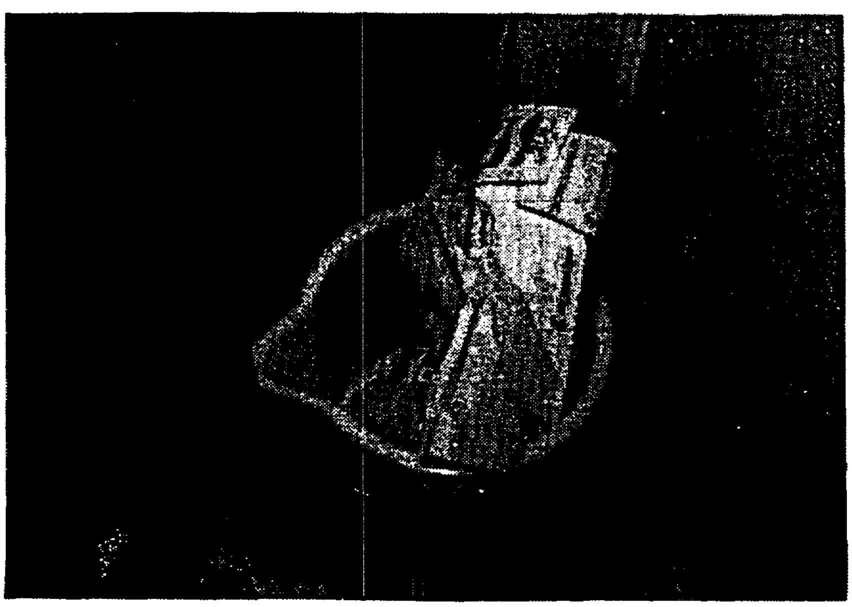

Figure 7. Photograph of Transient Ignition Source

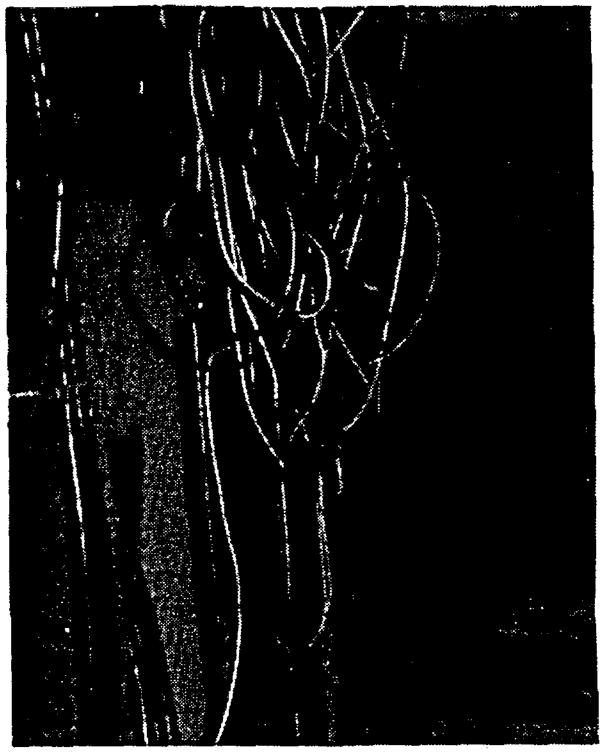

Figure 8. Photograph of Electrical Ignition Source

### 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.

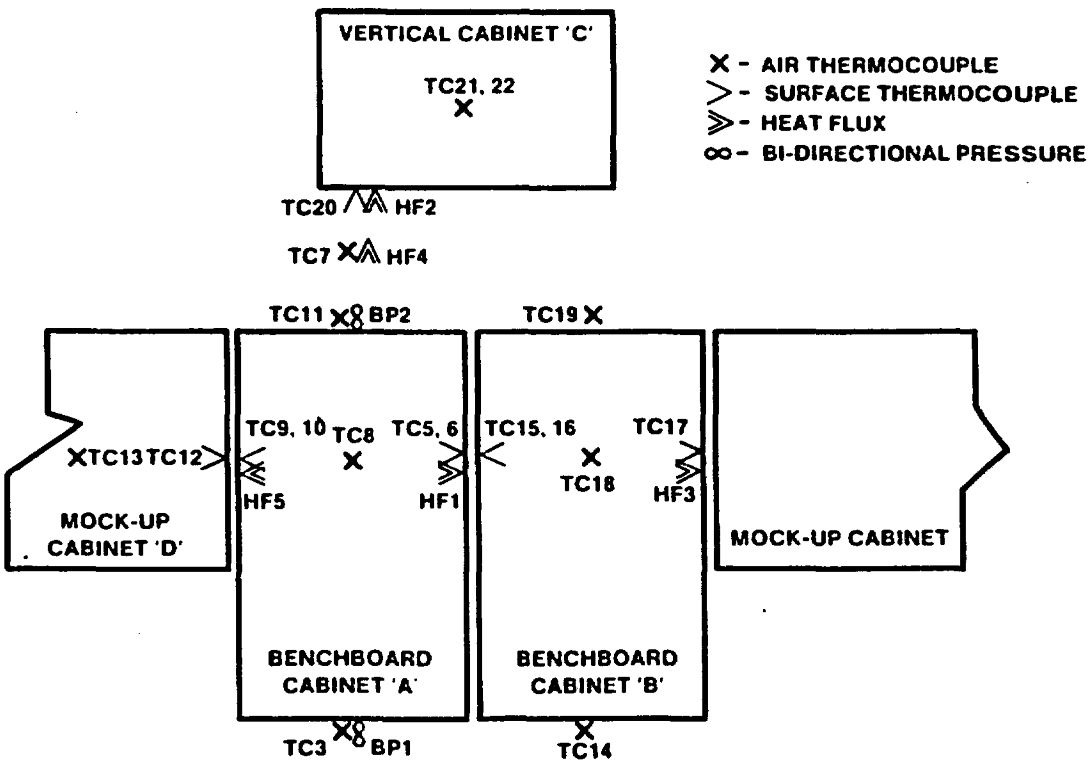


Figure 9. Schematic of Cabinet Instrumentation Layout

## 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

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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**

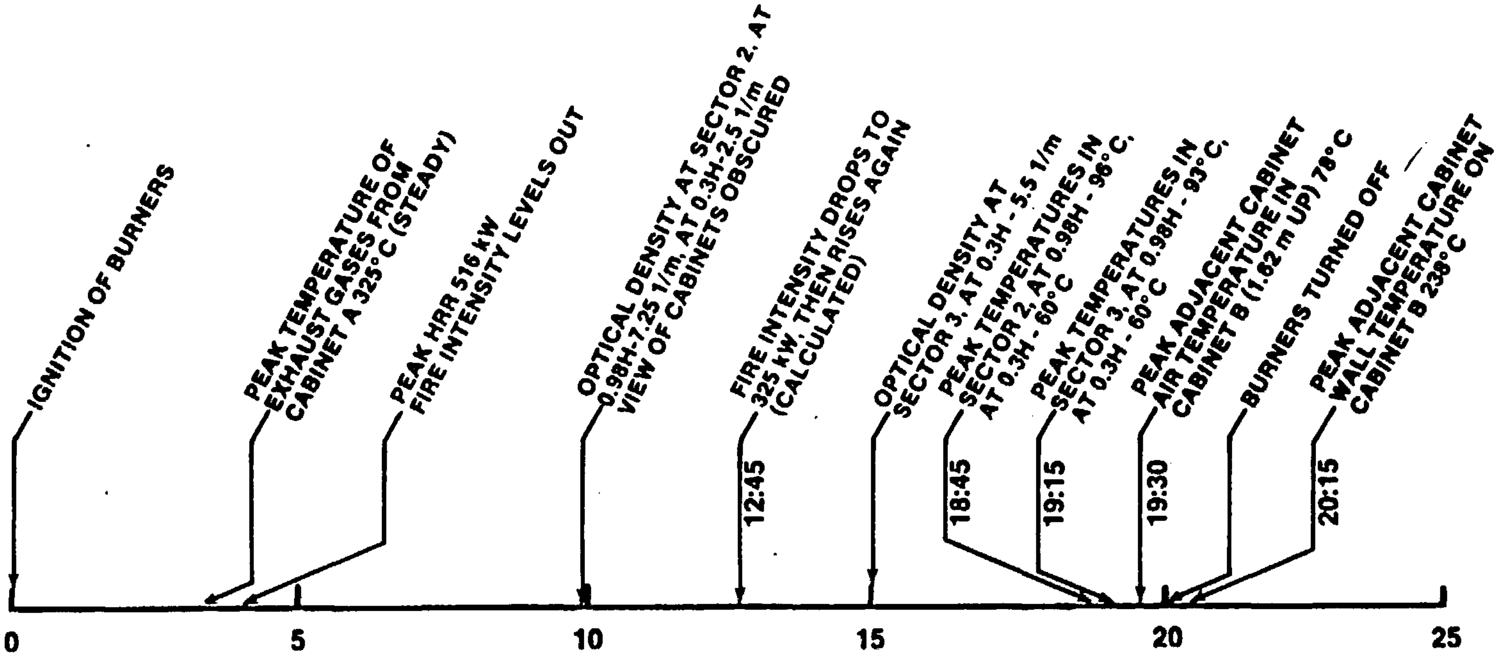



Figure 10. Description and Timeline for Test 21

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.

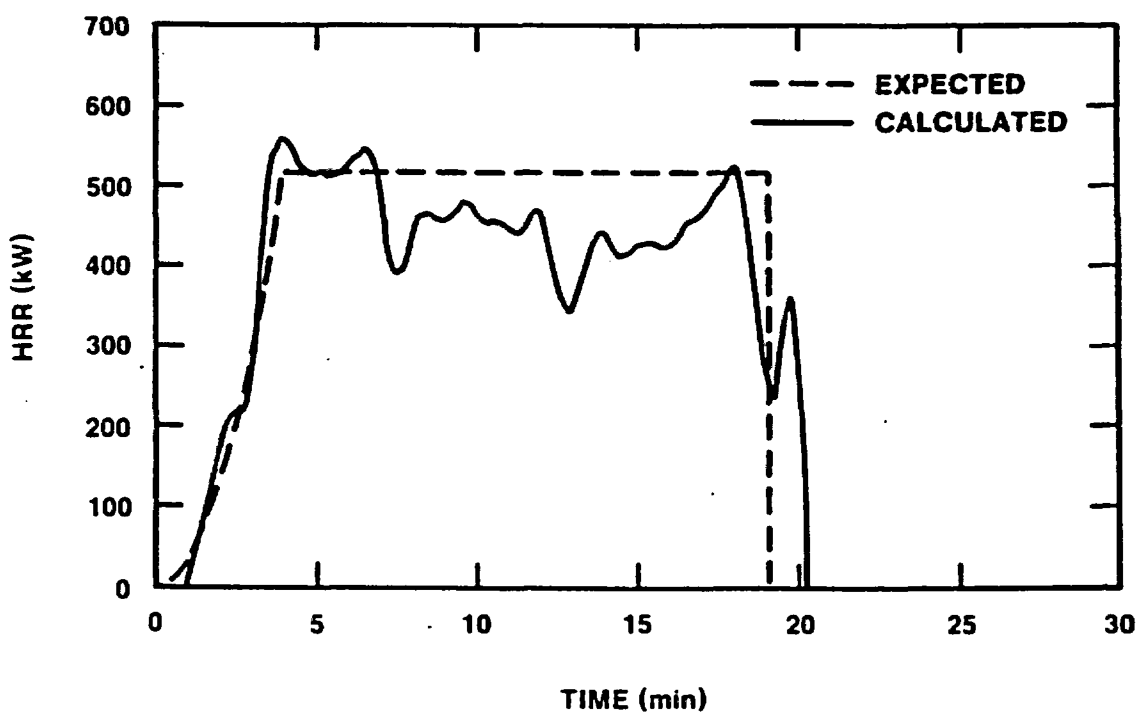



Figure 11. Expected and Calculated Heat-Release Rates During Test 21

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.

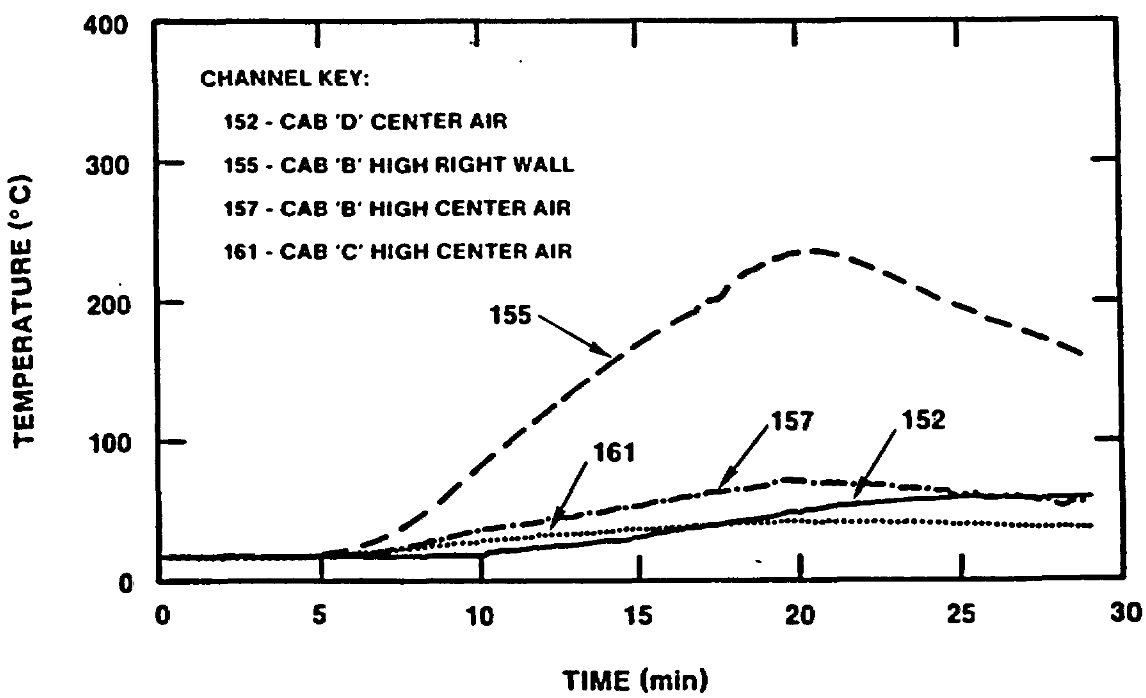



Figure 12. Temperatures in Noninvolved Cabinets During Test 21

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

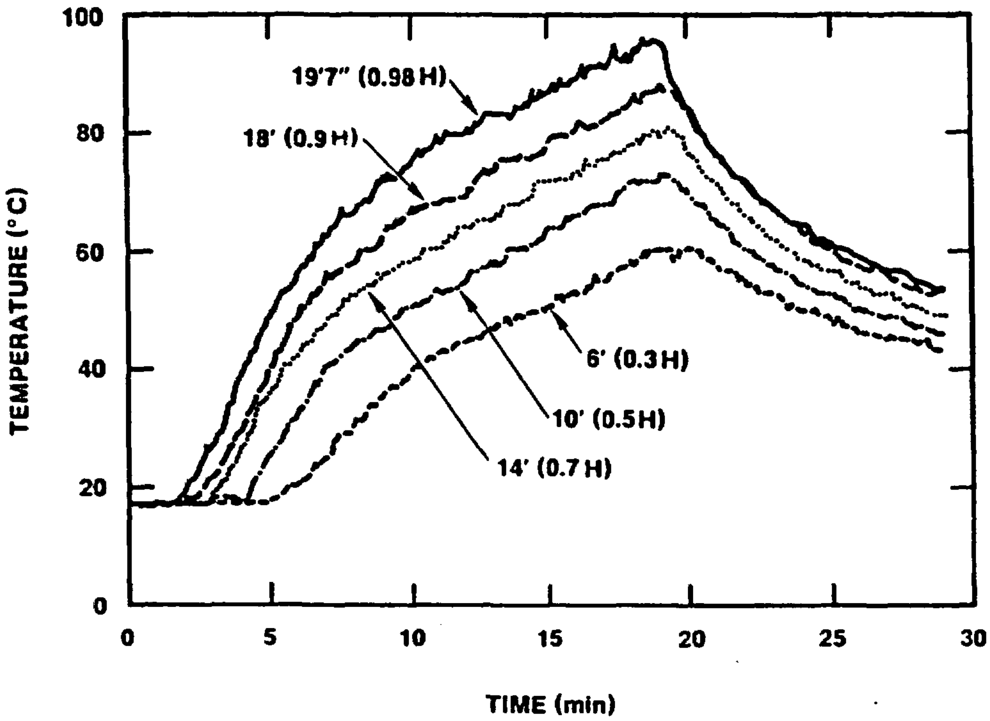



Figure 13. Aspirated Thermocouple Measurements at Sector 2 During Test 21

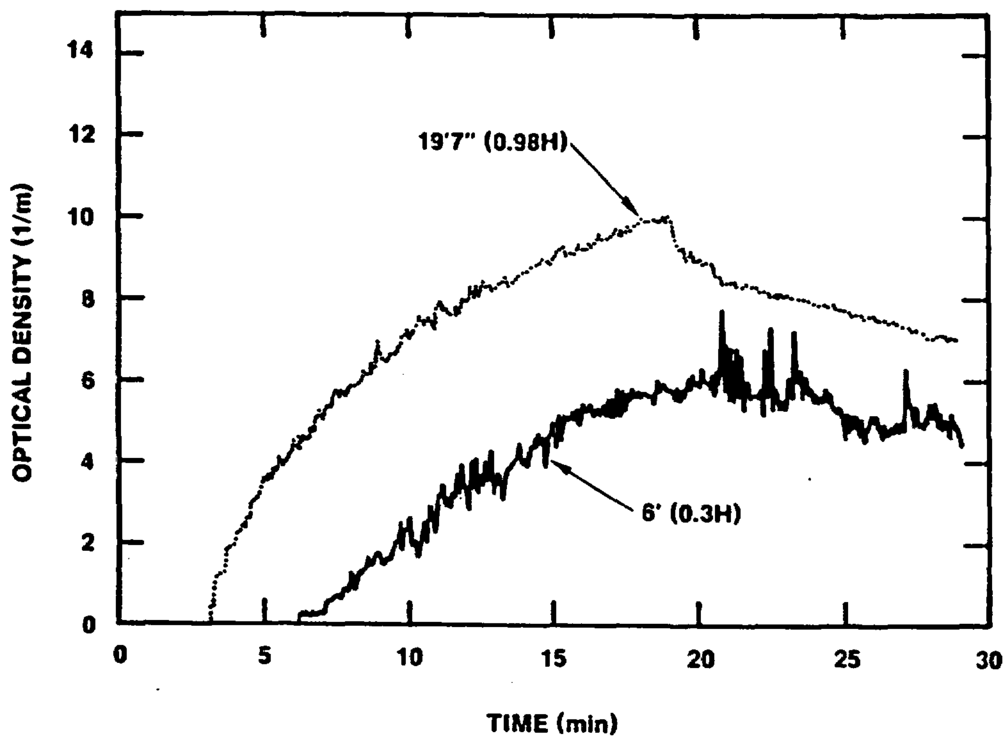



Figure 14. Optical Density at Sector 2 During Test 21

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**

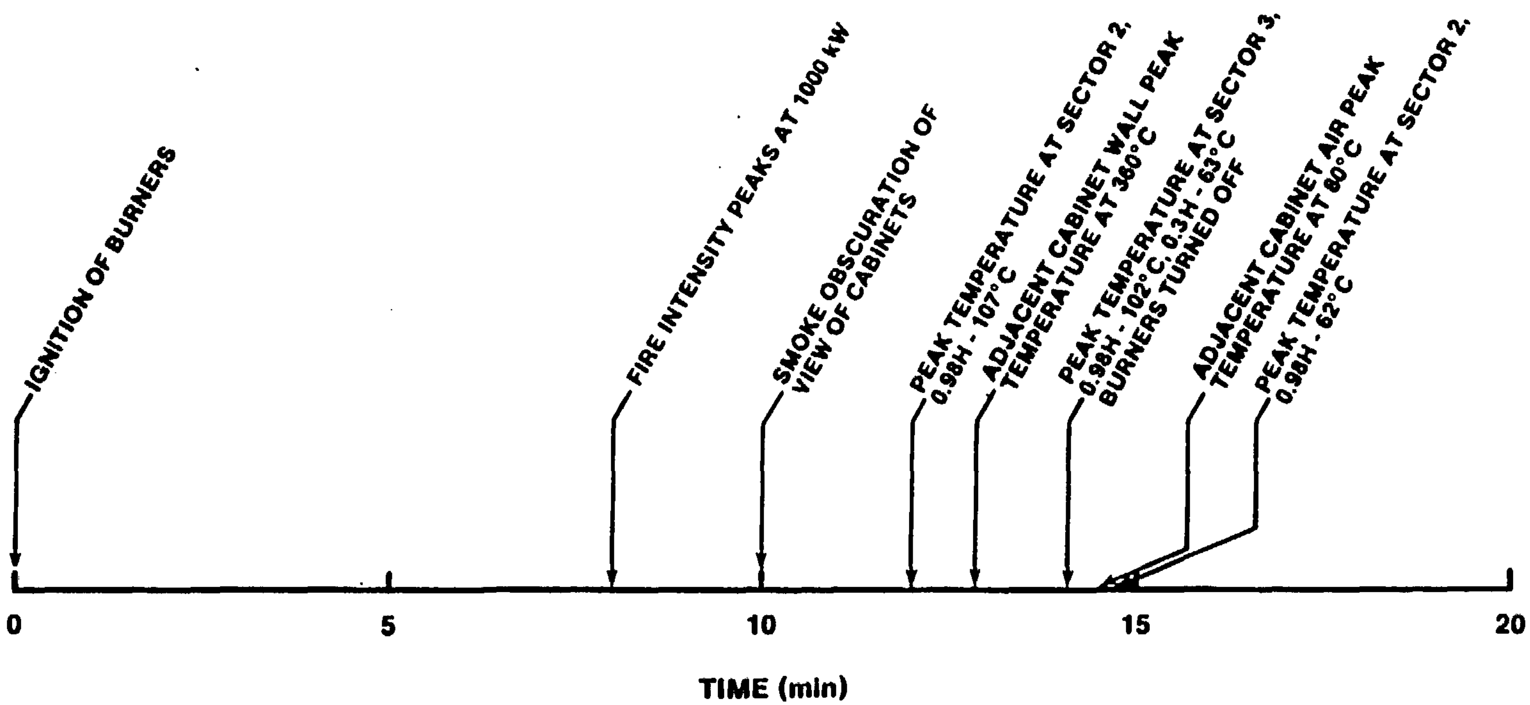



Figure 15. Description and Timeline for Test 22

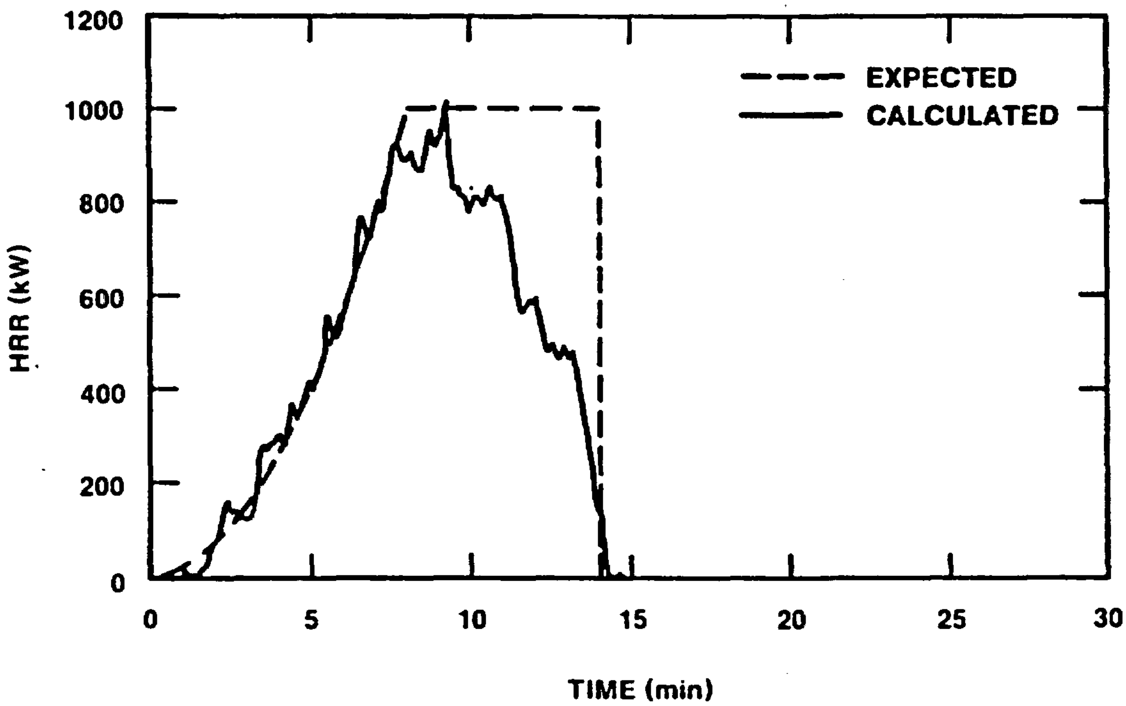



Figure 16. Expected and Calculated Heat-Release Rates During Test 22

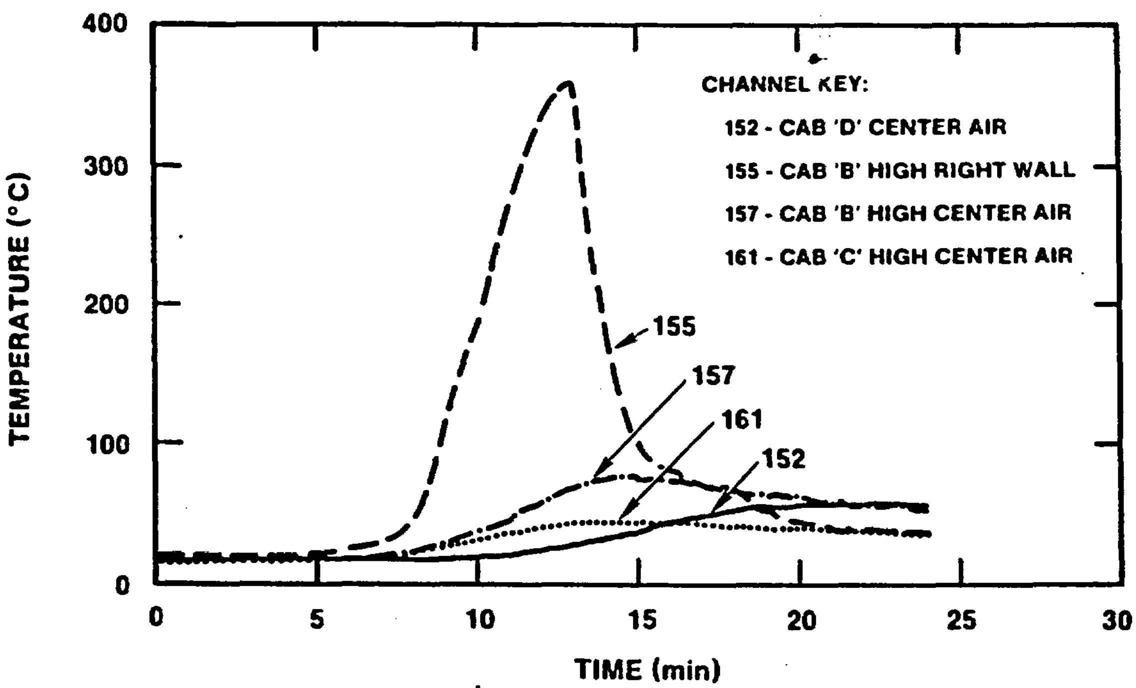



Figure 17. Temperatures in Noninvolved Cabinets During Test 22

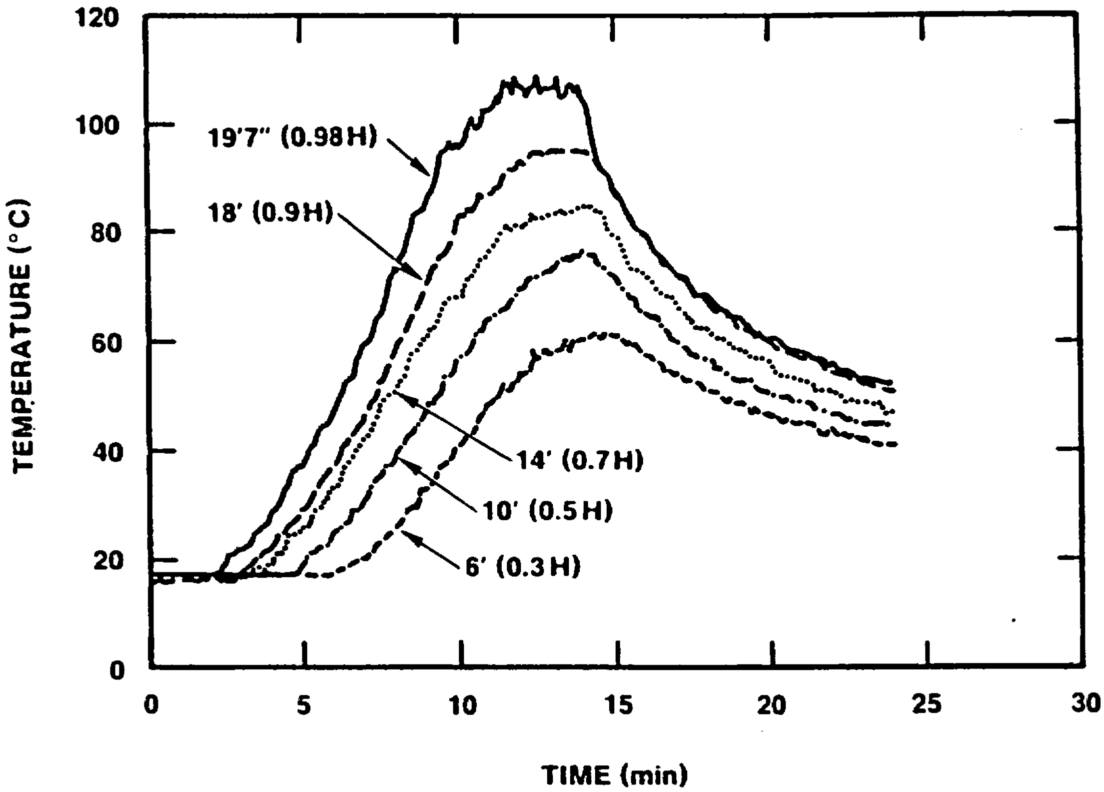



Figure 18. Aspirated Thermocouple Measurements at Sector 2 During Test 22

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 $1.55 \times 10^6$ kJ ($\approx 1.47 \times 10^6$ 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 $1.47 \times 10^6$ kJ (≈$1.44 \times 10^6$ 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), $1.55 \times 10^6$ kJ ($1.47 \times 10^6$ 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%

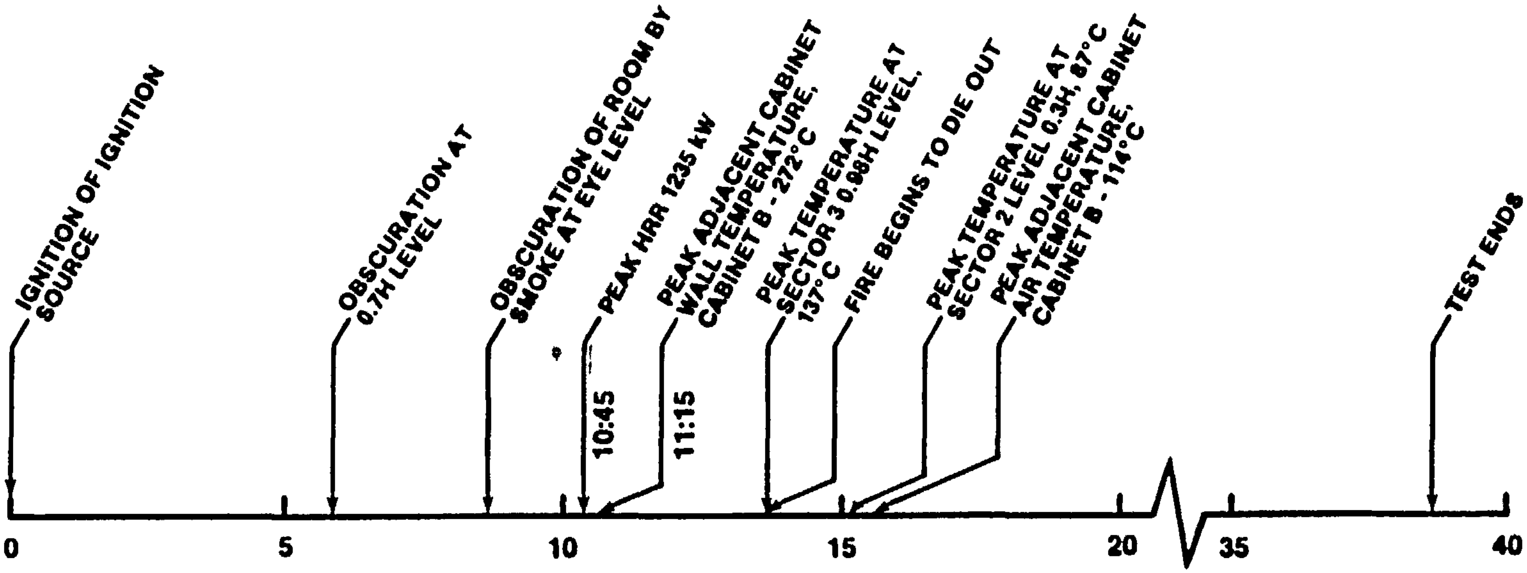
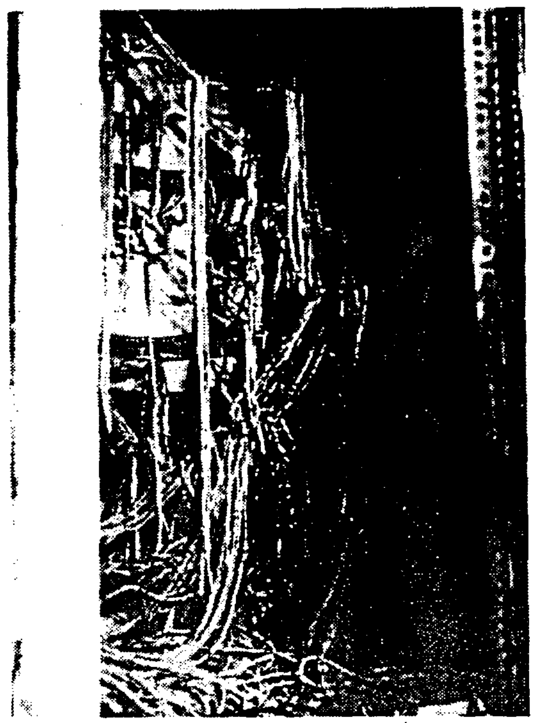



Figure 19. Description and Timeline for Test 23

a. 1:08 minutes

b. 3:40 minutes

c. 7:30 minutes



d. Posttest

Figure 20. Photographs of Test 23

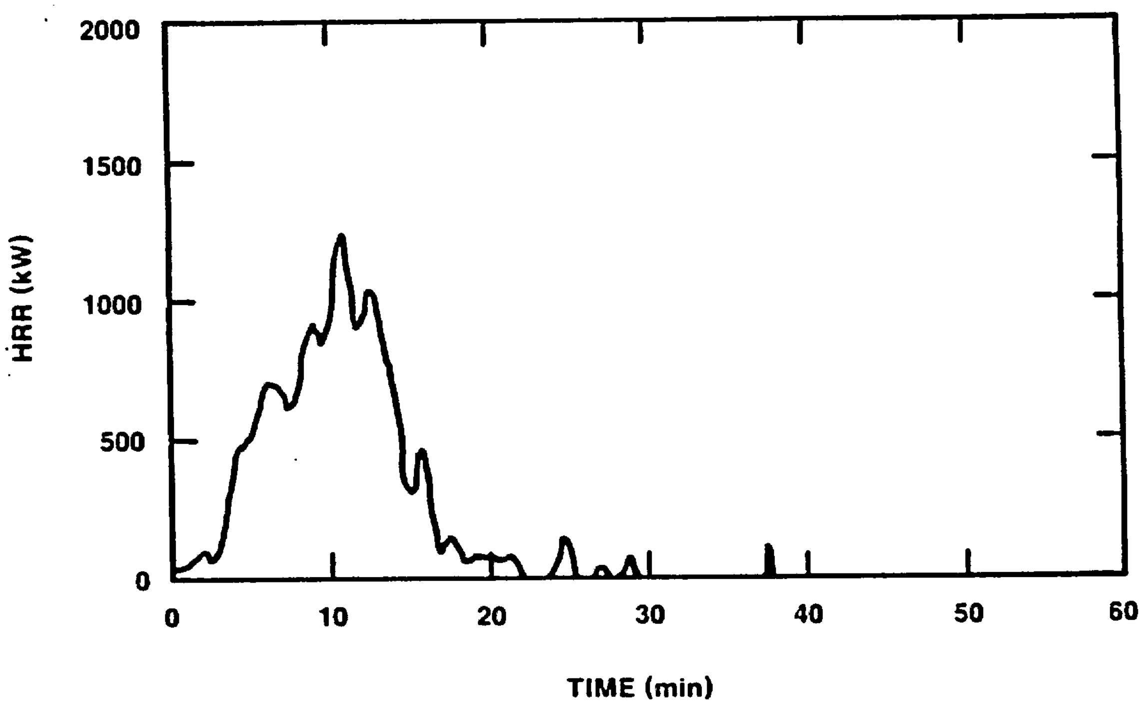



Figure 21. Calculated Heat-Release Rate for Test 23

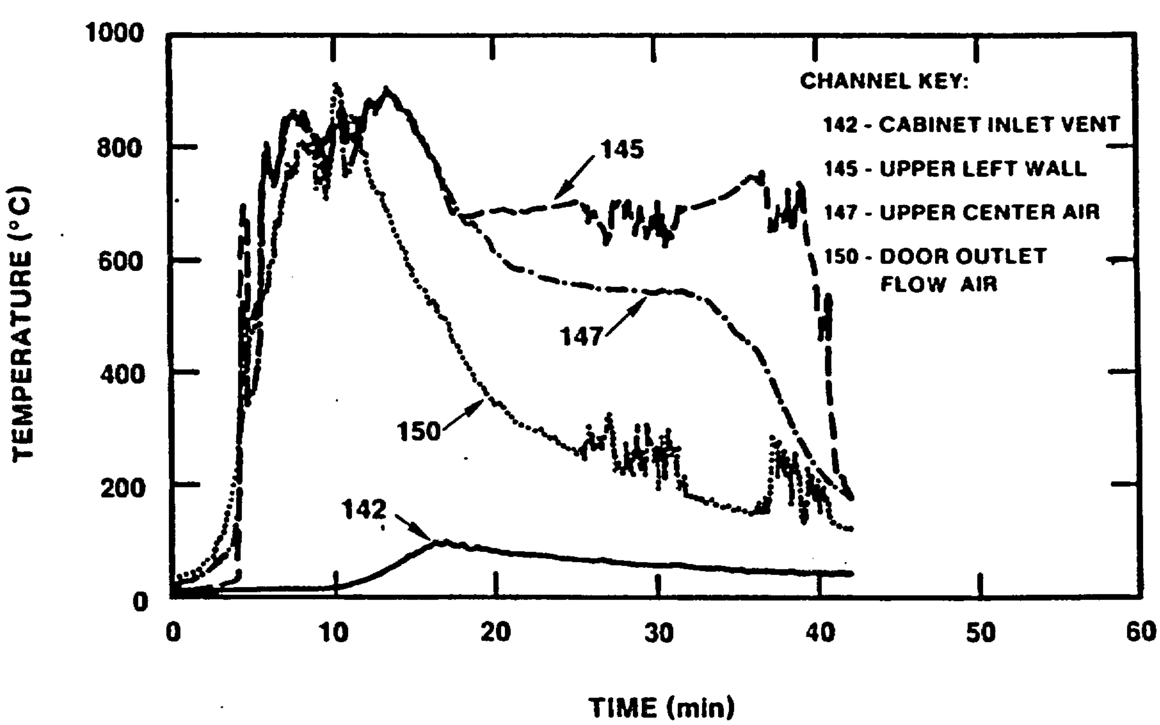



Figure 22. Temperatures in Cabinet A (Subject Cabinet) During Test 23

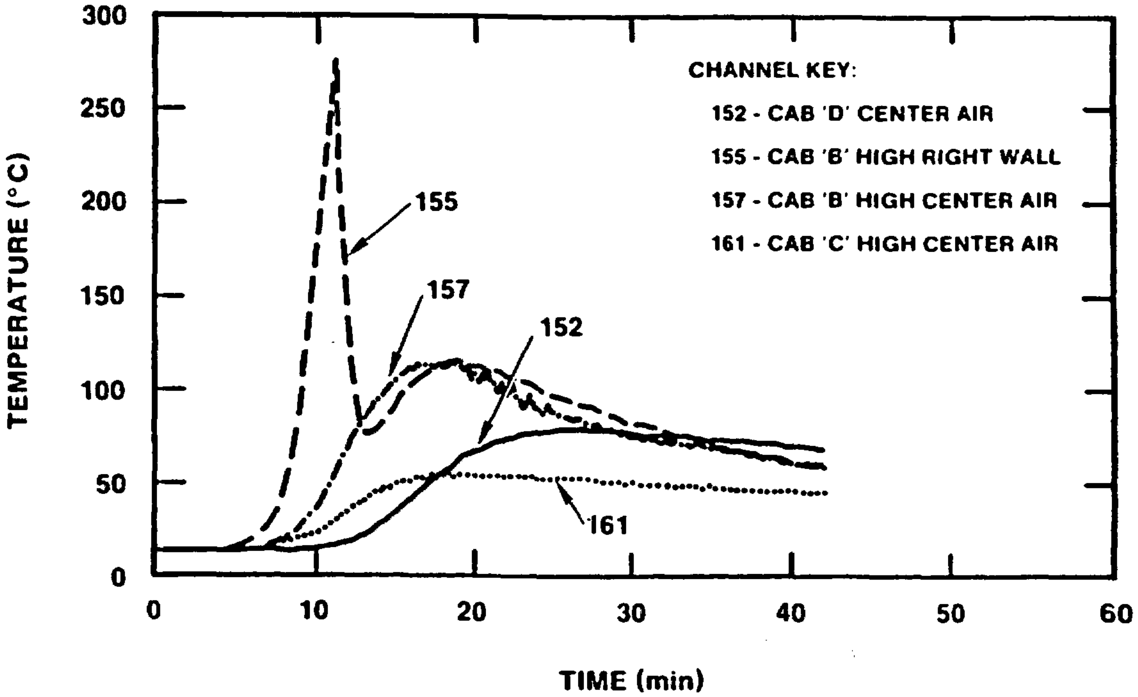



Figure 23. Temperatures in Noninvolved Cabinets During Test 23

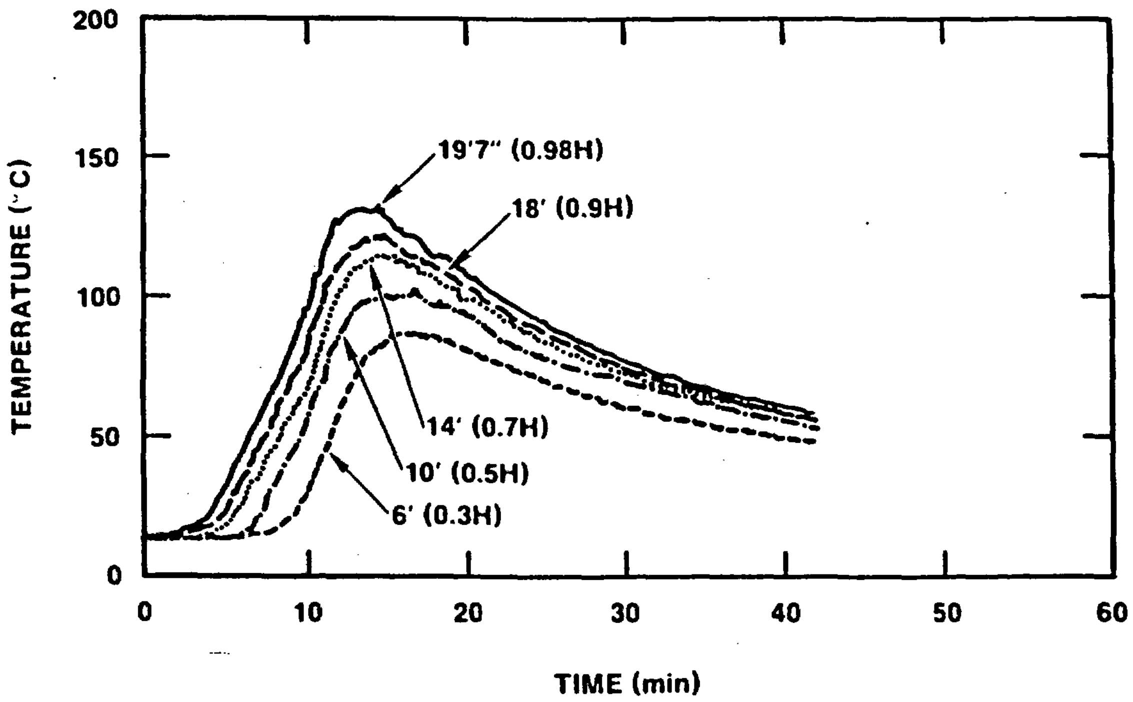



Figure 24. Sector 2 Air Temperatures at Each of Five Elevations During Test 23

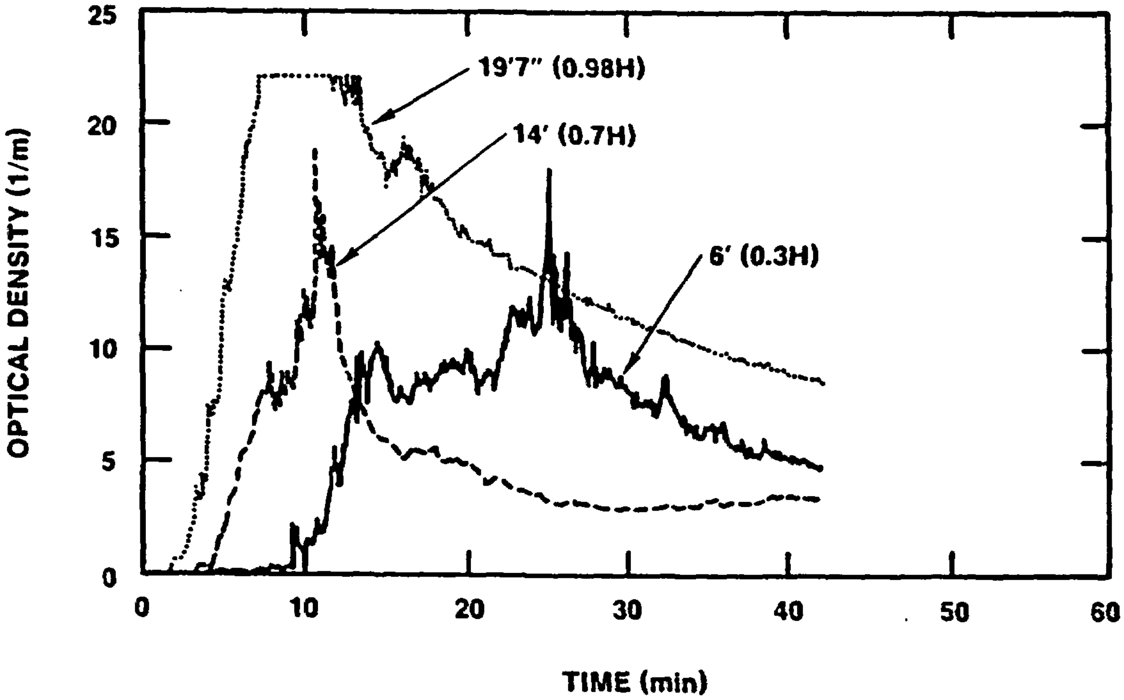



Figure 25. Sector 2 Optical Densities at Each of Three Elevations During Test 23

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), $1.47 \times 10^6$ kJ ($1.44 \times 10^6$ Btu)

**IGNITION TYPE & AMOUNT:** ELECTRICAL, IGNITION SOURCE

**ROOM VENTILATION RATE:** 1 rm ch/hr

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

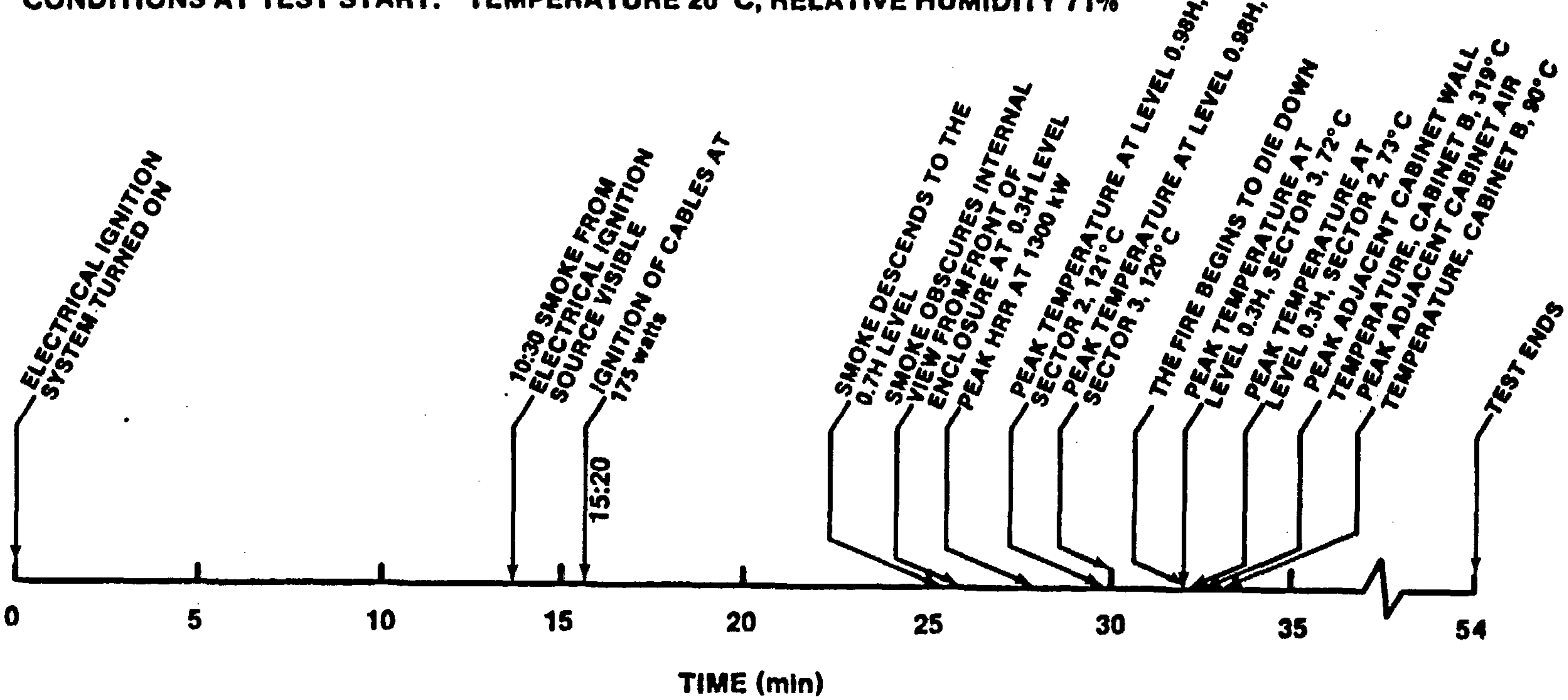
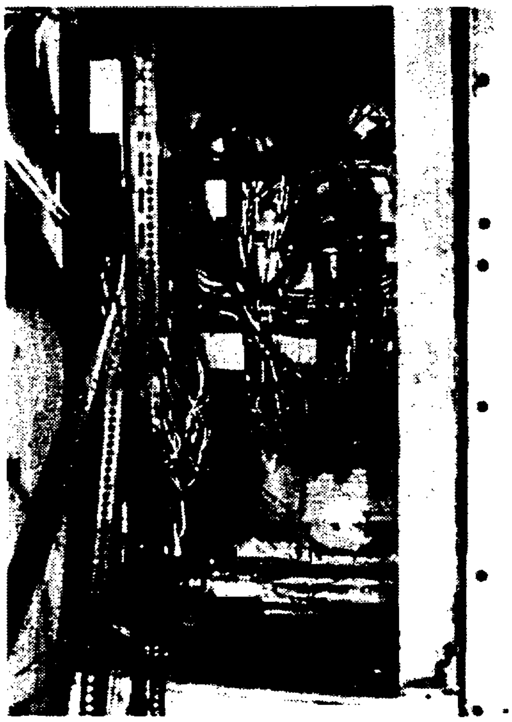



Figure 26. Description and Timeline for Test 24



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)

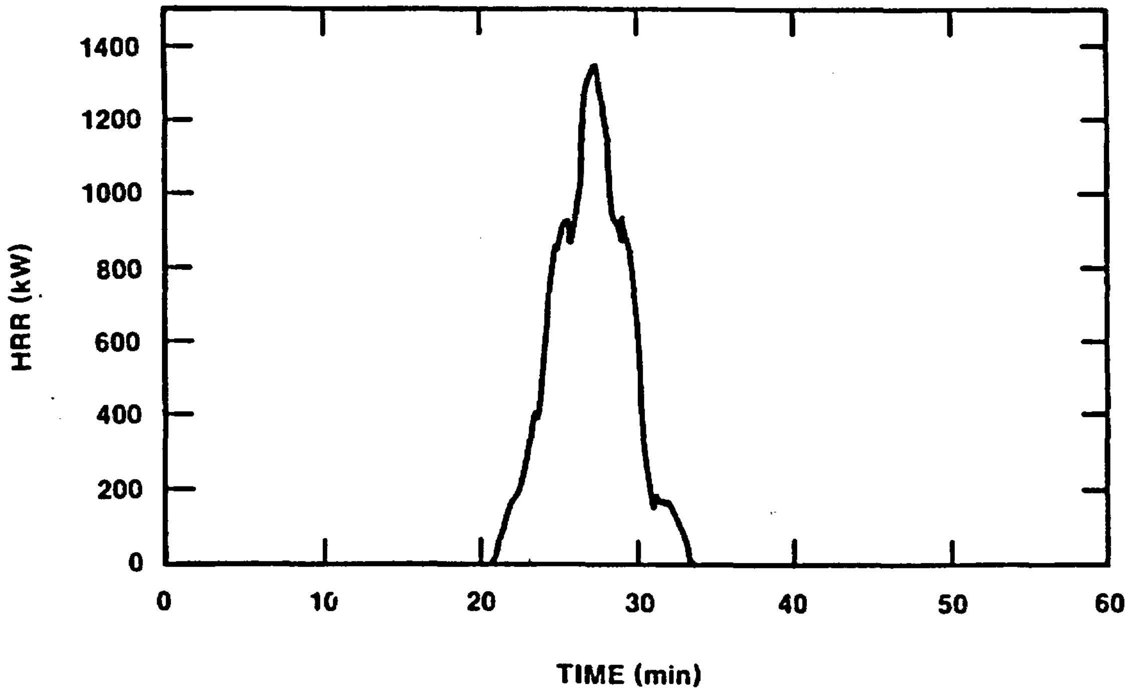



Figure 28. Calculated Heat-Release Rate for Test 24

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

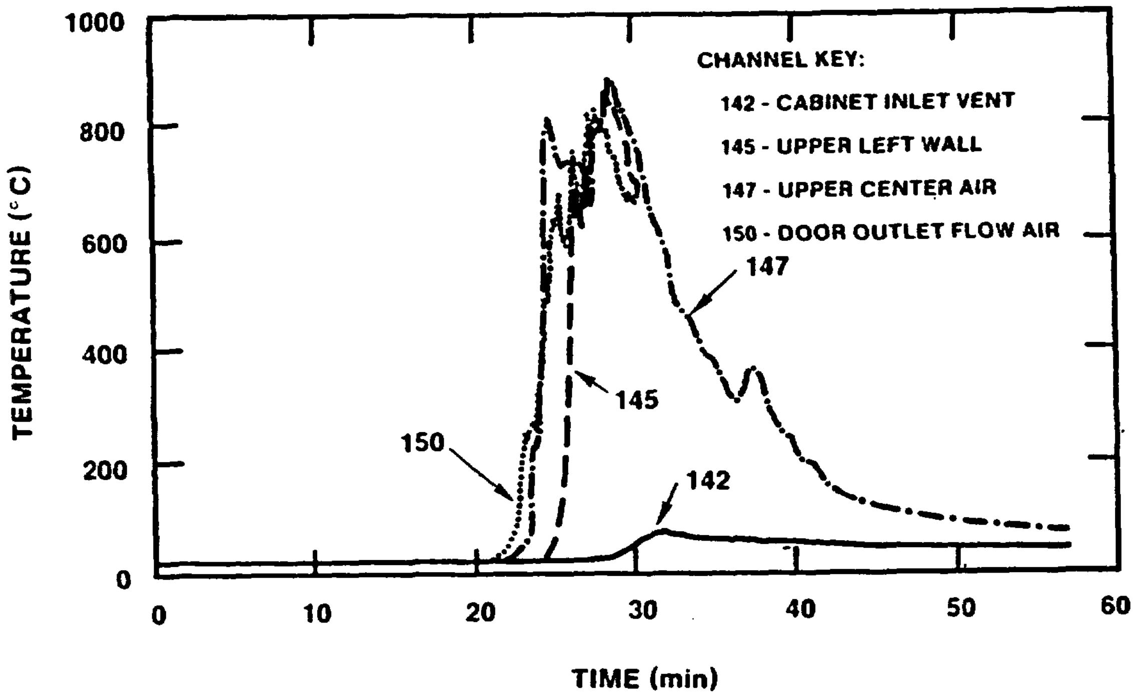



Figure 29. Temperatures in Cabinet A (Subject Cabinet) During Test 24. Note failure of TCs 145 and 150 at 30.5 min

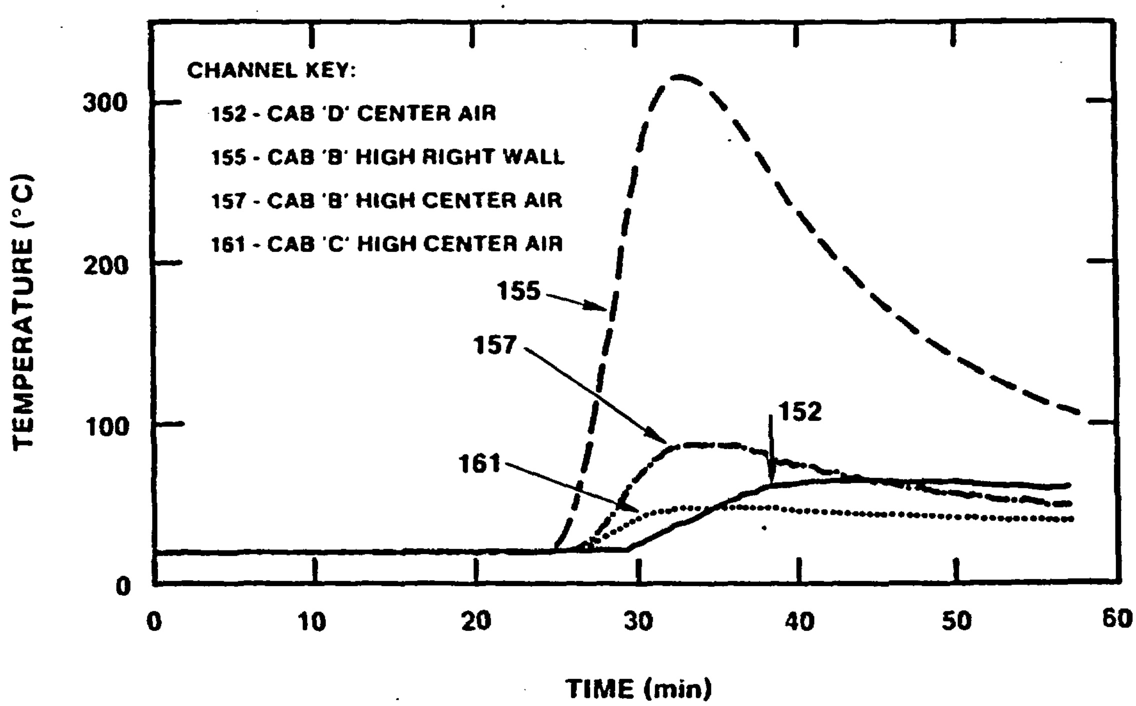



Figure 30. Temperatures in Noninvolved Cabinets During Test 24

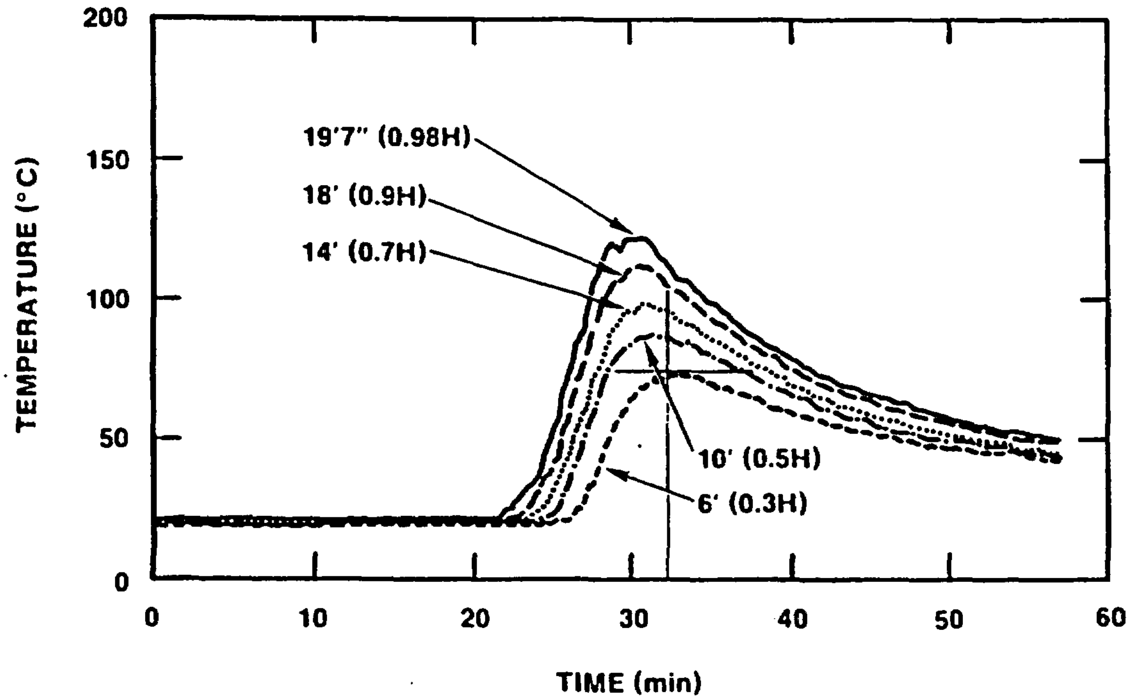



Figure 31. Sector 2 Air Temperatures at Each of Five Elevations During Test 24

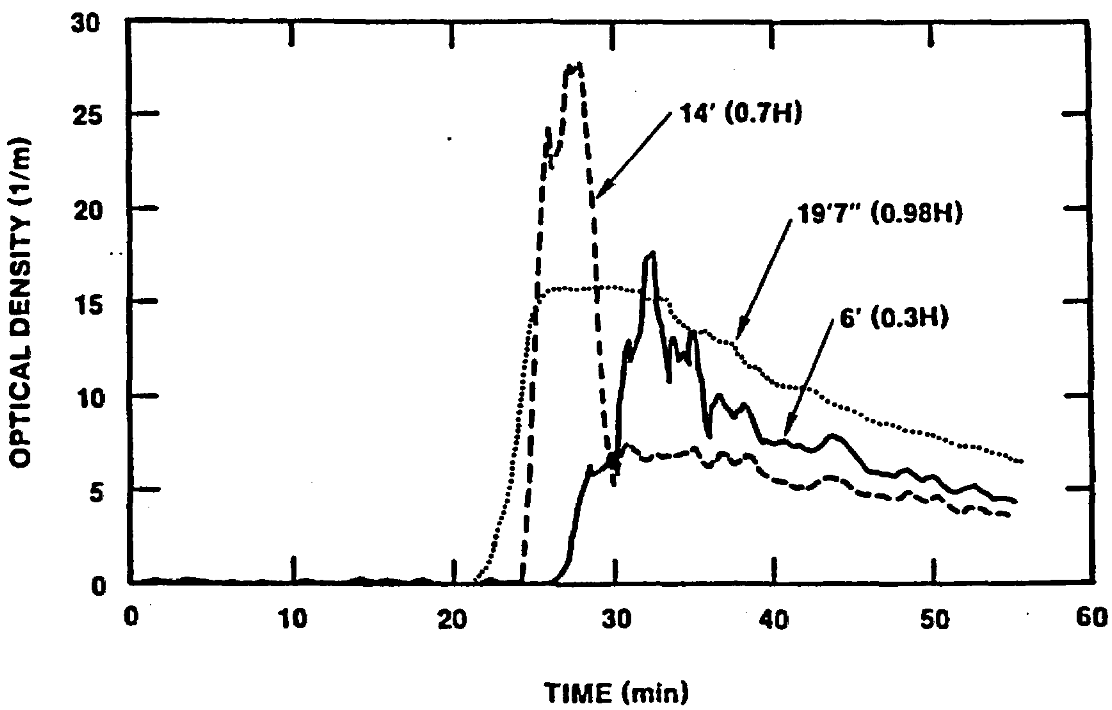



Figure 32. Sector 2 Optical Densities at Each of Three Elevations During Test 24

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 $1.05\times10^6$ kJ ($1.0\times10^6$ 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 x $10^6$ kJ (1 x $10^6$ Btu)

IGNITION TYPE & AMOUNT: ELECTRICAL IGNITION SOURCE

ROOM VENTILATION RATE: 8 rm ch/hr

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

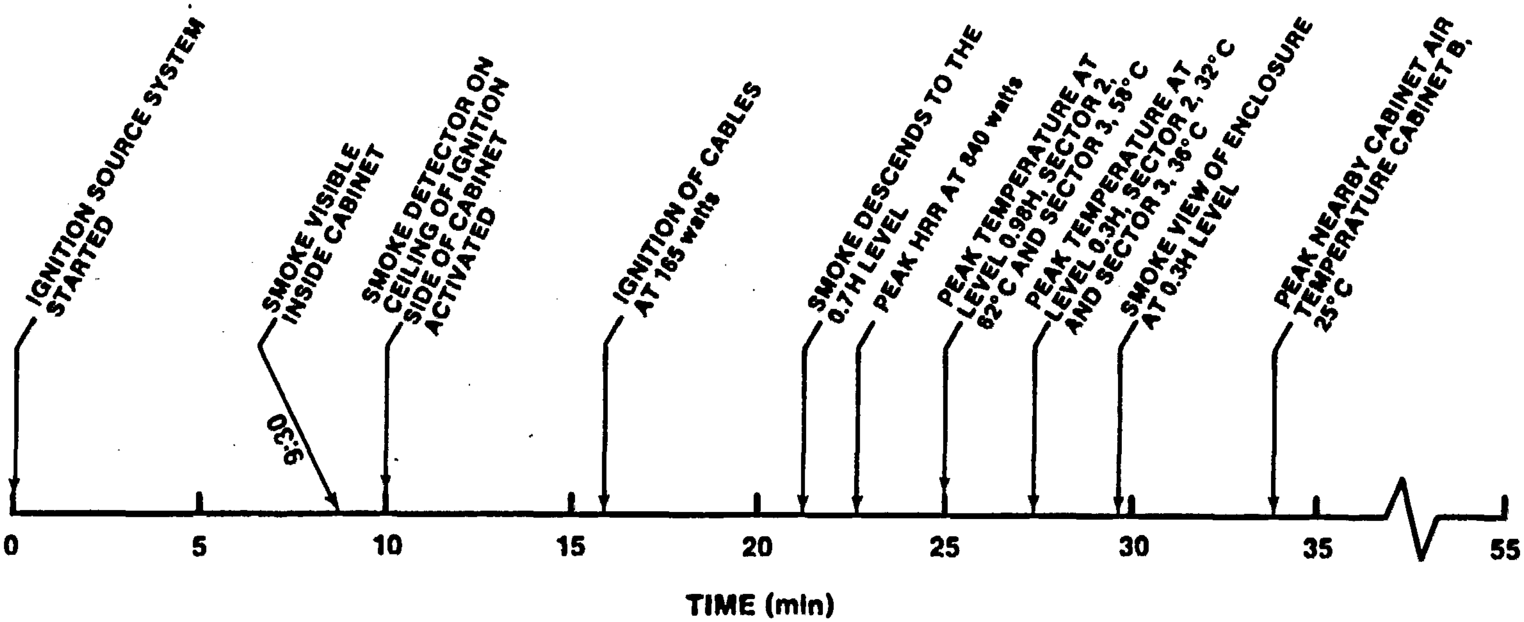
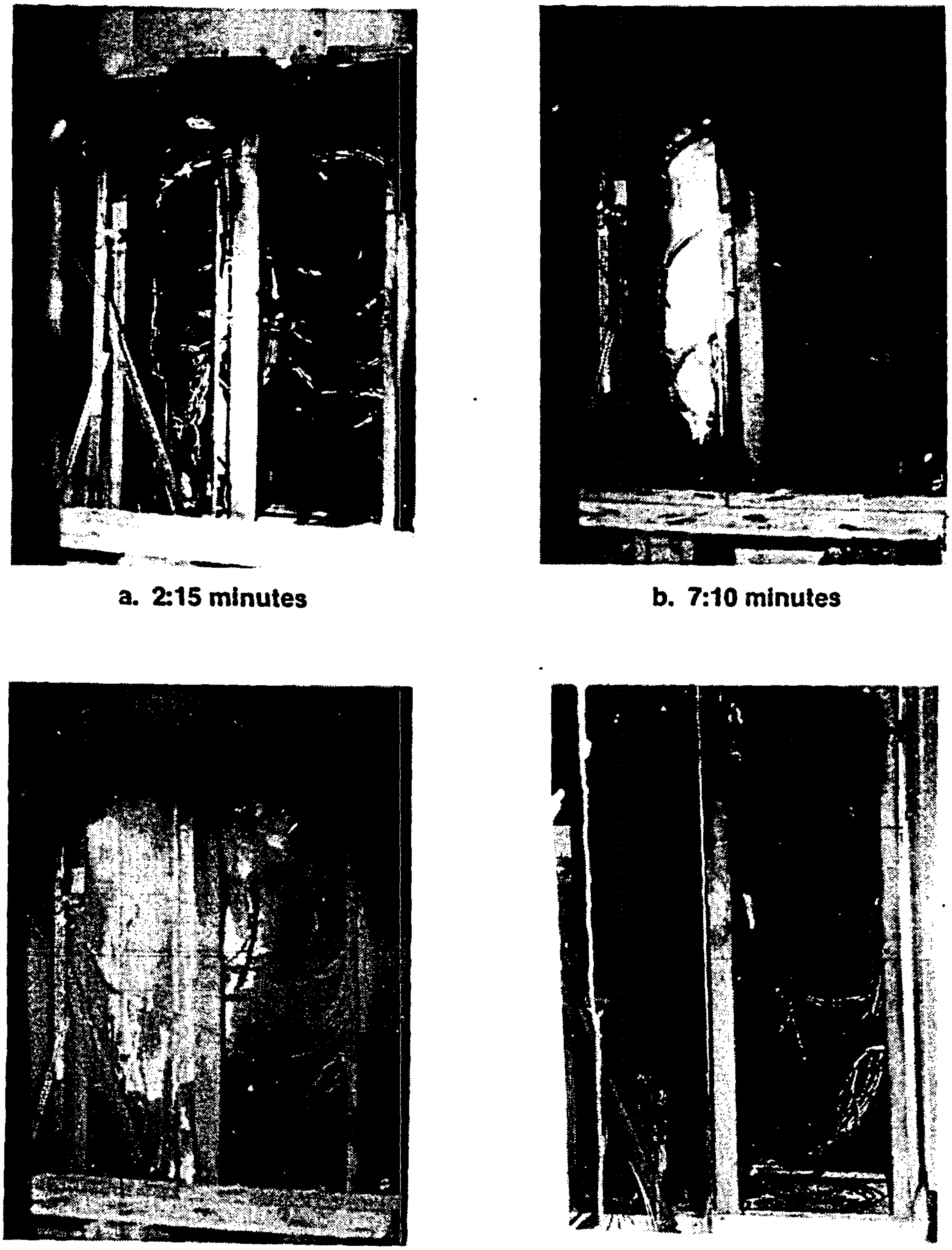



Figure 33. Description and Timeline for Test 25



a. 2:15 minutes

b. 7:10 minutes

c. 10:15 minutes

d. Posttest

Figure 34. Photographs of Test 25

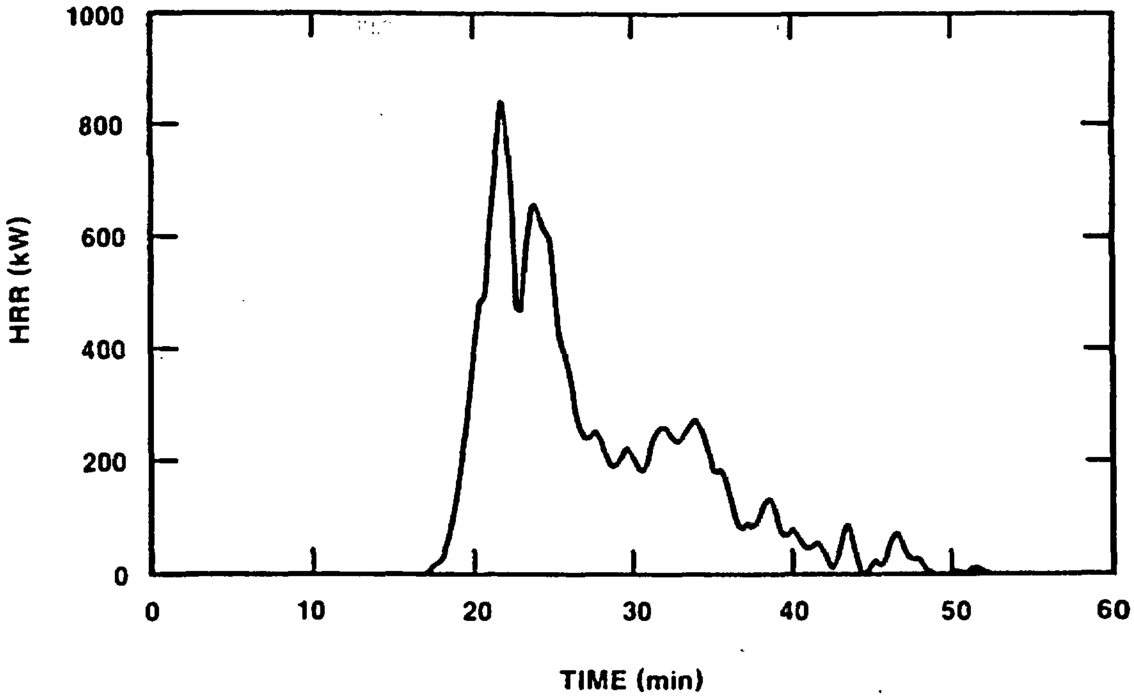



Figure 35. Heat-Release Rate for Test 25. Based on 8 rm ch/hr and then smoothed

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

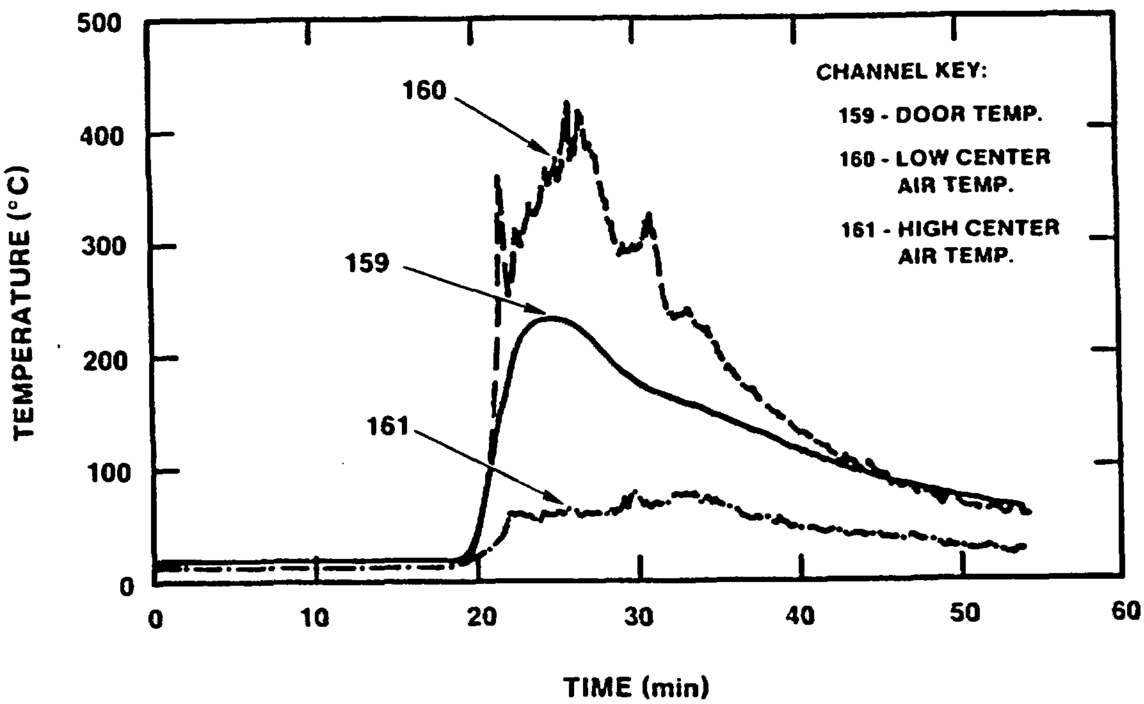



Figure 36. Temperatures in Cabinet C (Subject Cabinet) During Test 25

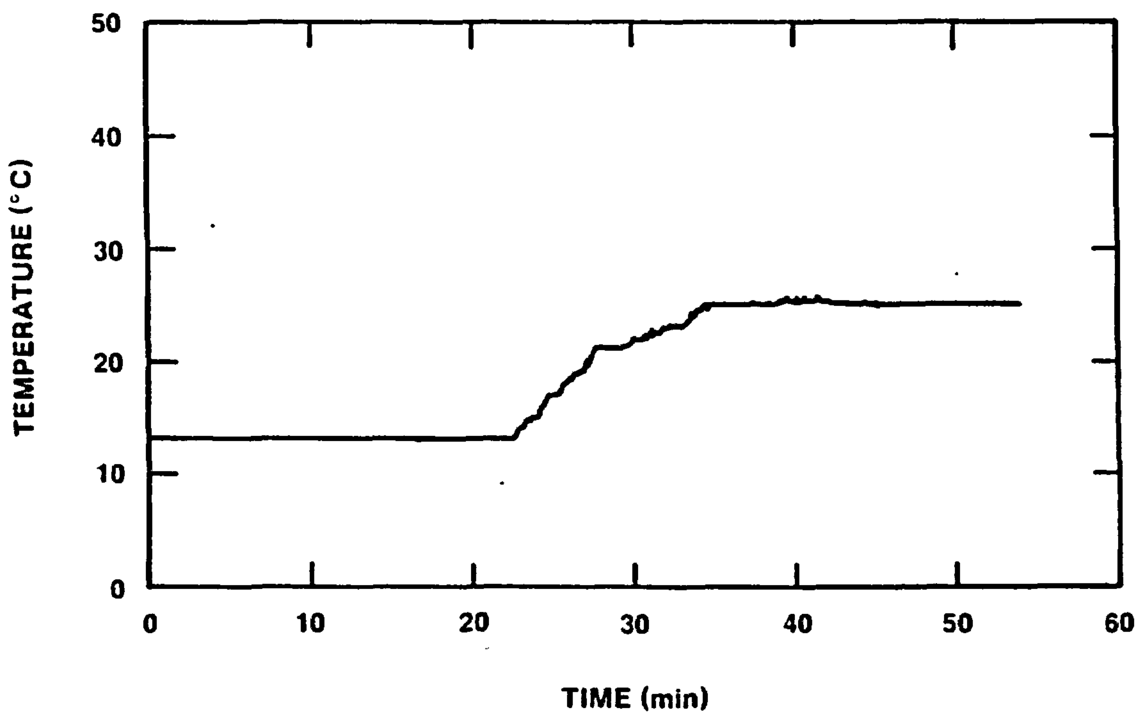



Figure 37. High Center Air Temperature in Cabinet B During Test 25

(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.

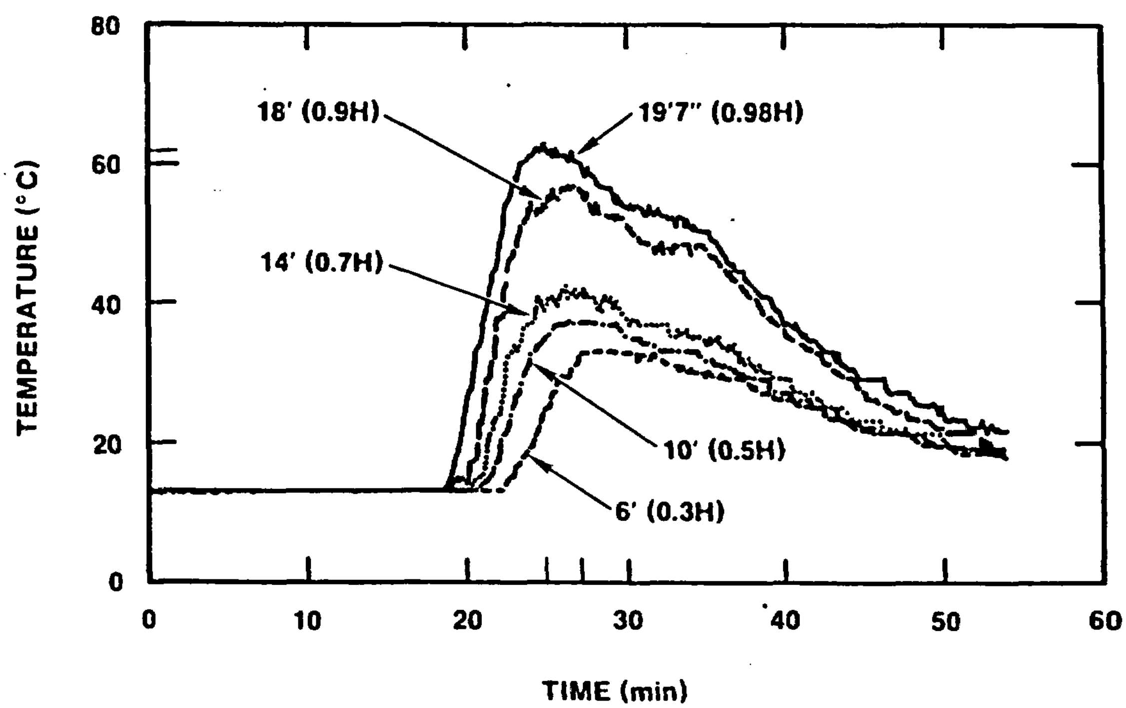



Figure 38. Sector 2 Air Temperatures at Each of Five Elevations During Test 25

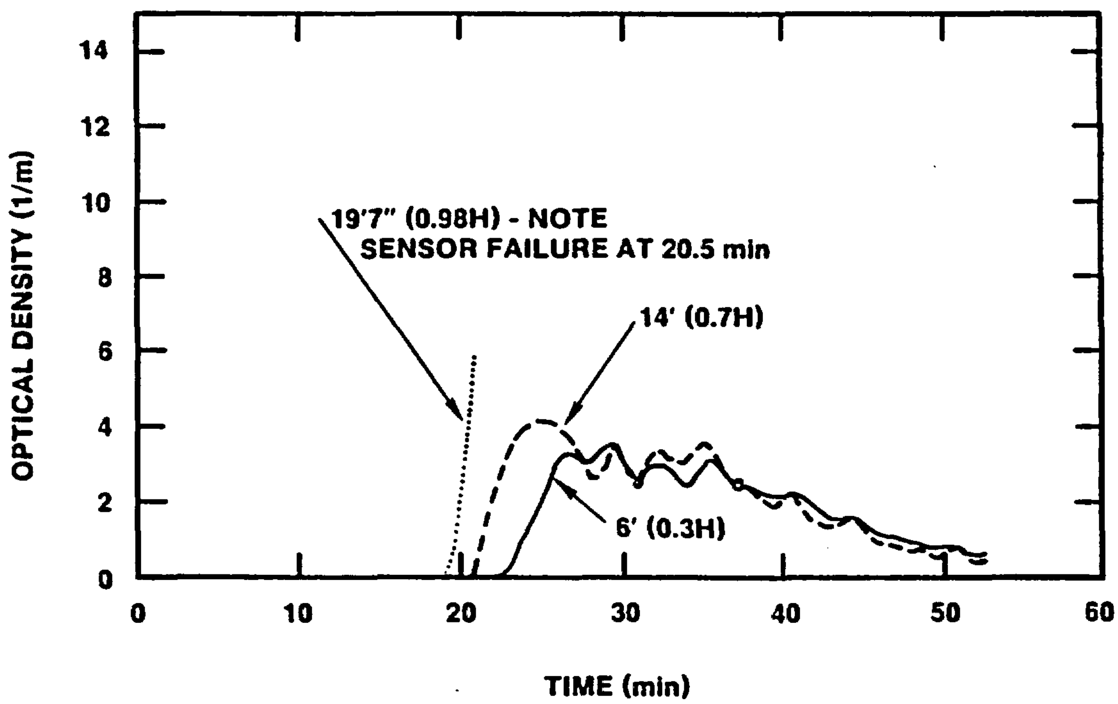



Figure 39. Sector 2 Optical Densities at Each of Three Elevations During Test 25

# 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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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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